GIS in Hydrology and Water Management

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Groundwater Hydrology

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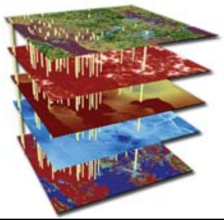
Introduction

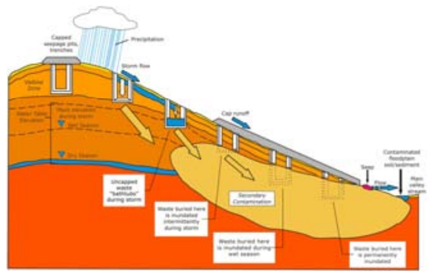
- Management of regional aquifers depends on models used for groundwater flow to predicting impacts – and thus, decisions.
- Mathematical models are based mainly on partial difference equations describing groundwater table, given aquifer parameters, and initial / boundary conditions.
- 1.5 billion people worldwide rely on groundwater – clearance of contamination.
- To some extent, this can be supported via GIS, e.g., coupling of GIS and groundwater models.



Conceptual model of aquifer vulnerability assessment (soil conductivity; density of sinkhole features; material overly; estimated aquifer recharge) (ESRI, 2009)

Introduction

- Groundwater is an integral part of the hydrologic cycle.
- Water is being recharged through infiltration of rainwater, snow melt, irrigation return flows and streams at the land surface.
- Discharging water to streams and wetlands during low-flow periods.



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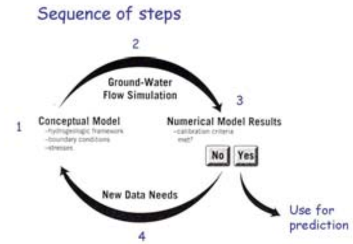
Introduction

- Usually involves two main stages:
  - Development of the conceptual, hydrogeological model (data import, interpolation, assessment, ...), e.g., static → GIS
  - Simulation of groundwater flow that time dependent, e.g., adopting (limited) dynamic capabilities → GIS (input pre-processing, post-processing, simulation, visualization)



Domenico and Schwartz (1998)

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Introduction

- Influences on (regional) groundwater flow:
  - Discharge for domestic water supply / storage / pipeline / agriculture / industry
    → management problem: location of wells, yield (capacity), quality, restrictions by water rights, ecological constraints, …
  - Discharge for 'other' water supply (hydro power stations, river regulations, road/railway construction, mining / tunnels (de-coupling of surface and groundwater), where groundwater is not the primary objective
    → Management problem: identify compensating / remediation measures to minimize negative impacts
- Hydrologic balance, prediction of long-term pumping capacity and effects, and evaluation of water-quality conditions.

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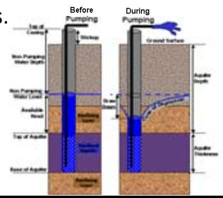
Introduction

- Aquifers – groundwater bearing formation yielding usable quantities of water (confined / un-confined).
- Guiding principle: "Safe Yield" (sustainability yield) – the amount of water that could be pumped on a continuing basis without depleting the storage reserve.
- Streams gain water from inflow of groundwater (most common) or lose water by outflow to groundwater (some do both).
- Adjustment to pumping of hydrologic system can take many years, depending on physical characteristics / connections / location / pumping (etc.) of aquifers.



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Introduction

SWMM, 2011

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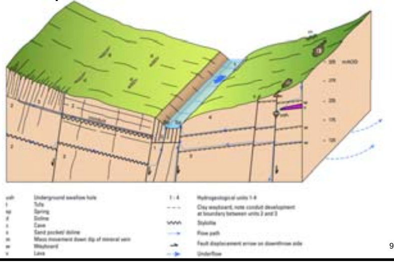
Introduction

- The conceptual groundwater modeling involves two groups of field observations:
  - Geologic = bore logs, geophysics, geological maps → building the geological framework
  - Hydrologic = groundwater hydrographs, pumping tests, groundwater chemistry → building the hydrologic framework
- → Hydrogeologic conceptual model



