Assessment of Intrinsic Vulnerability using the DRASTIC Model and GIS in the Kiti Aquifer, Cyprus

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Abstract: Approximately 70% of the world’s population lives in coastal areas and the majority of these people depend on coastal aquifers for freshwater. For this reason, coastal aquifers are vulnerable to pollution and are now recognised as a crucial arena for future progress towards global freshwater sustainability. This paper deals with an assessment of the groundwater vulnerability of the Kiti aquifer, South Cyprus. The Kiti aquifer, covering an area of about 30 Km² at a mean elevation of 20 m above sea level, is situated in the southern part of Cyprus, a region characterised by semi-arid climatic conditions. The groundwater resources are related to the Pleistocene coastal plain and the recent Tremithos river valley deposits. The concept of groundwater vulnerability is based on the assumption that the physical environment may provide some degree of protection for groundwater against human activities. The DRASTIC method, applied to evaluate aquifer vulnerability, was developed by the United States Environmental Protection Agency (EPA) as a technique for assessing groundwater pollution potential and is based on seven (7) parameters: Depth (D), Recharge (R), Aquifer media (A), Soil media (S), Topography (T), Impact of vadose zone media (I) and hydraulic Conductivity of the aquifer (C). Determination of the DRASTIC index (DI) involves multiplying each parameter weight by its site rating and summing the total. Based on DI values, a groundwater vulnerability map was produced using a Geographical Information System (GIS). The highest vulnerability values, covering a large expanse of the study area, are associated with shallow aquifers without great depth of vadose zone. The results provide important information, with the vulnerability map suitable for use by local authorities and decision makers responsible for groundwater resource management and protection zoning.

Keywords: Aquifer, Cyprus, DRASTIC method, GIS technique, Kiti, Vulnerability

1. INTRODUCTION

The socioeconomic development of a region depends on the availability of good quality water. Recent decades have seen a global increase in demand for freshwater, mainly satisfied by groundwater abstracted from aquifers via numerous wells and boreholes. Groundwater is under intense anthropogenic pressure in the Mediterranean basin, from sources such as changes in land use, urbanisation, a lack of proper sewerage, intensive agriculture and a general increase in demand. These factors can cause severe degradation of both the quality and quantity of groundwater resources (UNESCO, 1998; Civita, 1994; Polemio, 2005; Polemio et al., 2008).

The most efficient method of combating groundwater pollution is its initial prevention. The new EC Directive 2006/118 on the protection of groundwater against pollution and deterioration, developed under Water Framework Directive 2000/60, sets out criteria with which to assess the chemical status of groundwater bodies. The aforementioned Directives have also forced EC member states to ensure good chemical and ecological groundwater conditions. Given this description of the problem, it seems necessary to individuate and implement a water system management strategy in order to guarantee sustainability of water use and safeguard ecosystems depending on water resources (Foster & Hirata, 1998; Gianneli et al., 2007).

The concept of aquifer vulnerability to external pollution was introduced in the 1960s by Margat (1968), with several systems of aquifer vulnerability assessment developed in the following years (Aller et al., 1987; Civita, 1994; Vrba & Zaporozec, 1994; Sener et al., 2009; Polemio et al., 2009).
Vulnerability refers to the sensitivity of an aquifer system to deterioration due to an external action (Al-Zabet, 2002). It is an intrinsic property of an aquifer system and can vary with regard to the specific natural and/or human impact. It is pointed out that vulnerability is a general concept and can be used in the assessment of impacts from floods or droughts (Tsakiris, 2009). In the last few decades, many techniques have been developed to assess groundwater vulnerability, including index, rating, hybrid, statistical and simulation methods (Voudouris, 2009). The DRASTIC method has been the most commonly used for mapping vulnerability in porous aquifers (Aller et al., 1987).

