A novel method of sensitivity analysis testing by applying drastic method and fuzzy optimization method to assess Groundwater vulnerability to pollution, case of Senegal River basin in Mali.

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Abstract

Vulnerability to groundwater pollution from Senegal basin was studied by two different but complementary methods: the DRASTIC method (which evaluates the intrinsic vulnerability) and the fuzzy method (which assesses the specific vulnerability taking into account continuity of the parameters). The validation of this application has been tested by comparing the membership in groundwater and distribution of different classes of vulnerabilities established as well as the nitrate distribution in the study area. Three vulnerability classes (low, medium and high) have been identified by both the DRASTIC method and by fuzzy method (passing by normalized model). An integrated analysis reveals that high class with 14.64% (for the DRASTIC method), 21.68% (for normalized DRASTIC method) and 18.92% (for that of fuzzy) are not the most dominant. In addition, a new method for sensitivity analysis was used to identify (and confirm) the main parameters which impact de vulnerability to pollution with fuzzy membership. And the results showed that vadose zone is the main parameter which impacts groundwater vulnerability to pollution while net recharge has the least contribution to pollution in the study area. It was found also that Fuzzy method better assesses the vulnerability to pollution with a coincidence rate of 81.13% against 77.35% for the DRASTIC method. These results are a guide for policy makers on protection areas sensitive to pollution and identification of the sites before later hosting the socio-economic infrastructures.

Keywords: DRASTIC MODEL; Fuzzy Concepts; Groundwater Vulnerability; Senegal basin; Mali

Introduction

A key component to building a territory is the vulnerability map. It’s a fundamental water quality assessment document that aids the development of underground water resources. Among the myriad of functions delivered by a Geographic Information Systems are its capability for multi-criteria analysis, a feature that is essential for developing the vulnerability maps for an aquifer system. Water quality information is a basic data requirement for implementing any water management decisions. It provides necessary information for assessing risk of groundwater pollution, and remediation measures needed to control future pollution level. These set of information could be retrieved from the groundwater pollution vulnerability maps. The assessment of the vulnerability of groundwater to pollution, 24 methods exist, which are classified into three groups; • Comparison methods: used mainly for very large study areas and takes into consideration 2-3parameters;

• Methods of analog relationship and numerical models: based on simple or complex mathematical laws. Recommended for assessing the vulnerability of radioactive sites;

• Method of parametric systems: it is composed of three sub systems:

o The matrix system: This system, adapted for local use, is based on a limited number of parameters judiciously chosen. The procedure is a combination of classes to define descriptively the vulnerability of aquifers;

o The class system: for this group, to define a range for each parameter considered necessary for assessing vulnerability, then subdivides each of the intervals selected based on the variability of the parameter. The final score resulting from the summation (or multiplication) of each score for the different parameters should be divided by the number of classes chosen.

o Weighted class system: this group of methods is based on assigning ratings to the parameters which are retained as necessary for the evaluation of groundwater vulnerability by defining intervals as is the case with other methods cited previously. Subsequently a weight is applied for each parameter according to its importance in the assessment of vulnerability.

Water is one of the most important things we need for our daily life. Nowadays water management is being more and more a big problem because of many reasons as climate, pollution, environmental issues, etc. So, many surface water and groundwater are polluted. Water system is a cycle. So water in air, water on the land and water under the land are all connected Groundwater and surface water are connected through a very complicated hydrogeological system, that can lead to a mutual contamination which means that if groundwater is polluted, it can affect the upper surface water and if surface water is polluted, it can affect the underlying groundwater too.

Sustainable management of the Senegal River basin resources is a major issue for the four riparian countries which are Guinea, Mali, Mauritania and Senegal.

The multiple uses of water and the multinational nature of the basin led the riparian countries to create the Organization for the Development of the Senegal River (OMVS in french), to sound management of the basin's water resources. For this, each country needs data and information enabling it to monitor and predict the evolution of the resource, also in view of the importance of climate variability in the region marked by the recurrence of drought, the potential impacts of climate change and the increasing impacts of population pressure on water resources. Many other water uses in the basin also require data and information for their activities.

The Senegal River Basin in Mali is increasingly dominated by cultures and industries using chemicals. This strong demand for chemicals threatens the quality of groundwater resources. Groundwater reserves are substantial and are being used to cover different needs. They are also used as source of drinking water in the region experiencing rapid population growth with a growth rate of 3% per year (OMVS, 2013). The quality of this groundwater resource is constantly put to the test, because of the growth of both point and diffuse pollution sources. To prevent the risk of pollution of groundwater, an adapted approach is the knowledge vulnerable areas to pollution. Civita (1994) showed that aquifer groundwater’s changes(in quality and quantity) in time and space are due to natural process and/or human activities.

The work already done in the area (Newton, Joshua T, 2007; UNESCO 2012), mainly concern the quantity, and water resources management. Other studies (Anoh, 2009; Jourda et al., 2007) have focused on the quality of water resources but not in the same exact area or not to found the vulnerability zones.

However, none of these studies has been the event of the impact of human and natural activities on groundwater resources in the basin of the river Senegal to Mali. Thus, the present study uses fuzzy and Drastic methods which evaluate the intrinsic and specific vulnerability to pollution to highlight those impacts. Intrinsic vulnerability method is inflexible because its weights and ratings are fixed according to hydrogeological parameters, while specific vulnerability method is flexible and takes into account local hydrogeological conditions and continuity of parameters (Afshar et al., 2007; Antonakos et al., 2007; Alemi-Ardakani et al., 2016; Madhumita et al., 2016).

DRASTIC method is the most used method in the world to assess groundwater vulnerability to pollution (Denny et al., 2007; Bojórquez-Tapia et al., 2009; Dhar et al., 2014). But this method more and more subject to criticism for the reason that the choice hydrogeological features, the weights and the ratings does not agree necessarily with the reality on the study area and the its specificity(Denny et al., 2007; Dhar et al.,2013; Madhumita et al., 2016). So to improve and adapt DRASTIC model to study area particularity it is better to modify the classical model or combine it with other new developed models to get better results. Many studies proposed methods which combined DRASTIC and other methods (Yu et la., 2012; Dhar et al., 2012; Fernando et al., 2013; Madhumita et al., 2016). (Leone et al., 2009; Luis et al., 2009 and Neshat et al., 2015a and 2015b) all proposed modified models to assess groundwater vulnerability to pollution. But none of them focused on comparison between classical sensitivity analyses (single parameter and map removal) and fuzzy membership. DRASTIC method is essentially based on subjective setting of study area hydrogeological conditions (Nobre et al., 2007, Madhumita et al., 2016) while fuzzy concept is based on membership which is an objective setting of study area hydrogeological conditions (Pacheco et al., 2015; Madhumita et al., 2016). For example membership expresses the relations between two given parameters and also the degree of truth of falseness of these relations (Pacheco et al., 2015; Madhumita et al., 2016). This technique has been used by many authors such as (Pacheco et al., 2015; Madhumita et al., 2016), (Pathak et al., 2009; Sahoo et al., 2016a and 2016b), and (Saidi et al.,2011; Sener et al., 2013), however most of these studies assessed pollution risk (Pacheco et al., 2011 and 2012) and not comparison between intrinsic and specific vulnerability or comparison between different types of sensitivity analyses and memberships to identify parameters impacts on groundwater vulnerability to pollution.

The aim of our study is to find useful and relevant information to guide policy choices for prevention and management of risks of pollution of groundwater resources in this area by a sustainable management.

The DRASTIC method is one of weighted classes, which was developed by 'The US Environmental Protection Agency (EPA)' and the 'National Water Well Association (NWWA)' in 1987 to evaluate the groundwater vulnerability to pollution.

Although it is not originally designed for Geographic Information Systems, this model is a classic spatial analysis widely used in GIS.

The objective of DRASTIC is to give a standard methodology that gives reliable results for efforts to protect groundwater.

DRASTIC generates an index or 'score' for the potential pollution of ground water resources. This index covers the entire range from 23 to 226. Note that the vulnerability to pollution is higher for higher notes.

The DRASTIC method uses seven hydrological parameters: the depth of the water level of the water table [D], the net recharge [R], the lithology of the aquifer [A], the soil texture [S], the topography slope of the field- [T], the impact of the unsaturated zone [I] and finally the hydraulic conductivity or permeability of the saturated zone [C].

In GIS, each parameter is scored on a layer by assigning a weight coefficient corresponding to the parameter, that is to say, its influence on the vulnerability of the aquifer. Then these layers are superimposed on a layer where result will be calculated the index DRASTIC said 'DRASTIC Pollution Index (DPI)'. The layers will obviously have the same cartographic features: a single projection system, identical units of length, identical geographical area and also the same resolution, because this system uses matrix format for all calculations.

DPI is dimensionless. The number or the order of magnitude has no meaning in itself. The unity of the DPI occurs when comparing two sites or a site to several other sites. The site with the highest DPI will be considered most susceptible to contamination or pollution.

More than 24 vulnerability assessment methods of groundwater to pollution are identified in the international literature. The method most currently used in the world is the DRASTIC method.

It is a method that was developed by L. Aller et al in 1987 and is one of the assessment methods (Vulnerability aquifers) Weighted based and assigning a rating to used different parameters (generally between 1 and 10). A Weighting is also allocated according to the relative importance of each of the parameters used. The DRASTIC numerical rating system incorporates seven different physical parameters involved in the transportation process and mitigation of contaminants: water depth, effective recharge, aquifer, soil type. Step 1:A numerical value ranging from 1 to 5 is allocated to each of 7 parameters (parametric Weight Dp, Rp, Ap ...), topography, vadose zone and hydraulic conductivity of aquifer media. Each of these parameters is a weight (predetermined value) of between 1 and 5, which reflects the importance of the parameter in the transport processes and contaminant attenuation. A key parameter is assigned a weight equal to 5 while a setting with less impact on the fate of a contaminant is assigned a weight of 1. 2nd step: At each of the seven parameters is assigned a value ranging from 1 to 10, defined in terms of ranges of values. The smallest value represents lower vulnerability conditions to contamination (Dc, Rc, Ac ...). For each hydrogeological unit, the seven parameters must then be evaluated to give each a rating that can vary from 1 to 10. A rating of 1 corresponds to the least condition of vulnerability while a rating of 10 reflects the most likely to be contaminated conditions. Step 3: DRASTIC is an acronym, where each letter represents one of the seven factors that highlights DPI (Bezelgues et al., 2002): the depth to the water table (D); the effective aquifer recharge (R); the aquifer material (A); the type of soil (S); the slope or topography of the landscape (T); the impact of vadose zone (I) and the permeability or hydraulic conductivity of the aquifer (C).

All parameters were reclassified in ArcMap and assigned a score based on rankings ranging from 1 to 10 and a weighting to help merge factors together in the DRASTIC equation in GIS. Each of the seven parameters was then assigned a multiplicative factor (w) sets ranging (weight) from a value of 5 for the most significant factors and to 1 for factors that are less so.
The DPI was determined according to equation (1) according to Osborn et al. (1998): (Where D, R, A, S, T, I, and C are the seven parameters of the DRASTIC method, "w" is the weight of the parameter and "r" the associated rating). The weights of the parameters of DRASTIC method used (Table 1) are those defined by Go et al. (1987). The reference values of the index DRASTIC used are those provided by Engel et al. (1996) and represent the measurement of the hydrogeological aquifer vulnerability.
(1)

$$DPI = D_r D_w + R_r R_w + A_r A_w + S_r S_w + T_r T_w + I_r I_w + C_r C_w$$

Or (2)

$$\text{DPI} = \sum_{k=1}^{7} R_k W_k$$

Where R is the rating (1 to 10), W is the weight (1 to 5) and k is the parameter (1 to 7)

In the final step, the calculation of the DRASTIC index to each hydrogeological unit is obtained by the sum of the products of each side by its weight. DPI represents the level of risk of the aquifer unit to be contaminated. It can take a maximum of 226 (100%) and a minimum value of 23 (0%).

MATERIALS ET METHODS

The study area and hydrogeological settings:
The Senegal River Basin is among the largest rivers in Western Africa. The territory of its basin is bounded by parallels 10°30’ and 17°30 N and meridians 7°30’ and 16°30’ W. The Senegal ranks seventh in terms of basin area and runoff among African rivers and second in Western Africa after the Niger River. The Senegal River basin, located in West Africa, covers 1.6% of the continent and spreads over four countries (Guinea, Mali, Mauritania, and Senegal). The Senegal

River is formed by the confluence of two smaller rivers, the Bafing and Bakoye, which occurs near Bafoulabé, Mali, at about 1,083 km from the Atlantic Ocean. After crossing western Mali, the Senegal River constitutes the boundary between Senegal and Mauritania. The Senegal River basin occupies a total area of 289,000 km2. Along760 km, Bafing rises at an altitude of 800meters in the Fouta Djallon in Guinea and headed north across the plates of the Sudanese region before reaching Bafoulabé. It brings more than half of the total flow of the Senegal River with 430m3/s mean annual flow. His career is characterized by the presence of falls and rapids. Along 560 km, Bakoye takes source near the southern boundary of Mandingo tray in Guinea, at an altitude of 706 meters. At its confluence with the Bafing, Bakoye has a mean annual flow of 170 m3/s. This river also passes a relatively large number of small waterfalls and rapids.

Downstream Bafoulabé on the right bank, the main tributaries of the Senegal Riverare Kolombiné, Karakoro and Gorgol. On the left bank, Falémé is the largest tributary 650 Km long, it rises in the northern part of Fouta Djallon, at an altitude of 800 meters. It throws itself into the Senegal River 30 km upstream from Bakel. The annual flow at its outlet in the Senegal River is about 200 m3 / s.

