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Groundwater management and development by integrated remote sensing and geographic information systems: prospects and constraints

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Abstract Groundwater is one of the most valuable natural resources, which supports human health, economic development and ecological diversity. Overexploitation and unabated pollution of this vital resource is threatening our ecosystems and even the life of future generations. With the advent of powerful personal computers and the advances in space technology, efficient techniques for land and water management have evolved of which RS (remote sensing) and GIS (geographic information system) are of great significance. These techniques have fundamentally changed our thoughts and ways to manage natural resources in general and water resources in particular. The main intent of the present paper is to highlight RS and GIS technologies and to present a comprehensive review on their applications to groundwater hydrology. A detailed survey of literature revealed six major areas of RS and GIS applications in groundwater hydrology: (i) exploration and assessment of groundwater resources, (ii) selection of artificial recharge sites, (iii) GIS-based subsurface flow and pollution modeling, (iv) groundwater-pollution hazard assessment and protection planning, (v) estimation of natural recharge distribution, and (vi) hydrogeologic data analysis and process monitoring. Although the use of these techniques in groundwater studies has rapidly increased since early nineties, the success rate is very limited and most applications are still in their infancy. Based on this review, salient areas in need of further research and development are discussed, together with the constraints for RS and GIS applications in developing nations. More and more RS- and GIS-based groundwater studies are recommended to be carried out in conjunction with field investigations to effectively exploit the expanding potential of RS and GIS technologies, which will perfect and standardize current applications as well as evolve new approaches and applications. It is concluded that both the RS and GIS technologies have great potential to

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revolutionize the monitoring and management of vital groundwater resources in the future, though some challenges are daunting before hydrogeologists/hydrologists.

Keywords Remote sensing · Geographic information system (GIS) · GIS-based subsurface modeling · Groundwater vulnerability · Groundwater management

1. 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 (e.g., consistent temperature, widespread and continuous availability, excellent natural quality, limited vulnerability, low development cost, drought reliability, etc.), 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 direct to poor community far more cheaply, quickly and easily than canal water (IWMI, 2001). Of the 37 Mkm^3 of freshwater estimated to be present on the earth, about 22% exists as groundwater, which constitutes about 97% of all liquid freshwater potentially available for human use (Foster, 1998). Unfortunately, the excessive use and continued mismanagement of water resources to supply ever-increasing water demands to profligate users have led to water shortages, increasing pollution of freshwater resources and degraded ecosystems worldwide (e.g., Clarke, 1991; Falkenmark and Lundqvist, 1997; de Villiers, 2000; Tsakiris, 2004). Myriad consequences of unsustainable groundwater use are becoming increasingly evident and the key concern is to maintain a long-term sustainable yield from aquifers (Todd and Mays, 2005). It is now a well-recognized fact that water is a finite and vulnerable resource, and it must be used efficiently and in an ecologically sound manner for present and future generations. It is rightly said that groundwater will be an enduring gauge of this generation's intelligence in water and land management.

Remote sensing with its advantages of spatial, spectral and temporal availability of data covering large and inaccessible areas within short time has become a very handy tool in exploring, evaluating, and managing vital groundwater resources (Chowdhury *et al.*, 2003). The hydrogeologic interpretation of satellite data have been proved to be a valuable survey tool in areas of the world where little geologic and cartographic information exists or is not accurate (Engman and Gurney, 1991). Satellite data provide quick and useful baseline information about the factors controlling the occurrence and movement of groundwater like geology, lithology, geomorphology, soils, land use/cover, drainage patterns, lineaments, etc. (Bobba *et al.*, 1992; Meijerink, 2000). However, all the controlling factors have rarely been studied together because of the non-availability of data, integrating tools and/or modeling techniques. Structural features such as faults, fracture traces and other such linear or curvilinear features can indicate the possible presence of groundwater (Engman and Gurney, 1991). Similarly, other features like sedimentary strata (i.e., alluvial deposits and glacial moraines) or certain rock outcrops may indicate potential aquifers. The presence of ox-bow lakes and old river channels are good indicators of alluvial deposits (Farnsworth *et al.*, 1984). Shallow groundwater could also be inferred by soil moisture measurements and by changes in vegetation types and pattern (Nefedov and Popova, 1972). In arid regions, vegetation characteristics may indicate groundwater depth and quality. Groundwater recharge and discharge areas in drainage basins can be detected from soils, vegetation, and shallow/perched groundwater (Todd, 1980). Furthermore, differences in surface temperature (resulting from near-surface groundwater) measured by remote sensing have also been used to identify alluvial deposits, shallow groundwater, and springs or seeps (Mayers and Moore, 1972; Heilman and Moore, 1981; van de Griend *et al.*, 1985). Van de Griend *et al.* (1985) suggest that if surface temperature measurements were made using thermal infrared sensors after a long period without rain, it should be possible to map the regions of shallow water table and infer groundwater recharge and discharge.

The important physical features of the landscape which can be derived from satellite imagery or aerial photographs and used for assessing groundwater conditions (i.e., occurrence, depth, flow patterns, quantity, or quality) under a variety of hydrogeologic settings are summarized in Table 1. Excellent reviews of remote sensing applications in groundwater hydrology are presented in Farnsworth *et al.* (1984), Waters *et al.* (1990), Engman and Gurney (1991) and Meijerink (2000). These reviews indicate that remote sensing has been widely used as a tool, mostly to complement standard geophysical techniques. Meijerink (2000) recognizes the value of remote sensing in groundwater recharge-based studies and suggests that it can significantly aid to the conventional assessment and modeling techniques.

The geographic information system (GIS) has emerged as an effective tool for handling spatial data and decision making in several areas including engineering and environmental fields (Stafford, 1991; Goodchild, 1993). Remotely sensed data are one of the main sources for providing information on land and water related subjects. These data being digital in nature, can be efficiently interpreted and analyzed using various kinds of software packages (e.g., PCI, ENVI, ERDAS IMAGINE, etc.). It is easy to feed such information into a GIS environment for integration with other types of data and then do analyses (Faust *et al.*, 1991; Hinton, 1996). The combined use of remote sensing and GIS is a valuable tool for the analysis of voluminous hydrogeologic data and for the simulation modeling of complex subsurface flow and transport processes under saturated and unsaturated conditions (e.g., Watkins *et al.*, 1996; Loague and Corwin, 1998; Gogu *et al.*, 2001; Gossel *et al.*, 2004). These functions allow mainly overlay or index operations, but new GIS functions that are available or under development could further support the requirements of process-based approaches for analyzing subsurface phenomena (Gogu *et al.*, 2001). Undoubtedly, the GIS technology allows for swift organization, quantification, and interpretation of a large volume of hydrologic and hydrogeologic data with computer accuracy and minimal risk of human errors.

Unlike surface water hydrology, the applications of remote sensing (RS) and GIS techniques in groundwater hydrology have received only cursory treatment and are less documented. Furthermore, the roles of RS and GIS in groundwater hydrology have been reported separately in the past and a combined treatise with comprehensive reviews is not reported to date. Therefore, in the present paper, an attempt has been made to highlight remote sensing and GIS technologies as well as to present a state-of-the-art review on the application of these two emerging techniques in groundwater hydrology. Such up-to-date and systematic information will be of great importance for the researchers, practicing hydrogeologists and the concerned decision makers, particularly for new researchers of this field.

2. Overview of remote sensing technology

2.1. Historical perspective

The use of photography to record an aerial view of the earth's surface dates back to 1858, which was the starting point in the history of remote sensing. In succeeding years, numerous

Table 1 Salient physical features of the landscape used for assessing groundwater condition from remote sensing data (modified from Todd, 1980; Todd and Mays, 2005)

Surficial feature	Information obtained
• Topography	The local and regional relief setting gives an idea about the general direction of groundwater flow and its influence on groundwater recharge and discharge.
Low slope (0–5°)	Presence of high groundwater potential.
Medium slope (5–20°)	Presence of moderate to low groundwater potential.
High slope (>20°)	Presence of poor groundwater potential.
• Natural vegetation	Dense vegetation indicates the availability of adequate water where groundwater may be close to the land surface.
Phreatophytes	Shallow groundwater under unconfined conditions.
Xerophytes	Appreciably deep groundwater under confined or unconfined conditions.
Halophytes	Shallow brackish or saline groundwater under unconfined conditions.
• Geologic Landforms	
Modern alluvial terraces, alluvial plains, floodplains, and glacial moraines	Favorable sites for groundwater storage.
Sand Dunes	Give an idea about the presence of underlying sandy glacio-fluvial sediments, which indicate the presence of groundwater.
Rock outcrops	Presence of potential aquifer.
Thick weathered rocks	Moderate groundwater potential.
Rocks with fractures/fissures	Very good or excellent potential of groundwater.
Rocks without fractures/fissures	Unfavorable sites for groundwater occurrence.
Hillocks, mounds and residual hills	Unfavorable sites for groundwater existence.
• Lakes and streams	
Ox-bow lakes and old river channels	Favorable sites for groundwater extraction.
Perennial rivers, and small perennial and intermittent lakes	High to moderate potential of groundwater.
Drainage density	High drainage density indicates unfavorable site for groundwater existence, Moderate drainage density indicates moderate groundwater potential and less/no drainage density indicates high groundwater potential.
Drainage pattern	Gives an idea about the joints and faults in the bedrock which in turn indicates the presence or absence of groundwater.
• Springs Types (tentatively inferred from RS data)	
Depression springs, contact springs, and artesian springs	Presence of potential aquifer.
Moist depressions, seeps, and marshy environments	Presence of shallow groundwater under unconfined conditions.
• Lineaments (Applicable to rocky terrains)	Give an idea about the underground faults and fractures, and thereby indicate the occurrence of groundwater.

improvements were made in the photographic technology and in methods of acquiring earth's photographs from balloons and kites. The next milestone was the use of powered airplanes for taking aerial photographs. World War I (1914–1918) marked the beginning of acquiring aerial photographs in a routine manner. Photography in visible wavelengths was the first remote sensing technique to be used. During the World War II (1939–1945), the use of electromagnetic (EM) spectrum was extended from almost exclusive emphasis on the visible spectrum to its other regions, most notably the infrared and microwave regions (Campbell, 1996). The postwar era saw the continuation of trends set in motion by wartime research. The 1960s saw a series of rapid developments in rapid sequence. It was in this context the term “remote sensing” was coined by Evelyn Pruitt, a scientist working for the US Office of Naval Research, when she recognized that the widely used term “aerial photography” no longer accurately described the many forms of imagery collected using radiations outside the visible region of the EM spectrum (Campbell, 1996). In succeeding years, several remote sensing satellites were launched for various purposes and of various resolutions, which provided a new dimension to the remote sensing technology. Now, most common remote sensing systems operate in one or several of the visible, infrared, or microwave portions of the EM spectrum.

The series of satellites now known as LANDSAT (Land Space Application Technology) launched by the US evolved in concept from the photographic observations of the early Mercury and Gemini orbital flights. Data from those manned earth orbital flights indicated the practicality of observing from space orbits what is broadly referred to as “earth resources”. These observations and the thoughts they generated led to the NASA (National Aeronautic and Space Agency of the US) satellite program that developed the first satellite of the world called “Earth Resources Technology Satellite” (ERTS), which was launched in July 1972; it was later on renamed “Landsat-1” and the latest satellite in this series is Landsat-7 launched in 1999. Thereafter, the satellites were also launched by other countries such as former USSR, Japan, European Space Agency (ESA), India, France and Canada as well as China and Brazil. With the advancement of technologies, the nature of remote sensing itself has changed during past few decades from a relatively *qualitative art* relying on inference for information to a *quantitative science* capable of measuring system states in some cases. Thus, extensive improvements in the field of remote sensing have been made and it is still developing as an exploratory science to meet the growing challenges of the world.

2.2. Defining remote sensing

Remote sensing (RS) can be defined as the observation of targets or processes from a distance (without physical contact), in contrast to *in situ* measurements wherein measuring devices are in touch or immersed in the observed system and/or process. This is a broad definition, but this term usually refers to the gathering and processing of information about earth’s environment, particularly its natural and cultural resources, through the use of photographs and related data acquired from an aircraft or a satellite (Simonett, 1983). Thus, remote sensing is not just a data-collection process; rather it also includes data analysis: the methods and processes of extracting meaningful spatial information from the remotely sensed data for direct input to the geographic information system. Remote sensing techniques are divided into types: “active” and “passive” remote sensing depending upon the source of electromagnetic energy sensed (Lillesand and Kiefer, 2000). In the passive remote sensing, naturally emitted energy of the target is measured, while in the active remote sensing artificially generated signals are transmitted and the proportion of the return signal is measured. Conventional aerial photography and the satellite remote sensing instruments that obtain pictures of visible, near-infrared (NIR) and thermal infrared (TIR) energy belong to passive remote sensing techniques, while the radar and lidar belong to active remote sensing techniques.

