Application of GIS to Groundwater Modeling and Management

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INTRODUCTION

A Geographic Information System (GIS) is an information system that is used to input, store, retrieve, manipulate, analyze and output geographically referenced data or geospatial data, in order to support decision making for planning and management of land use, natural resources, environment, transportation, urban facilities, and other administrative records. The key components of GIS are computer system, geospatial data, and users. Sources of geospatial data are: digitized maps, aerial photographs, satellite images, statistical tables, and other related documents

Why GIS is Needed?

Common problems of handling geospatial information are: Geospatial data are poorly maintained; maps and statistics are out of date; data and information are inaccurate; there is no data retrieval service; and, there is no data sharing. Benefits once GIS is implemented for building a database are: Geospatial data are better maintained in a standard format, revision and updating are easier, geospatial data and information are easier to search, analysis and represent; geospatial data can be shared and exchanged freely; productivity of the staff improves with more efficiency so that time and money are saved; and, better decisions can be made. Figure 1 illustrates the comparison of information management with and without GIS. The advantages of using a GIS vs. manual works are further listed in Table 1.

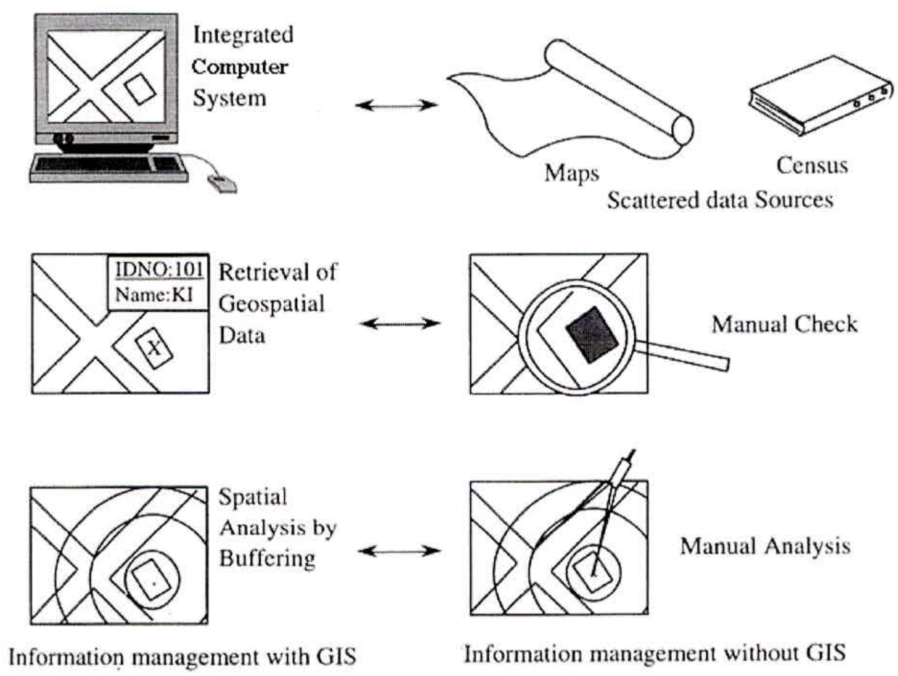

Fig. 1 Information management with and without GIS

Table 1. GIS vs manual works

Maps	GIS	Manual works
Storage	Standardized and integrated	Different scales on different standard
Retrieval	Digital database	Paper Maps, Census, Tables
Updating	Search by Computer	Manual check
Overlay	Very Fast	Expensive and time consuming
Spatial Analysis	Easy	Complicated
Display	Cheap and fast	Expensive

GIS SUPPORT FOR GROUNDWATER MODELING

Management of regional aquifers requires models of groundwater flow/ mass transport to predict the impacts of decisions taken by planners/ managers regarding various issues like maximum groundwater draft, pumping patterns, depth to water table, minimum submarine groundwater discharge in coastal aquifers etc. For example, groundwater levels in a region may be affected by groundwater draft to supplement water supply for domestic, agriculture, and/ or industrial purposes. In such a case, the groundwater management problem may involve issues like location of wells, yield, quality, restrictions by water rights, ecological constraints. Management problem may also address issues targeted to identify compensating/ remediation measures to minimise negative impacts like excessive lowering of water table.

