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Assessment of Groundwater Vulnerability in Upper Betwa River Watershed using GIS based DRASTIC Model

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ABSTRACT

Groundwater, the most vital water resource being used for irrigation, domestic and industrial purposes is nowadays under severe threat of contamination. Groundwater contamination risk assessment is an effective tool for groundwater management. In the study, a DRASTIC model which is based on the seven hydrogeological parameters viz: depth of water, net-recharge, aquifer media, soil media, topography, impact of vadose zone and hydraulic conductivity was used to evaluate the groundwater pollution potentiality of upper Betwa watershed. ArcGIS was used to create the ground water vulnerability map by overlaying the seven layers. Based on groundwater vulnerability map, the watershed has been divided in three vulnerable zones viz; low vulnerability zone with 42.83 km^2 of area, moderate with 369.21 km^2 area and high having 270.96 km^2 of area. Furthermore, the DRASTIC model has been validated by nitrate concentration over the area. Results of validation have shown that in low vulnerable zone, no nitrate contamination has been recorded. While in the moderate zone nitrate has been found in the range of 1.6-10ppm. However, in high vulnerable zone 11-40ppm of nitrate concentration in groundwater has been recorded, which proves that the DRASTIC model is applicable for the prediction of groundwater vulnerability in the watershed and in similar areas too.

INTRODUCTION

Groundwater (GW) vulnerability is a basic method for computing the risk of groundwater contamination and developing management techniques to preserve the quality of groundwater (Prasad et al., 2014). The DRASTIC index uses GIS to estimate groundwater vulnerability by overlaying different spatially referenced hydrogeological parameters affecting groundwater contamination (Hamutoko et al., 2015). The concept of groundwater vulnerability to contamination was first developed by Margat (1968). Then after, several studies were carried out to assess the groundwater vulnerability using different methods. These methods can be classified into three types, i.e., process-based, statistical and overlay/index methods (Tesoriero et al., 1998). Groundwater having low susceptibility to pollution and is considered as the major source of pure water supply in comparison to surface water (Navada et al., 1993; Jamrah et al., 2008). Groundwater contamination is a widespread environmental concern. Once aquifers are polluted, then it is difficult to remediate it quickly due to their large storage, long residence times and physical inaccessibility (Todd, 1980; Foster and Chilton, 2003). In our country (India), almost 70% of surface water resources and a great number of groundwater reserves are already contaminated by biological, organic and inorganic pollutants (Rao and Mamatha, 2004). Apart from this, groundwater quality is under threat for potential contamination as it is susceptible to contamination from rapid land use/land cover changes and other anthropogenic activities. Even today, more than 90% of our rural population is primarily dependent on groundwater (Chandrashekhar et al., 1999). The quantity, as well as quality of GW, is important because it is the major source of drinking water in most parts of our country. Thus, effective preventative measures of groundwater contamination must be adopted in groundwater management system.

The drastic model developed by the U.S. Environmental Protection Agency in 1985 with aiming to evaluate groundwater pollution potential for the entire USA. The word DRASTIC is an acronym formed the initial letters of the seven factors which are used for determining relative rankings. (D) refers to depth to water, (R) refers to net recharge, (A) refers to Aquifer media, (S) refers to soil media, (T) refers to topography, (I) refers to impact of the vadose zone media, and (C) refers to hydraulic conductivity of the aquifer (Aller et al., 1987).

DRASTIC is a standardized system, for assessing ground water pollution potential using hydrogeologic setting (Sahu and Nandi, 2015). It is a widely used overlay/index methods and serving as a powerful tool for assessing groundwater vulnerability (Al-Adamat et al., 2003; Hamza et al., 2007; Rahman, 2008; Leone et al., 2009; Knox et al., 1993; Kim and Hamm, 1999). The data required in the DRASTIC model are easily available, which makes it workable for regional scale assessments (Thapinta and Hudak, 2003). In addition, it is relatively simple and includes a high number of input data layers that limit the impacts of errors of the individual parameters on the final result.

