Groundwater

Resource Evaluation, Augmentation, Contamination, Restoration, Modeling and Management

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Edited by

M. Thangarajan

Senior Deputy Director (Retd.)
National Geophysical Research Institute
Hyderabad, India

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Cover Illustration: Crystal clear water in a highly weathered large well at Kannivadi village, Kodaganar river basin, Tamil Nadu, India. Photograph taken by editor.

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Foreword

The demand for water resources is increasing day by day due to ever increasing population, mostly from developing countries. This has resulted in abstracting more water from the subsurface stratum and forcing the water managers to manage the limited groundwater resources in a more scientific way, which in turn needs a more sophisticated way of assessing the underground resource and manage it optimally. There is an urgent need to locate high yielding boreholes in the hard rock region by using geophysical methods. Electrical imaging technique in conjunction with remote sensing and geographical information system (GIS) technique has proved to be a potential tool for the purpose. Hydrodynamics of fractured aquifer system in hard rock region is not yet fully understood. The understanding of the groundwater pollution migration in porous and fractured aquifer system and the seawater intrusion in the coastal aquifer has to be improved further. Various aspects of groundwater modeling and in particular issues related to model calibration, validation and prediction has to be understood in much better way. One should integrate all the above issues for effective understanding of the assessment and management of groundwater resources.

There is a need to have a comprehensive book to deal with all the above. My former colleague, Dr. M. Thangarajan, Retired Scientist-G, NGRI, Hyderabad, India has successfully edited a book on GROUNDWATER (Resource Evaluation, Augmentation, Contamination, Restoration, Modeling and Management) by inviting topics from various experts across the globe.

It is my firm view that this book will form a comprehensive text for those engaged in the resource evaluation, augmentation, contamination modeling and management.

I wish to congratulate Dr. M. Thangarajan to bring out this book in an excellent manner.

Dr. V.P. Dimri
Director
National Geophysical Research Institute
Hyderabad, India

Preface

Groundwater plays a major role in the livelihood of mankind by providing water for drinking, irrigation and industrial purposes. The rapid population growth in the last three decades all over the globe resulted in exploiting more groundwater. The distribution of groundwater—both in space and time—is more erratic as it depends on the subsurface geological and climatic conditions. In many countries, the decline of water level indicates that the resources are depleted very fast. It is, therefore, necessary to assess the available subsurface resource in a more judicious scientific manner and then apply it for evolving optimal utilization purposes. There is an urgent need to have a comprehensive book, which contains the entire spectrum of groundwater assessment and management aspects. I had seen many books, which cover only the specific aspects on groundwater exploration, exploitation, augmentation, pollution and remediation and mathematical modeling but not many books on the integrated aspects of all. It was, therefore, planned to bring a book, which covers the abovesaid aspects by inviting specific topics from various experts of the globe.

The aim of the book is to provide theoretical background on the application of remote sensing and GIS techniques in the delineation of subsurface resources as described in Chapter 1. Chapter 2 discusses the principles of electrical resistivity and imaging (tomography) techniques in the identification of potential boreholes in hard rock region. Principles of pumping test analysis and interpretation of data to evolve aquifer parameters transmissivity 'T' and storativity 'S' through numerical technique have been brought out in Chapter 3. Basic principles and the application of theory of regionalized variables (Geostatistics-Kriging) for the interpolation of sparse hydrogeological data and its estimation error have been stressed in Chapter 4. Augmentation of groundwater resources through aquifer storage and recovery (ASR) along with the quality problem due to reaction of rocks and injection fluid is dealt in Chapter 5. Chapter 6 deals with the environmental problem. The sources and the process of fluoride and arsenic contamination have been brought out clearly in this article.

Chapter 7 deals with the characterization of fracture properties in hard rock areas through hydrogeological investigation at different scales. A methodology was evolved to delineate the vertical distribution of conductive fracture zones and their permeability through flowmeter vertical profiles during fluid injection and evolving the spatial distribution of permeability by making use of slug test data. The above methodology was tested in Maheswaram watershed, a hard rock region in Andhra Pradesh (India). Groundwater flow and mass transport modeling play a major role in the assessment and management of groundwater resources. Modeling principles and various types of models, which are in vogue for various applications are presented in Chapter 8. An exclusive chapter on the model calibration and issues related to validation, sensitivity analysis, post-audit, uncertainty evaluation and assessment of prediction data needs is also presented. Groundwater development and management of coastal and island aquifers through field investigations and mathematical modeling is brought out in Chapter 10. Basic principles of SUTRA (USGS) finite element model are also highlighted. The management of groundwater resources through community participation approach and some aspects of remedial measures of contaminated aquifer may provide some insight to the groundwater professionals, which form the Chapter 11.

Groundwater management needs assessment, which in turn needs a model. A model needs a set of mathematical equations to describe the system. The equations have to be solved through a set of characteristic parameters, initial and boundary conditions of the aquifer system, which in turn have to be obtained through field investigations. Field investigations need a set of procedures, which in turn needs guidelines to carry out field investigations. I believe and hope that this book may provide the needed guidelines and answers for all the above.

I am thankful to Dr. V.P. Dimri, Director, National Geophysical Research Institute (NGRI), Hyderabad, India for providing infrastructure facilities at NGRI to complete this book. I extend my gratitude to all the contributors for this book who are well known experts in their respective fields. The following have contributed: F.M. Howari, Mohsen M. Sherif and Mohamed S. Al Asam from UAE University, Al Ain, UAE; V.P. Singh, Louisiana State University, Baton Rouge, USA; Ron D. Barker, University of Birmingham, Birmingham, UK; V.S. Singh, NGRI, Hyderabad, India; Shakeel Ahmed, NGRI, Hyderabad, India; Chris Barber, Center for Groundwater Studies, Adelaide, Australia; N. Madhavan and Prof. V. Subramanian from the School of Environmental Sciences, JNU, New Delhi, India; J.C. Maréchal and B. Dewandel from BRGM, France; K. Subrahmanyam, NGRI, Hyderabad, India; Claire R. Tiedeman and Mary C. Hill from USGS, USA; and A. Ghosh Bobba, National Water Research Institute, Burlington, Canada.

My colleagues at NGRI, Hyderabad viz. Dr. S. Thiagarajan, Mr. G. Ramandha Babu and Y.S.N. Murthy are thanked for their support in preparation of the manuscript. I take this opportunity to thank both Prof. V.P. Singh and Prof. Mary C. Hill who inspired me to bring out this book. Finally, Capital Publishing Company, New Delhi, India is thanked for their keen interest in publishing this book.

M. Thangarajan
Former Scientist-G & Head, Groundwater Modeling Group
National Geophysical Research Institute
Hyderabad, India

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Application of GIS and Remote Sensing Techniques in Identification, Assessment and Development of Groundwater Resources

Fares M. Howari, Mohsen M. Sherif[1], Vijay P. Singh[2] and Mohamed S. Al Asam[3]

Geology Dept., College of Science, UAE University, Al Ain, UAE
[1] Civil and Environmental Engineering Dept., College of Engineering, UAE University Al Ain, UAE
[2] Department of Civil and Environmental Engineering, Louisiana State University Baton Rouge, LA 70803-6405, USA
[3] Ministry of Agriculture and Fisheries, Dubai, UAE

PREAMBLE

Geographical Information Systems (GIS) and Remote Sensing (RS) techniques have emerged as efficient and powerful tools in different fields of science over the last two decades. The GIS has the ability to store, arrange, retrieve, classify, manipulate, analyze and present huge spatial data and information in a simple manner. The RS technique is used to collect detailed information in space and time even from inaccessible areas. Nowadays, both GIS and RS are regarded as essential tools for groundwater studies especially for extended and complex systems.