In order to arrive at a suitable groundwater management program for a region, mathematical models are required that are based on partial differential equations describing groundwater table, given aquifer parameters, initial and boundary conditions. The three-dimensional partial-differential equation of groundwater flow is (Bear, 1979):

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)+W=S_s\frac{\partial h}{\partial t} \quad (1)$$

where K_{xx}, K_{yy}, and K_{zz} are values of hydraulic conductivity along the x, y, and z coordinate axes, which are assumed to be parallel to the major axes of hydraulic conductivity (L/T); h is the potentiometric head (L); W is a volumetric flux per unit volume representing sources and/or sinks of water, with $W<0.0$ for flow out of the ground-water system, and $W>0.0$ for flow in (T^{-1}); S_S is the specific storage of the porous material (L^{-1}); and t is time (T). Equation (1), when combined with boundary and initial conditions, describes transient three-dimensional groundwater flow in a heterogeneous and anisotropic medium.

For real life complex conditions, Eq. (1) needs to be solved numerically using mathematical techniques like the finite elements (FE) or finite differences (FD), which require discretization of time and space domain using either FE or FD (refer Fig. 2).

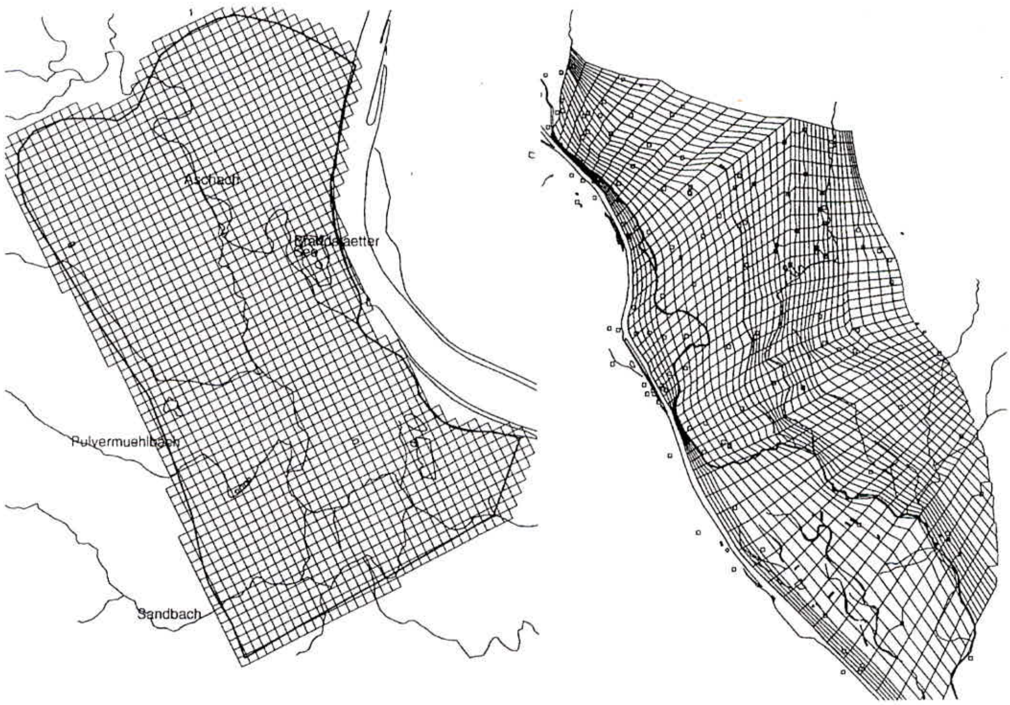

Fig. 2 Discretization of groundwater flow system

The aquifer parameters and boundary conditions in the set up model are assigned as per the field conditions. For groundwater flow, necessary parameters should be defined for each element (grid cell) e.g. aquifer bottom, aquifer thickness, hydraulic conductivity, storage coefficient of aquifer. At the domain boundaries, groundwater heads or fluxes are assigned. The numerical model is calibrated against historical groundwater level data. Thus, numerical groundwater models require a comprehensive data base of hydrogeological information, as well as monitored historical groundwater records for model calibration. For this purpose, data from various sources of different quality and spatial reference are collected (e.g. pumping tests, lab analysis, geophysical methods). Most data collected or monitored are spatial data available at limited points and data interpolation is a critical issue for assigning the data in the mathematical model. GIS plays an important role in handling, processing, analyzing and managing the data for the groundwater model.

