Application of Geographic Information System and Remote Sensing in Hydrogeological Investigations

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Abstract: The Geographic Information System and Remote Sensing has become a widely accepted tool in all fields of life and particularly in groundwater exploration and hydrogeological investigations, due to the robust integration of spatial features and tabular data, spatial analysis capability, intelligent maps, and a geographic user interface to the databases. This paper will focus specifically on the application of these emerging technologies in hydrogeological investigations. The integration of remote sensing with GIS provides a greater hydrogeological understanding by combining remotely acquired spectral information with other data including physiographical, geological, geophysical, hydrogeological, geochemical and geometrical data. The use of GIS in water resources evaluation has recently expanded with increasing emphasis in surface and subsurface applications. The combination of Remote Sensing, hydrogeology, applied geophysics and GIS show a tremendous promise for groundwater exploration, exploitation and development all over the world.

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Introduction

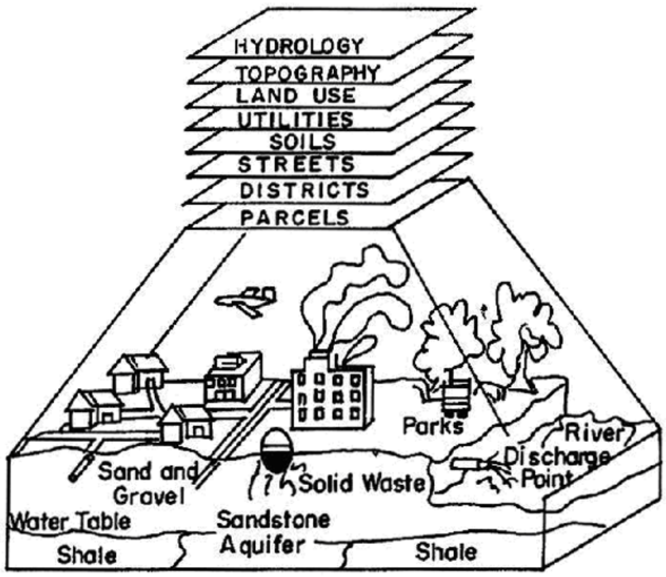
This paper will present two promising technologies: Geographic Information System (GIS) and Remote Sensing (RS) along with their application in groundwater exploration and hydrogeological investigations. Although this field is not very common in Pakistan but is being widely used internationally in almost all fields of life in general and in natural resources management particularly. The growth of GIS has been a marketing phenomenon of amazing breadth and depth and will remain so for many years to come. Clearly, GIS will integrate its way into our everyday life to such an extent that it will soon be impossible to imagine how we functioned before. Before discussing the applications of GIS and Remote Sensing in hydrogeological investigations, their brief introduction is presented.

Geographic Information System

Geographic Information System is a tool to efficiently capture, store, update, manipulate, analyze and display all forms of geographically referenced data. Many other definitions of a GIS have been evolved in different areas and disciplines (Clarke, 1995 and 2001; Burrough, 1986 and 1998; Duecker, 1979; Goodchild, 1992; and Star and Estes, 1990). According to Duecker (1979) geographic information system is a special case of information systems where the database consists of observations on spatially distributed features, activities or events, which are definable in space as points, lines, or areas. A geographic information system manipulates data about these points, lines, and areas to retrieve data for ad hoc queries and analyses.

All definitions of GIS recognize that spatial data are unique because they are linked to maps. A GIS at least consists of a database, map information, and a computer-based link between them. It stores data about the world as a collection of thematic layers, a pictorial representation of which is given in (Figure 1) to be linked together in spatial domain using geographical reference system. It lets the users to see, explore, and analyze data by location, revealing hidden patterns, relationships, and trends that are not readily apparent in spreadsheets or statistical packages. This simple but extremely powerful and versatile concept has proven invaluable in solving many real world problems from tracking delivery vehicles, to recording details of planning applications and managing natural resources.

Figure 1. The real world



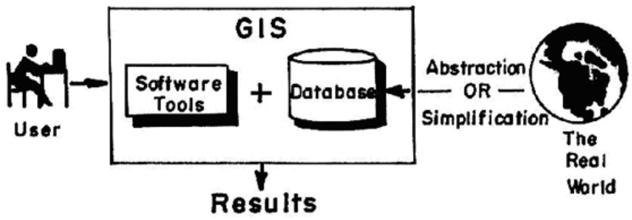
The real world consists of many geographic, which can be represented as a number of related data layers (after Nath et al., 2000).