Along 1800 km, Senegal River starts in northern GUINEA, crosses the western part of MALI and is on the rest of its route, the border line between the territories of the Republic of Senegal and the Islamic Republic MAURITANIA.

There are two main parts:

-SENEGAL upper Basin, located upstream of BAKEL, tormented and mountainous region, made up of the basins of the FALEME, the BAFING, the Bakoye and BAOULE;

-SENEGAL Lower Basin, downstream of BAKEL little accentuated area, very flat, where the maximum does not exceed 400 m (Massif Assaba), and where the river meanders in the middle of a very wide valley.

-The watershed of the river covers a total area of 289,000 km^2 with 155,000 km^2 in Mali (upper basin) spread between Kayes (Kéniéba, Bafoulabé, Kita, Kayes, Diéma, Yélimané and Nioro) and Koulikoro (Banamba, Kolokani and Nara).

Our study concerns the Upper Senegal (figure 1a) which is the part of the Senegal basin situated in Mali.

The working material consists of multiple data sources. This is the piezometric data from piezometric champagne conducted in different years in the region and complemented by those of the database "sigma" of the National Water Directorate (DNH).

Drilling data sheets available provided by the various campaigns of supply of drinking water as well as the National Water Laboratory (LNE) allowed to use the drilling depth data, groundwater levels, lithological cuts and pumping test ... These data helped to the achievement of several maps of vulnerabilities.

To these data, add map information with the geological map of the region and that of the soil sketch of Mali provided by FAO's work.

Thus, the coordinates of Shuttle Radar Topography Mission or SRTM picture (http://srtm.csi.cgiar.org) was used for the cover of the study area. This image treatment has established a digital elevation model (DEM) resolution of 90 m and highlights the slope map.

The processing of all this data is performed on ArcGIS 10.0 for cartographic processing, processing of satellite images and to generate the slope map and the combination of other thematic maps.

For this study we used two different methods: one to assess the intrinsic vulnerability (DRASTIC) and the second to find the specific vulnerability (Fuzzy).

The DRASTIC method is a method for mapping the inherent vulnerability of aquifers. This method has already been the subject of several applications through the literature. Mohamed (2001) evaluated aquifer vulnerability to pollution in El Madher (Algeria); Murat et al. (2003) assessed the south-western aquifer pollution in Quebec (Canada); Jourda et al. (2006) and Kouame et al. (2007) also used DRASTIC method to assess respectively Korogho (northern Cote d'Ivoire) and Bonoua (southern Cote d'Ivoire) aquifers vulnerability to pollution. Although if it often changed (Hamza et al., 2007), it remains effective as the vulnerability assessment tool. To test this ability it has been associated to the fuzzy method, which is one of these variants. The joint application of the two methods has the advantage of ensuring complementarity in evaluating the vulnerability of groundwater to pollution. These methods are in the form of numeric rating system, based on the consideration of the various factors influencing the hydrogeological system. In the assessment of the vulnerability process, seven parameters of interest to both the two methods including the depth of the water level, the effective recharge of the aquifer, soil types, topography, impact of vadose zone or the effect of self-purification of the vadose zone, the lithology of the aquifer and the hydraulic conductivity of the aquifer. The drastic method uses formulas that experiment the linear relationship between the parameters, while the fuzzy method uses formulas that take into account the continuity in pollution from one point to another.

Vulnerability assessment by the DRASTIC method

Polygon maps were initially generated for all the seven DRASTIC maps by geo-referencing, digitizing, and editing.

These polygon maps were classified according to their importance on aquifer pollution potential (a value from 0 to 10 was assigned to each map). So for each parameter we created specific polygon maps by adding these ratings to attribute table in GIS. Specific polygon maps were then converted into raster maps according to their ratings. We assigned weight to these raster maps and combined them then to get the final vulnerability map by using formula (1 or 2).

DRASTIC method is frequently used to study groundwater vulnerability (Shirazi et al., 2013; Sinha et al., 2016). In United States Hearne et al. (1992); Merchant J.W (1994);Atkinson et al. (1994); Kalinski et al., (1994) used this method to assess groundwater vulnerability.

The DRASTIC model was already used in many other countries worldwide. It was used for the assessment of groundwater pollution in Anekal Taluk 9n semi-arid area of Bangladore district (Chandrashekhar et al., 1999).

Jha et al. (2005) used DRASTIC method to assess Ranchi, Jharkland groundwater vulnerability.

To assess DRASTIC parameters we need to identify and study every hydrogeological and meteorological conditions of the study area (Anwar et al., 2003; M. H. Hamza et al. 2006)

The following parameters were used for the DRASTIC method:

Groundwater table Depth (D):

Groundwater table depth is the distance between upper most layer of unsaturated zone and groundwater static level. So it controls the thickness and amount of possible contaminants (Ckakraborty S et al., 2007). Therefore when this distance is high then it is more difficult for surface water to cross (under chemical, biological reactions) all this thickness and to reach groundwater.

We got depth to water table data from borehole data given by National Directorates in charge of water resources management in Mali.
These date show that the depth varies from 1.50m to more than 120m. As said Dhundi et al. (2009), for depth beyond 100 m, we assigned a rating of 0 because it is almost impossible for pollutant to reach groundwater, due to processes like, sorption, filtration, biodegradation, volatilization… Table 1 shows all the values for weight and scores for depth to groundwater static level, and it map is shown in figure 1.
To generate the map we used the inverse distance moving average to get a good accuracy (Samake et al, 2010, 2011). We assigned sensitivity rating values as did Dhundi et al.(2009): for D<1.5 m we assigned a rating r=10, if 1.5m<D<4.6 m then r=9, if 4.6m<D<9.1 m then r=7, 9.1m<D<15.2m then r=5, 15.2m<D<22.5m then r=3, if 22.5m<D<30 m then r=2 and for D>30 m and the region having no data we assigned a rating value r=1.

Recharge (R):

The yearly mean quantity of water that penetrates the unsaturated zone and touches the groundwater (Aller et al. 1987), groundwater recharge or net recharge is the movement of water from ground surface to groundwater. It can easily bring contaminant to groundwater. So, recharge value increases with aquifer vulnerability potential because dispersion, dilution, etc will increase in unsaturated zone also. There are many sources of recharge in the study area including precipitation, irrigation, waste water, return flow, infiltration from surface water (rivers, springs etc.).
Net recharge data was taken from hydrogeological synthesis of Mali (Mali Groundwater Resource Investigation, 1990). The different values of net recharge are in table 2. Figure 2 represents the recharge map.
We used the following formula to calculate net recharge:

Net recharge = (rainfall - evaporation) × recharge rate

Aquifer media (A):

Aquifer media was defined by many researchers in the world: Aquifer media describes the rocks (consolidated and unconsolidated) which are used as water storage (Chandrashekhar et al., 1999). According to Heath (1987) an aquifer is an underground rock or deposit unit that will produce enough amounts of water to a borehole. The aquifer is also designated as a geological or hydrogeological formation which can produce enough amounts of water for consumption (Anwar et al., 2003). It is very important in attenuating the pollution because it is the media where all reactions take place and grains size and sorting are very important in pollutant attenuation. Also the aquifer media governs flow path and length in an aquifer. Hence Piscopo (2001) indicates that the duration of time available for attenuation is determined by the path length. In this study, we used topographical map and well log data to prepare the aquifer media map. We assigned a high rating values to coarse media and low values to finer media. With the Mali hydrogeological synthesis maps and report on Senegal Basin groundwater simulations, the aquifer media data (table 3) for this research were computed (figure 3) from more than 2300 borehole data.

Soil media (S):

It is the ground surface part of vadose zone. The quantity and shrink/swell capacity of clay in soil, soil grain type, sorting and size are both important because they influence groundwater movement, potential dispersion, pollutants migration throughout biological and physic-chemical reactions (sorption, biodegradation, ionic exchange, oxidation, reduction…).

The permeability of the soil media was used as basis for assigning ratings on a scale of 1 to 10. The coarsest soils were assigned a rating of 10 and this decreased all the way to the finest media, which were assigned a rating of 1. Details for rating and index are shown on table 4 while soil map is shown on figure 4.

Topography (T):

Topography of an area accounts for the change in slope. It is a determining factor of how rainfall and pollutants will either run-off or infiltrate (Lynch et al., 1994).The longer the water and or pollutant get retained in an area, the greater the chance for infiltration and consequently, the potential for recharge is higher. Gentler slopes (slopes of 0-2 (%)) have higher retaining capacity for water and/or pollutants while steeper slopes (slopes of +18(%)) have lower retention capacity for water and or pollutants. According to Aller et al., 1987, topography has an effect on attenuation since it influences soil development.

Slope values extracted from (DEM) the Digital Elevation Model of the region were reclassified and ranked on a scale (table 5) of 1 to 10 to build the topography map (figure 5). This served as basis to be included in the multi-criteria analysis, where other DRASTIC factors play a role.

Impact of vadose zone (I):

Unsaturated zone or vadose zone is situated between ground surface and groundwater table. It highly impacts aquifer pollution potential by it permeability, reactions inside, etc. (Corwin, et al., 1997). Because vadose zone is closely related to soil media and groundwater depth, we used the formula developed by Piscopo (2001) to estimate it: (3)

$$I_r = D_r + S_r$$

Where: *I* is the impact of Vadose Zone, *D* is depth to water table, *S* is soil media and *r* is the rating

For groundwater depth we chose the following ratings: 5 for depth less than 10 m, 2 for zones with depth between 10 m and 30 m, and 1 for region which water table static level is higher than 30m. Similarly we chose 5, 3 and 1 for respectively high, medium and low permeable soils. And finally we combined the two map layers to get the impact of vadose zone layer (table 6 and figure 6).

Hydraulic conductivity (C):

Hydraulic conductivity designates the aquifer capacity to transport contaminant (Ckakraborty S et al,. 2007). It plays a very important role in aquifer contamination potential because an aquifer with high value of C is easy to be contaminated and one with low value of C is difficult to be polluted (Fritch et al., 2000).

We used trasmissivity values instead of hydraulic conductivity to build it map. We adopted the following rating system: for very high values (>450 m^2/day) we chose 10; for high values (300–450 m^2/day) we chose 8; for moderate values (100– 300 m^2 /day) we assigned 6; for moderately low values (30–100 m^2 /day) we assigned 4; for low values (20-30 m^2 /day) we chose 3; for very low values (10-20 m^2 /day) we chose 2 and for extremely low values ((<10 m^2/day) we assigned 1 as rating value. The different values and distribution of hydraulic conductivity are shown in Table 7 and figure 7.

Vulnerability assessment by the fuzzy method

DRASTIC method cannot consider the continuity passage from the highest polluted point to lowest one, this property expresses the blurring effect of the aquifer to be potentially polluted. So fuzzy concept can be utilized to evaluate the groundwater pollution potential. For instance, we know that for vulnerability evaluation, when the water table is shallow, recharge rate is high, and if aquifer and soil materials are coarser, groundwater potential to pollution is higher. Also if the hydraulic conductivity, recharge rate and slope are low then groundwater potential to pollution is low. The main concept using fuzzy logic is very simple and it expresses if a statement is true or untrue and also it degree of verity or wrongness for all the inputs (Pathak et al. 2009). A function of membership links all fuzzy sets. We coupled fuzzy optimized model with GIS to evaluate the vulnerability degree by converting the study area into raster map and taking into account membership degrees in continuous passage from highest polluted points to lowest polluted points in hydrogeological settings.

Optimized fuzzy model:

The fuzzy nature of groundwater vulnerability and groundwater vulnerability assessment can be considered as a particular property. For example instead of numerical measurement of factors in Drastic method, the fuzzy method describes continuously the links between those factors that affect groundwater.

The fuzziness can be expressed continuously by membership degree from 0 to 1. The following optimized model is used (Pathak et al. 2009):
Given a matrix for factors: (4)

$$X = (x_{ij})_{7*n}$$

X_{ij} denotes the value of tester j in element i

I=1,…,7;j=1,…,n with n the overall number of sampling points.

We can classify Drastic factors into two main groups which are:
-group 1 where the increasing of parameter value increases groundwater vulnerability to pollution.
-group 2 where the increasing of parameter value decreases groundwater vulnerability to pollution.
This membership degree can be expressed mathematically by:
For the group 1: (5)

$$r_{ij}\begin{cases}0 \ \ if\ x_{ij} \leq x_{minj} \\ \dfrac{x_{ij} - x_{minj}}{x_{maxj} - x_{minj}}\ if\ x_{minj}\ \geq x_{ij} \geq x_{maxj} \\ 1\ if\ x_{ij} \geq x_{maxj}\end{cases}$$

For the group 2:(6)

$$r_{ij}\begin{cases}0 \ \ if\ x_{ij} \geq x_{maxj} \\ \dfrac{x_{maxj} - x_{ij}}{x_{maxj} - x_{minj}}\ if\ x_{minj}\ \geq x_{ij} \geq x_{maxj} \\ 1\ if\ x_{ij} \leq x_{minj}\end{cases}$$

With rij the degree of membership for the sample j in factor i
minj is the smallest value of element i(i.e. 1) in Drastic method.
maxj is the maximum value of element i(i.e. 10) in Drastic method.
We can use equations (4), (5) and (6) to get the following connection of factors matrix: (7)

$$R = \left(r_{ij}\right)_{7n}$$

With the following conditions in matrix R:
-if rij=1 then the tester j has the highest potential to groundwater pollution according element i only.
-if rij=0 then the tester j has the lowest potential to groundwater pollution according the element i only.
For example when all element connection degrees to highest potential to groundwater pollution are 1, then:(6)
Rij=(1,…,1)
And when all element connection degrees to lowest potential to groundwater pollution are 0, then: (8)
Rij=(0,...,0)
So the membership degree of each or the parameters in sample j is: (9)
rj=(r1,…,r7)T
In Drastic system different parameters have different weights (from 5 to 1) in relation to vulnerability; these are normalized in evaluation process to sum to one.
Let (10)
W= (w1,…,w7)T the weight vector
The distance from one given sample j to the sample with the highest potential to groundwater pollution can be express as: (11)

$$d_1 = \sqrt[p]{\sum_{i=1}^{7}\left[w_i\left(r_{ij} - 1\right)\right]^p}$$

The distance from one given sample j to the sample with the lowest potential to groundwater pollution can be express as: (12)

$$d_2 = \sqrt[p]{\sum_{i=1}^{7} (w_i r_{ij})^p}$$

p in (11) and (12) is called distance factor, when p=1 the distances are named Hamming distances and when p=2 the distances are called Euclidean distances.

