GIS Integration of Remote Sensing and Electrical Sounding Data for Hydrogeological Exploration

Shamsuddin Shahid[1] and Sankar Kumar Nath[2]

[1]Assistant Professor
Department of Applied Physics & Electronics
Rajshahi University, Rajshahi-6205, Bangladesh
e-mail: sshahid@agni.com

[2]Associate Professor
Department of Geology & Geophysics
Indian Institute of Technology, Kharagpur-721 302, India
e-mail: nath@gg.iitkgp.ernet.in

Abstract

Interpretation of hydrogeological data frequently involves assimilating information from many sites each with a unique geographical location. Interpretation of these data requires that the spatial location be incorporated into the analysis. Geographic Information System (GIS) can be used efficiently for this purpose where hydrogeological data having different spatial identity can be analyzed objectively using different logical approaches. In the present paper GIS is used for the analysis of hydrogeological data acquired from remote sensing and surface geophysical techniques for the assessment of groundwater condition of a soft rock terrain in Midnapur District, West Bengal, India. Indian Remote Sensing (IRS-1B) LISS-II data is used for the generation of thematic map of geology. Geophysical survey is conducted using Vertical electrical sounding (VES) at 139 locations in the study area. The data is interpreted using evolutionary programming technique based on global optimization. Aquifer resistivity and thickness interpreted from VES data is used to generate the corresponding thematic maps. Weights are assigned to different ranges of resistivity and thickness values based on their position on geological map. Finally the weighted maps are integrated using a GIS based aggregation method to model the hydrogeological condition of the area.

Keywords: Groundwater, GIS, Remote Sensing, VES.

Introduction

Better interpretation of hydrogeological data often requires that their spatial location be incorporated into the analysis. Geographic information system can be used for storing hydrogeological data as well as their spatial locations in a relational database. It also provides the facility to analyze the spatial data objectively using various logical conditions. As a result, nowadays, GIS is widely used for spatial modeling of hydrogeological prospect of a large area with more reliability. Examples from recent literature spotlight several uses of GIS as applied to ground water exploration.

Gustafsson (1993) used a GIS for the analysis of lineament data derived from SPOT imagery for ground water potential mapping. Minor et al. (1994) developed an integrated interpretation strategy to characterize ground water resources for identification of well locations in Ghana using a GIS as the unifying element. For the assessment of ground water resources of Northwest Florida Water Management District, Richards et al. (1996) took the advantage of GIS for spatial analysis and data visualization. Krishnamurthy et al. (1996) developed a GIS based model for delineating ground water potential zones of Marudaiyar basin, Tamil Nadu, India by integrating different thematic layers derived from remote sensing data. The field verification of this model established the efficacy of the GIS in demarcating the potential ground water reserve. Application of GIS for ground water resource assessment has also been reported by Sander (1997), Teeuw (1999) and others.

In the present paper GIS is used for spatial modeling of hydrogeological condition of a soft rock terrain in Midnapur District, West Bengal, India through the integration of geological and geophysical thematic maps prepared from remote sensing data and vertical electrical sounding (VES) results respectively. Indian Remote Sensing (IRS-1B) LISS-II data is used for the generation of thematic map of geology. For the preparation of geophysical thematic maps vertical electrical sounding is conducted at 139 sites in the study area. The VES data are interpreted by using Evolutionary Programming (EP) technique based on global optimization (Shahid et al., 1999). The spatial location of VES point and corresponding aquifer parameters viz. aquifer resistivity and its thickness obtained from VES interpretation are stored in a GIS. The parameters are then contoured to prepared the corresponding thematic map. As the resistivity of the aquifer material depends on the geology of area, different features or resistivity range values of the aquifer resistivity thematic map are scored according their prospect in predicting groundwater condition by overlaying it on geology map of the area. One the other hand, the features in the thematic map of aquifer thickness are scored according the thickness values. The two thematic maps are then integrated to generate the spatial model of hydrogeological prospect of the study area.