This paper deals with the groundwater vulnerability in the alluvial aquifer of the Kiti aquifer, South Cyprus. Firstly, results from previous hydrogeological studies, including the development of aquifers, hydraulic parameters and groundwater quality are discussed. A vulnerability map is then presented, produced using the DRASTIC method in a GIS context (Vrba & Zaporozec, 1994; Polemio & Ricchetti, 2001; Panagopoulos et al., 2005; Gemitzi et al., 2006). This scientific work was carried out within the framework of an INTERREG III B ARCHIMED program, funded by the European Union (Voudouris et al., 2007).

2. DESCRIPTION OF STUDY AREA

The region of study is the River Tremithos basin (Kiti aquifer), situated in the southern part of Cyprus and covering an area of about 30 km² (Fig. 1). It extends from the border of the Kiti Community as far as the coast and contains both residential and rural land-use (Fig. 1). The most important economic activities in the area are tourism and agriculture.

At an elevation of 20 m above sea level, the region is characterised by semi-arid climatic conditions, with a mean annual rainfall of 342.5 mm and a mean annual temperature of 19.6 °C.

A simplified geological map is shown in Fig. 2. The study area is affected by many pollution sources (agricultural activities, municipal wastes) influencing groundwater quality.

![Figure 1. Topographic map of the Kiti area.](image)

The groundwater resources are related to the Pleistocene coastal plain and the recent Tremithos River valley deposits. The thickness of the deposits varies from 45 m near the mouth of the River Tremithos to about 20 m near the village of Kiti (MANR, 1982). Figure 3 shows a N-S geological cross-section through the Kiti aquifer system. The system is layered, consisting of an upper unconfined alluvial aquifer separated from a lower confined carbonate aquifer by Pliocene marls (Milnes & Renard, 2004).
Figure 2. Geological map of the Kiti area (above) and a typical geological profile (below; Geological Survey Department, with modifications).

Figure 3. Geological cross-section through the Kiti aquifer (Adapted from Milnes & Renard, 2004).
Over-exploitation during the last few decades has led to seawater intrusion. Water levels recovered in the 1990s, but today remain below sea level during the pumping season (Fig. 4). Until 1981, groundwater abstraction took place at an average rate of $3 \times 10^6$ m$^3$/yr, but has since decreased to $1.3 \times 10^6$ m$^3$/yr in recent years (Milnes & Renard, 2004). Saturated thickness is 2-3 m, while transmissivity values range between 6-135 m$^2$/d, as deduced from pumping tests (MANR, 1982). Permeability ranges from 2 to 80 m/d. Groundwater flow generally follows the topography of the area, moving towards the sea.

Degradation of groundwater quality is mainly caused by seawater intrusion and nitrate pollution. Seawater intrusion phenomena are recorded in the coastal part of the study area, while nitrate pollution is mostly associated with agricultural activity. High nitrate concentrations are recorded in the central part of the basin, reaching levels of up to 300 mg/l - much higher than the limit established by the European Union Nitrate Directive 91/676/EEC. Water quality is classified into two dominant types: Ca-HCO$_3$ (freshwater) and Na-Cl (brackish water in coastal areas affected by seawater intrusion).

Figure 4. Fluctuation of groundwater level in m a.s.l.

3. GROUNDWATER VULNERABILITY ASSESSMENT BY THE DRASTIC METHOD

The concept of groundwater vulnerability is based on the assumption that the physical environment may provide some degree of protection for groundwater against human activities. Vrba and Zaporojec (1994) defined intrinsic vulnerability as an inherent property of an aquifer. In other words, vulnerability represents the degree of weakness of an individual aquifer system to pollution. In this study, intrinsic vulnerability was evaluated using the DRASTIC method, a system typically used in groundwater assessment. The DRASTIC index is even more accurate as part of hydrogeological investigations on a local scale or when more detailed data are available (Gogu & Dassargues, 2000; Martínez-Bastida et al., 2010; Massone et al., 2010).