We used Euclidean distances in our study. We can see clearly that if d1=0 then the given sample j has the highest potential to groundwater pollution and when d2=0 then the given sample j has the lowest potential to groundwater pollution.

Let the membership degree of the highest potential to groundwater pollution be denoted by uj for a given sample j, so the membership degree of the lowest potential to groundwater pollution will be (1-uj) for the same given sample.

Membership can be regarded as weight in view of fuzzy concept. So the following equations express more clearly continuous changes from a given sample j to the highest potential to groundwater pollution as well as from the same given sample to the lowest potential to groundwater pollution: (13)

$$D_1 = u_j \sqrt[p]{\sum_{i=1}^{7} \left[w_i\left(r_{ij} - 1\right)\right]^p}$$

D_1 is the weighted distance to the highest potential to groundwater pollution and: (14)

$$D_2 = (u_j - 1) \sqrt[p]{\sum_{i=1}^{7} (w_i r_{ij})^p}$$

D_2 is the weighted distance to the lowest potential to groundwater pollution.

To get an optimized solution for uj the objective function is: (15)

$$min\{F(u_j) = (D_1^2 + D_2^2)\} = u_j^2 \left\{\sum_{i=1}^{7} \left[w_i\left(r_{ij} - 1\right)\right]^p\right\}^{2/p} + (1 - u_j)^2 \left\{\sum_{i=1}^{7} \left[w_i r_{ij}\right]^p\right\}^{2/p}$$

After differentiating (14) and solving it comes: (16)

$$u_j = \left[1 + \left\{\frac{\sum_{i=1}^{7} \left[w_{i(r_{ij}-1)}\right]^p}{\sum_{i=1}^{7} \left(w_i r_{ij}\right)^p}\right\}^{2/p}\right]$$

Equation (16) is called fuzzy optimization model and higer the value of u_j, higher the potential of groundwater vulnerability to pollution for a given tester j. This model is joined to GIS and used to evaluate the pollution potential or groundwater. The diagram of procedures used to evaluate this potential maps using DRASTIC and fuzzy methods in GIS is shown in figure8.

Results and Discussions

Fuzzy-DRASTIC parameters:

Using memberships defined by fuzzy concept depth to ground water table and topography maps were different from those of DRASTIC, but for the other five parameters the fuzzy optimized and DRASTIC maps were identical.

The depth to ground water table and topographic map obtained by using fuzziness are shown in figure 9 and figure 10:

The aquifer vulnerability maps

The final DRASTIC Potential Index (DPI) was obtained by using formula 1 (or 2) in ArcGIS 10.0 software on the seven individual map layers to produce the vulnerability map for DRASTIC method. The DPI rating scores were from 72 to 141 and the greater the score, the higher the aquifer vulnerability. We used natural break (jenks) classification to get three main classes namely low vulnerability area (DPI<110), moderate vulnerability area (110<DPI<120) and high vulnerability area (120<DPI<141). Table 8 and figure 11 show DPI scores and distribution. These values range from 72 to 141 and are classified into 3 distinct classes.

To facilitate and control scientific discussion, we used natural break (jenks) classification to get three vulnerability maps for both methods: DRASTIC method normalized DRASTIC method and fuzzy DRASTIC method.

Under these conditions figure 11(DRASTIC method) shows that high risk area of Senegal basin in Mali are mainly situated in northern and southwestern portion of the basin with 14.64% of total Senegal basin in Mali. The moderate risk areas which cover 6.51% of the total basin are somewhat disseminated and are mostly situated in the central and northern portion of the basin. Certain moderate risk areas are seen in the north eastern and extreme west zone. All the others portions of the Senegal basin in Mali are under low risk (78.85%) which are found in the western and Middle Western parts regions of the basin.

For the normalized vulnerability we got: 21.68% for high vulnerability, 15.22% for moderate vulnerability and 63.32% for low vulnerability. The map is shown in figure 12.

And for fuzzy DRASTIC method we got: 18.92% for high vulnerability zone, 8.94% for moderate vulnerability zone and 72.11% for low vulnerability zone (figure13).

Intrinsic method cannot show the influence of each individual feature on the final vulnerability index because the same weight and rating are assigned to a given parameter making this method subjective. But based on the relative significance (or importance) of a given parameter, specific method gives weight and rating to get the final vulnerability index. So with intrinsic method some parameters can be under or overestimated while with specific method each parameter will have it specific (or actual) estimation. These are the main reasons which explain why different zones of the study had different vulnerability index according to each method.

However, figures 14-16 showed that coincidence ratio with nitrate high concentration for fuzzy DRASTIC method is the highest (81.13%), followed by normalized DRASTIC method (79.54%) and the lowest coincidence ratio is for DRASTIC method (77.31%). This confirmed our assertion that fuzzy method better assesses groundwater vulnerability to pollution than simple DRASTIC method.

Sensitivity analysis

Seven hydro-geological parameters influence the transport of the contaminants to aquifers when using the DRASTIC approach. According to Rosen (1994), the great numbers of parameters are intended to decrease indecisions associated with using the individual parameters on the results. But, several researchers (Merchant, 1994;Barber et al. 1994) opine that groundwater risk assessment is possible without using all the seven parameters of the DRASTIC method. Other researchers (Napolitano and Fabbri, 1996) also criticized in what way the weights and the ratings for the seven parameters are assumed for DPI assessment and lead to uncertainties about the precision of the outcomes for pollution risk assessment. Many factors contribute to the output of the DRASTIC model(Rahman A., 2008;Ckakraborty, 2007) including map units in each layer , the weights, the overlay operation type that is performed, the number of data layers, the error or doubt associated to each map unit etc.

Sensitivity analysis was adopted to complement trial evidence for DRASTIC method to perfect the uncertainty about model precision.

Two (2) sensitivity analyses were then done (Babiker et al. 2005; Lodwick et al. 1990): the map removal sensitivity test and the single parameter sensitivity analysis.

The map removal sensitivity test defines the sensitivity of risk map to each parameter by eliminating a single or more layer map and is applied using the following equation: (17)

$$S = \left(\frac{\left| \frac{V}{N} - \frac{V'}{N} \right|}{V} \right) * 100$$

With S the sensitivity degree, V is the unperturbed risk index using N data layers and V' is the perturbed risk index with N' data layers. The real index V is found by using altogether the seven parameters while the V' can have a smaller number of parameters for the calculation procedure.

To estimate the impact of individual parameter on the risk potential, we used the single parameter sensitivity test. During this test we compared the effective or actual weight of every individual factor with it hypothetical or allocated weight by using the following formula: (18)

$$W = \frac{P_r * P_w}{V} * 100$$

W is the actual weight of the factor, Pr is the Rating, Pw is the Weigh, V is the risk index

The statistical summary of all parameters are shown in table 8 and table 9. We noted that using DRASTIC method and equation 17 the highest vulnerability source is topography which has a mean value of 9.83. The second main parameter affecting the risk is impact of vadose zone with 8.14, followed by soil media (5.71). After vadose zone comes depth to groundwater table with 5.52 as mean value. The fifth and the sixth positions are occupied respectively by aquifer media (4.27) and hydraulic conductivity (1.93) for their contribution to groundwater pollution potential. Finally net recharge showed the least mean value for contribution to pollution risk in Senegal basin in Mali.

The effective weight also called coefficient of variation (equation 18) shows that the main two parameters which impact the most DPI values are the unsaturated zone (or vadose zone) with 35.92% and depth to groundwater table with 24.17%. They are followed by aquifer media (11.25%), soil media (10.04%) and topography (8.73%). Hydraulic conductivity and net recharge

have relatively low variations with respectively 5.09% and 4.80%. A low percentage means a small influence on variation on DPI across the basin.
Table 8 shows statistics and the correlation on the seven parameters used in both Drastic and fuzzy model. The average values of factors show that vadose zone contributes the most DPI with a mean value of 35.90% for Drastic and 0.79 for fuzzy membership. Depth to water table (24.17% and 0.5), aquifer media (11.24% and 0.36) and soil media(10.02% and 0.52) have moderate contribution to final vulnerability index. And topography (8.72% and 0.02), hydraulic conductivity (5.08% and 0.1), recharge (4.8% and 0.04) have low contribution to final vulnerability index.

Map removal sensitivity analysis

The first step of this test shows the change in DPI value when we remove only one map layer a time. Table 10 and table 11 give the calculation results. Because the overall mean variation is not more that 1% the test does not describe very clearly DPI variation when removing only one map layer a time, also all mean values are almost the same here. But the maximum value of DPI variation was estimated when we removed unsaturated zone parameter map with a relative mean variation of 3.60%. This can be explained by its relative high theoretical weight in DRASTIC method and the nature of unsaturated zone material in the basin. Moderate variations were seen after removal of depth to groundwater table (1.72%), net recharge (1.58%) and hydraulic conductivity (1.53%). Only minor variations in mean values of DPI were remarked (from 0.67% to 0.92%) after removal of each of the other parameters from computation (table 10).

The second step of map removal sensitivity test shows the change in DPI value when we remove one or more map layers (or parameters) a time from calculation. Based on the first step we removed parameters in the second step (Rahman A., 2008; Babiker I.S et al. 2005) by removing preferentially the parameters which produced less variation on the final DPI value and then next smaller etc.
The smallest mean effective weight variation was seen after removal of net recharge (4.80%) from de calculation. The more we remove data layers from calculation the more the mean variation value increases because we keep the most effective parameters each time (Babiker I.S et al. 2005)..

Single parameter sensitivity analysis (effective weight)

The significance of each of the seven parameters has been shown in map removal sensitivity analysis. Now we need to understand if the theoretical weight affected to each parameter in DRASTIC model is its actual/real or effective weight after computation.
The actual weight represents the importance of the single factor compared with the other six factors and the weight given to it by the DRASTIC model (Rahman A., 2008; Babiker 2005).
The single factor sensitivity test data can be seen in table 12. The theoretical weights of both impact of unsaturated zone and groundwater static level are 21.73% but their actual or effective weights are respectively 35.92% and 24.17%. Because their actual weight is higher than their hypothetical (assigned) weight we can say that they are the two most effective factors (or [arameters) in this DPI calculation. The soil media parameter (10.04%) and topography parameter (8.73%) similarly indicate great effective weight in comparison to their theoretical

weight (8.69% and 4.34% respectively). In contrary, the other three parameters presented lesser effective weight.

The importance of the four most effective parameters focuses on the need of precise data for building the model. And the low recharge and hydraulic conductivity values in Senegal basin contributes to reduce the significance of these parameters in its groundwater vulnerability assessment.

This study has demonstrated the closed and linearly relationship between sensitivity analysis and fuzzy membership (table 9). So instead of sensitivity analysis, we can also use fuzzy membership to find the main parameters which influence the GW potential vulnerability to pollution.

Conclusion

Basically, analyses were done with the purpose of observing the correlation between the intrinsic risk evaluation outcome and groundwater pollution in Senegal basin in Mali. DPI main values were low, moderate and high. In this study, a methodology was adopted to improve DPI calculation to produce pollution potential map. This was achieved by including the homogeneous nature of vulnerability to pollution using DRASTIC factors in a vast area. In addition, field measured nitrate data were used to confirm risk to pollution map of Senegal basin. So we can say that passing from easiest to most difficult groundwater to be polluted can be continuous. This proves in fact the fuzzy nature of risk to groundwater pollution. So, combined GIS built fuzzy design model produces the continuous risk assessment function different stage DRASTIC index more accurate than the simple DRASTIC method. We compared simple DRASTIC, normalized DRASTIC and fuzzy DRASTIC outputs and it appeared that fuzzy index coincides the most with nitrate distribution in the study area. The outputs show that 18.92% of the study area's groundwater aquifer are under high risk to pollution due to fuzzy DRASTIC while 14.64% of the study area's groundwater aquifer are under high risk to pollution from simple DRASTIC method. From this outcome, it can be established that risk assumed by fuzzy method is more consistent than DRASTIC method. For several aspects of the local and regional groundwater resources protection and management, the groundwater risk to pollution maps established in this work are important tools in policy and decision making.