GIS stores both spatial and aspatial data. The geocoded spatial data defines an object that has an orientation and relationship with other objects in two or three-dimensional space, also known as topological data and stores in topological database. On the other hand, attribute data stored in a relational database describes the objects in detail. GIS links these two databases by manipulating a one-to-one relationship between records of object of location in the topological database and records of the object attribute in relational databases by using end-user defined common identification index or code. Different components of a GIS are pictorially represented in (Figure 2).

GIS uses three types of data (point, line, and polygon/area type) to represent a map or any georeferenced data, and can work with both vector and raster geographic models. The vector model is generally used for describing discrete features, while the raster model is used for continuous features.

GIS uses both operational and analysis tools for generating thematic maps. There are several commercial GIS packages available in the industry, namely, ESRI Arc/Info and ArcView, MapInfo, AutoCAD MAP, Geographic Resources Analysis Support System (GRASS), IDRISI, Maptitude, and Microstation MGE developed by various software vendors.

Figure 2. Components of a GIS



Pictorial representation of the components of a GIS (after Nath et al., 2000).

Remote Sensing

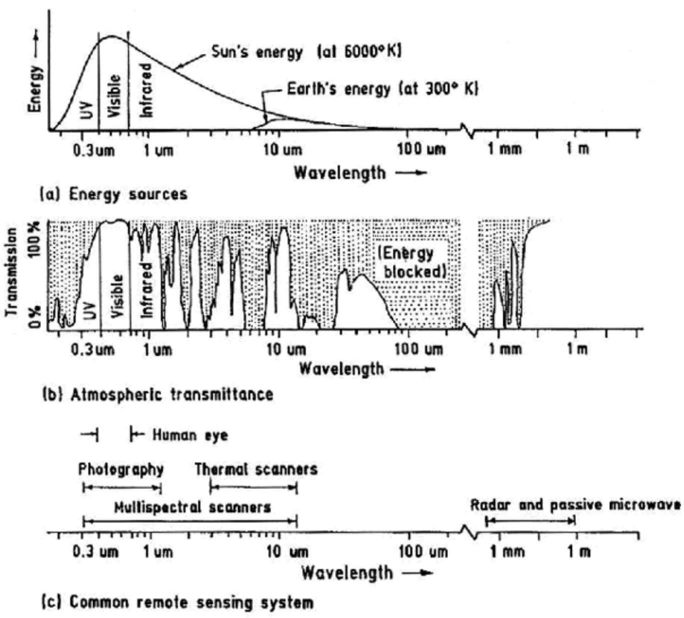
Remote sensing is the non-contact recording of information about the earth’s surface, from the ultraviolet, visible, infrared and microwave regions of the electromagnetic spectrum, by means of instruments such as scanners and cameras, located on mobile platforms such as aircraft or spacecraft and the analysis of the acquired information by means of photo interpretive techniques, image interpretation and state-of-the-art of image processing (Sabins, 1987). Although, there appears to be a lack of physical contact between the remote sensor and the target, in reality there exists a link between the two, in the form of electromagnetic energy (visible, thermal, infrared radiation), force fields (gravity, magnetic) or acoustic waves (sonar). Remote sensors measure the relative variation of these forms of energy that is either emanating from the body or being reflected from it to recognize and make detailed studies.

For most of the atmospheric and earth surface observations, electromagnetic energy is considered to be the supreme medium for two reasons. Primarily, this is the only form of energy that has the ability to propagate through free space as well as a medium. Further, its property to interact with the media and the target in a variety of ways ensures the sensor to capture the subtle variations that exist in the nature of the earth features.

Every part of the earth reflects the light incident upon it depending on its optical characteristics. This information, which characterizes objects, is called "signatures". Different objects of the earth’s surface return different amounts of reflected / emitted energy in different wavelengths of the electromagnetic spectrum depending on the atmospheric windows (Figure 3), and this reflectance / emittance from each object depends on the wavelength of the radiation, the molecular structure of the object and its surface conditions. Vegetation, in general, appears green during daytime, because it reflects the green band of visible radiation preferentially, while absorbing other color bands of the visible radiations.

