CHAPTER 8

GROUNDWATER VULNERABILITY ASSESSMENT
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8.1 GENERAL

Vulnerability assessment to define areas critical for the maintenance of groundwater quality has been shown throughout the world to be an effective tool for establishing monitoring networks required for surveillance of potential pollution sites. The main objective of this study is therefore to integrate the impact of extensive agricultural land use activity carried on over long periods of time upon aquifer media with regard to groundwater vulnerability to pollution as a supplemental parameter to the traditional DRASTIC model (Secunda et al., 1998).

Groundwater vulnerability assessment is an important process for understanding the intrinsic fragility that a certain region opposes to a given threat, whether this hazard has a natural or anthropogenic origin. Frequently, the vulnerability assessments are carried out in areas with water resources under stress originated from industrial activities. Therefore, the vulnerability studies can provide valuable information for stakeholders working on preventing further deterioration of the environment (Mendoza et al., 2006).

The assessment of groundwater vulnerability to pollution has proved to be an effective tool for the delineation of protection zones in areas affected by groundwater contamination due to the intensive fertilizer applications (Antonakos et al., 2007). The vulnerability of groundwater to pollution may be expressed as the sensitivity of its quality to anthropogenic activities (Bachmat et al., 1990). Bachmat and Collin stipulate that vulnerability assessment of water resources should aim at providing preliminary information and criteria for decision-making in such areas as: designation of land use controls, delineation of monitoring networks and management of water resources in the context of regional planning as related to protection of groundwater quality.

Vulnerability assessment of groundwater, as used in many methods, is not a characteristic that can be directly measured in the field. It is an idea based on the fundamental concept “that some land areas are more vulnerable to groundwater contamination than others” (Vrba and Zaporozec, 1994).
Often, the groundwater contamination level is determined by the natural attenuation processes, occurring within the zone located between the pollution source and the aquifer. Various natural, physical processes, and chemical reactions that operate in the soil, unsaturated, and saturated zones, may cause the pollutant to change its physical state and chemical form. These changes may attenuate the degree of pollution or change the nature of the contamination (Gogu et al., 2000).

Vulnerability mapping involves combining several thematic maps of selected physical resource factors into a groundwater vulnerability map that identifies different areas of the sensitivity of groundwater to natural and human impacts. The original concept of groundwater vulnerability was based on assumption that the physical environment may provide some degree of protection to groundwater with regard to contaminants entering the sub-surface. The earth materials may act as natural filter to screen out some contaminants. Water infiltrating at the land surface may be contaminated but is naturally purified to some degree as it percolates through the soil and other fine grained material in the unsaturated zone.

In recent years, groundwater vulnerability assessment has become a very useful tool for the planning and decision making of groundwater protection (Vias et al., 2005). The main value of vulnerability maps is that they can be used as an effective preliminary tool for the planning, policy and operational levels of the decision making process concerning groundwater management and protection. Firstly, vulnerability maps are valuable guides to planning and can help planners make informed, environmentally sound decisions regarding land use and protection of groundwater quality. Secondly, vulnerability maps can be used for the first cut screening of an area for regional planning, which would allow planners to direct emphasis to areas of highest priority (Vrba and Zeporozec, 1994).

Maps of aquifer vulnerability to pollution are becoming more in demand because on the one hand groundwater represents the main source of drinking water, and on the other hand high concentrations of human/economic activities, e.g. industrial, agricultural, and household represent real or potential sources of groundwater contamination. There is a need to conduct studies on groundwater pollution (Rehman, 2008). The objective of this study is to find out the groundwater vulnerable zones in the study area, using the DRASTIC model.
8.2. DRASTIC MODEL

DRASTIC is a groundwater quality model for evaluating the pollution potential of large areas using the hydrogeologic settings of the region (Aller et al., 1985, Aller et al., 1987, Deichert et al., 1992). This model was developed by EPA in the 1980's. DRASTIC includes various hydrogeologic settings which influence the pollution potential of a region. A hydrogeologic setting is defined as a mappable unit with common hydrogeologic characteristics. This model employs a numerical ranking system that assigns relative weights to various parameters that help in the evaluation of relative groundwater vulnerability to contamination.

The assessment of groundwater vulnerability to pollution has been subject to intensive research during the past years and a variety of methods have been developed. The simplest to apply – and for that reason the most widely used – are the Rating Models. These methods classify each parameter, which potentially influences the probability of pollution of the aquifer, in a scale and lead to a score, which designates the vulnerability of the groundwater (LeGrand, 1964; Foster, 1987; US Environmental Protection Agency, 1993). An evolution of these methods is the Point Count System Models (PCSM) or Parameter Weighting and Rating Methods, which – apart from classifying the various parameters – also introduce relative weight coefficients for each factor. The most widespread PCSM method of evaluation of the intrinsic vulnerability is the DRASTIC method (Aller et al., 1987).

