Chapter – 5

Groundwater Vulnerability Modelling

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5.1 Introduction:

Groundwater quality is a significant parameter of environment as it directly and indirectly affects human health. Hence, it is essential to ensure better quality of groundwater and identify the potential zones both in terms of quantity and quality. Thus, there is a need to investigate the issue in a systematic way and identify the vulnerability zones. The term 'Vulnerability of Groundwater by Contamination' was first used by **Margat** in 1968. According to the National Research Council (1993) the groundwater vulnerability due to contamination is the tendency of contaminants to reach to the particular position of the groundwater after introducing in the uppermost aquifer. The first step towards the identification of vulnerability zone is to identify the parameters that are to be used in the decision making. After the identification of the risk zones, it is possible to take necessary measures to minimize the current condition and plan for the future. The chosen parameters are based on their significance as well as availability. To identify the vulnerability of groundwater different types of parameters were applied in different models such as GODS, AVI, IVI (**Gogu** and **Dassargues** 2000). Moreover DRASTIC model is widely used in identifying the groundwater vulnerability zones (**Aller** et al. 1987, **Doerfliger** and **Zwahlen** 1997, **Samake** et al. 2010). In this model, seven critical parameters of groundwater viz. *depth to the water* (D), *recharge* (R), *aquifer media* (A), *soil media* (S), *topography* (T), *impact of vadose zone* (I) and *hydraulic conductivity* (C) were used. According to **Aller** et al.

(1987) the system comprises of designation of mapable units of groundwater and overlying of the relative ranking system. To find out the DRASTIC index of each parameter, relative ranking system and particular weight of each parameter was used. Finally to depict the composite DRASTIC index which helps in identifying the potential zones of contamination, all the seven vulnerability index maps were merged with each other. On the basis of their significance, relative weights were given to each of the factors. The most important factor was assigned with weight of 5 while the least important factor was designated with weight of 1. In this system, depth to the water (D) and impact of vadose zone (I) were given highest priority and were given the higher weights while the relative importance of the topography was assigned lowest weight of 1. After assigning weights of the factors, **Aller** et al. (1987) also specified the range of each of the factors with their respective weights. These weights (Table 5.1) and rates (Table 5.2) were used in the following formula (1) to find out the composite DRASTIC index of the groundwater-

$$D_R D_W + R_R R_W + A_R A_W + S_R S_W + T_R T_W + I_R I_W + C_R C_W = \text{Pollution Potential (DRASTIC)} \quad (1)$$

Where-

R = Rate,

W= Weight,

D = Depth to groundwater

R= Recharge,

A= Aquifer media,

S= Soil media,

T= Topography,

I= Impact of vadose zone,

C= Hydraulic Conductivity

Table: 5.1 Assigned Weights of Each Factors	
Factors	**Weights**
Depth	5
Net Recharge	4
Aquifer media	3
Soil	2
Topography	1
Impact of Vadose Zone	5
Hydraulic Conductivity	3
Source: Aller et al. (1987)	

Table: 5.2 DRASTIC Rating System for Different Factors					
Depth (D) (Feet)		**Net Recharge (R) (Inches)**		**Aquifer Media (A)**	
Range	**Rates**	**Range**	**Rates**	**Range**	**Typical Rating**
0-5	10	0-2	1	Massive Shale	2
5-15	9	2-4	3	Metamorphic/ Igneous	3
15-30	7	4-7	6	Weathered Metamorphic/ Igneous	4
30-50	5	7-10	8	Thin Bedded Sandstone, Limestone, Shale sequence	6
50-75	3	10+	9	Massive sandstone	6
75-100	2			Massive limestone	6
				Fine to medium sand	5
100+	1			Sand and gravel	8
				Coarse Sand	8
				Basalt	9
				Karst Limestone	10

Table:5.2 DRASTIC Rating System for Different Factors (continued)

Soil (S)		Topography (T) (% slope)		Hydraulic Conductivity (GPD/FT^2) (C)	
Range	Rates	Range	Rates	Range	Typical Rates
Thin or absent	10	0-2	10	1-100	1
Gravel	10	2-6	9	100-300	2
Sand	9	6-12	5	300-700	4
Peat	8	12-18	3	700-1000	6
Shrinking/ aggreted clay	7	18+	1	1000-2000	8
Sandy loam	6	Impact of Vadose Zone (I)		2000+	10
Loam	5	Range	Typical Rates		
Silty loam	4	Silt/Clay	1		
Clay loam	3	Shale	3		
Muck	2	Limestone	6		
Nonshrinking/ nonaggreted clay	1	Sandstone	6		
		Bedded Limestone, Sandstone, Shale	6		
		Sand and Gravel with significant Silt and Clay	6		
		Metamorphic/Igneous	4		
		Sand and Gravel	8		
		Basalt	9		
		Karst Limestone	10		

Source: Aller et al. (1987), Rahman (2008)