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Introduction

- Groundwater data:
  - Hydrology: Locations of pumps / pumping amount / precipitation / evaporation / stream-flow (gain and loss) / drainage network / …
  - Hydrogeology: Topographic data of drainage network, landforms, surface-water bodies / geologic maps / boundaries of aquifers / …
  - Water quality: Spatial distribution of water quality in aquifers / earth materials / sources and types of potential contaminants / lans-cover and land-use / …
  - Administrative: Jurisdictions / ownership / water rights / …
  - …

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Introduction

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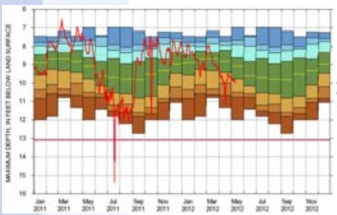
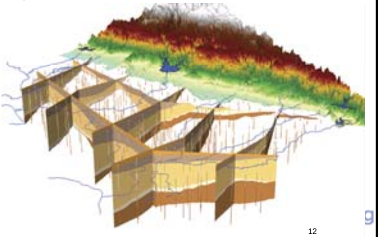
Introduction

- Partial list of supportive GIS operations:
  - Data management: database of spatial data (attributes related to specific locations and depths) / archives / visualization of input data (error checking and consistency) / statistical interpolations (water level extent) / collation of aquifer attribute data on hydrogeologic factors (and quality) / …
  - Modeling: aquifer model boundary conditions / interactive model simulations / sensitivity analysis / …





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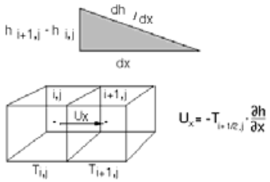
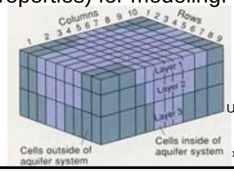
Groundwater Models

- Originates with Darcy's studies in the 1850s: velocity of flow is directly related to the hydraulic gradient and aquifer permeability.
- Natural hydraulic gradients usually 0.2%-0.4%; velocities are less than 100 m/y (sandstones) to 100 m/day (coarse gravels).
- u = -T*dh/dx = -T*s
  - u – Darcy velocity; h – drop in groundwater table of two points; x – horizontal distance; s – hydraulic gradient; T – Darcy's coefficient (soil material and fluid characteristics, hydraulic conductivity)



Groundwater Models – Finite Difference

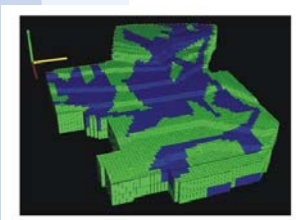
- Modular finite-difference groundwater flow model (MODFLOW, regular shape approach), simulating aquifer systems (flow and contaminant) where:
  - Saturated-flow conditions exist
  - Darcy's law applies
  - Density of groundwater is constant
  - Principal direction of horizontal hydraulic conductivity (transmissivity) do not vary within the system
- Using finite-difference method, by using rectangular grid blocks (cell with specific aquifer properties) for modeling.

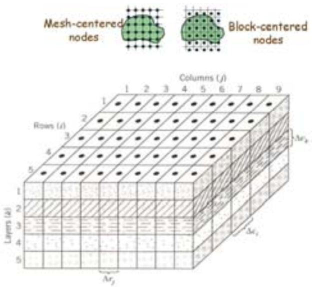


USGS (1997)

Groundwater Models – Finite Difference

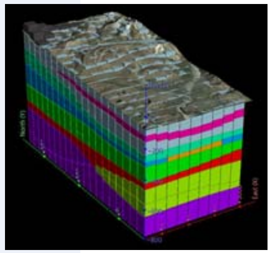
- MODFLOW – multi layered 3D discrete(ization) -> cells: columns, rows, layers
  - Divide study area into small segments (regular/rectangular grid)
  - Nodes (aquifers) are mesh-centered or block-centered
  - FDM – solves equations for *h* within each cell



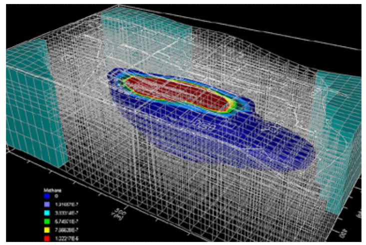


School of Natural Resource Science (1997)