Description of the study area

Situated at a distance of 115 km away from Calcutta, the capital of West Bengal, the area in Midnapur District lies between 22°16′ and 22°27′ of North latitudes, and 87°15′ and 87°21′ of East longitude (Figure 1). The area comprises several villages and two towns, Midnapur and Kharagpur. Climatologically, the area falls in the Gangetic West Bengal region with an average annual rainfall of 152.2 cm and average temperature of 31° C. An oppressive and hot summer, high relative humidity and well-distributed rainfall during the monsoon are some of the characteristics of its climate. The topography of this part of Midnapur District is very gentle. The average elevation above the mean sea level is about 48 meters. The upland areas are thickly vegetated with Sal (*Soria Robusta*) forest, whereas the low land areas are moderately cultivated. The area is mainly drained by the river Kasai and its tributaries (Shahid et al., 2000).
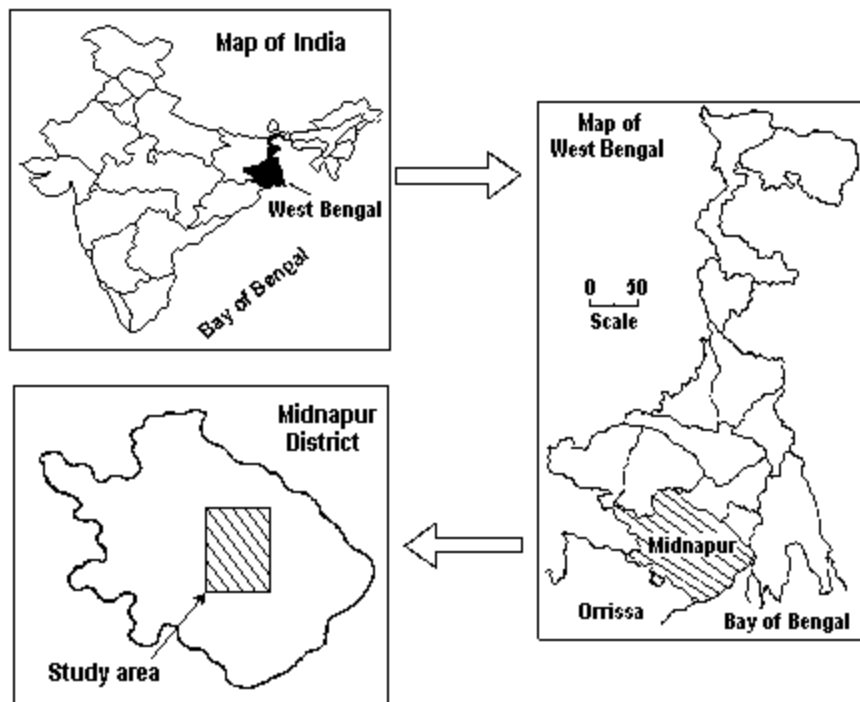

Figure 1: Location map of the study area in Midnapur district, West Bengal, India

Adequate water supply, particularly during summer, has always been a problem in the area. The problem is becoming progressively more acute with the growth of population and industry. It has been projected that the total water demand for the year 2011 comes to 27 MLD considering per capita demands as 135 liter/day for Kharagpur municipality area only. At present, only a part of the municipal areas are provided with piped water supply through the wells at riverbed. But it is far from requirements. Adjacent rural areas mostly inhabited by tribal face severe crisis of water throughout the year. If rainfall is low in a year the drought situation endangers the area. Therefore, in view of necessary augmentation of the present water supply a 226-km^2 area in and around Kharagpur and Midnapur towns is chosen for the proposed study.

Methodology

Geophysical data greatly help in locating the ground water potential in any hydrogeological setup. The property and thickness of various litho-units obtained from geophysical survey at different location if integrated can yield a ground water potential model of higher reliability and precision. Venkateswara Rao and Briz-Kishore (1991) proposed a method for the interpretation of geophysical data and estimation of ground water potential index (GWPI) at various survey locations. Edet and Okereke (1997) used a similar approach for Oban massif, Nigeria and calculated the ground water potential. In both the cases they used VES data for the estimation of layer parameters, namely, aquifer resistivity and thickness at different points. They assigned weights to different layer parameters and ratings to the features of the parameters according to the performance of the existing water wells in the vicinity and estimated the GWPI of the survey points. As the GWPI obtained in this process is derived from the physical properties of the subsurface layers, they showed that it gives an accurate measurement of ground water potential. In this investigation, for the estimation of hydrogeological condition, data obtained from VES surveys are interpreted for the estimation of the subsurface parameters viz. electrical resistivity of the aquifer and aquifer thickness. These parameters at different survey points are contoured using Krigging method (deMarsily 1986) and the corresponding thematic maps are prepared. The resistivity and thickness of aquifer media are directly related to transmissivity and hydraulic conductivity of the aquifer. Therefore, integration of these two data can give the groundwater potential of an area. However, different types of lithology with different resistivity ranges have different groundwater prospect. Therefore, different range of values or features should have a different score in a scale according to its importance in accumulating groundwater. An overlay operation would then evaluate the intersected regions by a sum of the scores, so that each resulting region is characterized by a score measuring its potential. Based on this method groundwater condition of the study area is estimated. In the present study, feature of an individual geophysical theme has been scored in the 1-10 scale in the ascending order of hydrogeologic significance. The raw score for each feature is then normalized using the following relation to ensure that no layer exerts an influence over the other,