5.2 Workflow of DRASTIC Modelling:

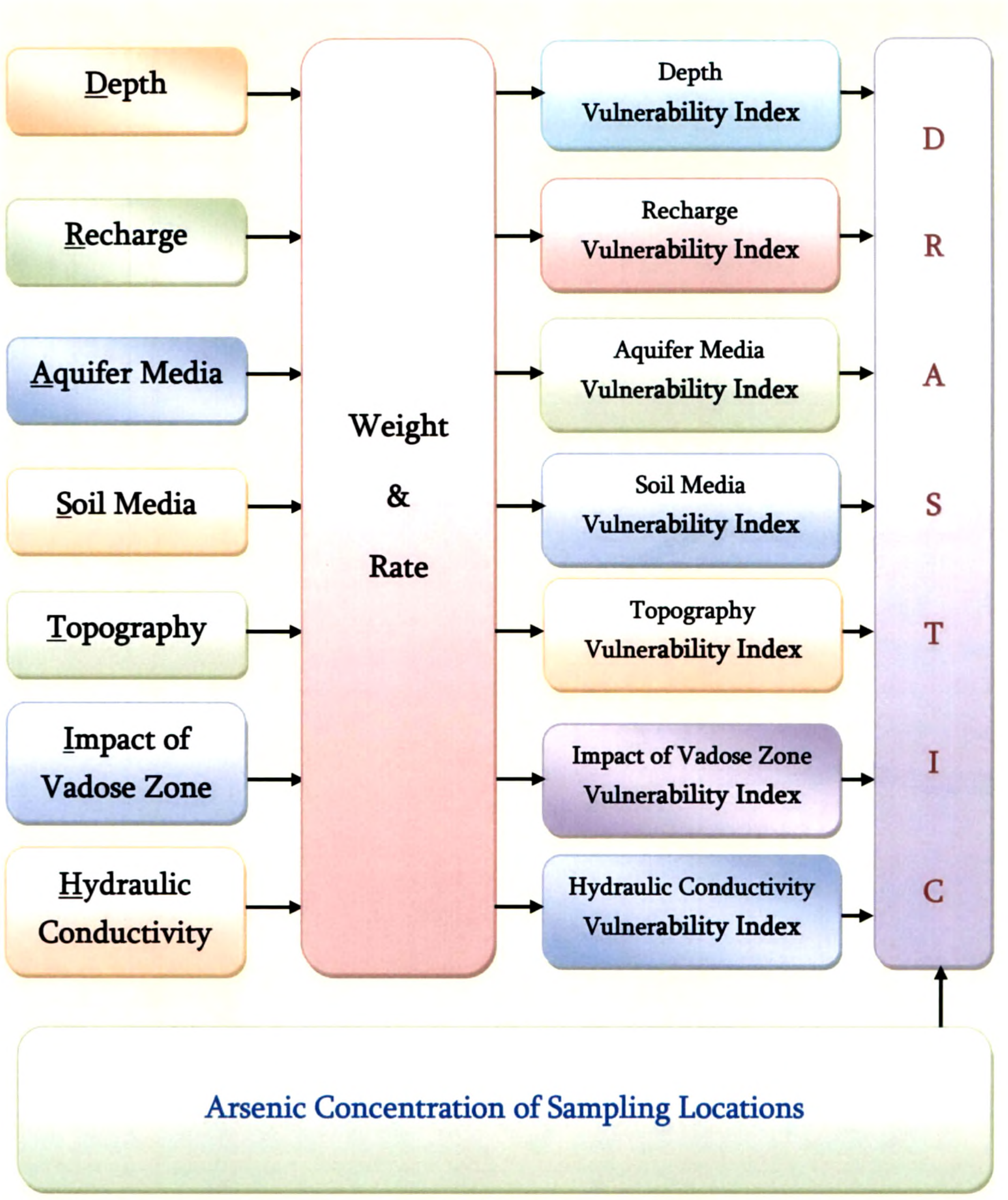


Fig. 5.1 Drastic Modelling Workflow

5.3 Database and Methodology:

The following data was used to generate the DRASTIC model-

1. *Depth to the water* was collected from the data base of Groundwater Authority Board of India website (http://gis2.nic.in/cgwb/Gemsdata.aspx).
2. *Recharge* data was acquired from the Groundwater year Book-2011-12 (http://www.cgwb.gov.in/documents/Ground%20Water%20Year%20Book%20-%202011-12.pdf), District Information Booklet of Murshidabad (http://www.indiawaterportal.org/sites/indiawaterportal.org/files/murshidabad.pdf), Resource Map of Murshidabad District (District Resource Map, Murshidabad, West Bangal, 2008) District Planning Series Map (District Planning Series Map, Murshidabad, West Bengal, 2002) .
3. *Aquifer media* data was generated from the bore well log data collected from the Public Health Engineering Departments, Murshidabad and non government agencies.
4. *Soil media* data was collected from the map prepared by National Bureau of Soil Survey and Land Use Planning, Kolkata.
5. *Topography* layer was generated from the 30 m SRTM data (http://glcfapp.glcf.umd.edu:8080/esdi/index.jsp).
6. *Impact of Vadose Zone* layer was prepared from the subsurface lithological data generated from the bore well logs collected from Public Health Engineering Departments, Murshidabad and non government agencies.
7. *Hydraulic Conductivity* layer was generated from the transitivity data collected from the Murshidabad District Information Booklet (http://www.indiawaterportal.org/sites/indiawaterportal.org/files/murshidabad.pdf).

   On the geo-referenced map of *Murshidabad* district the entire data was loaded in the GIS platform. On the basis of reassigned weights and ratings the vulnerability index for each parameter was calculated.

The calculated indices were tabulated as attributes in the GIS platform. Each of the layers were prepared and converted into raster format to prepare parameter wise vulnerability maps. All the raster layers were then combined with each other to find out the composite vulnerability index. The composite vulnerability index was further converted into vector layer to calculate the area of different vulnerability zones. To find out the percentage of surveyed hand pumps located in the particular vulnerability zones, the sample locations of hand pumps were overlaid on the composite vulnerability map.

5.4 Results:

5.4.1 Depth (D):

Depth to the groundwater is the most important parameter that indicates the distance between the surface of the earth and the water table. It also specifies the time taken by the contaminants before mixing with groundwater. As the distance between the surface and groundwater level increases the travel time of the contaminant increases and vice versa. The average depth to the groundwater in three seasons of 2012 was taken into considerations. In the entire region, the depth to the groundwater varied between 2.51 mbgl to 20.21 mbgl. Shallower depth (< 5 m) was observed in the eastern part of the *Murshidabad* district (Fig. 5.2) (Table 5.3) while in the western segment the depth of the groundwater was relatively higher (5-15 m). The obtained data was interpolated in the GIS environment and was classified in to three categories (< 5 m, 5-15 m and > 15 m). The lower value indicated shallower depth and therefore higher vulnerability, while higher value indicated lower vulnerability. The eastern segment of the study area depicted the depth vulnerability index of 50 while the entire western segment had a vulnerability index of 35 with two small patches of vulnerability index of 45 in the western portion.

Table: 5.3 Depth to Water Index

Vulnerability Indices *(D)*	Area Covered (%)
50	58.27
45	2.08
35	39.65

In terms of area, 58.27% of the area was related to high vulnerability, 2.08% fall under the category of medium vulnerability and 39.65% area depicted low vulnerability zone.

5.4.2 Net Recharge (R):

Net recharge is total quantity of water, from precipitation, surface water and all other artificial sources that penetrates to the groundwater (**Todd** and **Mays** 2005). With the increasing amount of precipitation, increased availability of surface water (like rivers), the rate of recharge increases. The relative weight of recharge (4) indicates its significance in terms of vulnerability as it is next in importance to the parameter of depth. As the rate of recharge increases, the ability of contaminants to move to a greater distance also increases. Thus, there is a positive relationship between the rate of recharge and possibility of higher rate of movement of contaminants.

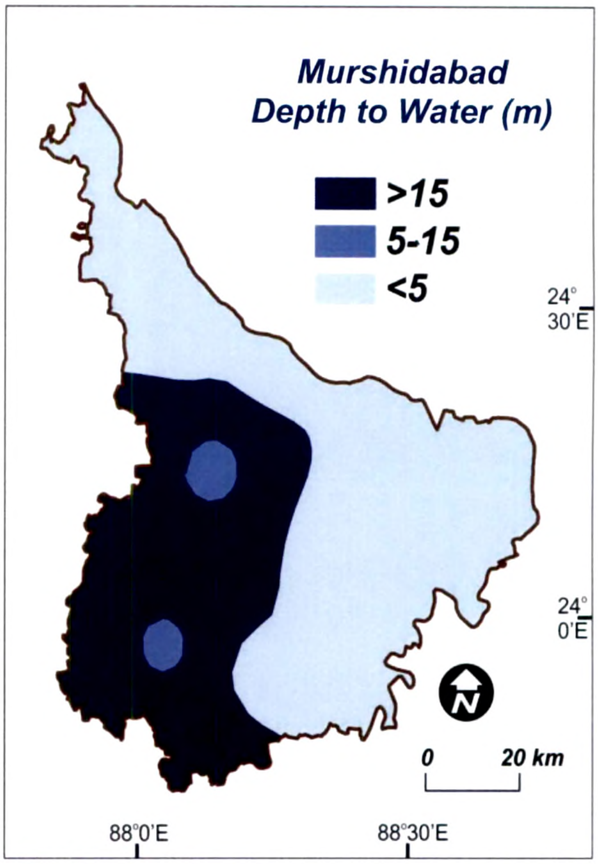


Fig 5.2 Depth to the Water Layer

The entire region is associated with the higher precipitation as it lies in the hot and humid type of climatic zone (**Mondal** 2012). The average rainfall in *Murshidabad* district is approximately 1600 mm. The other major source of recharge in the study area is the presence of River *Ganga*, its tributaries and distributaries.

