


Arc Hydro Groundwater Data Model And Tools: Overview and Use Cases

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Abstract: Arc Hydro Groundwater is a geographic data model, and a set of associated tools for representing groundwater information within a geographic information system (GIS). This paper describes some of the basic data structures defined by the data model and demonstrates how these together with the tools support common GIS-based workflows. Example workflows are the creation of water level and water quality maps from well and time series data, the development of 3D hydrogeologic models (including the generation of 3D features for representing fence diagrams and volume models) from borehole stratigraphy, and the creation of 2D cross sections from GIS features and from existing cross section images. We also present the MODFLOW data model, which is an extension to the groundwater data model specifically designed to support the integration of MODFLOW models into a GIS. The MODFLOW data model and associated tools support the integration of complete MODFLOW models into a spatial database (geodatabase), on top of which custom workflows can be developed. This capability is demonstrated by a well-permitting workflow developed to automate the process of editing a MODFLOW model, running scenarios, and creating maps that support approval/rejection of well applications.

Keywords:

GIS, groundwater, databases, hydrogeology, modeling

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Riassunto: *Arc Hydro Groundwater è un modello di dati geografici e un set di tools associati per rappresentare le informazioni degli acquiferi sotterranei all'interno di un sistema informativo territoriale (GIS). Questo lavoro descrive delle strutture dei dati di base definiti da un modello di dati e dimostra come questi creino dei flussi di lavoro insieme con le comuni tools basate sul GIS. Esempi di flussi di lavoro sono la creazione di carte del tetto della falda e della qualità delle acque da dati di buona qualità e in serie temporale, lo sviluppo di modelli 3D idrogeologici (che includono la generazione di oggetti geografici 3D per la rappresentazione di diagrammi a staccata e di modelli volumetrici) dalla stratigrafia dei pozzi, e la creazione di sezioni trasversali 2D dagli oggetti geografici GIS e dalla rappresentazione di sezioni esistenti. Viene qui presentato inoltre il modello dei dati MODFLOW, che è un' estensione del modello dei dati delle acque sotterranee specificatamente progettato per integrarsi all'interno di un GIS. Il modello dei dati MODFLOW e le tools associate permettono la completa integrazione dei modelli MODFLOW in un data base spaziale (geodatabase), alla cima del quale possono essere sviluppati flussi di lavoro personali. Questa capacità è dimostrata dalla buona possibilità dello sviluppo di un flusso di lavoro che automatizza il processo di implementazione di un modello MODFLOW, di variazione degli scenari e di creazione di cartografia che può avvalorare o inficiare la buona applicazione del metodo.*

Arc Hydro Groundwater Data Model:

Arc Hydro Groundwater is a geographic data model (and a set of associated tools) for representing spatial and temporal groundwater information within a geographic information system (GIS). The data model is a standardized representation of ground water systems within a spatial database (geodatabase) that provides a public domain template for GIS users to store, document, and analyze commonly used multi-dimensional spatial and temporal ground water data sets (Strassberg et al., 2007). The data model includes several components to represent different types of datasets including representations of aquifers and hydrogeologic units, wells and boreholes, 3D hydrogeologic models, temporal information, and data from groundwater simulation models. The data model is implemented within ArcGIS and is compatible with the Arc Hydro data model for surface water (Maidment, 2002). The first of many factors influencing the design of the Arc Hydro Groundwater data model was requests by users to combine key elements of surface and groundwater systems into a single data model that enables the representation of water resources in a single framework. Though in many cases we analyze groundwater and surface water separately for many reasons, there is a desire to manage data and analyze hydrologic systems in a more holistic fashion. To support this, the Arc Hydro data models (surface water and groundwater) were re-designed to include an Arc Hydro Framework that combines key elements of both systems. To this framework users can choose to add specific components to supply more detail about

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groundwater and surface water systems (Fig. 1). The description of temporal datasets that describe the properties of water over time is identical in the surface water and groundwater data models, which allows the same tools to be used to analyze and visualize surface water and groundwater datasets. The components of the groundwater data model are described in detail in a book: *Arc Hydro Groundwater: GIS for Hydrogeology* (Strassberg et al., in press).