COUPLING GIS AND NUMERICAL MODELS

Numerical modelling requires deeper insight into hydraulic and hydrological processes, numerical problems and pitfalls. The groundwater system can be represented by an abstract data model in the GIS (refer Fig. 3).

In order to couple GIS and numerical models by pre- and postprocessors, we require (1) User interface (2) Database (3) Pre-processor for data-acquisition, graphical-interactive design of grid or mesh with access to GIS data, formatting input for numerical model, and (4) Post-processor for selection of model results, transfer to GIS (Fig. 4). The interpretation of results, analysis, visualisation is done in GIS.

The GIS database may consist of point data (point coverages) such as wells, boreholes; line data (line coverages) such rivers, boundaries, and area data (point, line, polygon coverages) such as aquifer parameters, land use, ground surface. A pre-processor is then employed to input the GIS data into the numerical model (refer Fig. 5).

In loose coupling, GIS and numerical model are kept separate (refer Fig. 6). GIS functions are used as a toolbox to (1) prepare input data, and, for (2) visualisation and analysis of results. The procedure consists of generating GIS-dataset (e.g. polygon shape) equivalent to grid or mesh of numerical model. The data exchange is by simple ASCII tables which are joined to the attribute table of the shapefile.

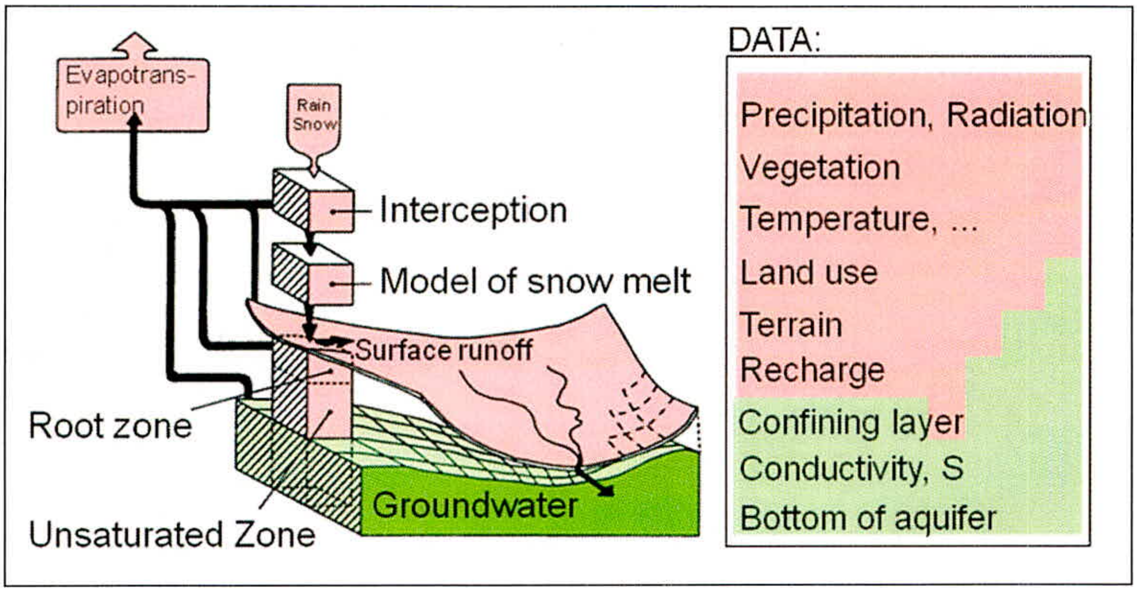

Fig. 3 Representation of groundwater system by an abstract data model in GIS

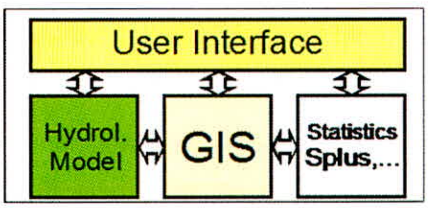

Fig. 4 Coupling GIS and numerical models by pre- and postprocessors

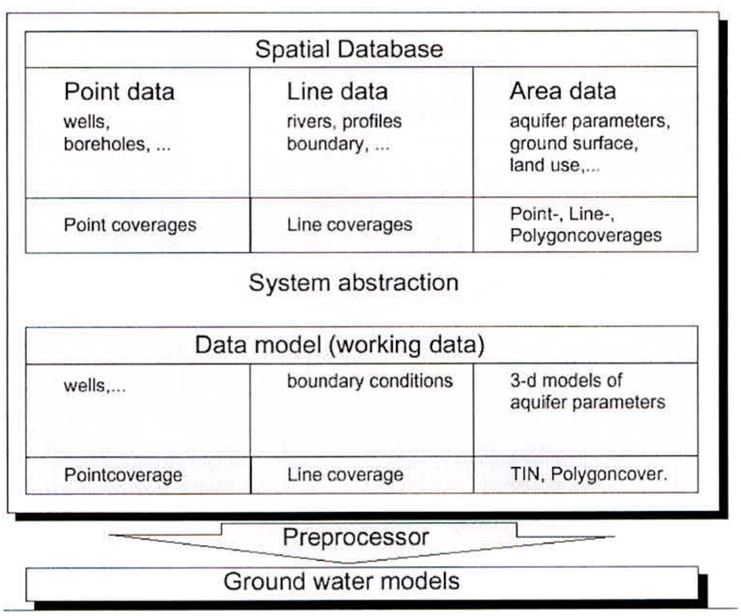

Fig. 5 Coupling 2D FD model and GIS

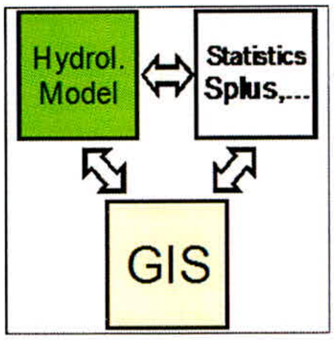

Fig. 6 Loose coupling of GIS and numerical model

GIS FOR DECISION SUPPORT IN GROUNDWATER MANAGEMENT

Groundwater management of regional aquifers requires

- hydrogeological and hydrological database
- tools for modelling flow and transport