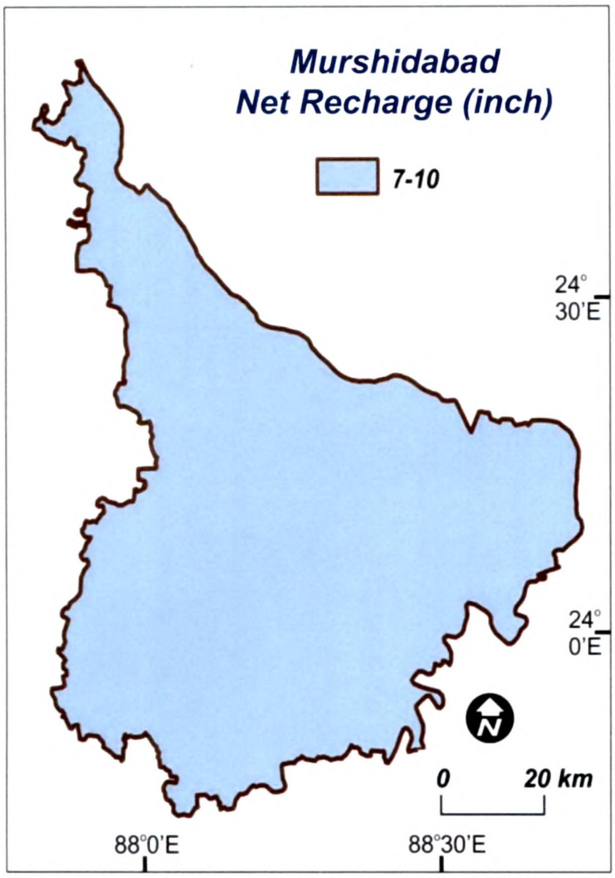


Fig 5.3 Groundwater Net Recharge Layer

Thus, it can be inferred that the entire region is having considerably higher rate of recharge (7-10 inches). Due to availability of only single data for the entire region the recharge of the entire region was considered as constant. After calculating the respective rate and weight it was found that the recharge index was quiet high (32) (Fig. 5.3). The higher value itself is the indicator of higher rate of recharge and the possibility of higher rate of movement of contaminants.

5.4.3 Aquifer Media (A):

To obtain subsurface lithological model, lithologs were placed to their individual positions in terms of longitudes and latitudes. The lithologs were first located and subsequently integrated in the software, which gave the characteristics of the aquifer media. The result showed that, the entire region is associated with the fine/medium sand and coarse sand type of media. Finer the texture of the particles, penetration of the water takes longer time. On the other hand, the rate of penetration of water is much higher in coarser textures. So it

Table: 5.4 Aquifer media Index

Vulnerability Indices *(A)*	Area Covered (%)
15	56.89
24	43.11

can be inferred that, aquifer media associated with finer texture is lesser vulnerable than

the aquifer media associated with coarser texture (Fig. 5.4 and Fig. 5.4). The characteristics of the aquifer media is calculated with the respective rating and weight. It was found that, the eastern part of the district has aquifer media vulnerability index of 24 while in the western side, the aquifer texture is finer and has an index of 15. Thus, higher rating indicates coarser texture and higher vulnerability while lower rating indicates finer texture and lower vulnerability index. In terms of area, 43.11% of the area was related to high vulnerability of aquifer and 56.89% of the area was depicted as low vulnerability zone (Table 5.4) (Fig. 5.5 and Fig. 5.6).