This article reviews practices, problems and prospects of using Geographic Information Systems and Remote Sensing in the exploration, assessment, analysis and development of groundwater resources. Review of literature indicates successful attempts that have used GIS and RS, and studies that have included conceptualizations of space and time embedded in the current generation of GIS and RS. However, there are limitations to applications of these techniques. For example, in many cases, incompatibility between hydrological and hydrogeological models and GIS and RS tools exist. By reframing the future research agenda from the emerging geographic information science perspective, it is believed that integration of hydrological/hydrogeological modeling with GIS should proceed with the development of a high-level common platform that is compatible with both GIS and hydrological/hydrogeological models. More research to better handle, communicate and reduce the uncertainties in the process of GI Science-based hydrological and hydrogeological modeling is needed. On the other hand, it is evident to water resources specialists that remote sensing provides efficient means of observing hydrological variables over large and remote areas.

This article also discusses issues and information that need to be considered while dealing with major hydrological/hydrogeological investigations, such as those dealing with land surface temperature from thermal infrared data, surface soil moisture from passive microwave data, selecting groundwater recharge sites, simulation of groundwater systems, water quality using visible and near-infrared data, and estimating landscape surface roughness using radar. Methods for estimating related variables of interest, such as fluxes, evapotranspiration and runoff, using state variables are also described. The article is concluded with an example for the employment of RS and GIS techniques in groundwater studies.

INTRODUCTION

Satellite remote sensing has become a common tool to investigate different fields of earth and natural sciences (Barret and Kidd, 1987; Barret and Curtis, 1982). The progress of the performance and capabilities of the optoelectronic and radar devices mounted on-board remote sensing platforms have further improved the capability of instruments to acquire information about water resources and hydrological/hydrogeological systems. With the advent of new high-spatial and spectral resolution satellite and aircraft imagery new applications for large-scale mapping and monitoring have become possible (e.g., Fortin and Bernier, 1991; Jensen, 1986). Integration with Geographic Information Systems (GIS) allows a synergistic processing of multi-source spatial data. Using of GIS in hydrogeology is only at its beginning, but there have been successful applications that started to develop (Barton, 1987; Bhasker et al., 1992; Clark, 1998; Gossel et al., 2004). Groundwater resources are dynamic in nature as they are affected by various human activities, including the expansion of the cultivated and irrigated lands, industrialization, urbanization, and others. Because it represents the largest available source of fresh water lying beneath the ground it has become crucial not only for targeting of groundwater potential zones, but also monitoring and conserving this important resource. In addition to targeting the groundwater potential zones, it is also important to identify suitable sites for artificial recharge to sustain groundwater systems and avoid their depletion due to over-pumping and/or insufficient natural recharge. When natural recharge from rainfall events cannot meet groundwater demands, the balance is disturbed and hence it calls for artificial recharge on a countrywise basis (Saswosky and Gardner, 1991; Shulz, 1994; More, 1991; Sameena et al., 2000). To improve the information and data feeding the GIS, pressure is put to advance the remote sensing platforms. The development and advancement of remote sensing platforms is crucially needed to improve our knowledge and monitoring ability on natural resources.

On the other hand, remote sensing with its advantages of spatial, spectral and temporal availability of data covering large and inaccessible areas within a short time has become a very handy tool in assessing, monitoring and conserving groundwater resources. Satellite data provides quick and useful baseline information on the parameters controlling the occurrence and movement of groundwater, such as geology, lithology, stratigraphy, structural controls, geomorphology, soils, land-use/cover and lineaments (Das, 1994, 1990). However, all the controlling parameters have rarely been studied together because of the non-availability of data, integrating tools and modeling techniques. Hence a systematic study of these factors leads to a better delineation of prospective zones in an area, which is then followed up on the ground through detailed hydrogeological and geophysical investigations.

Fotheringham and Rogerson (1994) indicated that for almost two decades in the 1960s and 1970s, geographic information systems (GIS) and hydrological modeling developed in parallel with a few interactions. Major research efforts toward the integration of GIS with hydrological modeling did not take place until the late 1980s, as part of the GIS community's efforts to improve the analytical capabilities of GIS (e.g., Goodchild et al., 1992) and hydrologists' new demand for accurate digital representations of the terrain (Clark, 1998; Singh & Fiorentino, 1996). Nowadays, both GIS users and hydrologists have increasingly recognized the mutual benefits of such integration from the successes of the last few years (Gossel et al., 2004).

Remote sensing images have been used successfully to identify boundaries of inaccessible watersheds and determine the order and slopes of channels. Outcropping and recharge areas of aquifers, soil and rock types, land cover, land erosion in coastal zones, movement of sand dunes, and development of agricultural, industrial, urbanization and tourism activities have been successfully studied using RS (Lanza et al., 1997; Sui and Maggio, 1999; Schmugge et al., 2000; Su Z.B. Troch P.A. 2003). Nevertheless, many studies require supporting field information to ensure the accuracy of the RS images. This information can be introduced to hydrological models, such as HEC-HMS, to estimate the surface water runoff and base flow. Information about permeable (active) and impermeable (inactive) areas (cells or elements) can also be imported to groundwater models, such as FEFLOW, MODFLOW and SUTRA, to simulate groundwater flow and solute transport in aquifers.

The most important feature of the RS images is that all information and data collected are geo-referenced and can be easily integrated in GIS databases and hydrological/hydrogeological models. In other words, study domains and other parameters and boundaries can be imported/exported among different surface and groundwater simulation packages with little or no errors.

INTEGRATING GIS AND REMOTE SENSING

Visual interpretation has been the main tool for evaluation of groundwater prospective zones for over two decades (Beven and Moor, 1992; Blyth, 1993; Das, 1990). It has also been found that remote sensing, besides helping in targeting potential zones for groundwater exploration, provides inputs towards estimation of the total groundwater resources in an area, the selection of appropriate sites for drilling or artificial recharge and the thickness of unconsolidated deposits. By combining the remote sensing information with adequate field data, particularly well inventory and yield data, it is possible to arrive at prognostic models to predict the ranges of depth, yield, success rate and types of wells suited to various terrains under different hydrogeological domains. Based on the status of groundwater development and groundwater irrigated areas (through remote sensing), artificial recharge structures, such as percolation tanks, check dams and subsurface dykes, can be recommended upstream of groundwater irrigated areas to recharge the wells in the downstream areas so as to augment groundwater resources. Examples of successful studies include the work of Engman et al. (1989), Gupta et al. (1996) and Hannaford and Hall (1980).

Sherif et al. (2004) conducted a comprehensive study to assess the effectiveness of dams in recharging aquifers in three selected Wadis in the United Arab Emirates. Remote Sensing images were used to identify watersheds contributing to the water storage in the ponding areas of different dams. Recharge areas and active (permeable) and inactive (impermeable) zones were also identified using the RS images. All information, including locations of pumping and observation wells, pumping rates, lithological cross sections, geologic and hydraulic parameters and climatic data, were integrated into a GIS database. Such information was in several layers that could be imported by most of the groundwater simulation models. The RS technique and GIS were also employed in another study for groundwater management in two coastal aquifers of the United Arab Emirates and Sultanate of Oman (Sherif et al., 2004b). Figure 1 presents a RS image for Wadi Ham in the UAE including the main hydrogeological/geological features of the Wadi.