Detection and measurements of these spectral signatures enable identification of surface objects both from air borne and space borne platforms. But often, similar spectral response from different surface objects creates spectral confusion leading to misinterpretation and misclassification, which can be avoided by systematic ground data verifications. However, spectral variation in reflectance or emittance from objects is not the only characteristic of electromagnetic radiation that helps in establishing their signatures. Signatures basically comprise of any set of observable characteristics, which directly or in directly lead to the identification of an object and/or it’s condition. These characteristics are spatial information, temporal (for example, seasonal) variation and polarization effects. The spatial information relates to shape, size, texture, pattern, association, etc.

Figure 3. Spectral characteristics



Spectral characteristics of energy sources, atmospheric effects and sensing system (after Nath et al., 2000).

Earth resources satellites collect information about the earth’s surface and transmit to the ground receiving stations. After carrying out initial corrections, two types of data products (visual imagery hard copy and computer compatible tapes (CCTs)) are generated for resources study. These data products are processed and interpreted for the identification and classification of different objects of the earth. Each satellite system is composed of a scanner with sensors. The scanner is the entire data acquisition system, such as the Landsat Thematic Mapper scanner or the SPOT panchromatic scanner (Lillesand and Kiefer, 2003). The sensor of a satellite, made up of detectors, is a device that gathers energy, converts it to a signal and presents it in a form suitable for obtaining information about the environment. A detector is the device in a sensor system that records electromagnetic radiation. For example, in a sensor system on the Landsat Thematic Mapper scanner there are 16 detectors for each wavelength band. Several characteristics of the common remote sensing system given in (Figure 3) have been described by Nath et al. (2000) are summarized in (Table 1).

Table 1. Characteristics of the common remote sensing system (after Nath et al., 2000)

SR. No.	Characteristics of the Remote Sensing system
1.	Circular orbits that go from north to south and south to north.
2.	Sun-synchronous orbits, meaning that it rotates around the earth at the same rate as the earth rotates on its axis, so data is always collected at the same local time of day over the same region.
3.	Records electromagnetic radiation in one or more bands.
4.	It's scanners produce nadir views (Nadir is the area on the ground directly beneath the scanner's detectors).

Many data acquisition options are available ranging from photography to aerial sensors using film, to sophisticated satellite scanners. A satellite system with detectors which produce digital data may be preferable for the reasons that the digital data can be easily processed and analyzed by a computer directly; the satellite is in orbit around the earth, so the same area can be covered on a regular basis for detecting change; once the satellite is launched, the cost of data acquisition is less than that for aircraft data; and satellites have very stable geometry, meaning that of remote sensing data is acquired from different types of satellites, viz., Landsat, SPOT, IRS-1B, IRS-1C, NOAA, etc.

Landsat has a 15m panchromatic sensor and a 30m enhanced Thematic Mapper sensor with 7 bands. SPOT has a 10m panchromatic sensor and a 20m multi-spectral sensor with 3 bands. IRS-1B has a 36m multi-spectral sensor with 4 bands. Raw remotely sensed data is not projected onto a plane. Therefore, rectification is necessary to project the data conforming to a map projection system before processing.

Several commercial software are used in the industry for the processing and interpretation of remotely sensed data, namely, ER-Mapper, Integrated Land and Water Information System (ILWIS) and Earth Resources Data Analysis System (ERDAS) developed by various software vendors.

Application in Hydrogeological Investigations

For sustenance of life water is most essential. The distribution of water on the earth is highly unbalanced. Nearly 97.41% of water is confined to the world's oceans and are unsuitable for human and livestock consumption (Nath et al., 2000). Major portion of the remaining 2.59% is locked up in the glaciers (1.953%) and beneath the surface as groundwater (0.614%), thus leaving only a meager 0.015% in the rivers and lakes for consumption by terrestrial inhabitants. This quantity of water was enough to support civilization. But, in recent years due to population explosion and urbanization, water resources from rivers, ponds and lakes have become inadequate. Therefore, an urgent need has arisen for exploring and managing surface as well as groundwater resources for continuous and dependable water supply for the growing needs of population. There is need also to safeguard terrestrial habitation from the water inundation caused by natural calamities like floods, tsunamis, cyclones etc. These problems can only be tackled effectively by using the technological advancements that have been achieved by GIS and remote sensing.