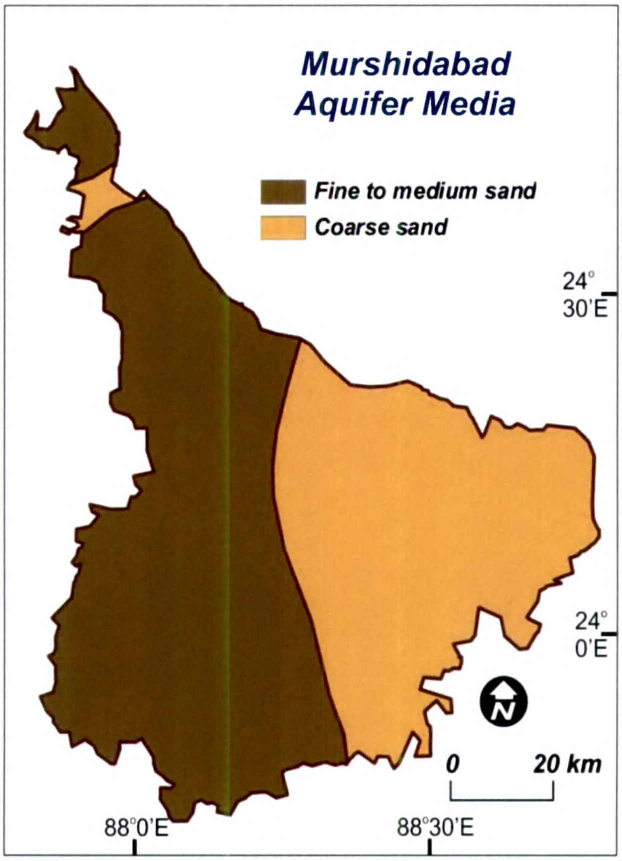


Fig 5.4 Aquifer Media Layer

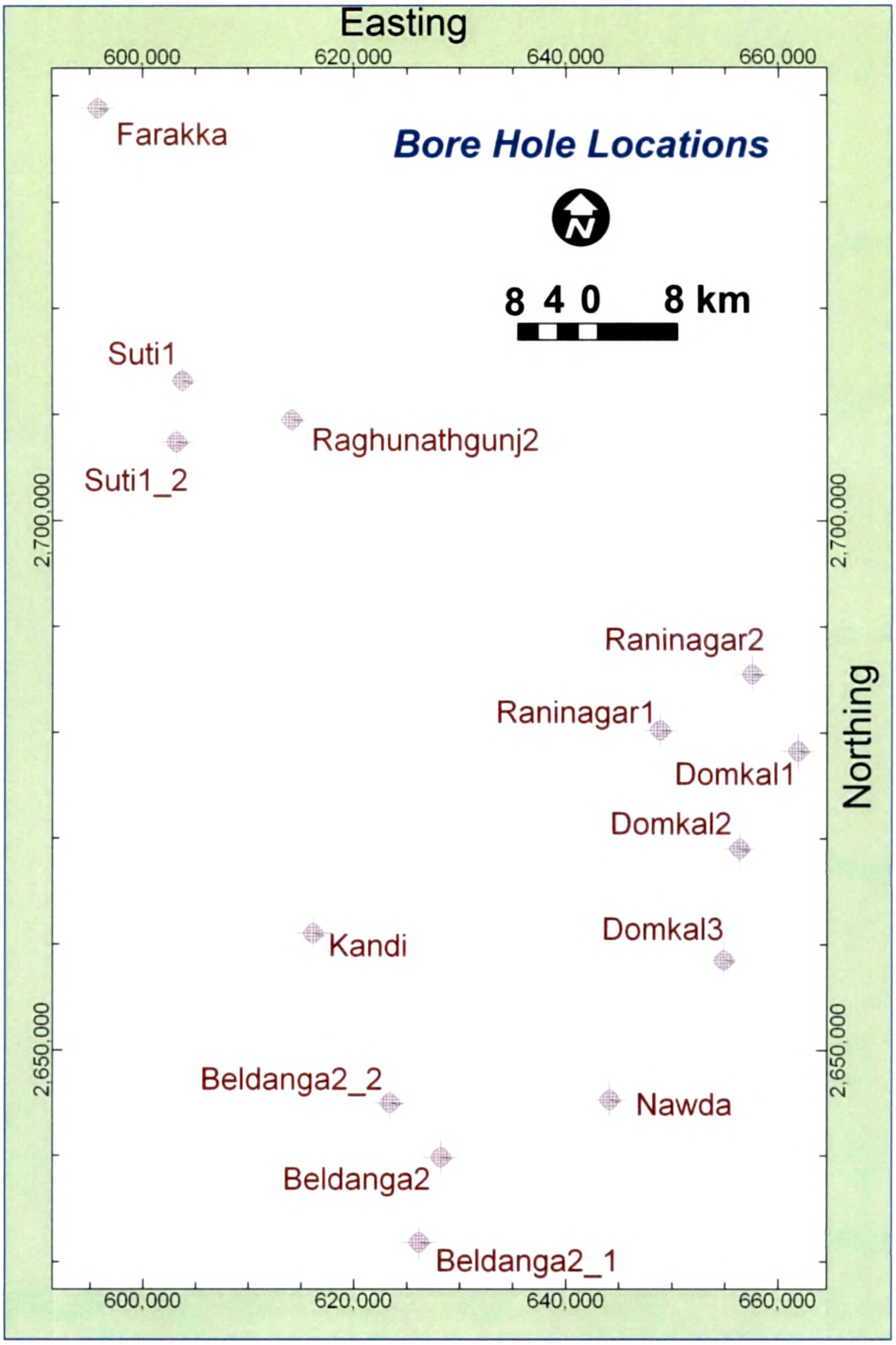
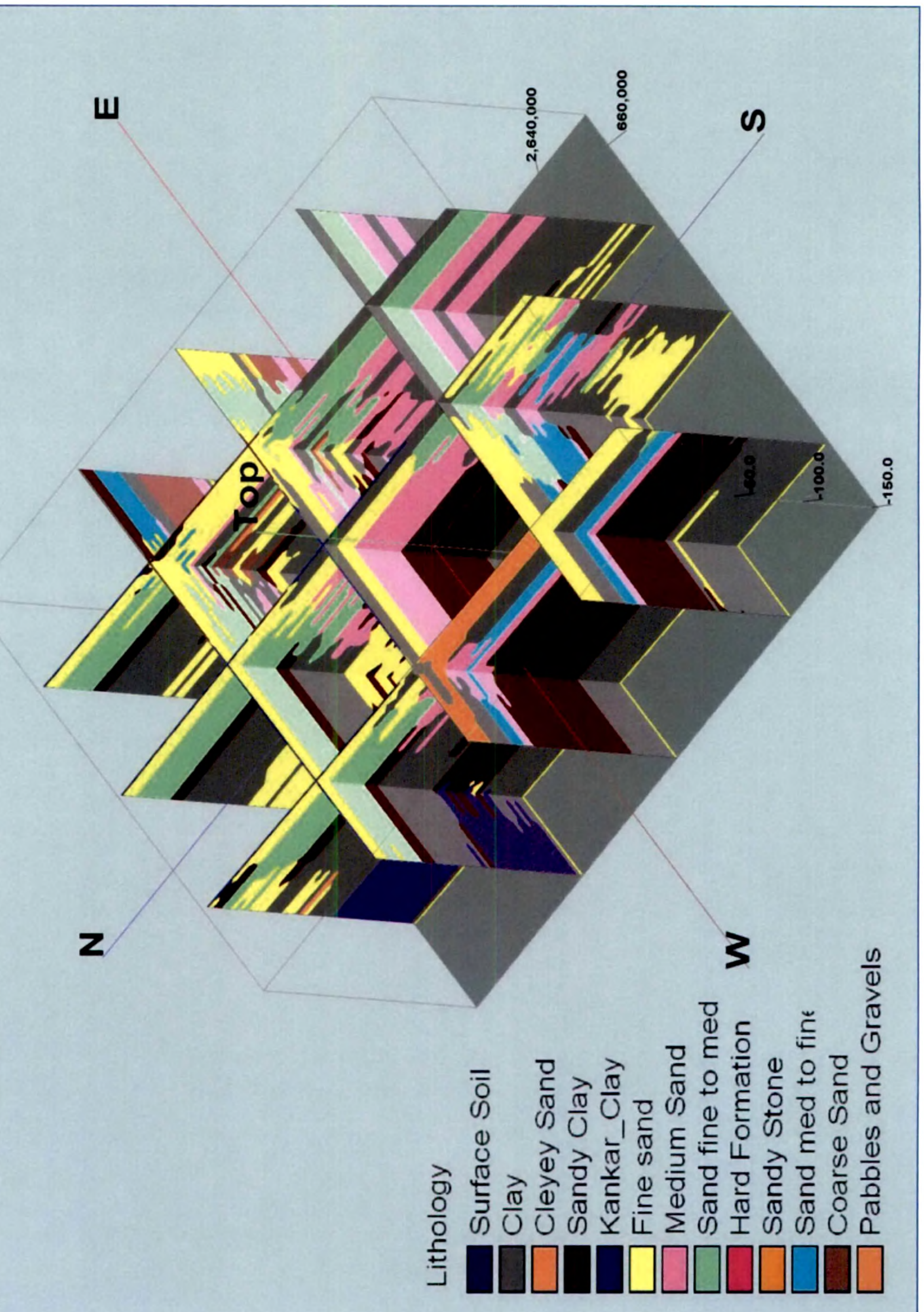


Fig. 5.5 Locations of the Bore Wells

Fig. 5.6 Subsurface Lithological Model



5.4.4 Soil (S):

Table: 5.5 Soil Vulnerability Index

Vulnerability Indices *(S)*	Area Covered (%)
10	80.87
12	19.13

Soil media is the next parameter that plays a crucial role in determining the contamination of groundwater. Soil is considered to be the first layer through which the surface water penetrates.

Permeability of water through the soil depends upon the texture of the soil. As the texture of the soil becomes finer, the distance between the soil particle decreases and void space between them reduces. This leads lesser water to infiltrate through the void space. On the other hand, as the texture becomes coarser, the rate of infiltration increases.

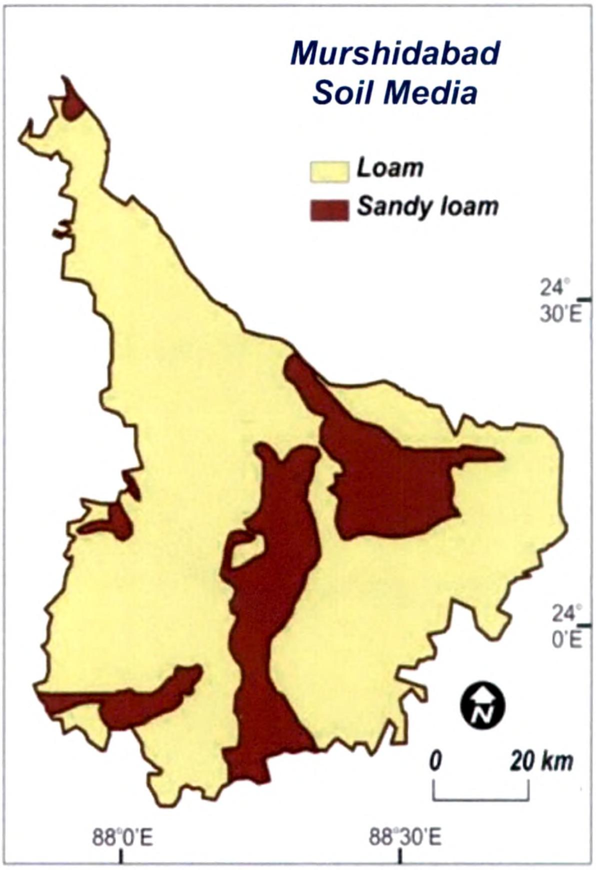


Fig. 5.7 Soil Media Layer (After NBBS &LUP Regional Centre, Kolkata).

The entire district is associated with loamy and coarse sandy type soil. According to the assigned rate and weight, the calculated value of the soil vulnerability index showed higher value (12) (Table 5.5) with 19.13% area in the central and north-eastern segment while the value was considerably lower (10) in the rest of the region and covered 80.87% of the total area (Fig. 5.7).

