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Delineation of Groundwater Prospect Zones Using Remote Sensing and GIS Techniques: A Case Study

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ABSTRACT: A systematic planning of groundwater development using modern techniques is essential for the proper utilization and management of this precious but shrinking natural resource. With the advent of powerful and high-speed personal computers, efficient techniques for water management have evolved, of which RS, GIS and GPS are of great significance. West Medinipur district in West Bengal, India is suffering from water shortages for both irrigation and domestic purposes. In the present study, an attempt has been made to delineate and classify possible groundwater prospect zones in the West Medinipur district of West Bengal using integrated Remote Sensing (RS) and GIS techniques. The thematic layers considered in this study are lithology, landform, drainage density, recharge, soil, slope and surface water body, which were prepared using the IRS-1D imagery and conventional data. All these themes and their individual features were then assigned weights according to their relative importance in groundwater occurrence and the corresponding normalized weights were obtained using Saaty's analytical hierarchy process. The thematic layers were finally integrated using ArcView software to yield groundwater prospect map of the study area. Thus, three different groundwater prospect zones viz., 'good', 'moderate' and 'poor' were identified. The area covered by 'good' groundwater potential zone is about 1400 km^2 (15% of the total area). The eastern portion and some small patches in the central and northern portions of the study area fall under 'moderate' groundwater potential zone, which encompasses an area of 5400 km^2 (55%). However, the groundwater potential in the western, southwestern and parts of northeastern portions of the study area is 'poor' encompassing an area of about 3000 km^2. Moreover, the average annually exploitable groundwater reserve in the 'good zone' is estimated to be 401 MCM, whereas it is 1334 MCM for the 'moderate' zone and 397 MCM for the 'poor' zone. Finally, it is concluded that the RS and GIS techniques are very efficient and useful for the identification of groundwater prospect zones.

Keywords: Groundwater Prospect Zoning, Remote Sensing, GIS, Analytical Hierarchy Process.

INTRODUCTION

Groundwater is one of the most valuable natural resources, which supports human health, economic development and ecological diversity. Because of its several inherent qualities, it has become an immensely important and dependable source of water supplies in all climatic regions including both urban and rural areas of developed and developing countries (Todd and Mays, 2005). Particularly, groundwater is emerging as a formidable poverty-alleviation tool, which can be delivered directly to poor community far more cheaply, quickly and easily than canal water (IWMI, 2001). However, the indiscriminate use of this vital natural resource is creating groundwater-mining problem in various parts of world. Several consequences of unsustainable groundwater use are becoming increaseingly evident worldwide, especially in developing countries and the key concern is to maintain a long-term sustainable yield from aquifers (Todd and Mays, 2005).

In order to determine the position of groundwater, quality of groundwater, physical characteristics and thickness of aquifers, etc. in any basin, test drilling and stratigraphy analysis are the most reliable and standard methods, which are very costly, time-consuming and requires skilled manpower (Sander *et al*., 1996). On the other hand, remote sensing technology, with its advantages of spatial, spectral and temporal availability of data covering large and inaccessible areas within a short time, has emerged as a very useful tool for the assessment, monitoring and management of groundwater resources (Engman and Gurney, 1991; Jha *et al*., 2007). Since delineation of groundwater prospect zones involves a large volume of multidisciplinary data from various thematic sources, it is necessary to use Geographical Information System (GIS), which can provide the ideal platform for convergent analysis of diverse datasets for decision-making in groundwater planning and management. Many researchers (e.g., Krishnamurty and Srinivas, 1995; Kamaraju *et al*, 1995; Krishnamurty *et al*., 1996; Saraf and Choudhury, 1998; Rao and Jugran, 2003; Solomon and Quiel, 2006) have applied integrated remote sensing and GIS techniques in the delineation of groundwater resources and potential zones with successful results. In the present study, the objective was to assess groundwater potential in West Medinipur district of West Bengal by considering suitable thematic layers that have direct or indirect control over groundwater occurrence using integrated Remote Sensing (RS) and GIS techniques. An attempt has also been made to quantify the groundwater potential in the study area.