Groundwater Models – Finite Difference



Visual MODFLOW 3D-Builder (2009)



Groundwater Models – Finite Difference

- MODFLOW
  - The differential equation for flow is replaced by difference equation (~ conservation of mass)
  - 3D flow for each cell is described by

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

flow parameters storage

K_{ij} - hydraulic conductivity on (x,y,z) axes
h - hydraulic head
w - flux (pumping, recharge, sinks, …)
s_s -specific storage
t - time

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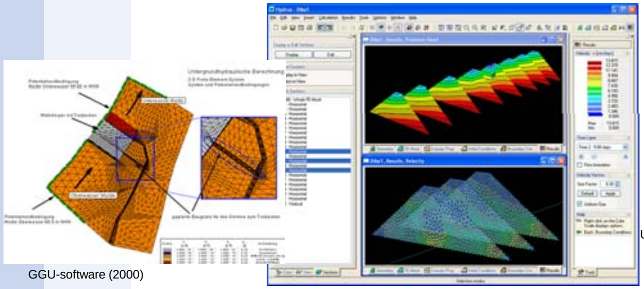
Groundwater Models - Finite Element

- Finite element geometric structure for representing the spatial variability of aquifer properties.
- Using triangular-based elements (similar to TIN data-structure).
- SUTRA, Hydrus, FEFLOW, COMSOL, …



USGS (1997)

GGU-software (2000)

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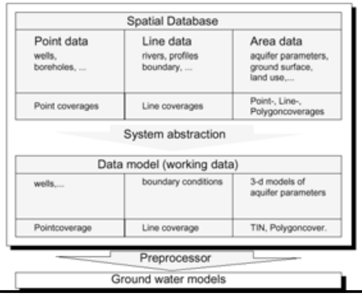
Groundwater Models

- Partial differential equations require continuity in space (derivatives)
- Analytical solutions apply only for simple conditions (well based formula)
- Numerical solutions: Finite Element, Finite Difference



USGS (1997)

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Groundwater Models – DRASTIC Index

- DRASTIC index – characterizing groundwater vulnerability to contamination at various locations via maps showing the different areas and potentials (hydrogeology and human factors) (Aller at al., 1985).
- Combining data layers: land use, soils, water depth – and more, giving different ratings and weights
  - **D**epth to water table (shallow water have greater risks)
  - **R**echarge (more recharge have greater risks)
  - **A**quifer material (media) (more travel time – greater risks)
  - **S**oil material (media) (larger water-holding capacity increase travel time having greater risks)
  - **T**opography (slope) (smaller slope with small runoff and erosion having greater risks)
  - **I**mpact of vadose zone (texture determines length of travel)
  - **C**onductivity (hydraulic) (highly permeable soil decrease travel time)

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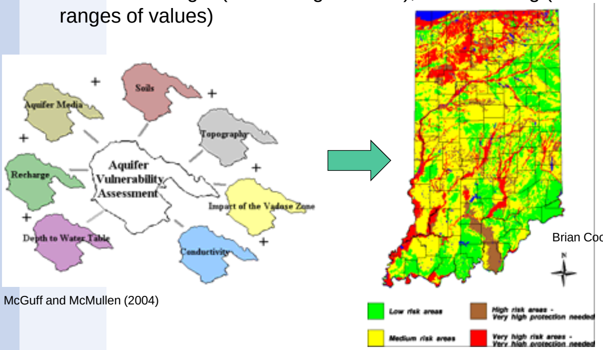
Groundwater Models – DRASTIC Index

- DRASTIC (index)
  $= D_rD_w+R_rR_w+A_rA_w+S_rS_w+T_rT_w+I_rI_w+C_rC_w$
  where *w* = weight (relative significance), and *r* = rating (for different ranges of values)



McGuff and McMullen (2004)

Brian Cooper (1996)

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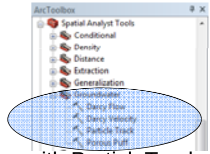
Groundwater Analysis – ArcGIS GW

- Specialized post-processing tools embedded in Spatial Analyst:
  - Darcy Flow
  - Darcy Velocity
  - Particle Track
  - Porous Puff



- DarcyFlow and DarcyVelocity, in conjunction with ParticleTrack and PorousPuff, are used to perform rudimentary advection-dispersion modeling of constituents in groundwater.
- This methodology models two-dimensional, vertically mixed, horizontal, and steady state flow, where head is independent of depth.

