**Title:**

# GIS-based DRASTIC Model for Groundwater Vulnerability and Pollution Risk Assessment in the Peshawar District, Pakistan

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## Abstract

Groundwater is the most economic natural source of drinking in urban and rural areas which are degraded due to high population growth and increased industrial development. We applied a GIS-based DRASTIC model in a populated urban area of Pakistan (Peshawar) to assess groundwater vulnerability to pollution. Six input parameters – depth to phreatic/groundwater level, groundwater recharge, aquifer material, soil type, slope and hydraulic conductivity – were used in the model to generate the groundwater vulnerable zones. Each parameter was divided into different ranges or media types, and ratings $R = 1$-10 were assigned to each factor where 1 represented the very low impact on pollution potential and 10 represented very high impact. Weight multipliers $W = 1$-5 were also used to balance and enhance the importance of each factor. The DRASTIC model scores obtained varied from 47 to 147, which were divided into three different zones: low, moderate and high vulnerability to pollution. The final results indicate that about 31.22%, 39.50%, and 29.27% of the total area are under low, moderate, and high vulnerable zones, respectively. Our method presents a very simple and robust way to assess groundwater vulnerability to pollution and helps the decision makers to select appropriate landfill sites for waste disposals, and manage groundwater pollution problems efficiently.

## Key words

Groundwater pollution, Pollution potential; Prioritization of risk areas; GIS for groundwater; Groundwater contamination.

# 1. Introduction

Groundwater plays an important role in both human health and many aquatic ecosystems but also facing a high pollution risk from agricultural activities, mining enterprises, industrial development and urbanization (Foster et al. 2002). Different types of activities such as pesticide or fertilizer applications in lawns and agriculture fields, treatment plants, leaking tanks and urban runoff make the groundwater resources more susceptible to pollution. Therefore, it is important to analyze the susceptibility of groundwater resources to pollution for their better planning and management. In addition, such susceptibility analysis could be used to select appropriate locations for different activities such as dumping sites or industrial locations, minimize the adverse consequence on groundwater resources, and achieve the safety and conservation of the aquifer (Gupta and Onta 1997).

Groundwater is the water from rainfall or surface water bodies such as lakes and streams that infiltrates into the soil and bedrock and deposits into the subsurface in small pores and spaces between rocks and soil particles. Groundwater vulnerability to pollution is defined as "the direction and probability for pollutants to contact the phreatic level (groundwater table) after infiltration at the ground surface" (Ball et al. 2004). During infiltration, water becomes polluted when it passes through a contaminated soil, carrying the contamination from the surface to the groundwater (Ritter et al. 2002). Similarly, soil or rock particles containing harmful substances also perform as a long-term source of groundwater pollution (Arias-Estévez et al. 2008). The presence of wells accessing the groundwater within an aquifer present higher vulnerability to pollution due to different anthropogenic and natural activities (Rahman 2008). The geological setting of the area also plays an important role in groundwater vulnerability (Baalousha 2011) because it controls the magnitude of time such as the residence time of the groundwater that infiltrates from surface to the subsurface (Prior et al. 2003). The US National Research Council (1993) has defined the groundwater susceptibility to pollution as ‘‘the trend or probability for pollutants to contact a specified location in the groundwater system after beginning at a certain place above the highest aquifer". Many studies are available on the topic of groundwater vulnerability assessment such as Evans and Myers (1990), Piscopo (2001), Al-Adamat et al. (2003), Shirazi et al. (2013), Kumar et al. (2014) and Wu et al. (2014). However, no such attempt has so far been made in the area of Peshawar (Pakistan), and this study case sets precedent for evaluating groundwater vulnerability to pollution using geographic information systems (GIS)-based models in other similar areas as well.

According to US National Research Council (1993), groundwater vulnerability assessment approaches include three major categories. (i) Indexed methods, which are based on overlaying and combining maps of different hydro-geologic attributes (for example geology, soil, or depth to water table). These methods include DRASTIC[1] model (Aller et al. 1987), California Hotspot (Cohen et al. 1986), Iowa Ground Water Vulnerability (Hoyer and Hallberg 1991) and Underground Injection Control (UIC) (Pettyjohn et al. 1991). (ii) Process-based simulation methods, which include numerical solution or mathematical models that represent the contaminate transport process, for example, MOUSE (Steenhuis et al. 1987) and RUSTIC (Dean et al. 1989). (iii) Statistical methods that incorporate data from known locations and provide categorization of contamination of the same geographic area. These methods include Discriminant Analysis (Teso et al. 1988) and Regression Analysis (Chen and Druliner 1988).

In this study, we focused on DRASTIC model because it is a simple, robust and standardized system developed by Environmental Protection Agency (EPA), USA to assesses contamination potential of large areas using their basic hydrogeologic settings (Aller et al. 1987). Another reason was that a detail physiochemical analysis of water quality parameters would be costly (Baalousha 2010). The model uses a numerical grading system that assigns comparative ratings

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[1] Each letter in the name DRASTIC represents a parameter: Depth to groundwater/Phreatic level, net Recharge, Aquifer media, Soil media, Topography, Impact of vadose zone and hydraulic Conductivity (see section 2.2).

($R$) and weights ($W$) to different parameters that are used as input to the model. Thanks to the technological developments of GIS, the DRASTIC model has been used in some GIS-based studies such as the procurement of groundwater vulnerability maps of the Castlereagh catchment in Australia (Piscopo 2001). Similarly, Evans and Myers (1990) used a modified DRASTIC approach and evaluated the pollution potential of groundwater in southern Delaware (US) but they excluded three parameters from the DRASTIC index (recharge, impact of vadose zone and aquifer media) and added new parameters such as septic tank density and land use/land cover (LULC). Wu et al. (2014) also used the DRASTIC model to calculate the intrinsic vulnerability index and they found that intrinsic vulnerability index decreased from east to west with an increase in depth to phreatic level and clay soil thickness. Based on their results, they recommended that the study area should be divided into preferential zones, feasible zones and unfeasible zones for reclaimed water irrigation planning and operation with suggested engineering measures. Shirazi et al. (2013) interpreted groundwater vulnerability of Melaka State (Malaysia) by integrating a land use map with DRASTIC index values to generate a risk map of the study area. They prepared three types of zones such as low, medium and high where the groundwater of important cities was highly vulnerable. Similarly, Kumar et al. (2014) prepared a small-scale map of groundwater vulnerability to pollution using DRASTIC Model in Kancheepuram district, India. They found a strong relationship between the DRASTIC index and nitrate concentration. These studies show that GIS-based DRASTIC method is an important tool for groundwater vulnerability and pollution risk assessment because it uses their basic hydrogeologic parameters which are supposed to have an impact on pollutant transportation from ground surface sources to groundwater (Kalinski et al. 1994) and are easy to obtain (Aller et al. 1987).