2.3. Components of remote sensing technology

There are four basic components of radiation-based remote sensing systems: *energy source* (Sun, Radar), *transmission path* (atmosphere, vegetation canopy), *target* (subject of any observation), and *remote sensors/satellites* (detection systems). Each of these components plays an important role in controlling what we can measure about the earth's surface (Engman and Gurney, 1991). A brief description of remote sensors and satellites, which constitute the heart of remote sensing technology, is provided below.

2.3.1. Remote sensors

Sensors provide the information in a specific spectral band, e.g., visible, infrared, near-infrared, mid-infrared, microwave, etc. Sensors are usually classified based on the portion of EM spectrum covered (Schultz, 1988). Careful matching of the sensor to the problem can ensure that the results of the study will be useful and easily quantifiable (Engman and Gurney, 1991). A summary of major remote sensors is presented in Table 2. It is apparent from this table that different sensors can provide unique information about properties of the earth's surface or shallow layers of the earth. A general advantage of microwave sensors as opposed to visible and infrared ones is that observations can be made under cloudy conditions. Also, measurements are not dependent on solar illumination and can be made at any time of the day or night. Instruments can be mounted on trucks, aircraft and spacecraft for repetitive large-area observations (Jackson, 2002). Interested readers are referred to Jackson *et al.* (1999) and Jackson (2002) for the details about the application of microwave remote sensing in soil hydrology. Overall, it can be inferred from Table 2 that the synergistic interactions of multiple sensors using various principles and technologies can help improve our knowledge and gain new insights about the earth, its resources and the environment.

2.3.2. Satellite systems

At present, there are a large number of satellites for observing the earth and atmospheric features. According to their purpose, the satellite systems can be broadly divided into two groups: *earth resources satellites* and *environmental satellites* (i.e., meteorological satellites, ocean monitoring satellites, and earth observing satellites). The first group of satellite systems observes the same area of the earth relatively infrequently (in the order of several days) but with relatively high spatial resolutions, and provides the mapping of terrestrial features and conditions. In contrast, environmental satellite systems observe frequently (in the order of hours) but with relatively low spatial resolutions, and provide information on weather conditions and large-scale surface phenomena.

Some important earth resources satellite systems of the world are Landsat (USA), OKEAN (Russia), SPOT (France), IRS (India), ERS (ESA and Canada), JERS and ADEOS (Japan), RADARSAT (Canada), and CBERS (China and Brazil), which provided or are providing a variety of precious information at different spatial, spectral, radiometric, and temporal resolutions (Simonett, 1983; Jensen, 2000). The NOAA series of environmental satellites have been providing since 1978 information useful for hydrologic, oceanographic and meteorologic studies in 5 spectral bands with a 1.1 km spatial resolution. Other meteorological satellites are Meteosat (ESA), GOES (USA), GMS (Japan), DMSP (USA), and INSAT (India), among others. Space Information-2 (SPIN-2) of Russia (2-m panchromatic resolution), OrbView-3 of USA (first commercial high resolution satellite providing 1-m panchromatic and 4-m multi-spectral resolution), IKONOS-2 of USA (1-m panchromatic and 4-m multi-spectral

Table 2 Brief description of the major types of remote sensors (modified from Engman and Gurney, 1991)

Sensor type	Description and utilities
1. Aerial photography	Earlier aerial photographs were of the visible part of the electromagnetic (EM) spectrum, but advances in photography and films enabled to make images of other parts of the spectrum, with a greater interest in near-infrared regions. The primary use of color infrared photography is for vegetation studies. This is because healthy green vegetation is a very strong reflector of infrared radiation and appears bright red on color infrared photographs. Further, it has a long history of use in environmental management (Slama, 1980) and the techniques for interpreting aerial photographs are well developed (Smith, 1968).
2. Gamma radiation sensor	Gamma radiation remote sensing is based on the attenuation of natural terrestrial gamma radiation emitted from the potassium, uranium and thorium radioisotopes in the upper 20 cm of soil or a layer of snow (Carroll, 1981). The gamma flux from the ground is a function primarily of the water mass and radioisotope concentration near the soil surface, which remains almost constant over time. Consequently, there is no need for additional background data collection once a radiation spectrum has been collected for a particular flight. It is used for estimating soil moisture changes and snow-water equivalent.
3. Multi-Spectral scanners (MSS)	This technique involves measuring simultaneously the spectral response of the landscape in two or more narrow wavelength bands of the EM spectrum and recording the information electronically, for example, 4-band MSS and 7-band mechanical scanner called “Thematic Mapper (TM)”. The MSS data are used for estimating land cover, snow cover, water area, impervious area, and various water-quality parameters.
4. Hyperspectral sensors	Recent advances in the sensor technology have led to the development of *hyperspectral sensors* (also called *imaging spectrometers*) capable of collecting imagery of the same area simultaneously in many (often hundreds) very narrow, contiguous spectral bands over the EM spectrum (Lillesand and Kiefer, 2000). The large number of bands provides an opportunity for more materials to be discriminated by their respective spectral response. Hyperspectral remote sensing is being currently investigated by researchers with regard to the detection and identification of minerals, terrestrial vegetation, and man-made materials and backgrounds. However, it has already been shown that the hyperspectral data can be used to quantify nitrogen and lignin concentrations in the forest canopy (Aber and Martin, 1995) as well as to assess the properties of the atmosphere such as water vapor content and other gases contributing to air pollution (Schaepman *et al.*, 1995).
5. Thermal sensors (TS)	Thermal sensors use photo detectors sensitive to the direct contact of photons on their surface, and directly measure the emitted thermal radiation from the earth’s surface. The detectors are cooled to temperatures close to absolute zero in order to limit their own thermal emissions. Thermal sensors essentially measure the surface temperature and the thermal properties of targets. Thermal imagery can be acquired during the day or night (because the radiation is emitted not reflected) and is used for a variety of applications such as military reconnaissance, disaster management (e.g., mapping of forest fire), irrigation management, agricultural applications, thermal plumes, and heat-loss monitoring.

(*Continued on next page*)

Table 2 (*Continued*)

Sensor type		Description and utilities	
6. Laser system		Laser technique involves projecting a narrow beam of coherent visible or near-infrared (NIR) light and measuring the reflected energy with a photomultiplier tube. Airborne laser systems have been used to collect data for topographic surveys as well as to estimate canopy height, stream valley cross-sections, air pollution and chlorophyll. They are also very useful for erosion and gully control studies. Airborne Laser Terrain Mapper (ALTM), for example, acquires digital elevation data with accuracies equivalent to those of GPS, but thousands of times faster. It can be operated during both day and night times.	
7. Microwave sensors (MS)	Active Microwave Sensors (e.g., SAR, Scatterometer)	An increasing amount of valuable information is obtained by the sensors that operate in the microwave portion of the EM spectrum, which are called *microwave sensors*. They use microwave radiation having wavelengths ranging from approximately 1 mm to 1 m, which enables observation under all weather conditions without any restriction by clouds, rain, snow, haze or smoke. Microwave remote sensing systems distinguish between different subjects primarily by the differences in the signal strength received by the radar. In addition, they provide unique information that are derived from frequency characteristics, Doppler effect, polarization, backscattering, etc., which cannot be observed by visible and infrared sensors.	The active microwave sensing system receives the backscattering which is reflected from the transmitted microwave incident on the ground surface. A synthetic aperture radar (SAR) is a coherent radar system, which directly measures the dielectric properties of surface soil or snow. Hence, the microwave data are very useful for estimating soil moisture, vegetation type, snow-water equivalent, condition of snowpack, frozen soil, and sea ice. Scatterometers can be used to measure the two dimensional velocity vectors of the sea wind. Moreover, InSAR (Interferometric SAR) is a technique where two SAR images acquired with a nearly identical incidence angle are combined producing a phase interference image called an *interferogram.* Though SAR images consist of both magnitude (brightness) and phase values, phase information in the *interferogram* is useful to extract topographic height information, height change information, and also in the classification of different land types.
	Passive microwave sensors (e.g., Microwave Radiometers)		The passive microwave sensing system receives the microwave radiation naturally emitted and/or reflected from ambient sources by terrain features. Passive microwave sensing is usually used for monitoring sea ice, currents and winds; detecting oil pollution as well as for atmospheric studies.

(*Continued on next page*)

Table 2 (*Continued*)

Sensor type	Description and utilities
8. Lidar sensors	Lidar system (also known as *laser altimeter* or *laser radar* or *optical radar*) is an active remote sensing technique and is a relatively new technique in remote sensing. It consists of active optical sensors that generate energy using lasers and are developed for extremely high resolution topographic mapping. Lidar system uses pulses of laser light directed toward the ground and measures the time of pulse return (Lillesand and Kiefer, 2000). The radiation used by lidar is at wavelengths which are 10,000 to 100,000 times shorter than that used by the conventional radar. As an active sensor, lidar can be flown at night; but unlike SAR, it is unable to penetrate clouds. A distinct benefit of lidar is that all the data are geo-referenced from inception, which directly interfaces to GIS applications. The lidar applications in general are well suited for generating digital elevation models (DEMs) and automatic feature extraction. Thus, lidar can be used to measure the depth of coastal waters and shoreline topography (*Lidar Bathymeters*), to measure the concentration of atmospheric constituents (*Differential Absorption Lidar*), the wind velocity (*Doppler Lidar*) as well as to monitor clouds (*Multi Field of View Lidar*). Applications are also being established for wireless communication design, forestry assessment of canopy attributes, and research continues for the evaluation of crown diameter, canopy closure, and other biophysical properties.

resolution), and QuickBird-2 of USA (the highest spatial resolution satellite system to date: 61-cm panchromatic and 2.5-m multi-spectral resolution) are prominent high resolution earth resources satellites.

Another increasing amount of valuable environmental and resource information is being acquired by the satellites on-board microwave sensors, for instance, USA's DMSP-SSM/I, India's Oceansat-1, and the AMSR and TRMM satellite systems of USA and Japan besides the several aircraft-based active and passive microwave remote sensing systems (Jackson, 2002). Furthermore, important earth observing satellites are CHAMP (Germany), GRACE (USA-Germany) and GOCE (ESA). The CHAMP satellite system (launched by Germany in July 2000 and scheduled to fly for 5 years) indirectly measures large-scale gravity features. The GRACE (launched by NASA-DLR in March 2002 and scheduled to fly for 5 years) and GOCE (scheduled to be launched by ESA in 2006) satellite systems are designed for making detailed measurements of earth's gravity field with high accuracy, which will lead to the discoveries about gravity and earth's natural systems.

2.4. Data extraction from satellite imagery

Once the required satellite images are purchased in digital form from a vendor of satellite images, the next step is to process the images for extracting the desired spatial and thematic information; satellite images without processing are not of much use, especially for scientific studies. This complex processing is done with the help of a computer by using image processing software packages and is known as *digital image processing* (Lillesand and Kiefer, 2000). User-friendly image processing software packages are usually available for PCs and workstations, and can interactively extract data from satellite imagery. Figure 1 illustrates the major three steps for extracting data from digital satellite images. Clearly, several operations are needed for extracting the required data and/or information. Since in most cases the data obtained from satellite systems are input to a GIS for analyses, modeling as well as for preparing different maps, a conversion from raster data to vector data is necessary. Most digital image processing software and advanced GIS software packages can perform raster-to-vector conversion. This conversion, however, will not be required if the GIS technology is able to process digital images and handle both vector and raster data (Lo and Yeung, 2003). The details of the procedures for extracting data from satellite images can be found in the books/manuals on digital image processing or image interpretation.

3. Overview of GIS technology

3.1. Historical perspective

The history of using computers for mapping and spatial analysis shows that there have been parallel developments in automated data capture, data analysis and presentation in several broadly related fields viz., cadastral and topographical mapping, thematic cartography, civil engineering, geography, soil science, mathematical studies of spatial variation, surveying and photogrammetry, rural and urban planning, utility networks, and remote sensing and image analysis (DeMers, 2000; Clarke, 2001; Lo and Yeung, 2003). Essentially all disciplines are attempting the same kind of operation: to develop a powerful set of tools for collecting, sorting, retrieving, transforming and displaying real-world spatial data for particular purposes. This set of tools constitutes a *'Geographic Information System (GIS)'*. The first geographic information system (also known as Geographical Information System) when first

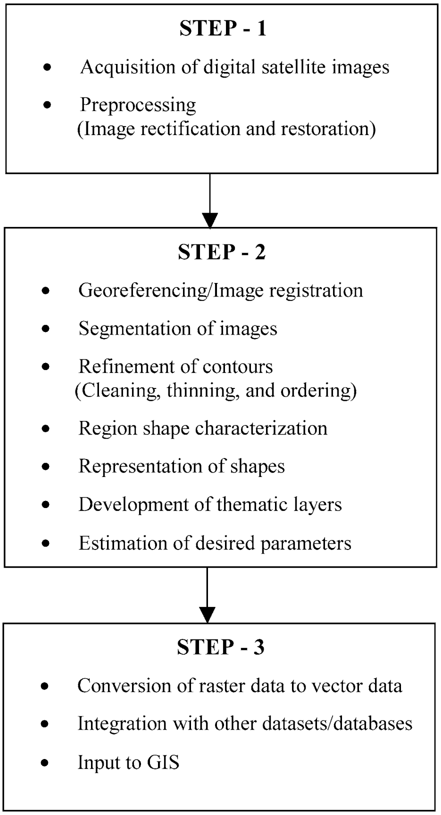

Fig. 1 Procedures for extracting data from digital satellite imagery

developed in the early 1960s in Canada (called ‘Canada Geographic Information System’), they were no more than a set of innovative computer-based applications for map data processing that were used in a small number of government agencies and universities only (Lo and Yeung, 2003). There was no efficient technique to convert maps into numerical form, computer storage capacity was quite limited, processing speed was very low and the cost for these technologies was very high. Table 3 summarizes important phases in the development of GIS technology. It is apparent from this table that during a short span of history, both the technology used to develop GIS and the functions of GIS have undergone considerable changes.