$$x_j = \frac{R_j - R_{min}}{R_{max} - R_{min}} \quad \text{------------------------------ [equation 1]}$$

where,

x_j is the normalized score

R_j is the raw score

R_{min} is the minimum score, and

R_{max} is the maximum score of a layer

The groundwater condition of the study area is then estimated as,

$$\text{Groundwater Prospect} = R_s + T_s \quad \text{-------------------------- [equation 2]}$$

where,

R_s represents score of aquifer resistivity, and

T_s represents score of aquifer thickness

The prospect of groundwater in an area is mainly depends on hydraulic conductivity and transmissivity. As the importance of hydraulic conductivity and transmissivity in groundwater exploration are more or less same, therefore, equal weight are assigned to aquifer resistivity and thickness. However, the resistivity range of any given rock type is wide and overlaps with other rock types. Therefore, different types of lithology may have same resistivity values. As for example, in the present area of investigation, gravel sand has more or less same resistivity as the morum sand. Whereas, groundwater prospect of gravel sand is very high and it is very poor for morum sand. Therefore, assigning score based solely on resistivity value may lead to misinterpretation of groundwater prospect. In the present study, the difficulty is overcome by assigning scores to different resistivity values by considering geology of the corresponding data point. This is done by overlaying the thematic map of aquifer resistivity on the thematic map of geology of the area, which is prepared from remote sensing data. The preparations of geological and different geophysical thematic maps are described below.

Geological mapping through remote sensing

It is well established that geology plays a vital role in the distribution and occurrence of ground water. Krishnamurthy and Srinivas (1995) and others carried out various geological studies in different terrains and proved that IRS-1A and IRS-1B data can be effectively used for geological mapping. In the present study, geological mapping is done using enhanced IRS-1B, LISS-II image. The image is first rectified by projecting it onto a plane by using UTM map projection method. A first order polynomial and Everest1830 spheroid are considered for the computation of transform matrix. The rectified image is then enhanced through linear stretching and principal component analysis by using image processing software ERDAS for better exposition of hydrogeological features. GIS is used for the mapping of features by activating a live-link facility between image processing software ERDAS and GIS package Arc/Info.

Three lithounits are identified on the satellite image: (i) *Laterite* by its bluish red tone with coarse texture, (ii) *Older Alluvium* by its reddish tone with fine texture, and (iii) *Newer Alluvium* by their blue tone with coarse texture. The geological map of the area is shown in Figure 2. Water bearing characteristics of Laterites vary from place to place. The rock is composed of disconnected vesicles. Multi-dimensional fractures may serve as infiltration path for ground water replenishment, but not suitable for bulk supply of water. The older alluvium formation consists of an intercalation of sandy and clayey layers. Grain size varies from extremely coarse angular pebbles to fine sand and silt, which have a good ground water bearing capability. The newer alluvium formation, on the other hand, consists of a succession of clay and sand layers. Coarse sand bodies are somewhat extensive and can act as excellent aquifers.
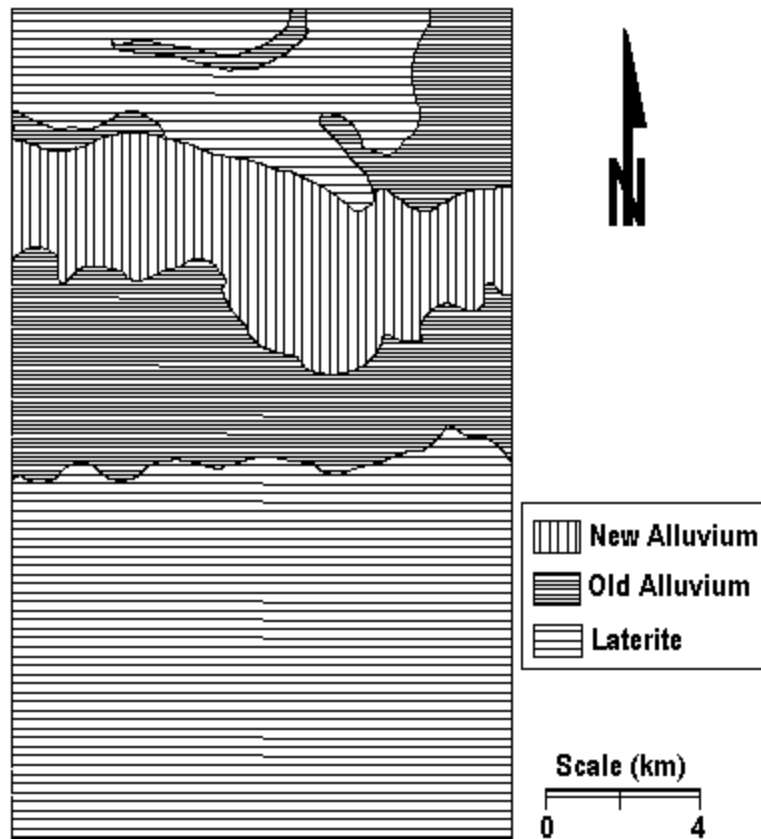
Figure 2: Geological map of the study area prepared from remote sensing data