Many researchers are now using digital techniques to derive the geological, structural and geomorphological details (Humes et al., 1994; Jensen, 1986; Jakson, 1977) to understand the aquifer system. The various thematic layers generated using remote sensing data like borehole lithology/structural, geomorphology, landuse/cover and lineaments can be integrated with slope, drainage density and other collateral data in a Geographic Information System (GIS) framework and analyzed using a model developed with logical conditions associated with groundwater zones as well as artificial recharge sites (Das, 1990; Peck, 1981; Perry et al., 1988; Rango et al., 2000; Gossel et al., 2004). Digital enhancement techniques are found to be suitable since they improve the feature sharpness and contrast for simple interpretation (Fig. 2).

Field data can also be integrated into GIS, since most of the groundwater related data would be available from pumping wells/bore hole logs, would be point information, and could be interpolated to get spatial data, i.e., each grid cell would have valid data without any gaps (e.g., Goodchild et al., 1993). Point data could be water level, water quality, weathered zone thickness, saturated zone thickness, elevation, yield of wells, rainfall at various rain gauge stations, porosity of soil, hydraulic conductivity, K, transmissivity (T) and storage coefficient (S), and others. Depending on the objectives of the study and the porous media under consideration the important layers of information data and other related variables that would be stored in different layers could be identified. A GIS database including various layers should be developed in such a manner as to allow for an efficient access, retrieval, organization, manipulation and analysis of the available information. On the other hand, contour or zonation maps can be developed from point information to provide a better understanding of the areal distribution of variables in the study domain (Fig. 2).

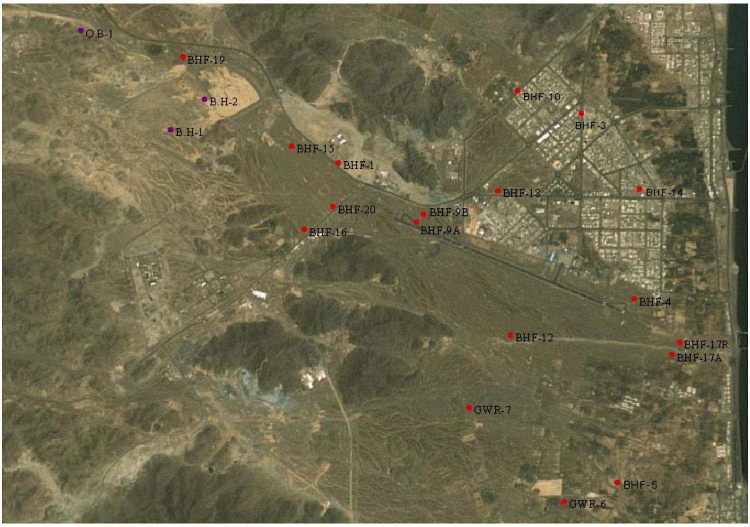
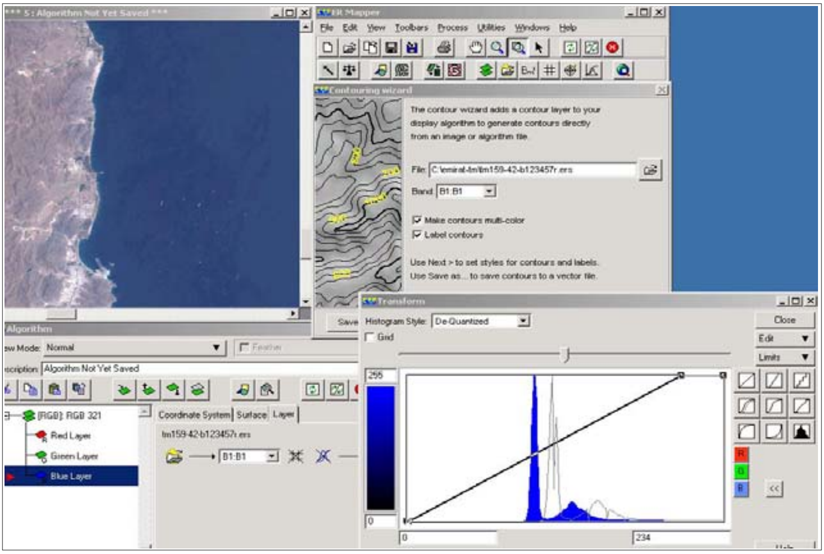


Figure 1. RS image of Wadi Ham in the UAE (after Sherif et al., 2004). (Colour reproduction on Plate 1)



The contour wizard adds a contour layer to your display algorithm to generate contours directly from an image or algorithm file.

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Band: B1:B1

☑ Make contours multi-color

☑ Label contours

Use Next > to set styles for contours and labels.
Use Save as... to save contours to a vector file.

Histogram Style: De-Quantized

☐ Grid

255

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234

Mode: Normal

☐ Feather

Description: Algorithm Not Yet Saved

[RGB]: RGB 321

Red Layer

Green Layer

Blue Layer

tm159-42-b123457r.ers

B1:B1

Figure 2. Image processing activities to improve feature sharpness and contrasts. (Colour reproduction on Plate 1)

HYDROLOGICAL APPLICATIONS AND ASSOCIATE VARIABLES

According to Chow (1986), aquifer recharge occurs in nature by rainfall, seepage from canals and reservoirs, lagoons, forested lands, irrigated fields, and return flow from irrigation. Geomorphic features, such as alluvial fans buried pediments, old stream channels and the deep-seated interconnected fractures, are indicators of subsurface water accumulation. These features represent natural recharge sites due to their high permeability and water holding capacity. Howari et al. (2002) and Howari (2003) studied soil permeability using remote sensing techniques. Moreover, it is clear that the higher the permeability the lower the drainage density and the higher the drainage density the higher the surface water runoff. Identification of lineaments has an immense importance in hard rock hydrogeology as they can identify rock fractures that localize groundwater (Das, 1990). Hydrogeologists usually infer subsurface hydrological conditions through surface indicators, such as aerial geological features, linear structures and others. Most of the geological linear features are assumed to be the zone of fractured bedrocks and the position of porous and permeable state where enhanced well yields can be expected (Das, 1997). The advent of increasing computing power and GIS technique, physically-based hydrologic modeling has become important in contemporary hydrology for assessing the impact of human intervention and/or possible climatic change on basin hydrology and water resources (Lanza et al., 1997; Sui and Maggio, 1999; Schmugge et al., 2000; Su Z.B. Troch P.A., 2003). The use of distributed physically based (conceptual) hydrological modeling with prudent simplification is appropriate for providing a reasonable solution to large scale hydrological problems associated with planning and optimal allocation of resources.

HYDROLOGICAL MODELING AND GIS

GIS has influenced the development and implementation of hydrologic models at several different levels, and it provides representations of these spatial features of the Earth, while hydrologic modeling is concerned with the flow of water and its constituents over the land surface and in the subsurface environment. Various hydrological modeling techniques have enabled GIS users to go beyond the data inventory and management stage to conduct sophisticated modeling and simulation. For hydrological modeling, GIS, especially through their powerful capabilities to process Digital Elevation Models (DEM), have provided modelers with new platforms for data management and visualization. The rapid diffusion of GIS has the potential to make various hydrological models more powerful, accurate, and transparent and can enable the communication of their operations and results to a larger group of users. The growing literature on the integration of GIS with hydrological modeling attests to the recognition of such benefits (DeVantier & Feldman, 1993; Maidment, 1993; McDonnell, 1996; Moore, 1996).