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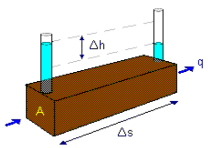
Groundwater Analysis – Darcy Flow/Velocity

- Darcy's Law states that the Darcy velocity *u* in a porous medium is calculated from the hydraulic conductivity *T* and the head gradient (the change in head per unit length in the direction of flow in an isotropic aquifer), as:

  $u = - T \nabla h$
- *u* has units of volume/time/area, and is also known as the specific discharge, the volumetric flux, or the filtration velocity.
- In the implementation the seepage velocity *V* is calculated on a cell-by-cell basis.



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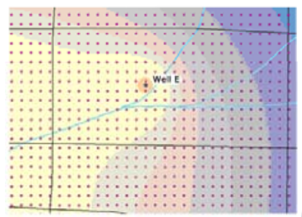
Groundwater Analysis – Darcy Flow/Velocity

- The first step in groundwater flow modeling is to determine the flow velocity and direction at each point in the flow field.
- Darcy Flow does this and calculates the volume balance within each cell, which should be small in the absence of sources or sinks, such as wells, infiltration, or leakage.
- A zero volume balance residual indicates a balance between flow-in and flow-out of the cell. The flow field is assumed to be steady (constant in time).



Groundwater flow direction via Darcy Flow and Darcy Velocity in understanding how a contaminant will move through groundwater.

(ESRI, 2009)

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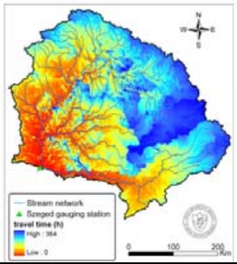
Groundwater Analysis – Darcy Flow/Velocity

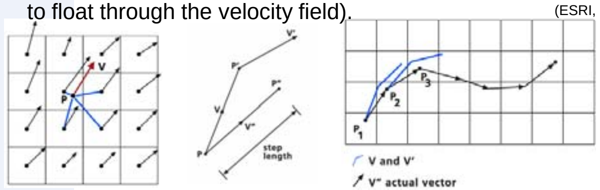
- Differences between two analyses:
  - Darcy Flow produces an output volume raster; Darcy Velocity does not
  - Darcy Velocity outputs only direction and magnitude rasters; Darcy Flow produces these outputs optionally
- Input required:
  - groundwater head elevation raster
  - effective formation porosity raster
  - saturated thickness raster
  - formation transmissivity raster



Tisza River flow travel time (Jolánkai, 2004)

Groundwater Analysis – Particle Track

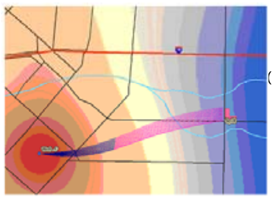
- Tracking a particle (prediction of future location) through a given velocity field using a predictor-corrector algorithm (free to float through the velocity field). (ESRI, 2009)



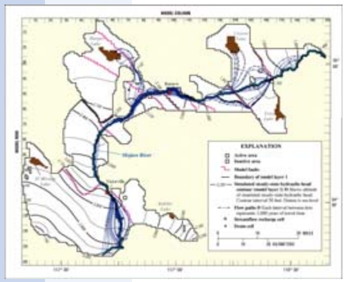
  - Beginning at point *P*, the velocity *V* is interpolated from 4 neighboring cell centers and is used to predict the particle location *P'* at a specified distance.
  - At point *P'*, a new velocity vector *V'* is interpolated from its neighbors and averaged with *V* to create a corrected velocity *V''*.
  - Applied in succession until either the specified time expires or the particle migrates off the raster or into a depression.
  - Cumulative length, and flow direction and magnitude are recorded.

