GROUND WATER VULNERABILITY ASSESSMENT OF KODOOR RIVER BASIN BY INTEGRATED DRASTIC METHOD

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Abstract

Groundwater vulnerability assessment techniques are useful tools in groundwater management. The purpose of the study is to assess the groundwater vulnerability of Kodoor river basin in Kerala by DRASTIC model and to modify the model to suit the regional scale by incorporating the land use and/ or land cover (LULC) pattern of the area of study in it to produce DRASTICA model. The interdependence of the nitrate concentration data and vulnerability indices from DRASTIC and DRASTICA models were calculated. Correlation coefficient values obtained for DRASTIC and DRASTICA model is 0.21 and 0.38 respectively which shows that the modified DRASTICA model suits the study area better. The study area was grouped into three zones based on the grades of vulnerability. The study also includes the sensitivity analysis of the DRASTICA model. The map removal sensitivity analysis and single parameter sensitivity analysis were carried out to validate the model results.

Keywords: Groundwater pollution, Vulnerability, DRASTIC, Sensitivity Analysis.

Introduction

The study of the evaluation and potentiality of groundwater resources is very important as it is one of the most valuable source of water on earth (Oikonomidis et al., 2015; Singh et al., 2015). Groundwater contamination is one of the pressing environmental issues faced by the world today. Rapid population growth, urbanization, industrialization, intensive agriculture and many other anthropogenic activities pose serious threat to ground water resources (Kattaa et al.,2010;Singha et al., 2019). In comparison to surface waters, groundwater is relatively less susceptible to contamination (Kumar et al., 2015; Jamrah et al., 2008; Pathak and Hiratsuka, 2011). However, the contamination of groundwater is invisible, complex and of long term impact (Barzegar et al., 2016). Also once contaminated it is difficult to remediate contaminated aquifers due to the huge cost and complicated technology involved (Jia et al., 2019; Jang et al., 2017; Fijani et al., 2013; Kumar et al., 2017). Hence the best groundwater management practice is to protect groundwater resources from contamination (Rezaeiet al., 2017). Identification of the areas that are highly susceptible to pollution is very important to prevent groundwater pollution (Jafari and Nikoo, 2016). For this purpose, groundwater vulnerability models are effective tools. Groundwater vulnerability analysis studies help to pick out the areas that are more prone to pollution so as to take substantial measures to protect the groundwater resources of vulnerable areas (Khodaparast et al., 2018).

Vulnerability of groundwater to pollution is a characteristic that cannot be directly measured on field but is a concept formulated on the principle that some land areas are to a greater extent prone to groundwater pollution than other areas (Barzegar et al., 2016; Barzegar et al., 2019). There is no standardized definition for groundwater vulnerability. It is the relative ease with which ground water resources could be contaminated (Al-Abadi et al., 2017). Groundwater vulnerability can be defined as the intrinsic characteristics that control the sensitivity of aquifers to be contrarily affected by an inflicted contaminant load (Shirazi et al., 2012; Ducci, 1999). Vulnerability can also be interpreted as the likelihood of infiltration and dispersion of the contaminants from the ground surface into the ground water systems. Pollution risk depends on vulnerability along with the existence of significant pollutant loading entering the sub surface environment (Jourda et al., 2013). The possibility of pollutants to seep through the ground surface to reach the ground water systems can be determined through vulnerability assessment techniques (Neshat and Pradhan, 2015). The hypothesis of vulnerability is formed on the idea that the physical environments impart some degree of protection to the aquifers in opposition to contamination (Al Hallaq and Abu Elaish, 2012).

Groundwater vulnerability assessments helps in dividing a geographical region into sub regions in terms of their vulnerability to contamination there by making it easy to conduct groundwater protection measures in the contamination prone areas (Neshat et al.,2014; Aydi, 2018). Vulnerability maps implements spatial model to symbolize the relative liability of an aquifer to pollution (Bojorquez et al., 2009). Vulnerability maps are used to prioritize areas where ground water protection is critical (Al Kuisi et al., 2006). Once these areas are ascertained, then they can be effectively monitored and earmarked for proper land use to protect groundwater resources.

At hand two, types of ground water vulnerability assessment studies are used: intrinsic vulnerability assessment and specific vulnerability assessment. In intrinsic vulnerability assessment, the vulnerability of the aquifer is assessed by taking into consideration only the hydrogeological conditions of the area without considering the properties of the pollutants. However, in the case of specific vulnerability assessment, the vulnerability of the aquifer is assessed by considering the hydrogeological conditions of the area along with the properties of the pollutants. The intrinsic vulnerability is invariant in time whereas the specific vulnerability is considered to be evolutionary and characterizes only one precise moment (Samey and Gang, 2008).