According to the Pakistan Council of Research in Water Resources (PCRWR), most of the groundwater resources in Pakistan are unsafe for drinking due to biological or chemical contamination (PCRWR 2007), and are continuously degrading due to high population growth and increased industrial development. A huge gap between rural and urban areas, and among provinces, exists with respect to drinking water coverage and accessibility. The Ministry of Planning, Development and Reforms, Government of Pakistan (2013) calculated that 65% of population is considered having access to safe drinking water and 35% are using contaminated water (bacteriological, fluoride, arsenic or nitrate). The sustainability of the existing safe water supply is also a major issue in Pakistan's water sector (Ministry of Environment, Government of Pakistan, 2009). Such inefficient water supply, hygiene and sanitation in Pakistan cause a high rate of diseases as, for example, mortality and morbidity rates and situates a major risk to the existence and growth of children in Pakistan. According to PCRWR (2007) assessment in the Peshawar district, 62% samples were microbiologically contaminated by *Escherichia Coli*, 38% samples were contaminated by iron, 23% by calcium and 8% by a high level of total dissolved solids. In this regard, we used a simple approach of GIS-based DRASTIC model to identify those areas where the groundwater resources may be vulnerable to pollution, which would help the decision makers in water-related policies and management.

## 2. Material and Methods

### *2.1. Study area*

Peshawar (34° 00' N, 71° 34' E) is the most populated district in the Khyber Pakhtunkhwa province of Pakistan, and extends for an area of 125,700 hectares (**Fig. 1**). The area is divided into four towns named Town 1, Town 2, Town 3, Town 4 and a cantonment area, respectively occupying 3%, 16%, 35% and 45%, and 1% of the total area (Adnan and Iqbal 2014). The mean maximum / minimum temperatures recorded are 30.25 / 1.28 ˚C in winter and 47.45 / 15.60 ˚C in summer. The average 30 years annual rainfall has been recorded as 400 mm, being higher in winter than summer.

****approximate position of Figure 1*****

### *2.2. DRASTIC Model*

The hydrogeologic settings which established the abbreviation of DRASTIC are;

[D] Depth to phreatic level or groundwater table. It is the depth from a ground surface to a phreatic level below ground. The deeper the phreatic level is, the lesser the probabilities of contaminants to affect groundwater.

[R] Net Recharge. It is the quantity of water in a unit area that infiltrates the earth surface and arrives the phreatic level. This is the most important cause for contaminants to reach the groundwater table.

[A] Aquifer material. These are consolidated or unconsolidated rocks such as gravel, limestone and sand beneath the earth's surface, which retain a quantity of water sufficient for its availability for drinking or irrigation. The smaller and finer the grain size, the higher will be the capacity of the aquifer to reduce contamination because the finer particles restrict the movement of contaminants.

[S] Soil material. It is the topmost and weathered part of a ground surface. Soil texture controls the descending movement of pollutants from surface to subsurface.

[T] Topography. The gradient of terrain slopes. Flat areas where slope is low are more susceptible to groundwater pollution than steep areas, because they are likely to preserve water for more time, thus allowing high penetration of water recharge and high potential for pollutant migration once contaminated.

[I] Impact of vadose zone material. Vadose zone is the portion of soil between the surface and phreatic level, where rock pores and spaces between soil particles are unsaturated. Its influence to the contamination potential is similar to that from soil or aquifer material, since it depends upon its permeability and the granulometric properties of the particles.

[C] Hydraulic conductivity. The capacity of aquifer material to transmit water. Thus, an aquifer will be highly vulnerable if the hydraulic conductivity is higher.

The DRASTIC model uses the above seven hydrogeologic parameters and evaluates the groundwater vulnerability of the area. **Table 1** shows all the required data layers for modelling which were acquired from various governmental agencies and during the field survey, however, the impact of vadose zone was excluded due to non-availability of data.

****approximate position of Table 1*****

Each parameter was divided into different categories, according to ranges or materials of different media types (**Table 2**), and a subjective rating $(R_j)$ from 1 to 10, representing an increasing impact on pollution potential was given to each range or material type (Aller et al. 1987; Rahman 2008; Srinivasamoorthy et al. 2011). To balance and enhance the importance of each factor, a weight multiplier $(W_j)$ from 1-5 was used (**Table 2**).

****approximate position of Table 2*****

The contaminant potential was measured using a DRASTIC index $(D_i)$, and it is computed as adding the products of weights and rating of each factor, mathematically;

$$D_i = \sum_{j=1}^{n}(W_j * R_j) \qquad (1)$$

Where, $D_i$ represents DRASTIC index score for a mapping unit $i$, in the study area. For each parameter $j$, $R_j$ and $W_j$ represent their rating and weight, respectively. To apply equation (1), a weighted overlay analysis was used in ArcGIS (version 10.2.0.3348, ©1999-2013, ESRI, Inc., California), which helped to combine these rated parameters and their respective weights. Mapping units having higher DRASTIC index score will have relatively higher pollution potential. The final vulnerability map of the study area was based on experts opinions and literature (Aller et al. 1987; Rahman 2008; Srinivasamoorthy et al. 2011), where the experts opinions were used to select appropriate weights of the parameters and ratings of their ranges or media types according to the hydrogeological setting of the area.

### *2.2.1. Depth to phreatic level*

This parameter is very important in DRASTIC model because the chances of attenuation increase as depth to phreatic level increases since pollutants will require more travel time to reach a deeper phreatic level. To map changes in phreatic level, borehole point data which include depth to phreatic level was collected from Public Health Engineering Department of Peshawar, and their coordinates (latitude and longitude) were collected during the field survey. The data were interpolated using inverse distance weighted (IDW) model, classified into different ranges, and then reclassified into DRASTIC ratings (**Table 2**) (Aller et al. 1987; Rahman 2008; Srinivasamoorthy et al. 2011). This way, a higher rating was given where the phreatic level was less than 5 m because the pollutants will require shortest travel time to reach it, and a lower rating was given where the phreatic level was higher than 25 m as the travel time to reach the phreatic level will be more in this case. Comparing all DRASTIC parameters, the phreatic level was considered by experts as the most influential factor in the vulnerability, and thus it was given the highest weight $W = 5$ (**Table 2**).