The DRASTIC method has been used for vulnerability mapping projects in the United States and discussed as a possible tool for such assessments (Atkinson and Thomlinson, 1994; Kalinski et al., 1994). As per EPA overlay and index-based screening tool such as DRASTIC developed by Aller et al. (1987) provides a viable option. The advantage of the overlay and index approach such as that used by DRASTIC is that modifications can be readily made and can be used for larger scale studies (Smith et al., 1994). DRASTIC has been used as a screening tool to investigate broad geographic areas for susceptibility to GW contamination by pesticides using existing hydrogeologic parameters in GISs (Fritch et al., 2000; Kim and Hamm, 1999; Rosen, 1994). Some applications of DRASTIC to predict vulnerability of GW to pesticides were successful and some were not (Lowe and Butler, 2003). Assessment of vulnerability or delineation of the vulnerable zone is not an easy task due to complex interactions of the parameters involved.

A calibrated drastic model was used to predict the intrinsic vulnerability as well as the groundwater pollution risk (Shahid, 2000; Smail, 2014; Kazakis and Voudouris, 2015; Mfumu Kihumba et al., 2017). The drastic model becomes the most popular technique in use for aquifer vulnerability mapping and assessments. The algorithm calculates an intrinsic vulnerability index based on a weighted addition of seven factors. In many studies, the method is subject to adjustments, especially in the factor weights, to meet the peculiarities of the studied regions (Pacheco et al., 2015).

Studies used the Drastic model in association with GIS for assessing the ground vulnerability include (Ghosh et al., 2015;

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Fig.1. Location map of the study area

Lathamani et al., 2015; Victorine Neh et al., 2015; Zghibi et al., 2016; Lobo-Ferreira and Oliveira, 1997). However, vulnerability mapping could be performed in relation to groups of polluting activities (Foster et al., 2003) such as sewage disposal, agriculture and particular groups of industries. Rundquist et al., (1991) have produced statewide GW vulnerability assessment in Nabraska using DRASTIC/GIS model and identified the areas vulnerable to GW pollution and concluded that DRASTIC methodology can be executed successfully with minimal training and experience. The study, therefore, utilized a procedure similar to the DRASTIC model (Aller et al., 1985) for evaluating GW vulnerability f existing aquifers in the study area.

STUDY AREA

The area under investigation comprises upper parts of Betwa river with a geographical area of 683 km^2. The study area falls in Survey of India (SOI) Toposheet No. 55 E/8, 12, 55 F/5, 9 and lies between 22°51' to 23°64' North latitude and between 77°20' to 77°45' East longitudes. The watershed forming the upper part of river Betwa, hence it is named as upper Betwa watershed. The watershed covering the part of Obedullahganj block of the Raisen district of Madhya Pradesh, which is highly industrialized and the water resources may be contaminated due to improper disposal of municipal, urban and industrial waste. Location map of the study area is given in (Fig.1).

MATERIALS AND METHODOLOGY

In the present study, the DRASTIC method, for evaluating ground water pollution potential was used. The DRASTIC model is used in many countries because the input information required for its application is readily available. The model was developed for the purpose of GW protection in the United States of America (USA) and its methodology is referred as "DRASTIC" (Rahman, 2008). A numerical ranking system to assess ground water pollution potential in hydrologic settings has been devised using the DRASTIC factors. The system contains three significant parts i.e. weights, ranges and ratings.

DRASTIC model evaluates the intrinsic vulnerability (IV) of groundwater in term of DRASTIC index using formula

$$\text{DRASTIC Index (IV)} = DrDw + RrRw + ArAw + SrSw + TrTw + IrIw + CrCw$$

Where, *D*- depth to water, *R*- net-recharge, *A*- aquifer media, *S*- soil media, *T*- topography, *I*- impact of Vadose zone, and *C*- hydraulic conductivity are the parameters, "*r*" is the rating value, and "*w*" the weight assigned to each parameter. The complete methodology followed in this study is shown in flow diagram (Fig.2) and described below.