The acronym DRASTIC (Aller et al., 1987; Al-Adamat et al., 2003) is derived from the initials of the seven (7) assessed parameters: Depth, Recharge, Aquifer media, Soil media, Topography, Impact of vadose zone media and hydraulic Conductivity of the aquifer.

In determining the DRASTIC index (DI), each parameter is assigned a numeric rating of between 1 (least pollution potential) and 10 (highest pollution potential), depending on its value at the site in question. Each parameter is also assigned a weighting factor ranging between 1 and 5, based on their relative influence in affecting pollution potential (Table 1). Calculation of the DI then involves multiplying each parameter weight by its site rating then summing the total and can be expressed as follows:
\[ DI = \sum_{j=1}^{7} r_j w_j \text{ or } DI = DrDw + RrRw + ArAw + SrSw + TrTw + IrIw + CrCw \]  

(1)

where: D, R, A, S, T, I and C are the parameters, \( r \) is the rating of each parameter for the study area and \( w \) is the importance weight for the parameter.

The higher the DRASTIC index value, the greater the groundwater pollution potential and aquifer vulnerability. Some researchers have modified the DRASTIC method and introduced additional parameters such as land use index, aquifer thickness etc. (Secunda et al., 1998; Voudouris & Mandilaras, 2004; Panagopoulos et al., 2005).

**Table 1. Relative weights given to the DRASTIC parameters (Aller et al., 1987).**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>DRASTIC Weight (typical)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D    Depth</td>
<td>5</td>
</tr>
<tr>
<td>R    Recharge</td>
<td>4</td>
</tr>
<tr>
<td>A    Aquifer media</td>
<td>3</td>
</tr>
<tr>
<td>S    Soil media</td>
<td>2</td>
</tr>
<tr>
<td>T    Topography</td>
<td>1</td>
</tr>
<tr>
<td>I    Impact of vadose zone media</td>
<td>5</td>
</tr>
<tr>
<td>C    Hydraulic Conductivity of the aquifer</td>
<td>3</td>
</tr>
</tbody>
</table>

The DRASTIC method was developed using 4 assumptions (Al-Zabet, 2002):
1. the pollutant is introduced at the ground surface
2. the pollutant is flushed into the groundwater by rainfall
3. the pollutant has the velocity of water
4. the area evaluated using DRASTIC is 40 hectares or larger.

Values of the parameters used in the aforementioned method are essentially derivable from monitoring gauges, hydrogeological field surveys including water level measurements, pumping tests and soil analyses, as well as remote sensing studies. A database was established in order to input the collected data into Arcview 3.2a GIS, which offers the ability to store, manipulate and analyse data in different formats and at different scales (Rahman, 2008; Voudouris, 2009; Sener et al., 2009). Once in the database, it is then possible to register all data as data layers with a common coordinate system and manipulate them to produce thematic maps, including the overall study area vulnerability map.

4. RESULTS

4.1 Model parameters

4.1.1 Depth to groundwater (D)

The value of the variable D (Depth to the water table) was obtained using piezometric maps. The depth to groundwater in the alluvial aquifer of the Kiti basin ranges from less than 4.5 to more than 18 m below the ground surface (Fig. 5). In general, the deeper the water levels are, the longer the pollutant takes to reach the groundwater table (Voudouris & Mandilaras, 2004).
4.1.2 Net recharge (infiltration) (R)

Net recharge is the total quantity of water which infiltrates from the ground surface to the aquifer on an annual basis. Leaching and transport of pollutants from the surface due to rainfall that infiltrates through the vadose zone is a very important associated process in terms of aquifer vulnerability. The variable R was calculated from rainfall data and coefficients of infiltration of geological formations. The amount of annual rainfall that infiltrates the aquifer varies from 10 to 20%, depending on soil type and lithology. As a result, net recharge in the study area ranges between 35-85 mm/yr, as shown by the thematic map in Fig. 6.