There is no method adopted globally for groundwater vulnerability assessment due to the difficulty in considering all the aquifer characteristics in a standard method (Mimi et al., 2012).Generally process based methods, statistical methods and index and overlay methods are used to assess ground water vulnerability to pollution. Usually the process based methods require large data to get an idea about the various physical chemical and biological reactions that take place from the surface through the groundwater regimes and are more elaborated and complicated. Hence these methods cannot be applied on a regional scale. The statistical methods have some uncertainties associated with it and is applicable only to those areas where the groundwater contamination is governed by much the same factors. In other words, they are not generic in nature (Kumar et al., 2015). The index and overlay methods do not have the limitations mentioned above and hence is the most widely used. Some of the common index and overlay methods are DRASTIC, SEEPAGE, SINTACS, GOD and EPIK. Out of all these index and overlay methods, the DRASTIC framework (Aller et al., 1987) is the most extensively used approach to evaluate groundwater vulnerability to pollution (Nadiri et al., 2017; Al-Adamat et al., 2003) as it is more economic and not time consuming.

As the DRASTIC model do not consider the pollution types and its characteristics, it needs to be calibrated and corrected for a specific aquifer and pollution (Javadi et al., 2011). Usually nitrate measurements of the study area are used for this purpose as it is generally not present in groundwater under normal conditions. Rates of the parameters can be modified by applying statistical analysis to correlate nitrate concentration with the DRASTIC parameters.

2. Methodology

2.1. Study Area

The study area is the Basin of Kodoor River, running between the Kottayam and Alappuzha districts of Kerala, South India. The river originates between the hills in between the Kottayam and Pathanamthitta districts and finally empties into the Meenachilriver. The mean annual rainfall of the study area is about 3093 mm/year. The average annual temperature is 27.3 ^{0} C.

The total area of the study area is about 258. 86 km^2. It is located between 9 ^{0} 35$^{'}$ 29.1876$^{''}$ N and 76^0 31$^{'}$ 19.8156$^{''}$ E.

2.2. DRASTIC

The DRASTIC model is the most popularly used overlay and index method to evaluate intrinsic vulnerability on a regional scale. This model was expanded by the US Environmental Protection Agency in collaboration with the National Water Well Association. The DRASTIC method has been prepared using the concept of hydrogeological settings (Aller et al.,1987). The hydrogeological setting is the set of all hydrological and geological factors which influence and control the ground water movement into, through and out of the area. The acronym DRASTIC stands for seven hydrological, hydrogeological and geological parameters namely Depth to ground water, Net recharge, Aquifer media, Soil media, Topography, Impact of vadose zone and Hydraulic conductivity. The DRASTIC model is a linear combination of these seven parameters. Each of these parameters are assigned with a relative rating ranging from 1 to 10 assumed on the pollution contribution potential and a fixed weight assumed on the significance of the parameter in assessing vulnerability ranging from 1 (least important) to 5 (most important). The DRASTIC vulnerability index can be calculated by the formula

$$DVI = D_wD_r + R_wR_r + A_wA_r + S_wS_r + T_wT_r + I_wI_r + C_wC_r \qquad - \quad [1]$$

where, the subscripts w and r represent the weight and rate of each parameter respectively. Higher the DRASTIC vulnerability index, greater is the vulnerability of the aquifer (Awawdeh and Jaradat, 2010). The model has low cost of application, requires limited input data, and has sound yield relative accuracy for extensive regions with complex geological structures (Jang et al., 2017). The main disadvantage associated with the model is its limited validation. Sometimes, little correlation may be obtained between the model results and field data.

To modify the model a new parameter named land use and land cover is added to the original DRASTIC model. This parameter is given a weight of 5. The modified formula for vulnerability index is

$$DVI_{mod} = D_wD_r + R_wR_r + A_wA_r + S_wS_r + T_wT_r + I_wI_r + C_wC_r + L_wL_r \qquad - \quad [2]$$

2.2.1. DRASTIC Parameters

Depth to Ground water: It is the length through which a pollutant should travel to reach the groundwater surface. If this distance is less, then there is greater pollution potential and vice versa. The depth to water table of 57 wells from the study area was measured for 4 seasons namely pre-monsoon and post monsoon seasons of 2018 and 2019. The locations of the 57 wells were marked using a hand held GPS meter. The average of the four values was calculated. This data was used to prepare the thematic layer for depth to water table by interpolation by the use of Inverse Distance weighted (IDW) method. Ratings are assigned to the classes of the raster layer created according to their risk of contamination.