Despite all the technical constraints during the sixties, many of the basic techniques of spatial data handling were invented and applied during that period (Tomlinson, 1984). Although the advancement in computer technology made the systems of the seventies much faster than those in the sixties, the seventies can be described as an era of consolidation rather than innovation in GIS technology. The 1960s and 1970s represented the important formative years of GIS (Table 3). In the 1980s, the pressure for natural resources management continued and so did the demand for GIS. It was the period of technological breakthroughs in the GIS technology — concept of topology evolved; powerful GIS software packages like ArcInfo, MapInfo, SPANS and several other PC-based systems were developed. With the theoretical complexity of data structure largely resolved by the mid-eighties, the focus of GIS development gradually shifted to the methods of data collection, quality and standards

Table 3 Summary of the evolution of GIS technology (after Lo and Yeung, 2003)

Development aspects	Primary stages of development and time frames		
	Formative years (1960–1980)	Maturing technology (1980-Mid-1990s)	GI Infrastructure (Mid-1990s-Present)
Technical environment	• Mainframe computer • Proprietary software • Proprietary data structure • Mainly raster form	• Mainframe and mini computers • Geo-relational data structure • Graphical user interface • New data acquisition technologies (GPS, RS, Redefinition of datum)	• Workstations and PCs • Network/Internet • Open systems design • Multimedia • Data integration • Enterprise computing • Object-relational data model
Major users	• Government • Utilities • Military	• Government • Universities • Utilities • Business • Military	• Government • Universities and schools • Business • Utilities • Military • General public
Major application areas	• Land and resource management • Census • Surveying and mapping	• Land and resource management • Census • Surveying and mapping • Facilities management • Market analysis	• Land and resource management • Census • Surveying and mapping • Facilities management • Market analysis • Utilities • Geographic data browsing

as well as data analysis and database organization. The development of GIS technology was greatly accelerated by the phenomenal growth of computer technology in the 1990s and GIS became multi-platform applications. The increasing access to computers coupled with the urgent need for effective geographic data management pushed the use of GIS to a new height. It is usually agreed that by the mid-nineties, GIS became relatively mature in terms of both technology and applications (Table 3). Since the mid-nineties, the development of GIS has entered a new era that can be aptly called the "Age of Geographic Information Infrastructure" (Lo and Yeung, 2003). The proliferation of GIS gradually led to the formation of a specialized sector in the traditional computer industry — one of the fastest growing sectors of the computer industry. Today, GIS has matured into an industry of its own and has become an important field of academic study, with increasing number of companies, overwhelming demand in various fields, and worldwide growing GIS market and professional organizations.

3.2. Defining geographic information system (GIS)

GIS is generally defined as a computer-assisted mapping and cartographic application, a set of spatial-analytical tools, a type of database systems, or a field of academic study (Lo and Yeung, 2003). In order to provide a simple working definition of GIS, the two widely-used definitions are: (i) "GIS is a system of hardware, software, and procedures designed to support the capture, management, manipulation, analysis, modeling, and display of spatially referenced data for solving complex planning and management problems" (Rhind, 1989); and (ii) "GIS is a computer system capable of assembling, storing, manipulating, and displaying geographically referenced information" (USGS, 1997). The basic ideas contained in these two definitions have been adopted in GIS textbooks such as by Burrough (1986), Aronoff (1989), DeMers (2000) and Clarke (2001). Simply put, GIS is a set of computer-based systems for managing geographic data (i.e., spatial data having the reference to geographic space and the representation at geographic scale) and using these data to solve various spatial problems.

Figure 2 shows the relationship between GIS and different types of information systems. It is obvious that only those information systems which are used for processing and analyzing geographic data can be labeled as GIS. At present, however, GIS not only represents the skills and procedures for collecting, managing, and using geographic information, but also entails a comprehensive body of scientific knowledge from which these skills and procedures are developed (Lo and Yeung, 2003).

3.3. Basic concept of GIS

The geographic data can be represented in GIS as *objects* or *fields (phenomena)*. In the object approach, real-world features are represented by simple objects such as points, lines and polygons. The objects (representing features) are characterized by geometry, topology, and non-spatial attribute values. On the other hand, in the field approach, real-world features are represented as fields of attribute data without defining objects. This approach provides attribute values in any location. In GIS, the distinction between objects and fields is associated with *vector data models* and *raster data models* (Goodchild, 1992). The *vector data model* is an object-based approach for representing real-world features and is best used to represent discrete objects. All vector data models are built on two common and interrelated concepts: the

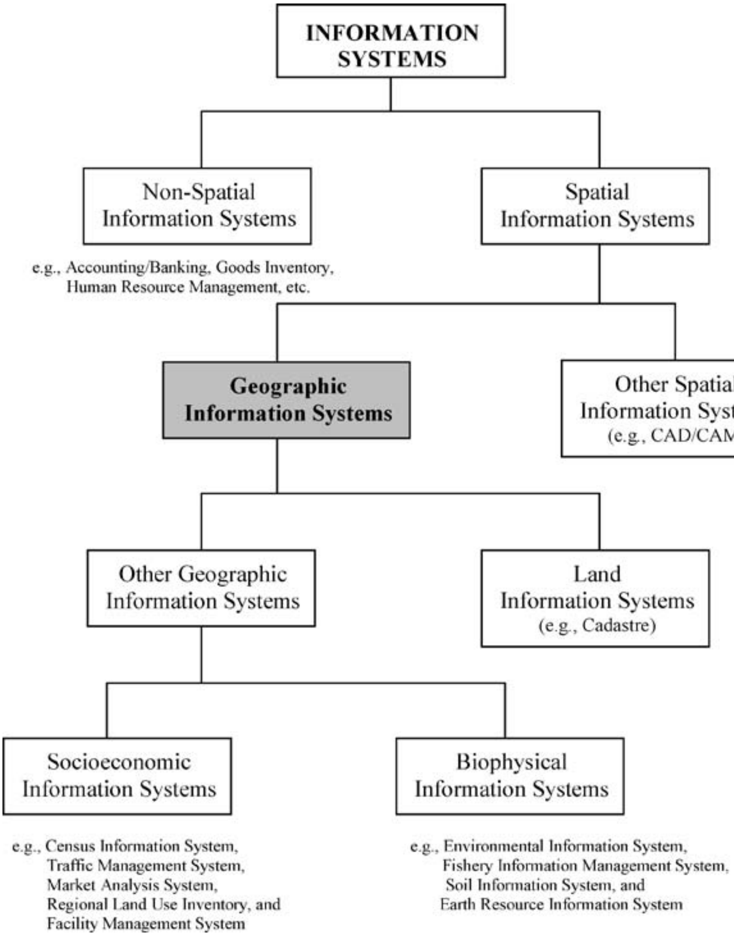

Fig. 2 Typology of information systems (after Lo and Yeung, 2003)

decomposition of spatial objects into basic graphical elements, and the use of topology (spatial relationship) and geometry (coordinates) to represent spatial objects. Thus, each layer is an adapted combination of one or more classes of geometrical features. The *raster data model* is a field-based approach for representing real-world features and is best employed to represent geographic phenomena that are continuous over a large area. This model is characterized by sub-dividing a geographic space into grid cells with values being assigned to each cell. The linear dimensions of each cell define the spatial resolution of the data, which is determined by the size of the smallest object in the geographic space to be represented. This size is also known as the "minimum mapping unit (MMU)". In raster data models, each cell is usually restricted to a single value. Hence, multiple layers are needed to represent the spatial distribution of a number of parameters (variables). A raster-based GIS has advantages over a vector-based GIS because virtually all types of data including attribute data, image data, scanned maps, and digital terrain models can be represented in raster form (Van Der Laan, 1992). Also, the vector data model is conceptually more complex and more technically difficult to implement than the raster data model. However, which data format to use depends actually on the type of applications.

4. RS and GIS applications in groundwater hydrology

4.1. Broad scenario

As far as the remote sensing applications in groundwater hydrology is concerned, aerial photographs, and visible and near-infrared satellite images have been used for groundwater exploration experimentally since 1960s with only limited success (Engman and Gurney, 1991). The absence of spectral resolution did not allow effective use in intrasite groundwater prospecting. However, with the advent of high resolution multi-spectral satellite sensors, the use of satellite imagery (including microwave imagery) for groundwater prospecting dramatically increased in late 1980s (Waters *et al.*, 1990; Engman and Gurney, 1991; Meijernik, 2000; Jackson, 2002). The use of remote sensing technique has been proved a very cost-effective approach in prospecting and preliminary surveys, because of high cost of drilling. Generally, the analysis of aerial photographs or satellite imagery is recommended prior to ground surveys and fieldwork, because it may eliminate areas of potentially low water-bearing strata and may also indicate promising areas for intensive field investigations (Revzon *et al.*, 1983). It should be, however, noted that the adoption of remote sensing does not eliminate the *in situ* data collection, which is still essential to verify the accuracy of remote sensing data and their interpretation. Of course, remote sensing helps minimize the amount of field data collection.

A review of GIS applications in hydrology and water management has been presented by several researchers during early nineties and mid-nineties such as Zhang *et al.* (1990), DeVantier and Feldman (1993), Ross and Tara (1993), Schultz (1993), Deckers and Te Stroet (1996), and Tsihrintzis *et al.* (1996). These reviews indicate that GIS applications in hydrology and water management are essentially in a modeling dominated context. Longley *et al.* (1998), on the other hand, while presenting the development of geocomputation, discuss various geoscientific applications of GIS as well as the role of geocomputation in the development and application of GI technologies. Although the use of GIS in groundwater modeling studies dates back to 1987, its use for surface-water modeling has been more prevalent than for groundwater modeling because the available standardized GIS coverages are primarily of the land surface; few standardized coverages of hydrogeologic properties are available (Watkins *et al.*, 1996). Watkins *et al.* (1996) present an excellent overview of GIS applications in groundwater-flow modeling as well as discuss its usefulness and future directions. On the other hand, Pinder (2002) provides step-by-step procedures for groundwater flow and transport modeling using GIS technology. The current status of GIS and RS applications in groundwater hydrology is presented in succeeding sections.

A detailed survey of the past literature concerning the applications of remote sensing and GIS techniques in studying groundwater problems was carried out. Attempts have been made to put together all the concerned literature available in scattered locations and in different forms. However, in the present review, the experimental and preliminary applied RS-based groundwater studies conducted from 1960 to mid-eighties (though limited) are not included because of the inaccessibility of their original sources. Interested readers are referred to Engman and Gurney (1991) for a brief description about such studies. Based on this comprehensive literature survey, the applications of RS and GIS techniques in groundwater hydrology to date have been categorized into six major groups and the case studies pertaining to each group are succinctly described in subsequent sections.

4.2. Exploration and assessment of groundwater resources

Rampal and Rao (1989) used MSS Landsat data of the Doddaguni area in Karnataka, India for targeting groundwater potential zones. The groundwater targeting was dependent on the identification and mapping of fractures, lithologic units and regional geology of the study area. They developed computer programs to enhance images using histogram equalization, combination and rationing of bands, and high and low-pass filtering. Using the various enhanced images, a geological map of the area was prepared and a relationship between the lithologic units and estimated water features was developed. The validity of the methodology was checked and found very encouraging in classifying the study area according to the groundwater potential.

Bobba *et al.* (1992), using the digital radiance Landsat data of Big Creek and Big Otter Creek basins in southern Ontario (Canada), delineated principal groundwater regimes according to the proximity of water table to the surface, i.e., discharge, recharge and transition areas. They reported that during the spring, the modulating influence of groundwater on the near-surface temperature could be detected only using the near-infrared band of the satellite imagery. However, during summer months, the presence of phreatophytic vegetation throughout the watershed required the visible energy band in conjunction with the near-infrared data to affect such a classification scheme. They concluded that the digital satellite data proved to be very useful in delineating groundwater flow systems, which are valuable input to the hydrological modeling, non-point source modeling, and the selection of solid-waste disposal sites.

Salama *et al.* (1994) used aerial photographs and Landsat (TM) data to prepare the maps of geomorphology, geology and structures of the Salt River System of Western Australia for classifying the units that control the mechanisms of groundwater recharge and discharge in the area. The hydrogeologic interpretation of geomorphologic patterns and the classified hydrogeomorphic units from the TM analysis were used to identify recharge and discharge zones. They inferred that the permeable areas around the circular granaitic plutons and the highly permeable areas of sand plains were good for recharge. Groundwater discharge was primarily found along the main drainage lines, on the edge of the circular sand plains, in depressions, and in lakes.