GIS researchers and hydrologists have recognized that lack of sophisticated analytical and modeling capabilities is one of the major deficiencies of GIS technology (Maidment, 1993). Several research initiatives worldwide have focused on the improvement of spatial analytical and modeling capabilities of GIS technology during the past 10 years (Goodchild et al., 1992). Integration of GIS with hydrological modeling was part of these broad research efforts to link spatial analysis and modeling with GIS. Although overlapping with many other GIS modeling efforts in terms of general methodology (e.g., Goodchild et al., 1993), integration of GIS with hydrological modeling has a set of different issues from other kinds of GIS-based environmental modeling (Goodchild, Parks & Steyaert, 1993). For example, unlike most other kinds of environmental modeling, hydrological modeling has a set of well-established practices and standards widely accepted by hydrologists and hydraulic engineers, and modeling results are sometimes used for regulatory purposes. Current practices of integrating GIS with hydrological modeling thus deserve a separate scrutiny (Lanza et al., 1997; Sui and Maggio, 1999; Schmugge et al., 2000; Su Z. B Troch P. A., 2003).

Improving Hydrological Modeling by Including GIS Functionalities

According to Sui and Maggio (1999), embedding GIS functionalities in hydrological modeling packages has been adopted primarily by hydrological modelers who think of GIS essentially as a mapping tool and conceptually irrelevant to the fundamentals of hydrological modeling. This approach usually gives system developers maximum freedom for system design. Implementation is not constrained by any existing GIS data structures, and usually this approach is capable of incorporating the latest development in hydrological modeling (Brimicombe and Bartlett, 1996; Clark, 1996). The downside of this approach is that the data management and visualization capabilities of these hydrological modeling software packages are, in no way, comparable to those available in commercial GIS software packages, and programming efforts also tend to be intensive and sometimes redundant. The developers of the latest version of River-CAD, HEC-HMS 2.0, River-Tools, MODFLOW and SUTRA have basically taken this approach (Djokic et al., 1995).

On the other hand, a few leading GIS software vendors in recent years have made extra efforts to improve the analytical and modeling capabilities of their products. Pioneered by HEC-SAS developed by the Army Corps of Engineers (Davis, 1978), several commercial software vendors have developed stand-alone GIS modules with functions that can be used for a variety of hydrological modeling needs. Certain hydrological modeling functions have been embedded in leading generic GIS software packages, such as ESRI's ArcStorm and ArcGrid, Integraph's InRoads, etc. This approach builds on the top of a commercial GIS software package and takes full advantage of built-in GIS functionalities, but the modeling capabilities are usually simplistic and calibrations must take place outside of the package. Also, these models tend not to be industry standard and/or have not been validated (Shamsi and Fletcher, 1994; Shuman, 1993).

Existing Problems

GIS have provided hydrologists and hydraulic engineers with the ideal computing platform for data inventory, parameter estimation, mapping and visualizing results for hydrological/hydraulic modeling, thus greatly facilitating the design, calibration, and implementation of various hydrological/hydraulic models (Lanza et al., 1997; Sui and Maggio, 1999; Schmugge et al., 2000; Su Z. B Troch P. A., 2003). However, we should not let the fancy maps and graphics of GIS blind us from the real issues in hydrological modeling. The current practices are dominated by technical concerns without adequately addressing some of the important conceptual issues involved in the integration of GIS with hydrological modeling. While the technical problems related to the database integration are well documented (Adam & Gangopadhyay, 1997; Buogo & Chevallier, 1995), only a few papers in the literature have discussed the broad conceptual issues involved in the integration of GIS with hydrological modeling. Several problems in both hydrological models and the current generation of GIS are usually observed. These problems must be addressed before we can make the integration of GIS with hydrological modeling theoretically consistent, scientifically rigorous, and technologically interoperable (Lanza et al., 1997; Sui and Maggio, 1999; Schmugge et al., 2000; Su Z. B Troch P. A., 2003).

Inherited Problems

According to Chow, Maidment and Mays (1988), hydrological models can be classified according to their conceptualization and assumptions of three key parameters—randomness, space and time. The models widely used in the current practices of GIS-based hydrological modeling are dominated by deterministic lumped models because of the availability of various modeling packages, such as the US Army Corps of Engineers HEC-HMS and HEC-RAS, the US Soil and Conservation Service's TR-20 and TR-40, USDA's SWAT, DoT's WSPRO, EPA's WASP and BASINS, and USGS's DRM3 and PRMS, etc. (Singh and Frevert, 2002a, b). Several researchers have challenged the foundations of these models (Grayson, Moore & McMahon, 1992; Smith & Goodrich, 1996) and many researchers have been active to develop spatially distributed and stochastic models (Beven & Moore, 1992; Romanowicz, Beven & Moore, 1993; Wheater, Jakeman & Beven, 1995). However, these newly developed models are still mostly confined to research laboratories and not widely used in practice. Obviously, our primary objective should not only focus on doing the thing right in the technical sense but also, perhaps more importantly, challenge whether it is the right thing to do in a scientific sense.

Computational Problem

With its historical roots in computer cartography and digital image processing, the development of GIS to date has relied upon a limited map metaphor (Burrough & Frank, 1995). The majority of GIS datasets are currently represented in vector format, which is convenient due to storage efficiency but can be difficult to manipulate analytically. To achieve tractability, vector format GIS data is often rasterized (e.g., conformed to a grid-cell representation). The processes involved in vectorization of map data as well as rasterization of vector data have indiosyncratic errors that manifest as representational error in a given GIS system. Consequently, the representation schemes and analytical functionalities in GIS are geared toward map layers and geometric transformations. The layer approach implicitly forces a segmentation of geographic features (Raper and Livingstone, 1995). This representation scheme is not only temporally fixed but is also incapable of handling overlapping features (Hazelton, Leahy & Williamson, 1992). The absolute conceptualization of space has forced space into a geometrically indexed representation scheme via planar enforcement, and time is conceptualized as discrete slices. In contrast, depending on how randomness is handled, space and time in hydrological models can be conceptualized quite differently. Although technically we can plug in various hydrological models into GIS through the strategies outlined in the previous section, GIS and hydrological models are just used together, not really integrated because of the fundamentally different spatial data representation schemes involved

(Abel, Kilby & Davis, 1994). Therefore, in order to accomplish the seamless integration of GIS and hydrological models, more research is needed at a higher level to develop and incorporate novel approaches to conceptualizing space and time that is interoperable both within GIS and hydrological models (Lanza et al., 1997; Sui and Maggio, 1999; Schmugge et al., 2000; Su Z. B Troch P. A., 2003).

Obviously, the current practices of integrating GIS and hydrological modeling are essentially technical in nature and have not touched upon the more fundamental issues in either hydrological models or GIS. Simply being able to run a HEC-HMS or HEC-RAS model in Arc/Info or a CAD system improves neither the theoretical foundation nor the performance of the model. GIS-based hydrological modeling has resulted in a tremendous amount of representational compromise (Gan, Dlamini & Biftu, 1997). Such problems call for a fresh look at the integration of GIS with hydrological modeling.