STUDY AREA

In this study, West Medinipur district located in the southern part of West Bengal state, India has been considered as the study area in order to demonstrate the capabilities of integrated RS and GIS techniques in delineating groundwater potential/prospect zones (Figure 1). Geographically, the study area is situated between 86° 45′ E 21° 45′ N and 88° E 23° N and falling under Gangetic West Bengal region with a total geographical area of about 9800 km^2. The major river systems in the study area are Subarnarekha River to the south and Kasai River in the heart of the area. Climatologically, the study area falls in Indo-Gangetic West Bengal region with an annual average rainfall of 1500 mm, precipitating more than 70% from June to September. January–February is the coldest month with the average temperature of 14°C and April–May being the hottest month with an average temperature of 35°C. The district has unique geomorphological setting with hard rock upland, laterite covered fringe areas and flat alluvial plains. Extremely rugged topography is seen in the western part of the district, where Archaean rock areas of Purulia and Bankura district of West Bengal is in juxtaposition with the recent unconsolidated sediment in the alluvial plains. The northwest and southwest part of the district is mainly laterite-covered area and the terrain is very irregular. The

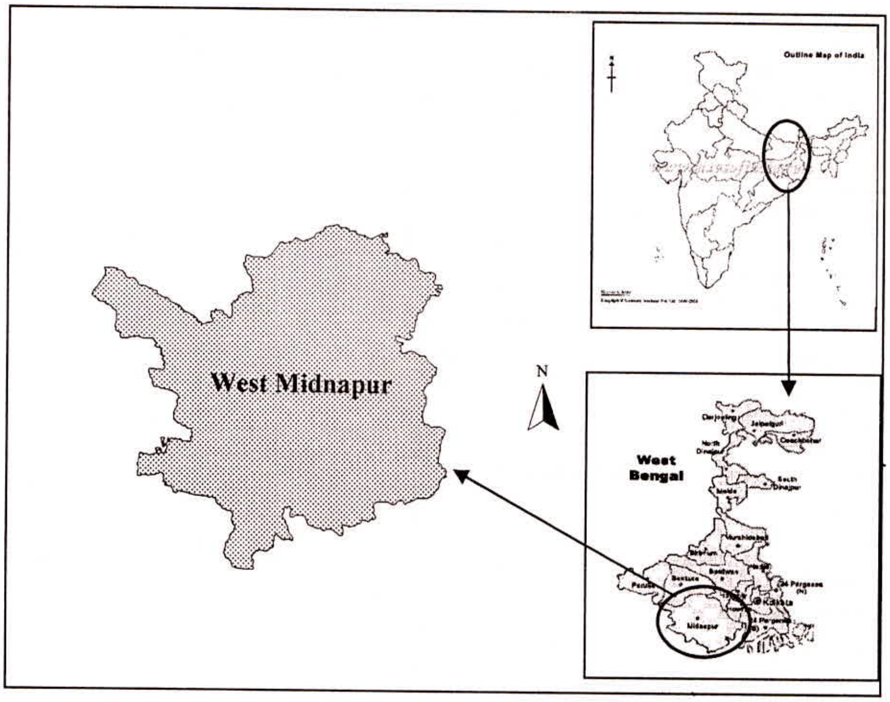

Fig. 1: Location map of the study area

district has flatter and rolling topography in the further east consisting of laterite covered areas, but underlain by deposits of older alluvium. The district shows a varied geological with the western portion covered by the crystalline rocks of Archean age.

METHODOLOGY

In order to demarcate the groundwater potential zones in the study area, a multi-parametric dataset comprising satellite data and other conventional maps including Survey of India (SOI) topographic sheets was used. Seven themes namely, geomorphology, geology, net recharge, drainage density, topographic slope, soil and surface water body were considered in the present study. IRS-1D LISS-III data collected from National Remote Sensing Agency (NRSA), Hyderabad has been used for preparation of thematic maps on drainage density and surface water body. The SOI toposheets collected from Geological Survey of India (GSI), Kolkata were used to prepare the thematic layer on slope. Further, the thematic layers on geology and geomorphology were prepared from existing maps obtained from State Water Investigation Directorate (SWID), Government of West Bengal, West Medinipur. The soil layer was prepared by digitizing the soil map available from the NBSS & LUP, Government of India, Nagpur at 1:250,000 scale. Considering the data availability in the study area, the groundwater fluctuation method was used to estimate groundwater recharge. Average annual groundwater fluctuation at all the 222 sites over the study area was calculated using the 14 years (1990 to 2003) pre- and post-monsoon groundwater level data from each site collected from SWID, West Medinipur. Thereafter, these fluctuations were multiplied by the corresponding storage coefficient values ranging from 0.0005 to 0.09, which yielded average annual groundwater recharge estimates at 222 sites. Based on these recharge estimates, a recharge map of the study area was prepared using ArcView software.