The groundwater is the major contributor for agriculture, domestic and industrial uses in the study area. The first group of aquifer which is mostly unconfined throughout the study area is very potential for various contaminants through agriculture, industrial and domestic uses. Therefore a groundwater vulnerability map is prepared using modified DRASTIC approach (Aller et al., 1987). The parameters like Depth to water, Net recharge, Aquifer media, Soil media, Impact of vadose zone and Hydraulic conductivity of the aquifer were considered for 39 evenly spaced monitoring points. The topography is not accounted in the present study because it is mostly flat in nature and gradient is gentle. These factors have been arranged to form the acronym, DRASIC for ease of reference. This model employs a numerical ranking system that assigns relative weights to various parameters that help in the evaluation of relative groundwater vulnerability to contamination. The hydrogeologic settings which make up the acronym DRASIC are given below.
8.2.1 Depth to Water (D)

The water table is the expression of the surface where all the pore spaces are filled with water below the ground level. The water table may be present in any type of media and may be either permanent or seasonal. In the present study the depth to water is used to delineate the depth to the top of the aquifer.

The depth to water is important, primarily because it determines the depth of material through which a contaminant must travel before reaching the aquifer, and it may help to determine the amount of time during which contact with the surrounding media is maintained (Aller et al., 1987). In general, there is a greater chance for attenuation to occur as the depth to water increases because deeper water levels infer longer travel times. Areas with shallow water tables pose a greater chance for the contaminant to reach the groundwater surface as opposed to deep water tables if the overlying materials are the same. Generally, high water table does not allow contaminated infiltrating waters enough contact time with aquifer material for their associated attenuation process to be effective in removing contamination. The depth to water is also important because it provides the maximum opportunity for oxidation by atmospheric oxygen (Herlinger et al., 2007). Therefore, the depth to groundwater is assigned the maximum weight (5) in determining the vulnerability using DRASTIC method (Table 8.1). The depth to water table in the study area ranges from 9.67-29.38 m bgl during November 2007. The depth to water table is assigned ratings of 5, 3 and 2.

8.2.2 Net recharge (R)

The primary source of groundwater is precipitation which infiltrates through the surface of the ground and percolates to water table. Net recharge is the amount of water per unit area of the soil which penetrates the ground surface and reaches the water table. This is the principal vehicle that transports the contaminant to the groundwater. The more the recharge, the greater the chances of the contaminant to be transported to the groundwater table. In areas where the aquifer is unconfined, recharge to aquifer usually occurs more readily and the pollution potential is generally greater than in areas with confined aquifers. This recharge water is thus available to transport a contaminant vertically to the water table and horizontally within the aquifer. (Aller et al., 1987). The net recharge in the study area is >254 mm and
assigned common rating of 9. The net recharge was assigned a weight “4” in the DRASTIC method.

### Table 8.1: Assigned weight for DRASTIC parameters (after Aller et al., 1987)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Rating (R)</th>
<th>Weight Scale (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth to water table (D)</td>
<td>2, 3, and 5</td>
<td>5</td>
</tr>
<tr>
<td>Net Recharge (R)</td>
<td>9</td>
<td>4</td>
</tr>
<tr>
<td>Aquifer media (A)</td>
<td>8</td>
<td>3</td>
</tr>
<tr>
<td>Soil media (S)</td>
<td>5 and 6</td>
<td>2</td>
</tr>
<tr>
<td>Topography (T)</td>
<td>NA</td>
<td>1</td>
</tr>
<tr>
<td>Impact of Vadose Zone (I)</td>
<td>1 and 2</td>
<td>5</td>
</tr>
<tr>
<td>Hydraulic Conductivity (C)</td>
<td>4, 8, and 10</td>
<td>3</td>
</tr>
<tr>
<td>LULC (L)</td>
<td>8, 9, and 10</td>
<td>5</td>
</tr>
</tbody>
</table>

### 8.2.3 Aquifer media (A)

It refers to the consolidated or unconsolidated rock which serves as an aquifer. An aquifer is defined as a sub surface rock unit which will yield sufficient quantities of water for human use (Herlinger et al., 2007). The material of the aquifer determines the mobility of the contaminant through it. An increase in the time of travel of the pollutant through the aquifer results in more attenuation of the contaminant.

The aquifer media exerts the major control over the route and path length which a contaminant must follow. The path length is an important control (along with hydraulic conductivity and gradient) in determining the time available for attenuation processes such as sorption, reactivity, dispersion and also the amount of effective surface area of materials contacted in the aquifer (Aller et al., 1987).