Uncertainties of GIS as Related to Hydrological Investigations

In spite of well-known quality issues in spatial data handling, most applied modeling in practice neglects error and uncertainty. If we succeed in developing GIScience-based hydrological modeling interoperable across computing platforms, hydrological modeling will be more widely accessed and used to address water-related issues of great societal concerns. Robust hydrological modeling will be an integral part of management tools for sustainable watershed development. The interoperable GIScience-based hydrological model will also greatly empower citizens and communities in flood-prone areas to play an important role in flood control, flood mitigation, floodplain mapping, and flood insurance studies. However, every single step in the process of integrating GIS with hydrological modeling is full of uncertainties, ranging from data acquisition to model calibration to results visualization. Currently, we still lack effective methods to handle and communicate these uncertainties (Heuvelink, 1998; Tung, 1996; Kundzewicz, 1995). Second, new methods of communicating results of uncertainty measures need to be developed. Both visual and non-visual methods of communicating uncertainties are worth exploring (Lanza et al., 1997; Sui and Maggio, 1999; Schmugge et al., 2000; Su & Troch, 2003). It has long been recognized by the GIS community that the ability to communicate to users the uncertainty of the digital databases is a critical step in maintaining professional integrity in applications of great societal concerns, such as floodplain mapping, flood insurance rating, and watershed development planning (Clark, 1996; Hwang, Karimi & Byun, 1998; Klinkenberg & Joy, 1994). Although there is no general agreement or professional protocols, the methods of communicating uncertainties of spatial databases reviewed by Hunter and Goodchild (1996) can be applied to convey the uncertainties of integrating GIS with hydrological modeling.

REMOTE SENSING AS A SOURCE OF INFORMATION TO GIS: CAPABILITIES AND LIMITATIONS

Remote sensing is the process of inferring surface parameters from measurements of the upwelling electromagnetic radiation from the land surface. This radiation is both reflected and emitted by the land. The former is usually the reflected solar radiation while the latter is in both the thermal infrared (TIR) and microwave portions of the spectrum (Jensen, 1986; Sabins, 2002). There is also reflected microwave radiation as in imaging radars. The reflected solar radiation is used in hydrology for snow mapping vegetation/ land cover and water quality studies. Active microwave or radar has promise because of the possibility of high spatial resolution. However, surface roughness effects can make it difficult to extract soil moisture information. Remotely sensed observations can contribute to our knowledge of these quantities and, especially, their spatial variation. With remote sensing we not only observe the surface but can also obtain the spatial variability and if observations are made repeatedly the temporal variability can be obtained. In this section we will concentrate on those applications of remote sensing which are most promising in hydrology (e.g., Shultze, 1988).

Major focus of remote sensing research in hydrology has been to develop approaches for estimating hydrometeorological states and fluxes. The primary set of state variables include land surface temperature, near-surface soil moisture, snow cover/water equivalent, water quality, landscape roughness, land use and vegetation cover. The hydrometeorological fluxes are primarily soil evaporation and plant transpiration or evapotranspiration, and snowmelt runoff. We will describe methods which have been used to quantify the components of the water and energy balance equation using remote sensing methods as described by Sui and Maggio, 1999; Schmugge et al., 2000 and Su and Troch, 2003. The water balance is commonly expressed as:

$$\frac{\Delta S}{\Delta t} = P - ET - Q \qquad (1)$$

where $\Delta S/\Delta t$ is the change in storage in the soil and/or snow layer, P is the precipitation, ET is the evapo-transpiration, and Q is the runoff. Because the energy and water balance at the land surface are closely linked we also need to consider the energy balance equation which is typically written as:

$$R_{\mathrm{N}} - G = H + LE \qquad (2)$$

where R_{N} is the net radiation, G is the soil heat flux, H is the sensible heat flux and LE is the latent heat flux, all in W m^{-2}. The quantity $R_{\mathrm{N}} - G$ is commonly referred to as the available energy, and ET and LE represent the same water vapour exchange rate across the surface–atmosphere interface, except that ET is usually expressed in terms of the depth of water over daily and longer time scales, namely mm/day.

REMOTE SENSING TECHNIQUES TO ASSESS WATER QUALITY

Water quality is a general descriptor of water properties in terms of physical, chemical, thermal, and/or biological characteristics. In-situ measurements and collection of water samples for subsequent laboratory analyses provide accurate measurements for a point in time and space but do not give either the spatial or temporal view of water quality needed for accurate assessment or management of water bodies. Substances in surface water can significantly change the backscattering characteristics of surface water (Forster and Wittman, 1983). Remote sensing techniques for monitoring water quality depend on the ability to measure these changes in the spectral signature backscattered from water and relate these measured changes by empirical or analytical models to water quality parameters. The optimal wavelength used to measure a water quality parameter is dependent on the substance being measured, its concentration, and the sensor characteristics (Howari et al., 2002).

Major factors affecting water quality in water bodies across the landscape are suspended sediments (turbidity), algae (i.e., chlorophylls, carotenoids), chemicals (i.e., nutrients, pesticides, metals), dissolved organic matter (DOM), thermal releases, aquatic vascular plants, pathogens, and oils (Sui and Maggio, 1999; Schmugge et al., 2000; Su and Troch, 2003). Suspended sediments, algae, DOM, oils, aquatic vascular plants, and thermal releases change the energy spectra of reflected solar and/or emitting thermal radiation from surface waters, which can be measured by remote sensing techniques. Most chemicals and pathogens do not directly affect or change the spectral or thermal properties of surface water; they can therefore only be inferred indirectly from the measurements of other water quality parameters affected by these chemicals (Shultze, 1988).

Empirical or analytical relationships between spectral properties and water quality parameters are established. The general forms of these empirical equations are:

$$Y = AX^{\mathrm{B}} \tag{3}$$

where Y is the remote sensing measurement (i.e., radiance, reflectance, energy), X is the water quality parameter of interest (i.e., suspended sediment, chlorophyll), and A and B are empirically derived factors. In empirical approaches statistical relationships are determined between measured spectral/thermal properties and measured water quality parameters. Often information about the spectral/optical characteristic of the water quality parameter is used to aid in the selection of best wave length(s) or best model in this empirical approach. The empirical characteristics of these relationships limit their application to the condition for which the data were collected.

Suspended sediments are the most common pollutant both in weight and volume in surface waters of freshwater systems. Significant relationships between suspended sediments and radiance or reflectance from spectral wavebands or combinations of wavebands on satellite and aircraft sensors have been shown. Ritchie and Cooper (1991) and Ritchie et al. (2000) showed that an algorithm for relating remotely sensed data to the sediment load developed for one year was applicable for several years.

Direct measurement of rainfall from satellites for operational purposes has not been generally feasible because the presence of clouds prevents observation of the precipitation directly with visible, near infrared and thermal infrared sensors (Sui and Maggio, 1999; Howari et al., 2002; Schmugge et al., 2000; Su and Troch, 2003). However, improved analysis of rainfall can be achieved by combining satellite and conventional gauge data. Useful data can be derived from satellites used primarily for meteorological purposes, including polar orbiters, such as the U.S. National Oceanographic and Atmospheric Administration (NOAA) series and the Defense Meteorological Satellite Program (DMSP), and from geostationary satellites, such as Global Operational Environmental Satellite (GOES), Geosynchronous Meteorological Satellite (GMS) and Meteosat, but their visible and infrared images can provide information only about the cloud tops rather than cloud bases or interiors. However, since these satellites provide frequent observations (even at night with thermal sensors), the characteristics of potentially precipitating clouds and the rates of changes in the cloud area and shape can be observed. From these observations, estimates of rainfall can be made which relate cloud characteristics to instantaneous rainfall rates and cumulative rainfall over time. For the practicing hydrologist, satellite rainfall methods are most valuable when there are no or very few surface gauges for measuring rainfall (Sui and Maggio, 1999; Schmugge et al., 2000; Su and Troch, 2003).