Net Recharge: It is the amount of water available per unit area of soil. Net recharge acts as the principal carrier of pollutants from the ground surface to the groundwater. The greater the net recharge, greater will be the chance for the pollutants to reach the aquifer. Despite this statement, more net recharge helps in dispersion and dilution of pollutants there by alleviating the pollution (Jafari and Nikoo, 2016; Aller et al., 1987). The rainfall statistics was collected from the Indian Meteorological Department (IDM) and the thematic layer was generated after calculating the net recharge of the area.

Net recharge is calculated by modified Chaturvedi formula

$$R = 1.35\ (P\text{-}14)^{0.5} \quad - \qquad [3]$$

Where R is the net recharge in inch/year and P is the precipitation in inch/year

Aquifer Media: Aquifer media is the consolidated and unconsolidated rock, which serves as the water storage media. The contaminant attenuation capacity depends on aquifer media characteristics like grain size and sorting of the media. Larger grain size increases permeability and decreases attenuation capacity. The aquifer media types were ascertained from geological logs and geological map of the study area. Ratings are assigned to the raster layer according to the type of rock comprising the aquifer media.

Soil Media: This is the layer above vadose zone where there is highest biological activity. The water penetration rate, dispersion and attenuation potentiality of the pollutants depends on the texture of the soil (Singh et al., 2015). Maximum rate of penetration of water belongs to gravel, sand, and sandy loam in comparison to fine grain soil. Soil media types were obtained from geological logs and bench mark of soil. Higher ratings are assigned to coarse soils as these facilitate recharge of groundwater there by increasing the possibility of percolation of contaminants to the aquifer.

Topography: It refers to the slope of the land surface. If the land surface is relatively flat or has mild slope, then there is greater chance of pollutant migration due to prolonged percolation to subsoil. Also topography gives some indication about the points at which pollutants will be concentrated. The thematic layer for topography for the area was produced using the Shuttle Radar Topography Mission- Digital Elevation Model (SRTM-DEM) of 30 m spatial resolution. The percent slope was extracted from DEM and numerical ratings were assigned to it. Higher ratings are assigned to flat slope and lower ratings are assigned to steeper slope.

Impact of Vadose Zone: Vadose zone is the layer between the ground surface and ground water table or it is the unsaturated zone above the water table. Similar to soil media, this layer also controls the aquifer pollution potential. The characteristics of the vadose zone layer was determined from geological logs. Numerical values were assigned to the area based on the total depth of the vadose zone and the different lithological layers in the vadose zone. Ratings are assigned according to the permeability of the material of vadose zone.

Hydraulic Conductivity: Hydraulic conductivity shows the ability of the aquifer to transmit water (Prasad et al., 2011; Al-Amoush et al.,2010). The value of hydraulic conductivity was approximately estimated from sieve analysis of soil. Thirty soil samples were collected from the study area and sieve analysis was conducted. Hydraulic conductivity values were calculated from the effective size using formula. Thematic map for hydraulic conductivity was prepared after assigning numerical ratings to the hydraulic conductivity values.

Land use and/or Land cover (LULC): LULC parameter is incorporated in the vulnerability assessment to reflect the impact of human activity on the sensitivity of groundwater to pollution. Land use shows the use of land for human activities whereas land cover shows the physical materials such as crops, grass, land, forests, and water that covers the land surface (Yankey et al., 2020). The LULC map was deduced from Google Earth Pro Image after geo-referencing. It was then classified into different categories.

2.3. Sensitivity Analysis

The seven parameters in the DRASTIC model are chosen with the belief that they influence the transport of contaminants to the groundwater. However, there are some subjectivities related with the selection of the parameters and the assignment of ratings and weights of the parameters. The DRASTIC method relies on expert judgment for the assignment of weights and rates to the contributory parameters which leads to uncertainties associated with the vulnerability maps (Nadiri et al., 2017). This can lead to uncertainty about the precision of the vulnerability assessment results. Sensitivity analysis is carried out to support experimental confirmation for DRASTIC model implementation (Samake et al., 2011). Usually two types of sensitivity analysis are carried out. They are the map removal sensitivity analysis and the single parameter sensitivity analysis.

2.3.1. Map Removal Sensitivity Analysis

The map removal sensitivity analysis as put forward by Lodwick et al., 1990 evaluates the influence of a single parameter on the groundwater vulnerability assessment (Yin et al., 2013). It helps in computing the sensitivity associated with removing one or maps from the final vulnerability map. The formula for sensitivity is as follows

$$S = [(V/N - V^1/n)/V] * 100 \qquad - \quad [4]$$

Where V and V^1 are the unperturbed and perturbed vulnerability indices respectively.
N and n are the number of maps used to compute V and V^1
The vulnerability index calculated using all the seven parameters is known as the perturbed vulnerability index whereas the vulnerability index calculated after removing one or more layers is known as the perturbed vulnerability index.

