Remote Sensing and Geographic Information System in Groundwater Studies

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1.0 Introduction

Water is an extremely important resource. Life on the planet Earth, evolved in aquatic environment, depends on water for sustenance. However, distribution of this resource is highly uneven. About 97.41% of water on the Earth is saline and is contained in oceans, and the balance 2.59% water is fresh and is distributed in glaciers (1.95%), groundwater (0.62%), and surface water (0.02%). Thus only 0.02% of the total water available on the Earth, which is contained in rivers, lakes and atmosphere etc., is easily available to mankind.

Because of the uneven distribution, the requirement of the water can be met either by transporting water from reservoirs, lakes, rivers etc., or from withdrawal of subsurface water. Fortunately, groundwater is a fairly widely distributed natural, renewable resource, which gets replenished almost regularly by precipitation.

Groundwater is a very important natural resource and is widely used for different purposes like drinking, irrigation etc. However, it can only be used if it is available in good amount and is of good quality. The occurrence and movement of groundwater in any terrain is mainly controlled by geology, topography, landuse, soil, geomorphology and structures. Depending on the terrain characteristics, one or several of these parameters contribute to the localization of groundwater.

In India groundwater is used both for drinking as well as irrigation purposes. The status of groundwater availability and development is given below.

Dynamic Groundwater Resources of India (2004)

1.	Annual Replenishable Groundwater Resources	433 BCM
2.	Net annual Groundwater Availability	399 BCM
3	Annual Groundwater Draft for Irrigation, domestic and Industrial Use	231 BCM
4	Stage of Groundwater Development	58%

Source: CGWB, 2006

Remote sensing data provides surface information, whereas groundwater occurs at depth and may be a few meters or several tens of meters deep. Therefore, remote sensing data are unable to provide any direct information on groundwater in most cases. However, the surface morphological – hydrological – geological regime, which primarily

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governs the subsurface water conditions, can be well studied and mapped on remote sensing data products. Therefore, remote sensing acts as a very useful guide and efficient tool for regional and local groundwater exploration, particularly as a fore runner in a cost effective manner.

The results of groundwater studies are traditionally presented in the form of thematic maps, tables etc. This type of data representation however, has its own limitations as often these maps give information of a certain point or location and that too is of limited type. Moreover, it is time consuming and cumbersome to derive various derivatives from these maps and at the same time it is difficult to draw significant inferences based on number of maps. In this context, Geographic Information System (GIS) can be used, which is a computer based system designed to accept large volume of spatial data derived from a variety of sources. GIS can efficiently store, retrieve, manipulate, analyze and display various data according to the user defined specifications.

Remote sensing data can provide information to GIS, where it can be combined with other spatial data. Therefore, the two technologies are complementary to each other and if used in conjunction can provide excellent results. Remote sensing analyses are improved by the verification of data retrieved from the GIS, and application of GIS can greatly benefit from the information that remote sensing data contain. Often the image data are the most current spatial information available for an area. The use of digital image data offers the additional advantage of a computer compatible format that can be input directly to a GIS.

In the present lecture, application of remote sensing and geographical information system in groundwater studies will be discussed.

2. Application of Remote Sensing in Groundwater Studies

Groundwater resource estimation needs knowledge of the areal extent of the related phenomena. Remote sensing data have proven their importance as an additional tool in groundwater prospecting by outlining geology, structures, surface anomalies, drainage and geomorphic indicators for location of recharge and discharge sites. Features associated with groundwater related phenomenon can be recognized in the satellite data due to their spectral characteristics and spatial association.

Remote sensing is an extremely invaluable tool for mapping landuse, land cover categories and geomorphic elements needed for water resources planning and management. The importance and use of remote sensing data in geohydrological application is based on the fact that the images aid the investigator in locating morphological and structural features that may influence groundwater flow.

Appropriate compilation of (i) fractures, (ii) geology, (iii) geomorphology, (iv) landuse and (v) drainage results in location of groundwater exploratory targets, recharge and discharge sites.

The conventional approaches for groundwater investigation, which are ground based field surveys and exploratory drilling, are time consuming and uneconomical. The remote sensing technique provides temporal and spatial information on geological and hydrological parameters required for groundwater studies. Repetitive coverage of the earth provides temporal and real time information on static and dynamic resources. The geological and hydrologic information can be inferred by analysis and interpretation of remote sensing data. Hence, remote sensing technique provides vital information on groundwater, which can be supplemented and verified by other field techniques like detailed ground survey, geophysical resistively survey and shallow seismic survey.

For groundwater exploration, the various surface features amenable to observation on remote sensing data products can be grouped into two categories:

(i) First - order or direct indicators, i.e. those ground parameters that are directly related to groundwater occurrence, (e.g. springs, canals, ponds, lakes, rivers and soil moisture etc.)

(ii) Second - order or indirect indicators, i.e. those hydrogeological parameters which regionally affect and therefore reflect the groundwater regime, e.g. drainage characteristics fracture systems, soil/rock type, structure, landform etc.

A list of features which can be extracted from satellite data include landforms, drainage characteristics, landuse / land cover, soils, and lineaments and are given in Table 1. The landuse / land cover reflect the availability of groundwater in a particular area. Vegetation indicates the availability of adequate water where the groundwater may be close to the surface. The remotely sensed drainage information indicates the presence or absence of groundwater as the surface and subsurface drainage are inversely related. For instance, absence of a well-defined drainage network over large areas subject to good rainfall may indicate occurrence of groundwater. The lineaments are straight to slightly curvilinear features formed in many different types of landscapes. In hard rock terrain lineaments have considerable bearing on subsurface water resources. Faults, fractures and lineament intersection can be mapped using remotely sensed data. Information on soils and topography gives idea on groundwater replenishment by rainfall. The infiltration of rainwater and evaporation are greatly influenced by permeability of the soil.

3.0 Application of GIS in Groundwater studies

The accuracy of classification of groundwater potential zones can be improved by using the remotely sensed data along with ancillary data like topographical, meteorological and geophysical data. An effective and integrated utilization of remote sensing and other data requires an efficient spatial data processing system which can handle both spatial and non-spatial data. GIS is rapidly evolving technology that consist of computer based programs containing specialized algorithms and associated data base management structures, frequently in an integrated package

The increasing volume of available spatial and non-spatial data with all its complexity and subsequent demand for the storage, analysis and display of these voluminous data has led in recent years, to the use of computer for data handling and creation of sophisticated information systems. Effective utilization of large volumes of spatial data depends upon the existence of efficient systems that can transform these data into usable information.

Table 1: Important indicators of groundwater on remote sensing data products.

(a) First-order or direct indicators: • Features associated with recharge zones: rivers, canals, lakes, ponds, etc. • Features associated with discharge zones: springs and other sites of effluent seepage • Soil moisture • Anomalous vegetation
(b) Second - order or indirect indicators • Topography • Landforms • Weathering • Type of rocks - hard rock (igneous, sedimentary and metamorphic) and soft rock areas • Regional structural features • Vegetation • Soil type • Soil moisture • Drainage density • Fracture systems in hard rock areas • Special geological features like sink holes, alluvial fans, dykes, faults, shear zones, buried channels etc., which may have unique bearing on groundwater occurrence and movement • Extra-hydraulic continuity of formations - surface and sub-surface water divides vis-a-vis recharge and discharge zones from synoptic overviews.

For the evaluation of groundwater potential of a basin, extensive exploration and management studies are carried out. This involves hydrogeological and hydrogeochemical studies of the basin. The result of such studies is usually been presented in the form of various maps, tables, graphs and data such as:

- Contour maps
- Lithological maps
- Geological and structural maps
- Soil maps
- Landuse / land cover maps
- Drainage maps
- Tables of varying data/observations
- Point data (rainfall, chemical characteristics, hydraulic conductivity, etc.)

The application of GIS for groundwater exploration and management is basically for mapping, analysis, predicting and modelling. With the use of Digital Elevation Model (DEM) geomorphic characteristics of an area can be analyzed and classified according to ground conditions and project requirements.

In the context of groundwater studies, GIS technology is considered useful as it facilitates handling of diverse type of spatial information, e.g. topographic maps, landform maps, geological maps, various contour maps of water table and water quality etc. and offers flexibility of operation, speedy proceeding and higher accuracy. The evaluation of the groundwater potential of a basin involves extensive exploration and management studies to be carried out. This incorporates hydrological and hydrogeochemical studies of the basin.