There are, of course, many types of satellite in operation. Here, we will look at some important satellites that provide a background to the dynamical data produced by the meteorological satellites of hydrological applications; LANDSAT, SPOT and ERS are known as the 'Earth Resources' satellites. The availability of meteorological and Landsat satellite data has produced a number of techniques for inferring precipitation from the visible and/or infrared (VIS/IR) imagery of clouds. The GOES Precipitation Index (Arkin, 1979) derived from thresholding the infrared brightness temperature of cloud tops has been used to study the distribution of tropical rainfall. The University of Bristol (Barrett and Martin, 1981; D'Souza and Barrett, 1988) has led the development of a cloud indexing (Moses and Barrett, 1986) approach and a thresholding (Barrett et al., 1988) approach. A life-history approach, developed by Scofield and Oliver (1977), considers the rates of change in individual convective clouds or clusters of convective clouds. This approach is the basis of a flash flood system that assimilates GOES data with ground-based and atmospheric data to forecast precipitation amounts for use in a flood forecast model (Clark and Morris, 1986).

Evapotranspiration: In general, remote-sensing techniques cannot measure evaporation or evapotranspiration (ET) directly. However, remote sensing does have two potentially very important roles in estimating evapotranspiration. First, remotely sensed measurements offer methods for extending point measurements or empirical relationships, such as the Thornthwaite (1948), Penman (1948) and Jensen-Haise (1963) methods, to much larger areas, including those areas where measured meteorological data may be sparse. Secondly, remotely sensed measurements may be used to measure variables in the energy and moisture balance models of ET. Although, there has been progress made in the direct remote sensing of the atmospheric parameters which affect ET, such as the Raman Light Detection And Ranging (LIDAR). This is essentially a ground-based, point measurement and will not be covered in this report. A common approach in estimating *ET*, as described by Schmugge et al., 2000; Sui and Maggio, 1999 and Su and Troch, 2003, is to solve for the latent heat flux, *LE*, as a residual in the energy balance equation for the land surface, namely,

$$LE = R_N - G - H \tag{4}$$

Remote sensing methods for estimating these components are described in various places in literature. Typically, with reliable estimates of solar radiation, differences between remote sensing estimates and observed $R_N - G$ are within 10%. The largest uncertainty in estimating *LE* comes from computing *H*.

Additional approaches for estimating *ET* from remote sensing data are being explored. Barton (1978) and Davies and Allen (1973) have modified this formula for evaporation from an unsaturated land surface by the surface layer soil moisture. Barton used air-borne microwave radiometers to sense soil moisture remotely in his study of evaporation from bare soils and grasslands. Soares et al (1988) demonstrated how thermal infrared and C-band radar could be used to estimate bare soil evaporation. Choudhury et al., (1994) have shown strong relationships between evaporation coefficients and vegetative indices. Another approach being pursued is the development of numerical models that simulate the heat and water in the soil and drive it with the energy balance at the surface (Camillo et al., 1983, Taconet et al., 1986). Taconet and Vidal-Madjar (1988) have used this approach with Advanced Very High Resolution Radiometer (AVHRR) and Meteosat data.

Radar remote sensing has been used as a potential tool for soil moisture measurement since the pioneering work in the 1970s and 1980s (Ulaby, 1974; Ulaby et al., 1978; Ulaby et al., 1986; Toll, 1985; Schmugge, 1983). Radar is sensitive to variations in soil moisture because of the changes in the dielectric properties of soil produced by changes in water content. The sensitivity of radar to variations in moisture content potentially results in contrasting backscatter. The experimental bases of the dielectric properties of natural materials are provided by Ulaby et al. (1986) and Soulis et al. (1998). Figure 3 shows the relationship between the dielectric constant of a typical soil and its volumetric moisture content. As moisture content increases, the real component of the dielectric constant increases and on reaching a transition value of moisture, it increases more rapidly (Ulbay et al., 1986; Soulis et al., 1998; Tansey et al., 1999). Tansey et al. (1999) indicated that for particular volumetric soil moisture, the real component of the dielectric constant is greater for sand-rich soils than for clay-rich soils. This is due to the greater availability of free water that can interact with the radar signal in sand-textured soils. Consequently, the strength of the signal returned to the satellite or the backscatter is less for a dry soil than for a wet soil.

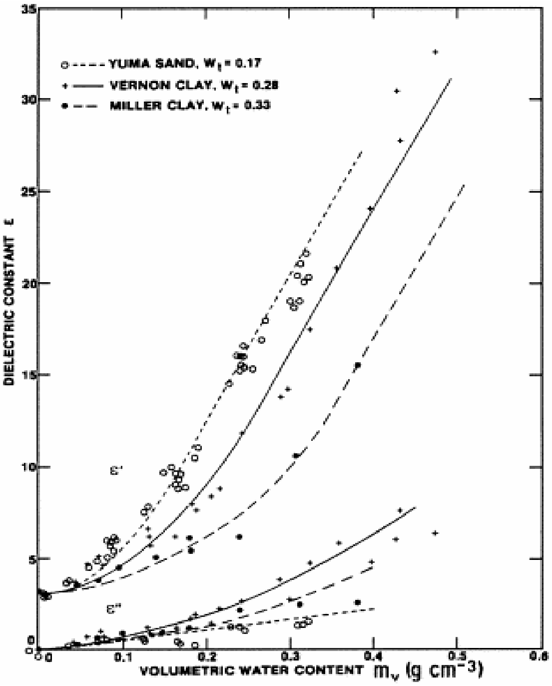

Figure 3. The complex dielectric constant, comprising real (') and imaginary ('') parts, shown as a function of volumetric moisture content for three soil types at 5 GHz. Also shown are the approximate transition volumetric soil moisture values (W_t) discussed in the text (after Wang & Schmugge, 1980).

Generally, field soil moisture measurements are used to calibrate and establish a relationship between in-situ and remote sensing estimates. Relating point measurements with radar responses over an aerially averaged pixel scale can be difficult. Glenn and James (2003) presented a geostatistical method to tackle this problem which is described below. Van Oevelen (1998) was able to downscale high-resolution aerial soil moisture estimates to low-resolution soil moisture estimates from the HAPEX-Sahel 1992 (Goutorbe et al., 1994). Other studies incorporating geostatistics in radar remote sensing of soil moisture include the works of Dempsey et al. (1998a, b). These studies use kriging and principal component analyses to discriminate variations in soil texture and soil moisture over time and space (Glenn and James, 2003).

Other previous studies on synthetic aperture radar (SAR) imagery have shown qualitative relationships between radar backscatter and soil moisture. Following the launch of the European Space Agency (ESA). European Remote Sensing Satellite (ERS-1) in 1991 and the Japanese Earth Resources Satellite (JERS-1) (1992), there has been a multitude of SAR sensors in space during the 1990s including the Shuttle Imaging Radar (SIR-C) (1994), Radarsat (1995), ESA ERS-2 (1995) and the Radarsat 2 launched in 2004. However, to be able to use airborne or satellite based radar data in operational programmes it will be necessary to establish quantitatively how the returned signal of radar is related to soil moisture and the effects of surface roughness, soil type, and vegetation cover and growth stage, as a function of frequency and polarization.

Runoff and Hydrologic Modeling: Remote sensing data can be used to obtain almost any information that is typically obtained from maps or aerial photography. In many regions of the world, remotely sensed data, and particularly Landsat, Thematic Mapper (TM) or Systeme Probatoire, d'Observation de la Terre (SPOT) data, are the only sources of good cartographic information. Drainage basin areas and the stream network are easily obtained from good imagery, even in remote regions (Lanza et al. 1997; Sui and Maggio, 1999; Schmugge et al., 2000; Su and Troch P. A., 2003). There have also been a number of studies to extract quantitative geomorphic information from Landsat imagery (Haralick et al., 1985). Topography is a basic need for hydrologic analysis and modeling. Remote sensing can provide quantitative topographic information of suitable spatial resolution to be extremely valuable for model inputs. For example, stereo SPOT imagery can be used to develop a Digital Elevation Model (DEM) with 10 m horizontal resolution and vertical resolution approaching 5 m in ideal cases (Case, 1989). A new technology using interferometric SAR has been used to demonstrate similar horizontal resolutions with approximately 2 m vertical resolution (Zebker et al., 1992).