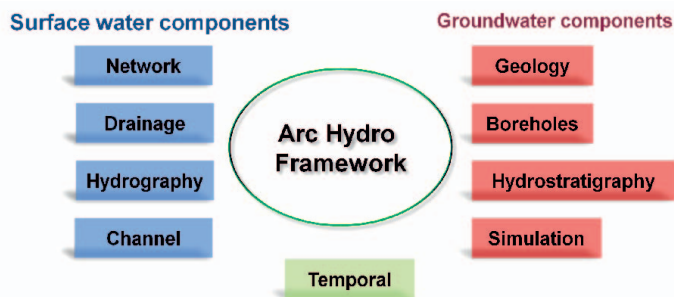


Fig. 1: Components of the Arc Hydro data model. In the center is the Arc Hydro framework that includes the basic features for representing a hydrologic system. Surface water and groundwater components can be added to the framework to provide more detailed descriptions of surface water and groundwater (figure from Strassberg et al., in press).

Arc Hydro Framework:

The Arc Hydro framework is a simple set of data structures for storing the most basic geospatial datasets describing hydrologic systems (Fig. 2). The framework includes common datasets that support basic water resources analysis such as tracing water as it flows over the terrain in drainage areas, streams, and water bodies; creating basic maps such as groundwater level and groundwater quality maps; and viewing temporal information related with monitoring stations and wells. The framework serves as a starting point for groundwater projects to which more detailed components can be added. The framework includes classes representing drainage areas (Watershed) and hydrography (WaterPoint, WaterLine, and WaterBody), and monitoring stations (MonitoringPoint) where water properties are measured. In addition, the framework includes a representation of aquifers (Aquifer) and wells (Well) to represent basic datasets

available for groundwater projects. For storing and mapping temporal data, the framework includes a set of tables (TimeSeries, VariableDefinition, and SeriesCatalog), that when joined with the spatial features support the creation of common map products.

The Arc Hydro framework is a set of core spatial datasets and tables that can be easily implemented, but can still support a wide array of mapping and analysis procedures and data queries. Some simple example queries are: “show me a specific type of wells (domestic, industrial, irrigation, etc.) within a selected aquifer,” or “select all streams and water bodies within a selected river basin,” or “select all stream segments related with an aquifer outcrop”. More sophisticated queries joining features and tabular time series can be used to generate groundwater level and groundwater quality maps for aquifers of interest. Because the framework represents both surface water and groundwater features, we can visualize and analyze data for surface water and groundwater in conjunction. For more detailed descriptions of groundwater systems one can implement additional components.

Groundwater components

Geology: Geologic maps are basic cartographic products available on a wide range of scales (national, state, local) that provide a basic understanding of the geology of an area, and are commonly used as base datasets in groundwater analysis. The geology component includes a set of simple point, line and polygon features that are used to represent data from geologic maps. For example, polygon features can represent rock units and alteration zones; line features represent linear map features such as faults, contacts, and dikes; and point features can represent locations such as springs, caves, sinks, and observation points.

Well and borehole data: Well/borehole databases are probably the most common datasets available for use in groundwater related projects. Different organizations (from national to the city level) document and issue permits for well construction, and many agencies have established well databases containing information on well locations and their usage, construction elements, and subsurface strata along boreholes. These databases provide important information for the development of groundwater management plans and groundwater simulation models. This component of the data model is com-