Kamaraju *et al.* (1995) evaluated the groundwater potential in West Godavari District of A.P., India using GIS. They used the existing maps and records as input data which were in different forms and scales, and created a GIS database using ArcInfo software. The descriptive information was converted into "groundwater favorability index" by rating the various groundwater-controlling characteristics according to their weightings to the output. The groundwater potential map thus generated showed three major hydrogeologic conditions with distinct groundwater prospects. They emphasized that the GIS technique is very time- and cost-effective and could be employed successfully in the planning stage of a groundwater exploration programme.

Teeuw (1995) proposed an integrated approach of remote sensing and GIS techniques to improve the site selection of borehole drilling in the Volta basin of Northern Ghana. He reported that the sites selected for groundwater potential based on the aerial photographs, lineament mapping and geophysical surveys in the area were mostly failed. The very low success rate of this initial groundwater exploration program was attributed to the difficulties encountered at the stage of aerial photograph interpretation and lineament mapping, rather than those at the follow-up geophysical survey stage. In order to improve the success rate of groundwater exploration in the basin, a low-cost GIS software package "IDRISI" was used along with the Landsat TM satellite image. It was demonstrated that unlike the single broad sector of the electromagnetic spectrum observed in aerial photographs, the seven-band Landsat image produced good quality lineament maps that helped in proper delineation of groundwater potential areas. Consequently, the success rate improved to 55% using the integrated approach of remote sensing and GIS techniques compared to the alone use of aerial photographs where the success rate was only 5%.

Krishnamurthy *et al.* (1996) used remote sensing and GIS for demarcating groundwater potential areas in the Marudaiyar basin of Tamil Nadu, India. They prepared the maps of lithology, landforms, lineaments and surface water bodies from the remotely sensed data, and those of drainage density and slope from SOI (Survey of India) toposheets. These thematic maps were integrated and analyzed using a model developed with logical conditions in a GIS. Finally, the groundwater potential zone map thus developed was verified with field data, which indicated a good agreement.

Sander *et al.* (1996) developed better well-siting strategies for the violtanian Sedimentary basin in central Ghana using remote sensing, GPS and GIS. Remote sensing data used were from Landsat TM, SPOT, and infrared aerial photographs. These data were interpreted for lineament, vegetation, drainage and bedrock features to evaluate groundwater potential. Lineaments were also examined in the field and integrated with the information from several GPS-positioned boreholes. They integrated these data into a GIS to develop optimal strategies for future well siting. GPS improved the spatial accuracy of various data integrated in the GIS. They concluded that though GIS proved to be an effective integration tool for analyzing spatial data and developing well-siting strategies, the implementation of a GIS in a groundwater project requires careful planning to avoid costly and unnecessary data acquisition and entry.

Edet *et al.* (1998) applied remote sensing technique for delineating the areas expected to be suitable for future groundwater development in the Cross River State of southeastern Nigeria. Radar imagery and areal photographs were used to define some hydrologic and hydrogeologic features in parts of the study area. Lineaments and drainage patterns were analyzed using length density and frequency. The results were then used to delineate the areas of high, medium, and low groundwater potential. They found good correlations between the lineament and drainage patterns, lithology, water temperature, water conductivity, well yield, transmissivity, longitudinal conductance, and the occurrence of groundwater.

Travaglia and Ammar (1998) proposed a methodology for the integration of GIS data extracted from satellite imagery with traditionally-gathered data. Based on the analysis of these data and selected field investigations, it was revealed that in the basaltic terrain of southern Syria, the groundwater movement along faults and features occurred mainly due to tectonic movements. The statistical analysis of the lineaments interpreted from the Landsat TM data indicated two major directions of fracturing, which was considered as "open" for groundwater storage and transmission. It was concluded that the developed methodology could be applied in other parts of Syria as well as in other countries with similar hydrogeologic conditions.

Goyal *et al.* (1999) used a multi-criteria evaluation technique (MCET) to evaluate the inter class and inter-map dependencies for groundwater evaluation in the Rawasen and Pili watersheds of Uttar Pradesh, India. They developed various thematic maps such as land use, geomorphology and lineament maps from satellite images and aerial photographs. A drainage map was prepared using the Survey of India (SOI) toposheets. The slope map was obtained by creating DEM after interpolating spot elevation and contours in GIS. For integration, all the maps were converted into digital formats in the GIS environment, which were then used for the zonation of groundwater availability in the Rawasen and Pili watersheds.

Musa *et al.* (2000) used an integrated remote sensing and GIS system to produce various thematic maps for classifying groundwater potential zones in Langat Basin, Malaysia. They used Landsat TM data, topographic map, soil map and other relevant field data for preparing various thematic layers such as annual rainfall, lithology, lineament density, drainage density, land use, land elevation, slope steepness and soil type, and combined all the layers using a modified DRASTIC (**D**epth to water, net **R**echarge, **A**quifer media, **S**oil media, **T**opography, **I**mpact of vadose zone media, and aquifer hydraulic **C**onductivity) model. The polygons in each of the thematic layers were categorized depending on their suitability/relevance to the groundwater potential, and suitable weights were assigned to them. Finally, all the thematic layers were integrated using a groundwater potential model to derive the final layer. It was concluded that the integrated assessment of thematic maps using a GIS-based model proved to be the most suitable method for groundwater potential zoning in hard-rock terrains.

Based on research work in the Truyère River catchment of the Massif Central, France, Lachassagne *et al.* (2001) developed a new methodology for delineating favorable prospecting zones of a few square kilometers within basement areas of several hundred square kilometers for the purpose of siting high-yield water wells. The methodology adopts a functional approach to hard-rock aquifers using a conceptual model of the aquifer structure and of the functioning of the main aquifer compartments: the alterites (weathered and decayed rock), the underlying weathered-fissured zone, and the fractured bedrock. It involves an economically feasible method of mapping the thickness and spatial distribution of the alterites and the weathered-fissured zone, on which the long-term exploitation of the water resource chiefly depends. The potential groundwater resources were mapped by GIS multi-criteria analysis using various parameters characterizing the structure and functioning of the aquifer. It was concluded that the developed methodology involves a coherent process of downscaling that, through applying methods that are increasingly precise but also increasingly costly, enables the selection of sites with diminishing surface areas as the work advances.

Shahid and Nath (2002) analyzed the hydrogeologic data obtained from remote sensing and surface geophysical techniques for evaluating the groundwater condition in a soft-rock terrain of Midnapore District, West Bengal, India. The IRS LISS-II data were used for generating the thematic map of geology. Vertical electrical sounding (VES) survey was conducted at 139 locations in the study area, and the data were interpreted using genetic algorithm and Ridge Regression techniques. The aquifer resistivity and thickness thus obtained were used to prepare the corresponding thematic maps. Weights were assigned to different ranges of resistivity and thickness values based on their position on the geological map. Finally, the weighted maps were integrated using a GIS-based aggregation method to identify groundwater potential zones in the study area.

Singh and Prakash (2002) combined remote sensing, geophysics and GIS techniques to demarcate groundwater potential zones in the hard-rock region of India. They prepared hydrogeomorphological and lineament maps from IRS LISS-III data by using visual interpretation. The topographic information was obtained from the SOI toposheets of 1:50,000 scale and TIN was generated from elevation contours. Slope maps were prepared from TIN, and the surface drainage maps were prepared from the toposheets and satellite data. Electrical resistivity surveys were also conducted to investigate the lithology and the horizontal and vertical extent of aquifer systems. A groundwater potential map was developed by integrating the relevant layers (i.e., hydrogeomorphology, lineament, slope, drainage, and overburden thickness) in ArcInfo GIS environment, and then assigning appropriate weights to each layer based on their relative contribution to the existence of groundwater. The verification of the developed groundwater potential map indicated that the demarcated groundwater potential zones are in fair agreement with the well-yield data.

Singh *et al.* (2002) used remote sensing, geoelctrical and GIS techniques for groundwater exploration in Sonebatra, Mirjapur and Chaundali districts of Uttar Pradesh, India. They used

IRS LISS-II data for preparing hydro-geomorphological and lineament maps. The groundwater potential was assessed through the integration of relevant layers in the ArcInfo grid environment, which included hydro-geomorphology, slope, lineament, aquifer thickness, and clay thickness. The generated groundwater zone map was verified with the well-yield data and a good correlation was found.

Srivastava (2002) integrated the remote sensing data with the hydrologic data in order to investigate subsurface details, aquifer geometry and groundwater quality in Ken Graben, Uttar Pradesh, India. He used IRS LISS-I/II data to explore the geological, geomorphological and structural aspects of the terrain. Buried channels and two different types of basement depressions were identified in the study area which affected the aquifer geometry, groundwater potential and quality. The variations in tone and texture associated with vegetation and geological features, coupled with the inferred groundwater migration pattern in the area enabled the delineation of brackish groundwater pockets, which was in close agreement with the field observation. Furthermore, an overlay of the enhanced image on the digital terrain model of the study area revealed the exact surface geometry of aquifers and their relationship to the surficial geomorphic features.

Hadithi *et al.* (2003) evaluated the groundwater potential in the Ratmau-Pathri Rao watershed in Haridwar district, India using geo-electrical, remote sensing (RS) and GIS techniques. They integrated various thematic maps, viz., geology, hydro-geomorphology, drainage density, slope, aquifer thickness, and depth to water table in a GIS framework. Then appropriate weights were assigned to various factors affecting the occurrence of groundwater to evaluate groundwater potential in each segment of the study area. They found that the categorization of groundwater potential by RS and GIS techniques was in agreement with the available well-yield data.

Sikdar *et al.* (2004) used remote sensing and GIS techniques to explore the land use/land cover changes and to delineate groundwater potential zones in and around Raniganj coal mining area of Bardhaman District, West Bengal, India. They used IRS LISS-III data and toposheets to identify land use/land cover changes from 1972 to 1998 in the area. It was found that the land covered by vegetation and settlement has decreased during this period at the expense of mining activities. Various thematic layers namely geomorphology, lithology, drainage texture, slope, lineament density and current land-use pattern were considered to delineate groundwater potential zones. These thematic layers were prepared using ILWIS GIS package, and ranked in a scale of 0 to 5 depending upon their suitability for groundwater occurrence. The rank of each map was then converted to a probability weight using Bayesian statistics and finally a multi-criteria overlay analysis was used to find groundwater potential zones. The groundwater abstraction structures (i.e., dug wells, mini-deep tubewells or deep tubewells) feasible in each of the delineated potential zones were also suggested.

4.3. Selection of artificial recharge sites

Elango and Arrikkat (1998) integrated and analyzed various thematic layers related to groundwater recharge using GIS for the identification of recharge sites in parts of Ongur sub-basin, south India. Seven thematic layers were prepared using both remotely sensed and conventional data. These layers were ranked, reclassified, and overlayed in ArcInfo GIS. Based on the GIS analysis, the study area was divided into four zones viz., ‘very good’, ‘good’, ‘poor’, and ‘very poor’ according to the potential for natural recharge. The unfavorable areas were further classified into four classes on the basis of potential for artificial recharge. It was concluded that remotely sensed data, conventional data, and GIS overlay analyses provide a powerful and practical approach to identify groundwater recharge areas in a basin.

Ramlingam and Santhakumar (2002) used remote sensing and GIS techniques to explore suitable recharge areas and structures to augment an aquifer system in Tamil Nadu, India. The thematic maps such as geomorphology, geology, soil, slope, land use, drainage density, lineament density, runoff isolines, depth to weathered zone, depth to basement, groundwater level fluctuations and the water quality were used in this study. These maps were prepared using IRS LISS-III satellite data and other collateral information obtained from the field. The ArcInfo GIS package was used to identify suitable artificial recharge areas. They used 1-sigma criteria to divide the rechargeable area into various categories namely 'highly favorable', 'moderately favorable', 'less favorable' and 'poor'. Suitable recharge structures were proposed depending on the terrain condition and favorable zonation. They concluded that the zonation created using GIS as well as the type and location of water-harvesting structures suggested were agreeable, and the success rate was more than 90%.

Vasanthakumaran *et al.* (2002) used remote sensing and GIS techniques for selecting suitable sites for artificial groundwater recharge in the rocky terrain of Southern India. They used toposheets and satellite data for preparing soil, lineament, and drainage density maps. The developed themes were integrated using ArcView and ArcInfo GIS software and appropriate weights were assigned to each theme, which resulted in the identification of suitable artificial recharge sites.

The methodology adopted by researchers for the identification of groundwater potential zones and for the selection of suitable sites for artificial recharge or rainwater harvesting is illustrated in Figure 3. In this figure, the dashed arrows show the optional step that is not always followed because of the lack of appropriate field data.