5.4.5 Topography (T):

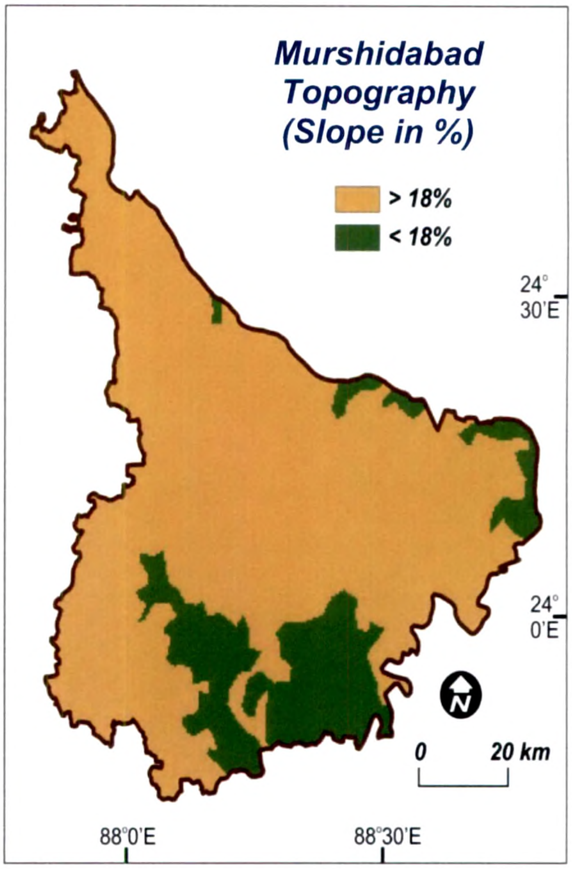


Fig. 5.8 Topography Layer

The parameter is important and is taken in to considerations although the relative weight of topography is least (1). The slope of the land determines the water to retain at a specific position for particular time. As the slope of the land increases, water tends to move at greater speed with less infiltration rate. On the other hand, as the slope of the land decreases the corresponding potential of water to move from one place to another place also decreases. This leads to greater chance of surface run off to remain in a particular position for longer time and gets more time for infiltration. Thus, there is an inverse relationship between the slope of the land and the infiltration rate of surface run off.

The entire region is associated with flat topography or plain area. The western part of the district is the extension of *sub -vindhyan* region having the slope of > 18%. On the other hand, the eastern part of the region is associated with flat topography with numerous marshy lands. To depict the elevation of the region 1:50,000 toposheet map and the 30 m SRTM data was combined with each other. It was found that the western part of the district has relatively higher elevation while the rest of the part has a flat topography (Fig. 5.8).

As the elevation of the region increases the relative weight also increases and vice versa. The entire region has a slope of > 18% and corresponding vulnerability index of 1, while the southern portion and some parts of north has a slope of < 18% with corresponding index of 1 (Table 5.6). 83.70% of the area had lower vulnerability index of topography (1) while 16.29% had high vulnerability index (3).

Table: 5.6 Topography Vulnerability Index

Vulnerability Indices *(T)*	Area Covered (%)
1	83.70
3	16.29

5.4.6 Impact of Vadose Zone (I):

Vadose zone is the portion of the subsurface where the inter-granular space is unsaturated with water. The characteristics of the vadose zone is quite complex as it is associated with the surface as well as subsurface characteristics. The geo-chemical condition and transport of the contaminants through the vadose zone plays an important role and that is the reason of giving high (5) relative weight. The characteristics of impact of vadose zone is similar to the soil media. The vadose zone having coarser materials allow

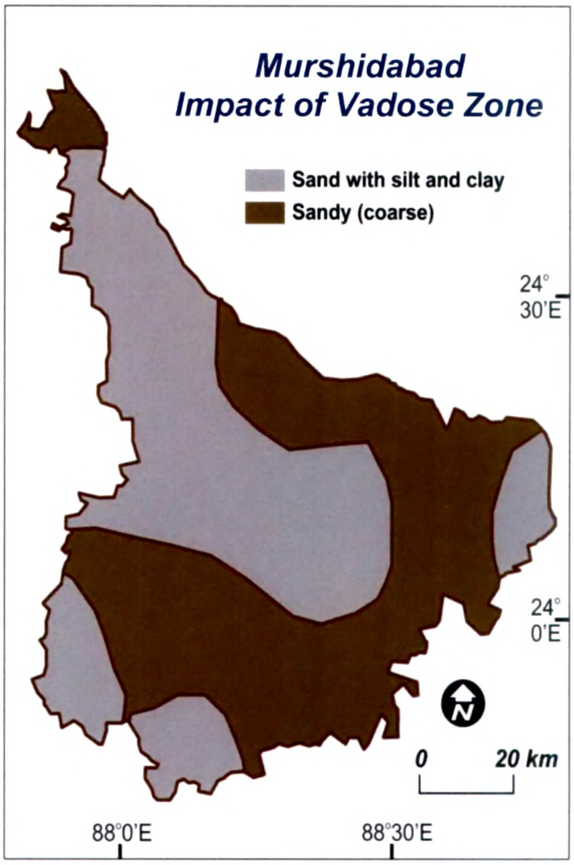


Fig. 5.9 Impact of Vadose Zone Layer

higher rate of infiltration and higher rate of movement of contaminants while lesser movement of water as well as contaminants is associated with finer material. The water table, topography and subsurface lithological data were put in a single frame and the zone between the surface and water table is considered as the vadose zone.

The condition of the vadose zone was analysed through the subsurface lithological model. The eastern part of the vadose zone largely composed of sandy coarser type of texture while western side is associated with sand with significant layers of silt and clay. As the texture of the material increases, the vulnerability index also increases and vice versa.

Table: 5.7 Impact of Vadose Zone Vulnerability Index

Vulnerability Indices *(I)*	Area Covered (%)
30	50.02
40	49.97

In this case, the eastern side of the district has higher index value (40) covering 49.97% of the area (Table 5.7) of the entire district. The western part has relatively lesser value (30) covering 50.02% area (Fig. 5.9).

5.4.7 Hydraulic Conductivity (C):

Hydraulic conductivity is the capacity of the aquifer to transmit water from one place to another place. This parameter is given higher weight of 3, which indicates its relative significance. This parameter is associated with the rate of water flow and the movement of contaminants. There is a direct relationship between hydraulic conductivity and movement of

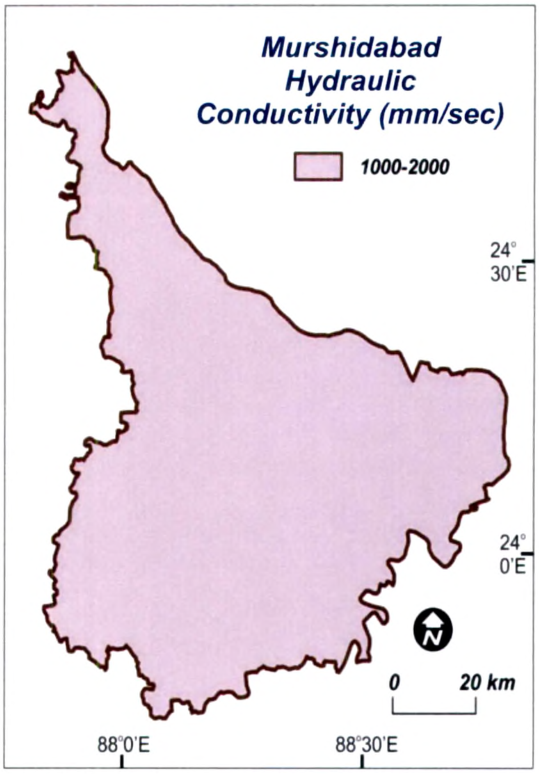


Fig. 5.10 Hydraulic Conductivity Layer

contaminants.

The vulnerability index of hydraulic conductivity was prepared by using transitivity data. The relative weight and rate was used to calculate the corresponding vulnerability index of the particular parameter. The results obtained from the analysis showed that the entire *Murshidabad* district has 24 vulnerability index of hydraulic conductivity (Fig. 5.10).