- decision support by scenario analysis
- integrated modelling packages (PMWIN, Visual Modflow, GMS, etc.) focused on groundwater hydrology
- GIS coupled packages - analysis of related spatial criteria

Approximate GIS based solution by superposition

Setting-up of mathematical model and its calibration is complex and time consuming. The decision maker may only formulate and evaluate different management scenarios. The initial phase may consist of (1) model set-up and calibration, (2) basic management scenario for which the model specialist uses tools of choice. Subsequently, for scenario analysis, superposition in GIS may be carried out by decision makers.

For example, a groundwater management problem requires decision about optimal location of wells, where drawdown is main hydrological criterion, and approximate solution by superposition is acceptable. Other complex management criteria for the problem at hand may involve accessibility of well locations, land ownership, protected areas, etc. Here, among several criteria, computation of drawdown requires a flow model, other criteria can be studied by GIS analysis and visualisation. By establishing zones of similar response to pumping, a 2D FD model can be utilized to compute drawdown of a typical well in a demarcated zone. The approximate solution for drawdown in the study area can be obtained by superposition.

Later on, a thorough study of the groundwater flow with a well-proven numerical groundwater flow model can be done by a groundwater specialist. The accuracy and validity of the approximate solution can be assessed and the constraints can easily be implemented. In this way, a decision maker can consider not only groundwater related, but also environmental and economic criteria, can do a 'safe' scenario analysis in one convenient GIS environment with only the subset of groundwater hydraulics needed. The decision maker will not be overwhelmed by the full catalogue of options in a groundwater modelling package.