4.4. GIS-based subsurface flow and pollution modeling: model development, applications and evaluation

Adams *et al.* (1993) developed a GIS-based spatial data model called WELLHEAD to view and retrieve subsurface data interactively and graphically. The relational model of WELLHEAD that represented the relations and data dictionary for WELLHEAD as well as the construction of WELLHEAD as a feature-based system using object-oriented data modeling is described. It was reported that the abstraction mechanisms could be used to build a richer and more natural object-oriented data model for the boring log management system. Further, the relational systems are useful because of their nonprocedural data manipulation language, embedded and ad hoc query languages, and a high degree of data independence.

Baker *et al.* (1993) using GIS calculated the variables of input to the uniform flow analytical model which was used in conjunction with the hydrogeologic mapping for wellhead protection areas (WHPAs) of the Rhode Island Department of Environmental Management (RIDEM) to evolve groundwater protection strategies. The proposed model is composed of four modules: RESSOC, MWCAP, GPTRAC, and MONTEC and each module independently calculate a "capture zone" (i.e., surface and subsurface areas contributing groundwater to a pumping well). They found that the integration of GIS and WHPA groundwater flow model proved to be a valuable tool in the state wellhead protection program. The limitations of the model are also highlighted.

Camp and Brown (1993) developed a GIS-based methodology for developing subsurface profiles from well-log data. They examined the accuracy and the reliability of well-logs with the help of geophysical logs and formation logs for each borehole from as many sources as possible. It was found that the geophysical logs were the most important and formed the nucleus of the GIS-well-log database. It was also demonstrated that any number of cross-sectional profiles or three-dimensional images of well-log data could be created and

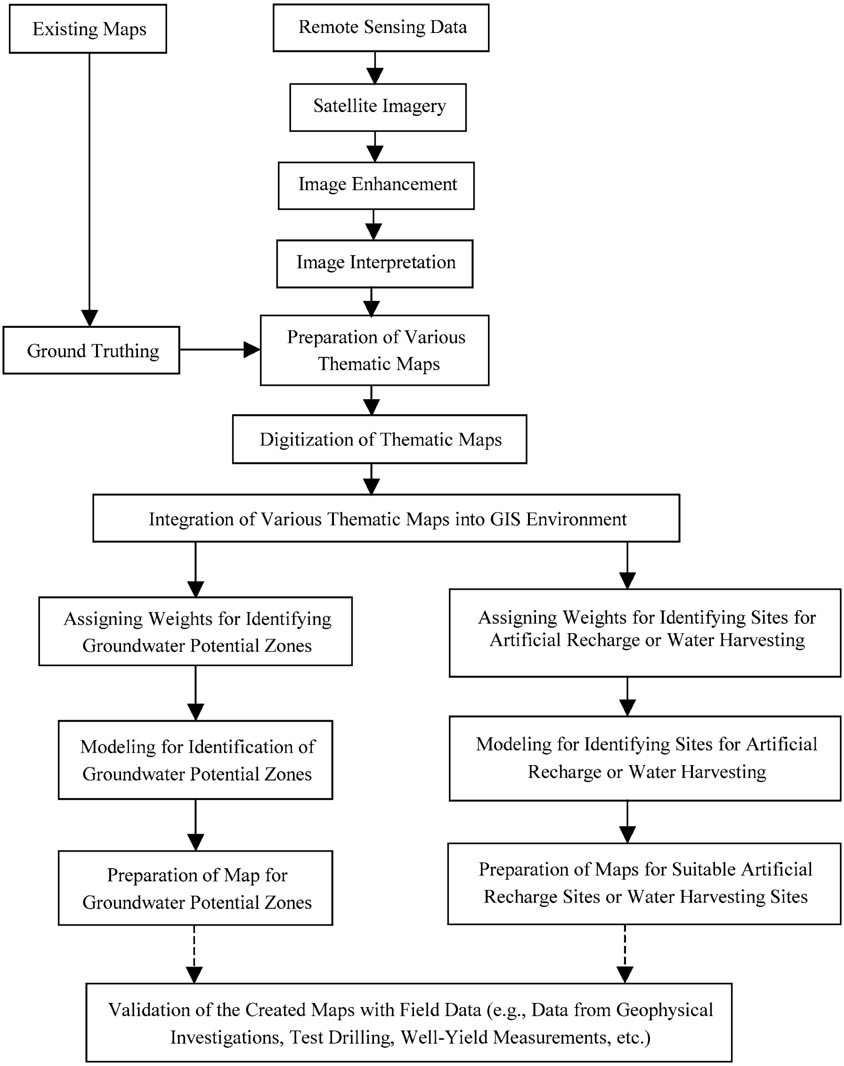

Fig. 3 Flowchart for evaluating and managing groundwater resources by integrated remote sensing and GIS techniques

viewed interactively from this database. Furthermore, for each of the subsurface units, a GIS-MODFLOW interface was developed that computes the geo-hydrographic parameters from the well-log database. It was concluded that a GIS-based interface provided a powerful method for overcoming data generation problems in groundwater-flow modeling.

Hinamann (1993) demonstrated the use of GIS for assembling input datasets for a FDM-based three-dimensional groundwater flow model, MODFLOW through a case study in the middle Patuxent River basin of Howard County, Maryland. The model grids were developed with GIS. They considered various attributes such as model boundaries, regolith thickness, stream length, stream location, etc. After preparing the input layers using GIS, the output layers were prepared in a format which was suitable for the MODFLOW input. It was emphasized that the ability of GIS to change large sets of spatial data quickly and accurately enhanced the model calibration process.

Richards *et al.* (1993) used a numerical groundwater model, MODFLOW in a GIS environment using ArcInfo software to optimize well-field design and to analyze aquifer stress problems in a coastal area of Santa Rosa County, Florida. They used GIS as a primary tool for the development of the model grids, in studying the performance of modeling procedure and the model analysis. They demonstrated that the model calibration became very quick and efficient using GIS tools. They concluded that GIS was well-suited to efficiently manage resource modeling projects by allowing data management, data analysis and graphic outputs within a single integrated software system. Model systems for specific modeling projects could also be developed very quickly and easily.

Roaza *et al.* (1993) developed a FEM-based three-dimensional, density-dependent transport and flow model using the SWICHA code to study the hydraulics of the aquifer in Escambia County, Florida. The modeling technique was integrated with ArcInfo GIS to develop a system for optimal management of the resource. The GIS was the primary tool in the development of the model grid, as well as being the integral component in the modeling procedure. Multiple model grids were developed for simulating regional flow and local flow/transport phenomena. Further, the model calibration was conducted within the GIS environment through a combination of visual and relational querying. It was inferred that the GIS provided an integrated environment which facilitated model analyses, and data storage and retrieval.

El-Kadi *et al.* (1994) presented a GIS-embedded groundwater modeling approach and illustrated the procedure considering the Oahu Island, Hawaii as a case study. They linked the USGS model, MOC into the MapInfo GIS package and then applied to the study area. It was emphasized that the linkage was generic in nature and could be extended to other models as well. The availability of a programming language in the GIS package facilitated pre- and post-processing efforts within custom-made dialogue boxes and pull-down menus. It was concluded that the integrated system was suitable for extracting and interpolating point measurements from maps. The drawback of the integrated system, however, was highlighted as the relative difficulty in extracting spatially distributed data owing to the vectorized nature of GIS.

Wylie *et al.* (1994) tested a Nitrate Leaching and Economic Analysis Package (NLEAP) model in conjunction with a GIS for regional irrigated agriculture in eastern Colorado. The results indicated that the NLEAP NO_3-N-leached (NL) index, an index of the amount of NO_3-N leached below the rooting zone, was useful for describing the distribution of groundwater NO_3-N concentrations across a 736 km^2 area when used in combination with a GIS. Comparison of observed NO_3-N distributions in the South Platte alluvial aquifer with simulated NL distributions gave regional Pearson correlation coefficients of 0.59 and showed that the model could simulate the major observed groundwater NO_3-N patterns.

Barber *et al.* (1996) studied the impact of urbanization on groundwater quality in relation to land-use changes in a groundwater supply field near Perth, Western Australia. They analyzed 23-year (1974–1996) groundwater-quality data from eleven production wells and investigated land-use changes occurred during this period. It was found that the land was converted from natural bush land to its present urban situation. The groundwater quality in production wells was found to be contaminated by increasing nitrate and volatile organic compounds (VOCs) derived from urban and industrial developments. Also, they integrated a numerical groundwater model (FEFLOW) with GIS to demonstrate transient character of the capture-zone boundaries of production wells due to seasonal changes in recharge and water demand, and its relation to areas of different land uses. It was predicted that the full impact of the unsewered urban development will occur in about 15–20 years.

Watkins *et al.* (1996) evaluated the three methods of interfacing between GIS and groundwater models (viz., models linked to GIS, models integrated with GIS, and models embedded in GIS) and emphasized the usefulness of GIS in groundwater modeling. The linking of GIS and groundwater models was recognized as a powerful platform for developing models, calibrating and validating them, and displaying results. Some of the disadvantages of the integrated GIS-groundwater program were identified as high hardware and software costs, and a high level of initial user effort. It was concluded that despite the limitations of each interfacing method, each has the potential to make traditional 'stand-alone' modeling programs obsolete, and that the researchers have only just scratched the surface in GIS to improve groundwater modeling. Furthermore, current needs are identified and the suggestions for future work are made.

Corwin *et al.* (1997) presented a critical review on the GIS-based modeling of non-point source (NPS) pollutants in the vadose zone. Areas discussed include the significance of NPS pollutants as a global environmental problem, the justification for the GIS-based modeling of NPS pollutants in the vadose zone, the basic components of environmental modeling with GIS, a review of existing GIS-based NPS pollutant models, the application of geostatistics to GIS-based NPS pollutant modeling, the influence of scale, the reliability of NPS pollutant models based on model errors and data uncertainties, and the future direction of GIS-based NPS pollutant modeling. It was concluded that the proliferation of GIS-based NPS pollutant models holds promise, yet caution is needed to avoid the misuse of a potentially valuable environmental assessment tool for decision makers.

Lasserre *et al.* (1999) developed a simple GIS-linked model for nitrate transport using the IDRISI GIS software. They found that significantly less data are required for this GIS-linked model compared to the more classical hydro-geochemical model. They also linked this model with an unsaturated-zone transport model called AgriFlux for simulating water and nitrate fluxes leaving the root zone. The results indicated that the simulated nitrate concentrations were in good agreement with the measured values. Further, in order to compare the GIS-linked model with a more complete model, simulations were also performed using the standard software, MT3D-MODFLOW. The similarities between the results of these two models confirmed the validity of the developed GIS-linked model.

Balteman and Smedt (2001) developed a physically-based model called WetSpass for the estimation of long-term average spatial patterns of surface runoff, actual evapotranspiration and groundwater recharge. They integrated the developed model in the GIS ArcView as a raster model, and the parameters such as land-use and related soil type were connected to the model as attribute tables of the land-use and soil raster maps. The model was calibrated with recharge as input and then validated satisfactorily. It was suggested that the model is especially suitable for studying the long-term effects of land use changes on the water regime in a basin.

Boutt *et al.* (2001) presented an approach to examine potential relationships between land use-derived solutes and baseflow surface water quality by estimating chloride concentrations in surface water due to road-salt transport through groundwater at the Michigan's Grand Traverse Bay Watershed (GTBW) using groundwater modeling and GIS. They developed a three-dimensional groundwater flow model of the GTBW using MODFLOW and incorporated ArcInfo GIS software in the model which was beneficial for the model development and the analysis of model output as large amount of spatial data were required to execute the model. They reported that the developed geologically parameterized model offers a method to estimate spatially and temporally variable solute fluxes via groundwater to streams and lakes in the study area. A considerable legacy of land use influencing surface water quality was found in the area. It was concluded that this approach could also be used to examine the impacts of other land-use related solutes on baseflow surface water quality.

Gogu *et al.* (2001) designed a hydrogeologic GIS database that offered facilities for groundwater-vulnerability analysis and hydrogeologic modeling for the Walloon region in Belgium. A loose-coupling tool was created between the spatial-database scheme and the groundwater numerical model interface GMS (Groundwater Modeling System). Following time and spatial queries, the hydrogeologic data stored in the database can be easily used within different groundwater numerical models. They found that most GIS could easily accomplish overlay and index operation, but could not perform the process-based groundwater flow and transport phenomena. However, the coupling of a GIS to process-based models could provide an efficient tool for processing, storing, manipulating and displaying hydrogeologic data. Also, a well-designed GIS could significantly reduce the time needed for data preparation and presentation.

Hall *et al.* (2001) conducted an extensive series of leaching simulations with the NLEAP model using best estimates of local agricultural practices to clarify the relative roles of the different nitrate leaching controlling variables under irrigated agriculture in northeastern Colorado. The results of these simulations were then used with GIS to estimate the spatial variability of leachate quality for a 14,000 ha area overlying the alluvial aquifer of the South Platte River. Simulations showed that differences in soil type might lead to 5–10 kg/ha of N variation in annual leaching rates, while the variability due to crop rotations was as much as 65 kg-N/ha for common rotations. Land application of manure from confined animal feeding operations may account for more than 100 kg-N/ha additional leaching. It was inferred that the land application of manure is the most important factor determining the mass flux of nitrate leached, and the combination of sprinkler irrigation and manure application yields highest leachate concentrations.