5.4.8 Composite Vulnerability Index: (DRASTIC)

All the seven layers (depth, recharge, aquifer media, soil media, topography, impact of vadose zone, hydraulic conductivity) were merged and the final composite vulnerability index was attained. The results show that, the vulnerability index is associated with five classes (< 151, 151-160, 160-170, 171-180 and > 180). A continuous patch was observed which stretched from the north central portion to the eastern segment with highest composite vulnerability index of > 180. In the southern part of the district a similar kind of vulnerability zone of highest index was observed in smaller patches. The next class of the vulnerability index ranged between 171 to 180. This **'Zone of Vulnerability'** stretched in the southern as well as in the eastern portion of the district. Some smaller patches of vulnerable zone 2 were observed in the northern peripheral zones in a discontinuous manner and also observed in patch in western part of the district. The third vulnerability zone covered the entire district in the form of discontinuous patches which ranged from 161 to 170 (Table 5.8). Small patches were noticed in the eastern most, central and southwestern part while major patches were observed in the western and north western part. Fourth zone of vulnerability was found in the western, central and south western part of Murshidabad district with a

Table: 5.8 Composite Vulnerability Index

Vulnerability Indices	Vulnerability Category	Area Covered (%)
< 150	Highest	14.13
151-160	High	30.91
161-170	Moderate	25.31
171-180	Low	10.24
> 180	Least	19.41

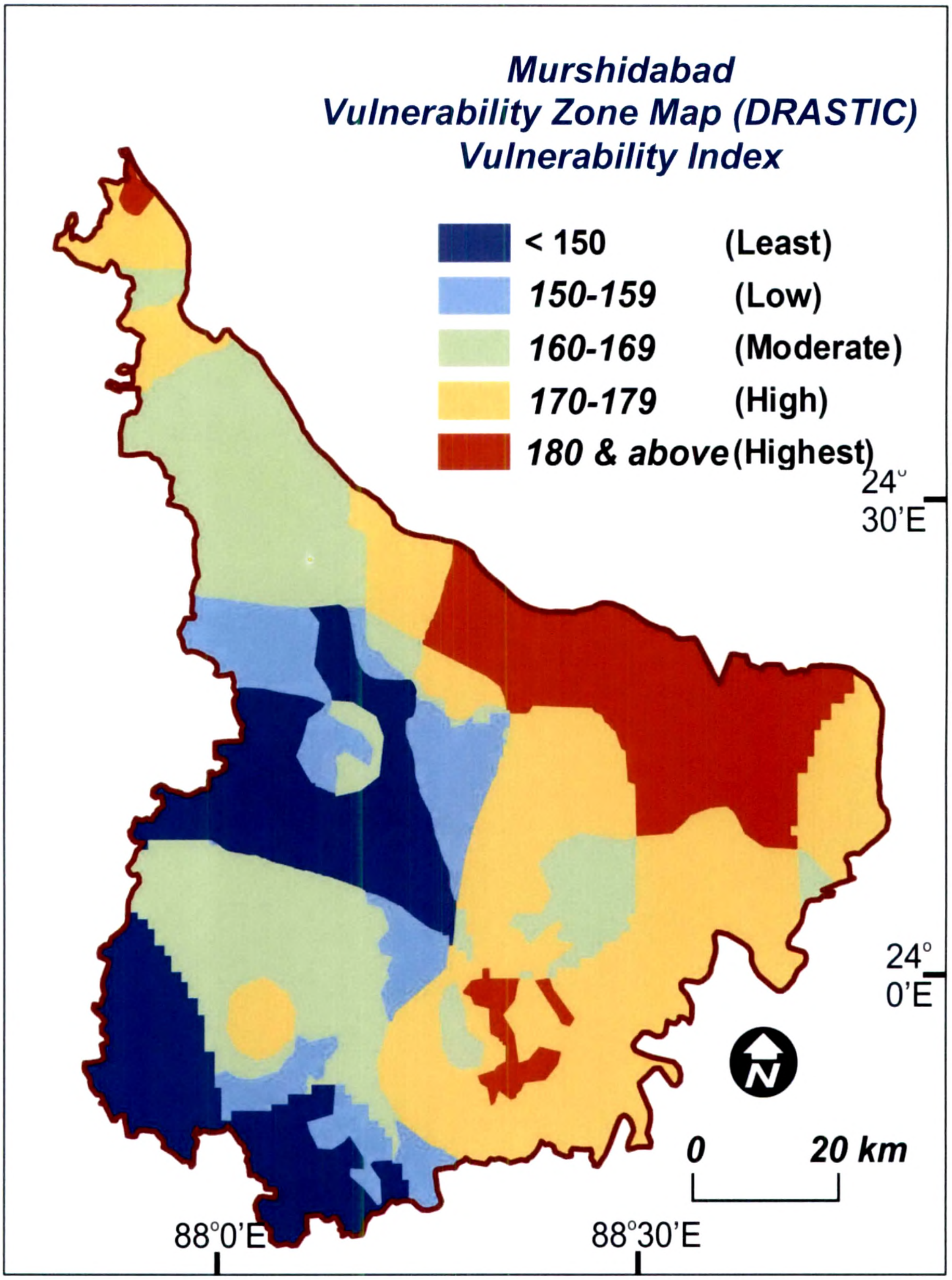


Fig. 5.11 Composite Vulnerability Zone Map

range of 151 to 160 in smaller patches (Fig.5.11). The fifth class of vulnerability was observed in the central and north western part of the study area (< 150).

A portion of the least vulnerability was also found in the western and south western part of the district. In terms of area, 14.13% of the total area was very highly vulnerable. 30.91% of area was under the second category. The third and fourth classes depicted relative percentage of area of 25.31% and 10.24%. The last class illustrated least vulnerable area with 19.41% area.

5.5 Single Map Removal Variation Index:

Composite vulnerability map represents the input of all seven hydrological factors. To understand the contribution of each of the factor, in terms of composite DRASTIC model, sensitivity of each factor is to be examined. Removal of one or more layer from the composite DRASTIC model is one of the ways to analyse the input of different layers. **Napolitano** and **Fabbri** (1996) proposed the following expression for calculation of variation analysis-

$$V_{arix} = \frac{V_i - V_{xi}}{V_i} X\,100 \qquad (2)$$

Where

V_{arix} = Variation Index,

V_i= Vulnerability Index using eq. (1) on the sub-area,

V_{xi}=Vulnerability Index of the sub-area excluding one map layer.

The results obtained from the variation index (eq.2) indicated that among the seven layers of hydrological factors, *Depth* is the major factor with 24.69% impact on the DRASTIC model after its removal. The next factor, i.e. *vadose zone* is related to 22.24% variation index. Thus, it can be analysed from the variation index that, removal of these two parameters *(depth* and *impact of vadose zone)* contributed 46.93% variation to the composite DRASTIC model.

Other than these two factors, the remaining factors like recharge, conductivity, aquifer media and soil layer removal was associated with the variation indices of 18.27%, 14.59%, 13.66% and 5.3% respectively. Among these seven layers, topography had the least variation index of 1.25% (Table 5.9).

Table. 5.9 Layer Removal Result

Layers Used	Layers Removed	Variation Index	Cumulative Variation Index
DRASTI	*C*	14.59	14.59
DRASTC	*I*	**22.24**	36.84
DRASIC	*T*	1.25	38.08
DRATIC	*S*	5.3	43.38
DRSTIC	*A*	13.66	57.04
DASTIC	*R*	18.27	75.31
RASTIC	***D***	**24.69**	100

5.6 Overlay of Sampling Locations on DRASTIC Model:

To establish the relationship between the groundwater vulnerability and location of the sampling wells, both the layers (DRASTIC and sampling locations of the wells) were overlaid. It was found that 12.82% of the total sampling wells were located in the vulnerable zone with highest index (> 180). 39.74% of the total sampling locations were found in the next category

Table: 5.10 Category wise % of Wells

Vulnerability Indices	Vulnerability Category	% of wells located
> 180	Highest	12.82
171-180	High	39.74
161-170	Moderate	26.28
151-160	Low	10.27
< 150	Least	10.89

of vulnerability index (171-180). Third vulnerability zone was associated with 26.28% of the wells. In the last two categories (151-160 and < 151) the percentages of wells were 10.27% and 10.89% respectively (Table 5.10) (Fig. 5.12).