2.3.2. Single Parameter Sensitivity Analysis

This analysis was executed to compare the effective weights of each parameter with the theoretical weights allocated to the parameters during the implementation of the DRASTIC model. From this sensitivity analysis, it is possible to identify whether the assigned weights of the parameters are perfect or in need of modification (Shirazi et al., 2012). The discrepancy between the theoretical weights and effective weights can be computed from the following equation

$$W_e = (P_r P_w / V_p) * 100 \qquad - \quad [5]$$

Where W_e is the effective weight of the parameter.
P_r is the rating of the parameter
P_w is the weight of the parameter
V_p is the vulnerability index

3. Results and Discussion

3.1. DRASTIC Vulnerability map

The land use and/or land cover parameter of the study area was added to the DRASTIC map to reflect the anthropogenic effects on the groundwater vulnerability to pollution. The final DRASTIC vulnerability map was prepared by overlaying all the eight thematic map layers using the raster calculator. The thematic maps of the parameters as drawn from the field and the vulnerability indices are given in figures 1 to 10. The reclassified thematic maps and vulnerability indices are given in figures 11 and 20. The correlation coefficient values obtained reveals that the DRASTICA model suits better to the study area. The statistical summary of the DRASTICA vulnerability map is given in the table 1. The vulnerability index obtained from both DRASTIC and DRASTICA map were divided into different grades of vulnerability based on the Natural Breaks function of ArcGIS.

Table 1: Statistical Summary of DRASTICA Model

Statistics	**D**	**R**	**A**	**S**	**T**	**I**	**C**	**A**
Min	1	10	2	3	10	1.54	10	1
Max	10	10	8	10	10	10	10	5
Mean	6.99	10	3.56	6.56	10	6.12	10	2.86
SD	0.73	0	2.24	1.33	0	1.71	0	1.15

3.2. Model Validation

According to the US Environmental Protection Agency, the concentration of nitrate in groundwater can be considered as an indicator of pollution. In this study, nitrate is taken as the contamination parameter. Groundwater samples from 57 wells were taken and the exact location of these wells were marked with a hand held GPS meter. These samples were then analyzed for their ground water concentration. The coefficient of correlation between the observed nitrate values and the vulnerability indices were calculated to evaluate the accuracy of the model. A correlation coefficient of 0.21 was obtained for the DRASTIC model and a correlation coefficient of 0.38 was obtained foe the DRASTICA model.

3.3. Map Removal sensitivity Analysis

To evaluate the significance of each parameter on the final vulnerability index, map removal sensitivity analysis was carried out by detaching each layer of thematic map from the final vulnerability map. The land use and/ or land cover as well as the vadose zone media of the area was found to has the most significant impact on the vulnerability to contamination followed by net recharge, depth to groundwater, hydraulic conductivity, soil media, aquifer media, and topography.

3.4.Single Parameter Sensitivity Analysis

Single parameter sensitivity analysis was conducted by identifying the impact of each parameter in the final vulnerability index. This analysis collates the effective weight or real weight of each parameter in the model to the theoretical weight already assigned to the model at the time of its implementation. The summary of the statistics of the single parameter sensitivity analysis is given in table 2.

Table 2: Statistical Summary of Single Parameter Sensitivity Analysis

Parameters	Theoretical weight	Theoretical weight (%)	Effective Weight (%)			
			Min	Max	Mean	SD
D	5	21.7	3.4836	27.6526	20.6561	2.1618
R	4	17.4	19.7044	27.8689	23.6740	1.2148
A	3	13.043	3.1413	15.7136	6.340	4.1413
S	2	8.695	3.6870	10.4712	7.7137	1.4286
T	1	4.347	0.0	39.5524	5.8127	3.9479
I	5	21.7	4.7519	26.1780	17.9419	4.7729
C	3	13.043	14.7783	20.9017	17.755	0.9111
A	5	21.7	4.896	27.372	18.867	4.972