Shivraj and Jothimani(2002) developed a comprehensive groundwater information system (GWIS) with extensive capabilities of GIS. It is a 32-bit Windows-based groundwater data management and analysis software that can comprehensively manage, evaluate and present most types of groundwater information – both spatially and non-spatially. They reported that one of immediate uses of the software is to create basic spatial and non-spatial databases and generate documents and reports, with all the data processed in graphs, maps, and tables. Such information is useful for further characterization and evaluation of sites, contaminant potentials, need for remediation, and water development potential.

Chowdary *et al.* (2003) integrated a groundwater flow model and GIS to estimate the spatial distribution of groundwater recharge and to simulate the behavior of Godavari Delta aquifer in Andhra Pradesh, India. They divided the entire study area into a set of basic simulation units (BSUs) that were homogenous with respect to the factors affecting recharge processes. A daily field soil water balance model and a simple canal flow model were used to estimate percolation and seepage losses, respectively. The loose link between models and GIS enabled model and GIS development to proceed independently and easy adaptation of existing models, which was both time- and cost-effective. The spatial distribution of recharge derived from the GIS and of pumping based on a heuristic approach was validated by using a finite element groundwater flow model. It was concluded that the integrated framework could be used as a decision support tool to assess groundwater resources and to identify suitable conjunctive use strategies for large canal-irrigation projects.

Herzog *et al.* (2003) developed a three-dimensional (3-D) hydrostratigraphic model of the complex glacial-drift aquifer system in central Illinois to identify possible areas where a regional water supply could be obtained from the aquifer with minimal adverse impacts on existing users. Geologic information from more than 2200 existing water well logs was supplemented with new data from 28 test borings, water level measurements in 430 wells, and 35 km of surface geophysical profiles. A 3-D hydrostratigraphic model was developed using a contouring software package, a geographic information system (GIS), and the 3-D geologic modeling package, EarthVisionR. The hydrostratigraphy of the glacial-drift sequence was depicted as seven uneven and discontinuous layers, which could be viewed from an infinite number of horizontal and vertical slices and as solid models of any layer. Several iterations were required before the 3-D model presented a reasonable depiction of the aquifer system. Layers from the resultant hydrostratigraphic model were imported into MODFLOW, where they were modified into continuous layers. It was reported that this approach of developing a 3-D hydrostratigraphic model can be applied to other areas having complex aquifer systems, and is also useful in helping lay audiences visualize aquifer systems.

Almasri and Kaluarachchi (2004) presented a GIS-based modeling approach to estimate the variability of on-ground nitrogen loading and the corresponding nitrate leaching to groundwater. The methodology integrates all point and nonpoint sources of nitrogen, the national land cover database, soil nitrogen transformations, and the uncertainty of key soil and land use-related parameters to predict the nitrate mass leaching to groundwater. The analysis considered 21 different land use classes with information derived from different nitrogen sources. The model was applied to a large aquifer of 376 square miles in Washington State and monthly simulations were performed to capture seasonal trends. The simulation results indicated that dairy manure is the main source of nitrogen in the area followed by fertilizers. A change in the land use pattern has a noticeable impact on nitrate leaching. Further, the uncertainty analysis revealed that denitrification rate is the most influential parameter on nitrate leaching. It was concluded that combining management alternatives is a successful strategy, especially with the use of nitrification inhibitors.

Gossel *et al.* (2004) developed a three-dimensional GIS-based groundwater flow model for the Nubian Sandstone Aquifer in the eastern Sahara. The model was calibrated under steady-state and transient conditions and then was used to simulate the response of the aquifer to climatic changes that occurred during the last 25,000 years. The simulation results indicated that the groundwater in this aquifer was formed by infiltration during the wet periods 20,000 and 5,000 years B.P. The recharge of groundwater due to regional groundwater flow from more humid areas in the south was excluded. It was also found that the Nubian Aquifer System is a fossil aquifer, which had been in an unsteady-state condition for the last 3,000 years.

4.5. Groundwater-pollution hazard assessment and protection planning

Baker and Panciera (1990) used GIS technology to develop a groundwater database called RIGIS for groundwater protection planning at state and local levels. The Rhode Island GIS (RIGIS) focused on the preparation of a groundwater classification map. The data layers required for this classification were glacial geology, significant stratified drift aquifers, aquifer recharge areas, water table contours, transmissivity, saturated thickness, hydrograph, community water-supply wells, and known potential sources of groundwater contamination. To develop a groundwater protection plan on local basis, various data were required which were not always available all the time. However, GIS could provide many of such information. They concluded that though the RIGIS provided a good tool for groundwater protection planning for the Rhode Island, there were some inherent limitations of geographic analyses which might be recognized by the government to avoid inappropriate applications of information.

Evans and Myers (1990) presented a GIS-based approach to evaluate regional groundwater pollution potential of an unconfined aquifer in Columbia. The ERDAS GIS package was used to overlay and evaluate the various input layers of spatially oriented data to determine the potential for negative groundwater impacts in the study area. They primarily aimed at developing map products from geographic databases using ERDAS software in conjunction with the DRASTIC groundwater evaluation system. Two different types of groundwater evaluation were made. In the first type of evaluation, an evaluation of the pollution potential for any given location was made based on the local depth to groundwater, aquifer hydraulic conductivity, land slope and soil permeability. A risk assessment map was prepared to display the results. In the second type of evaluation, a qualitative determination of the probability of groundwater pollution due to human-related factors was made, which resulted in a "hazard assessment" map. They inferred that these GIS-based risk and hazard assessment maps could be used to develop strategies to safeguard groundwater resources.

Shih and Jordan (1990) investigated the serious saline contamination problem of artesian wells in Florida using remote sensing technique. They used ground-based Kodak 2236 color infrared (GCIR) slide photographs and Kodak 2443 aerial color infrared photographs (ACIR) to study the spectral reflectance from different land cover types associated with artesian well sites. It was found that both the ground-based color infrared (GCIR) and aerial color infrared (ACIR) showed similar patterns of spectral reflectance for the same component class of land surface features. The soil of well site had a higher spectral reflectance than the soil not associated with a well, and the well-pool water had a higher spectral reflectance than the pond and ditch water. It was also found that the combination of red and green channels of spectral reflectance video digitized from the ACIR photographs is useful for classifying land cover types and for distinguishing flowing wells. It was concluded that both the GCIR and ACIR photographs could be used for the analysis of the spectral reflectance of land surface features, which in turn can help in detecting flowing wells.

Halliday and Wolfe (1991) linked the GRASS GIS software with the DRASTIC model to identify the degree of correlation between the susceptibility of groundwater to pollution and the availability of nitrogen fertilizer. The input data for the model included an agricultural pollution susceptibility map, county and state boundary maps, major aquifer outcrop areas, and the recommended nitrogen fertilizer application rates for nine crops. The county map layer was used as the base data layer for graphically representing the cropping and fertilizer data. The results of this study confirmed that GIS is a helpful tool in analyzing groundwater contamination problems.

Flockhart *et al.* (1993) examined three cases each with different approaches for using GIS for groundwater protection planning in northeast America where most of water supply is from groundwater. They carried out tests at: (i) Wellfleet, Massachusetts, (ii) Hadley, Massachussets and (iii) Cortland County, New York. In Wellfleet, Massachusetts, build-out scenarios were used to support regulatory and land acquisition decisions for siting a public water supply well. In Hadley, Massachussets, the focus was on a decision support model for the septic suitability assessment in support of regulatory efforts and infrastructure expansion. For Courtland County, an intensive graphic user interface was created to facilitate the manipulation and recombination of a large volume of data by County officials to target groundwater pollution prevention efforts. It was concluded that once appropriate data are input, a GIS can efficiently and effectively be used to derive the outcomes of various land use plans and regulations.

Griner (1993), as part of a larger model to identify lands suitable for acquisition, developed a water-supply protection model using the Southwest Florida Water Management District's GIS. Several hydrologic and hydrogeologic data layers were overlaid to develop maps showing ground-water supply suitability, protection areas for surface-water supply, protection areas for major public supply wells, susceptibility to ground-water contamination, and recharge to the Floridan aquifer. These intermediate layers were combined into a final map to prioritize protection areas for water supply. The advantages of GIS applications in water-supply protection modeling are also highlighted.

Rifai *et al.* (1993) developed GIS database using SYSTEM 9 software and a wellhead modeling user interface (WMUI) for linking SYSTEM 9 GIS package and the EPA groundwater flow model, WHPA in order to implement groundwater protection strategies by state and local governments and regulatory agencies. The WMUI facilitates the automatic extraction of necessary information from the GIS database for modeling and analyses. The GIS database can store the delineated WHPAs for further analysis and display. Thus, the developed WMUI can allow local agencies to delineate and manage WHPAs for hundreds of wells more efficiently and effectively than with traditional paper maps and overlay system. To demonstrate the efficiency of this user interface, a pilot study was conducted in the city of Houston and surrounding Harris County wherein WHPAs for 202 active water supply wells were delineated using the GIS and WMUI. They also performed a detailed sensitivity analysis to evaluate the effect of uncertainty in model parameters on the delineated WHPAs. Potential sources of contamination within the delineated WHPAs were then identified using the GIS database. They reported that while GIS is perceived as an important tool that can enhance users' ability for spatial data analysis, there exist many problems. The system hardware and software require a substantial investment in financial and human resources. Database development is a tricky process requiring planning and commitment; in most cases, the anticipated outcome from GIS software development is not immediately realized.

Hammen and Gerla (1994), considering a multifaceted approach to wellhead protection mandated by the 1986 Amendments to the Safe Drinking Water Act, presented an application of common GIS functionality in facilitating a comprehensive wellhead protection scheme for an agricultural municipality in North Dakota. It was demonstrated that in functioning both as a research tool and as a decision support system, a geographic information system (GIS) is very useful in addressing the technical, administrative, and educational issues involved in the multifaceted approach to wellhead protection.

Maslia *et al.* (1994) developed procedures that combine the groundwater simulation models and demographic databases under a GIS platform to automate the exposure assessment phase of a typical health assessment study. The developed procedures are reported to significantly simplify the post-processing phase of the analysis, and to render the overall task more “user friendly”. A spite-specific application is presented as a demonstration of the proposed methodology. It was emphasized that the geographic information system provided a platform in which layered, spatially distributed databases can be manipulated with ease, thereby simplifying the integrated exposure-analysis tasks significantly.

Hudak *et al.* (1995) developed a GIS-based underground storage tank (UST) management system and applied to 136 current and former gasoline service stations in Denton, Texas. The system was found to be effective for tank inventory and can be applied in a proactive fashion to identify potentially problematic facilities. In the event of a leak or spill, the management system can support the implementation of reactive measures to mitigate subsurface contamination. Potential beneficiaries of such a system are reported to be planning departments, environmental regulatory agencies, emergency management officials, lending institutions, gasoline distributors, and oil companies.

Basagaoglu *et al.* (1997) used GIS technology to identify candidate sites for a solid-waste disposal facility in the Golbasi region of Turkey that has suffered from the negative impact of a poorly-located existing open-dump site on the environment. The procedure followed under a GIS framework rejects the unacceptable sites considering environmental factors exclusively, other than economic and political issues, contained in the form of multiple layers of attribute information to select the candidate sites for landfilling wastes through an overlay analysis performed by the ArcInfo GIS software. In this application, GIS was considered as a screening tool in a site-selection process to narrow the number of candidate sites, subsequently leading to one or more sites for detailed investigation. Finally, preliminary ranking for a group of potential sites was done on the basis of simple calculations coupled with on-site field studies.

Laurent *et al.* (1998) proposed a method for water resources protection based on the spatial variability of vulnerability. A spatial modelling method was defined in this study to estimate a travel time between any point of a catchment and a resource (river or well), which was based on spatial analysis tools integrated in a GIS. The method was illustrated by an application to an area of Massif Central, France where three different types of flow appear: surface flow, shallow subsurface flow, and permanent groundwater flow (i.e., baseflow). The proposed method was found to yield results similar to the classical methods of estimation of travel time. The GIS improved the mapping of vulnerability by taking the spatial variability of physical phenomena into account.

Loague and Corwin (1998) presented a review of the simulations of NPS groundwater vulnerability resulting from historical applications of the agrochemical DBCP (1, 2-dibromo-3-chloropropane) for east-central Fresno County, California. Through the Fresno case study, the data requirements for the process-based 3-D simulations of coupled fluid flow and solute transport in the unsaturated-saturated subsurface at a regional scale are demonstrated. The strengths and weaknesses of using GIS in regional-scale vulnerability assessments, and the critical problem of estimating the uncertainties in these assessments are discussed. Finally, a regional GIS-driven integrated assessment approach is proposed, which is based on cost-benefit analysis, and incorporates both physical and economic factors that can be used in a regulatory decision process.