In general, the larger the grain size and the more fractures or openings within the aquifer, the higher the permeability and the lower the attenuation capacity, consequently the greater the pollution potential. In the study area aquifer material is almost homogeneous which is sand mixed with gravel and assigned a uniform rating of 8. The recommended weight for aquifer media is 3.
8.2.4 Soil media (S)

Soil media is the uppermost portion of the unsaturated vadose zone characterized by significant biological activity. This along with the aquifer media will determine the amount of percolating water that reaches the groundwater surface. Soils with clays and silts have larger water holding capacity and thus increase the travel time of the contaminant through the root zone. Moreover, where the soil zone is fairly thick, the attenuation process of filtration, biodegradation, sorption, and volatilization may be quite significant. In general, the pollution potential of a soil is largely affected by the type of clay present and the grain size of the soil. The quantity of organic material present in the soil may also be an important factor. The study area is characterized by two types of soil viz. loam, and sandy loam which corresponds to a rating of 5, and 6. The parameter was assigned a weight ‘2’ in the DRASTIC method.

8.2.5 Impact of Vadose Zone (I)

The unsaturated zone above the water table is referred to as the vadose zone. The texture of the vadose zone determines how long the contaminant will travel through it. The layer that most restricts the flow of water will be used. The media also control the path length and routing, thus affecting the time available for attenuation and the quantity of material encountered. The routing is strongly influenced by any fracturing present. The materials at the top of the vadose zone also exert an influence on soil development (Aller et al., 1987).

In the present study impact of vadose zone parameter has been calculated by harmonic mean approach (Hussain et al., 2006) and it has been applied to calculate the exact rating values at each location. Aller et al rating is used in calculation. Following equation has been used for the above purpose.

\[ I_r = \frac{T}{\sum_{i=1}^{n} \frac{T_i}{I_{r_i}}} \]

Where, \( I_r \) = the weighted harmonic mean of the vadose zone

\( T \) = total thickness of the vadose zone

\( T_i \) = thickness of the layer i

\( I_{r_i} \) = rating of layer i.
On the basis of the database of lithologs of bore wells were utilized for the calculation of thickness of layers in vadose zone. Based on geological description of the study area, vadose zone has been observed to consist of clay, silt, fine and loamy sand which is corresponding to the rating 1 and 2 (Hussain et al., 2006). This parameter was assigned a weight “5” in the DRASTIC method.

It was observed that the characterization of vadose zone is significant due to presence of alternation between clay and fine sand generally, both possessing distinct hydrological character. Thickness of the top clay layer is persistent throughout the area and it is determining the behavior of each location in terms susceptibility to contamination.

8.2.6 Hydraulic Conductivity (C)

Hydraulic conductivity refers to the ability of the aquifer materials to transmit water, which in turn, controls the rate at which groundwater will flow under a given hydraulic gradient. The rate at which the groundwater flows also controls the rate at which a contaminant will be moved away from the point at which it enters the aquifer. An aquifer with high conductivity is vulnerable to substantial contamination as a plume of contamination can move easily through the aquifer (Rehman, 2008) This is different from an aquifer media as an aquifer with an impermeable media can still conduct water in the presence of fractures (Fritch et al., 2000). Hydraulic conductivity is controlled by the amount and interconnection of void spaces within the aquifer which may occur as a consequence of factors such as intergranular porosity, fracturing and bedding planes.

The highest range of hydraulic conductivity i.e. >10 m/day is assigned a rating of 10 given by Aller et al in 1987 but it is not fit in the present study, so it would not be considered. However, in the study area, the hydraulic conductivity values have been observed to range from 14.17 m/day to 54 m/day. Thus, the original range of Hydraulic Conductivity would not be sufficiently reflected variation of hydraulic conductivity and its impact while estimating the aquifer vulnerability. A new range of Hydraulic Conductivity proposed by Qinghai et al., (2007) in similar area is applied in the present study (Table 8.2). According to Qinghai et al., (2007) the assigned ratings are 4, 8, and 10.
Table 8.2: Hydraulic conductivity ranges and their rating (After Aller et al. 1987 and Qinghai et al. 2007)

<table>
<thead>
<tr>
<th>Hydraulic conductivity (m/day) (Original range)</th>
<th>Hydraulic conductivity (m/day) (New range)</th>
<th>Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.005-0.5</td>
<td>0-5</td>
<td>1</td>
</tr>
<tr>
<td>0.5-1.5</td>
<td>5-10</td>
<td>2</td>
</tr>
<tr>
<td>1.5-3.5</td>
<td>10-15</td>
<td>4</td>
</tr>
<tr>
<td>3.5-5.0</td>
<td>15-20</td>
<td>7</td>
</tr>
<tr>
<td>5.0-10.0</td>
<td>20-25</td>
<td>8</td>
</tr>
<tr>
<td>&gt;10.0</td>
<td>&gt;25</td>
<td>10</td>
</tr>
</tbody>
</table>