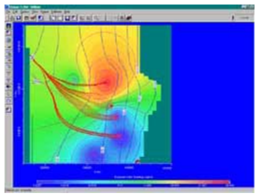
Groundwater Analysis – Particle Track

Tracking particles from a contaminant spill to a pumping well using the *Particle Track* tool, determining if the contaminant is getting into the drinking water (a nearby town).



(ESRI, 2009)





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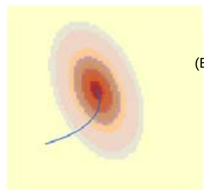
Groundwater Analysis – Porous Puff

- Solute transport in a porous medium involves two principal mechanisms: *advection* and hydrodynamic *dispersion*.
  - Advection describes the passive transport of a solute with the transporting fluid.
  - Dispersion is the mixing of the solute with the fluid by differential movement of the fluids through pore spaces.
- The Porous Puff function assumes the aquifer is vertically mixed - the concentration is the same throughout a vertical section (a 2D model can be applied).



(ESRI, 2009)

Porous Puff and Particle Track used to examine the distribution and track of a contaminant.

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Groundwater Analysis – In Summary (ArcGIS GW)

- Darcy Flow generates a groundwater flow velocity field from geologic data.
- Particle Track follows the path of advection through the flow field from a point source.
- Porous Puff calculates the hydrodynamic dispersion of an instantaneous point release of a constituent as it is advected along the flow path.
- The typical sequence for groundwater modeling is to perform Darcy Flow, then Particle Track, then Porous Puff.

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Groundwater Analysis – Arc Hydro Groundwater

- ESRI and Aquaveo - manage and analyze groundwater and subsurface data within ArcGIS.
- Import variety of datasets (wells, time series, cross sections, volumes) into a geodatabase, manage symbology of layers in ArcMap and ArcScene, map and plot time series, and create common products (water level, water quality, flow direction maps, and more).
- Free to all ArcGIS users with an ArcMap level license.
- Download: http://www.aquaveo.com/downloads
- Help center: http://www.aquaveo.com/ahgw-learning
- Wiki: http://www.archydrogw.com/ahgw/Main_Page

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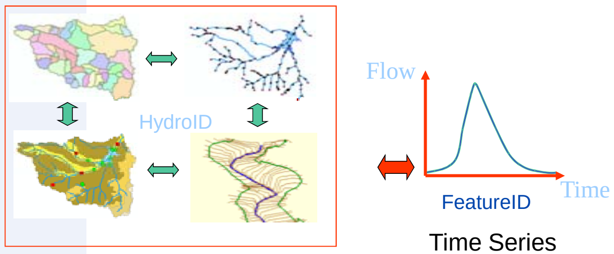
Groundwater Analysis – Arc Hydro Groundwater

- Arc Hydro connects space and time: hydro features are linked to time series.
- For groundwater resources we need:
  - 3D representation of boreholes and hydrogeologic units
  - Integration with groundwater models, especially MODFLOW



Hydro Features

Time Series

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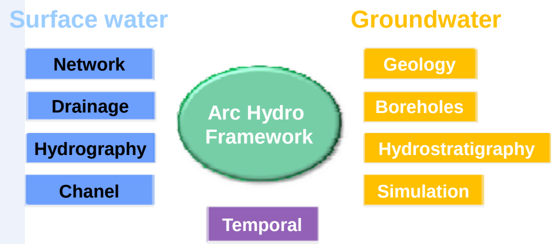
Groundwater Analysis – Arc Hydro Groundwater

- Data Model: general model for representing water resources, including surface water components and groundwater components centered on a common framework.



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Groundwater Analysis – Arc Hydro Groundwater

- Components:
  - **Framework** – surface water features, wells, and aquifers
  - **Temporal** – representation of time series data
  - **Geology** – representation of data from geologic maps
  - **Boreholes** – borehole log table and 3D description of borehole lines and contact points
  - **Hydrostratigraphy** – 2D and 3D description of hydrogeologic units
  - **Simulation** – representation of groundwater simulation models

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Groundwater Analysis – Arc Hydro Groundwater

- Components:
  - **Framework** – surface water features, wells, and aquifers

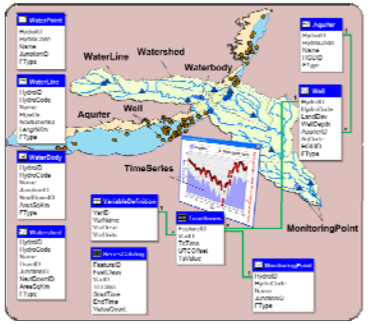
Hydrography: {WaterLine, WaterBody} to represent hydrography; {Watershed} to represents drainage areas.