Weights

Each DRASTIC factor has been evaluated with respect to the other to determine the relative importance of each factor. Each DRASTIC has been assigned a relative weight ranging from 1 to 5 (Table 1). The most significant factors have weights of 5; the least significant, a weight of 1. This exercise was accomplished by using a Delphi (consensus) approach. These weights are a constant and may not be changed.

Ranges

Each DRASTIC factors have been divided into ranges/classes which have an impact on pollution potential.

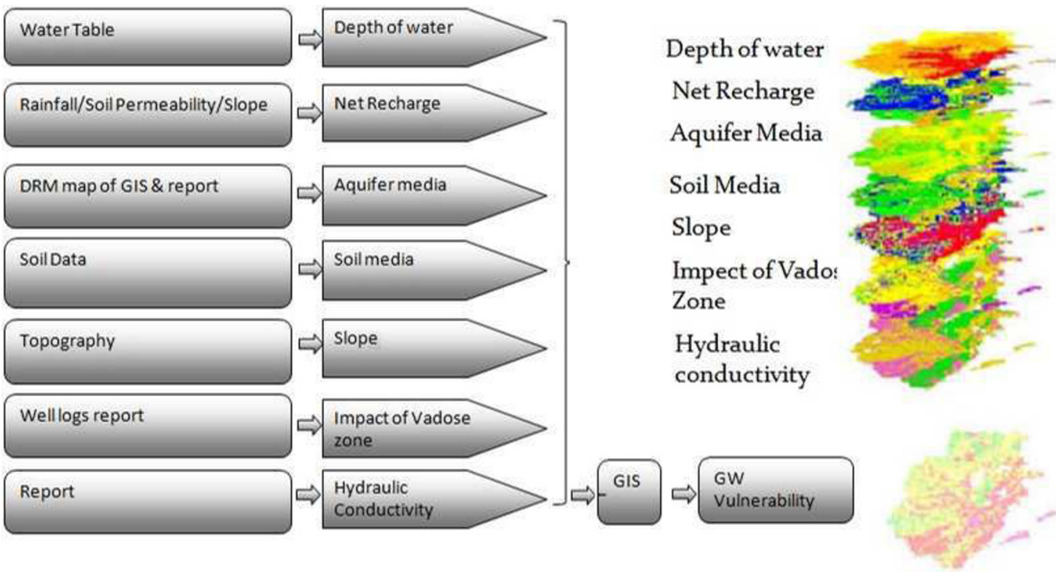

Fig.2. Flow Diagram depicting methodology

Table 1. Assigned weight for DRASTIC parameters (Aller, 1985)

Factors/Hydrological settings	Description	Relative weights
Depth to Water	It is depth from ground to water table, deeper the water table lesser will be the chances of pollutions to interact with ground water.	5
Net-Recharge	It is the amount of water/unit area of land that penetrates the ground surface and reaches the water table, it is the reporting agents for pollutants to the ground water.	4
Aquifer Media	It is the potential area for water storage, the contaminant attenuation of aquifer depends on the amount and sorting of fine grains, lower the grain size higher the attenuation capacity of aquifer media.	3
Soil Media	Soil media is the uppermost and weathered part of the ground, soil cover characteristics influence the surface and downward movement of contaminants	2
Topography	It refers to slope or steepness, areas with low slope tend to retain water for longer, this allows a greater infiltration of recharge of water and a greater potential for contaminant migration and vulnerable to ground water contamination and vice versa.	1
Impact of Vadose zone	It is the ground portion found between the aquifer and the soil cover in which pores or joints are unsaturated, its influence on aquifer pollution potential similar to that of soil cover, depending on its permeability, and on the attenuation characteristics of the media.	5
Hydraulic Conductivity	It refers to the ability of the aquifer formation to transmit water; an aquifer with high conductivity is vulnerable to substantial contamination as a plume of contamination can move easily through the aquifer.	3

Ratings

Each range for each DRASTIC factor has been evaluated with respect to the others to determine the relative significance of each range with respect to pollution potential. The range for each DRASTIC factor has been assigned a rating which varies between 1-10.