ARC HYDRO: GIS FOR WATER RESOURCES

Arc Hydro is an ArcGIS data model for water resources with Arc Hydro toolset for implementation and Arc Hydro Framework for linking hydrologic simulation models. The Arc Hydro data model started as a data model for representing surface water systems within an ArcGIS geodatabase. Arc Hydro has been highly successful and has been widely adopted in industry. The Arc Hydro data model and application tools are available in the public domain The ESRI and Aquaveo team developed Arc Hydro Groundwater Tools in 2007 that were released in 2009. The groundwater data model has been developed as a companion to the surface water data model. The data model is based on a newly designed Arc Hydro framework which is shared by the surface water and groundwater data models. Users can add groundwater and surface water components to the framework as necessary, or develop their own components. This new componentized approach enables tailoring the geodatabase design to meet specific project needs.

Taking a variety of spatial information and integrating into one Arc Hydro geospatial database (refer Fig. 7) with a common terminology results in better communication, integration of data, and common base for applications.

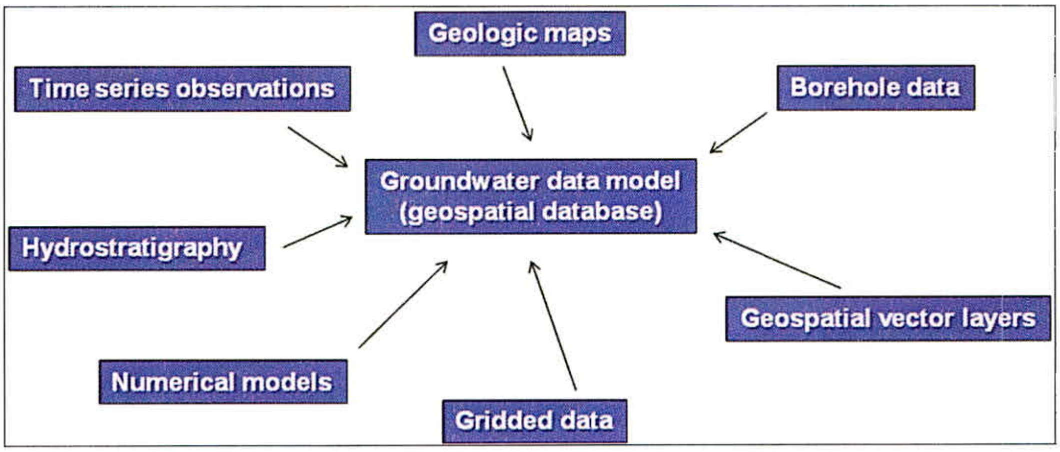

Fig. 7 Geospatial database

For basic representation of surface water and groundwater, components can be added to the Arc Hydro Framework to represent specific themes in more detail (refer Fig. 8). The common framework supports analysis of surface water and groundwater data together.

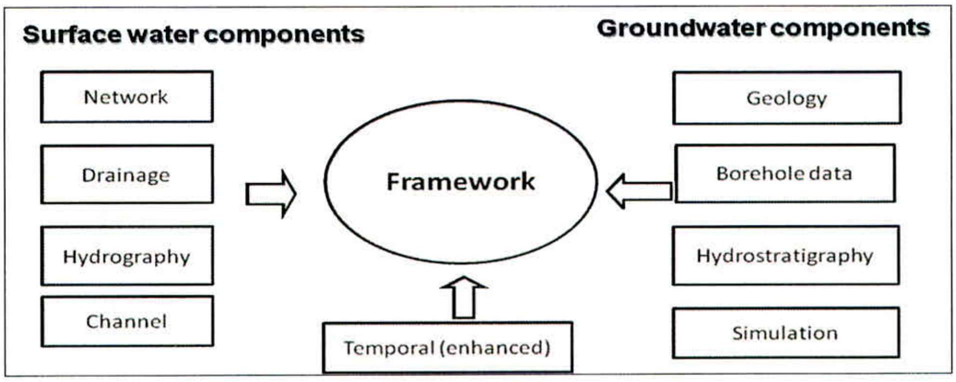

Fig. 8 Arc Hydro Framework

Components of Arc Hydro Groundwater

Each component of Arc Hydro Groundwater data model is described below (refer Fig. 9).

Framework Component

The Arc Hydro framework provides a simple data structure for storing basic spatial datasets describing hydrologic systems. The framework supports basic water resources analysis such as tracing water as it flows over the terrain in watersheds, streams, and water bodies, creating groundwater level and groundwater quality maps, and viewing time series data related with monitoring stations and wells.