### *2.2.2. Net Recharge*

It is the amount of water that infiltrates into the ground surface and reaches the groundwater table level below. Recharge is the main vehicle for transporting and leaching solid or liquid pollutants to the phreatic level as well as responsible for the vertical and horizontal transportation of contaminants. The higher the water recharge is, the higher will be the pollution potential of groundwater. Net recharge was calculated as a product of precipitation and recharge rates while subtracting the amount of water lost during evapotranspiration (Rahman 2008).

$$Net\ Recharge = Precipitation - Evapotranspiration * Recharge\ rate \quad (2)$$

Since only one rainfall gauge station was available in the study area installed by Pakistan Meteorological Department (PMD) and was not possible to generate a rainfall map. For this reason, Tropical Rainfall Measuring Mission (TRMM) average accumulated rainfall data were downloaded from TRMM Online Visualization and Analysis System (TOVAS). TRMM data was calibrated with PMD data using five years' time series (2004-2008) rainfall data of both PMD station and TRMM points (locations). A linear regression model was developed from both data (**Fig. 2**) and PMD rainfall was predicted at each TRMM point (**Table 3**). The resulting model $PMD = 0.954 \cdot TRMM - 0.5895$ reached a coefficient of determination $R^2 = 0.94$. After predicting the PMD rainfall, surface interpolation for the average annual accumulated precipitation was generated using IDW technique (**Fig. 3**).

****approximate position of Table 3*****

****approximate position of Figure 2*****

****approximate position of Figure 3*****

Recharge ratings were calculated from land use/land cover (LULC) map obtained from a Landsat thematic mapper (TM) satellite image of 26 June 2011. The image was classified into five major LULC classes such as wetlands and water bodies, vegetation/agricultural fields, built-up, open lands and mountains, using supervised image classification techniques in Erdas Imagine (Version 13.00.00 Build 281, ©1990-2012 Intergraph Corporation) (**Fig. 1**). The image was reclassified and highest rating value of $R = 5$ was given to highest recharge areas such as wetlands and water bodies due to the lower water table and direct exposure to the pollution; rating $R = 4$ was given to agricultural fields; rating $R = 3$ was given to open lands, and lowest rating $R = 1$ was given to lowest recharge areas, mountains and urban areas, due to either their high slopes or impermeable surfaces.

Potential Evapotranspiration (PET) of Willmott and Matsuura (2001) (**Fig. 4**) was used in the study, and final net recharge was calculated using equation 2, which was then reclassified to DRASTIC ratings (**Table 2**). Net recharge was considered as the second most important factor in the analysis and, therefore, a weight $W = 4$ was given to it (**Table 2**).

****approximate position of Figure 4*****

### *2.2.3. Aquifer Material*

The aquifer materials (like gravel, limestone and sand) directly affect the amount of groundwater available in the aquifer and its pollutant attenuation capacity. For example, if the grains sizes of the aquifer materials are larger and having more fractures or openings, then permeability will be high and attenuation capacity will be low.

An aquifer map obtained from water and power development authority (WAPDA), Pakistan was digitized and converted to raster using ArcGIS. The raster map was then reclassified into DRASTIC ratings. Aquifer materials were considered as the third most important parameter and was given a weight $W = 3$ (**Table 2**).

### *2.2.4. Soil Media*

Soil significantly affects the amount of recharge by allowing water to infiltrate and reach phreatic level, thus it affects the pollution movement. The soil permeability is decreased by the occurrence of small textured materials such as silts and clay that restrict the pollutant migration, however, the larger textured materials improve soil permeability as well as pollutant migration. The study area soil map was obtained as a scanned hardcopy from the Institute of Geographical

Information System (IGIS) library, National University of Sciences and Technology, Pakistan. The map was digitized, converted to raster, and a lowest DRASTIC rating was given to fine-textured soils such as clay and a higher rating was given to larger textured soil such as gravel and stones (**Table 2**). Soil types and aquifer materials have a similar characteristic, therefore weight $W = 3$ was also given to soil type (**Table 2**).

### *2.2.5. Topography*

Flat areas retain water for longer time, permit high penetration or recharge of water and provide high potential for pollution movement. While areas with steep slopes provide a high amount of runoff, less infiltration and are less vulnerable to groundwater pollution. Slope ranges were calculated from an ASTER digital elevation model (DEM). Lowest rating was given to steep slopes, and highest rating was given to flat areas (**Table 2**) (Aller et al. 1987; Rahman 2008; Srinivasamoorthy et al. 2011). The influence of topography was the lowest than all other parameters and therefore, it was given a lowest $W = 1$ (**Table 2**).

### *2.2.6. Impact of Vadose Zone Material*

The materials in the vadose zone, the area between the surface and the water table, has similar effects on vulnerability to pollution as those in the surface soil or aquifer. Vulnerability to contamination depends on its particle sizes, permeability (Rahman 2008) and thickness (Wu et al. 2014). Due to non-availability of useful data, the impact of vadose zone material was excluded from this study.

### *2.2.7. Hydraulic Conductivity*

Measuring the hydraulic conductivity (HC) provides a quantification of the capacity of aquifer material to transmit water. The amount and interconnection of void spaces in the aquifer are responsible for controlling hydraulic conductivity. Freeze and Cherry (1979) calculated the HC values for different aquifer materials and we obtained those values according to the aquifer materials (gravel-sand with some silt and clay, and sand with minor silt and clay) in our study area. DRASTIC ratings were assigned according to Aller et al. (1987) (**Table 2**) and was given a weight $W = 3$ , similar that for the aquifer materials (**Table 2**).

## 3. Results

### *3.1. DRASTIC parameter maps*

**Figure 5** shows the maps obtained for each of the parameters considered in the DRASTIC model, wherein **Fig. 5a** illustrates variations in phreatic level which ranged from 1.5 m to 78.0 m. The phreatic level was categorized into four ranges such as <5 m, 5-10 m, 10-25 m and > 25 m, and were given ratings $R =$ 10, 9, 7 and 5, respectively (**Table 2**). It was found that the phreatic level was much higher (< 5 m) on the northern sides as compared to the southern sides (> 25 m) of the study area.

The net recharge map obtained using equation 2 was divided into low, medium and high recharge zones, and were given rating $R =$ 1, 5 and 8, respectively (**Table 2**). The spatial patterns of net recharge shown in **Fig. 5b** are in clear relationship with land use patterns in the district of Peshawar (**Fig. 1**), since medium recharge zones are those mainly covered by agricultural fields, low recharge zones correspond to urban areas in the center and mountains in the south, and the presence of higher recharge values is mainly where wetlands and water bodies are located.

The study area is mostly homogenous in terms of aquifer materials and is composed of only two types of aquifer materials. First, gravel along with sand, silt and clay, which occupies most of the area and was given rating $R = 8$. The second type of aquifer material was sand along with some silt and clay, which occupies the northern parts of the study area and was given a rating $R = 5$ (**Fig. 5c**).

Different soil types exist in different parts of the study area such as silt loam with some sands in northern parts, silt loam in southern parts, gravel and stones in the eastern parts and silt-clay in the central parts (**Fig. 5d**). The lowest rating $R = 1$ was given to the fine-textured soils such as clay and silt-clay, and the highest rating $R = 10$ was given to the gravels and stones because fine-textured particles help to prevent and the larger particles accelerate the movement of pollutants.