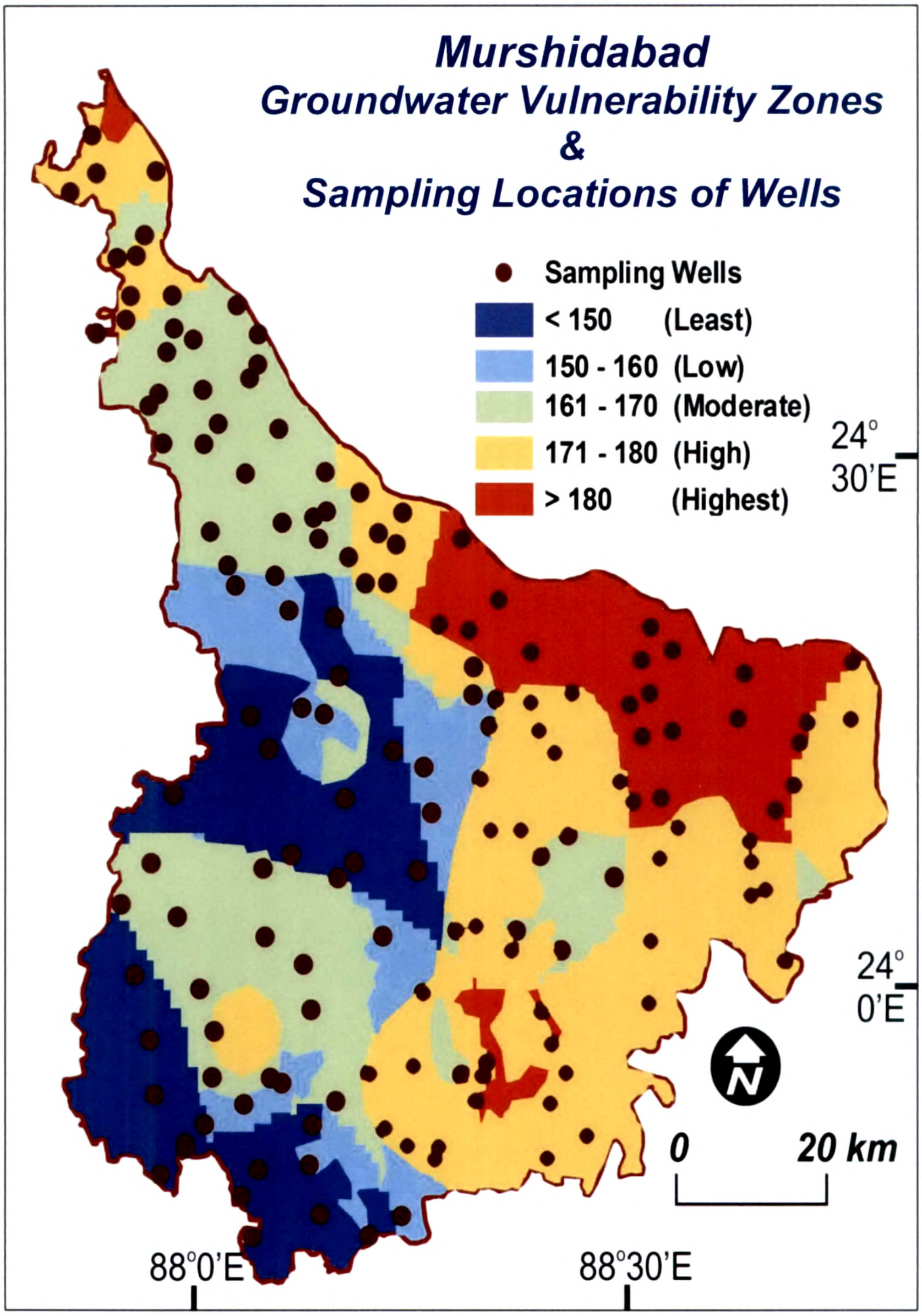


Fig. 5.12 Overlay of Vulnerability Map and Sampling Locations

5.7 Overlay of Arsenic Concentration on DRASTIC model:

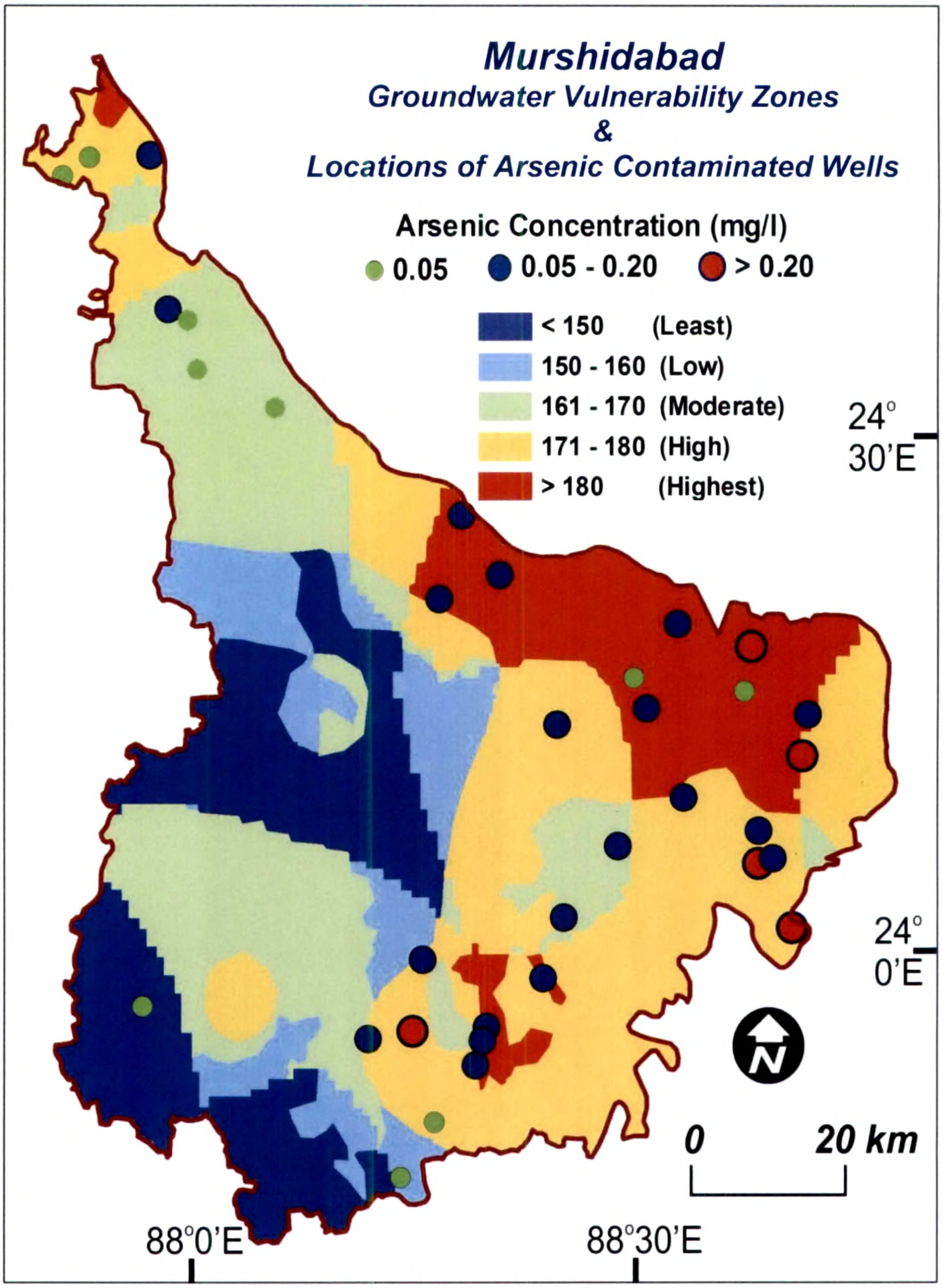


Fig. 5.13 Overlay of Vulnerability Map and Sampling Locations with Average Arsenic Concentration > 0.05 mg/l

The sampling locations of the wells were plotted over the composite DRASTIC model. The average arsenic concentration was taken into considerations.