Groundwater data has been traditionally presented in the form of maps, tables etc. This type of data representation has many limitations and drawbacks. The problem of analog and tabular data becomes all the more tangible when collective or integrated interpretations of different data (or maps) are required. Using GIS analysis functions various user defined constraints images/maps of any basin can be generated involving several groundwater quality parameters, such as TDS, pH, chloride, bicarbonate etc. along with groundwater table maps. Various output images can be generated which may show areas of groundwater suitable for drinking, irrigation and industrial purposes. Different overlays of groundwater quality parameters can be combined in the form of false colour composite. These composite images provide an integrated interpretation of continuously varying different groundwater quality parameters.

4.0 Application of Remote Sensing in Groundwater Modeling

Groundwater resources assessment, modeling and management are hampered considerably by a lack of data. Usually, only a limited number of point measurements are available, while groundwater models need spatial and temporal distributions of input and calibration data. If such data are not available, models cannot play their proper role in decision support as they are notoriously underdetermined and uncertain. Recent developments in remote sensing have opened new sources for distributed spatial data. As the relevant entities, such as water fluxes, heads or transmissivities cannot be observed directly by remote sensing, ways have to be found to link the observable quantities to input data required by the model. An overview of the possibilities for employing remote-sensing observations in groundwater modeling is discussed below. The main possibilities are: (1) use of remote-sensing data to create some of the spatially distributed input parameter sets for a model, and (2) constraining of models during calibration by spatially distributed data derived from remote sensing. In both, models can be improved conceptually and quantitatively.

The term remote sensing should not be confined to Earth observation systems with sensors measuring in the visible, infrared and radio wave regions of the electromagnetic radiation spectrum. It also includes geophysical surveys of gravity, magnetic, and electromagnetic. Only the geophysical surveys offer the possibility of exploring the subsurface. Remotely sensed data can be obtained from various platforms such as satellites, airplanes, drones, blimps and masts. The ways in which remote sensing can contribute to groundwater modeling are so numerous that this lecture can by no means cover all aspects. The selection is based on the authors' experiences. Other aspects are covered, for example, in Becker (2006).

Regional hydrological models such as groundwater models require distributed input data. Classical hydrological measurements provide only point data obtained for example at a weather station, a gauging station, or a borehole. One of the main problems in hydrological research today is how to pass from point information to regional distributed information. Remote sensing offers a possibility to do this for certain parameters required in groundwater modeling. In principle, the patterns from remote sensing can be translated into a deterministic distribution of input data on a cell-by-cell basis or in the form of zones. Even if absolute values of these data are uncertain, they still reduce the degrees of freedom of the model and thus lead to a better posed inverse problem and a robust solution. Remote sensing is, therefore, an extremely useful tool in the acquisition of spatially distributed data for modeling. All raw remote-sensing data present spatial patterns which can be related to features or processes above the surface (such as clouds), on the surface (such as evapotranspiration), or in the shallow subsurface (such as electrical conductivity). However, the parameters directly accessible by remote sensing are often not the ones required in groundwater models. This means that the utilization of remote-sensing data requires another modeling step to convert them to data usable as input data or verification data in spatially distributed models (e.g. Kemna et al. 2002). It is the combination of the pattern information with the point information at ground observation stations that allows spatial distributions of the parameter in question to be obtained. The correlations between ground measurements and remote-sensing data are subject to noise. Such stochastic relationships can, however, still be utilized in the conditioning of stochastic models and data assimilation.

Take precipitation as an example for a distributed data set. From remote-sensing data such as cloud temperature distributions (e.g. Herman et al. 1997) or weather radar data (e.g. Collier 2002) on drop spectra, estimates of precipitation can be derived through a model. The resulting distribution of precipitation is uncertain as far as absolute values are concerned, while the relative intensities are much more reliable. If the resulting distribution is scaled with precipitation measurements obtained at stations on the ground, a map of absolute precipitation quantities results which is superior to maps obtained from the mere mathematical interpolation of station data.

In regions where spatial observation networks are extremely dense, remote sensing may be of less interest. However, the main water problems of today are in developing regions of the world with weak infrastructure, low accessibility, and data scarcity. It is in such cases that remote sensing can develop its largest use for water resources management. Combined with traditional methods remote sensing has a great potential in improving the quality of modeling work.

In the following sections, the types of information which can be extracted from remote sensing are described. Then four examples illustrate ways of using this information in groundwater modeling. These examples include:

- The direct construction of an input data set (aquifer thickness)
- The reduction of degrees of freedom in inverse groundwater modeling
- The calibration of a groundwater model by pattern information on a quantity that can both be measured by remote sensing and calculated from the model

- The conditioning of a stochastic groundwater model with noisy input data from remote sensing

What information contained in remote-sensing images is of potential use in groundwater modeling?

Airborne geophysical surveys allow for the identification of faults and dikes, changes in lithology and the depth of magnetic features (e.g. Danielsen et al. 2003; Doll et al. 2000; Jorgensen et al. 2003a,b; Thompson 1982). This information is helpful in constructing more realistic conceptual models of aquifers. An aquifer that is compartmentalized by dikes and faults will behave differently from an aquifer without such flow guides.

Geomagnetic surveys have, up to now, mainly been used in the search of Earth resources of high economic value such as minerals and hydrocarbons. However, once acquired, the geophysical data retain potential for many other applications including groundwater exploration and management (LaBrecque and Ghidella 1997). Botswana, for example, has embarked on airborne high-resolution magnetic surveys to cover the whole country, the primary aim being the exploration of formations bearing diamonds and other minerals (MFDP 2003). Hydrogeologists in Botswana are now beginning to benefit at almost no cost from the data acquired (e.g. DWA 2004, 2006).

Lineaments on the surface have been identified early as conduits for groundwater flow in fractured aquifers and hence targeted for locating production wells. Their use in geology is already widespread (e.g. Lattmann 1958; Meijerink 1996; Tam et al. 2004).

The overlaying of lineaments mapped from conventional remote-sensing techniques (aerial photographs and satellite images) and those derived from airborne geophysical methods can be implemented using geographical information systems (GIS) at both local and regional scales. Some lineaments detectable by airborne geophysics may be due to deep-seated sources (up to several tens of kilometers) and hence have no effect on groundwater flow in aquifers of interest, which are mostly within a few hundreds of meters below the ground surface. Therefore, the depths to magnetic sources must be estimated in order to retain only lineaments that are deemed relevant to groundwater flow. On the other hand, lineaments identified with conventional methods give only information on structures with surface expression and no information on depth and vertical continuity of the structures.

Space-borne gravitational surveys such as the Gravity Recovery and Climate Experiment (GRACE) mission can be used to detect temporal changes in the total water storage (surface water, soil water and groundwater). A 2- cm thick, infinitely extended layer of pure water located at any depth below a gravimeter generates an incremental gravitational acceleration of $1\times10-8$ m/s2 or 1 μGal (microgal). The temporal change in total water storage (TWS) in the Earth system is therefore directly proportional to the temporal change in the measured gravitational acceleration. The potential of time-lapse gravity surveys to monitor the status of water resources systems has been recognized for a long time. Ground-based time-lapse gravity surveys were used successfully to determine alluvial aquifer storage and specific yield, which is a key parameter for the sustainable management of groundwater resources (Pool and Eychaner 1995). Moreover, it has been demonstrated that superconducting ground-based gravimeters reflect hydrological signals on the order of several microgals (Amalvict et al. 2004; Bower and Courtier 1998; Neumeyer et al. 2006). The GRACE twin satellites have dramatically improved the accuracy and resolution of regional observations. This satellite mission delivers an accuracy of 0.4 μGal or 1 cm of groundwater on spatial scales larger than 1,300 km (Andersen and Hinderer 2005; Andersen et al. 2005) and delivers reliable observations of the regional part of the global hydrological cycle. Although the spatial resolution is still less than the size of typical groundwater systems, the prospects of this method for future use in verification of models, especially for the determination of the storage coefficient, are bright. For a phreatic aquifer, the surface of the terrain is also the upper boundary of the aquifer and constrains the groundwater levels. Surface elevations can be determined by various remote-sensing techniques, from airborne platforms (e.g. light detection and ranging LIDAR (Bufton et al. 1991), interpretation of stereo orthophotos (Kaab 2002), or satellite platforms using, for example, radar interferometry (Madsen et al. 1993; Rabus et al. 2003; Slater et al. 2006; Zebker and Goldstein 1986). In the latter case, the phase differences in pixels seen from different points in orbit allow a translation into differences in elevation. To obtain absolute elevation data and to verify their relative distribution, accurate elevation data at ground control points are required. These can be obtained, for example, with differential GPS (global positioning system). In many applications, the depth to groundwater is of importance for environmental reasons, including water supply to vegetation or salinization by phreatic evaporation. This distance is the difference between the surface elevation given by the digital elevation model (DEM) and the groundwater level.