- **WaterLine** - Line features representing mapped streams and water body center lines.
- **Waterbody** – Polygon features representing areas such as ponds, lakes, swamps, and estuaries.
- **Watershed** – Polygon features representing drainage areas contributing water flow from the land surface to the water system.
- **WaterPoint** – Point features representing hydrographic features such as springs, water withdrawal/discharge locations, and structures.
- **MonitoringPoint** – Point features representing locations where hydrologic variables are measured, such as stream-gage stations and precipitation gages.
- **Aquifer**- Polygon features representing aquifer boundaries. The features can be classified to represent different zones such as outcrop and confined sections of the aquifer.
- **Well** – Point features representing well locations and their attributes.
- **TimeSeries** – Table for storing time varying data such as water levels, flow, and water quality.
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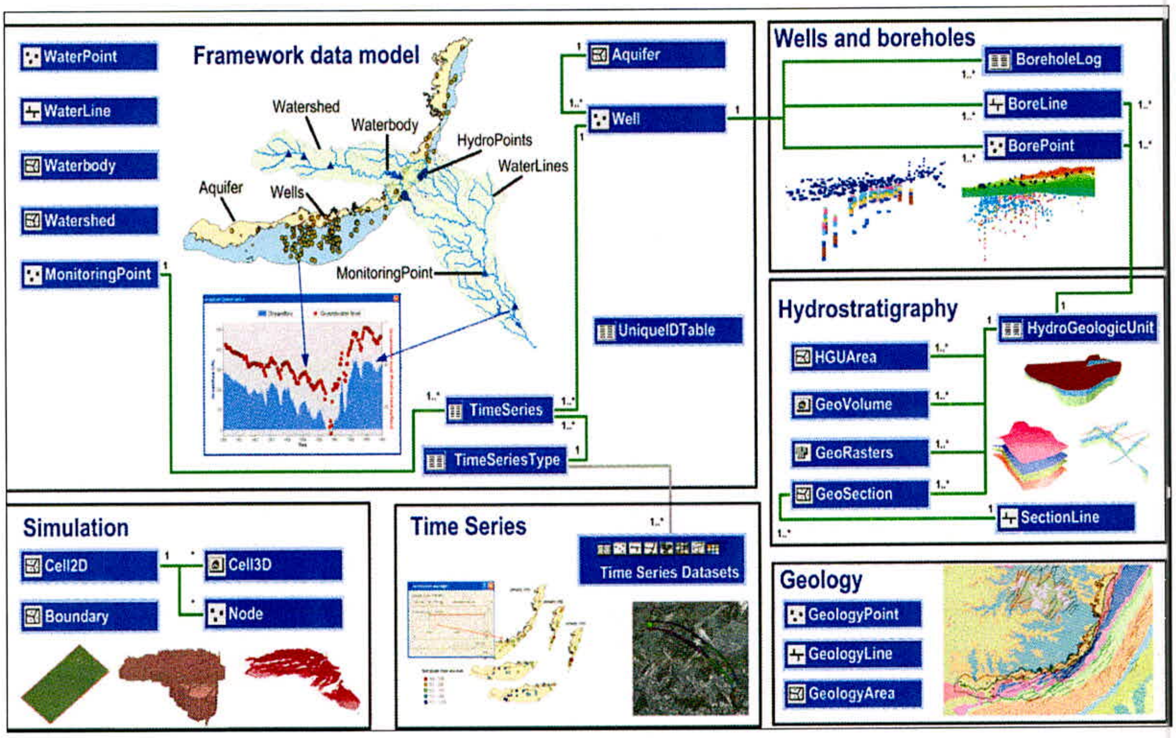

Fig. 9 Arc Hydro Groundwater Data Model

Geology Component

The Geology component provides a set of feature classes for representing data from geologic maps and to integrate geologic data with other groundwater-related datasets.

- **GeologyPoint** – Points that represent locations such as springs, caves, sinks, and observation points.
- **GeologyLine** – Line features that describe objects such as faults, contacts, and dikes.
- **GeologyArea** – Polygon features describing areal features such as rock units and alteration zones.

