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Groundwater Exploration: Geophysical, Remote Sensing, and GIS Techniques

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### PREFACE

Groundwater plays a major role in the livelihood of mankind by providing water for drinking, irrigation, and industrial purposes. Groundwater, a renewable and finite natural resource, vital for man’s life and social and economic development, and a valuable component of the ecosystem, is vulnerable to natural and human impacts. There is a great need for the assessment and monitoring of quality and quantity of groundwater resource required at local level to develop an exact scenario of watershed. The rapid population growth in the last three decades all over the globe resulted in exploiting more groundwater. In many countries, the decline of water level indicates that the resources are depleted very fast. It is, therefore, necessary to assess the available subsurface resource in a more judicious scientific manner and then apply it for evolving optimal utilization purposes.

The chapter introduces the concept of integrated approach of various cutting edge techniques for groundwater exploration. The motivation for integrating a number of techniques stems from the realization that from conceiving the plan to explore new groundwater potential sites, groundwater modeling, quantification, and interpretation of large quantities of geohydrological data becomes a cumbersome approach. The integration of techniques like remote sensing, GIS, and geophysical methods helps us to identify, explore, model, and manage the water resources in a very scientific manner.

### 11.1 Introduction

Groundwater resource is a multidimensional concept—defined by its location, its occurrence over time, its size, properties, conditions of accessibility, and the effort required to mobilize it, all of which are to be considered in the context of demand [11]. The use of groundwater for drinking and irrigation depends
on environmental factors affecting long-term sustainability and the costs of extraction that affect the economic viability. The cost of extraction depends upon the depth of drilling required and the rates of groundwater extraction that can be achieved [10]. In arid and semiarid areas, surface water resources are generally scarce and highly unreliable; therefore, groundwater is often the primary water resource in these areas [9]. Thus, groundwater monitoring is particularly important for sustainable groundwater resource management in arid and semiarid areas. Geophysical exploration is the scientific measurement of physical properties of the earth crust for investigation of mineral deposits or geological structures. Electrical and electromagnetic geophysical methods have been widely used in groundwater investigations because of good correlation between electrical properties (electrical resistivity), geology, and fluid content. Presence of groundwater largely depends upon the availability of porosity in the rocks, on degree of weathering, and intensity/nature of fractures and lineaments [5–7]. The various surface features are normally captured through remote sensing data, which serve as guides for groundwater investigation, and could be grouped into two categories: first-order or direct indicators, that is, features directly related to groundwater occurrence and movement, and second-order or indirect indicators, that is, surface features indirectly linked with groundwater regime [1,2,12].

Subsurface geological features play an important role in groundwater replenishment. The access to surface data such as landforms, drainage density, and water bodies is easier than the subsurface data. Subsurface data characterization such as lithology, geological structure, weathered/fractured thickness, and stratigraphy, relying on geologic framework, is difficult due to the variability of geologic environments and the sparseness of geologic data. In addition, a variety of data types must be combined or synthesized. Through conventional methods alone, it is not an easy task to study all the surface and subsurface parameters of a large area and to identify a satisfactory hydrogeological framework. Since many controlling parameters must be independently derived and integrated, this involves additional cost, time, and man power. Consequently, a centralized database capable of manipulation and analysis of a great variety of data is required such as GIS techniques. These technologies have many advantages over older conventional methods, due to their facility of integration and analysis of large volumes of data, and have proved to be useful for studying geological, structural, and geomorphologic, hydrodynamic conditions together with conventional surveys. Each of these steps can be accomplished utilizing a GIS for (1) data management, analysis, and visualization; (2) integration of diverse data sources; and (3) rapid development, visualization, and testing of alternative hypotheses. The integration of GIS has proven to be an efficient tool in groundwater studies [4,8]. GIS allows the hydrogeologist to interact with the database in ways that retain the spatial relationships in order to visualize the subsurface in two or three dimensions [3,13]. The development of 3-D spatial models is the result of surface and subsurface characterization and field conceptualization. Surface and subsurface characterization is accomplished using careful data gathering and preparation techniques. GIS tools have proved their usefulness in hydrogeology over the years, but standard multilayered systems are quite limited for modeling, visualizing and editing subsurface data, and geologic objects and their attributes. Hence, the main purposes of this chapter are to present and define the following:

- The suitable locations based on remotely sensed data and GIS and then going for selected resistivity and magnetic survey in these locations
- Performing drilling at these selected sites using DTH rigs
- Constructing hydrogeological framework and 3-D geological model of a multilayered aquifer system based on GIS approach
- Constructing hydrogeological framework (solid litholog and aquifer model) that thereof can be used to expedite geological and hydrogeological categorization and conceptualization

To conceptualize these objectives, we decided to opt for a multilayered micro-watershed in the university campus, which actually had problems with groundwater availability and required a suitable plan of action for sustainable hydrogeosciences.
11.2 Study Area

The study area lies 77.15°E and 28.52°N in national capital of India, Delhi. Geologically, the area can be divided into three categories (Figure 11.1):

1. Delhi (quartzitic) Ridge
2. Older alluvium on both sides of the Delhi Ridge
3. Alluvium deposits of Chattarpur enclosed basin

The quartzite ridge enters the area from the southeastern part and passes through the eastern part extending up to the eastern bank of river Yamuna and Wazirabad. The rocky ridge has a length of about 35 km and shows trends in a NNE–SSW direction. Isolated exposures of the quartzite are also found in the western part of the area. The elevation of the crest of the ridge varies from 213 to 314 m above mean sea level with an average elevation of 40 m from the surrounding plain. The alluvial plain in the area is almost flat and is interrupted by a cluster of sand dunes and quartzite ridges. The alluvial plain in the area is almost flat and is interrupted by a cluster of sand dunes and quartzite ridges. Geologically, the area is occupied by the alluvium/buried pediment plain at an elevation ranging from 198 to 270 m above mean sea level. It is occupied by the quartzite interbedded with mica schist belonging to Delhi Supergroup. The rock type exposed in the area belongs to Delhi Supergroup of Lower Proterozoic age and consists of quartzite of the Alwar Group, phyllite, and slate of the Ajabgarh Group. The quartzite is massive, thickly bedded, hard, compact, highly jointed, and intercalated with thin beds of phyllite and slates. The strike of the beds is NNE–SSW and dip westerly at moderate angles. These rocks are mostly covered by quaternary sediments and are exposed in isolated residual and structural hills and pediments. The hills are exposed in south and southwest of Delhi.

11.3 Methodology

Surface manifestations of subsurface geological features can be inferred using satellite data. We used satellite imageries of the year 2000 and 2005 of the month of October to investigate the changes in the

![Figure 11.1 Location and geology of study area.](image-url)
land cover patterns. Normalized difference vegetation index (NDVI) was used to study the changes in vegetation pattern in these 2 years.

Geoelectrical survey was carried out in and around JNU campus, using DC resistivity meter (IGIS, DDR3). Geological investigation based on electrical measurements help in understanding the subsurface geological conditions so that the exploratory drilling can be restricted to only favorable areas. In VES, the goal is to observe the variation of resistivity with depth. The Schlumberger configuration is most commonly used for VES investigation. The midpoints of array are kept fixed, while the distance between current electrodes is progressively increased.

During VES, the alignments were restricted to particular orientation so that it should encounter minimum lateral inhomogeneities (Figure 11.2). The interpretation of sounding data is complicated and more of quantitative nature. The apparent resistivity for a given electrode spacing of one area was compared with that of the adjoining area to evaluate the relative geological and hydrogeological condition. The data was used to identify zones of low resistivity of weathered and fractured rock, which are generally favorable location for groundwater storage.

11.3.1 Gridding Methods

The program RockWorks® reads the depth intervals for the selected water level data and internally translates depths to elevations based on the boreholes’ surface and downhole surveys. There are various gridding methods available in RockWorks®—closest point, cumulative, directional weighting, distance to point, inverse distance, kriging, multiple linear regression, sample density, trend surface polynomial, trend surface residuals, triangulation (grid based), and hybrid (Figure 11.3). Since the dataset is not very huge, thus, inverse-distance gridding methods was selected for application due to its simplicity.

11.3.1.1 Inverse Distance

It is a common method using a weighted average approach to compute node values.