Shukla *et al.* (1998) developed a GIS-based attenuation factor (AF) model to evaluate the relative degree of groundwater vulnerability to pesticide contamination in Louisa County, Virginia. Spatial (land use, soils, and groundwater recharge) and tabular databases (soils and pesticides) were used within a GIS environment to create contamination livelihood maps based on the AF values. The data layers were overlaid within a GIS for the spatial computation of AF for the actual and 2-m groundwater depths. The spatial database was divided into five contamination potential categories namely ‘high’, ‘medium’, ‘low’, ‘very low’ and ‘unlikely’ based on the numerical values of AF for each cell (1/9 ha), and the results for three most mobile pesticides (i.e., Picloram, Carbofuran, and Atrazine) were presented. Among these three pesticides, Picloram was found to have the highest leaching potential. The performance of the AF model was evaluated by comparing its predicted results with the field data from an experimental watershed. The AF model was able to identify most of the frequently detected pesticides in the watershed. They concluded that the results of this study can be used for formulating an appropriate land-use management plan to protect the groundwater quality.

Dubey and Sharma (2002) developed a decision support system for evaluating the groundwater pollution potential (GWPP) of an area using remote sensing, ancillary data and GIS. They represented the GWPP system by a factor analytical model (FAM). The FAM was used to develop a decision support system to assign a weight to a particular characteristic based on its contribution in GWPP. Groundwater pollution potential was determined by the linear mixing of above surface, surface and subsurface environmental parameters influencing the GWPP. The generated database was put to FAM to classify the study area into different classes in terms of their potential to pollute groundwater. The model efficacy was tested by carrying out a field survey and it was found above 80%. It was concluded that the developed model could be used for evaluating GWPP in any area after calibration.

Lamble and Fraser (2002) developed a GIS-based predictive groundwater model using satellite imagery and ancillary data for the Murray Valley Irrigation Region of New South Wales, Australia. The developed model enabled the prediction of salinity risks due to rising groundwater levels. In addition, a regression model showed a great promise in predicting the areas of high groundwater in the study area.

Dixon (2004) developed a modeling approach that loosely couples Neuro-fuzzy techniques and GIS to predict groundwater vulnerability in a relatively large watershed in northwest Arkansas. He used GRASS and ArcView GIS packages, GPS, remote sensing, and a fusion of neural network and fuzzy logic techniques along with relevant interactions of soil properties and land use/land cover on the groundwater quality of the study area. The Neuro-fuzzy model was developed in JAVA using four plausible parameters namely soil hydrologic group, depth of the soil profile, pedality points of the soil A horizon, and land use that are deemed critical in transporting contaminants in and through the soil profile. The model was validated using nitrate-N concentration data. It was found that the majority of the highly vulnerable areas predicted by the model coincided with agricultural land use, moderately deep to deep soils, soil hydrologic group C (moderately low K_{sat}) and high pedality points. It was concluded that the proposed methodology has the potential for facilitating groundwater vulnerability modeling at a regional scale and can be used for other regions. This study is reported to be a first step toward incorporation of Neuro-fuzzy techniques, GIS, GPS and remote sensing in the assessment of groundwater vulnerability from non-point source contaminants.

Saykawlard *et al.* (2005) presented a methodology to predict the spatial variation in subsurface water-level change with crop-growth stages using the satellite data of Thabua Irrigation Project, Thailand. They analyzed the relationship between subsurface water-level change due to pumping for irrigating rice in the dry season and the age of rice. The spatial model of subsurface water-level change was developed from the classification using greenness (i.e., normalized difference vegetation index (NDVI)) derived from the Landsat-5 TM data. The NDVI values of 52 rice fields' data during the 1998–1999 dry-season cropping period were used to assess the relationship between NDVI and the age of rice. It was found that the NDVI and rice age have a good correlation ($R^2 = 0.73$). The low NDVI values (-0.059 to 0.082) in the rice fields were related to the young rice stage (0–30 days). Also, a high correlation between the NDVI and the subsurface water-level change was found. It was concluded that this simple method of using NDVI relationships with water-level change and crop-growth stages proved to be useful in identifying the areas prone to excessive lowering of the subsurface water level during dry seasons.

4.6. Estimation of natural recharge distribution

Fayer *et al.* (1996) estimated the areal distribution of natural recharge at the Hanford Site in southeastern Washington State to serve as input to a groundwater flow and transport model. A GIS was used to identify all possible combinations of soil type and vegetation and assign to each an appropriate estimate of recharge. The strategy was to assign estimates based on field data and supplement with simulation results only when necessary. The estimated rates varied from 0.7 to 127.1 mm/yr.The GIS software was used to estimate the annual recharge volume attributable to specific soil-vegetation combinations and to construct a recharge map. The recharge map showed the impact of a 1984 fire on increasing recharge; it also illustrated the higher recharge rates associated with disturbed soils in the waste storage areas.

Stone *et al.* (2001) presented a method to estimate the distribution of groundwater recharge within hydrographic basins in the Great Basin region of the southwestern United States on the basis of estimated runoff from high mountainous areas and subsequent infiltration in alluvial fans surrounding the intermontane basins. It involves a combination of GIS analysis, empirical surface-runoff modeling, and water-balance calculations. The method addresses the need to develop and incorporate constraints on the distribution of recharge in regional-scale groundwater flow modeling of arid and semiarid environments. The conceptual approach and methodology were developed for Crescent Valley, Nevada and it was demonstrated that the method resulted in a more accurate representation of actual recharge conditions.

Jyrkama *et al.* (2002) developed a practical methodology incorporating the hydrologic model HELP3 in conjunction with a GIS to generate a physically based and highly detailed recharge boundary condition for groundwater modeling. It uses daily precipitation and temperature records in addition to land use/land cover and soils data. The importance of the method in transient groundwater modeling is demonstrated by applying it to a MODFLOW modeling study in New Jersey. Besides improved model calibration, the modeling results clearly indicated the importance of using a physically based and highly detailed recharge boundary condition in groundwater quality modeling, where the detailed knowledge of the evolution of the groundwater flow-paths is imperative. The results also indicated that the combination of temperature and precipitation plays an important role in the amount and timing of recharge in cooler climates. A sensitivity analysis further revealed that increasing the leaf area index, the evaporative zone depth, or the curve number in the model results in decreased recharge rates over time, with the curve number having the greatest impact.

Szilagyi *et al.* (2003) estimated naturally occurring long-term mean annual base recharge to groundwater in Nebraska with the help of a water-balance approach and an objective automated technique for base-flow separation involving minimal parameter-optimization requirements. Evapotranspiration was calculated by the WREVAP model at the Solar and Meteorological Surface Observation Network sites. Long-term mean annual base recharge was derived by determining the product of estimated long-term mean annual runoff and the base-flow index (BFI). The BFI was calculated from discharge data obtained from the USGS's gauging stations in Nebraska. Mapping was achieved by using GIS and geostatistics. Long-term mean annual base recharge rates in excess of 110 mm/year resulted in the extreme eastern part of Nebraska. The western portion of the state expressed rates of only 15 to 20 mm annually, while the Sandhills region of north-central Nebraska was estimated to receive twice as much base recharge (40 to 50 mm/yr) as areas south of it. It was emphasized that the methodology adopted in this study does not require complex hydrogeologic modeling nor detailed knowledge of soil characteristics, vegetation cover, or land-use practices.

Brunner *et al.* (2004) presented a methodology for obtaining the recharge map for two sites in Botswana, South Africa. The relative distribution of recharge was obtained from remotely sensed data using surface water balance method, which was calibrated with local recharge values determined by Chloride Method. The Meteostat-5 satellite data (5-km spatial resolution) were used to estimate rainfalls, which were validated against the measured rainfall data collected from four stations. A simpler algorithm was used to estimate ET which involved multiplication of daily net radiation and evaporative fraction. The daily net radiation data were obtained from the satellite imagery and astronomical data using a simple algorithm and the evaporative fraction was obtained from the satellite imagery for each pixel value. Finally, correlation coefficients between the recharge estimates obtained by the water balance model and those by Chloride Method were determined. Based on these correlation coefficients, a scaled recharge map was developed. They inferred that if the assumptions of the surface water balance and Chloride Method are satisfied and the precipitation as well as chloride data are available in the required resolution, the methodology could easily be adapted to other arid or semi-arid regions.

Cherkauer (2004) estimated natural groundwater recharge in watersheds of varying sizes using a distributed parameter model and GIS. This procedure simplifies the PRMS calibration observed streamflow hydrographs by reducing degrees of freedom from dozens to four. For seven watersheds (60 to 500 km^2), the GIS-aided calibrations had average errors of 5% on recharge and 2% on total streamflow, verifying the accuracy of the process. Recharge was also calculated for 63 local-scale sub-watersheds (average size 37 km^2), and the calculated recharges were found to average 11 cm/yr. The model was extended to uncalibrated watersheds where GIS and climatic information were known. It reproduced total annual discharge and recharge to within 9 and 10%, respectively, indicating the process can also be used to calculate recharge in ungauged watersheds.

Szilagyi *et al.* (2005) estimated naturally occurring long-term mean annual recharge to groundwater in Nebraska by a novel water-balance approach. This approach uses GIS layers of land cover, elevation of land and groundwater surfaces, base recharge, and the recharge potential in combination with monthly climatic data. Long-term mean recharge $>$ 140 mm per year was estimated in eastern Nebraska, having the highest annual precipitation rates within the state, along the Elkhorn, Platte, Missouri, and Big Nemaha River valleys where ground water is very close to the surface. Similarly, high recharge values were obtained for the Sand Hills sections of the North and Middle Loup as well as Cedar River and Beaver Creek valleys. The westernmost and southwesternmost parts of the state were estimated to typically receive $<$30 mm of recharge per year.

4.7. Hydrogeologic data analysis and process monitoring

Hudak *et al.* (1993) integrated the GIS capabilities for managing spatial data with a groundwater-quality monitoring network design methodology. They applied a ranking methodology for monitoring network design for the Butler County Municipal Landfill in Southwest Ohio. GIS was utilized effectively in a number of tasks related to the groundwater monitoring network design, together with the display of the results. They concluded that the ranking approach augmented with GIS provided a practical and effective alternative for the problem of detection-based groundwater-quality monitoring network design.

Salama *et al.* (1996) presented three methods (manual, geostatistical and hydrogeological-GIS-based (H-GIS)) for preparing hydraulic head surfaces (HHS). In the manual method, two techniques namely equal spacing technique and hydrogeological interpretative technique were used. In the second method, a geostatistical package was used, and in the third method, two different hydrogeological techniques incorporating GIS modeling were used. The results indicated that of the manual methods, the hydrogeological interpretative technique was better than the equally spaced approach. It was also demonstrated that the newly developed H-GIS techniques, which take into account the hydrogeomorphic classification and topographic controls, yielded the most realistic surface and the areas of groundwater discharge. The major advantage of the GIS-based techniques was their ability to prepare HHS maps with a small number of data points. It was concluded that the geostatistical method is unsuitable for preparing HHS maps and it could be used only in the absence of other methods along with hydrogeomorphic and hydrogeological controls.

Endres *et al.* (2000) imaged the temporal and spatial response of an unconfined aquifer during a pumping test using ground-penetrating radar (GPR) profiling. Besides observing drawdowns during the pumping test, several other drainage-related phenomena were also observed on the GPR profiles such as the development of a series of diffractions indicating localized irregularities in water saturation, and the velocity pull-up of stratigraphic reflections due to increased electromagnetic wave velocity in the overlying section. Comparing the GPR profiling data and piezometer measurements, it was found that the drawdown of the transition zone reflection was smaller and delayed relative to the measured hydraulic head drawdown. Using the distance-drawdown relationship obtained from GPR profiling, the drained water volume due to the downward movement of transition zone was estimated. It was reported that the results of this analysis accounted for only a fraction of the pumping well production – approximately 45% on the first day and about 25% on the second day.

Lane *et al.* (2000) evaluated the suitability of common-offset ground-penetrating radar (GPR) to detect free-phase hydrocarbons in bedrock fractures using numerical modeling and physical experiments. The results of one- and two-dimensional numerical modeling at 100 MHz indicated that GPR reflection amplitudes are relatively insensitive to fracture apertures ranging from 1 to 4 mm. The numerical modeling and physical experiments indicated that differences in the fluids that fill fractures significantly affect the amplitude and the polarity of electromagnetic waves reflected by sub-horizontal fractures. Furthermore, it was found that it is possible to distinguish water-filled fracture reflections from air- or hydrocarbon-filled fracture reflections, nevertheless subsurface heterogeneity, antenna coupling changes, and other sources of noise will likely make it difficult to observe these changes in GPR field data. Hence, the routine application of common-offset GPR reflection methods for detection of hydrocarbon-filled fractures will be problematic.