8.2.7 Landuse Pattern

Groundwater quality in the study area is being deteriorated due to ongoing industrial and sewage pollution. The land use pattern has strong bearing on groundwater quality. Therefore, land use pattern is included in vulnerability mapping. For the present study, analysis of groundwater, surface water and Trace elements and subsequent interpretation indicated that urban land use (industrial and sewage pollution) demonstrated maximum impact followed by rural (pesticides and fertilizers) land use. Similar study was conducted by Hussain et al., (2006), utilizing land use pattern in DRASTIC approach for vulnerability mapping. Based on these observations, qualitative ratings were proposed for the different types of land use categories. The assigned weight of this parameter is 5 and their corresponding ratings are 8, 9, and 10. Based on this, following ratings were used to categorize land use in the study area as given in Table 8.3.

Table 8.3: Land use categories ratings

<table>
<thead>
<tr>
<th>Land use Category</th>
<th>Ratings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urban and Industrial</td>
<td>10</td>
</tr>
<tr>
<td>Rural and Industrial</td>
<td>9</td>
</tr>
<tr>
<td>Rural and Agriculture</td>
<td>8</td>
</tr>
</tbody>
</table>
The DRASIC Index (Appendix IV), a measure of the pollution potential, is computed by summation of the products of rating and weights for each factor as follows:

\[
\text{DRASIC Index} = Dr \times Dw + Rr \times Rw + Ar \times Aw + Sr \times Sw + Ir \times Iw + Cr \times Cw + Lr \times Lw
\]

Where:
- \(Dr\) = Ratings to the depth to water table
- \(Dw\) = Weights assigned to the depth to water table.
- \(Rr\) = Ratings for ranges of aquifer recharge
- \(Rw\) = Weights for the aquifer recharge
- \(Ar\) = Ratings assigned to aquifer media
- \(Aw\) = Weights assigned to aquifer media
- \(Sr\) = Ratings for the soil media
- \(Sw\) = Weights for soil media
- \(Ir\) = Ratings assigned to vadose zone
- \(Iw\) = Weights assigned to vadose zone
- \(Cr\) = Ratings assigned of hydraulic conductivity
- \(Cw\) = Weights given to hydraulic conductivity
- \(Lr\) = Weights assigned of Land use
- \(Lw\) = Ratings assigned of Land use

The vulnerability index range from 140 to 180 and it is classified into four categories i.e. <140-150, 150-160, 160-170 and 170-180 corresponding to low, moderate, high and very high vulnerability zones, respectively.

Using this classification a groundwater vulnerability potential map was generated (Figure 8.1) which shows that 5% area falls in low vulnerable zone and 39% fall in moderate vulnerable zone. About 33% of the study area falls in high vulnerable zones and 23% of the study area is characterized by very high vulnerability zone. A perusal of the vulnerability map (Figure 8.1) depicts a very high to high vulnerability zone along the Hindon River.
Figure 8.1- Aquifer vulnerability map of the study area
Major portion of the study area comes under the moderate category. In the middle part there is a small patch showing low vulnerability zone. The area in the vicinity of Krishni River has got a high vulnerable zone but its middle part shows moderate vulnerability. The vulnerability increases towards both the rivers and therefore they are more susceptible to groundwater pollution. High to very high vulnerability zones are characterized by very high values of vulnerability index, and are attributed to high values of Hydraulic Conductivity and Water levels.

The sites with high and very high categories are more vulnerable to contamination and consequently need to be managed more closely. The weights assigned are relative, therefore a site with a low pollution potential may still be susceptible to groundwater contamination but it is less susceptible to contamination compared to the sites with high ratings.

Vulnerability maps are a good tool to make local and regional assessment of groundwater vulnerability potential, to identify areas susceptible to contamination, to design monitoring network, and to evaluate groundwater contamination, particularly non point contamination. Vulnerability maps also are helpful for educating and informing planners, managers, and decision- and policy- makers about groundwater protection, risk of contamination, and contamination prevention. The maps also can be used to educate the public about groundwater being a part of a larger, interconnected ecological system.

8.3 INFEERENCE
The vulnerability map categorizes the area in low to very high vulnerability zones. Major portion of the study area comes under low to moderate categories with values of vulnerability index being <160. The vulnerability increases towards both the rivers and values of >160 are encountered all along the course of Hindon and also along Krishni, except in its central stretch. It may be inferred therefore that areas lying in the vicinity of the two streams are more susceptible to groundwater pollution.