The DRASTIC model is based on seven parameters, corresponding to seven layers to be used as input parameters for modelling. The sources of data for each parameter are given in (Table 2).

RESULTS AND DISCUSSION

Depth to Water

In the study, water level depth of 23 observation wells has been taken during the pre-monsoon season, June 2015. The maximum and minimum water level depths measured in the watershed are 33m and 2m bgl respectively. This point data were contoured by interpolating and divided into four categories i.e. <10m, 10-20m, 20-30m and >30m (Table 3). Areas with shallow water table depth are more vulnerable because pollutants have to pass the shortest distance to join the water table. The deeper water table levels imply lesser chance for contamination to occur. The depth to water table map was then classified into ranges defined by the DRASTIC model and assigned rates ranging from 1 (minimum impact on vulnerability) to 10 (maximum impact on the vulnerability) and index was calculated by multiplication of weight (5) to ratings for each range which is shown in (Fig 3) and (Table 3).

Table 2. Hydrogeological parameters and their sources used for DRASTIC model

Parameters	Sources	Format
Depth to water *(D)*	Primary data (through well inventory)	Map
Net Recharge *(R)*	Secondary data (Slope/Rainfall/ Soil Permeability)	Map
Aquifer media *(A)*	Secondary data (District Resource Map, Published by GSI, 2003)	Map
Soil media *(S)*	Secondary data (National Bureau of Soil Survey and Land use Planning, ICAR) (NBSS Publ.59)	Map
Topography *(T)*	Secondary data SRTM satellite data	Map
Impact of the vadose Zone *(I)*	Secondary data (District Resource Map, published by GSI, 2003)	Map
Hydraulic conductivity *(C)*	Secondary data (Ritzema 2006)	Table

Net-Recharge

Net-Recharge is the amount of water which penetrates the ground surface and reaches the water table, recharge water represents the medium for transporting pollutants. Recharge water thus available to transport a contaminant vertically to the water table and horizontally within the aquifer. Rainfall is an important factor which transports surface pollutants and landfill leachate by infiltration. Recharge data were not available for the study area. Therefore, Net recharge was calculated by a combination of ratings for slope, soil permeability and rainfall (Table 4) using the following the formula (Piscopo, G.);

Recharge value = Slope (%) + Rainfall+ Soil permeability

Ranges of slope and permeability of soil have been taken from slope map (Fig. 7) and soil map (Fig. 6) and for rainfall (IMD 2015 data) and ratings were assigned as per significance of class for GW vulnerability and then index were calculated (Table 5). Net recharge map is shown in (Fig 4).

Aquifer Media

Aquifer media refers to consolidated or unconsolidated rocks serve that as an aquifer. It is the saturated zone material, which controls the pollution attenuation processes which determine the flow rates and

Table 3. Depth to water level Range, Rating and Index

Depth to water level (m)	Rating	Weight	Index ($D_r D_w$)
<10	10	5	50
10-20	9		45
20-30	8		40
>30	7		35

Table 4. Slope, Rainfall, Permeability of soil Range and Rating

Slope Range	Rainfall (mm) 2015 data Rating	Range	Rating	Permeability of Soil class Texture of soil	Range	Rating
0-2	10	1051	4	Clay loam	Slow	1
2-6	9			Silty loam	Moderate	2
6-12	5			Sandy loam	Moderate rapid	4
12-18	3					
>18	1			Loam	Moderate rapid	4