Oldenborger *et al.* (2003) determined the spatial structure of hydraulic conductivity on a controlled excavation of a glacial-fluvial sand and gravel deposit in the Fanshawe Delta area of Ontario, Canada using GPR (Ground-Penetrating Radar) and permeameter. The hydraulic conductivity field of a 45, 2, 3 m vertical exposure was characterized using constant-head permeameter measurements performed on undisturbed horizontal sediment cores. GPR data were collected along the excavation face in the form of both reflection and common midpoint surveys. A comparison of geostatistical analyses of the permeameter measurements and the radar data suggested that the horizontal correlation structure of radar stack velocity can be used to directly infer the horizontal correlation structure of hydraulic conductivity. The averaging nature of the common midpoint survey was manifest in the vertical correlation structure of stack velocity, making it less useful. Furthermore, it was found that the radar reflection data didn't exhibit a spatial structure similar to that of hydraulic conductivity.

5. Need for future research and development

5.1. Remote sensing technology

The applications of RS technology in groundwater hydrology are very limited compared to other fields of study because of its inherent limitations. Although there is growing interest in exploring this technology, there is a long way to go in order to use RS technology effectively for the development and management of vital groundwater resources. Based on the present review, the focus of future advancements in RS technology should be in the following areas of concern:

- A general problem of using remote sensing in hydrological studies is that very few remotely sensed data can be directly applied in hydrology, they measure only a part of electromagnetic spectrum and different hydrological parameters are only inferred from them. Therefore, there is an urgent need to improve the accuracy and reliability of remote sensing estimates, which are highly uncertain until now (Beven, 2001). It could be possible by refining analysis techniques as well as developing new and improved sensors and their applications in conjunction with improved field measurements. New RS applications will emerge and mature as new instruments and new types of data become available in the future.
- The major constraint for the utility of RS in hydrogeology is that it can only detect changes at the ground surface or a shallow layer (<1 m deep) of the earth, though the airborne exploration of groundwater using electromagnetic prospecting sensors developed for the mineral

industry is reported to map aquifers at depths greater than 200 m (Paterson and Bosschart, 1987). However, with the growing pollution and lowering of groundwater worldwide, it is often necessary to explore deep aquifers in which case the usual remote sensing data are of no use, except for the especially acquired data by GPR (Ground-Penetrating Radar) which can penetrate up to about 20 m depth. Although ongoing research activities using GPR, subsurface methods of groundwater investigations, and tracers are expected to enhance our knowledge about complex and hidden subsurface processes, a routine use of any of these techniques seems a long way off (Beven, 2001; Lane *et al.*, 2000). Future research should focus on the development of easy-to-use techniques to quantify subsurface water storage and visualize fluid flow and transport processes in the subsurface environment. Furthermore, in our quest to have more accurate and reliable non-invasive techniques for monitoring subsurface processes as well as to combat the heterogeneity and anisotropy of aquifer and vadose-zone systems, the RS technology offers the greatest promise. Future advancements in RS technology in this direction will certainly revolutionize the hydrogeological thinking, theory and model development.

- More and more RS-based groundwater studies together with field studies should be carried out in order to examine the reliability of RS data. The combined use of multi-spectral data obtained from different sensor systems is necessary to extract more and better information (Engman and Gurney, 1991). Future research should also be directed towards developing linkages between surface observations and subsurface phenomena. Such studies will not only enhance and refine RS applications in groundwater hydrology, but will also significantly contribute to the sensor development program.
- There is a need to develop an optimal sensor system including both active and passive microwave techniques for more effective soil-moisture monitoring. It will allow a range of applications and the synergism of the two types of measurements to provide more useful and new information (Jackson *et al.*, 1999).
- Recent developments in microwave remote sensing, theory and sensor availability have resulted in new potential and capabilities. Very limited studies have revealed the potential to extract/detect subsurface parameters and features using these techniques. More and more research is required to refine and implement these approaches (Jackson, 2002). The multi-temporal and spatial availability of microwave remote sensing data can complement the monitoring and modeling of groundwater recharge. In addition, through the synergistic use of earth's gravity-field monitoring satellites (e.g., GRACE and CHAMP) data and satellite microwave remote sensing data, it may be possible to monitor seasonal groundwater recharge over large regions in the near future (Jackson, 2002). Future studies should be carried out in this stimulating direction.
- Last but not the least, there must be strong cooperation between space agencies and soil & water scientists (e.g., soil scientists, hydrologists, hydrogeologists, and environmentalists) for the planning and development of sensor systems, which will ensure timely implementation of suitable and efficient sensor systems for the effective mapping of land and water resources. Such cooperation will undoubtedly lead to wide-scale research and applications in the fields of hydrology and hydrogeology, which in turn will ensure efficient land and water management by the promising remote sensing technique.

5.2. GIS technology

The present applications of GIS in groundwater hydrology have utilized only a few features of GIS, and there exists large potential to exploit further. As noted by Watkins *et al.* (1996), engineers and scientists have only just scratched the surface in GIS to improve groundwater modeling. Also, a number of GIS capabilities are to be developed for further enhancing the groundwater modeling process. Considering the current status of GIS use in groundwater hydrology, the following research and development needs for GIS technology are identified in the future:

- Several researchers have demonstrated that GIS, because of its sophisticated analysis and graphics capabilities, can provide a powerful platform for developing GIS-based groundwater and vadose zone models, calibrating and validating them, and presenting their results. However, the most difficult task in this approach is the linking of models with GIS (Watkins *et al.*, 1996). Therefore, multi-disciplinary research is needed for the automation of linking tasks and the development of customized and user-friendly GISs solely devoted to subsurface flow and transport modeling (e.g., excellent compatibility between GIS and groundwater models, availability of subroutine library to perform GIS functions, standardized and versatile interfacing between GIS and models, more embedded spatial analysis and GIS technology within groundwater and vadose zone models, advanced modeling and simulation capabilities embedded in GIS, etc.). Research should also continue at a greater pace to address the problems associated with user interface, database, and model-based integration (Tsihrintzis *et al.*, 1996; Watkins *et al.*, 1996). Another active GI research area is spatio-temporal modeling (Longley *et al.*, 1998), which is domain specific and presents a special demand in groundwater modeling. Modeling objects with partially known, indeterminate, or vague is another important GI research direction of interest to groundwater modeling.
- Future modeling efforts should address the issues pertaining to the unjustified precision and the misrepresentation of accuracy involved in GIS-based groundwater modeling (Watkins *et al.*, 1996; Corwin *et al.*, 1998). Concentrated research efforts are also required for much better understanding of data structure and data analysis capabilities of GIS in order to address other GIS-based modeling issues (e.g., parameter estimation, grid design and effects, sensitivity and reliability analyses, etc.). In addition, a sound GIS education structure is needed for the extensive and effective use of GIS technology (Marble, 1998).
- Further research is necessary in the area of GIS-based distributed modeling with applications to groundwater and vadose-zone processes, which will ensure more efficient assessments of groundwater pollution hazards (Loague and Corwin, 1998; Gogu *et al.*, 2001). To this end, enhanced spatial servers resting on extended relational database management systems are needed as a means by which the vast amount of data necessary as input into the models can be efficiently supplied to end users. However, besides the computational burden, the most imposing barrier to the use of sophisticated mechanistic subsurface flow and transport models for field-scale applications is obtaining adequate and reliable data. According to Halford (2004), hydrogeologic understanding is limited currently by field measurements, not by a lack of models. Thus, the greatest advancements are undoubtedly required in the area of cost-effective and accurate measurements of scale-relevant input and parameter data where a statistical knowledge of measuring uncertainty is also provided (Corwin *et al.*, 1997).
- Integration of expert systems (ES) and spatial decision support systems (SDSS) with GIS has not been much applied in water resources engineering in general and groundwater hydrology in particular. This is an area of potential research to aid to the effective and timely decision making concerning planning, design, analysis, operation and maintenance of water resources systems (McKinney *et al.*, 1992; Evans *et al.*, 1993) as well as to greatly reduce time and efforts required in traditional approaches. Such a system can automate the process of solving regional water problems and help in selecting cost-effective management

alternatives. Much of decision making can also be automated through the use of an expert GIS. A crucial problem, however, is the integration of heterogeneous data sources in order to support query answering and problem solving.

- To provide a checklist for GIS users, research dealing with the comparison of various available GIS software packages and their pros and cons is also required (Tsihrintzis *et al.*, 1996). It will help select a suitable GIS software package as per the specific need and will promote effective GIS applications in hydrology/hydrogeology.
- Data availability and compatibility is still a problem in implementing and running any GIS system, especially in developing nations. Davis *et al.* (1991) discuss some basic scientific issues and research needs in the joint processing of remote sensing and GIS data for environmental analysis. Of course, there is an urgent need that the RS and GIS data for different regions of a country should be made available in ready-to-use formats with good compatibility and at affordable price through centralized data banks. Such data availability will certainly boost up wide-scale applications, analyses, and decision-making processes.

6. Constraints for RS and GIS applications in developing nations

Based on the present review, it is evident that the groundwater studies using RS and GIS techniques in developing countries including India have shown some new application areas, but such studies are very limited. In addition, barring few, most studies are ad hoc in nature and demonstrate merely the use of RS data and/or GIS software. Standard methodology and the validation of RS- and GIS-based results with field data are usually missing. GIS-based subsurface modeling is also highly restricted in developing nations, despite growing knowledge-base in this field in some developing nations. The principal reasons behind the limited and sub-standard applications of RS and GIS techniques in developing nations could be the security restrictions on maps and RS data imposed by the government and their unavailability for genuine uses (Narayana, 1999) as well as the scanty or lack of reliable field data because of poor or sometimes no groundwater monitoring facilities. It is unfortunate that while developed nations have started real-time groundwater monitoring using modern techniques (Todd and Mays, 2005), most developing nations have no adequate and dependable groundwater-monitoring programs even by traditional means. Apart from these major constraints, there are some more intricate problems related to the implementation of RS and GIS techniques in developing nations such as: (i) non-availability of high-resolution RS data for private, public and academic uses; (ii) poor data-distribution facility; (iii) high costs of RS data; (iv) poor knowledge about these developing technologies; (v) lack of adequate infrastructure, training, and support; (vi) insufficient skilled manpower in the government's planning and development departments; and (vii) expensive RS and GIS software packages as well as their accessories.

The feasible and immediate solutions to some of the above constraints could be: (a) development of a system to ensure faster accessibility and better distribution of RS data at affordable price, (b) increasing awareness and proficiency in using RS and GIS techniques in government and private sectors through proper training and support, and (c) enhancing and updating infrastructure facilities to cope up with latest developments in these technologies. Thus, besides the widespread availability of RS and GIS outputs in digital mode, there is a need to evolve a well-coordinated program in this area with a focus on developing standard methodologies and software as well as training and technology transfer on a wider scale. Also, there is a need to introduce RS and GIS curricula at undergraduate and graduate levels to promote better education and training in these specialized fields. As far as the restrictions of RS data are concerned, in view of liberal distribution and relatively easy accessibility of RS data including the high-resolution data from some developed nations, it would be prudent to remove or relax the security restrictions on the RS data and maps in developing nations, except for very rare cases where national security may be jeopardized (Narayana, 1999). Furthermore, there is an urgent need to develop adequate groundwater-monitoring facilities on a regular and long-term basis throughout the country, and to boost up field investigations in order to ensure effective applications of emerging RS and GIS technologies for the sustainable development and management of vital but shrinking groundwater resources.

7. Conclusions and recommendations

The present paper succinctly highlights remote sensing (RS) and GIS technologies and presents a state-of-the-art review on the application of these two emerging techniques in groundwater hydrology. The detailed reviews presented in this paper indicated that the current applications of RS and GIS techniques in groundwater hydrology are limited to six areas: (i) exploration and assessment of groundwater resources, (ii) selection of artificial recharge sites, (iii) GIS-based subsurface flow and pollution modeling, (iv) groundwater-pollution hazard assessment and protection planning, (v) estimation of natural recharge distribution, and (vi) hydrogeologic data analysis and process monitoring. Although the use of these techniques in groundwater studies has appreciably increased since early nineties, the success rate has been very limited and most applications are still in their infancy. Considerable basic research and developments are indispensable in the future for enhanced and wide-scale applications of these two highly promising and economically viable techniques in groundwater hydrology. More and more RS- and GIS-based applied groundwater research is also required in conjunction with field investigations to effectively exploit the expanding potential of RS and GIS technologies, which will perfect and standardize current applications as well as evolve new approaches and applications in the future. Developing technologies like RS, GPS and GIS are really catalysts for innovative approaches to currently unsolvable water resources problems. The constraints for RS and GIS applications in developing nations must be overcome to reap maximum benefits of these promising technologies.

Finally, it is concluded that the remote sensing technology has great potential to revolutionize groundwater monitoring and management in the future by providing unique and new data to supplement the conventional field data. Rapidly expanding GIS technology will play a central role in handling the voluminous spatio-temporal data and their effective interpretation, analysis, and presentation, though such applications will raise some new problems. The daunting challenges ahead for the hydrogeologists/hydrologists are to map and/or visualize subsurface flow and transport processes by RS technology, to efficiently interpret RS data as well as to develop cost-effective and non-invasive field-measurement techniques in order to expand groundwater hydrology in new and exciting directions. Such advancements will certainly enable us to develop and manage precious groundwater resources in a real sustainable and environment-friendly way.

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