The terrain of the area was mostly flat, which was given the highest ratings. However, some steep slopes, greater than 12%, also existed in the southern areas of Peshawar district (**Fig. 5e**). The slope was divided into different ranges such as 0-2, 2-6, 6-12 and > 12%, which were given ratings of $R = 10$, 9, 5, and 2, respectively.

Based on the above two types of aquifer material in the study area, the hydraulic conductivity values obtained were 2.3 meters/day for gravel-sand with silt and clay (first type) and 10.4 meters/day for sand with minor silt and clay (second type). Therefore, these soil types also depicted in **Fig. 5c** were given ratings $R = 2$ and 5, respectively, with regards of their HC (**Fig. 5f**).

****approximate position of Figure 5*****

### *3.2. Final Vulnerability Map of the Study Area*

The final vulnerability map of DRASTIC model was obtained by combining the parameters ratings and their respective weights as discussed in section 2.2 and 3.1. The DRASTIC scores obtained from the model varied from $D = 47$ to $D = 147$. These values were reclassified into three classes i.e. low, moderate and high vulnerable zones using a quantile classification scheme (**Fig. 6**). This classification resulted in a low vulnerable class corresponding to DRASTIC Index scores $D < 92$, moderate vulnerable being the values from $D = 92$ to $D = 107$, and those which were $D > 107$ corresponding to highly vulnerable areas. **Table 4** summarizes the final results obtained after calculating the final areas of vulnerable zones. We found that 31.22% (399.7 km$^2$) of the total area was under low vulnerable zone, where Achni Bala, Pawaka, Sheikhan, Sarband, and Sufaid Dherai are included. Moderate vulnerability corresponded to 39.50% (505.7 km$^2$) of the total area, including Jogani, Mehl Tari, Sheikh Muhammadi, Urmar Miana, Badabher, Hazar Khwani. Finally, 29.27% (374.6 km$^2$) of the total area was classified as being highly vulnerable to pollution, which included Mathra, Panam Dherai, Kaaniza, Haryana, Hasan Garhi, Shaheen Town, Wadpaga, Suraizi.

****approximate position of Table 4*****

****approximate position of Figure 6*****

## 4. Discussion

Groundwater is one of the major sources of water which is used for all purposes such as agricultural, commercial, domestic and industrial (Visnuvarthanan et al. 2016), but a high dependency on groundwater resources causes an increasing pressure on its quality and quantity (Piscopo 2001), thus facing a pollution risk from different activities such as agriculture, mining enterprises, industrial development and urbanization, in Pakistan (PCRWR 2007) as well as worldwide (Foster et al. 2002). Therefore, a quantitative and qualitative assessment of groundwater vulnerability to pollution is important for decision-making. Due to high groundwater contamination in the study area, an assessment of groundwater pollution was needed (PCRWR 2007). But a detailed physiochemical analysis of groundwater can be costly and time-consuming (Baalousha 2010). Therefore, we attempted to assess the groundwater vulnerability to pollution using GIS-based DRASTIC model as it has been applied in other various study areas (Aller et al. 1989, Evans and Myers 1990, Shirazi et al. 2013, Wu et al. 2014).

The phreatic level has a significant impact on groundwater vulnerability because vulnerability to pollution decreases as the phreatic level increases (Wu et al. 2014). In this study case, a huge difference was found between the northern area of the Peshawar district, where the phreatic level was < 5 m, and the south-eastern areas where the phreatic level was > 25 m (**Fig. 5a**). This shows that the chances of vulnerability would much likely to decrease from north to south-east areas because the pollutants will have longer distances to travel before contacting groundwater (Rahman 2008). Whereas, wetland areas and water bodies in the north of the study area (**Fig. 5b**) are highly vulnerable to pollution due to high phreatic level in the north (**Fig. 5a**). Fertilizers and pesticides used in the nearby agricultural fields can have direct or indirect effects to groundwater as these pollutants infiltrate along with groundwater recharge (Rahman 2008). Groundwater recharge is the second most important factor in vulnerability analysis (Rahman 2008; Srinivasamoorthy et al. 2011; Rahmati et al. 2015), and hence a high weight was given in this study (**Table 2**). But a classification of a medium-resolution image (30 m) of Landsat TM satellite and TRMM precipitation data was used for recharge calculations which could have affected the final vulnerability. However, recharge map could be improved further by using a high-resolution image such as Quickbird or SPOT, and field rainfall measurements or direct recharge measurement in the field. In soil type and aquifer material, the particle size greatly affects the vulnerability. Larger sizes of particles leads to higher vulnerability, because the water and pollutants would easily move in larger particle size materials (Rahman 2008; Srinivasamoorthy et al. 2011). Therefore, a higher rating was given to coarse size particles such as gravel and sand, and a lower rating was given to fine size particles such as clay and silt (Jamrah et al. 2008) (**Figs. 5c and 5d**). Based on literature and experts opinions, soil and aquifer material was considered as the third most important factor in vulnerability, and thus it was ranked with a corresponding weight (**Table 2**). The study area is mostly flat (**Fig. 5e**) having higher recharge potential which speeds up vulnerability to pollution, therefore, maximum rating of 10 was given to flat slopes and rating 1 was given to steep slopes (Rahman 2008; Srinivasamoorthy et al. 2011). The lowest weight was given to the effect of topography (**Table 2**), because its influence is mostly related to rainfall occurrences. For example, if rainfall occurs, water will retain for a longer time in flat areas, as compared to the steep slopes, permitting higher penetration or recharge of water. The hydraulic conductivity which depends on the particle size of the aquifer materials (Odong 2007) was the most challenging and difficult to calculate (Aller et al. 1987). However, since Freeze and Cherry (1979) calculated the HC for different aquifer materials, their values were used to account for the effect of HC according to the aquifer materials in the study area (**Fig. 5f**). Due to the dependency of hydraulic conductivity on aquifer materials, a similar weight was assigned to it (**Table 2**).