Several preprocessed DEMs are available. A recent one is the shuttle radar topography mission (SRTM) data set, a DEM covering all land areas between 60°N and 56°S latitude at a 90-m pixel resolution and a vertical accuracy of at best 5 m (Rodriguez et al. 2005; Slater et al. 2006). While the spatial resolution is sufficient for most groundwater applications, the vertical accuracy is not. Only LIDAR can presently supply a sufficient vertical accuracy and spatial resolution to determine reliable depths to groundwater. However, new missions aiming to acquire a global DEM with very high accuracies and fine resolution are currently being developed, e.g. Tan- DEM-X (Microwave and Radar Institute 2006; launch planned for 2009). If radar or LIDAR techniques cannot be applied, be it for cost or for accuracy reasons, correlations between vegetation type, vegetation density or other land surface characteristics reflected in multispectral satellite images on one hand, and topographic elevation on the other, can be exploited. In some cases, particularly in wetlands, topography can be inferred from land-cover maps at an accuracy not reached with radar interferometry (Gumbricht et al. 2005).

High-precision measurements of the surface elevation changes can reveal regional subsidence caused by piezometric depression around well fields (e.g. Hoffmann et al. 2001) or seasonal variations of the groundwater level (Chang et al. 2004). Once a relation is given between subsidence and drawdown, a spatial distribution of drawdown can be obtained from the amount of surface subsidence observed. Differential GPS can also serve the purpose of determining temporal variations in the ground level related to groundwater pumping or recharge. This information is, however, again point like.

Finally, river and lake levels can be determined by using radar satellites (e.g. Berry et al. 2005; Jekeli and Dumrongchai 2003). Such data are available close to real time, for example, see European Space Agency work on rivers and lakes (ESA 2005). Lake and river levels can be of relevance for subsurface hydrology if they are indicative of groundwater levels.

The bulk of remote-sensing data relevant for groundwater modeling are data that allow for quantification of the distribution of recharge or discharge. Recharge is one of the most important quantities for sustainable ground- water management. In dry regions, its estimation has been, up to today, a challenge, as it may occur only sporadically at intervals of several years. It may also be spatially very heterogeneous due to the distribution of precipitation, soil properties, water use by plants or runoff processes. One of the earliest applications of remote-sensing relevant in hydrology was the characterization of vegetation type, density and its status (e.g. Fensholt et al. 2006). This information is also of interest as a proxy for evapotranspiration (e.g. Loukas et al. 2005). Vegetation may be an indicator for the presence of water and the depth to groundwater level.

For flat terrain, the groundwater recharge potential over long time intervals is the long-term average residual between precipitation P and evapotranspiration ET. Both quantities can be estimated from remote-sensing data. The precipitation can be estimated from cloud temperature data by certain algorithms (e.g. Herman et al. 1997) in combination with precipitation data from meteorological stations on the ground. The Famine Early Warning Systems Network (FEWS 2006) offers such data at a 10-day temporal resolution for all of Africa. Evapotranspiration can be derived from multispectral satellite data via a surface energy balance. To put it simply, a dry pixel will heat up to higher temperatures than a pixel which has a large amount of water available for evaporative cooling. In this sense, radiation data can be related to evapotranspiration. The fraction of net radiation energy consumed by evaporating water can be estimated with different methods. In SEBAL (surface energy balance algorithm for land; Bastiaanssen et al. 1998a,b), the energy fluxes in the surface energy balance are calculated explicitly, while in a simplified method described by Roerink et al. (2000), this fraction is determined from a pixel-wise plot of surface temperature versus albedo. Other methods use different dimensions of the feature space instead, e.g. the Normalized Difference Vegetation Index (NDVI), which is a measure of the vigor of vegetation growth (Sandholt and Andersen 1993).

Unfortunately, both ET and P obtained from remote sensing are inaccurate. Calculating the difference, P–ET, leads to error propagation, especially when both quantities are of similar magnitude. This is often the case in semiarid and arid areas. Still, the spatial patterns of P-ET may be of help in regionalization of traditional point measurements of recharge, e.g. obtained with the chloride method (Brunner et al. 2004).

The spatial distribution of recharge may be very heterogeneous even if the distribution of precipitation is homogeneous. If water collects and infiltrates in depressions, those may dominate the total recharge of an area. This process has been documented in Niger (Leduc et al. 2001). Water surfaces forming in the landscape and their temporal behavior can be identified by remote sensing, e.g. via radar or multi-spectral characterization (e.g. McCarthy et al. 2003; Roshier and Rumbachs 2004). Their density and distribution are indicative of the spatial distribution of recharge.

In wetlands, the interaction between surface water and groundwater is crucial for the understanding of the wetland behavior. The development of water surfaces and flooding patterns over time is, in this case, a valuable data set for model calibration (Bauer et al. 2006a,b).

Groundwater recharge from rivers, streams and wetlands, under certain circumstances, can also be inferred from remote sensing through anomalies in temperature or electrical conductivity. In arid environments, evaporation is mostly through plants in the form of transpiration. This increases salinity in groundwater and hence electrical conductivity. The freshly infiltrated water beneath a stream, in contrast, has a low electrical conductivity. The varying electrical conductivity of the underground can be detected by airborne electromagnetic methods (e.g. Paine and Collins 2003). On the fringes of the Okavango Delta, Botswana (Fig. 1) the variations in groundwater salinity could be seen clearly from an airborne electromagnetic survey (Fig. 2). Sattel and Kgotlhang (2004) also used this approach for salinity mapping in the Boteti area just south of the Okavango Delta. The data was validated by ground geoelectrical methods and drill hole information.

In arid and semi-arid areas, the discharge of groundwater via direct evaporation from the water table and evapotranspiration by trees may account for most of the discharge of an aquifer. Discharge via a draining stream, as in a humid zone, rarely occurs. The estimation of discharge via trees has been the subject of remote-sensing studies looking both at ET derived from energy balance calculations as well as single tree counts according to species and canopy size and combining this remote-sensing information with information on the single tree, e.g. obtained from sap flow measurements (e.g. Lubczynski and Gurwin 2005).

Salt crusts indicate high water tables with phreatic evaporation. They can be mapped by multispectral satellite data and used as an indicator for phreatic fluxes and depth to groundwater (e.g. Metternicht and Zinck 2003; Brunner et al. 2006).

Soil-water balance calculations as a function of time require data in addition to average ET and P to account for water storage in the soil. A soil-water balance model requires some information on the field capacity of a soil which could be estimated on the basis of the soil type. Here, hyperspectral satellite information can help (e.g. Chabrillat et al. 2002; Leone and Escadafal 2001; Shepherd and Walsh 2002; Ben-Dor et al. 2004) as well as gamma radiation counts from airborne platforms (e.g. Cook et al. 1996) indicating clay content (e.g. Rainey et al. 2003). Soil moisture itself and its temporal variation may in the future be accessible from passive and active microwave sensors. A mission planned for early 2007 by ESA has been designed to observe soil moisture over the Earth's land mass. It has to be stressed though that the moisture seen relates only to the top centimeters and the use of this data type requires substantial modeling. For more information, see also Becker (2006).

The vegetation vigor derived from multi-spectral satellite data can be used as an indicator for irrigation and can, therefore, be employed as a relevant parameter in monitoring the irrigated areas and for timing of irrigation (Droogers and Bastiaanssen 2002). The main application of remote sensing of hydrological variables already in operative use today is the scheduling of irrigation.

General Process of Applying Remote-Sensing Data in Groundwater Modeling

Groundwater models are based on the flow equation

$$S_0 \frac{\partial h}{\partial t} = \nabla(K\ \nabla h) + w$$

where S_0 is the storativity, h the hydraulic head, t is time, K the hydraulic conductivity tensor and w the distribution of sources and sinks. Together with boundary conditions in space and time, the flow problem is uniquely defined. The equation and boundary conditions contain the spatially distributed functions of hydraulic conductivity, storativity, and recharge. Via those distributions as well as the boundary conditions, the geometry of the aquifer is defined.