After preparing different thematic maps, the behavior of different themes and the features of different themes with respect to groundwater potential in the study area were studied and accordingly, the themes and the features of different themes were given suitable weights obtained through the Saaty's (Saaty, 1980) analytical hierarchy process. In the Saaty's analytical process, a pair-wise comparison matrix was constructed between the different factors and weights were assigned according to their relative importance in causing groundwater occurrence in the study area on a 1- to 9-scale. Finally the normalized weights of the factors were obtained. The weights assigned to the themes are presented in Table 1. Then all the thematic layers were integrated in the GIS environment to prepare a map showing suitability of different areas for groundwater development. The total weights of each polygon of the final integrated layer were derived from the following equation to compute groundwater potential index,

$$\begin{aligned} GWPI = {} & GG_wGG_{wi} + GM_wGM_{wi} + GR_wGR_{wi} + \\ & DD_wDD_{wi} + ST_wST_{wi} + SL_wSL_{wi} + W_wSW_{wi} \quad \ldots (1) \end{aligned}$$

Where, GWPI = groundwater potential index, GG = geology, GM = geomorphology, GR = groundwater recharge, DD = drainage density, ST = soil type, SL = slope, SW = surface water body, '*w*' = normalized weight of a theme, and '*wi*' = normalized weight of the individual features of a theme. GWPI is a dimensionless quantity that helps in indexing probable groundwater potential zones in the area. The range of GWPI values were divided into three equal classes (called zones) and the GWPI of different polygons falling under different range were grouped into one class. Thus, the entire study area was qualitatively divided into three groundwater potential zones and a map showing these zones was prepared using ArcView GIS software.

Moreover, the mean annual dynamic exploitable groundwater reserves in different groundwater potential zones of the study area were estimated as follows (CGWB, 1984),

$$GW_R = WL_d \times A \times S \quad \ldots (2)$$

Where, GW_R = average annual dynamic exploitable/ utilizable groundwater reserve, WL_d = average groundwater level decline between November of the current year and May next year, A = area of the groundwater potential zone, and S = storage coefficient of the aquifer.

RESULTS AND DISCUSSION

Geomorphology Map

On the basis of the physiographic characteristics, the landforms of the study area are classified into seven different units namely (i) Valley fill deposit, (ii) Flood-plain deposit, (iii) Deep to buried pediment, (iv) Deep to moderately buried pediment with lateritic capping, (v) Moderately buried pediment with lateritic capping, (vi) Pediment, (vii) Rocky outcrops. The landforms namely valley fill deposit and the flood-plain deposit are considered as most suitable for groundwater recharge as given highest weights. The rocky outcrops type pediment was given lowest weight. And the other landforms types were assigned weights in between. The weights assigned to different features are presented in Table 2.

Geology Map

In the present study area six types of geology classes were found namely younger alluvium, older alluvium, fluviodeltaic sediment with primary and secondary lateritic capping, platform margin conglomerate and basement crystalline complex. The geologic formations like younger alluvium and older alluvium is considered best for causing recharge. Platform margin conglomerate and basement crystalline complex is considered as the most unsuitable for recharge occurrence. The weights assigned to different geologic formations are shown in Table 2.

Groundwater Recharge Map

The groundwater fluctuation method yielded the average annual groundwater recharge in West Medinipur district varying from 0.03 to 82 cm. These recharge values indicate the actual groundwater recharge from different sources. Based on these recharge estimates, the area can be divided into 5 recharge zones: (i) 0–10 cm/year; (ii) 10–30 cm/year; (iii) 30–50 cm/year; (iv) 50–70 cm/year; and (v) >70 cm/year. A recharge rate of 10–30 cm/year is dominant in the district. A very low recharge rate (≤10 cm/year) is found in the western portion of the area and in small scattered patches over the area. A small strip having relatively high recharge rate (ranging from 30 cm/year to >70 cm/year) is present in the eastern portion of the area.

Drainage Density Map

The drainage density, expressed in terms of km km^{-2} is an inverse function of permeability. Actually, the less a rock is permeable, the less the infiltration of rainfall, which conversely tends to be concentrated in surface runoff. This gives origin to a well-developed and fine drainage system, which cause less recharge. The study area was delineated into micro watersheds in which area of these micro watersheds ranges from 500–1000 ha. The drainage density of the micro basins were grouped into three classes: (1) 0–0.75 km km^{-2}; (2) 0.75–1.15 km km^{-2}; (3) 1.15–2.25 km km^{-2}. Accordingly, these classes have been assigned good, moderate and poor categories, respectively and the weights assigned are presented in Table 2.