{WaterPoint}: to represent poi (structures, dams, springs, diversions, etc.)

{**MonitoringPoint**}: to represent locations of measured water.

Aquifer features: defined by one (or more) polygon features (identified by a unique ID - HGUID).

Wells: defined as a 2D point (location where the subsurface has been drilled) in the Well feature class with basic attributes (are related to aquiferID – 1:M).



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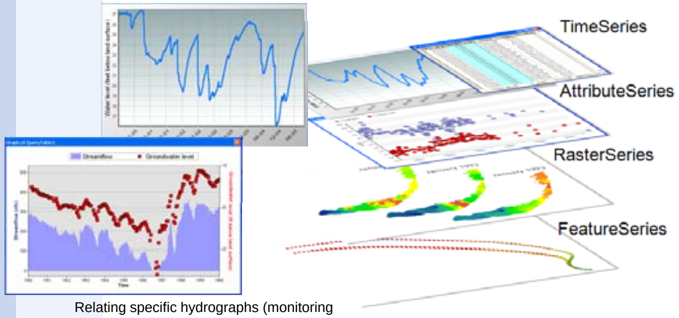
Groundwater Analysis – Arc Hydro Groundwater

- Components:
  - **Temporal** – representation of time series data



Relating specific hydrographs (monitoring points - wells, aquifers) to a series of time-related measurements (water quality, water levels,…).

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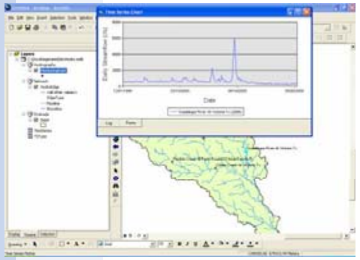
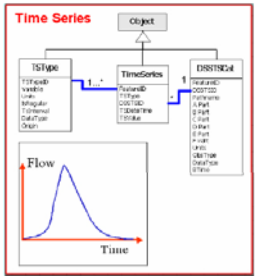
Groundwater Analysis – Arc Hydro Groundwater

- Components:
  - **Temporal** – representation of time series data





Relating specific hydrographs (monitoring points - wells, aquifers) to a series of time-related measurements (water quality, water levels,…).

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Groundwater Analysis – Arc Hydro Groundwater

- Components:
  - **Geology** – Representation of data from geologic maps

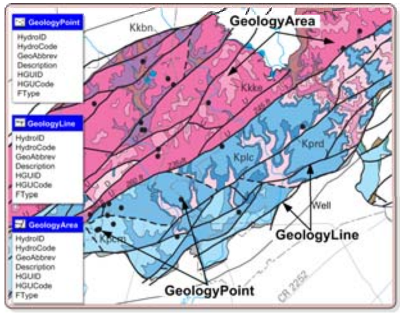
A geologic map is a cartographic product that portrays information about the geologic character of a specific geographic area.

Groundwater features are closely tied to geology; maps can vary in scale (continental, regional, local); provide with a simple data structure to support mapping.

{GeologyPoint}: caves, sinks, observation points, …

{GeologyLine}: faults, contacts, …

{GeologyArea}: rock units, alteration zones, ...



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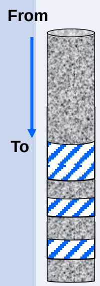
Groundwater Analysis – Arc Hydro Groundwater

- Components:
  - **Boreholes** – borehole log table and 3D description of borehole lines and contact points



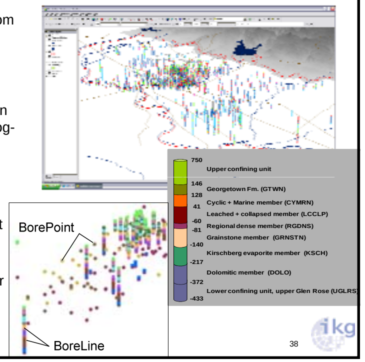
3D data is referenced along wells: from depth (top = TopElev) – to depth (bottom = BottomElev) - each row represents a point/interval along a borehole.