Borehole data

The Borehole component contains classes for representing 3-D information recorded along boreholes. The data can be stored as tabular information related to well features or as 3-D point and line features.

- **BoreholeLog** - Table for representing vertical data along boreholes. Each row in the BoreholeLog table represents a point or interval along the borehole.
- **BorePoint** - 3D point feature class for representing point data along boreholes
- **BoreLine** - 3D line feature class for representing interval data along boreholes.

Hydrostratigraphy

The hydrostratigraphy component represents hydrogeologic units using 2D and 3D features (refer Fig. 10). Classes in this component enable the representation of hydrogeologic models including 2D polygons representing the extent of hydrogeologic units, cross sections, surfaces representing the top and bottom of hydrogeologic units, volume elements. In the Arc Hydro Groundwater data model, the 2D representation of cross-sections is implemented with multiple feature classes, and these are given the 'XS2D' prefix (e.g., XS2D_Boreline and XS2D_Panel).

- **HydrogeologicUnit** – Table for defining conceptual hydrogeologic units.

- **GeoArea** - Polygon feature class for representing the 2D extent of hydrogeologic units or parts of them.

- **GeoSection** – 3-D multipatch feature class representing vertical cross sections.

- **SectionLine** – Line feature class for representing 2-D section lines.

- **GeoRasters** - Raster catalog for storing rater surfaces. The catalog enables storing rasters within the geodatabase and adding attributes describing raster datasets.

Time Series

The Time Series component provides a new design for dealing with temporal data within Arc Hydro. The new design provides better support for utilizing multiple representations of time series data and a new table to describe time series variables. Types of time varying datasets in Arc Hydro are:

Single variable time series (time series) – A single variable recorded at a location, such as stream discharge or groundwater levels

Multi-variable time series (attribute series) – Multiple variables recorded simultaneously at the same location, such as chemical analysis of a water sample

Time varying surfaces (raster series) – Raster datasets indexed by time. Each raster is a "snapshot" of the environment at a certain time.

Time varying features (feature series) – A collection of features indexed by time. Each feature in a feature series represents a variable at a single time period.