The water regime of an area can be explained in terms of the interplay of four critical parameters, namely, rainfall, surface flow, evapo-transpiration by vegetative cover and finally, the infiltration capacity of the surface rocks. In order to manage and regulate water resources, the knowledge of these parameters is essential. These data can be collected through conventional methods like ground survey and by locating gauging stations. In recent times the potential of space borne sensors are also being employed quite effectively in eliciting some of this information.

GIS is built upon knowledge from geography, cartography, computer science and mathematics and can be applied in any field, directly or indirectly. The use of GIS in the natural resource industry is widely recognized and has been used extensively for the exploration of minerals (Ramadan et al., 1999 and 2003), hydrocarbon exploration (Williams, 2000; Porter et al., 2000; Shah, 2003 and Iqbal, 2004) and groundwater exploration and hyrdogeological investigations (Nath et al., 2000; Chi and Lee, 1994; Laurent et al., 1998; Gardino and Tonelli, 1983; and Gustafsson, 1993).

The use of GIS in groundwater investigations is growing tremendously in recent years. Currently, it is used for groundwater potential (Chi and Lee, 1994 and Krishnamurthy et al., 1996) and vulnerability assessment (Rundquist et al., 1991 and Laurent et al., 1998), groundwater modeling (Ross et al., 1991; Baker et al., 1993; Chieh et al., 1993 and Watkins et al., 1996) and management (Hendrix and Buckley, 1989). Using GIS one can play around with the data and generate themes as required for specific applications. Some other common uses of GIS in groundwater modeling have been described by Nath et al. (2000) are summarized in (Table 2).

Table 2. Common uses of GIS in groundwater modeling (after Nath et al., 2000).

SR. No.	Common uses of GIS
1.	Preparation of data for model input. Contours or Triangular Irregular Networks (TIN) created from point data coverages of aquifer properties are intersected with the model grid. Effective parameters for each cell are assigned automatically and systematically.
2.	Assessment of the adequacy of the model input through the visual display and/or comparison of contour or TIN values (such as in making sure the top of the aquifer is not above the land surface).
3.	Allocation of pumping and recharge rates to each grid cell.
4.	Visual comparison of simulated and measured head or concentration values.
5.	Interactive revision of parameter values and/or spatial discretion.
6.	Display of model results such as contours of hydraulic head, flow vectors and water quality contours.

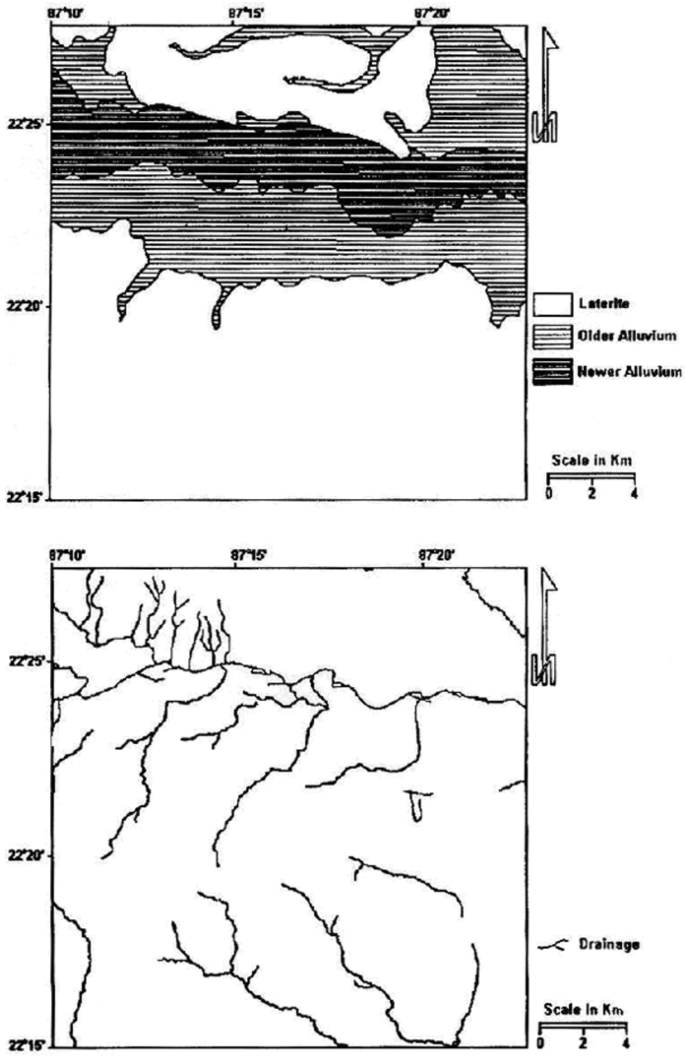
GIS technologies greatly facilitate the development, calibration and verification of groundwater models, as well as the display of groundwater model parameters and results. Through the linking of a digital mapping system to database, GIS has the ability to integrate data layers and perform spatial operations on the data. Thus, GIS can automate many of the data compilation and management duties in groundwater modeling. Spatial statistics and grid design capabilities of GIS can improve the modeling effort and aid in reliability assessment. Furthermore, GIS have many visual display capabilities that can aid in calibration, verification and the production of final results (Watkins et al., 1996).