Combining the well spatial information (x,y) with vertical data stored in the log-table **{BoreholeLog}** - to describe a set of 3D geometries (x,y,z).

Ideal to present as 3D features in ArcScene.

{BorePoint} 3D representation point locations along a borehole (geologic contacts, samples).

{BoreLine} is a 3D representation for intervals along a borehole.



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Groundwater Analysis – Arc Hydro Groundwater

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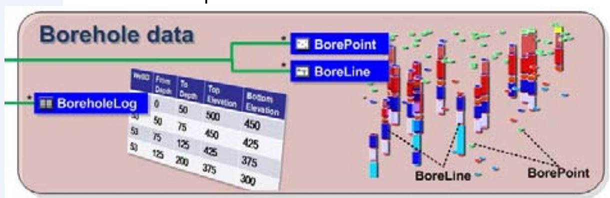

WellID *	RefElev	FromDepth	ToDepth	TopElev	BottomElev	HGUID	HGUCode	LogType
64554	79.533	37	60	42.533	19.533	1107	1107	<Null>
64554	79.533	2	37	77.533	42.533	1110	1110	<Null>
65163	73.257	66	88.7	7.257	-15.443	1125	1125	<Null>
65163	73.257	12	58	61.257	15.257	1110	1110	<Null>
65163	73.257	58	66	15.257	7.257	1107	1107	<Null>
65136	42.499	0	57	42.499	-14.501	1110	1110	<Null>
65136	42.499	57	58.4	-14.501	-15.901	1107	1107	<Null>
65685	85.014	17	77	68.014	8.014	1110	1110	<Null>
65685	85.014	77	90	8.014	-4.986	1107	1107	<Null>

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Groundwater Analysis – Arc Hydro Groundwater

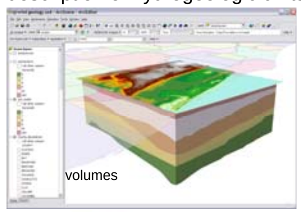
- Components:
  - Hydrostratigraphy – 2D and 3D description of hydrogeologic units

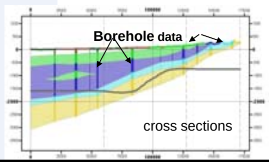
"Hydrogeologic unit is any soil or rock unit or zone which by virtue of its hydraulic properties has a distinct influence on the storage or movement of ground water" (USGS glossary).

Hydrogeology can be derived by classifying stratigraphic units.

Hydrogeologic units can be attributed with an AquiferID, such that they can be grouped to represent an aquifer.

Spatial features are indexed with a HGUID to relate to the conceptual representation of the units.





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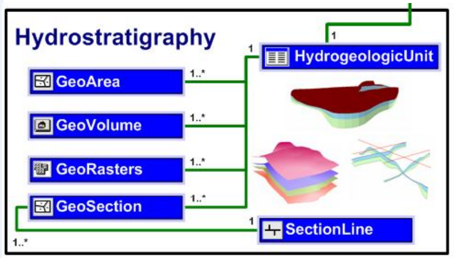
Groundwater Analysis – Arc Hydro Groundwater

- Components:
  - Hydrostratigraphy – 2D and 3D description of hydrogeologic units



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Groundwater Analysis – Arc Hydro Groundwater

- Components:
  - Simulation – representation of groundwater simulation models

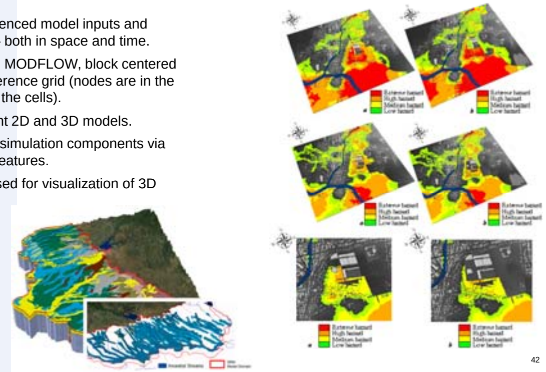
Georeferenced model inputs and outputs – both in space and time.