Geophysical Survey through vertical electrical sounding

In the present investigation, a total of 139 VES data are collected using Schlumberger electrode configuration with an electrode spacing varying between 100 and 300 m. The sounding locations are shown in Figure 3. All the VES data are interpreted using evolutionary programming (EP) techniques based on global optimisation (Shahid et al., 1999).

In D.C. resistivity sounding we are concerned with the parameters like ρ_1, ρ_2, ..., ρ_n and h_1, h_2, ...,h_{n-1}. For each parameter we have a pair of bounds i.e., the upper and lower limits. EP involves a learning process to find the exact solution within the specified domains by using three main steps (Shahid et al., 1999): generation of population, computation of fitness and mutation. In the first step n real coded individuals in the population are generated randomly within the specified bounds. Fitness function of each newly generated individuals of the population is then calculated by using the concept of chi-square error. In the last step, an equal number of individuals are generated by perturbing each member of the population by step function mutation. The modified n models after a particular iteration are then mixed with those from the previous iteration. $2n$ models are arranged in the decreasing order of fitness value. The best n models are retained for the next iteration. The process is repeated until the population converges to a high fitness value.
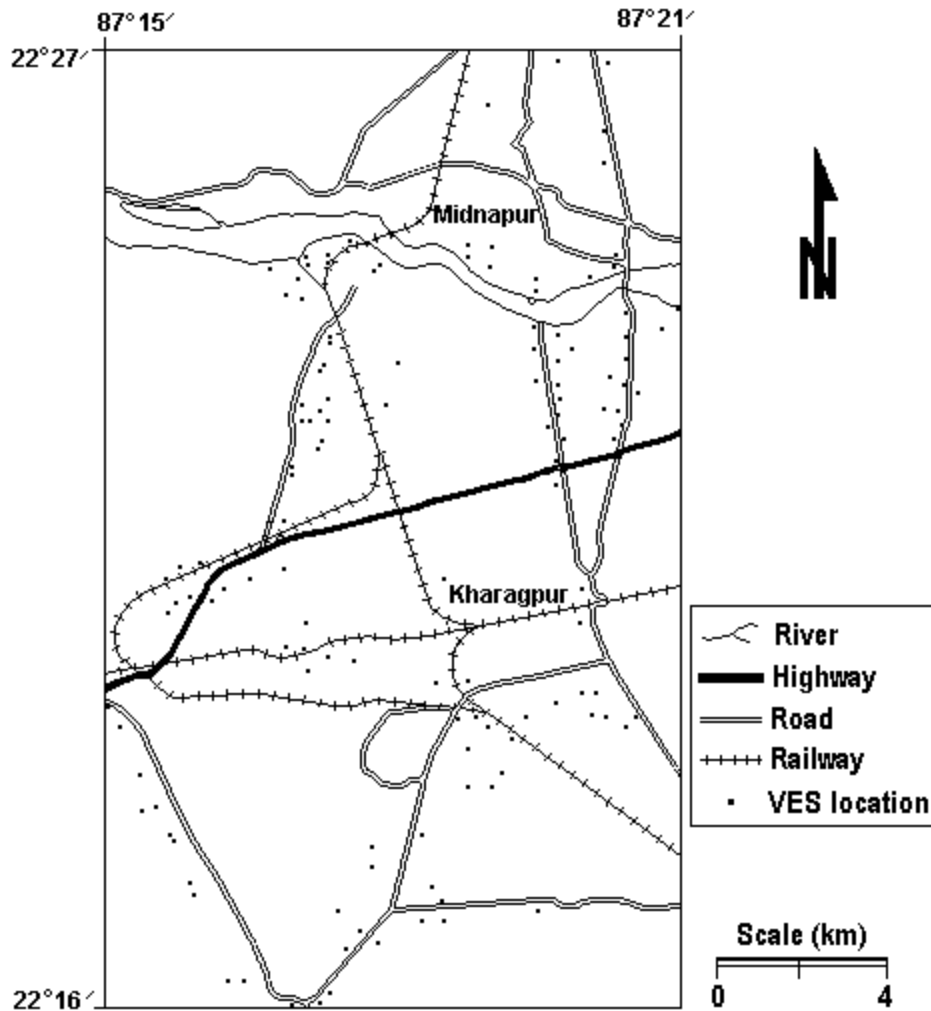
Figure 3: The locations of vertical electrical sounding points