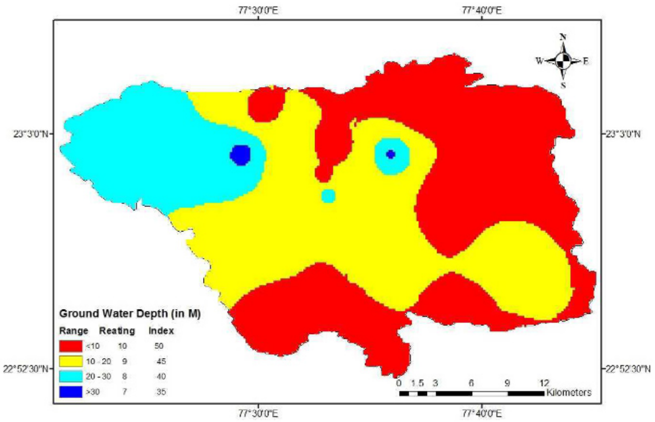

Fig.3. Depth to Ground Water Level Range, Rating and Index Map.

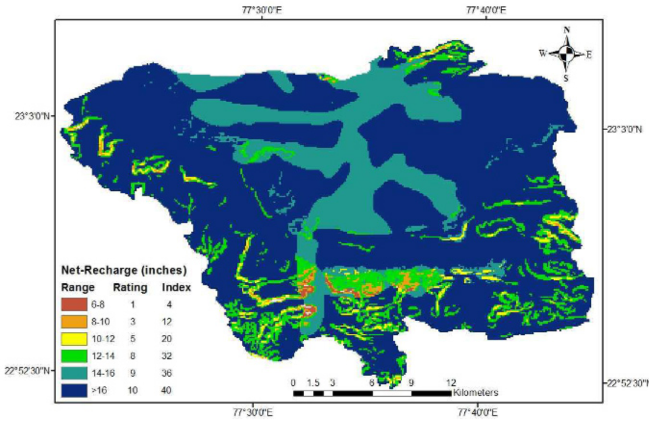

Fig.4. Net-Recharge Range, Rating and Index Map

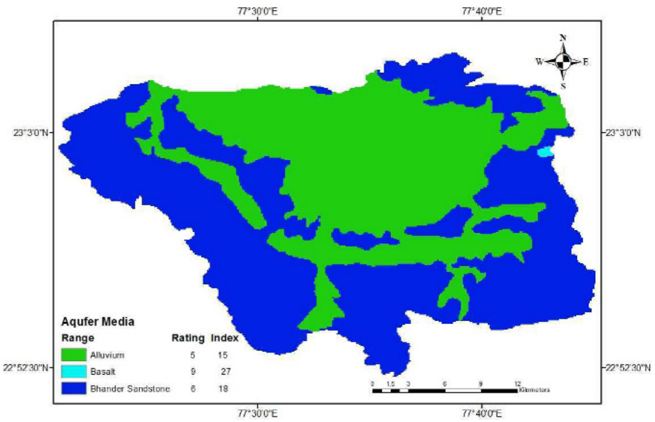

Fig.5. Aquifer Media Range, Rating and Index Map

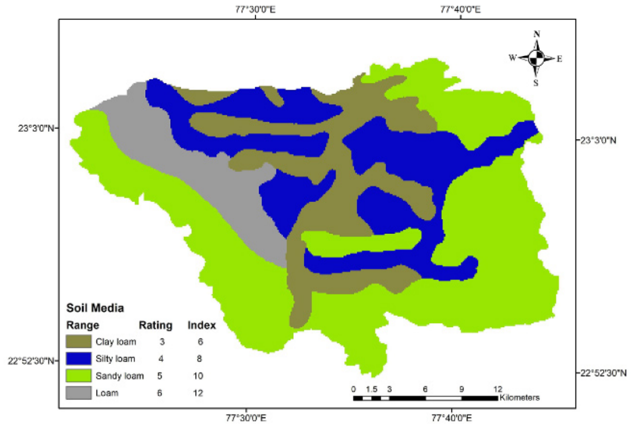

Fig.6. Soil Media Range, Rating and Index Map

types of contamination. The sand and gravel are the basic rock formation in the study area. The assigned rating for aquifer media is found to be in the range, rating and index were calculated by multiplication of weight (3) to rating for each range which is shown in (Fig. 5) and (Table 6).