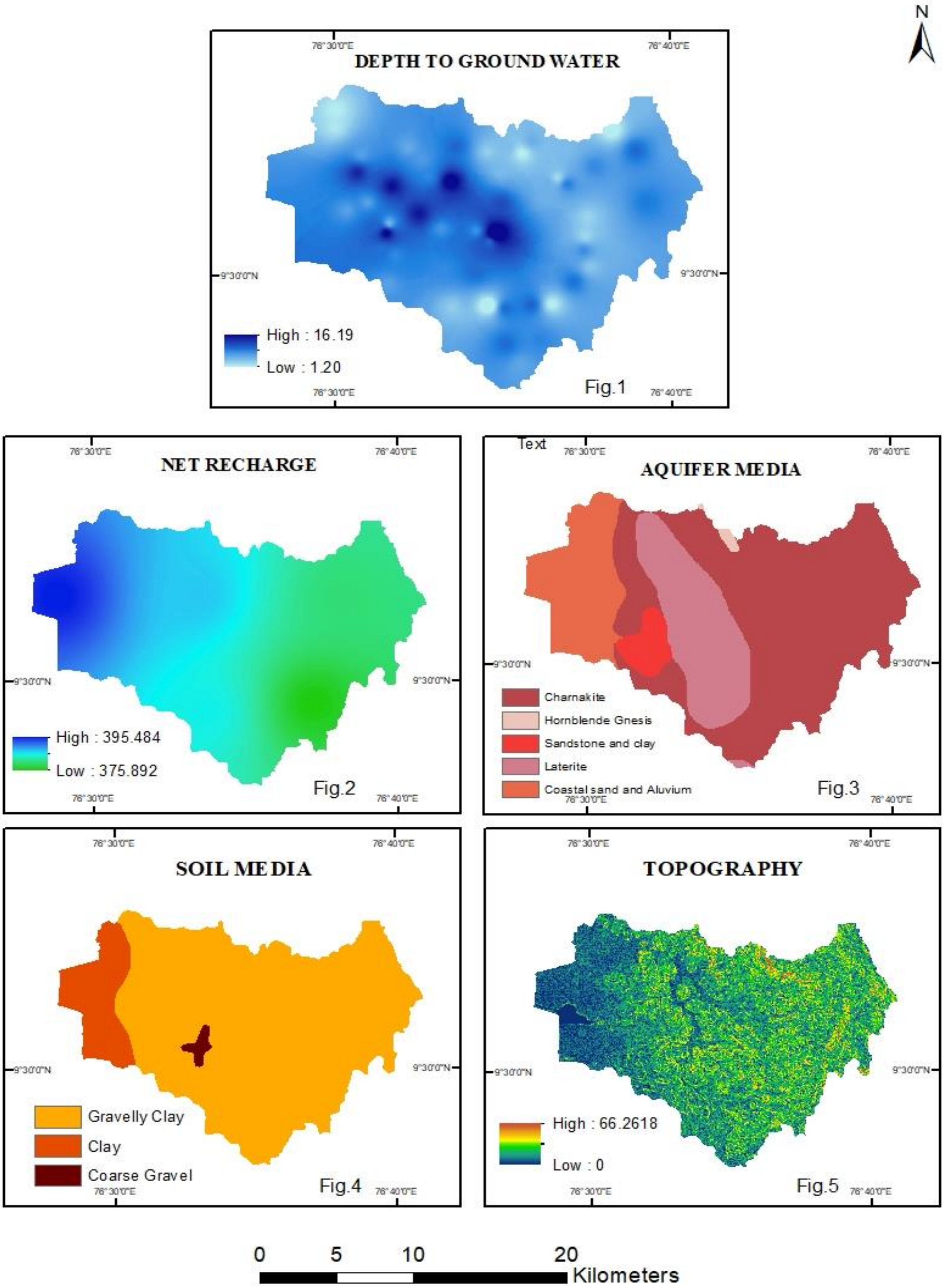

Fig 1: Thematic map of depth to groundwater, Fig 2: Thematic map of Net Recharge, Fig 3: Thematic map of Aquifer Media, Fig 4: Thematic map of Soil Media, Fig 5: Thematic map of Topography