In general, only limited information on the spatial distribution of these input parameters is available. Yet, a model computation needs a complete set of parameters. There are different ways to determine or estimate those. In traditional model calibration, the aquifer is divided into a limited number of zones. Within these zones, aquifer properties are assumed to be constant. This means a strong reduction in degrees of freedom. The zonation should be such that the parameters are expected to show little spatial variation within the defined zones. Remote sensing can play a role in the definition of these zones. For subsurface features, structural elements as seen in areal geophysical surveys together with point data from drillings and pumping tests allow zoning. So the first main use of remote-sensing data is seen in the spatial modulation and interpolation of input data, where otherwise a homogeneous value or a purely mathematical interpolation function would have to be used. During the process of model calibration, updated estimates of the missing parameters such as hydraulic conductivity (for the defined zones), are obtained such that a historical record of head and/or flux observations can be reproduced. This process is non-unique.

Piezometric head data do not reduce the uncertainty of the estimated parameters of storativity, hydraulic conductivity and recharge, in case those parameters are only known within large error intervals. If, however, the spatially distributed input data can be constrained, the calibration problem stabilizes. Let us assume the spatial distribution of relative recharge can be estimated from land use and soil type. And let us further assume that the yearly regional variation can be estimated from local lysimeter data. Then the total function of recharge in space and time R(x, t) could be reconstructed as the product of the temporal-spatial average of recharge Rav, a weighting factor f(x) expressing the relative values on areas with different land use and a weighting factor g(t) expressing the relative proportion of recharge in a certain time interval, i.e.

$$R(x,t) = R_{av} f(x) g(t)$$

If f(x) can be obtained from remote-sensing data and g(t) can be determined from point data at a few lysimeters there is only one unknown parameter left and the large number of degrees of freedom residing in a temporal spatial distribution collapses into one single number, the temporal-spatial average value Rav.

Alternatively, remote-sensing information on properties such as recharge could also be introduced in the traditional model calibration in the form of prior knowledge. As Carrera and Neuman (1986) show, ill-posedness of the model calibration can be mitigated by prior knowledge about the parameters to be estimated. Remote sensing can even be introduced as a kind of soft (not exact) information into the traditional zone based model calibration strategy.

A more modern strategy of obtaining model parameters is the stochastic modeling approach. It acknowledges that all parameters are uncertain due to heterogeneity and/or measurement errors. Instead of a single best parameter set, a large ensemble of possible parameter sets is determined using stochastic information. This procedure also allows quantification of the uncertainty of the model results.

Remote-sensing information intrinsically contains uncertainty because the correlation between remote-sensing patterns and ground truth will not be perfect. The stochastic modeling approach is able to use this type of information. The remote-sensing-based data and ground truth can be used to generate a series of equally likely images of the variable of interest within the uncertainty of the correlation. The co-located co-simulation algorithm, developed in the geostatistical community (Almeida and Frykman 1994), is suited for this purpose as it is especially designed to handle exhaustive data on a regular grid. This algorithm simplifies the relation between the remote-sensing data and the variable of interest to a linear correlation coefficient (Markov assumption) (e.g. Goovaerts 1997). The generated images are conditioned to the two different data sources, and take into account their estimated errors, a (linear) correlation between them, and a variogram estimated from the spatially distributed remote-sensing data. These equally likely images of the variable of interest sample the high dimensional space of possible spatial distributions of the variable of interest within the uncertainty bounds mainly given by the mismatch between remote-sensing data and ground truth. In a case where the resolution of the hydrological model coincides with that of the remote sensing raster, and further, if the remote-sensing data are perfect (perfect correlation between variable of interest and the measured signal), this space of possible spatial distributions would be reduced to one deterministic "truth". As this truth will never be known, the stochastic calibration of a groundwater flow model consists of the selection of an ensemble of realizations of input data (combined from stochastic and deterministic information), which reproduce hydraulic head, flux and possibly tracer data to a predefined degree.

There are different ways to proceed. An extremely large amount of equally likely realizations (millions) of the variable of interest can be generated in the way described before and processed through the hydrological model, until enough realizations have been found that are consistent with the hydraulic head, flux, and possibly tracer data. The disadvantage is that this is very inefficient, especially for strongly non-linear models. In case of conceptual model errors, no valid solutions will be found.

Alternatively, a limited number of realizations (hundreds) of the variable of interest can be generated and inversely conditioned to the observed hydraulic head data and tracer test data by a Monte-Carlo-based stochastic inverse conditioning approach. These methods have been developed to accommodate more qualitative facies pattern data obtained from outcrops. Examples are the sequential self-calibration method (e.g. Gómez-Hernández et al. 1997; Hendricks Franssen 2001), the pilot point method (e.g. LaVenue et al. 1995) or the representer method (e.g. Valstar et al. 2004). The inverse conditioned realizations are conditional to hydraulic head data, tracer test data and the direct measurements of the variable of interest, but not necessarily to the remote-sensing information, as the relationship between the remote-sensing data and the variable of interest cannot be handled by these algorithms. However, for all these algorithms, the remote-sensing information would be preserved in some way in the inverse conditioned realizations.

In the literature, some approaches are presented that partially circumvent the problem. A possibility is to constrain the variogram of the variable of interest in the inverse-modeling procedure (Oliver et al. 1997). However, this does not preserve the full information potential of the remote-sensing image, as it only considers area-averaged two-point statistics. Capilla et al. (1999) developed the method of conditional probabilities, which includes exhaustive soft information in the sequential self-calibration procedure by perturbing the conditional probabilities (conditioned to the exhaustive soft information as well) instead of directly perturbing the values for the variable of interest. Also, this approach has some drawbacks: a large number of indicator variograms has to be inferred, and the indicator variograms are area-averaged two-point statistics. In addition, the perturbation of the image is only constrained by the inferred univariate local-conditional probability density functions. Hendricks Franssen et al. (2006) modify the sequential self-calibration approach and introduce an extra term in the objective function that penalizes a too strong deviation between the calibrated pattern for the variable of interest and the satellite information related with the variable of interest. This method does not need to make the stationarity assumption. Other geostatistical methods require that the spatial distributions are stationary. The method, however, allows any kind of remote-sensing information to be included in groundwater models that are available as exhaustive gridded information, and that show a correlation with a variable of interest (e.g. recharge rate, aquifer thickness). Notice that a critical step in the methodology consists of establishing the (statistical) relationship between the remote-sensing signal and the values for the variable. Together with the statistical relation, the uncertainty of the established relation should also be quantified.

Conclusions

The potential of remote sensing for improving models is considerable and still to a large degree untapped. The range of applications is substantial as the introductory examples from literature show. They are even wider if more qualitative results of purely visual interpretations are considered, which were not discussed here. With all justified optimism, expectations for the easy use of remote-sensing data in groundwater modeling should not be exaggerated. The defaults of any single method can be counteracted by combining several methods. As in the case of environmental tracers, it is the combination of methods that makes information conclusive. The remotely sensed data unfold their usefulness usually in combination with a model in which even noisy or correlated data can be used for conditioning. Finally, it should be remembered that the largest and most costly effort in applying remote sensing data to groundwater models lies in the field work necessary to obtain a sufficient data base of ground truth.

5.0 GIS in Groundwater Modeling

5.1 Modeling and GIS

A model is a representation of the real world. In the GIS world, this occurs through mathematics. A series of mathematical formulas are linked together to explain the workings of a particular phenomenon. A good model has the ability to predict the outcome of a set of inputs, as they would affect the real world.

5.1.1 Simulation Models:

A **simulation model** is used to analyze the known information about a data feature. This could be a stretch of stream, a point-source of pollution, or a census tract. A simulation model uses information from the data table associated with the object, plugs that information into a formula, and creates a new result based on the information from one or more variables. An example of this would be using a model to find all the upstream tributaries of Section X of a river. The model would look for a field in the associated information table that indicated what sections flowed into Section X. From those sections, it would look and find what sections flowed into them. The model would continue to look until it reached all the headwaters of the upstream tributaries. It would then return the results of all the upstream waters for Section X. This is just one example of a simulation model.