4.1.3 Aquifer material (A)

The evaluation of variable A (Aquifer material) was based on data from the geological map and drilling analyses. Based on this information, the aquifer media was classified as (Fig. 7):
1. Gravel,
2. Sand and Gravel,
3. Sandstone and
4. Limestone
In general, the larger the grain size of a material, the higher its permeability and the lower its attenuation capacity.

4.1.4 Soil media (S)

Soil type plays an important role in the net recharge of an aquifer, with the presence of fine material decreasing infiltration and therefore also pollution potential.

The value of variable S (Soil type) was obtained from soil classification maps produced by the Geological Survey Department of Cyprus. The predominant soil types are (Fig. 8):

- fine textured,
- medium textured,
- coarse textured,
- thin layer of soil and
- no soil.
4.1.5 Topography (T)

The variable T (Topography) was obtained via elevation points, using the triangulation method in the ARC/INFO system (Fig. 9). This parameter controls the likelihood of a pollutant to be transported by runoff or to remain on the ground where it may infiltrate the surface.

The topography of the Kiti area is for the most part a flat plain where slopes are generally shallow (<2%), although some in a small area in the northern part of the basin reach almost 10%.

![Figure 9. Slope rating map.](image)

4.1.6 Impact of the vadose zone (I)

The vadose zone is the unsaturated zone of subsoil above the water table and plays an important role in the percolation of rainfall and surface flow. The characteristics of the vadose zone therefore also determine the pathway and concentration of a pollutant, with the degree of attenuation related to the structure, mineral composition and organic matter content.

The evaluation of variable I was based on data from drilling reports (Fig. 10). The vadose zone in the study area is composed of unconsolidated gravel, sand and clay materials, except in the northwest where it is constituted by conglomerates.

![Figure 10. Vadose zone media rating map.](image)
4.1.7 Hydraulic conductivity (C)

The value of hydraulic conductivity is controlled by the properties of the aquifer and determines the rate of groundwater movement in the saturated zone. As hydraulic conductivity increases, groundwater velocity as well as the speed at which pollutants are transported also increase, raising aquifer vulnerability. However, achieving an accurate estimate of hydraulic conductivity is difficult and is considered a weakness of the DRASTIC method (Fritch et al., 2000; Stigter et al., 2006; Martinez-Bastida et al., 2010). As a result, similar values may be assigned across large and non-homogeneous areas.

The variable C was calculated from pumping test data and ranges between 2-80 m/day. The distribution of hydraulic conductivity values is shown in Figure 11. The values of the seven assessed parameters are summarised in Table 2.

Figure 11. Hydraulic conductivity rating map.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Ranges</th>
<th>Ratings</th>
<th>Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth to groundwater</td>
<td>&lt; 4.5</td>
<td>9</td>
<td>45</td>
</tr>
<tr>
<td></td>
<td>4.5-9</td>
<td>7</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td>9-12</td>
<td>6</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>12-15</td>
<td>5</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>15-18</td>
<td>4</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>&gt;18</td>
<td>3</td>
<td>15</td>
</tr>
<tr>
<td>Net recharge</td>
<td>&gt;85</td>
<td>9</td>
<td>27</td>
</tr>
<tr>
<td></td>
<td>55-85</td>
<td>4</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>35-55</td>
<td>3</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>&lt;35</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>Aquifer media</td>
<td>Limestone</td>
<td>9</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>Gravel</td>
<td>8</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>Gravel-sand</td>
<td>7</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>Sandstone</td>
<td>6</td>
<td>18</td>
</tr>
<tr>
<td>Soil media</td>
<td>No Soil</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>Thin</td>
<td>9</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>Coarse texture</td>
<td>8</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>Medium texture</td>
<td>6</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>Fine texture</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td>Topography</td>
<td>&lt;2</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>2-5</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>5-10</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Impact of the vadose zone</td>
<td>Conglomerate</td>
<td>9</td>
<td>45</td>
</tr>
<tr>
<td></td>
<td>Gravel</td>
<td>8</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>Gravel-Sand</td>
<td>7</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td>Sand-Gravel</td>
<td>6</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>Sand</td>
<td>5</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>Clay-Sand-Gravel</td>
<td>4</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>Clay-Sand</td>
<td>3</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>Clay</td>
<td>2</td>
<td>10</td>
</tr>
<tr>
<td>Hydraulic conductivity</td>
<td>&gt;80</td>
<td>9</td>
<td>27</td>
</tr>
<tr>
<td></td>
<td>60-80</td>
<td>8</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>40-60</td>
<td>7</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>&lt;40</td>
<td>6</td>
<td>18</td>
</tr>
</tbody>
</table>
4.2 DRASTIC index vulnerability