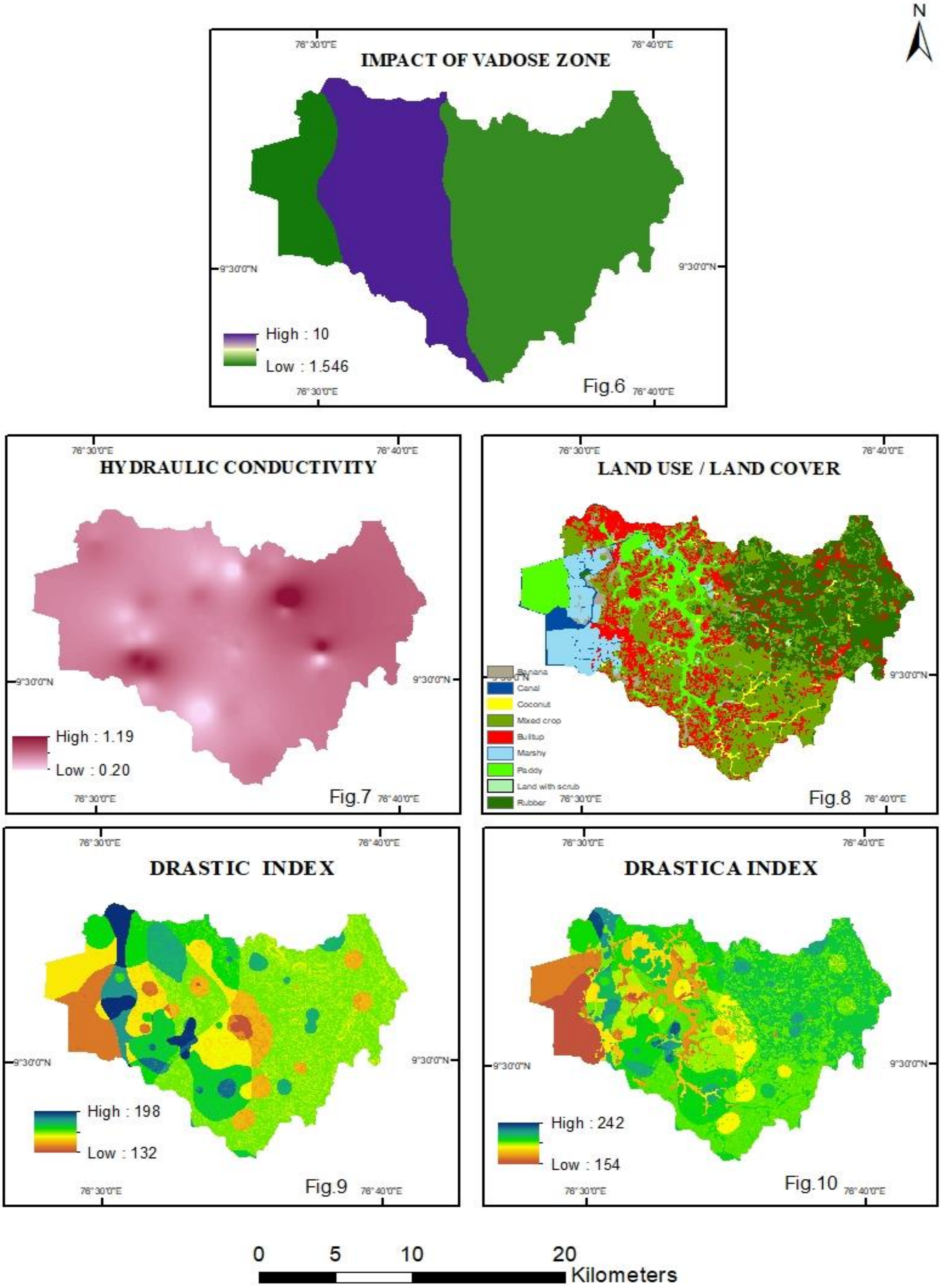

Fig 6: Thematic map of Vadose zone impact, Fig 7: Thematic map of Hydraulic conductivity, Fig 8: Thematic map of Land use and/or land cover, Fig 9: DRASTIC vulnerability map, Fig 10: DRASTICA vulnerability map.