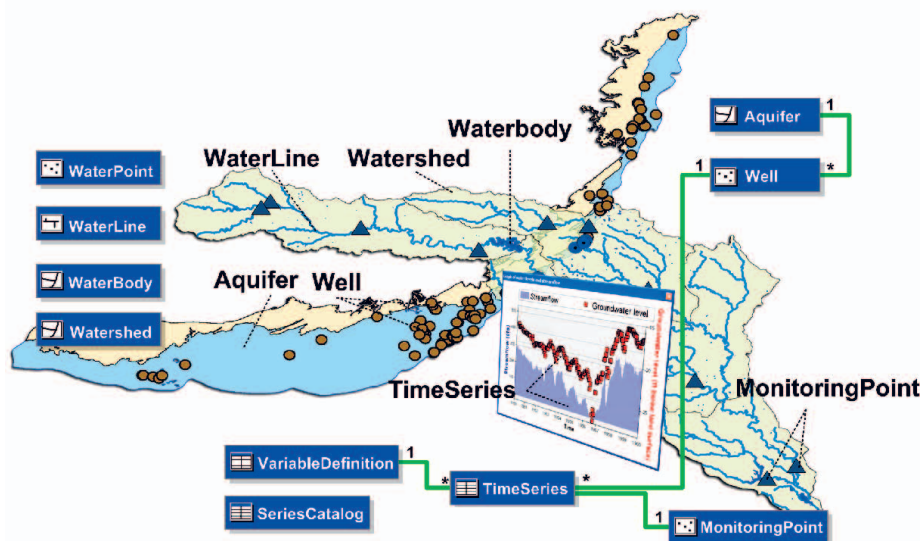


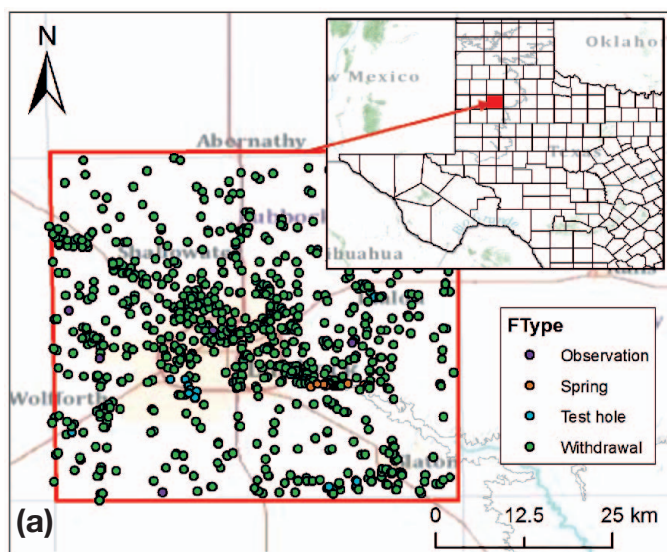
Fig. 2: Data classes in the Arc Hydro framework. Blue rectangles represent classes (spatial or tabular) and the green lines represent the relationships between the objects. 1--* represents a one-to-many relationship, e.g. one aquifer object can be related with multiple well objects.

posed of spatial features representing the well locations, and tabular information to store 3D borehole data (e.g. well construction, stratigraphy). The component also includes a set of 3D features to help visualize borehole data in a 3D GIS environment.

Hydrostratigraphy: Defining a hydrogeologic framework, a geologic framework that defines a distinct hydrologic system, is a key part of many groundwater-related projects. Because we cannot directly measure and classify subsurface strata continuously, we develop conceptual models that reflect our best understanding of the arrangement and properties of subsurface material. These conceptual models can be based on observations from outcrops, borehole stratigraphy, and geophysical measurements, but are also based on interpolation and interpretation. The creation of a hydrogeologic framework commonly involves the creation of 3D objects such as cross sections, surfaces, and volume elements. The hydrostratigraphy component supports the representation of 3D hydrogeologic models using 2D and 3D objects. Classes in the component enable the representation of hydrogeologic models including a 2D representation of the extent of hydrogeologic units, cross sections/fence diagrams, surfaces representing the top and bottom of hydrogeologic units, and volume elements.

Simulation: Simulation models are used to build mathematical representations of complex hydrologic systems and to interpret the flow of water and transport of contaminants within the subsurface. Simulation models typically involve some type of numerical grid where the model inputs are discretized into values associated with grid cells. The simulation component supports the integration of groundwater simulation models within a GIS by representing this grid as 2D and 3D features. We can then use GIS functions to automate the process of preparing model inputs, and visualize simulated results in context with other GIS datasets.

Temporal: Measurements of water quantities and properties (e.g., flow, pressure, temperature, and concentrations) define much of our understanding of how water moves and changes in composition while it travels through a hydrologic system. The temporal component provides a set of classes for representing different types of temporal datasets including tabular datasets for representing variables and storing time series, and spatial datasets (vectors and raster surfaces) for representing time varying spatial phenomena.



Arc Hydro Groundwater Tools and Use Cases:

The groundwater data model is the basis for a rich set of tools, named Arc Hydro Groundwater Tools, developed to help users implement the data model, organize their groundwater-related data, and visualize the data through GIS products such as maps and 3D scenes. Arc Hydro Groundwater Tools have been developed by collaboration between Aquaveo and ESRI, and are available on the Aquaveo Web site (www.aquaveo.com/archydro). The following sections provide a more detailed review of the tools available together with a number of common use cases that illustrate the use of the tools for analysis and visualization of groundwater data within a GIS framework.

Groundwater Analyst – creating a workflow for mapping temporal data

Groundwater Analysts is a basic set of GIS-based tools for managing groundwater data and for creating basic GIS products such as water-level, water-quality, and flow direction maps. The tools can be used to import data, assign attributes of related features to establish relationships between features, and create summary statistics of time series to support creation of maps such as water quality and water level maps.