The wells which showed concentration above 0.05 mg/l throughout the time were taken into consideration. 22.43% wells (out of total surveyed wells) had average arsenic concentration above 0.05 mg/l. 31.43% of the affected wells were located in the highest vulnerability index regions. The subsequent class of vulnerability (171-180) recorded 48.58% sampling locations (Table 5.11) (Fig. 5.13). Together, the two categories covered 83.99% of the total affected wells with arsenic concentration > 0.05 mg/l. Rest of the three classes recorded 14.29%, 2.85% and 2.85% respectively.

Table: 5.11 Category wise % of Arsenic Affected Wells

Vulnerability Indices	Vulnerability Category	% of wells located
> 180	Highest	31.43
171-180	High	48.58
161-170	Moderate	14.29
151-160	Low	2.85
< 150	Least	2.85

5.8 Discussion:

In order to understand vulnerability of groundwater in the *Murshidabad* district, it is necessary to understand the contribution of parameters used in the analysis.

The condition of the aquifer plays an important role in terms of depth (Bhattacharya 1997). The aquifers associated with confining layers of clay (confined aquifer) can slower down the process of permeability of the water, which may lead to delay in travelling of contaminants to reach and mix with groundwater. On the other hand, the aquifers that do not have significant confining or intervening layers (unconfined aquifer) can easily transfer the contaminants within a short time (**Fritch** 2000). Thus, the confined aquifer has a natural advantage over the unconfined aquifer. Thick unconfined aquifer is found in the eastern part of the study area while in the western portion the aquifer condition is semi-confined. As no confining layer is present, the unconfined aquifer allows large amount of infiltration of water while the western part of the district has several discontinuous confining layers. Depth to the water is an important factor as the water moves from surface to subsurface and is subjected to higher or lower rate of movement due to absence or presence of the confining layers (**Rahman** 2008). As compared to the western part the eastern segment is more prone to vulnerability. Vulnerability index of the depth factor is ranged between 35-50. The index 50 indicated a very high vulnerability as it is associated with very shallow depth of groundwater. The vulnerability map also depicted similar condition with higher values located in the eastern side and lower values being confined in the western part of the district. The Map Removal Variation Sensitivity Analysis (MRVSA) depicted that due to removal of the layer of Depth from the model, the variation index was 24.69%, indicating the fact that due to removal of this layer there was 24.69% variation in the entire model. Thus, the Depth factor in the present model plays a significant role.

The rate of recharge is also an important parameter, as it determines the movement of the contaminants through the aquifers (**Samake** 2010). In this respect, the characteristics of the aquifer plays a significant role as it controls the rate of recharge. In the entire study area, the recharge is very high (vulnerability index of 32) and is mainly recharged by the rainfall during the monsoon season and also from the numerous tributaries and sub tributaries of the river *Ganga*. The rate of recharge is found to be constant in the entire region. Thus, in continuation with the previous parameters of depth the addition of recharge data indicates higher vulnerability in the eastern part rather than in the western part of the district. The single map removal variation sensitivity had 18.27% variation. Thus, the particular factor contributed 18.27% in the entire vulnerability model. The layer of depth and recharge collectively contributed a significant percentage of 42.94% in the entire vulnerability model.

Aquifer media is the parameter which to a great extent controls the overall groundwater processes (**Chandrashekhar** 1999). The eastern segment of the study area depicted vulnerability index of 24 which indicates the presence of medium to coarser sand while the western part has vulnerability index of 15 indicating the presence of relatively finer sand particles. As the particles get finer, the permeability of water to the aquifer lowers and vice versa (**Anwar** 2003). Thus, the western portion which is composed of relatively finer sand has lesser vulnerability than the western segment. The central and north eastern part showed two patches of moderate vulnerability while the western part depicted least vulnerability. The variation index of aquifer media was 13.66% that indicated a relatively lower percentage of contribution than the former two factors.

The influence of topography is not very much reflected in the result as the entire region is plain, but some smaller patches of low lying area (< 18% slope) were observed in the southern part of the district. The variation index of topography depicted the least percentage (1.25%) and it can be said that the removal of this layer from the model would create least variation.

Composite vulnerability index was classified into five categories viz. highest, high, moderate, low and least. In terms of total area, the highest vulnerable zone has an area of 752.20 sq. km which is 14.13% to the total area, the second zone of vulnerability depicted 1646.45 sq. area (30.93%). The following three categories had relatively lower area of 1367.68 sq. km, 1272.47 sq. km and 285.20 sq. km (25.69%, 23.90% and 5.36% area to the total area respectively). A considerable amount of area in the district is under the condition of high vulnerability, largely located in the eastern side of River *Bhagirathi.* On the other hand, the western part of the river had vulnerability index much lower than the former. A few smaller patches of less vulnerability can be observed in the peripheral region of the district.

The generated model reveals that the two major parameters which are responsible for the present groundwater condition are the depth to the water and impact of vadose zone.

The groundwater vulnerability zone map and results obtained from the analysis of geochemical parameters were overlaid on each other and the percentage of sample hand pumps located in the vulnerable regions were depicted. From the results of the chapter-3 it was found that different geochemical parameters had a probable surface subsurface relationship. Thus, it is essential to classify the surveyed wells according to the categories of vulnerability. Among 156 sampling wells 52.56% of the wells were found in the first two categories of vulnerability zones. Most of these wells were located in the eastern side of the river *Bhagirathi*. Rests 47.44% of the well were found in the remaining three categories.

The *arsenic* concentration in wells were averaged for three years and from three different seasons. 22.43% of the wells had *arsenic* concentration above permissible limit of 0.05 mg/l throughout the time period (2010-2012). The wells associated with higher *arsenic* concentration (> 0.05 mg/l) were largely concentrated in first three categories of the vulnerability. 93.30% to the total sampling wells were located in '***Dual-risk Zones***'. On one hand, they are located in the highest vulnerability zone as suggested by the DRASTIC model and on the other; they also lie in the region of higher arsenic concentration in groundwater.

It is important to note that the blocks of *Bhagawangola-1*, *Bhagawangola-2*, *Raninagar-1*, *Raninagar-2*, parts of *Domkal* and *Jalangi* were highly vulnerable while, the blocks of *Raghunathgunaj-1*, *Sagardighi*, *Nabagram*, *Khargram*, parts of *Kandi* and *Behramapur* depicted moderate to low vulnerability condition.

Resume: The present chapter groundwater vulnerability model was created by using different groundwater hydrological factors. The result obtained from the model depicted different vulnerability zones. The highest risk zone was found in the east and north-eastern portion. The overlaying of the arsenic affected wells on the vulnerability map depicted the wells that are in located in the 'Dual Risk Zone'. The following final chapter summurises the finding of all the chapters and future aspect of the present study.