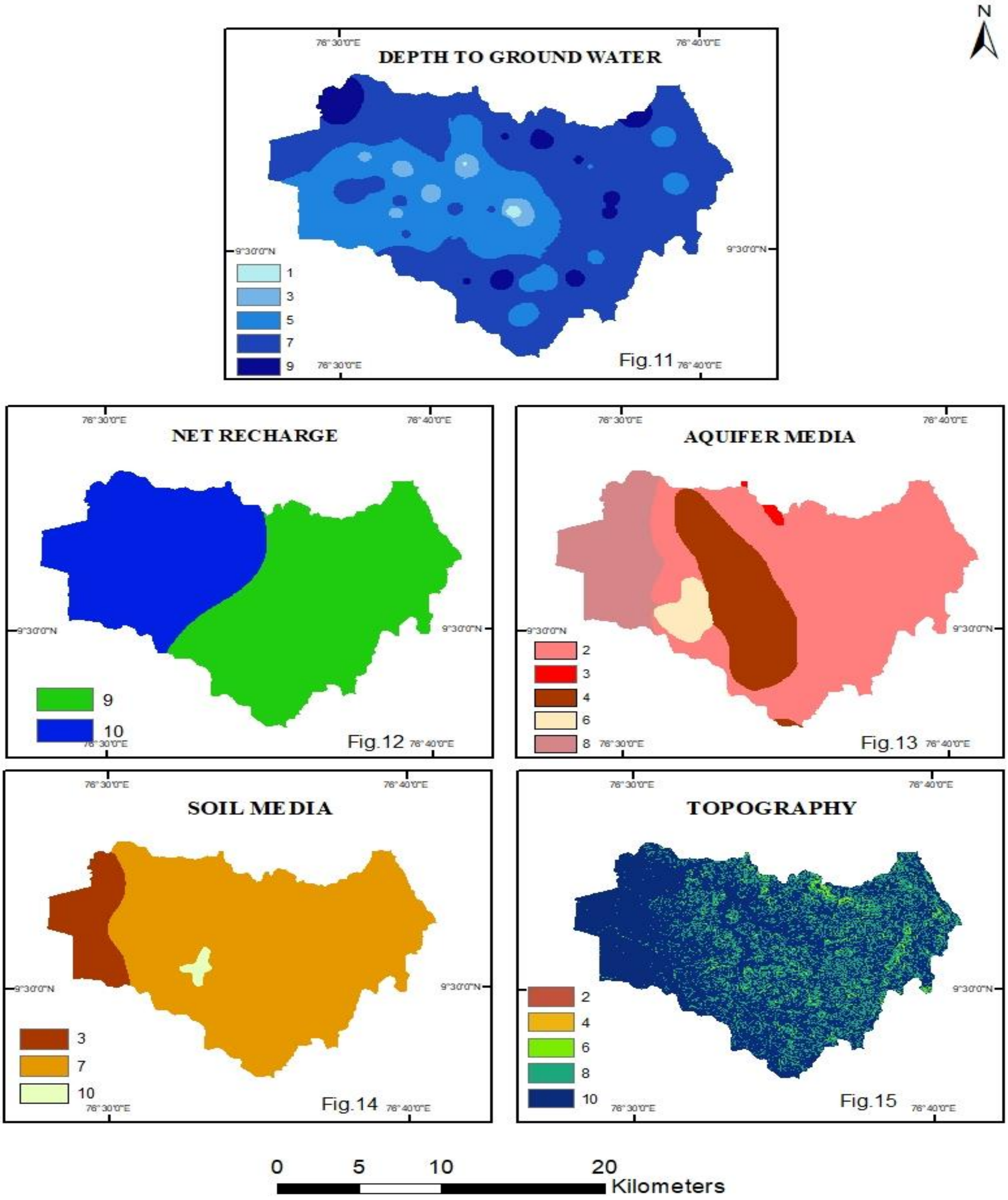

Fig 11: Reclassified map of depth to groundwater, Fig 12: Reclassified map of Net Recharge, Fig 13: Reclassified map of Aquifer media, Fig 14: Reclassified map of Soil media, Fig 15: Reclassified map of Topography