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Table 1: Range and Rating for Depth to Water

Range (m)	Rating	Index
≤ 1.5	10	50
1.6 – 4.6	9	45
4.6 – 9.1	7	35
9.1 – 15.2	5	25
15.2 – 22.5	3	15

22.5 – 30	2	10
≥ 30	1	5

Weight: 5

Table 2: rang and rating for net recharge

Range(mm/a)	rating	index
20-50	1	3
50-100	3	9
100-300	6	18

Weight:3

Table 3: Range and Rating for Aquifer Media

Range	Rating	Index
Silty sand	3	9
Fine Sand	4	12
Medium Sand	6	18
Coarse Sand	8	24
Gravel and Sand	9	27
Gravel	10	30

Weight: 3

Table 4: Range and Rating for soil media

Range	Rating	Index
Gravel	10	20
Sand	9	18
Sandy loam	6	12
Loam	5	10
Silty-loam	4	8
Clay-loam	3	6

Weight: 2

Table 5: Range and Rating for Topography(slope)

Range (%)	Rating	Index
0-2	10	10
2-4	9	9
10-12	5	5
14-16	3	3

Weight: 1 (Source Ckakraborty S et al. 2007)

Table 6: Range and rating for vadose zone

Range	Rating	Index
Clay and Silt	3	15
Sandy/ Clay	4	20
	5	25
Clay Sand	6	30

	7	35
Sand and Gravel	8	40
	9	45
	10	50

Weight: 5

Table 7: Range and Rating for hydraulic conductivity

Range (transmissivity)	Rating	Index
<10 m^2/d	1	4
10-20 m^2/d	2	8
20-30 m^2/d	3	12
30-100 m^2/d	4	16

Weight = 3

Table 8: DRASTIC parameters

DRASTIC parameters	Ranges	Rating	Index	Weight
	0-1.5	10	50	
	1.5-4.6	9	45	
	4.6-9.1	7	35	
	9.1-15.2	5	25	
	15.2-22.5	3	15	
	22.5-30	2	10	
Depth to gw(m)	>30	1	5	5
Net recharge(mm/a)	0-50	1		4
	50-100	3		
	100-175	6		
	175-225	8		
	>225	9		
Aquifer media	Silty sand	3	9	3
	Medium sand	6	18	
Soil media	gravel	10	20	2
	Sandy loam	6	12	
	Loam	5	10	
	Clay loam	3	6	
Topography (%)	0-2	10	10	1
	2-4	9	9	
	10-12	5	5	

	14-16	3	3	
Impact of vadose zone (soil+recharge)	15-18	10	50	5
	13-15	9	45	
	10-13 8-10 6-8 4-6 <4	8 7 5 3 1	40 35 25 15	
Hydraulic conductivity (transmissivity m2/d)	<10	1	3	3
	10-20	2	6	
	20-30 30-100	3 4	9 12	

Table 9: Statistical summary of the seven parameters for the two methods

	D		R		A		S		T		I		C	
	d	f	d	f	d	f	d	f	d	f	d	f	d	f
Min	1	0.33	1	0	3	0.22	3	0.22	3	0	3	0.22	1	0
Mean	5.52	0.5	1.36	0.04	4.27	0.36	5.71	0.52	9.83	0.02	8.14	0.79	1.93	0.10
Max	7	1	3	0.22	6	0.55	10	1	10	0.77	10	1	4	0.33
SD	1.41	0.16	0.77	0.08	1.48	0.16	2.20	0.24	0.72	0.08	1.24	0.13	0.87	0.09

Noted: Drastic method and f:fuzzy method

Table 10: Map removal sensitivity analysis (One parameter is removed at time)

Parameters removed	Variation Index (%)			
	Max	Mean	Min	SD
D	3.69	1.72	0	0.76
R	2.99	1.58	0	0.44
A	3.61	0.67	0	0.42
S	2.99	0.83	0	0.42
T	3.40	0.92	0.06	0.18
I	7.19	3.60	0	0.88
C	4.85	1.53	0.05	0.38

Table 11: Map removal sensitivity analysis (One or more parameters are removed at time)

Parameters removed	Variation Index (%)			
	Max	Mean	Min	SD
DASTIC	2.99	1.58	0	0.44
DASTI	5.71	3.73	1.38	0.72
DASI	8.44	6.06	2.92	0.88
DAI	13.18	9.49	4.32	1.54
DI	22.04	15.76	1.94	2.72
I	43.18	21.63	0	5.33

Table 12: single parameter sensitivity analysis (effective weights)

Parameters	Theoretical weight	Theoretical weight (%)	Effective weight (%)			SD
			Max	Mean	Min	
D	5	21.73(22)	43.20	24.17	4.42	5.59
R	4	17.39(17)	15.58	4.80	2.85	2.65
A	3	13.04(13)	23.37	11.25	6.71	3.65
S	2	8.69(9)	21.97	10,04	4.61	3.70
T	1	4.34(4)	13.88	8.73	2.41	1.09
I	5	21.73(22)	57.47	35.92	14.27	5.37
C	3	13.04(13)	13.95	5.09	2.14	2.27