One of the first applications of remote sensing data in hydrologic models used Landsat data to determine both urban and rural land use for estimating runoff coefficients (Jackson et al., 1976). Land use is an important characteristic of the runoff process that affects infiltration, erosion, and evapo-transpiration. Distributed models, in particular, need specific data on land use and its location within the basin. Most of the work on adapting remote sensing to hydrologic modeling has involved the Soil Conservation Service (SCS) runoff curve number model (U.S. Department of Agriculture, 1972) for which remote sensing data are used as a substitute for land cover maps obtained by conventional means (Jackson et al., 1977, Bondelid et al., 1982). In remote sensing applications, one seldom duplicates detailed land use statistics exactly. For example, a study by the Corps of Engineers (Rango et al., 1983) estimated that an individual pixel may be incorrectly classified about one-third of the time. However, by aggregating land use over a significant area, the misclassification of land use can be reduced to about two percent, which is too small to affect the runoff coefficient or the resulting flood statistics. Investigations have shown (Jackson et al., 1977) that for planning studies the Landsat approach is cost effective. The authors estimated that the cost benefits were on the order of 2.5 to 1 and can be as high as 6 to 1 in favour of the Landsat approach. These benefits increase for larger basins or for multiple basins in the same general hydrological area. Mettel et al. (1994) demonstrated that the recomputation of pmf's for the Au Sable River using Hydrologic Engineering Center (HEC-HMS) and updated and detailed land use data from Landsat TM resulted in 90% cost cuts in upgrading dams and spillways in the basin.

Other types of runoff models that are not based only on land use are beginning to be developed. For example, Strubing and Schultz (1983) have developed a runoff regression model that is based on Barrett's (1970) indexing technique. The cloud area and temperature are the satellite variables used to develop a temperature weighted cloud cover index. This index is then transformed linearly to mean monthly runoff. Rott (1986) also developed a daily runoff model using Meteosat data for a cloud index. Recently, Papadaakis et al. (1993) have used a cloud cover index from satellite imagery to estimate monthly area precipitation. A series of non-linear reservoirs then transforms the precipitation into monthly runoff values. This approach was successfully demonstrated for the large (16,000 sq. km) Tano River Basin in Africa and illustrates the value of remote sensing data when conventional data are not readily available. Ottle et al. (1989) have shown how satellite derived surface temperature can be used to estimate ET and soil moisture in a model that has been modified to use these data. Duchon et al. (1992) have used Landsat to identify uniform land cover areas and GOES data for input insulation for a monthly water balance model. RADARSAT-1 is sensitive to median soil moisture levels, returning low brightness values for low moisture contents and high brightness values for high moisture contents (Fig. 4).

APPLICATIONS OF GIS AND RS IN GROUNDWATER STUDIES

Remote sensing and GIS techniques are regarded as powerful tools for presentation and analysis of data and information. RS images provide important information related to the soil type, land use, orientation and intensity of fractures, identification of recharge and discharge areas, outcropping areas, coordinates of pumping and observation wells, and others. Depending on the soil texture, radar images can also provide useful information about the subsurface formation. Digital elevation models can be used to acquire the topography of the land surface from RS images. Topographic (contour) maps can thus be developed and exported directly as shape files or others to groundwater simulation packages. On the other

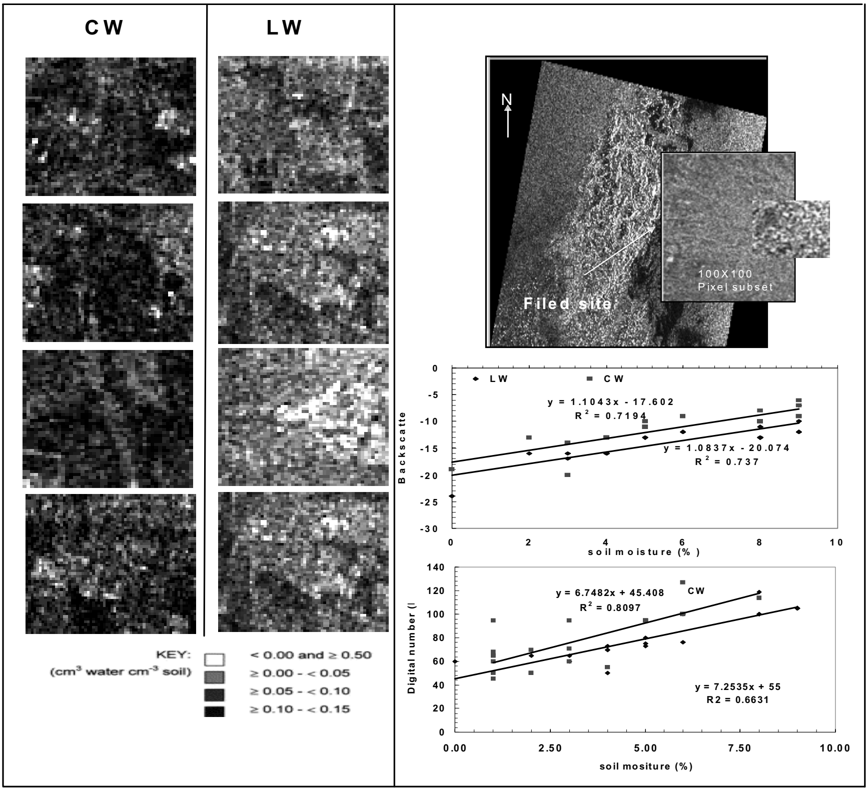

Figure 4. Relationship between soil moisture, backscattered coefficients and digital numbers in Fujairah, United Arab Emirates (after Howari, 2004)

hand, all data including the RS images can be organized and stored in different layers using ARC-GIS or any other GIS system. Contour maps for groundwater levels, aquifer bottom, thicknesses of the different layers, hydraulic parameters (porosity, permeability, transmissivity, storativity, and others), water quality, and other types of analyses can be done using GIS. Such information can also be exported directly as input files for groundwater simulation packages. An example for the application of GIS and RS in groundwater studies is elaborated hereafter.

Sherif et al. (2004), in collaboration with the Ministry of Agriculture and Fisheries, UAE, conducted a project to assess the groundwater recharge from three recharge dams in Wadi Bih, Wadi Tawiyean, and Wadi Ham, UAE. Figure 5 presents a remote sensing image for the location of these three wadis. Rain gauge stations are also located on the images. The sub-basins, boundaries and the order of all tributaries were identified and delineated using ARC-View. The total catchment area and the areas of all sub-basins were calculated by the same GIS system. All other information including the length and average slope of streams, soil type, and land cover/ land use were deduced from the RS image. Vegetation areas in the three wadis were also calculated.

This information was introduced to the HEC-HMS and simulation runs were conducted for calibration. A comparison between the simulated and observed water storage values of the three dams was made. The difference between the observed and simulated storage values was on the order of 5% for most events. For some small events, the difference was on the order of 20%. A sensitivity analysis was also performed to reduce uncertainties. The model was then used to assess the surface water runoff and water storage that would result from rainfall events of different intensities and different durations in the three wadis.