5.1.2 Predictive Models:

A **predictive model**, on the other hand, is used to predict how a change in a variable will affect other conditions. Once again, this can be applied to any data feature, but it applies more to the attributes of a feature than the feature itself. For instance, such a model might be used to predict the effect of a specific discharge on oxygen demand. Let us say this model predicts the dissolved oxygen curve downstream of the discharge. This model has been tested extensively against the known behavior of certain discharges and found to be accurate. For a particular analysis, one might want to know what effects will result from a new wastewater treatment plant that is in the planning stage. Using the model, one could find what downstream sections of a river will be affected and how the dissolved oxygen curve will respond. This model could account for the other discharges that are already being released into the river and calculate the cumulative effect.

As you can see, there is quite a difference between simulation and predictive models. Simulation models deal with extracting more information from what is already known about a feature. Predictive models deal with changes that will occur if certain variables of a feature change. Both these types of models can apply to groups of features or whole coverages, as well. These both have a variety of applications for managing environmental problems.

One area that has made good use of models is groundwater pollution. There are many models that deal with groundwater flow and the transport of pollutants in groundwater. These formulae predict the groundwater flow rate, direction, and volume, based on inputs like precipitation, porosity of certain layers of rock, and other variables. Knowing the behavior of certain pollutants, pollution modelers can predict the plume of a chemical spill and how it will affect groundwater. One of the most common examples is when a subterranean gasoline tank leak causes a plume that floats along the top of the water table. Using a model, analysts can predict the extent of the plume.

Linking models to a GIS makes the model easier to interpret. In the example above, users can graphically display a pollution plume and analyze its extent. This could be combined with population data to show what population could be affected by the leak. This is just one example of how GIS and models can work collectively. The next section discusses how they can be joined together.

5.1.3 Joining GIS and Models:

There is a spectrum of methods for joining GIS to analytical models. This is usually divided into three broad categories: tightly coupled, closely coupled, and loosely coupled. These three divisions are not sharply defined, but represent a general categorization scheme. The characteristics of each group are explained below:

Tightly Coupled:

When a GIS and a model are tightly coupled, it means that they share a common interface and the model is embedded within the GIS software. This requires that the software vendor create specialized software specifically for the application involved. Consequently, tightly integrated models are not as common as more loosely coupled models. Some tightly coupled models exist for common applications like flow direction and shortest-route functions. Two examples of tightly coupled models are ESRI's ArcView Street Map and Tracking Analyst extensions for ArcView.

Closely Coupled:

A much more common scheme is to have a closely coupled model. In this scheme, the model and the GIS once again can share a common interface, but the model is created as a program in the GIS scripting language. This allows GIS users to join their own models without waiting for the software company to do it for them. It requires a lot of time to create the modeling functions in the GIS script, but after the initial investment the model can be directly accessed from the GIS by using a button or a special screen. ESRI has compiled a **Script Library** containing scripts written by ESRI staff and other GIS users. Unfortunately, problems can occur if the model needs to be updated (which results in hours of coding) or if the model is too slow.

Loosely Coupled:

The final scheme for joining GIS to a model is known as loose coupling. In this method, the GIS and model remain separated, including a separate interface. However, there is a link between them that allows data to be transferred from one to the other. A set of data from the GIS can be imported to the model, analyzed, and sent back to the GIS for interpretation. This is probably the cheapest method of integration, but it has its drawbacks. Controlling the data flow from two different interfaces can be difficult and inefficient. This method is probably best for scientists who already have a well-established computer-driven model, and need to integrate it with GIS data for analysis.

5.1.4 GIS/Model integration

So we have to develop interface processes that generate model input or out put in a format that is easily uploaded in GIS, or transformed from GIS to the model. The GIS-Model interface consists of a series of computer program that transfer the database to model, and from model to GIS data base. Integration of GIS and model consists of the three levels which are described below:

Lowest Level of Integration:

Figure 4.1 depicts several levels of integration between models and a GIS. The lowest level of integration consists essentially of using the GIS as an aid in developing the input data file for the model. A user then takes the preliminary data file and modifies it to produce a complete input file in the format required by the model.

Second Level of Integration:

The next level of integration is to use an interfacing program specifically written to communicate between the GIS and the model. The interface program may serve as a control program issuing commands to the GIS and the model output from the GIS is converted into the proper input format for the model and then read in to the model output from the model may likewise be converted to a GIS format and then displayed by the GIS. All of these operations are carried of under controlled of the interface program.

Third Level of Integration:

A third level of integration occurs when the interface program is incorporated into the model. This requires modification to the input/output routines of existing models or developing special input/output routines for new models. Some programming may also be done within the GIS to alter its input/output structure to make it more compatible with that of the model. If one is making extensive changes to a model or developing a new model, this level of integration would be appropriate.

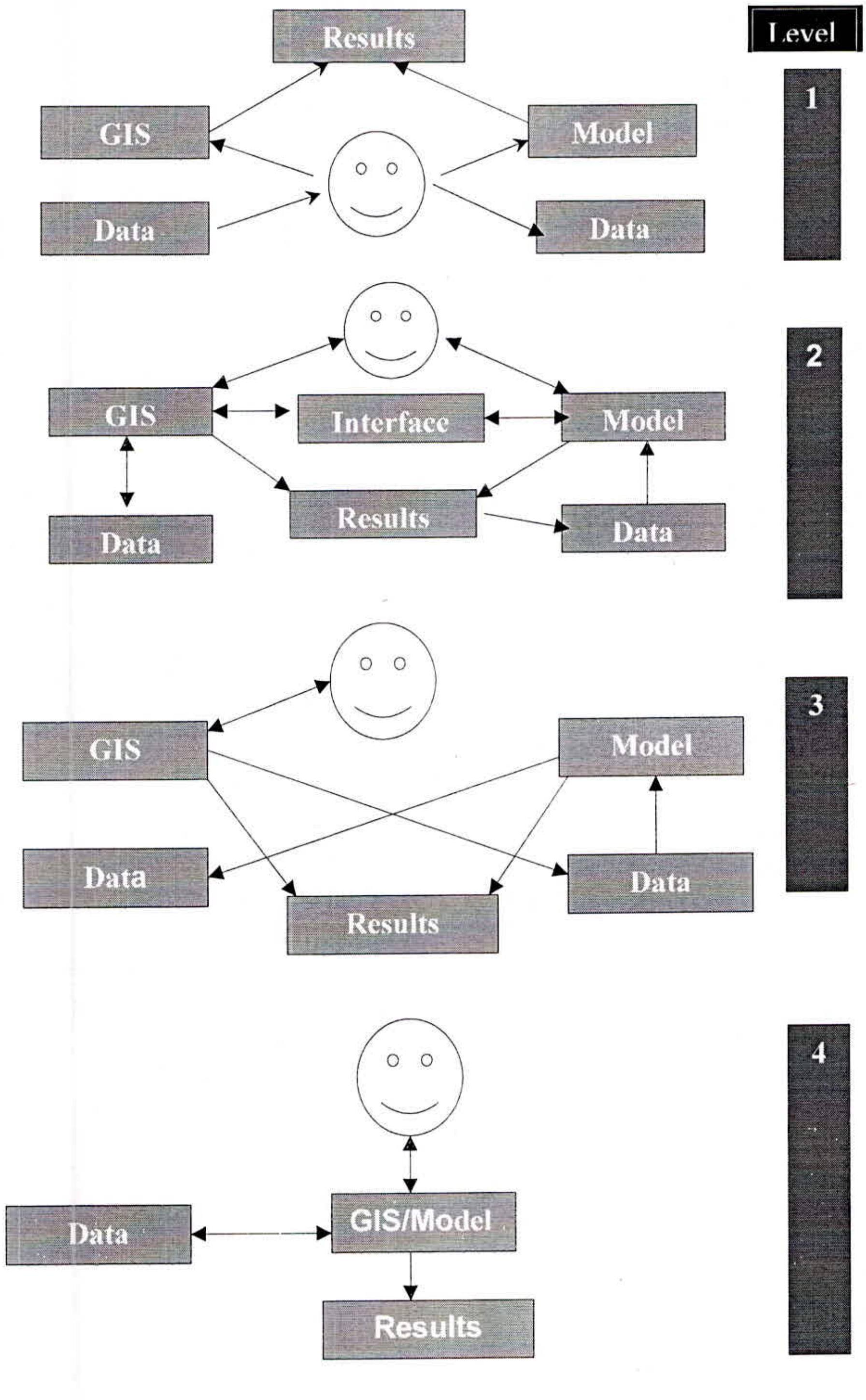

Figure 5.1: Interface between GIS and groundwater model (after Singh *et al.*, 1996).

