Challenges of using remote sensing and GIS in developing nations

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Introduction

The total water requirement of India by the year 2050 has been estimated at 1,450 km^3/year (MOWR 1999). This is significantly more than the current estimate of utilizable water resources potential of 1,122 km^3/year (surface water=690 km^3/year and groundwater=432 km^3/year) through conventional development strategies (Gupta and Deshpande 2004). India's water problems basically stem from disparate precipitation, mismanagement, and the fact that while nearly 70% of precipitation occurs in 100 days, the water requirement is spread over 365 days. Indeed, water is the biggest crisis facing India in terms of spread and severity. Water is rationed, even in the big cities of Chennai, Bangalore and Delhi. Currently, eight of India's 20 major river basins in its rural areas are in water deficit. Over 5.6 million tubewells and 3.5 million hand pumps have lowered groundwater levels beyond the economic lifts of pumping and new tubewells are being drilled to a depth of 200 m across the country (Aiyar 2003); overuse of groundwater is reported from many different parts of the country. Consequently, India's food security is under serious threat and the lives and livelihoods of millions are at risk. Water scarcity is very common in other developing nations also. Thus, there is an urgent need for the widespread realization in developing countries (including India) that water is a finite and vulnerable resource, which must be used efficiently, equitably, and in an ecologically sound manner for both present and future generations.

Apart from the water scarcity, salient groundwater issues in India are: (1) over-exploitation of groundwater resources; (2) lowering of groundwater levels in the upstream portion of canal commands (areas irrigated by a canal system), and waterlogging and/or salinization in the downstream portion of canal commands; (3) growing groundwater contamination by point and non-point sources of pollution; (4) groundwater contamination by arsenic and fluoride; and (5) seawater/saltwater intrusion into freshwater aquifers.

The use of conventional techniques/tools (e.g., geophysical, statistical or geostatistical techniques, numerical modeling, etc.) for groundwater management is often severely limited by the lack of adequate data in developing nations, and hence innovative technologies like remote sensing (RS) and geographic information systems (GIS) have an immense role to play. This article focuses on the constraints and challenges of RS and GIS technologies in groundwater development and management with a particular reference to developing countries, considering India as an example. This aspect of these modern technologies is often ignored amidst complexity and overwhelming support to boost new techniques/tools.

Remote sensing and hydrogeology in India

The operational utilization of Landsat TM satellite data for groundwater studies in India was initiated during 1987–1992 when the Department of Space (India) made efforts to identify and map groundwater potential zones at a 1:250,000 scale for the 447 districts in the country under the National Drinking Water Mission using visual interpretation techniques (ISRO 1988). Thereafter, a national project called 'Rajiv Gandhi National Drinking Water Mission Project' was launched in the five states of the country by the Department of Space. Under this project, different thematic maps such as geology, geological structures, geomorphology and recharge conditions are being prepared at a 1:50,000 scale and integrated in a GIS for the demarcation of groundwater prospects (NRSA 2000).

Besides the above efforts, many groundwater-related studies in India have used multi-spectral data acquired

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by the Indian remote sensing satellites (IRS-1A, 1B, 1C and 1D) carrying sensors namely LISS-I (72.5 m spatial resolution), LISS-II (36.25 m spatial resolution), LISS-III (23.6 m spatial resolution), TM (5.8 m spatial resolution), and WiFS (188 m spatial resolution). Many studies from India are reported that deal with the RS and GIS applications to groundwater potential assessment compared to the RS-and GIS-based studies dealing with other vital aspects of groundwater hydrology (Jha and Peiffer 2006). Krishnamurthy et al. (1996) used RS and GIS techniques for demarcating groundwater potential areas in the Marudaiyar basin of Tamil Nadu in southern India. They prepared the maps of lithology, landforms, lineaments and surface water bodies from the IRS-1A LISS-II imagery, 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 ArcInfo, and finally a groundwater potential zone map was prepared. To demonstrate the capabilities of RS and GIS techniques for groundwater development in hard-rock terrains of the Kallar basin of Tamil Nadu, Krishnamurthy et al. (2000) mapped lithology, lineaments, landforms, land use, drainage density, thickness of weathered zone, thickness of fractured zone, hydrological soils and well yield using data collected by the IRS-1C and conventional methods. They were integrated and analyzed using a GIS model. Jaiswal et al. (2003) conducted a pilot study in the Gorna sub-basin of Madhya Pradesh (central India) for the identifying locations for extracting potable water for rural population. Information on lithology, geological structures, landforms, and land use/land cover was extracted from IRS imagery and on drainage networks, soil characteristics and slope using conventional methods. These thematic layers were integrated using a GIS to depict village-wise groundwater prospect zones. Chowdary et al. (2003) integrated a groundwater-flow model with GIS to estimate the spatial distribution of groundwater recharge and to simulate groundwater flow in the Godavari Delta aquifer of Andhra Pradesh (southeastern India). Sikdar et al. (2004) used multi-criteria approach involving different themes such as drainage, texture, geomorphology, lithology, current land use and slope steepness, and lineament frequency to identify potential groundwater zones in the Raniganj area of West Bengal (eastern India). Sreedevi et al. (2005) used RS, GIS and geophysical techniques to delineate groundwater potential zones in the Pageru River basin, Andhra Pradesh. They used IRS-1B LISS-II FCC at 1:50,000 scale to delineate various geomorphological units based on structural trends, lineaments, soil tones, vegetative cover, and relief linearity. The geomorphology, hydrogeology, and resistivity interpretation were then integrated using a GIS to prepare a map of groundwater potential zones for the study area. Recently, Chatterjee et al. (2006) used differential radar interferometry to detect and measure land subsidence due to pumping during 1992–1998 in Kolkata City of West Bengal. This study revealed a subsidence rate of 5–6.5 mm/year.