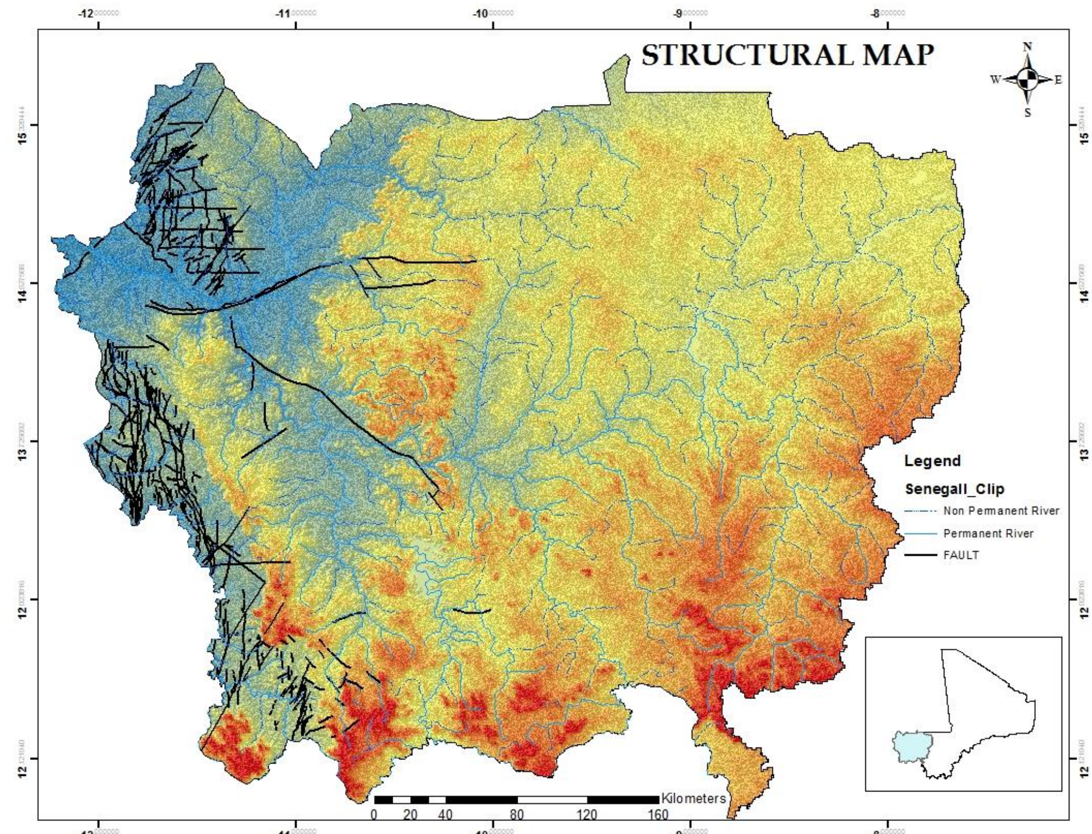

Figure 1a: study area location and hydrogeological map

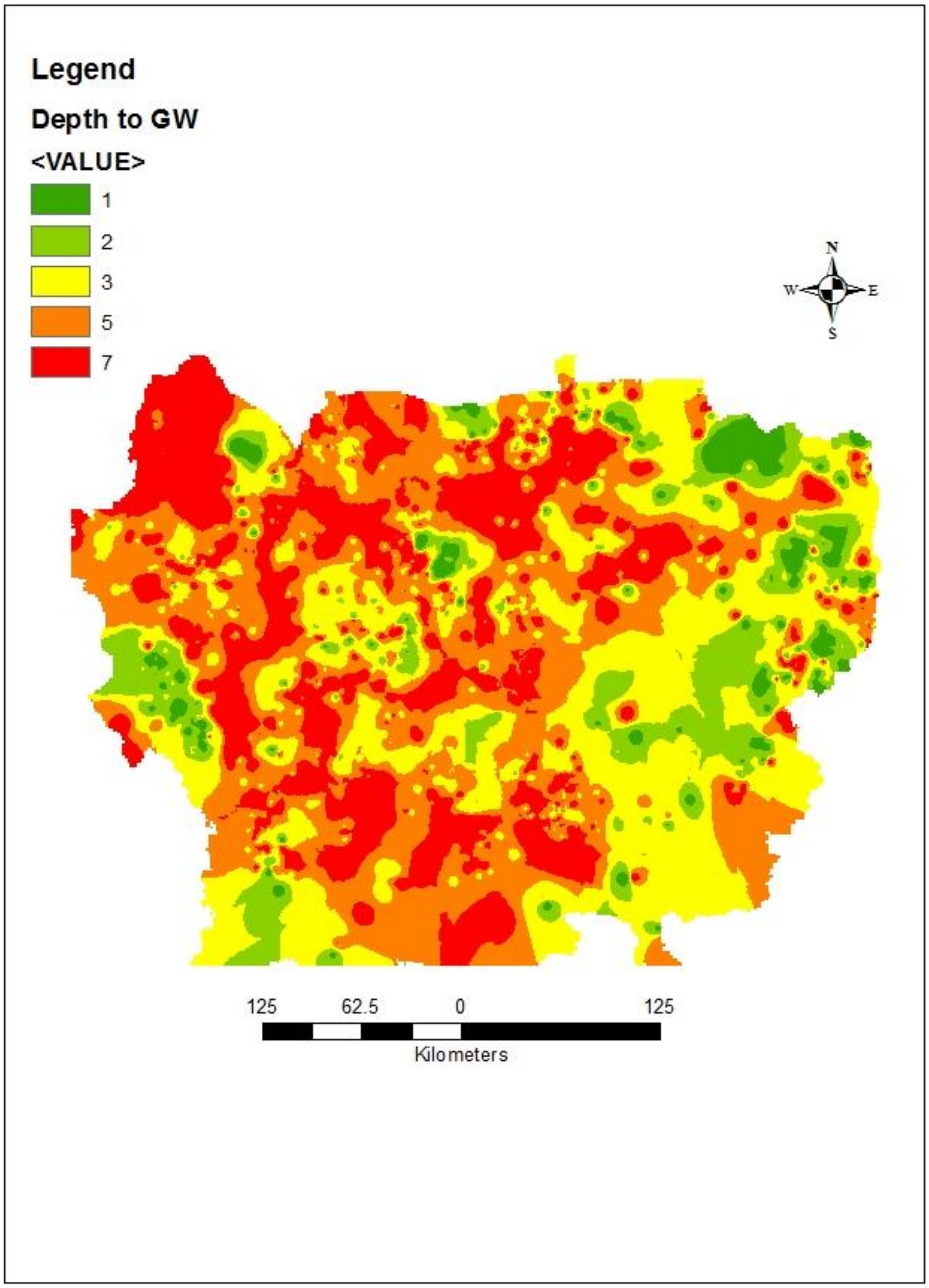

Figure 1: Groundwater Depth distribution map

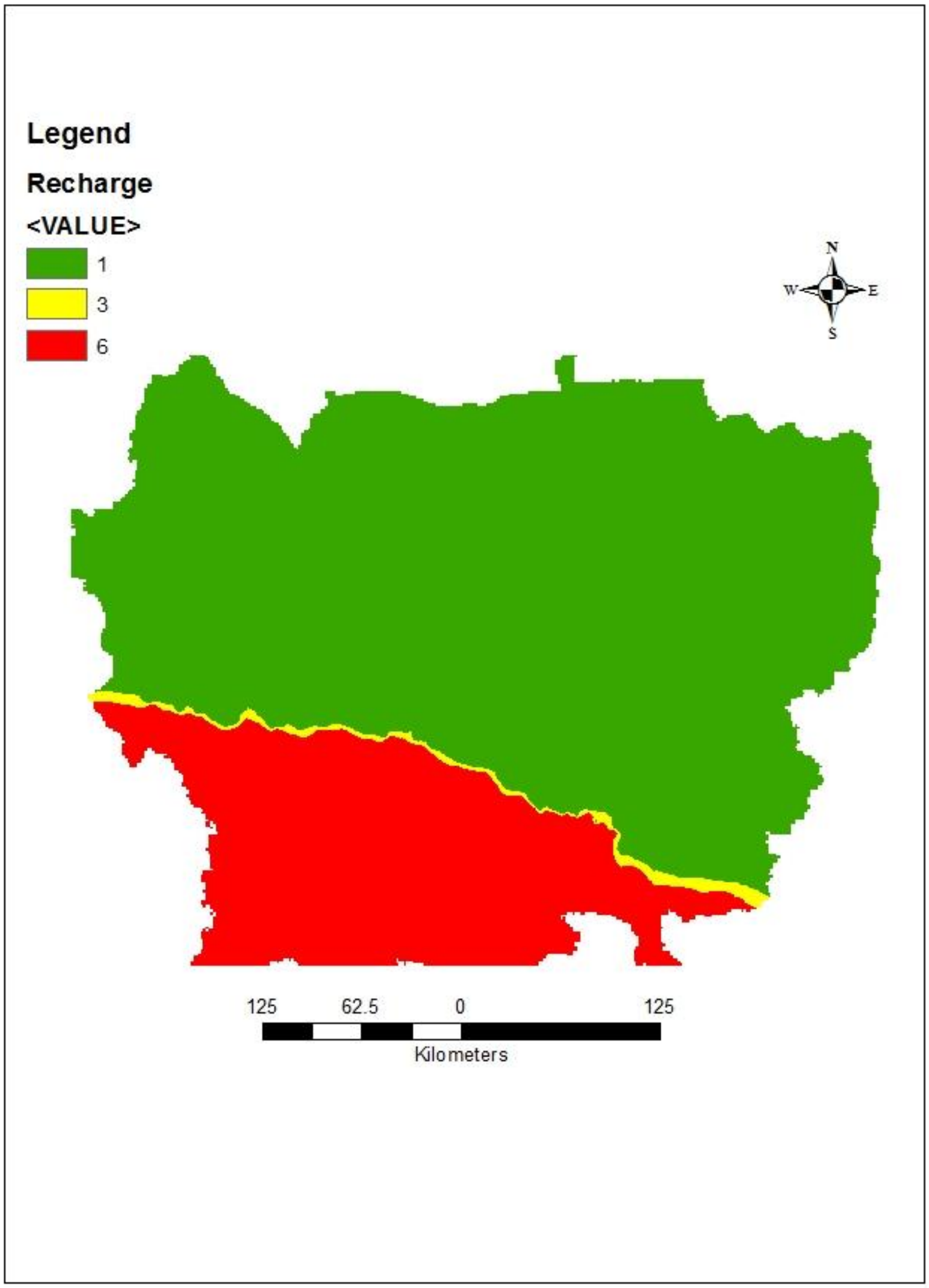

Figure 2: Groundwater Recharge distribution map

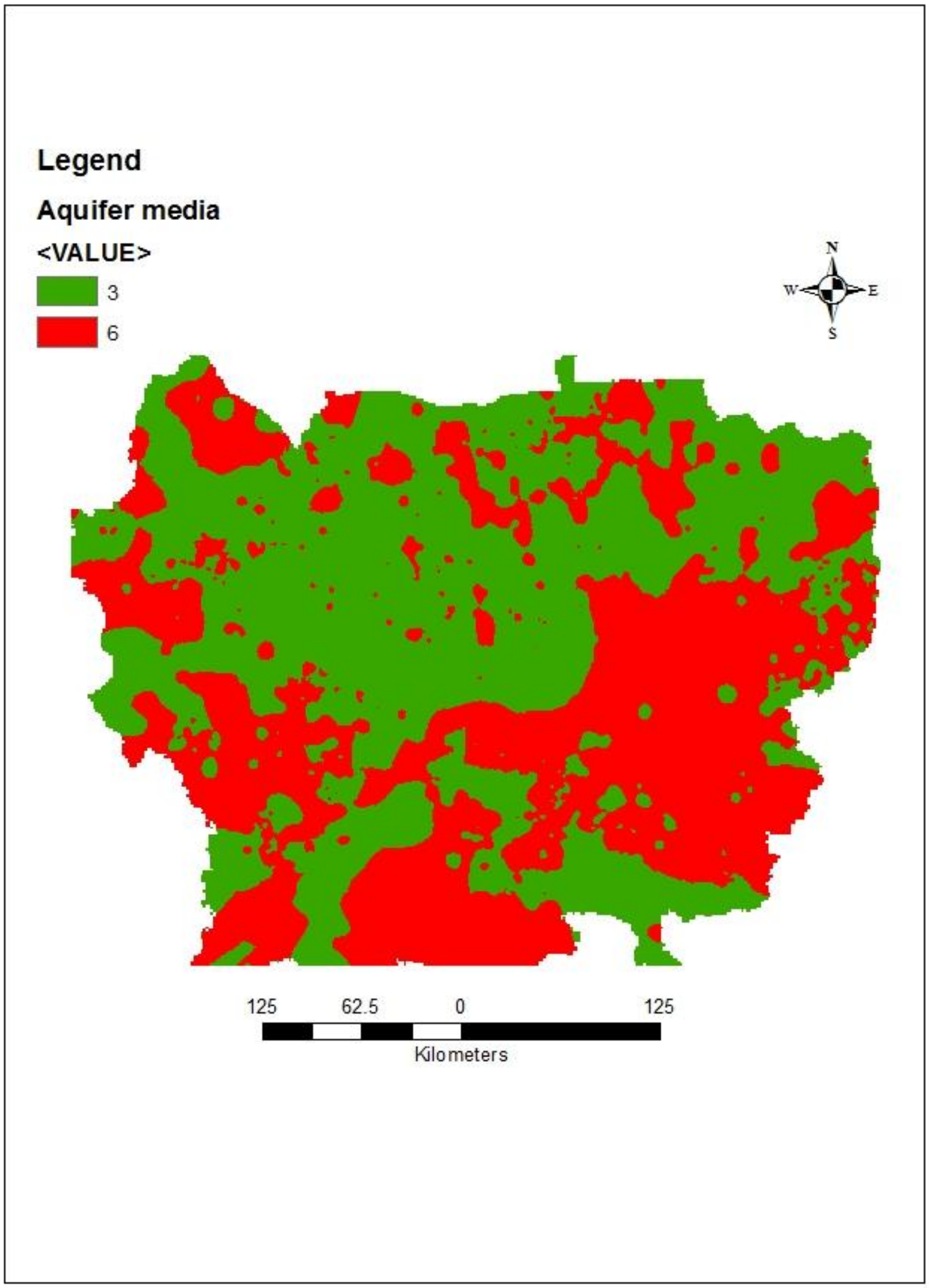

Figure 3: Aquifer media distribution map

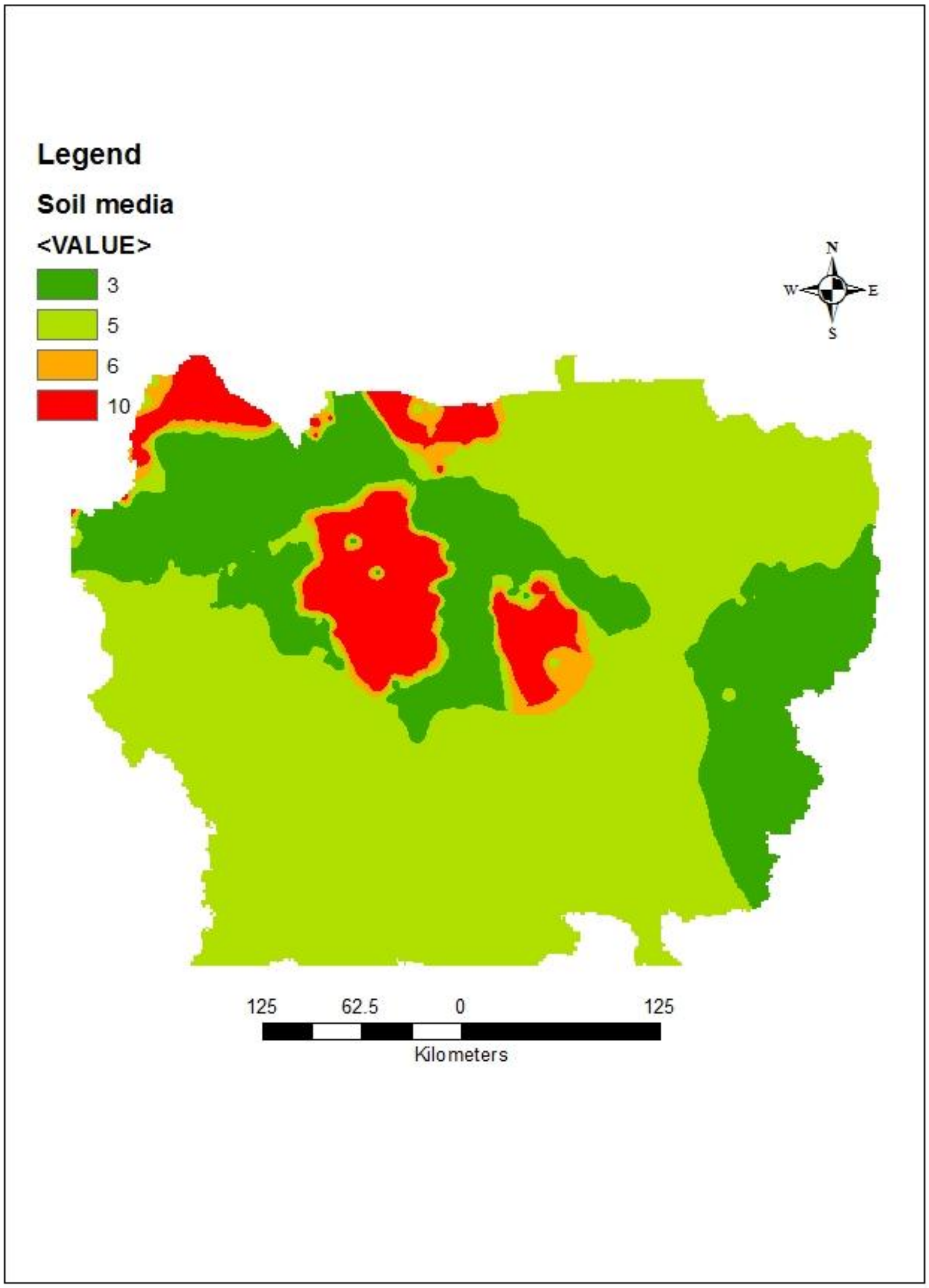

Figure 4: Soil type distribution map

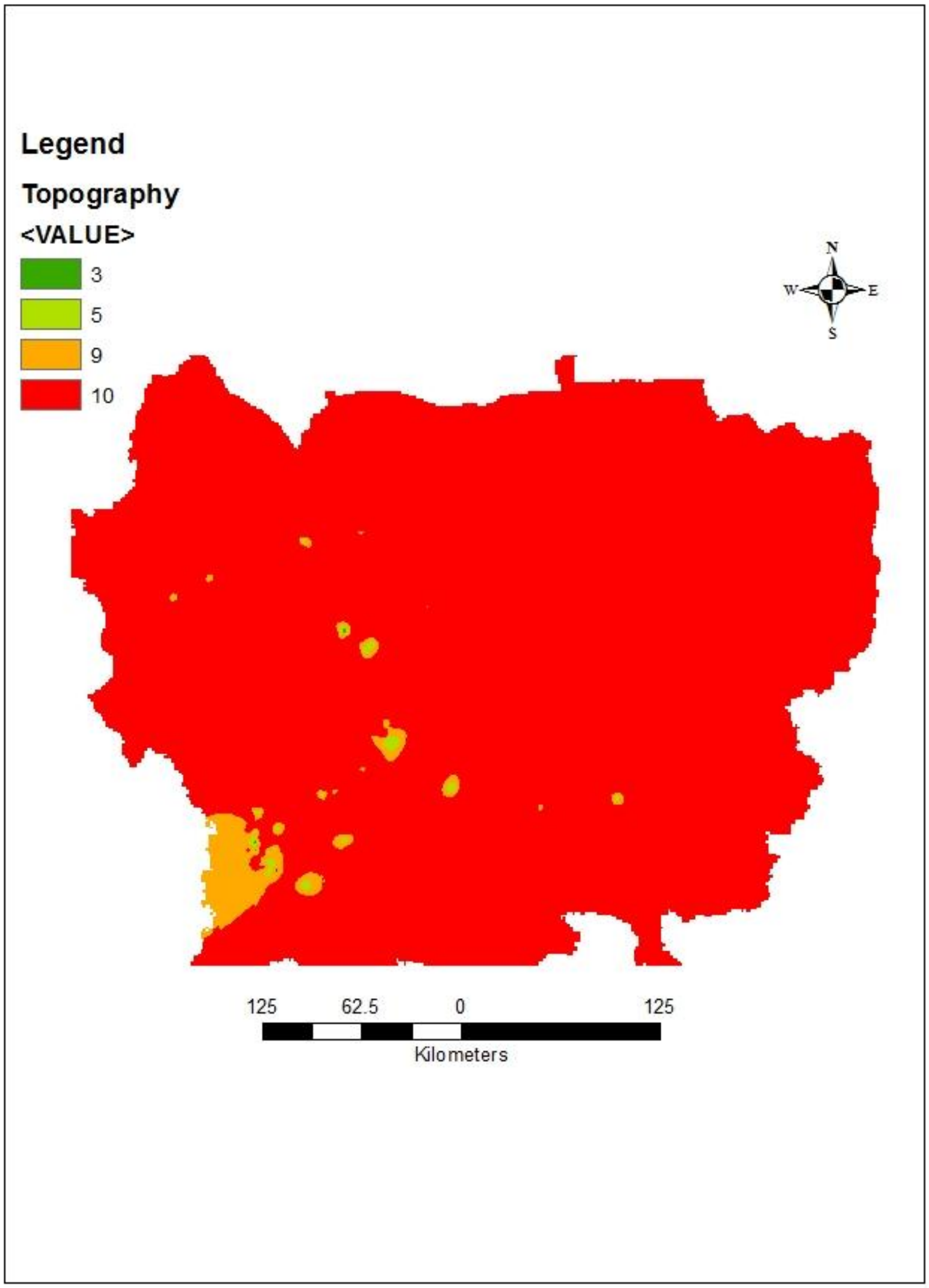