11.3.1.2 Triangulation (Grid Based)

It uses a network of triangles to determine grid node values.
Both gridding methods produced quite similar results, but finally, the output from inverse-distance method was chosen because it produces smooth and continuous grid and will not exaggerate its extrapolations beyond the given data points (range of grid values will be smaller than the data point range: The highest grid value will be less than the maximum data point, and the lowest grid value will be greater than the minimum data point). Inverse-distance is one of the more common gridding methods. With this method, the value assigned to a grid node is a weighted average of either all of the data points or a number of directionally distributed neighbors. The value of each of the data points is weighted according to the inverse of its distance from the grid node, taken to a user-selected power. The greater the value of the exponent specified, the more localized the gridding since distant points will have less influence on the value assigned to each grid node.

Weighting exponent: This value determines how “local” or “global” the gridding process will be in assigning node values; the value of each data point is weighted according to the inverse of its distance (d) from the grid node, taken to the nth power, as shown in the following diagram.

Sector-based searching: Tells the program that instead of simply finding the nearest neighbors for the inverse-distance gridding, regardless of where they lie, it should look for points in each x-degree sector around the node. This kind of directional search can improve the interpolation of grid values that lie between data point clusters. It can also increase processing time.

More refined gridding was not required simply because the area of the region covered by seven drilling sites is not much and shows very less variability in terms of slope, strike, and aspect that was again reconfirmed from the statistical report of the generated grid. Refining the grid parameters even more would have resulted in unnecessary increase in processing time and varied outputs. Thus, a grid model of the layer’s upper elevations or thickness was created using the selected gridding method, and from

![Diagram](image)
this model a 2-D map with the selected layers and 3-D model was created. The maps illustrate the surface elevations (superface) of the aquifer or the aquifer’s thickness (isopach).

### 11.4 Normalized Difference Vegetation Index

The NDVI map generated showed that the NDVI values were quite higher in year 2000 than in 2004 and 2005 (Figure 11.4). The decrease in NDVI values can be attributed to cutting of plantations for new built-ups, but what was more interesting to observe is that the NDVI increased in the area from year 2004 to 2005. The drilling site 1 showed that the NDVI value that was 0.395 in year 2000 decreased to mere 0.175 in year 2004 and then increased to 0.246 in year 2005. Similar trends were observed for drilling sites 3, 4, 5, 6, and 7. Only site 2 accounted for a good amount of increase in NDVI values even in comparison to year 2000, that is, the NDVI increased from 0.338 in year 2000 to 0.393 in year 2005. The NDVI values were not very high but it was observed that the selected sites showed anomalous vegetation growth, and thus, these sites were selected for drilling as this suggested that the vegetation growth was not hampered as it regained in one year (Figure 11.5).

### 11.5 Geophysical Survey

However, the resistivity survey was carried out in several locations, but to summarize the results of these sites, we will be dealing with interpretation of only a few locations (Figure 11.6). The soil resistivity on site 2 shows more than 100 Ω-m initially that is suggestive of arenaceous soil and low moisture content that is supported by low NDVI value (0.228873) and the litholog also. Further down to 6 m,
the resistivity value sharply decreases to 35 Ω-m, which is supported by silt and clay in the litholog record. Further down to 10 m, the ferrogenous intercalation overlying ferrogenous quartzite shows the possibility of shallow aquifer material that is further supported by the resistivity value, ranging in between 25 and 40 Ω-m. Further down to 50 m, the resistivity value remains low ranging between 40 and 60 Ω-m, which is further supported by the presence of weathered mica schist, quartz vein, and ferrogenous quartzite. Magnetic value recorded at this site was very low (29,000 gamma), which further suggests the possibility of interconnected fractures with good aquifer zones. The resistivity data interpretation of site 3 (JNU3) shows that initially top soil mixed with weathered rock shows very high resistivity of 400 Ω-m. Down to the depth of 4 m, the resistivity value shows further rise up to 600 Ω-m, which is suggestive of top layer of hard ferrogenous quartzite, and from 10 m, the resistivity value started decreasing and it was ranging in between 200 and 300 Ω-m down to 20 m. It shows