Spatial variability in groundwater vulnerability to pollution shows that, generally, the southern and western areas are low vulnerable, whereas north-eastern and south-eastern areas are moderately vulnerable, and the higher vulnerable areas are distributed in the northern and eastern zones parts of the of the Peshawar district (**Fig. 6**). This categorization was similar to those carried out by Shirazi et al. (2013) and Wu et al. (2014), in which they divided their study area into low, medium and high vulnerable zones, or, preferential zones, feasible zones and unfeasible zones, respectively. A detailed spatial analysis of groundwater quality in the study area shows that different water quality parameters such pH, electrical conductivity, calcium and magnesium hardness, alkalinity (Adnan and Iqbal 2014), and bacteriological contamination (Khan et al. 2013) are mostly concentrated in the northern and eastern areas. In the present study, DRASTIC model accurately predicted high vulnerability in those areas. This is a good indication that the DRASTIC model can be useful for determining groundwater vulnerability to pollution, as an alternative to the high costs of a more detailed physiochemical analysis (Baalousha 2010). However, the central, western and south-western parts of the study area were predicted as medium to low vulnerable, where Adnan and Iqbal (2014) obtained nitrate concentrations with high to medium values. The final results of our DRASTIC model implementation (minimum and maximum DRASTIC index score) were similar to those obtained by Rahman (2008), Srinivasamoorthy et al. (2011), Shirazi et al. (2013), Wu et al. (2014) or Kumar et al. (2014), which demonstrates consistency and robustness in the method. Thus, we recommend that DRASTIC model may easily be employed at very other different areas. We also observed that our results were very dependent on ratings and weights of the parameters. Therefore, we recommend further research on the sensitivity of the DRASTIC model to different choices for rating and weighting the input parameters, in order to analyze their effects and importance on the final results.

## 5. Conclusions

The DRASTIC model was useful for determining groundwater vulnerability to pollution, and it can be a good alternative to physiochemical analyses, sparing their high costs. The overall results of our study case were satisfactory, and we are confident that it would help the decision makers in waste disposal sites selection and development of reliable policies for efficient management and exploitation of groundwater resources. Areas found less vulnerable to groundwater pollution thus suitable for industries or waste disposal sites were Achni bala, Sheikhan, Aza khel, Sheikh Muhammadi, Pawaka and Sarband. Highly vulnerable priority areas needing protection and conservation were Panam Dheri, Charghar Matti, Mathra, Kaniza, Dagg, Hasan Garhi, Khazana, Urmar, and Budhni. This study suggests that GIS-based DRASTIC model could be used for groundwater vulnerability assessment and prioritization of vulnerable areas, and it could be easily employed elsewhere.

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## Table Titles

**Table 1**. Data types and sources of data used in the DRASTIC Model

| Sr. No | Data Type | Source | Output Layer |
|---|---|---|---|
| 1 | Tube wells locations | Field survey | X,Y coordinates |
| 2 | Tube wells<br>Strata charts | Public health engineering department Peshawar | Depth to groundwater |
| 3 | Rainfall and satellite image | TRMM rainfall data, PMD rainfall, Landsat thematic mapper (TM) image | Recharge |
| 4 | Aquifer map | Water and power development authority (WAPDA), Pakistan | Aquifer material |
| 5 | Soils map | University (institute of GIS) liberary | Soil type |
| 6 | DEM | SRTM DEM from internet | Topography |
| *7* | Hydraulic conductivity | Literature (DRASTIC manual) | Hydraulic conductivity |

Note: TRMM, tropical rainfall measuring mission; PMD, Pakistan meteorological department; SRTM, shuttle radar topography mission; DEM, digital elevation model.

**Table 2**. Rating and weights of DRASTIC parameters

| **1: Depth to groundwater** | | **2: Net recharge** | | **3: Aquifer media** | | 4: **Topography** (slope) | | **5: Soil media** | | **6: Hydraulic conductivity** | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Ranges (m)** | **Rating** | **Category** | **Rating** | **Material** | **Rating** | **Ranges** | **Rating** | **Material** | **Rating** | **Value (m/day)** | **Rating** |
| < 5 | 10 | Urban, built-up and mountain/ low recharge | 1 | Gravel, sand, clay | 8 | 0—2 | 10 | Clay and silt clay | 1 | 2.3 | 2 |
| 5—15 | 9 | Vegetation/ medium recharge | 5 | Sand with minor clay | 5 | 2—6 | 9 | Silty clay and clays with sand | 3 | 10.4 | 5 |
| 15—25 | 7 | water bodies and wetlands/ high recharge | 8 | | | 6—12 | 5 | Silt loam | 4 | | |
| >25 | 5 | | | | | >12 | 2 | Silt loam with sand | 5 | | |
| | | | | | | | | Sandy loam with gravel | 6 | | |
| | | | | | | | | Sand | 8 | | |
| | | | | | | | | Gravel and Stony | 10 | | |
| Weight = 5 | | Weight = 4 | | Weight = 3 | | Weight = 1 | | Weight = 2 | | Weight = 3 | |

**Table 3.** TRMM annual accumulated precipitation at various locations and their corresponding PMD predicted precipitation

| S. No | Latitude | Longitude | TRMM Precipitation (mm) | Predicted PMD (mm) |
|---|---|---|---|---|
| 1 | 33.625 | 71.375 | 509.4 | 485.4 |
| 2 | 33.625 | 71.625 | 461.5 | 439.7 |
| 3 | 33.625 | 71.875 | 548.2 | 522.4 |
| 4 | 33.875 | 71.375 | 547.2 | 521.4 |
| 5 | 33.875 | 71.625 | 550.02 | 524.1 |
| 6 | 33.875 | 71.875 | 614.5 | 585.7 |
| 7 | 34.125 | 71.375 | 527.6 | 502.8 |
| 8 | 34.125 | 71.625 | 552.5 | 526.5 |
| 9 | 34.125 | 71.875 | 638.8 | 608.8 |
| 10 | 34.375 | 71.375 | 501 | 477.3 |
| 11 | 34.375 | 71.625 | 559.5 | 533.2 |

**Table 4.** Groundwater vulnerable zones

| S. No | Status | DRASTIC Index | Area ($km^2$) | Union Councils |
|---|---|---|---|---|
| 1 | Low Vulnerable | <92 | 399.7 | Achni bala, Sheikhan, Aza khel, Sheikh Muhammadi, Sarband, |
| 2 | Moderate Vulnerable | 92-107 | 505.7 | Badbher, Hazar Khwani, Shaheen town, Sikandar Town, Faqeer abad, Mehl Tari, Tehkal, Hayatabad |
| 3 | High Vulnerable | > 107 | 374.6 | Panam Dheri, Charghar matti, Mathra, Kaniza, Dagg, Hasan Garhi, Khazana, Urmar, Budhni |