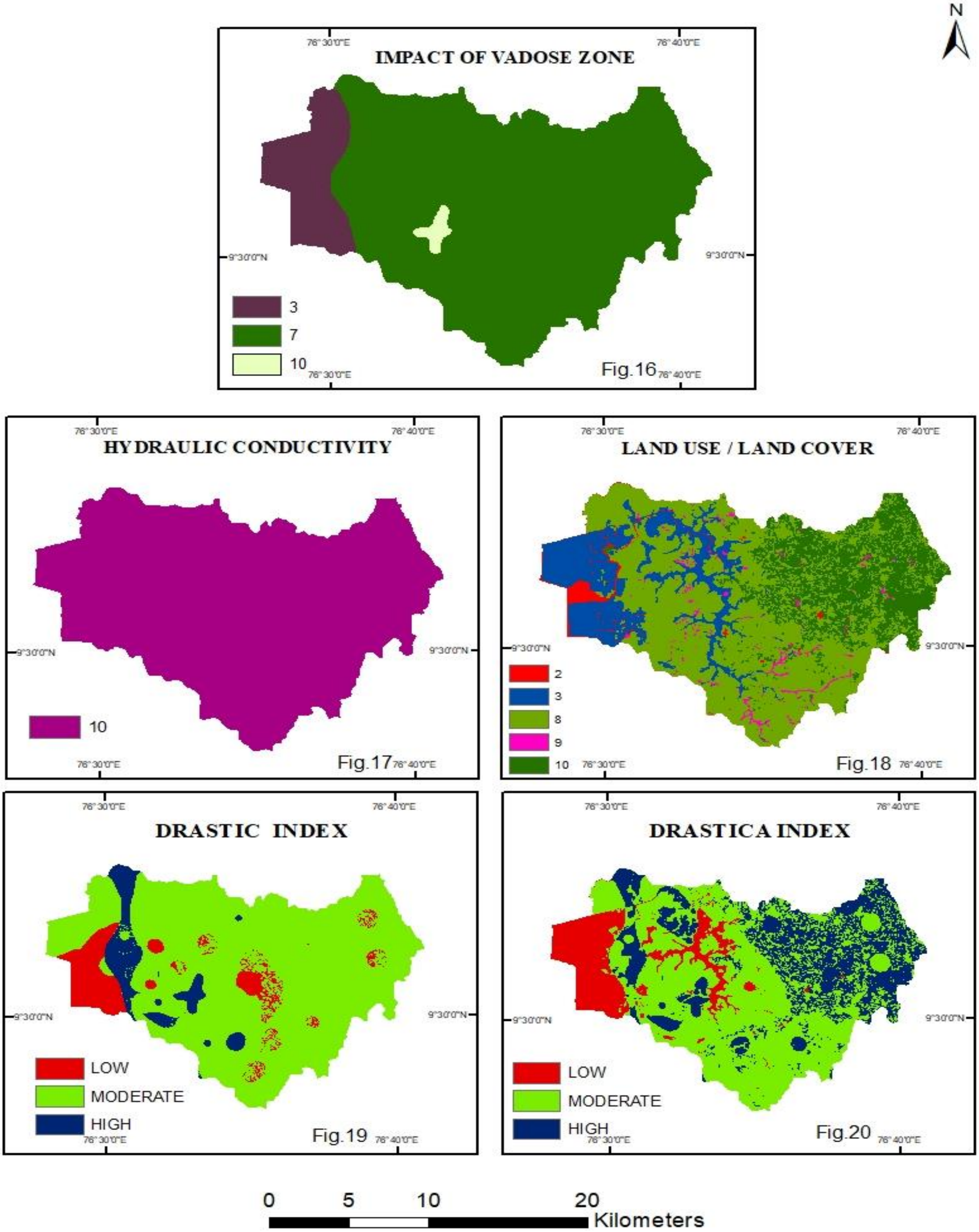

Fig 16: Reclassified map of Impact of vadose zone, Fig 17: Reclassified map of Hydraulic Conductivity, Fig 18: Reclassified map of Land use and/or land cover, Fig 19: Reclassified DRASTIC vulnerability map, Fig 20: Reclassified DRASTICA vulnerability map.

After preparing the thematic maps of all the individual parameters, the final DRASTIC and DRASTICA vulnerability maps were prepared by linear combination of the parameters. Agriculture is the predominant activity of the study area which indicates that the main reason for the existence of nitrate in the study area is due to agriculture. Hence nitrate can be chosen as the indicator parameter of pollution. The nitrate concentration map of the study area shows positive correlation with the vulnerability indices maps. The correlation can be improved by adding more number of parameter maps to the vulnerability maps. But it is difficult in obtaining the necessary data for more parameter maps in spite of the fact that more number of parameters can increase the reliability of the results.

From the final vulnerability maps, it can be seen that most of the land under the study area are moderately vulnerable to contamination which emphasizes the importance of adoption of some groundwater pollution control strategies by the concerned authorities. Some sort of land use restrictions should be imposed on the medium and high vulnerable to pollution areas. If the activities that can hamper the quality of groundwater is not restricted, the groundwater resources of the study area may get polluted in the near future.

4. Conclusions

The vulnerability of the basin of the Kodoor River was assessed primarily using the DRASTIC model. The region was classified into different zones based on the vulnerability index. The correlation analysis reveal that vulnerability of the area has a positive correlation of 0.21 with the nitrate data. This indicates that the DRASTIC model is suitable for ground water vulnerability analysis in the study area. However to modify the model to suit better to the hydrogeological characteristics of the area, an anthropogenic factor namely land use and land cover parameter was added to the model. The correlation analysis of the model with the nitrate concentration of the study area gave a better correlation of 0.38. This indicates that natural parameters alone are not sufficient for vulnerability analysis of groundwater to pollution. The sensitivity analysis revealed that the land use and/or land cover as well as the vadose zone impact has the most significant influence on ground water vulnerability followed by net recharge, depth to groundwater, hydraulic conductivity, soil media, aquifer media, and topography. More anthropogenic parameters which can influence groundwater vulnerability to pollution should be identified and incorporated in the model.

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