Slope Map

Slope has a direct control on the runoff and therefore on infiltration and finally on recharge. The slope percentage in the area varies from 0–20%. On the basis of the slope percentage, the study area was classified into four slope categories. The area having 0–2% slope falls in excellent category and are assigned highest weight due to the nearly flat terrain and optimal infiltration rate. Most of the study area is falling under this category. The area with 2–4% slope is categorized as good for groundwater recharge due to slightly undulating topography with partly runoff. The area with slope 4–10%, with relatively high runoff and small infiltration is kept in moderate category. The fourth category is poor with slope percentage ranging from 10–20% due to the high surface runoff in the area. The weights of different slope classes are presented in Table 2.

Soil Map

The thematic layer on soil for the study area reveals seven main soil classes, viz., coarse sandy loam, fine sandy loam, loam, silty loam, fine silty clay, clay loam, and clay. The majority of the study area is dominated by clay loam to coarse sandy loam soils, with other soil types covering relatively small areas. These seven soil classes can be categorized into four classes namely 'very good', 'good', 'moderate' and 'poor' according to their influence on groundwater occurrence and their weights were assigned accordingly.

Surface Water Bodies

The surface water bodies were identified from the satellite imagery of the study area. The water bodies are small in aerial extent and are distributed sporadically all over the area. A map on 75 m buffer around the surface water body was prepared. The thematic layer was classified into two different classes, viz., buffered area and the area outside it. The buffered area was considered as more suitable zone for groundwater potential and weights were assigned accordingly.

Table 1: Weights of the Themes for Groundwater Prospect Zoning

Theme	*Weight*
(i) Geomorphology	5
(ii) Geology	4
(iii) Net Recharge	4.5
(iv) Drainage Density	4
(v) Soil	3.5
(vi) Slope	3.5

Table 2: Weights Assigned to Different Groundwater Controlling Parameters

Theme	*Class*	*Weight Assigned*
Geomorphology	(i) Floodplain deposit	7
	(ii) Valley fill deposit	6.5
	(iii) Deep buried pediment	4.5
	(iv) Deep to moderately buried pediment with lateritic capping	3.5
	(v) Rocky outcrops	2.5
	(vi) Moderately buried pediment with lateritic capping	1.5
	(vii) Pediment	1
Geology	(i) Younger alluvium	7
	(ii) Older alluvium	6
	(iii) Fluvio-deltaic sediment with secondary lateritic capping	4
	(iv) Fluvio-deltaic sediment with primary lateritic capping	3.5
	(v) Basement crystalline complex	1.5
	(vi) Platform margin conglomerate	1
Recharge	>70 cm/year	8
	50–70 cm/year	7
	30–50 cm/year	5
	10–30 cm/year	3
	0–10 cm/year	1.5
Drainage Density	0–0.75 km/km^2	5
	0.75–1.5 km/km^2	3
	1.5–2.25 km/km^2	1.5
Soil Type	(i) Coarse sandy loam	6
	(ii) Fine sandy loam	4.5
	(iii) Loam	4
	(iv) Silty loam	3
	(v) Fine silty clay	2
	(vi) Clay loam	1.2
	(vi) Clay	1
Slope (%)	0–1	6
	1–3	5
	3–5	3.5
	5–10	2
	10–30	1.2
Surface Water Body (Buffer distance)	<75 m	4
	>75 m	1

Groundwater Prospect Map

The above-mentioned thematic·maps were registered with one another and integrated using the Geoprocessing Utility Wizard of ArcView GIS software using the UNION option. The final weights of the polygons in the final integrated layer obtained from Eqn. (1) were considered as the groundwater potential index of individual polygons. The total range of the weights of the polygons was then classified into three classes by dividing the total class range by three. The weights of the polygons coming under each range were clubbed to divide the area into different zones. The groundwater prospect map of West Medinipur district (Figure 2) thus prepared reveals three distinct zones representing 'good', 'moderate' and 'poor' groundwater potential in the area.

The 'good' groundwater prospect zone mainly encompasses the younger alluvium and flood-plain zones around the major river systems. It demarcates the areas where the terrain is most suitable for groundwater storage, and also indicates the availability of water below the ground. The area covered by 'good' groundwater prospect zone is about 1400 km^2 (15%). Debra block and parts of Keshpur, Medinipur, Kharagpur blocks fall under this zone. The eastern portion and some small patches in the central and northern portions of the study area fall under moderate groundwater prospect zone, which dominates the area. It encompasses an area of 5400 km^2, which is about 55% of the total area. The hydrogeomorphic feature available in this portion is deep to moderately buried pediment with lateritic capping, which also suggests moderate capacity of groundwater storage. About 14 blocks out of 29 blocks fall under this zone. However, the groundwater prospect in the western, southwestern and parts of northeastern portions of the study area is poor covering an area of about 3000 km^2 is poor. The 'poor' groundwater potential is attributed to the higher slope and unfavorable geology and geomorphology in this zone. These prospective groundwater zones can form a basis for the detailed hydrological and/or geophysical investigations required for well siting and proper management of vital groundwater resources.