Soil Media

Soil media refers to the weathered portion of the earth surface characterized by considerable biological activity. Soil act as transport media for contaminants to travel vertically into the groundwater because, of its ability to infiltrate impurities through rainfall recharge. Soil pollution potential is mostly affected by the soil types. Soil types were analyzed and identified from different sampling stations using soil texture analysis. Based on soil texture, the soil map was classified into four classes-clay loam, silty loam, sandy loam and loam with ratings 3, 4, 5 and 6. The rating value of 6 was the greatest in the study area. This result was then compiled into a soil media map as an index. The range, rating and index of soil media of the study area are given in (Table 7) and (Fig. 6).

Topography

Topography refers to the slope and slope variability of the land surface. Topography helps control the likelihood that a pollutant will run off or remain on the surface for long to infiltrate. Therefore, the greater the change of infiltration, the higher the pollution potential associated with the slope. Topography influences soil development and therefore has an effect on attenuation. Topography is also significant from the standpoint that the gradient and direction of flow

Table 5. Net-Recharge value, Rating and Index
Net-Recharge (inches)

Range	Rating	Weight	Index (R_rR_w)
6-8	1		4
8-10	3	4	12
10-12	5		20
12-14	8		32
14-16	9		36
>16	10		40

Table 6. Aquifer media Range, Rating and Index

Aquifer Media	Rating	Weight	Index (A_rA_w)
Alluvium	5	3	15
Sandstone	6		18
Basalt	9		27

Table 7. Soil media Range, Rating and Index

Soil Class	Rating	Weight	Index (S_rS_w)
Clay loam	3	2	6
Silty loam	4		8
Sandy loam	5		10
Loam	6		12

Table 8. Topography Range, Rating and Index

Slope Range (%)	Rating	Weight	Index (T_rT_w)
0-2	10	1	10
2-6	9		9
6-12	5		5
12-18	3		3
>18	1		1