Highest Level of Integration

The highest level of integration occurs when the model and the GIS are essentially a single, integrated unit. One way of achieving this is by programming the model using the program language appropriate to the GIS being employed.

5.2 Application of GIS in Groundwater Modelling

Starting works in ground water modeling requires the translation and transform of information on maps, charts, and tables into computer readable form. The work was lengthy, tedious, and error prone. Changes those were required in the data sets in the course of calibrating the models often involved sifting through thousands of numbers to make what often turned out to be minor modifications to the input data sets.

The specification of hydrological information such as rainfall, parameter information such as hydraulic conductivity, design parameter specification such as well locations and discharge values, and auxiliary conditions such as boundary conditions all involve the organization and manipulation of enormous quantities of data. Virtually all of this information is spatially, and in some instances temporally distributed. Much of it is available in computerized database either as maps in bitmap or vector image format or as data tables. Due to advantages in computer-graphical technology, the information in such database is now accessed most efficiently through GIS systems.

Using the GIS approach, the analyst works with the original spatial information: for example, information provided on maps. Such information is generally accessible and is normally cataloged and presented in commonly understood terminology rather than in the more specialized vocabulary of the groundwater modeling professional. A visually based, computer-graphical approach, this method of data organization and analysis is much more intuitive than cumbersome utilization of numerical arrays.

Collecting the large number geographical data required for ground water modeling is very laborious if done by hand. For both the pre processing as well as the post processing stage, the use of the GIS saves much time and becomes possible to improve more results. In general the input parameters for existing hydrologic models are prepared in the GIS and passed on to the model via an interface.

During the compilation of the model parameters, for example, the configuration of the aquifer bottom may be estimated by interpolation of data from bore holes and other data sources. The permeability values may also have been interpolated. There could be interactions between GIS and hydrologic model at various stages of the modeling if the model produces spatial output, such as groundwater flow model.

For the transient modeling mode, time variant spatial input of recharge in time steps of decades may be required. This could be estimated by preparing in the GIS a soil moisture model based on a combination of soil or over burden and rooting depth associated with cover types and rainfall and evaporation data. Where relevant, estimated river bed transmission losses could be added to estimate.

5.2.1 Calibration of Groundwater Model by GIS:

During the calibration of groundwater model the GIS could be effectively used. An example illustrates the strength of rapidly comparing the patterns of modeled results with the patterns of ancillary data for the calibration processes. The results of the model heads within the alluvial region before calibration are shown in Figure 5.1 A. A map of the observed heads has been made by using the well data and an interpolation procedure in the GIS. By subtracting the two maps, the difference map was prepared (Figure 5.1 B).

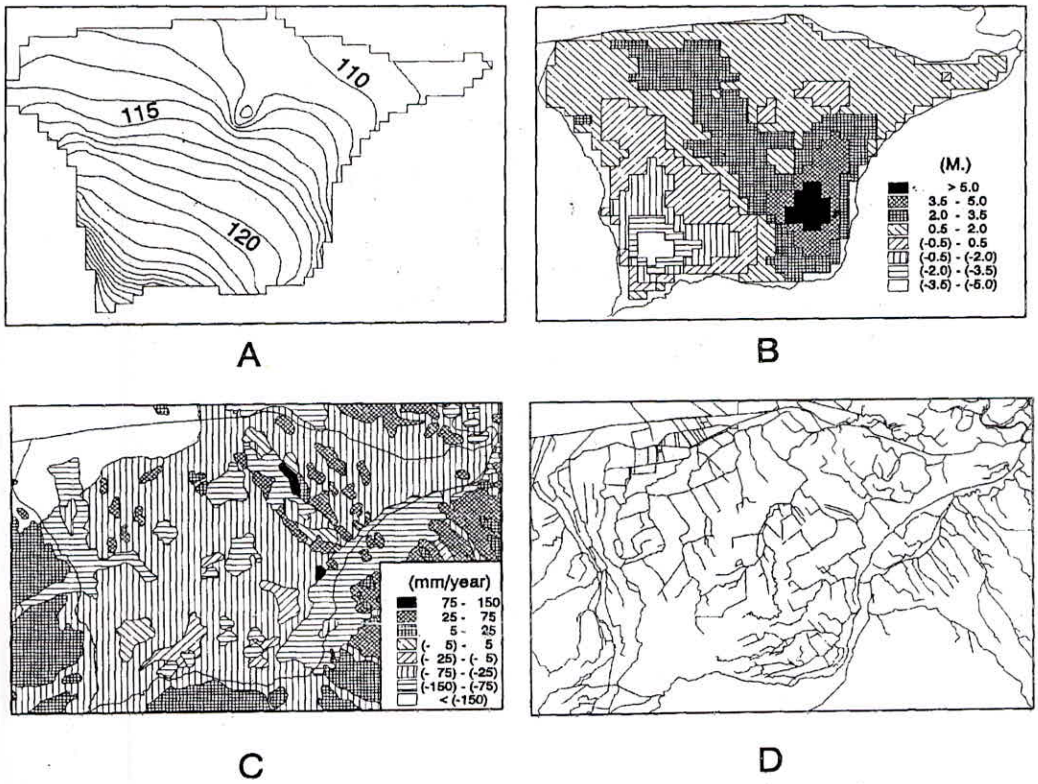

Figure 5.1: Example of use of GIS for calibration procedure of groundwater modeling results (after Meijerink *etal*, 1994).

A) The results of the model heads within the alluvial region before calibration;

B) Difference of heads between observed heads and heads interpolated from GIS.

C) Estimated recharge map.

D) Drainage map.

As can be seen there are places with important deviations which need to be clarified and the input parameters have to be changed. Recharge was estimated independently from soil and climatic data using a simple budget model. Based on the soil map the estimated recharge map (Figure 5.1 C.) was prepared. As can be noted from the patterns, however only minor or no improvements can be expected by changing this input in the groundwater model. Comparison of the patterns on map (B) and the drainage map (D) reveals that the model predicts outflow areas but the result are exaggerated. Possibly the denser drainage reflects the need to drain the surface and thus outflow resistance has to be interpolated in the model.

5.2.2 Automated Model Calibration:

Calibration is the process of modifying the input parameters to a groundwater model until the output from the model matches an observed set of data. Some GIS package (as for example GMS) includes a suite of tools to assist in the process of calibrating a groundwater model to point and/or flux observations. When a computed solution is imported to GIS, the point and flux residual errors are plotted on a set of calibration targets and a variety of plots can be generated showing overall calibration statistics. Most of the calibration tools can be used with any of the models in GIS.

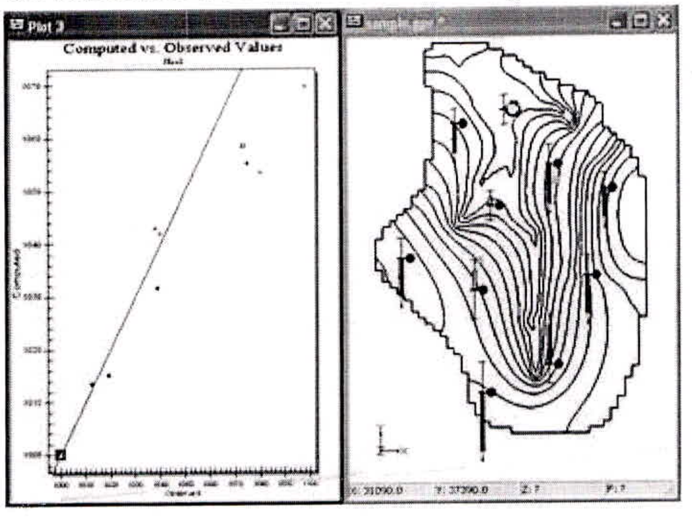

Figure 5.2: Automated model calibration by Groundwater Modelling System.

5.2.3 Background Images:

GIS generated maps of simulation results with relevant background information are an integral part of the key project decisions made with the ground model. GIS can view the model result on its background image or information (such as roads and other key features of the study area). This ensures the proper location and also helps to relate the model results to the other key features of the study area.