Focus on MODFLOW, block centered finite difference grid (nodes are in the center of the cells).

Represent 2D and 3D models.

Creating simulation components via existing features.

Mostly used for visualization of 3D models.



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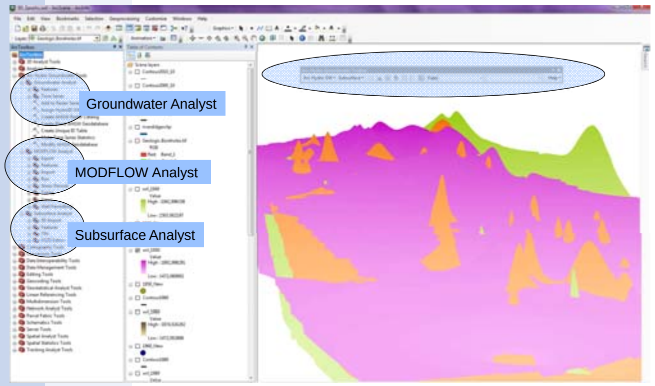
Groundwater Analysis – Arc Hydro Groundwater

- Screenshots:



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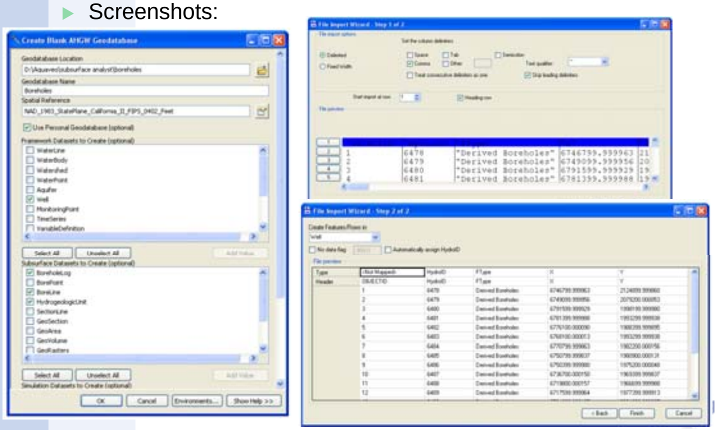
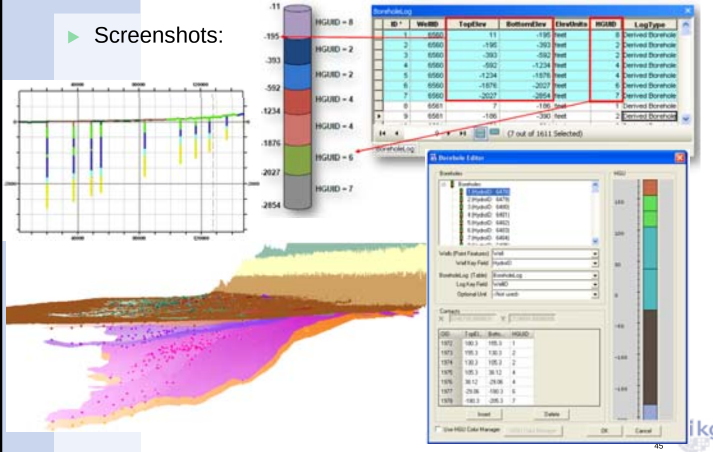
Groundwater Analysis – Arc Hydro Groundwater

- Screenshots:



Groundwater Analysis – Arc Hydro Groundwater

- Screenshots:



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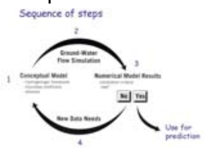
Groundwater Models and Analysis - summary

- Effort for acquisition and management of required data is significantly reduced; resulting in a more reliable database.
- Modeling in GIS allows only simplified models:
  - Integrating GIS and external model software with pre- and post-processing: most efficient result (might be costly), and
  - Loose coupling
- Visualization mostly done in GIS (2D and 3D).
- Desktop-GIS as integrative software-platform.
- Common database and visualization tools lead to better, more consistent, more readable results and reports -> decision making.



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