Figure 5: Slope distribution map

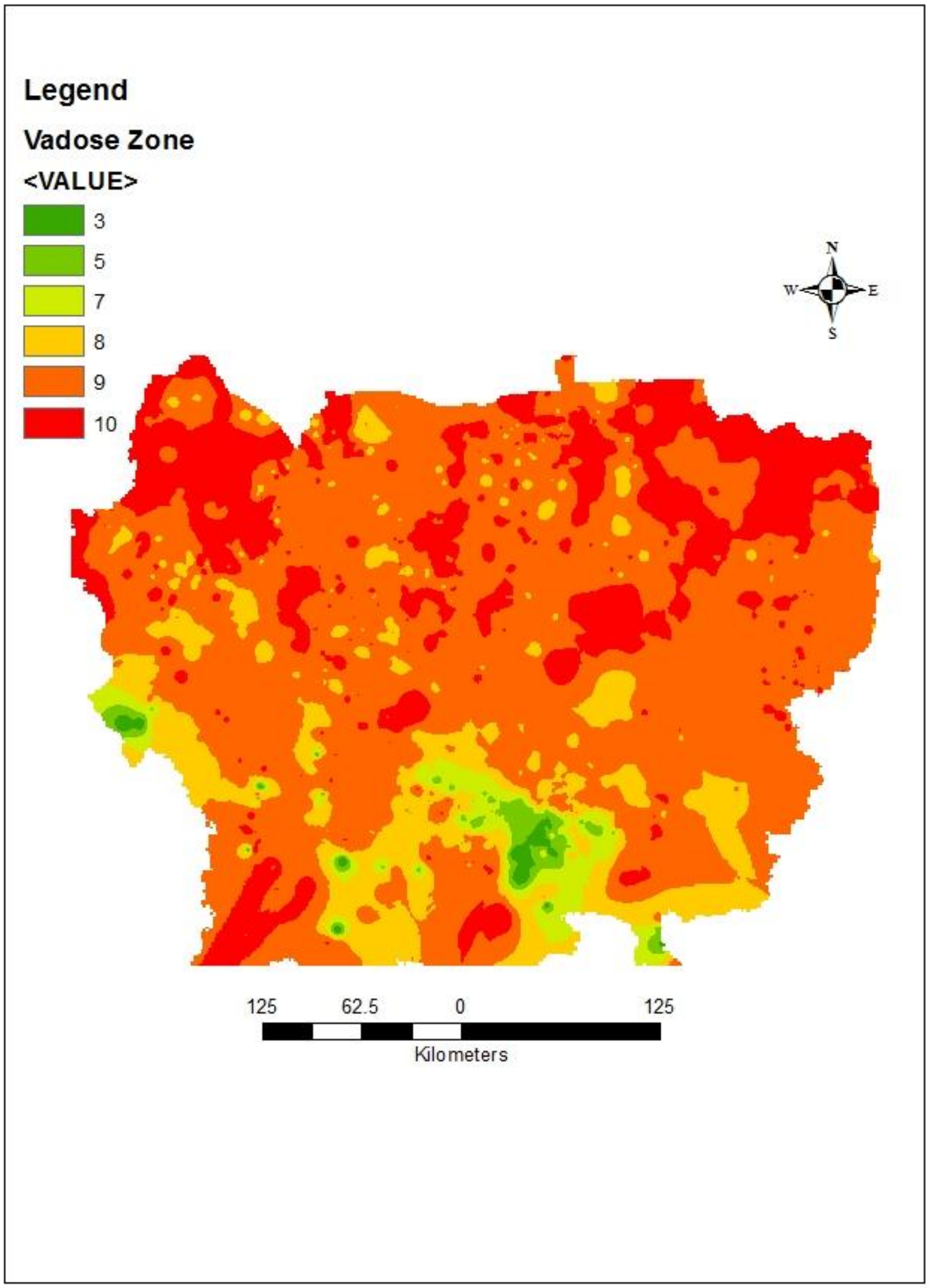

Figure 6: Vadose zone distribution map

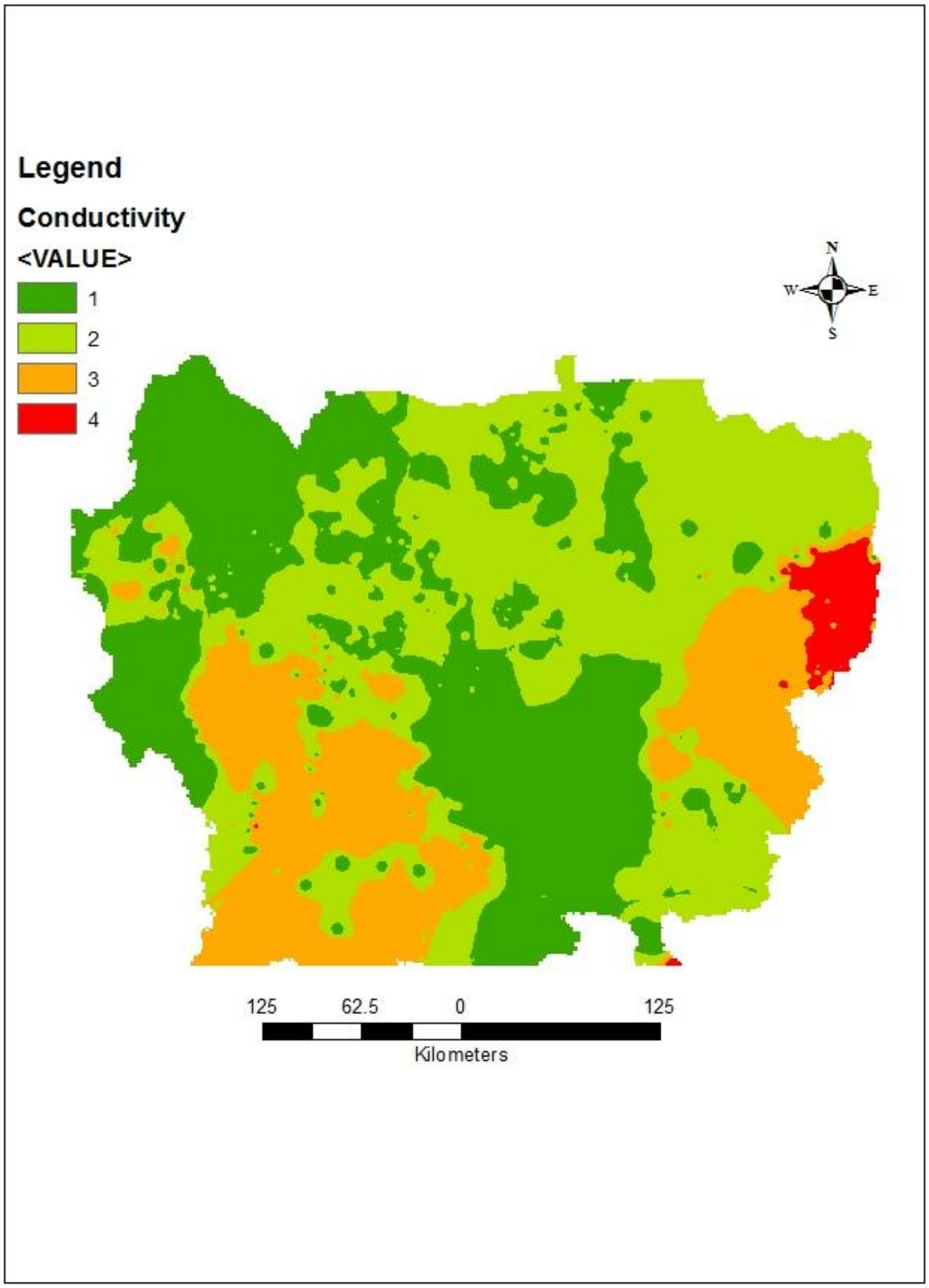

Figure 7: Hydraulic conductivity distribution map

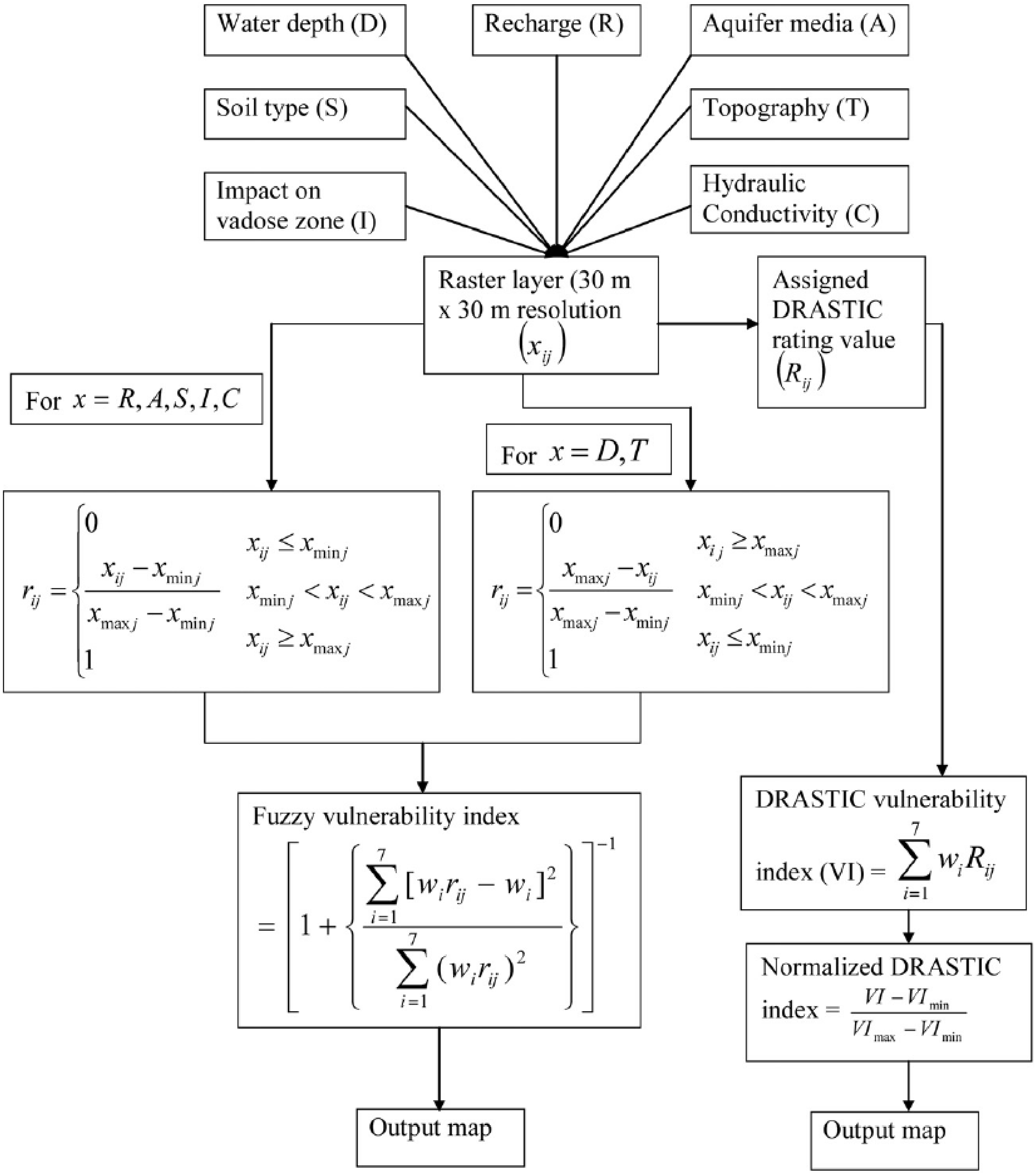

Figure8: Flow chart of methodology adopted to develop groundwater contamination potential map using DRASTIC and fuzzy pattern recognition model in framework of GIS(source Pathak et al.2009).