5.2.4 GIS Based Model Conceptualization:

Conceptual model development is necessary precursor to groundwater model development. One of GIS's (as for example GMS's) greatest strengths traditionally have been the conceptual model approach. With this approach, a conceptual model is created using GIS objects (points, arcs, and polygons) and elevation data (solids, scatter points, or boreholes). The conceptual model is constructed independently of a grid or mesh. The conceptual model defines the boundary conditions, sources/sinks, and material property zones for a model.

5.2.5 Grid/Mesh Creation:

Once the conceptual model is created, a grid or mesh can be automatically generated by GIS from the conceptual model. The grid is fit to the model boundary and refined around wells or other user-specified refine points.

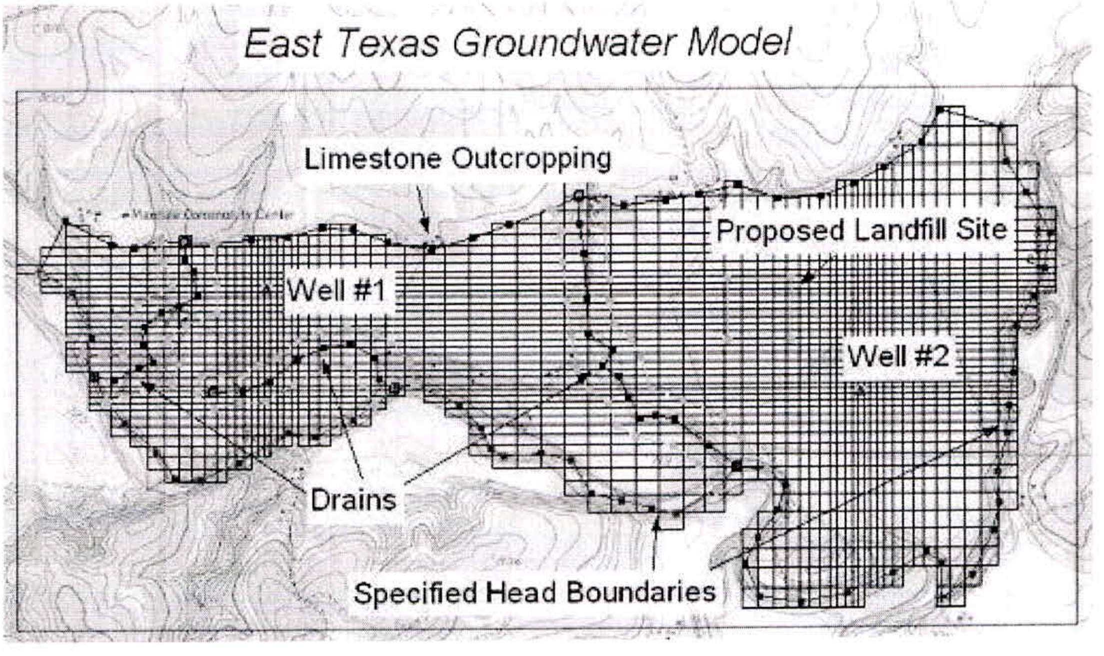

Figure 5.3: Finite Element Grids created by GMS

5.2.6 3D Model Conceptualisation:

GIS presents new and improved tools for the creation of complex 3D stratigraphy models and the ability to translate that 3D object directly to a finite-difference grid model or finite-element mesh model. The "Horizons" of GMS approach allows to create complex solids from borehole and cross section data quickly and easily. These tools allow to create solids with complex stratigraphy such as pinch out zones, truncations, and outcroppings.

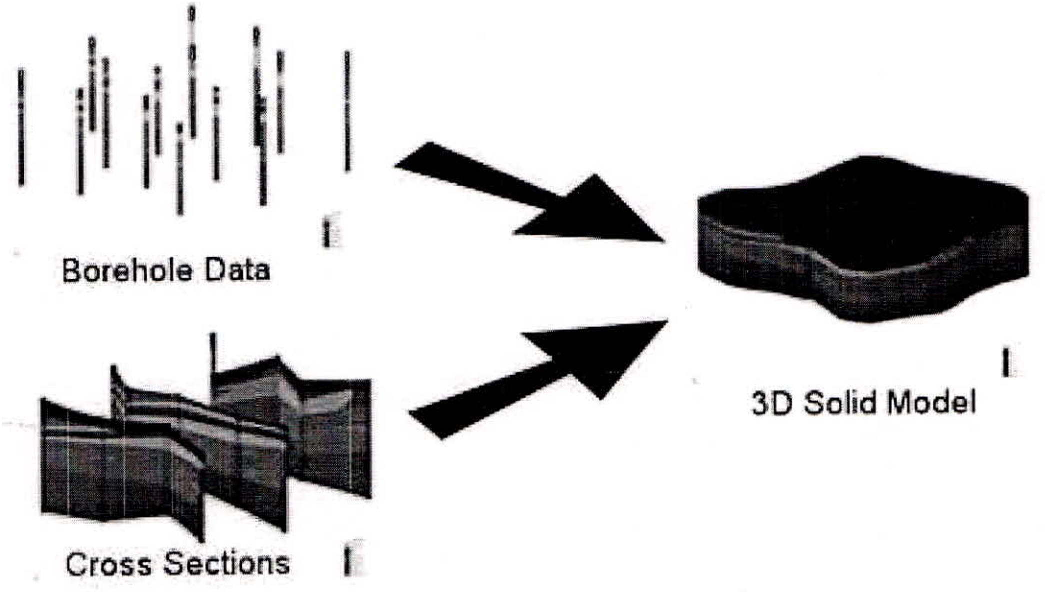

Figure 5.4: Construction of 3D Solid model By GIS

We can transfer the results (material properties) of a solid model directly to a numerical model such as a MODFLOW grid or a FEMWATER mesh.

5.2.7 Displaying Isosurfaces:

An isosurface is a 3D planar surface defined by a constant parameter value in 3D space and is easily created by GIS. Isosurfaces are typically used for demonstrating the spatial distribution of a selected parameter. For groundwater modeling purposes, isosurfaces are generally used for represent heads, drawdowns and concentrations (examples are give nting the spacial distribution of n bellow).

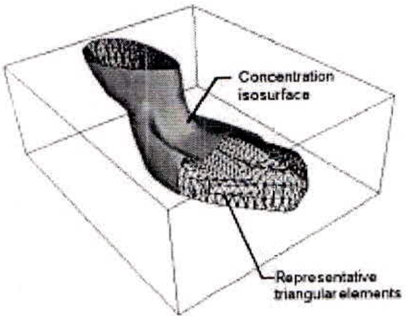

Figure 5.5: Construction an isosurface (by 3D Master™), the visualization program first reads the data in all active cells and then locates nodes having a given constant value by using a tri-linear interpolation scheme. Through triangulation, those nodes are used to construct a finite-element-mesh representing the isosurface.

5.2.8 Animation:

Both steady-state and transient solutions can be displayed in an animated format (as if viewing a movie) using either vector, iso-surface, color fringe, or contour animation. For example, animation of a transient solution allows the user to observe how head, drawdown, velocity, and contaminate concentration vary with time. Creating 3-D animations and "fly-by's" as well as time-varying simulations allow to clearly communicate complex subsurface conditions, temporal variations and trends to the entire project team, in an intuitive and easy-to-understand visual format.

Few examples are given below:

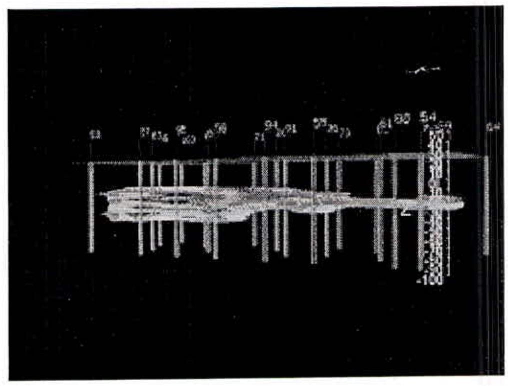

Figure 5.9: An animation displays isosurfaces created using user-specified sample values. An aerial photo is mapped on the ground surface and the boreholes are displayed for orientation (Generated by 3D Master™).