## Figure Captions

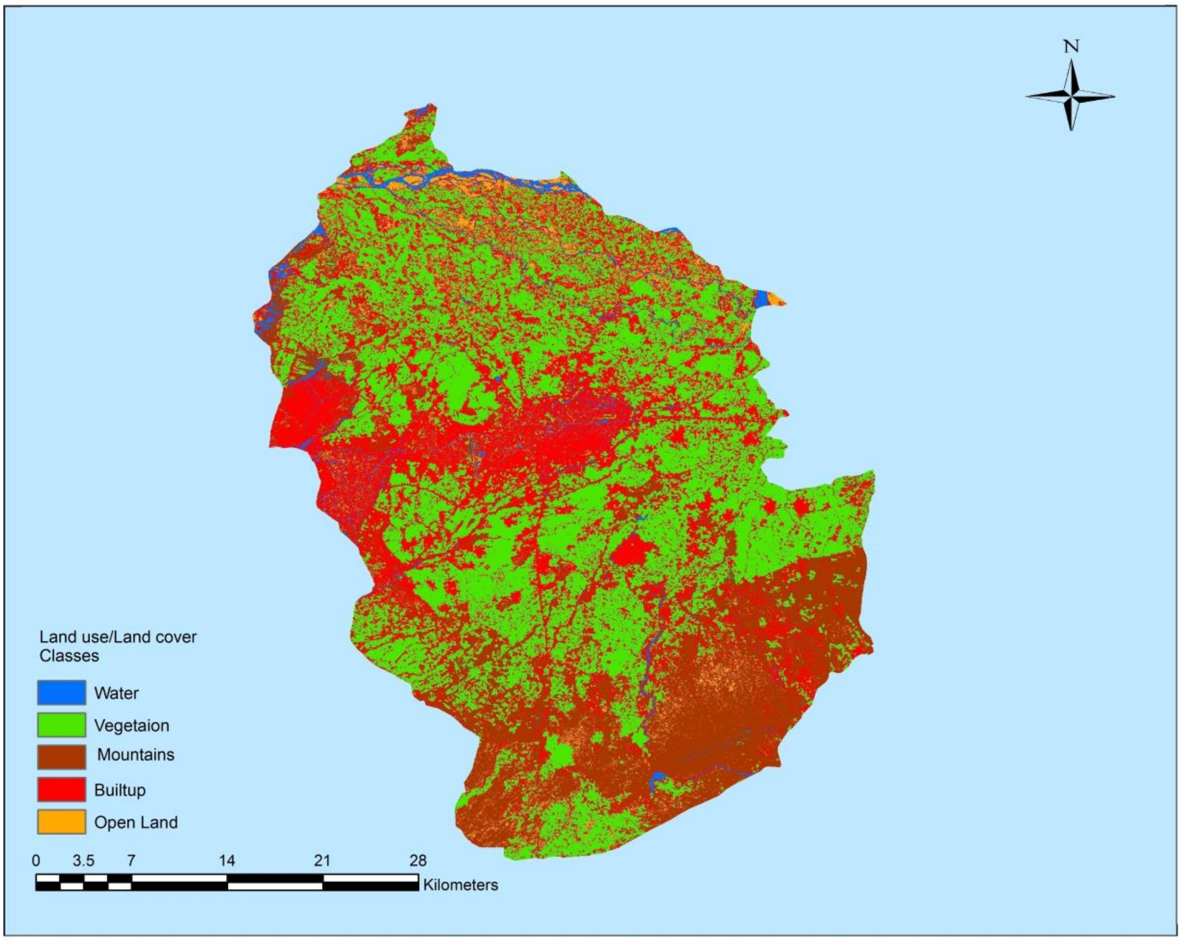

**Figure 1**. Map of the study area (Peshawar, Pakistan).

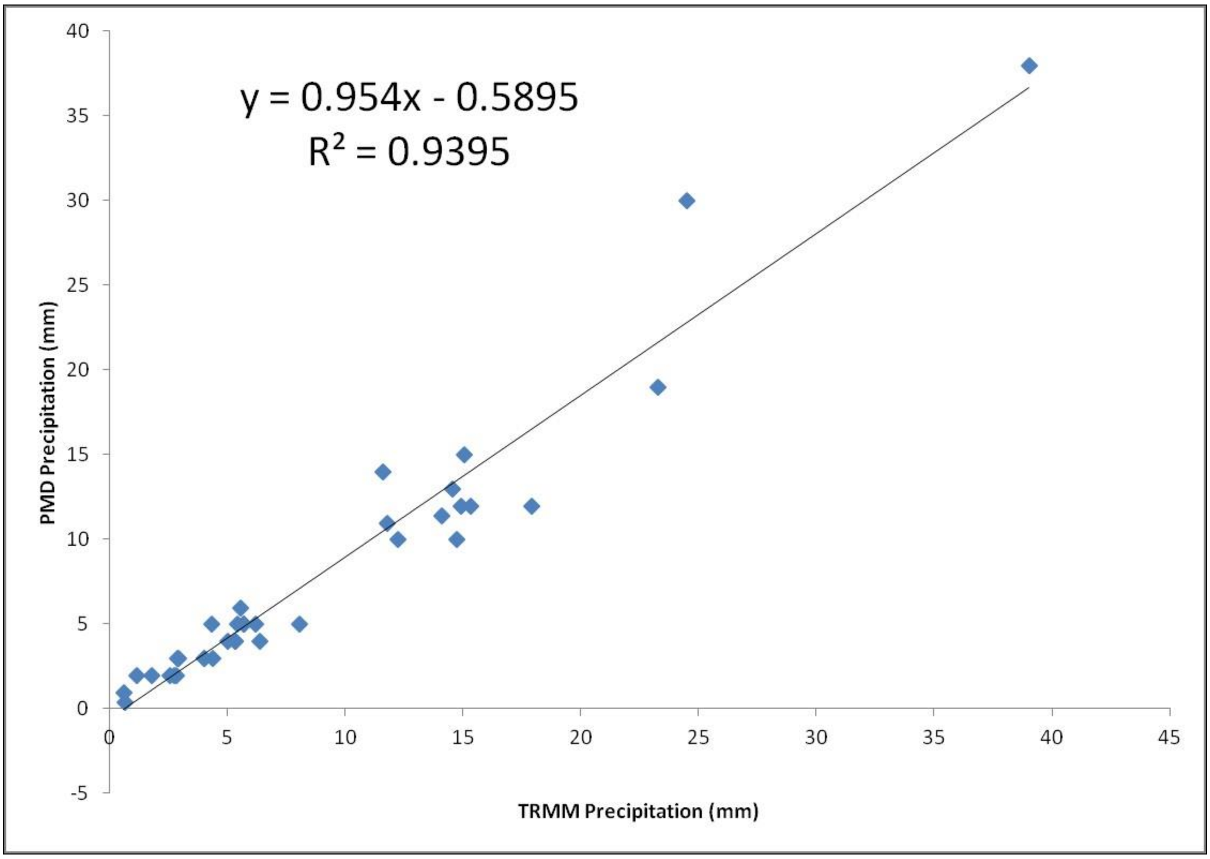

**Figure 2**. Model for predicting the PMD precipitation from TRMM precipitation data.

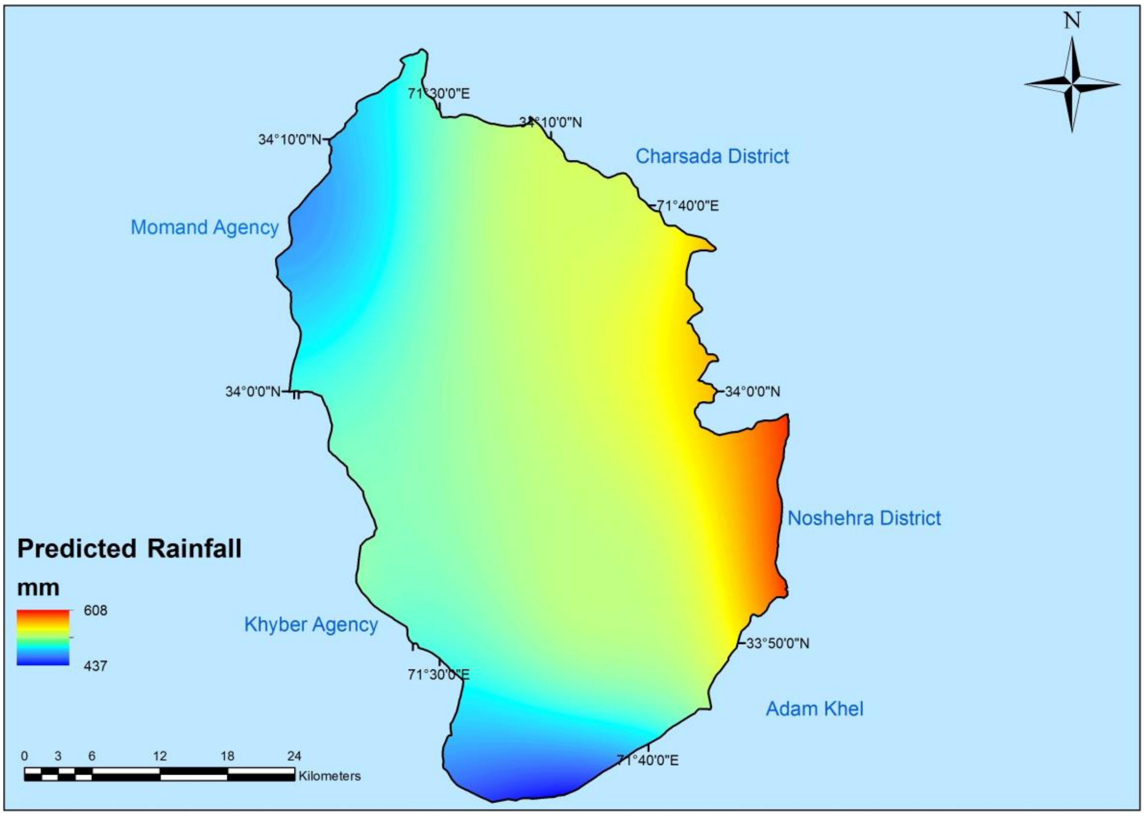