Salient constraints and challenges of RS and GIS applications in groundwater studies

RS-and GIS-based studies in developing countries, including India, have shown some new application areas, but such studies have been very limited, scratching only the surface of these technologies. Barring a couple of studies, most studies are ad hoc in nature and demonstrate merely the use of RS data and/or GIS software packages. Standard methodology and the validation of RS-and GIS-based results with adequate field data are missing in many cases. GIS-based subsurface modeling, development of decision support systems (DSS) or expert systems (ES), pollution management, etc. are also very much lacking despite growing knowledge-base in this field in India. As a result, RS and GIS technologies have not proved very helpful to the water authorities as yet in developing nations; developing nations are lagging behind in harnessing even the current potential of these promising technologies. Besides the inherent limitations of RS technology in groundwater assessment (Jha and Peiffer 2006), there are several practical impediments to the effective use of these technologies in developing nations. The major constraints and challenges of the applications of RS and GIS technologies in India could be grouped under two broad headings: *technical and educational impediments* and *institutional impediments,* which are succinctly described below in order of importance. It should be noted that these problems are typical for most developing nations.

Technical and educational impediments

1. Negligence of proper groundwater monitoring, resulting in no or scarce and/or poor-quality groundwater data. Undoubtedly, these limitations severely hinder research and development activities in the field of groundwater hydrology. They are indispensable for complementing and validating RS observations.
2. Poor facility for the distribution of RS data; this problem is much more serious in relatively poor developing nations, which restricts the use of promising RS and GIS technologies in such countries.
3. Inadequate digital data and high costs of RS data. The former poses a problem in the combined use of non-digital and digital data, whereas the latter restricts the application of RS to research. The availability of georeferenced maps in the public domain is extremely limited. The problem of information access is not unique to a particular theme, but also applies to many other types of research data (climate, geology, topography, etc.). This problem is more acute in developing countries, including India. In addition, because of expensive RS imagery, the researchers often have to compromise with the quality and quantity of the RS data, resulting in poor-quality research.
4. A plethora of file formats exist along with a variety of distribution media that present a technical challenge to those wishing to access satellite/spatial data from multiple types of media. One challenge facing the

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spatial database development community is the perceived incompatibility between regional and global efforts and local interests.
5. Expensive RS and GIS software. Only top-ranking academic institutes and research organizations of India have RS and GIS laboratories—even many of such institutes/organizations are lacking in adequate RS and GIS facilities.
6. Poor knowledge about RS and GIS technologies; proper education of potential users remains a key factor inhibiting the use of geospatial datasets in most developing nations (including India). This impediment has resulted in the lack of basic research in RS and GIS and inefficient use of these technologies for solving real-world problems.
7. Lack of adequate infrastructure, training, and support for RS and GIS technologies. Very few RS and GIS institutes currently exist in many developing nations (including India). Therefore, progress in the field of RS and GIS is very slow in these countries compared to the developed countries.

Institutional impediments

1. Restricted access to the coastal and boarder areas maps/imagery as well as medium-and high-resolution RS data for private, public and academic uses. Consequently, in-depth investigations and analyses (i.e., high-end research) are greatly limited in India, as is evident from salient examples presented in the previous section.
2. Poor/absence of linkage between the researchers, decision makers or planners and end users because of inadequate dissemination structure, restricted accessibility or unsuitable presentation. Therefore, there is very poor dissemination of knowledge base or technologies/tools among these three levels of users. For instance, scientists create data and information from RS imagery, but they often sequester these data in personal files or obtuse locations and hence render them unavailable to other appropriate users. In fact, dissemination mechanisms have generally been neglected during the design of existing projects, which makes it difficult now for them to promote their findings and inform stakeholders (Kline et al. 2000). Thus, attempts to inculcate distributed data management practices among the scientific community remain a major challenge for many scientific organizations in both developing and developed nations.