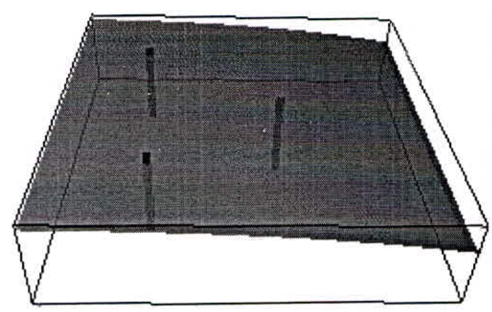

Figure 5.10: An animation shows fluctuations of the water table due to pumping (red) and injection (blue) wells. After all wells have been shut down, the groundwater table recovers.

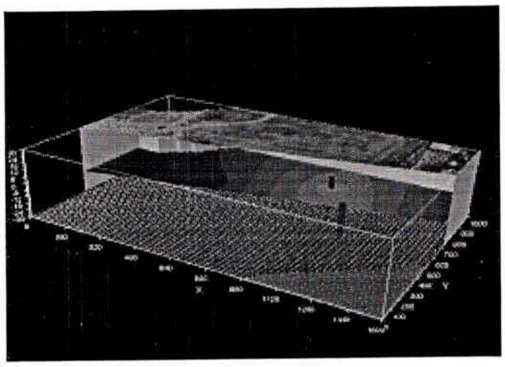

Figure 5.11: Animation of a concentration plume. The source of the plume is located on the ground surface to the left of the model. Due to pumping in the lower aquifer and recharge at the ground surface, the concentration plume flows through the confining layer (not displayed) and reaches the lower aquifer.

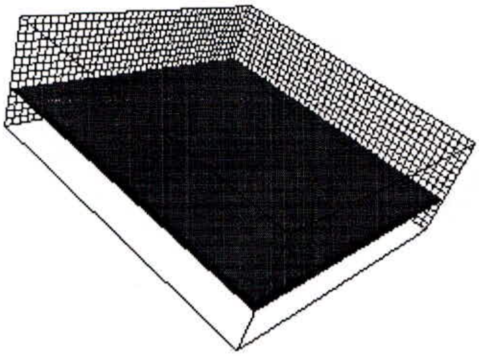

Figure 5.12: An animation shows the water table mound resulting from local recharge (only a quadrant of the aquifer is simulated and the recharge is applied to 4 cells located at a corner of the model).

5.3 GIS: Concepts and Application in Groundwater Vulnerability Assessment

GIS represents a new, powerful set of tools that can significantly improve the usefulness of results obtained during the groundwater modeling process. Bridging the disciplines of groundwater modeling, computer graphics, cartography, and data management, it represents a computer-based set of tools to display and analyze spatial data (e.g., water level elevations, groundwater quality data, modeling results, groundwater pollution potential). GIS can be defined as a computer-assisted system for the efficient acquisition, storage, retrieval, analysis, and representation of spatial data. Most GIS platforms consist of numerous subsystems that perform the listed tasks (Ross and Beljin, 1994).

GIS has been widely used for natural resources management and planning, primarily during the past decade. GIS can be combined with a ground-water quality model to identify and rank the areas vulnerable to pollution potential for different scenarios and land use practices. Many GIS software packages are available like GRASS. It's raster-based public domain software developed by the U.S. Army Construction Engineers Re-search Laboratory (U.S. CERL, 1990). This software can assign different weights to, or reclass, the data layers and combine map layers, and is suitable for implementing the DRASTIC and SEEPAGE models. ArcView is GIS software developed by Environmental Systems Research Institute (ESRI) in Redlands, California

(Navulur and Engel, 1994).

Three separate data models are supported by GIS: (1) vector data, (2) raster data, and (3) Triangulated Irregular Networks (TINs) (Figure 2.5). Vector data includes feature representation with points, lines, or polygons. For example, the monitoring wells for a site could be mapped as a point data source. Example line features include rivers, roads, and boundaries. Some polygon feature examples are buildings, lakes, and watersheds. While vector data are the most common format, other data sets are better represented with grids, where each cell in the grid has a particular value. This type of format is referred to as raster data and is effective for representing elevations and concentrations. Triangulated irregular Networks are the final type of data model and are particularly useful for surface representation and three-dimensional mapping. TINs are constructed by connecting a group of points, such as surveyed elevations. The lines that connect these points form triangles, and since each point in the TIN has an associated value, each triangle in the model (i.e., continuous surface of planar triangles) is sloped. This allows for powerful visualization capabilities with a three dimensional viewer. The most common method of connecting points to form a TIN model is Delauney triangulation, which maximizes the minimum interior angles of the triangles formed, thereby avoiding long and thin triangles (Jones, *et al.*, 1990).

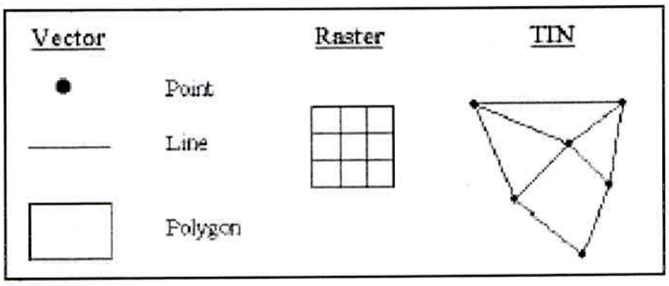

Figure 2.5: GIS data model

Any one of the commercially available GIS software packages can be used in the groundwater vulnerability assessment process. However, the prodnete of Environmental Systems Research Institute, Inc. (ESRI) (ArcView GIS Version 3.2a) has been employed in this research work. This software has been chosen based on ease of use and worldwide availability. ArcView's graphical interface allows a user to display spatial data, build maps, query data sets, create charts, and perform calculations. For purposes of a spatial environmental vulnerability assessment, ArcView is the most effective software tool. Its analytical capabilities have improved significantly over the past few years, and unless otherwise noted, all the methods discussed in this document can be performed with ArcView.

One of the advantages of a GIS such as ArcView is its ability to connect with many different applications in a PC-based environment (Figure 2.6).

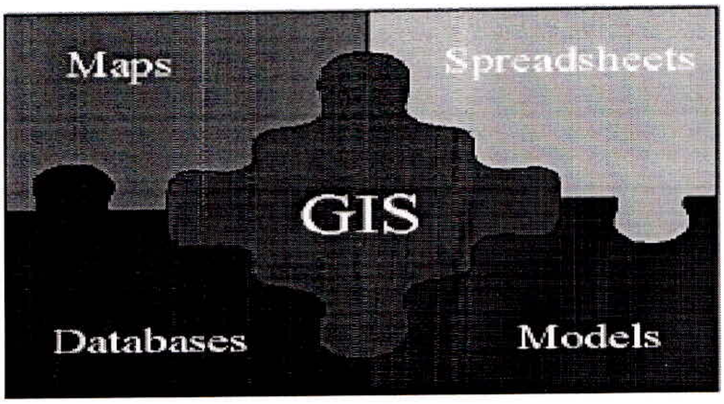

Figure 2.6: GIS Application in PC-Based Environment
(Source: Hay Wilson, 1998)

The examples of the application of GIS in groundwater vulnerability assessment can be broadly grouped into two categories.

i. The first category includes those studies which combine geoscientific information, either raw data or results of groundwater modeling, with information characterizing the hazardous activities in order to assess either the environmental impact or human exposure risk resulting from groundwater contamination (Hiscock et al., 1995). The literature in this group include; Schmidt (1987), Evans and Myers (1990), Halliday and Wolfe (1991), Furst (1992), Harper et al. (1992), Padgett (1992),Von Braun (1993,1998), Pipes et al. (1994), Hiscock et al. (1995), Doerfliger et al. (1999), Kelly and Lunn (1999), Lake et al. (2001and 2003), Magiera and Wolff (2001),Thapinat and Hudak (2003) and Al-Adamat et al. (2003).

ii. In the second category, geosientific information is handled within the GIS and then interfaced with a groundwater model to assist input and displayed with an amount of groundwater data at both the pre and post processor stages of modeling. El-Kadi et al. (1994), Baker et al. (1993) and Rifai et al. (1993) used GIS interfaced with a groundwater flow model to delineate well head protection areas. Harris et al (1993) demonstrated the coupling of GIS with a three dimensional, finite element model, and Turner (1989, 1992) discussed advanced use of three dimensional GIS for modeling groundwater contamination. Interactive ground and surface water resources modeling for environmental management, where systems are designed to integrate GIS, large databases, simulation models, expert systems and tools for graphical display, have been discussed by Loucks and Fedra (1987) and Fedra and Diersch (1989).