**Figure 3.** PMD predicted precipitation map.

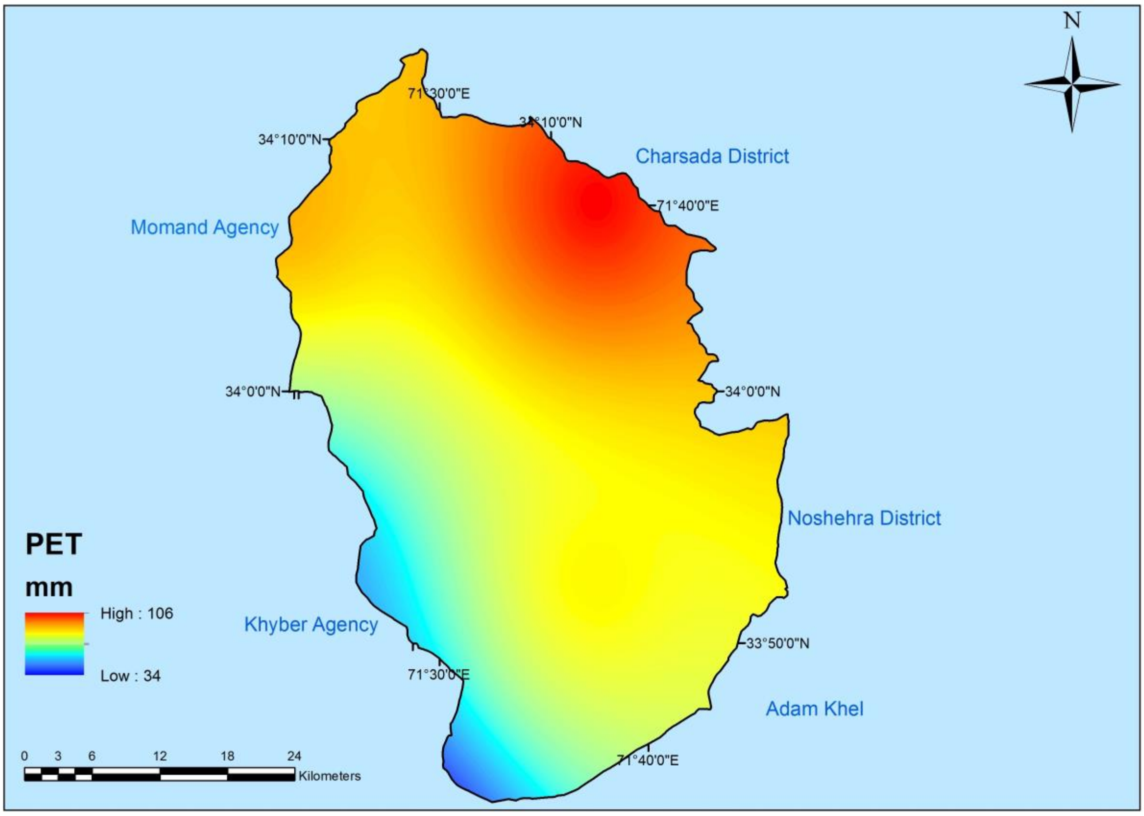

**Figure 4.** Potential evapotranspiration map (Willmott and Matsuura, 2001)

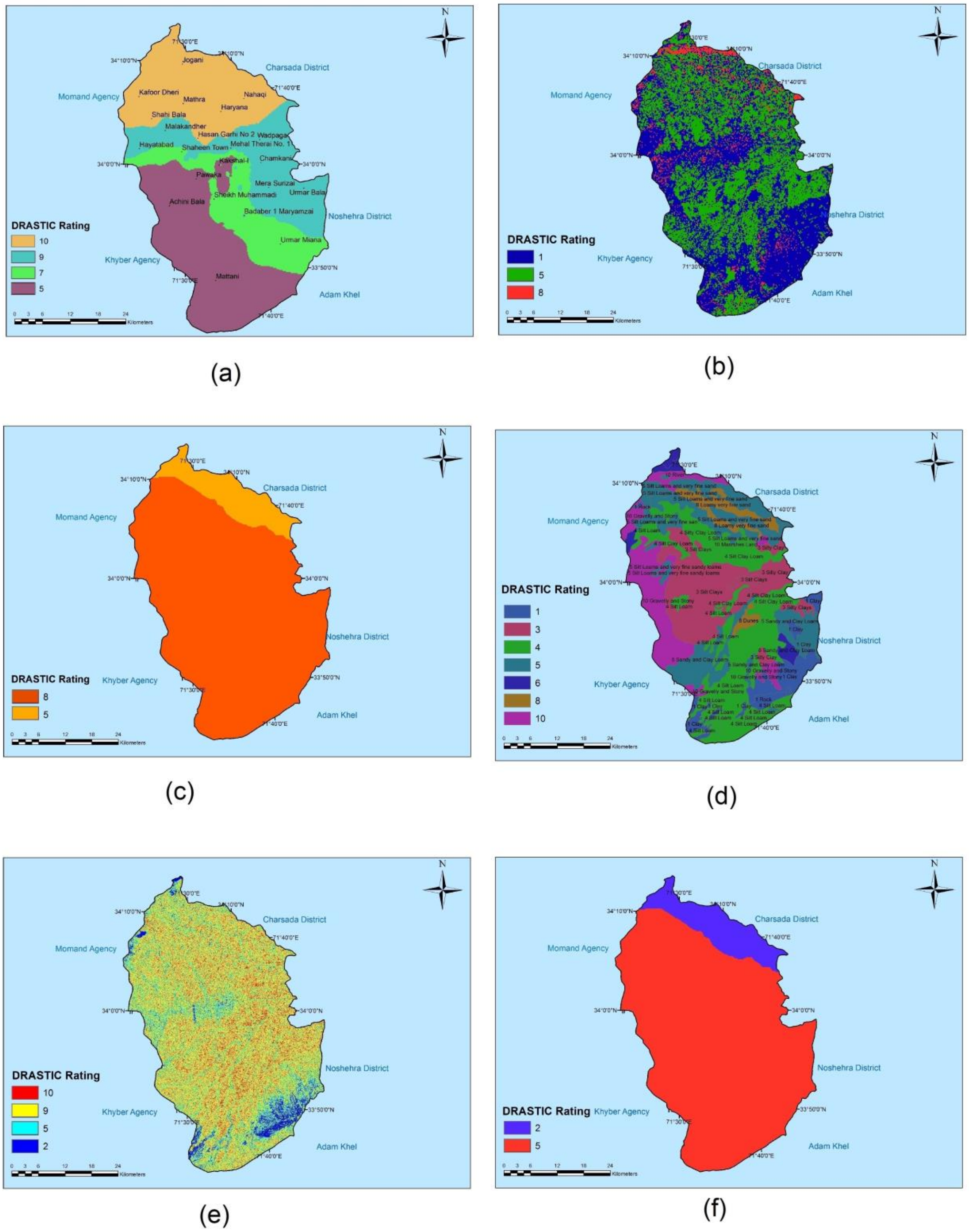