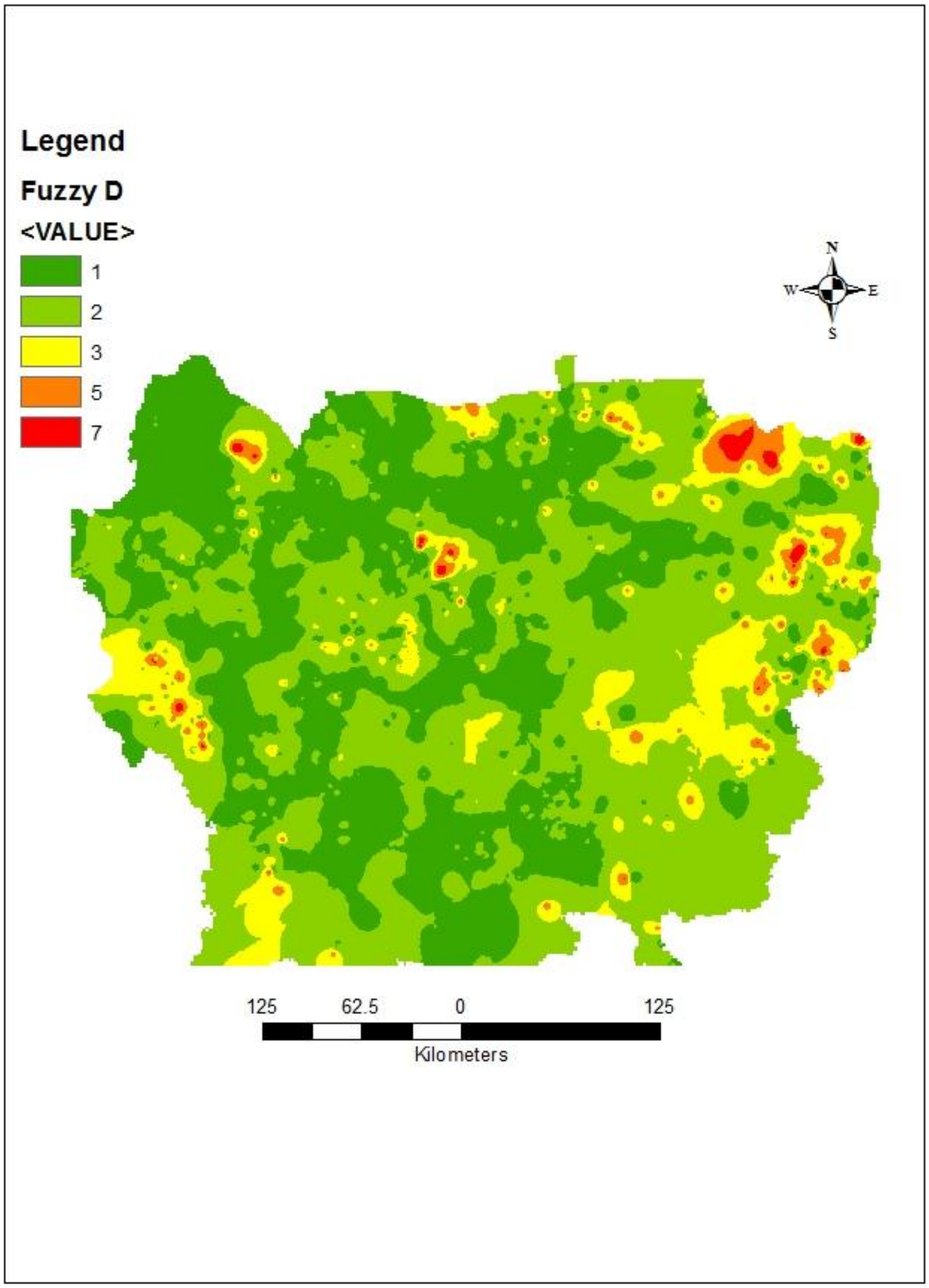

Figure 9: fuzzy concept Ground water depth distribution map

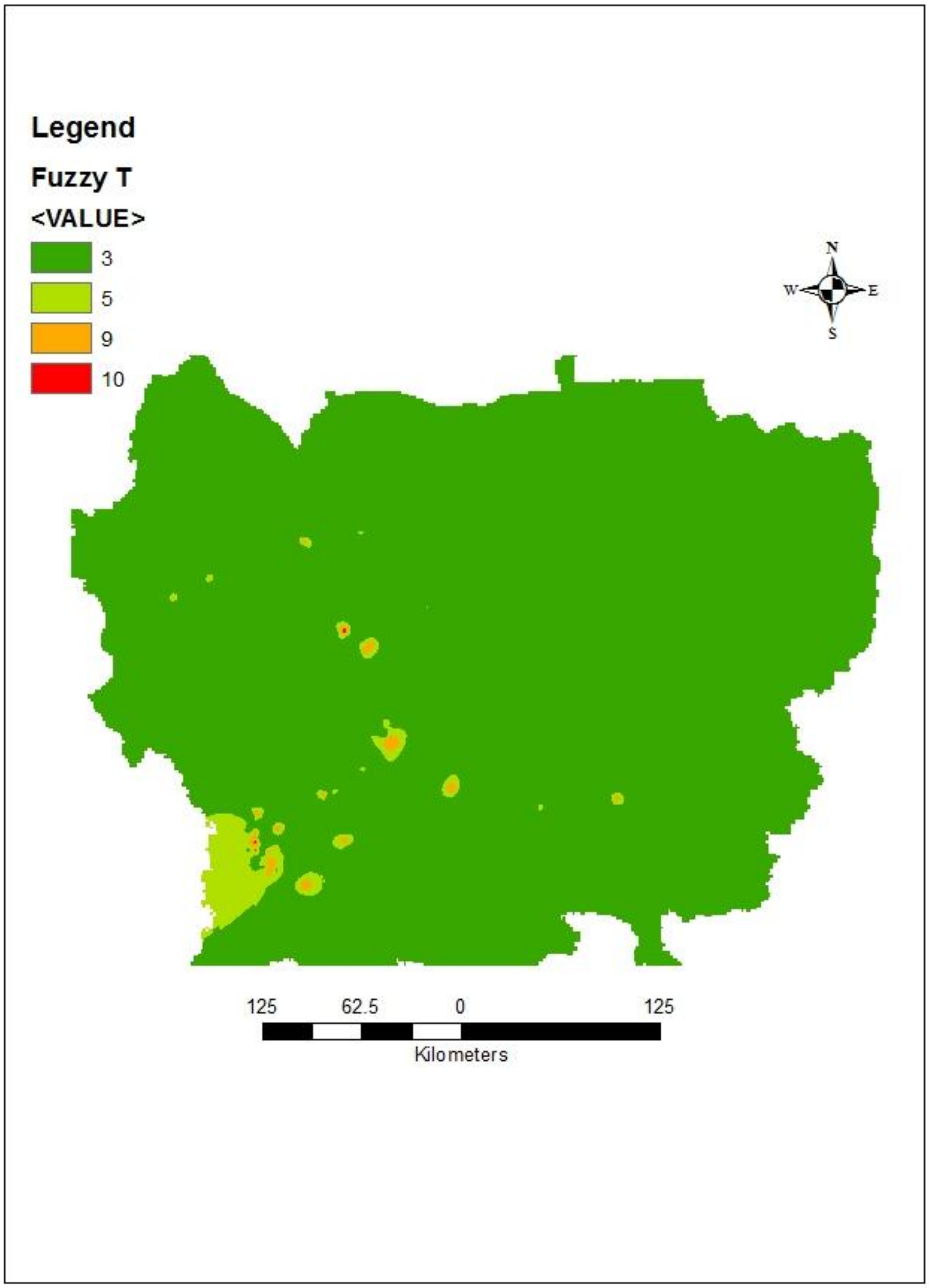

Figure 10: fuzzy concept topography(or slope) distribution map

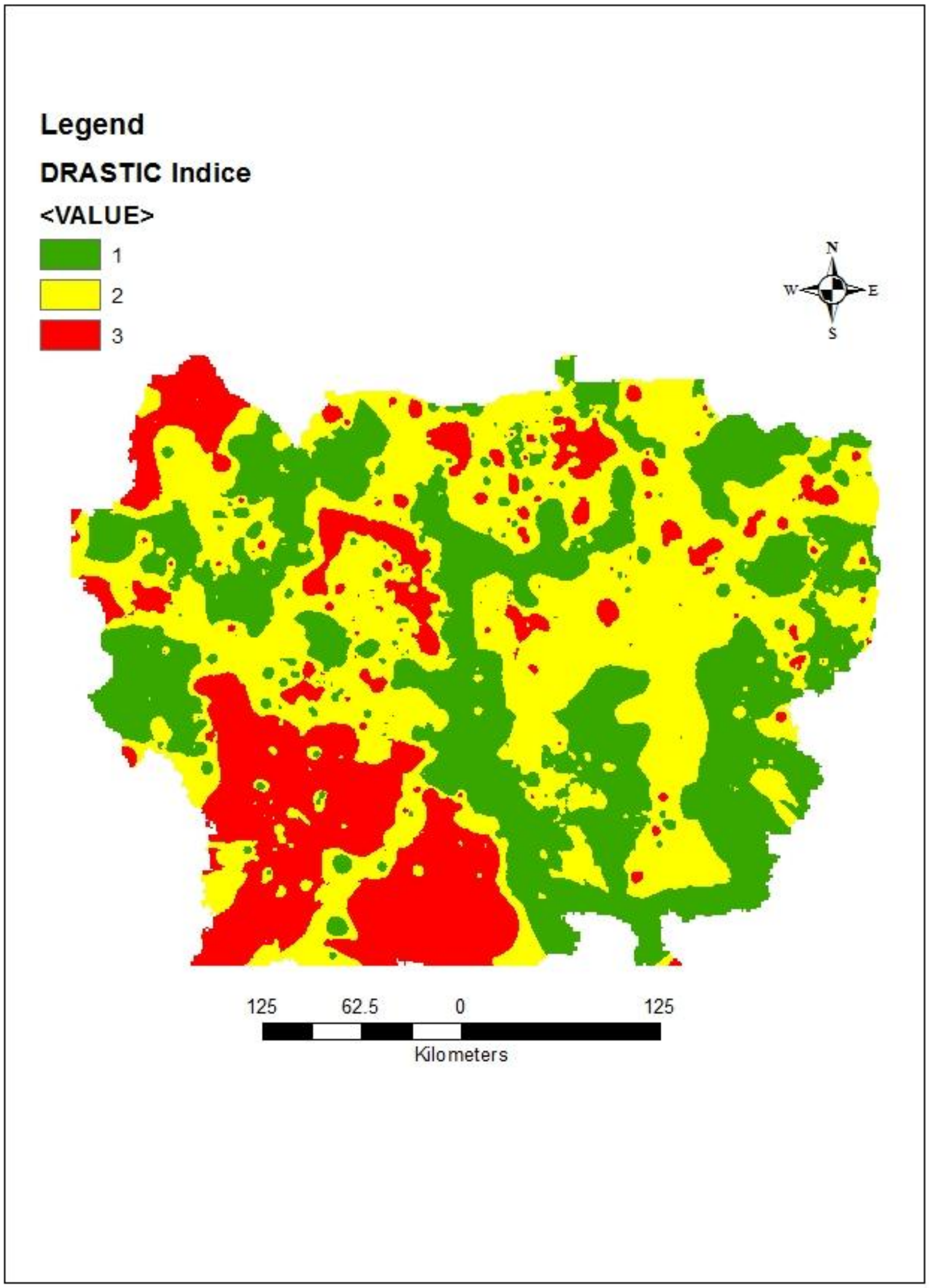

Figure11: DRASTIC vulnerability map

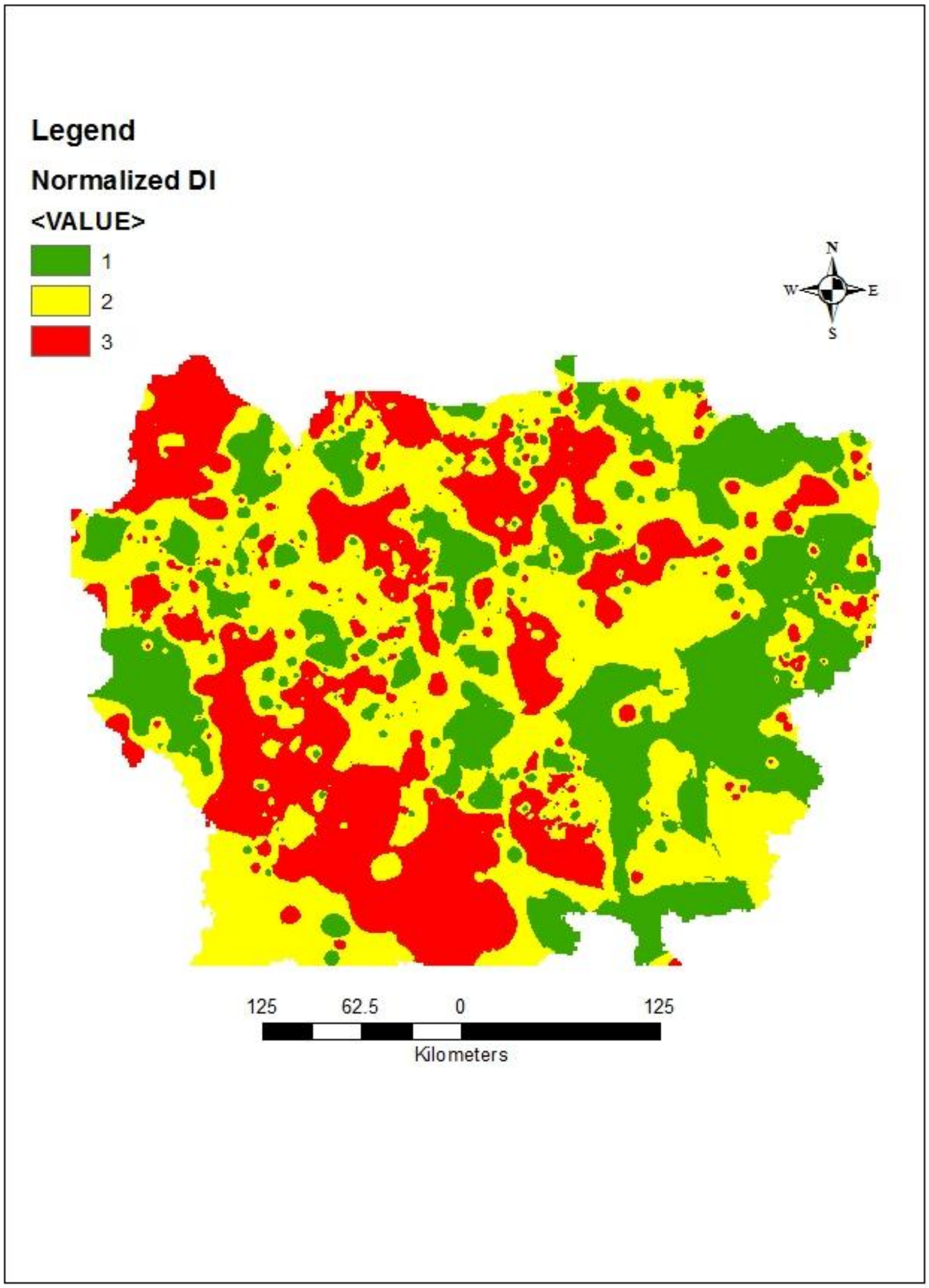

Figure 12: Normalized vulnerability map