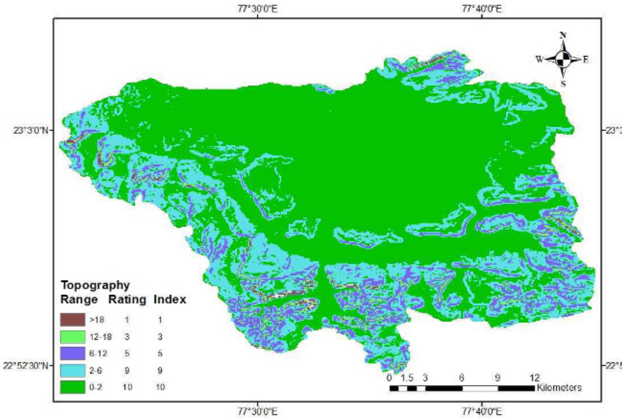

Fig.7. Slope Range, Rating and Index Map

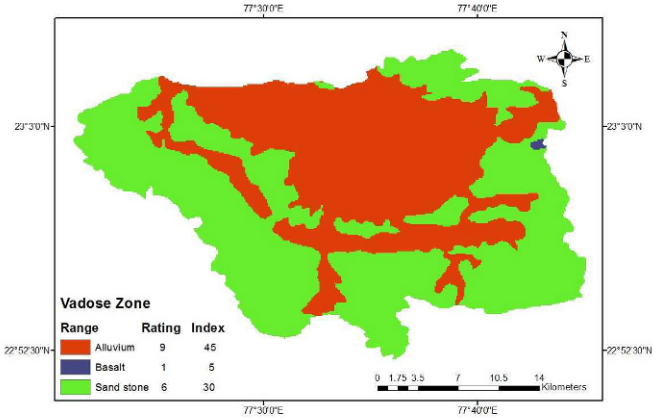

Fig.8. Vadose Zone Range, Rating and Index Map

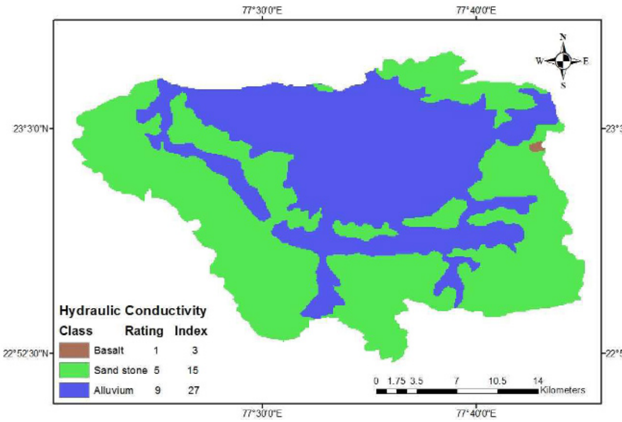

Fig.9. Hydraulic Conductivity Map

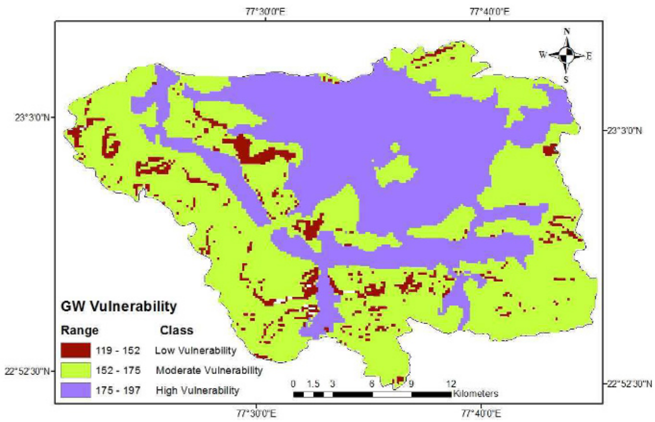

Fig.10. Groundwater Vulnerability Map

are controlled by topography. Generally, steeper slopes signify high surface runoff. The details of slope classes are given in Table 8 and shown in (Fig. 7).

Impact of the Vadose Zone

The vadose zone is defined as the zone above the water table which is unsaturated. When evaluating a confined aquifer, the "impact" of the vadose zone is expanded to include in the case of a confined aquifer, the significantly restrictive zone above the aquifer which forms the confining layer is used as the type of media which has the most significant impact. The type of vadose zone media determines the attenuation characteristics of the material below the typical, soil horizon and above the water table. The materials at the top of the vadose zone also exert an influence on soil development. The details of vadose zone classes are given in (Table 9) and (Fig. 8).

Table 9. Impact of the Vadose zone Range, Rating and Index

Class	Rating	Weight	Index (I_rI_w)
Alluvium	9	5	45
Sandstone	6		30
Basalt	1		5

Table 10. Range rating and index of hydraulic conductivity

Class	Hydraulic conductivity K (m.day^{-1})	Rating	Weight	Index (C_rC_w)
Sandstone	10 – 50	5	3	15
Alluvium	0.5 – 2	9		27
Basalt	< 0.002	1		3

Hydraulic Conductivity

Hydraulic conductivity refers to the ability of the aquifer materials to transmit water, which in turn, controls the rate at which ground water will flow under a given hydraulic gradient. The rate at which the ground water flows also controls the rate at which a contaminant will be moved away from the point at which it enters the aquifer. Hydraulic conductivity is controlled by the amount and interconnection of void space within the aquifer which may occur as a consequence of factors such as inter-granular porosity, fracturing and bedding planes. Hydraulic conductivity values for different soil medium determined by Ritzema (2006) have been used in the study (Table 11). The details of Hydraulic conductivity classes are given in (Table 10) and shown in (Fig. 9).