FIGURE 11.6  VES curve at some of the drilling locations.
the fractured quartzite with potential groundwater zone possibility at a shallow depth. The resistivity values were found to be fluctuating in between 150 and 400 Ω-m in between 12 and 40 m that comprises groundwater-bearing fracture zone. From 42 to 45 m, the resistivity value has shown a rising trend that is suggestive of mica schist and quartzite intercalations. From 46 to 80 m, the resistivity data show a sharp downfallof; it was ranging in between 300 and 150 Ω-m. This zone comprises of two sets of groundwater-bearing fracture in quartz mica schist and gneissose granite. Further down to 100 m, the resistivity value shows a rise up to 300 Ω-m, which is suggestive of granite and quartzite with less fracture. From 100 m down to 150 m, a sharp decrease in the resistivity value infers groundwater-bearing fractured quartzite. Resistivity value at site 4 shows compact overburden below the ferrogenous quartzite. At a depth of 27 m, ferrogenous quartzite was found overlying on a quartzite and aplite veins, thus, beginning of potential groundwater-bearing zone. Further down to 50 m, fractured quartzite with high discharge of groundwater encountered. The resistivity curve shows an initial rise due to presence of ferrogenous quartzite. When the curve was matched with standard curve, it was found that the angle in between X–Y plot shows less than 45°, which further suggests the possibility of groundwater-bearing zone at 27 m. The litholog also supports the interpreted resistivity curve. The magnetic value shows very high anomaly from its standard value in Delhi area that is suggestive of multiple fractures below ground level. Beyond 100 m, the presence of mica schist intercalated with thin quartzite veins further lowers the resistivity value that suggests that wherever there is change in lithofacies, it is a marker of potential fracture zone. Resistivity survey carried out at site 5 shows high top soil resistivity down to 2 m that falls abruptly from 120 to 100 Ω-m at 2.5 m, which is suggestive of very shallow weathered quartzite with some moisture content. Resistivity value further rises up to 300 Ω-m from 5 to 35 m below ground depth that suggests presence of massive quartzite. From 35 to 45 m, the resistivity shows the presence of groundwater in the fractured metamorphics. The striplogs for the four sites discussed are shown in Figure 11.7. Quantitative interpretation of VES data in corroboration with borehole data suggests with precision the availability of groundwater in-depth. Based on the resistivity and magnetic surveys carried out in the study area, seven sites were selected within JNU campus area for primary drilling (Table 11.1).

11.6 Aquifer Thickness and Solid Lithology Model

The pumping results at the selected drilling sites are shown in Table 11.2. The interconnected fracture in Aravalli quartzite has been found to have potential for groundwater exploration. Within Aravalli quartzite, the ferrogenous variety was found more fracture prone. Pegmatites, aplite, and quartz vein intercalated with schistose rocks have multiple fracture system. Aquifer thickness was modeled for the area covered by seven primary drilling locations in JNU based on the water level data from each of the borewells, total depth, and elevation contours (Figure 11.8). As per the results, thickest layers of water are found toward northeastern part of the sampled area. Southwestern part of the sampled area also shows moderate aquifer thickness, but for this part, the accuracy of predicting aquifers with ample water is lesser due to lesser number of primary drilling sites. But for the southeastern and eastern parts, it was found that aquifer thickness decreases to 5–10 m. Aquifer thickness alone can’t be criteria for groundwater exploration or management. It should be considered coupled with the topography as per the elevation contours (or rather flow direction of rainwater) as well as the aquifer depth model and the geology of the terrain. As water follows the natural depressions over the terrain, the chances of water getting accumulated in these areas increase. If such pockets are having high primary porosity or interconnected fractures (particularly in hard-rock terrain such as JNU), then the chances of finding water increase. Confined aquifers in such cases may show lesser aquifer thickness. These conditions can be studied remotely using satellite data but that has to be again reconfirmed through ground-based geophysical surveys (resistivity and magnetic). Even in this case, the change in aquifer thickness toward northeastern and southwestern parts coincides to a larger extent with the changes in elevation contours (rapid decrease in elevation).
FIGURE 11.7 Striplogs constructed based on drill cuts collected during drilling.
The six lithologic categories of the quaternary system (clay, clay and sand, fine sand, coarse sand, sand and gravel, and gravel) are represented as spatially repeated sequences that have significant spatial changes in terms of their occurrence, thickness of individual categories, and elevation of top and bottom of each layer. Interfingering and presence of lenses is a main characteristic of the sedimentary basin represented in the study area. Due to these characteristics, heterogeneity of the aquifer system is represented by a spatial variation in hydraulic conductivity ranging between that of clay and gravel. Results of the lithologic models and the generated 3-D fence diagrams revealed that there is a wide range of hydraulic conductivities in the modeled area, which vary spatially and control the groundwater flow regime.