Figure 6 presents a RS image for the selected study domain of groundwater flow in the area of Wadi Ham. The study area extends from the coastline of the Gulf of Oman in the east to the upper catchment area of the dam of Wadi Ham in the west. Within the study domain, two ophiolite outcrops (mostly impermeable layers) are observed and are regarded as inactive or no-flow zones. The dam of Wadi Ham and the ponding area are also marked on the RS image, as shown in Fig. 6. Two well fields, Saharaah and Khalba, are also located within the study area and are regarded as discharge zones. The exact locations of existing observation wells were determined in the field using a GPS and were introduced to the RS image. The pumping schedule and rates were provided for the purpose of this study. Several boreholes and wells were drilled and pumping tests were conducted to identify the hydrogeological parameters of the aquifer system in the area. In addition, intensive geophysical investigations were conducted and several geological profiles were outlined. Figure 7 presents a typical geological cross section along the main course of Wadi Ham.

A constant head boundary condition was assumed at the coastline of the Gulf of Oman. A specified flux (inflow boundary) was also considered wherever a base flow was expected. Otherwise, hard rocks surround the domain and the boundaries were considered impermeable.

The RS image and all other information were introduced to ARC-View. The main advantage of the establishment of such a GIS database is that all the information and data were geo-referenced. In addition, important data that are needed for any groundwater model could be directly extracted or evaluated from the GIS database. For example, the total area of the ophiolite outcropping (inactive impermeable zones) within the selected domain was calculated from the ARC-View tools as 6.65 km^2. Likewise, the ponding area at the flooding level was estimated as 0.4 km^2. In other words, the statistical, contouring, mapping, tabulating and all other powerful tools of GIS systems can be easily and efficiently integrated into groundwater simulation models, especially at the stage of preparation of input data (pre-processing).

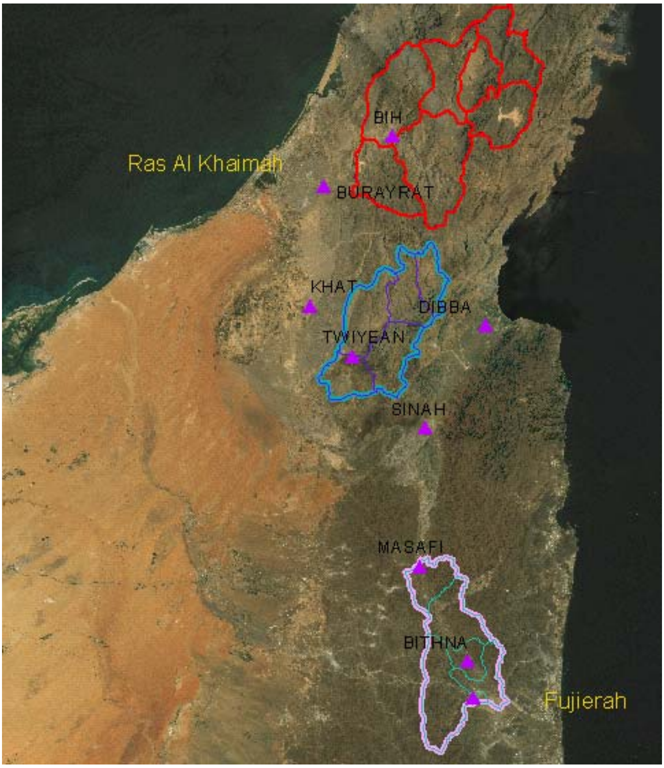

Figure 5. Remote sensing image for three locations in Wadi along with rain gauge stations. (Colour reproduction on Plate 2)

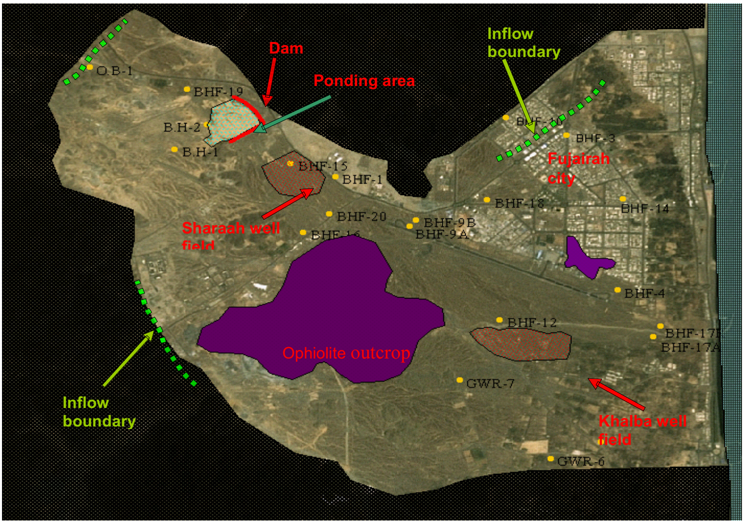

Figure 6. RS image including the main features of the study area in Wadi Ham, UAE (Sherif et al., 2004). (Colour reproduction on Plate 2)

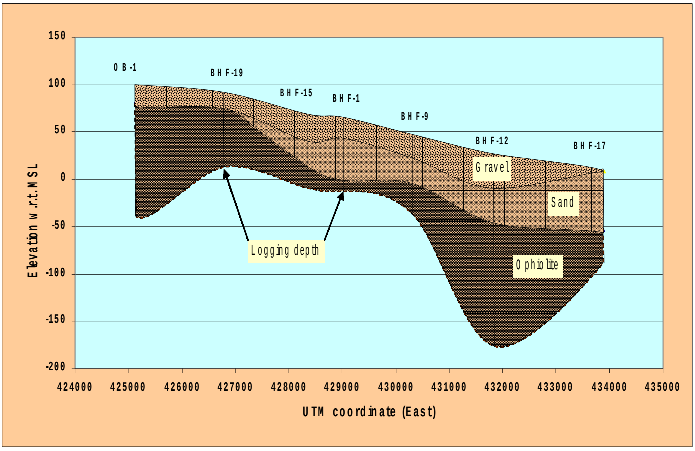

Figure 7. Typical geological cross-section along the course of Wadi Ham (Sherif et al., 2004). (Colour reproduction on Plate 2)

Sherif et al. (2004) employed the USGS model “SUTRA, a model for saturated-unsaturated variable-density ground-water flow with solute or energy transport (Voss, 1984; Voss and Provost, 2002)” to evaluate the recharge from the dam of Wadi Ham. SUTRA is a computer programme that simulates the groundwater flow in porous media and the transport of either energy or dissolved substances in a subsurface environment. The code employs a two or three dimensional finite element and finite difference method to approximate the governing equations that describe the two interdependent processes that are simulated:

1. Fluid density dependent saturated or unsaturated groundwater flow
2. Either (a) transport of a solute in the groundwater, or (b) transport of thermal energy in the groundwater

SUTRA-GUI (Winston and Voss, 2003) may be employed in one, two or three–dimensional simulation problems. Flow and transport simulation may be either steady state which requires a single solution step, or transient, which requires a series of time steps in the numerical solution. SUTRA may be employed for two-dimensional areal, cross sectional, and fully three-dimensional modeling of saturated groundwater flow systems and unsaturated zone flow. Although the simulation was limited to the groundwater flow, SUTRA-GUI, a flow and solute/energy transport model, was selected because of the vicinity of the study area from the Gulf of Oman. Simulation runs were conducted using the calibrated flow model to study the seawater intrusion problem upon availability of proper data.

All the required input data files were prepared as layers of information using ARC-View. In addition, stress periods from rainfall events and water storage in the ponding area as well as the pumping rates and schedules were