Development of the DRASTIC Vulnerability Index

The DRASTIC index was calculated by combining all seven layers in the ArcGIS environment to delineate the groundwater vulnerability zones shown as the GW vulnerability map (Fig. 10) have been divided into three vulnerable zones: Low vulnerable zones ranging from 119

Table 11. Hydraulic conductivity: K-value range by soil texture (Ritzema 2006

Texture	Hydraulic conductivity K (m.day^{-1})
Gravelly coarse sand	10 – 50
Medium sand	1 – 5
Sandy loam, fine sand	1 – 3
Loam, clay loam, clay (well structured)	0.5 – 2
Very fine sandy loam	0.2 – 0.5
Clay loam, clay (poorly Structured)	0.002 – 0.2
Dense clay (no cracks, pores)	< 0.002

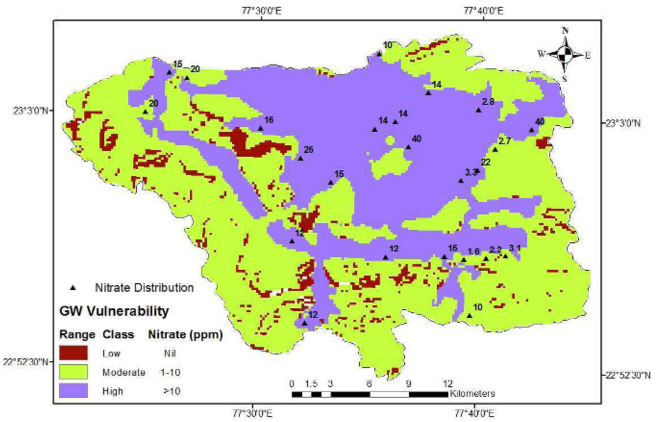

Fig.11. Nitrate Concentration in Groundwater

to 152 DRASTIC index with a geographical area of about 42.83 sq. km, moderate vulnerable zones ranging from 152 to 175 with 369.21 sq. km geographical area and high vulnerable zones with DRASTIC index ranging from 175 to 197 with 270.96 sq. km area.

Validation

The Groundwater vulnerability map was validated with nitrate concentration in groundwater as shown in (Fig.11). Results of validation have shown that in the low vulnerable zone, no nitrate contamination has been recorded. While in the moderate zone nitrate has been found in the range of 1.6-10ppm. However, in high vulnerable zone, 11-40 ppm of nitrate concentration was recorded. As per the standards of WHO Guidelines for Drinking Water Quality (1984), the permissible limit of nitrate in groundwater is 10 ppm and beyond this range it is harmful.

CONCLUSION

In the study, an assessment the groundwater vulnerability of the upper part of Betwa watershed using DRASTIC model was carried out. During the study, seven parameters i.e., depth to water table, net-recharge, aquifer media, soil media, topography, impact of the vadose zone, and hydraulic conductivity which represent the natural hydro-geological conditions of the watershed were combined in ArcGIS and a groundwater vulnerable map has been prepared. The watershed has been divided in to three vulnerable zones viz; Low = 6.27 % (42.83 sq.km), Moderate= 54.06 % (369.21 sq.km) and high = 39.67 % (270.96 sq.km). The areal distribution of vulnerability zones is shown on the vulnerability map (Fig.10). Furthermore, Groundwater vulnerability map has been validated with nitrate concentration. This study also indicated that the GIS technique could provide an efficient way to deal with a large quantity of spatial data used in the DRASTIC model. This study gives a very comprehensive picture of vulnerability to groundwater to contamination in the area.

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