**Figure 5**. DRASTIC ratings for different ranges or media types of; (a) phreatic levels (b) net recharge (c) aquifer materials (d) soil types (e) slopes, and (f) hydraulic conductivity

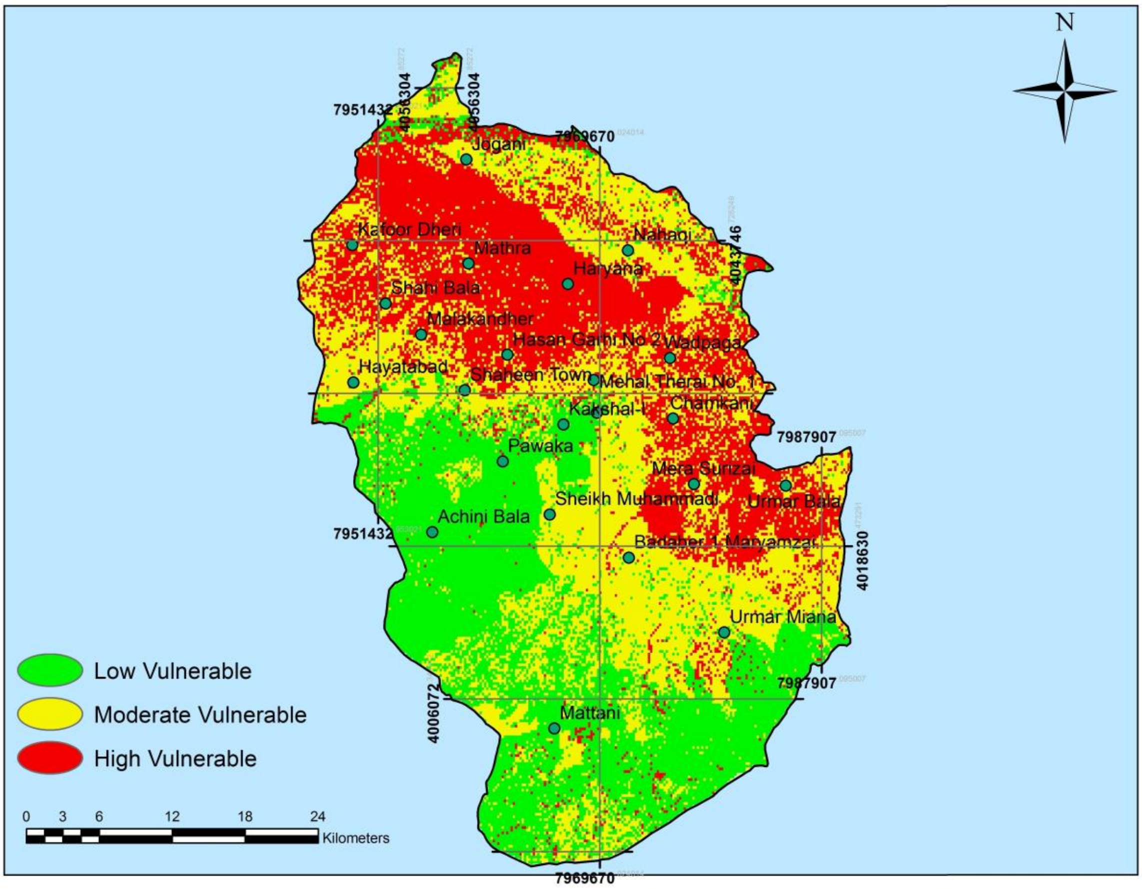

**Figure 6.** Final map of groundwater vulnerability in the study area.