The layer parameters derived from VES using EP at different points are used for the generation of geophysical thematic maps. Since Krigging (de Marsily 1986) provides an unbiased spatial estimation of a regionalized variable and, therefore, widely used for their mapping, in the present study we used it for contouring the aquifer layer parameters on a 500 m × 500 m grid. Semi-variograms are used to estimate the spatial correlation between different points relating to aquifer resistivity and its thickness. For better spatial correlation nearest eight points are clustered. The thematic maps of aquifer resistivity and its thickness are displayed in Figures 4(a) and (b) respectively.
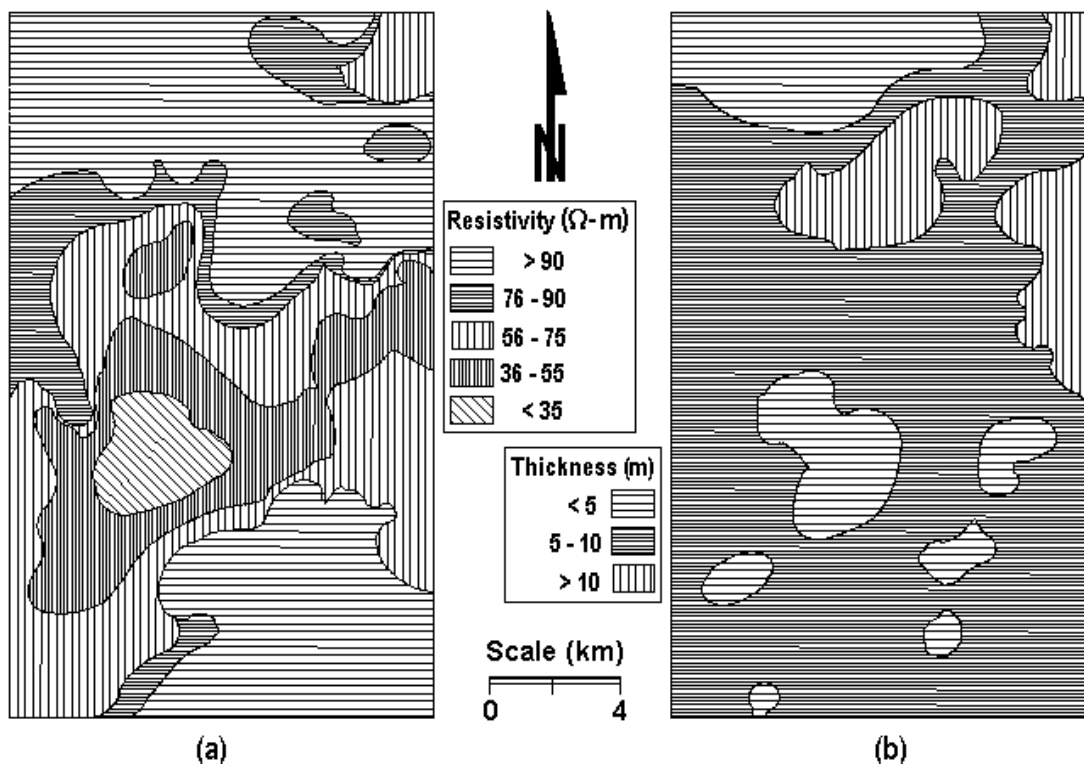
Figure 4: Thematic maps of (a) aquifer resistivity and (b) aquifer thickness

Assignment of ratings to different geophysical features

Ratings of individual features of each thematic map are assigned as follows.