Subsurface lithologic information was used to generate a lithology solid model for drilling sites predicting the possible subsurface lithologic connections and extrapolating the information to the whole region apart from primary drilling sites. The software (RockWorks®) determines the lithology types

<table>
<thead>
<tr>
<th>TABLE 11.1</th>
<th>Location of the Seven Drilling Sites with Total Depth Drilled</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bore</td>
<td>Longitude</td>
</tr>
<tr>
<td>JNU1</td>
<td>77.17186</td>
</tr>
<tr>
<td>JNU2</td>
<td>77.17406</td>
</tr>
<tr>
<td>JNU3</td>
<td>77.17019</td>
</tr>
<tr>
<td>JNU4</td>
<td>77.17078</td>
</tr>
<tr>
<td>JNU5</td>
<td>77.1563</td>
</tr>
<tr>
<td>JNU6</td>
<td>77.1619</td>
</tr>
<tr>
<td>JNU7</td>
<td>77.17251</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TABLE 11.2</th>
<th>Individual Cumulative Water Yields of Seven Borewells</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drilling Sites</td>
<td>JNU 1</td>
</tr>
<tr>
<td>Head of water in tube above the center of orifice in in.</td>
<td>9</td>
</tr>
<tr>
<td>4 in. pipe with 2.5 in. opening in L/h</td>
<td>20,475</td>
</tr>
</tbody>
</table>

FIGURE 11.8 Aquifer model generated for seven primary drilling sites.
along each borehole in the project and assigns certain values to those nodes along the wells. It then uses the “lithoblending” method to assign lithology to nodes lying between wells. Finally, it will reset those nodes above the ground surface to a value of 0.

11.7 Summary and Conclusions

The land use of National Capital Region (NCR) in general and Delhi in particular has gone under drastic change in the last few decades. The rapid change in land use/land cover, population growth, and seismic instability, all have contributed in changing the hydrogeoenvironment of NCR. The present work aims at hard rocks and colluvial and alluvial aggregates for exploration, exploitation, and management of water resources in one of the most water-vulnerable regions of India. Although it is difficult to accurately estimate subsurface water available in a region, nevertheless, the present work attempts to estimate and give a clear-cut estimation of groundwater in hard-rock area of Delhi. To achieve the specific objective, a systematic approach of understanding the terrain characteristic using satellite data and then a detailed geological mapping, geophysical surveys (resistivity and magnetic), DTH drilling, and analysis of drill cuttings have been adopted. The information from satellite data, resistivity, and magnetic anomaly values were used to locate seven locations for deep drilling at identified favorable sites for groundwater exploration. Deep drilling was conducted at selected locations using DTH rig up to maximum depth of 198.17 m, and it was found that the discharge at all the locations was more than 20,475 lph. However, it was conceptualized that these wells need some time to recover as the recharge in this area takes place through laterally interconnected fractures that have high transmissivity.

It was found that wherever the lineament density were high, there were also resistivity and magnetic anomaly with lower values; at all such places, groundwater availability is very high. If NDVI is high, the vegetation is thick due to high moisture-laden lineament that is suggestive of high mineral availability and hence the groundwater availability. Resistivity survey threw light on the different levels of water availability. Further, it was found that wherever there has been change in the land use, the natural recharge potential too has declined. Digital elevation model could tell us about the course of water runoff and it will help in recharging the aquifer. The study also came to the conclusion that wells may not be directly recharged. There can be indirect method of recharging them. Recharging the lateral dry wells can be done by the lateral homogeneity. In view of the total area of study in JNU that is approximately 5 sq. km, the number of tube wells was restricted to seven based on the delineation of micro-watershed. As per the National Water Policy, there should not be more than one tube well in one micro-watershed. The discharge of the tube wells ranged between 24,475 and 34,125 L/h with less than 10 m drawdown in 72 h of pumping. In this area, most of the drilling site fractures are interconnected with high transmissivity; it has been observed that 80% recovery of drawdown takes place within 1 h, if surrounding tube wells are also stopped. Remaining 20% recovery takes 4 h due to elastic nature of the aquifer.

References