Values of the DRASTIC vulnerability index vary across the study area, ranging between 70 and 185. These values were classified into four classes, namely: Very high (>140), High (120-140), Medium (100-120) and Low (<100). The vulnerability map of the Kiti area is shown in Fig. 12.

The majority of the Kiti region is characterised by high and very high vulnerability levels, which are associated with shallow aquifers without a great depth of vadose zone. For this reason, a set of measures should be applied in order to protect groundwater quality. Medium and low levels of vulnerability are located in the north central part of the area (Dromolaxia village), in which the aquifer has a great depth of vadose zone composed of layers of clay and silt, as well as a great depth to groundwater level.

Based on chemical analysis of groundwater samples (Republic of Cyprus, 1982 and 2003), it can be concluded that those areas of high vulnerability are also associated with high nitrate concentrations.

Martinez-Bastida et al. (2010) highlight that none of the parameters used in the DRASTIC method account for the influence of groundwater flow direction, a property that greatly influences whether some parts of the aquifer receive groundwater from a larger area than others. Stigter et al. (2006) also note another limitation of the DRASTIC method; excessive emphasis on the attenuation capacity of the vadose zone is not necessarily appropriate in the case of stable and mobile pollutants such as nitrate, for which dilution processes are more influential. For these aforementioned reasons, several researchers have argued of the necessity to modify the DRASTIC method (Al-Adamat et al., 2003; Panagopoulos et al., 2005). However despite these limitations, the results gathered from its application to the Kiti aquifer provide useful conclusions concerning the latter’s vulnerability status.

Furthermore, based on the vulnerability map, a Decision Support System (DSS) could be developed in which different factors, e.g., irrigation type, crop type, type of fertilizers, water consumption, are gathered together to create a more comprehensive tool in order to define appropriate land use and groundwater quality protection zones (Manos et al., 2009 and 2010).
5. CONCLUSIONS

The Kiti aquifer is under great pressure from a variety of sources, including urbanisation, tourism and agricultural activity. The study area is also characterised by several sources of pollution affecting groundwater quality.

The DRASTIC index was used to assess the intrinsic vulnerability to pollution of groundwater in the Kiti aquifer. Low and very low values of vulnerability are found in the northern part of the study area, but the majority of the region falls within high and very high vulnerability zones. Highest vulnerability values are associated with shallow aquifers without a great depth of vadose zone. In order to validate the DRASTIC method, the vulnerability map was compared with a nitrate concentration distribution map. This comparison showed that high nitrate concentrations are related to areas of high vulnerability values.

Assessment of groundwater vulnerability is a useful tool for groundwater resource management and protection zoning. The results provide important information, while the vulnerability map could potentially be used by local authorities and decision makers in order to prevent further pollution of already contaminated areas. Finally, it could also be of help to planners in selecting the location for waste disposal and industrial sites etc.

Future investigations of the intrinsic vulnerability of groundwater in the Kiti aquifer system would benefit from the application of isotopic analysis and/or geophysical measurements to estimate hydraulic conductivity more accurately, computer modelling to simulate groundwater flow and net aquifer recharge, as well as improved water table data monitoring methods.

REFERENCES