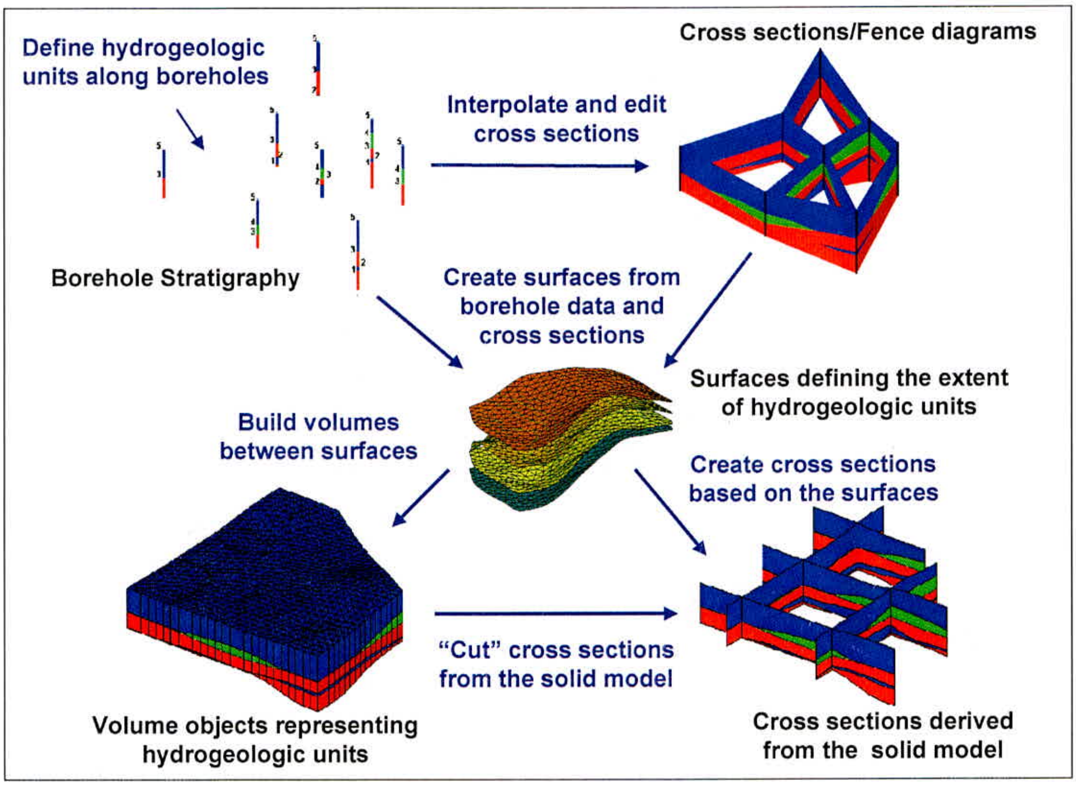

Fig. 10 Representations of hydrogeologic units

Simulation

The Simulation feature dataset is a set of vector feature classes that can represent common modeling objects and it is designed to allow for representation of finite element and finite difference systems in a GIS. The simulation feature dataset includes four feature classes: Boundary, Cell2D, Cell3D, Node2D, and Node3D. These feature classes enable storage and representation of model inputs and outputs related to the simulation objects.

- **Boundary** - Polygon feature class that represents the two-dimensional extent of a model. It is not an essential part of the model representation but it can be useful to illustrate the location of the simulation model to support a simple spatial reference or database query.
- **Cell2D** – Polygon feature class used to represent cells or elements associated with two-dimensional simulation models or a single layer of a three-dimensional model.
- **Cell3D** – Multipatch feature class for representing three-dimensional cells and elements of simulation models.
- **Node2D** – 2-D Point feature class that represents nodes in a 2-D model grid/mesh or the nodes in a single layer of a 3-D model grid/mesh.
- **Node3D** – 3-D Point feature class that represents nodes in a model grid/mesh.

Implementing the Arc Hydro Framework

- Create the classes of the Arc Hydro Framework (manually using ArcCatalog or by importing from an xml schema)
- Add project specific classes, attributes, relationships, and domains as necessary
- Document datasets and changes made to the data model
- Import data into the framework classes (e.g. streams, wells, aquifers, time series)
- Assign key attributes to uniquely identify the features and establish relationships
- Apply tools to create new features and calculate attributes
- Visualize data and create products (maps, scenes, reports)

In short, Arc Hydro Groundwater extends Arc Hydro to represent groundwater datasets in GIS; includes components for aquifers, wells, hydrogeologic features, time series, and simulation model output; and links features to hydrogeologic layers and to aquifers. Recently, the Arc Hydro Groundwater Tools have been released. by Aquaveo, a software development company. The Arc Hydro Groundwater tools include three sets of tools:

Groundwater Analyst – Import a variety of datasets (wells, time series, cross sections, volumes) into the geodatabase, manage symbology of layers in ArcMap and ArcScene, map and plot time series, and create common products such as water level, water quality, and flow direction maps.

MODFLOW Analyst – Create, archive, and visualize MODFLOW models within ArcGIS. Tools in the toolkit enable you to import an existing model into the geodatabase and geo-reference the model so you can visualize and analyze the results in context with other GIS data, as well as create new models from GIS features.

Subsurface Analyst – Create and visualize both 2D & 3D geologic models, starting with classification and visualization of borehole logs, creation and editing of cross sections, and generation of 3D geosections and geovolumes. For details, the Arc Hydro Groundwater Tools Website may be referred: www.aquaveo.com/archydro.

SUMMARY AND CONCLUSIONS

Effort for acquisition and management of required data is significantly reduced on using GIS and results in a more reliable database. Modeling 'in GIS' allows only simplified models. Integrating GIS and external model software with pre- and post-processor gives most efficient results, but is costly. Another option is loose coupling of GIS and modeling tools. Data visualisation can be mostly done in GIS with the GIS as integrative software-platform for different models. Common database and visualisation tools lead to better, more consistent, more readable results and reports.

REFERENCES

Bear, J. (1979) Hydraulics of Groundwater, McGraw-Hill, New York.

Arc Hydro Groundwater Data Model. http://resources.arcgis.com/content/groundwater-data-model.