Resistivity of water bearing formation: Resistivity of aquifer in the study area varies from 23.1 to 327 Ω m. The lithological variation from the nearby borehole logs in the survey area when superimposed on the resistivity-depth section, is found to fit into the following categories.

Alluvium :	Resistivity range
Clayey/silty sand	20 - 35 Ω m
Fine sand	35 - 55 Ω m
Fine to medium sand	55 - 75 Ω m
Medium sand	75 - 90 Ω m
Medium to coarse sand with gravel	> 90 Ω m
Laterite :	Resistivity range
Clayey/silty sand	20 - 40 Ω m,
Fine sand	40 - 70 Ω m,
Morum sand or morum gravel	70 - 200 Ω m,
Lateritic sand	> 200 Ω m

It is well known that hydraulic conductivity increases with the resistivity. Hence, a higher yield is expected from an aquifer with higher resistivity. A higher rating is, therefore, assigned to the maximum resistivity range and least to the lowest one. In the lateritic terrain, hard cap laterites, which do not hold any water register high resistivity values and the associated

lithomargic clay shows low resistivity. The positive correlation between the resistivity of the aquifer materials and the hydraulic conductivity cannot be applicable in this terrain. Roy and Niyogi (1961) also pointed out that the lateritic formation does not have significant ground water potential. Therefore, different scores are required to assign to the same resistivity ranges in the lateritic zone to that in the Alluvium zone. This is done by overlaying the thematic map of aquifer resistivity over the thematic map of geology, which is shown pictorially in Figure 5. According to Patra et al. (1972) only the find sand formation in the lateritic zone with a resistivity range between 40 and 70 Ω m has a little prospect of groundwater. Therefore, a raw score of 2 is assigned to this formation. Lowest scores are assigned to all other formations in the lateritic zone as they have not any capability to store groundwater. Assigned scores to different resistivity ranges and their normalized values are given in Table1.
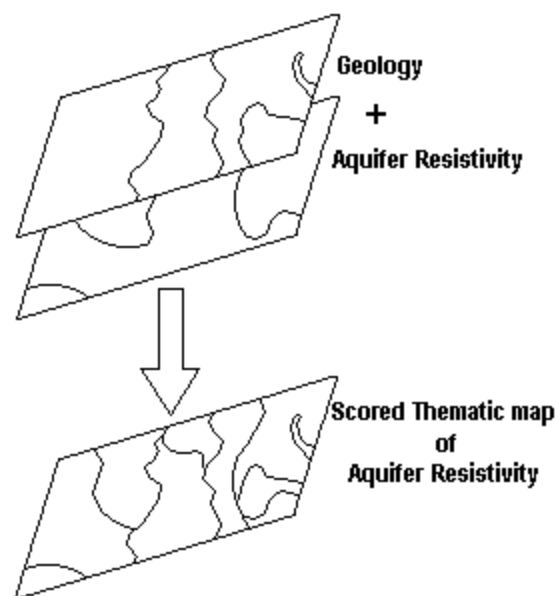

Figure 5: Integration of the thematic maps of geology and aquifer resistivity

Thickness of aquifer: The thickness of the aquifer in the area is found to vary between 3.1 and 17.1 m. It is well known that transmissivity increases with the thickness of the aquifer. In the present area, the transmissivity is higher for an aquifer of thickness more than 10 m, moderately high when the thickness is between 5 and 10 m, and poor when it is below 5 m. Accordingly, raw scores are assigned and normalized as tabulated in Table 1.