The utility of GIS in hydrologic parameter estimation is demonstrated by Bhaskar et al. (1992) by using 12 watersheds from eastern Kentucky, USA. A GIS database comprising the hydrography, soils, and land use of these watersheds was created. They found that GIS is capable of putting together the voluminous information typically required in hydrologic modeling. Compilation of various geomorphic properties of drainage basins like drainage densities and channel frequencies could also be efficiently done using the GIS.

Gardino and Tonelli (1983) used remote sensing to detect freshwater submarine springs in the coastal areas of Italy, Sicily and Sardinia. About seven hundred such springs have been studied along a coastline of 1500 km. Gustafsson (1993) used SPOT multi-spectral and panchromatic data to study hydrogeological properties of a large semi-arid region in southeastern Botswana.

Nath et al. (2000) used GIS and Remote Sensing tools and found them best suited for hydrogeological investigations. The study area was Midnapur District, West Bengal, India covering an area of 631 km^2 with an average annual rainfall of 152cm and temperature of 31°C. It is a typical soft rock area with hydrogeological conditions favorable for shallow groundwater reserves. For groundwater investigations, thematic maps of surficial geology and drainage pattern were prepared from IRS-1B LISS-II data. The data has spatial and radiometric resolutions of 36m and 7 bits respectively. A thematic map of drainage pattern of the study area was prepared using False Color Composite (FCC) using bands 1, 2 and 3 (red, green and blue) of the image. The water bodies were identified by their blue tone and fine texture. A GIS package was used to digitize the rivers, streams and channels from the image. The evolved thematic model to assess the groundwater potential of a soft rock area by integrating seven geological and hydrogeological themes (lithology, geomorphology, soil, net recharge, drainage density, slope, and surface water body) is presented in (Figure 4). The field verification of this model undoubtedly establishes the efficacy of the GIS integration tool in demarcating the potential groundwater reserve in soft rock terrain.

Figure 4. Thematic map of geology and drainage pattern



Thematic map of geology (above) and drainage pattern (below) generated from IRS-1B LISS-II data (after Nath et al., 2000).

Conclusions

Geographic Information System and Remote Sensing has become a widely accepted tool in all fields of life and particularly in groundwater exploration and hydrogeological investigations. Together these technologies help in taking care of business by leveraging technology that facilitates to see the big picture, make the best decisions, and capitalize on the organization's investment both in terms of data and resources. The GIS software offers an innovative solution that helps to create, visualize, analysis and present information better and more effectively.

During the development of a GIS database for comprehensive analysis, all avenues of data collection should be pursued including literature survey, public and private organizations and computer networks. The integration of remote sensing with GIS provides a greater hydrogeological understanding by combining remotely acquired spectral information with other data including physiographical, geological, geophysical, hydrogeological, geochemical and geometrical data. The use of GIS in water resources evaluation has recently expanded with increasing emphasis in surface and subsurface applications. The combination of Remote Sensing, hydrogeology, applied geophysics and GIS show a tremendous promise for groundwater exploration, exploitation and development all over the world.

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