Possible remedial measures and suggestions

The feasible and immediate solutions to some of the above constraints could be: (1) development of a system to ensure faster accessibility, and better distribution of RS data at an affordable price (e.g., creation of a spatial data infrastructure), (2) increasing awareness and proficiency in using RS and GIS technologies in government and private sectors through enhanced/proper training and support, and (3) enhancing and strengthening of infrastructure facilities to better utilize RS and GIS technologies as well as to cope with the latest developments. In addition, there is an urgent need to boost scientific field investigations in order to ensure effective applications of emerging RS and GIS technologies for the sustainable development and management of vital groundwater resources.

Besides the widespread availability of RS and GIS outputs in the digital form, there is a need to evolve a well-coordinated program focusing on developing standard methodologies and cost-effective software, coupled with training and technology transfer on a wider scale. Basic research needs to be carried out for the efficient use of gradually emerging high-resolution RS data, which have great potential to lead to new insights and applications in the future because of improved and in-depth information. As far as the restrictions of RS data are concerned, awareness should be created by the geospatial community in developing nations to encourage them to eliminate restrictions on information sharing and/or local access to RS data, which are based on outdated national security considerations (George 2000). As the technology develops towards civil Earth-observation satellites with 1-m spatial resolution, maps at finer scales can be produced. When nations can buy 1-m resolution satellite data in a commercial market place, the old paradigms of secrecy and the necessity of military control on geospatial data need to be rethought (Kline et al. 2000). It would be prudent to eliminate or relax the security restrictions on the RS data and maps in developing nations (Narayana 1999).

Spatial data infrastructures (SDIs) are promising to create a spatial database wherein all stakeholders (from users to producers) can cooperate with each other and interact with the technology to better achieve their spatial data objectives at different political and administrative levels. Many countries of the world are developing SDIs to facilitate better management of their spatial data including environmental data by taking a perspective that starts at a local level and proceeds through state, national and regional levels to a global level (Rajabifard et al. 2000). Such an effort is highly desirable in developing nations as well in order to reap the maximum benefits of RS and GIS technologies. Moreover, RS and GIS curricula as well as adequate groundwater courses at undergraduate and graduate levels should be introduced to promote better education and training in these specialized fields, which in turn will improve efficient application of modern innovative techniques for solving water problems.

Concluding remarks

The crux of water-resources management problems is that the assessment of the magnitude of such problems and the formulation of effective management and control strategies warrant more reliable data at different scales, an improved understanding of the spatial and temporal patterns involved, and better modeling and prediction methods. Particularly, frequent and long-term monitoring of groundwater and vadose zone systems by conventional methods is expensive, laborious, time-consuming and destructive. RS technology holds a great promise in this regard, and is very useful for developing nations where adequate and good-quality data are often lacking. It can cost-effectively provide frequent data on a relatively large scale that allow specific groundwater problems to be monitored regionally or globally on a long-term basis. Treating RS data as unique measurements of hydrologic/hydrogeologic characteristics can offer the best opportunity for advances in our knowledge about hydrologic and hydrogeologic processes at basin, regional or global scales and for addressing new questions and challenges. Thus, RS technology has tremendous potential to revolutionize groundwater development and management in the future by providing unique and completely new hydrologic/hydrogeologic data. Such advanced and/or new information will expand our knowledge, which in turn will help formulate efficient groundwater management strategies. However, the RS data at present should be considered as complementary to the conventional field data and their combined use is strongly recommended for useful and reliable analyses. Much more RS-and GIS-based groundwater research is also required to be carried out in conjunction with extensive field investigations to effectively exploit the current and expanding potential of RS and GIS technologies. Such studies will perfect and standardize present applications, as well as lead to the evolution of new insights and entirely new applications in the future. The existing constraints and challenges of RS and GIS applications in developing nations must be overcome without much delay to reap the maximum benefits of these promising technologies of the twenty-first century.

In the words of Engman and Schultz (2000), “Without remote sensing, it is very possible that future progress in the hydrological sciences will be severely retarded if not completely stopped”. Rapidly expanding GIS technology will play a central role in handling the vast amount of spatio-temporal data and their effective interpretation, analysis, and presentation, though such applications will raise some new problems. In the words of Lo and Yeung (2003), “GIS empowers us to solve environmental problems of a changing world faced by humankind in the new millennium”. RS and GIS technologies will indeed play a crucial role in the development of effective decision support systems or expert systems for the sustainable development and management of vital but shrinking water resources.

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