Integration and Modelling

The two thematic maps are registered with one another through ground control points and integrated using the aggregation method in GIS. The fourteen polygons of aquifer resistivity are integrated with eleven polygons of aquifer thickness resulting in a layer of 55 polygons. The new score for each polygon of this layer is calculated using equation (2). Finally, the polygons are classified according to their score and the ground water potential map of the

area is prepared as shown in Figure 6. The figure ascertains that various regions have different ground water potential. The area having a score above 0.75 has a high aquifer transmissivity represents good zone for groundwater exploration. The area with a score between 0.5 and 0.75 represents moderate zone of groundwater potential and the area with a score below 0.5 represents poor zone for groundwater. The characteristics of different zones are given is Table 2. The resultant model is verified with pumping test data available in six test sites in the study area. A high transmissivity and storativity values are observed in the area where GWPI is greater than 0.75, and moderate transmissivity and storativity values in the zone where GWPI is between 0.5 and 0.75.

Table 1: Score assigned to different features of geophysical thematic maps

Parameter		Attribute	Raw score	Normalized score
Resistivity of Aquifer	Alluvium	> 35 Ω m	1	0.00
		36 - 55 Ω m	2	0.25
		56 - 75 Ω m	3	0.50
		76 - 90 Ω m	4	0.75
		> 90 Ω m	5	1.00
	Laterite	20 - 40 Ω m	1	0.00
		40 - 70 Ω m	2	0.25
		70 - 200 Ω m	1	0.00
		> 200 Ω m	1	0.00
Thickness of Aquifer		< 5m	1	0.00
		5m - 10m	2	0.50
		> 10m	3	1.00

Table 2: Groundwater prospect of various regions in study area

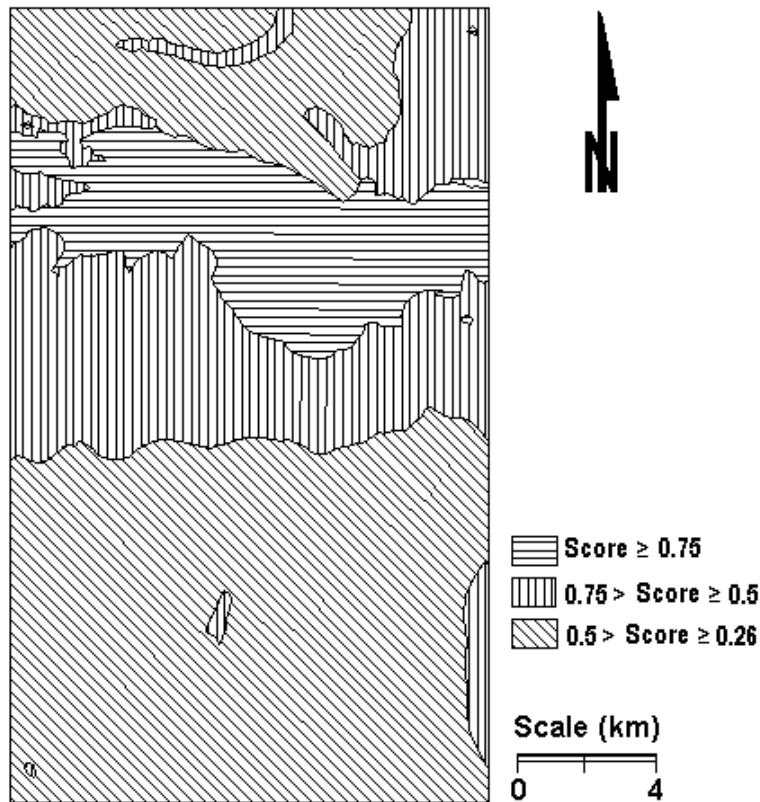| Zone	Score	Aquifer Resistivity (ohm-m)	Aquifer Thickness (m)	Average transmissivity and hydraulic Conductivity	Groundwater condition
I	0.75-1.0	75 - 150	> 10	High	Good
II	0.5-0.75	55 – 75	5 – 10	Moderate	Moderate
III	< 0.5	35 – 55 or > 150	< 5	Poor	Poor

Figure 6: The ground water potential model of the study area

Conclusion

Integration of geophysical data using GIS is carried out for hydrogeological study over an area of 226-km^2 in Midnapur District, West Bengal, India. The geological study using remote sensing data shows that the area is covered mainly by three types of lithology viz. Laterite, Older Alluvium and Newer Alluvium. Laterites are found to be the predominating unit all over the area. Geophysical survey using VES points to promising shallow ground water resources in the area. Integration of the geophysical thematic maps using a GIS revealed that 18.1% of the area has a score more than 0.75 representing highly prospective, 39% between 0.5 and 0.75 presenting moderately prospective, and the rest below 0.5 meaning poor for groundwater. The model is verified with available pumping test data and found to be in good agreement.

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