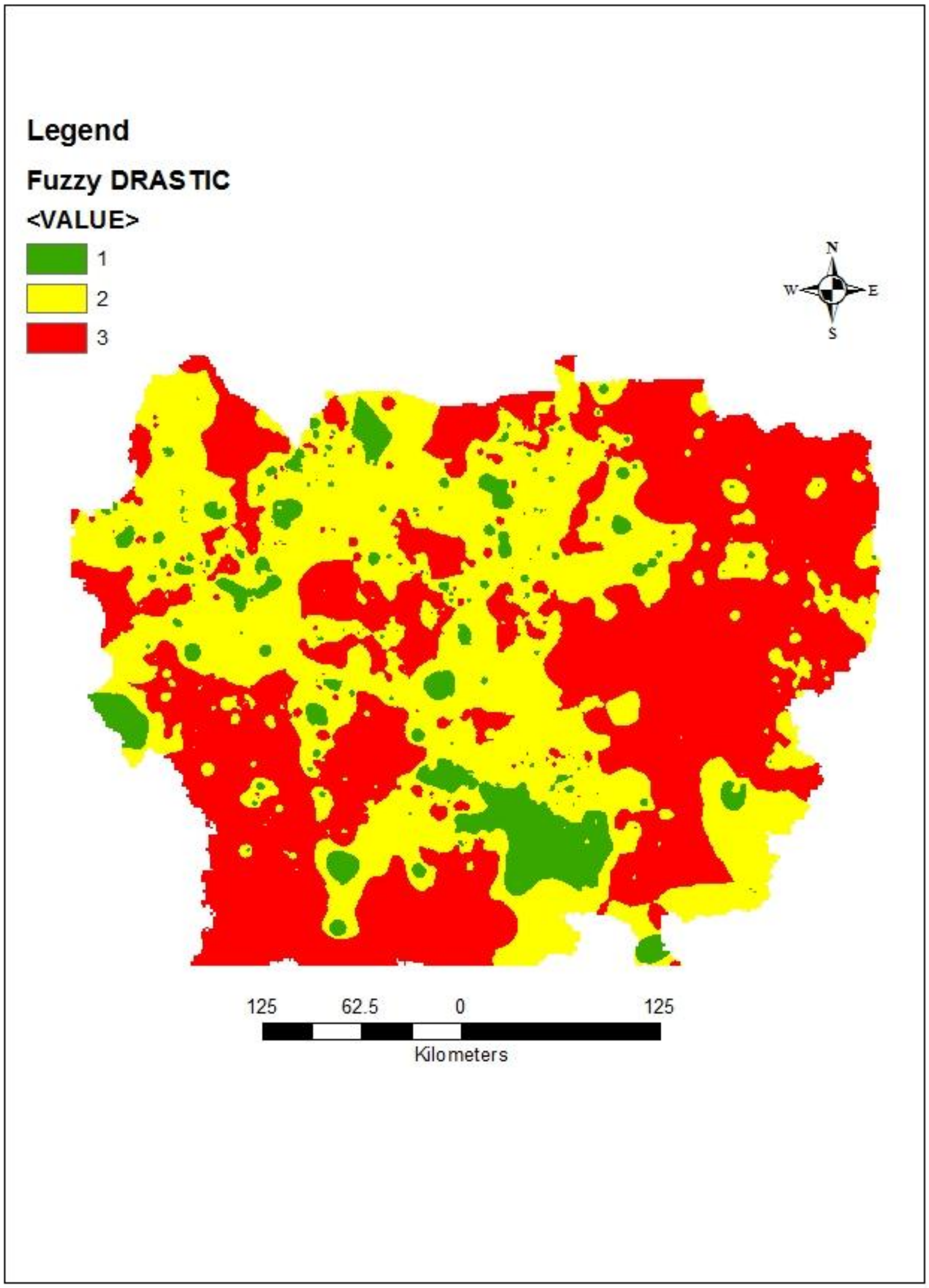

Figure 13: fuzzy DRASTIC vulnerability map

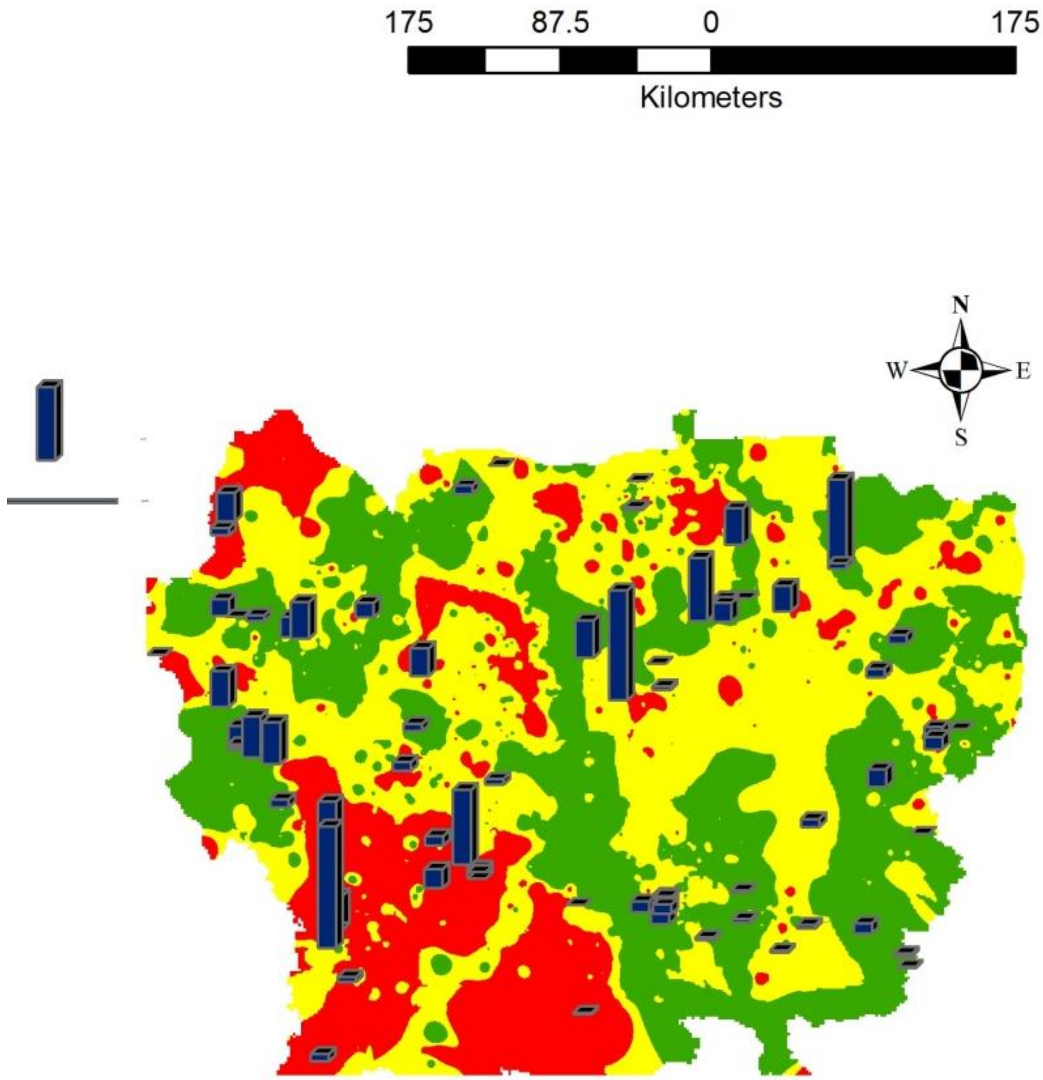

Figure14: Nitrate distribution in DRASTIC model

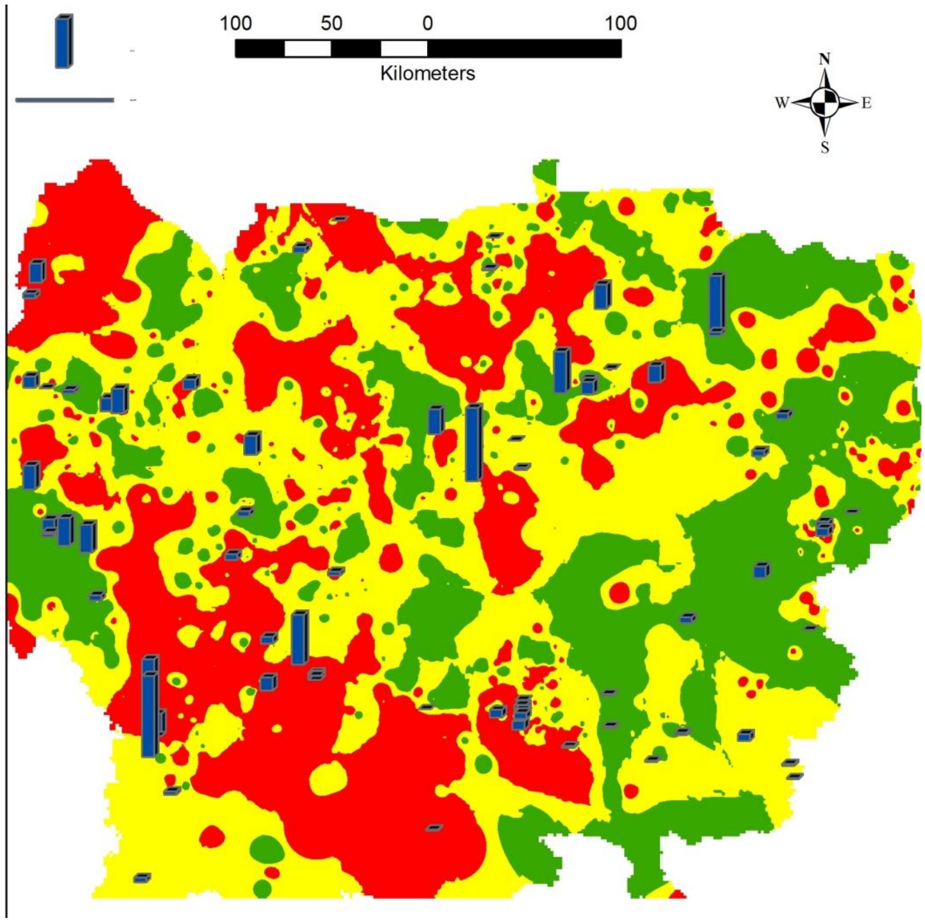

Figure15: Nitrate distribution in Normalized model

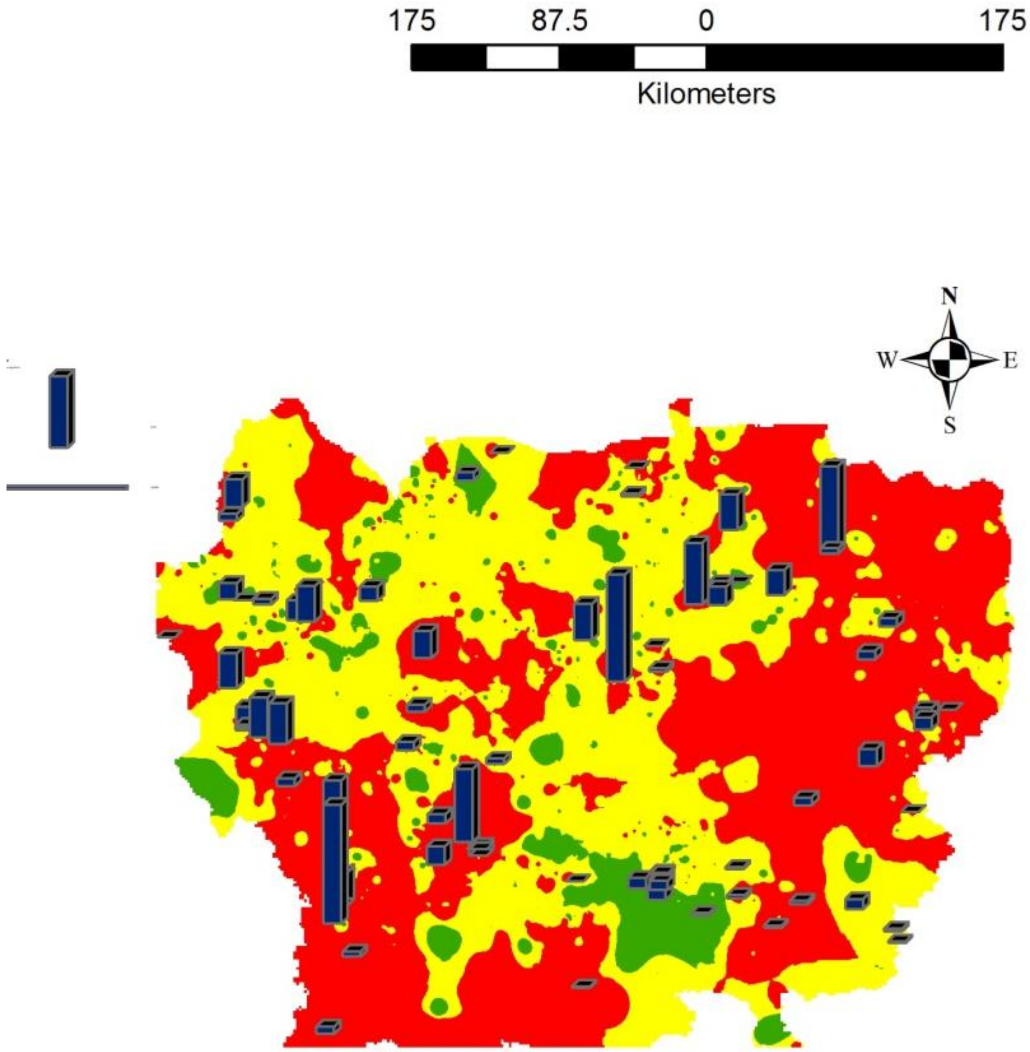

Figure16: Nitrate distribution in Fuzzy model