Moreover, the minimum and maximum values of exploitable groundwater reserve for the 'good', 'moderate' and 'poor' groundwater prospect zones were estimated using the average groundwater level decline at various sites over the study area. In the 'good' zone, the average annually exploitable groundwater reserve is estimated to be 401 MCM (million cubic meter) (0.29 MCM/km^2), whereas it is 1334 MCM (0.25 MCM/km^2) for the 'moderate' zone and

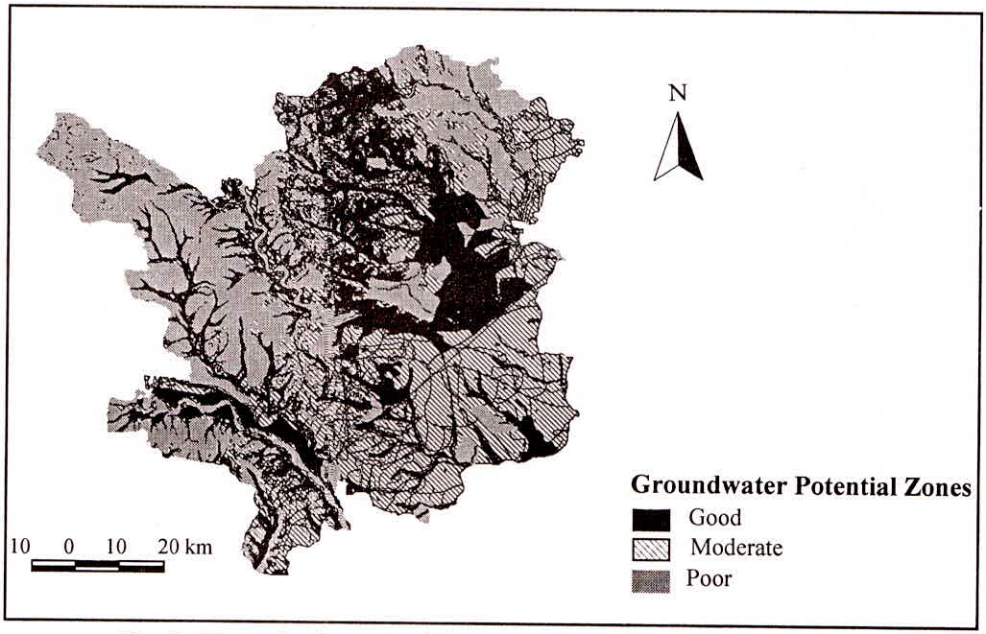

Fig. 2: Groundwater potential zone map of West Medinipur district.

397 MCM (0.13 MCM/km^2) for the 'poor' zone. Thus, the total amount of average annually exploitable groundwater reserve is more for the moderate zone compared to the good zone, which is due to the larger area under moderate zone.

CONCLUSIONS

A study was carried out to delineate groundwater prospect zones in West Medinipur district of West Bengal, India using remote sensing and GIS techniques. Seven hydrogeologic parameters namely geomorphology, geology, slope, soil, drainage density, recharge and surface water body were used in delineating groundwater potential zones. The thematic layers and their corresponding features were assigned weights after deciding the relative importance of different themes in groundwater occurrence on a 1- to 9-scale and the normalized weights were obtained using Saaty's analytical hierarchy process. The layers were then integrated in the GIS environment using ArcInfo software to delineate different groundwater prospect zones in the study area. Thus, West Medinipur district was divided into three different groundwater prospect zones namely 'good', 'moderate' and 'poor' covering 15, 55 and 30% of the study area, respectively. Furthermore, in the 'good' zone, the average annually exploitable groundwater reserve is estimated to be 401 MCM, while it is 1334 MCM for the 'moderate' zone and 397 MCM for the 'poor' zone. Since the major portion (more than 80%) of the study area exhibits 'poor' to 'moderate' groundwater prospect, it can be inferred that groundwater resource is somewhat limited in the study area. Overall, the results of this study demonstrated that the integrated RS and GIS-based approach is a powerful tool for assessing groundwater potential based on which suitable locations for groundwater withdrawals could be identified.

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