Creation of maps summarizing time series measurements (e.g. water level, water quality) over a given time period is a common process. In fact almost any groundwater-related report will include maps of water quality or water levels. A typical workflow for creating a map of time series data contains the following steps:

1. Measurements taken at wells are summarized over a given time period (for example to calculate the average water level for a given month).
2. The summary values are related with a map location (usually by adding the X, Y coordinates of a well) to create a new set of points holding the summarized time series.
3. Interpolation tools are applied to create a continuous surface of the mapped phenomenon (e.g. a potentiometric surface, surface of concentrations).
4. Derived products such as contours and flow direction arrows are derived from the surface and added to the map.

The following example demonstrates how the data structures defined in the groundwater data model and the Groundwater Analyst tools support a workflow to automate the creation of water level and water quality maps. In this example we use data from a groundwater database for Texas maintained by the Texas Water Development

OBJECTID	FeatureID	VarID	TsTime	TsValue
7259	2334902	1	1/17/2007	3003.83
7260	2334902	1	1/19/1959	3036.08
7261	2334902	1	1/19/2005	3004.83
7262	2334902	1	1/21/1965	3029.68
7263	2334902	1	1/24/1962	3033.07
7264	2334902	1	1/24/1964	3031.61
7265	2334902	1	1/26/1988	3020.24
7266	2334902	1	1/30/1987	3018.22
7267	2334902	1	2/1/1996	3013.34

Fig. 3: (a) Well features in Lubbock County in the Texas panhandle. Wells are symbolized by the well feature type. (b) TimeSeries table for storing measurements. Each measurement (TsValue) is indexed by a variable identifier (VarID), location (FeatureID), and time (TsTime).

Board (http://www.twdb.state.tx.us/gwrd/waterwell/well_info.asp). The example demonstrates the creation of a water level map for Lubbock County in the Texas panhandle. We start the process of creating a water level map with a set of well features. The wells shown (Fig. 3a) are connected to the Ogallala aquifer, a shallow unconfined aquifer located beneath the Great Plains in the United States. The design of the Arc Hydro Groundwater data model allows the connection between aquifer and well features, by indexing each well with an aquifer identifier. Also, well features can be related with time series representing water properties. The temporal component of the data model includes a TimeSeries table for storing observations (Fig. 3b). The observation values (TsValue) are indexed by a variable identifier (VarID) that relates to a variable description in a separate table. In the example shown, VarID = 1 means the values stored in the TsValue field represent water level measurements in feet above mean sea level. Each measurement is also indexed with a feature identifier (FeatureID) that relates it to a well feature (point feature), and enables mapping of the time series values (or summary statistics of them). Finally, the values are indexed with a Date/Time value (TsTime) to enable querying measurements over a given time period.

Often, groundwater measurements are collected infrequently and across a large time frame. Thus, to create a map of measurements covering an area it is necessary in many cases to define a representative time period and not look only at a specific date. This allows for measurements across larger sets of wells to be included in the map and analysis. Some wells may have a single measurement over the defined time period while others may have multiple measurements. Where there are multiple measurements it is necessary to calculate a representative value. For example, if we want to map measurements for a given month or season we can create a summary statistic (e.g. mean) that represents the values at that well over the given time frame, and that value is attached to the appropriate spatial feature so it can be added to a map. Groundwater Analyst includes a custom tool, *Make Time Series Statistics*, to query the TimeSeries table, aggregate the values over a specified time range, and attach the summary values to the related well features. Figure 4a shows an example of a map layer created by averaging water levels over the winter of 2002. The next step in the process is to spatially interpolate the summa-

rized values into a continuous surface. These can be stored within a GIS as a Triangular Irregular Network (TIN) or as a cell based raster. The interpolation of the surface is necessary for analysis such as the creation of flow direction maps, generation of contours, and calculating changes in water levels and water storage (by calculating the difference between surfaces at different times). Figure 4b shows an interpolated water level surface derived from the mean water level values.

The groundwater data model also provides a raster catalog (RasterSeries) for storing rasters representing time varying phenomena. The rasters are loaded into the catalog and then additional attributes can be assigned to the rasters. Important attributes are "time stamp" attributes (TsTime) that index the rasters with the appropriate time values and the variable identifier (VarID) which relates the raster with a defined variable (the data model includes a VariableDefinition table for defining and indexing variables). Indexing the rasters enables querying the RasterSeries catalog to retrieve specific rasters (by variable type, date, etc.) to automate analysis of the datasets. In addition, having the time stamp as an attribute of the raster enables the creation of animations showing the change in water properties over time. In the example shown in Figure 5, raster surfaces representing the average water level in different winter periods are indexed with the TsTime attribute and additional attributes for storing the start date and end date of the averaging time period.

Most of the Arc Hydro Groundwater tools are developed as Geo-

Attributes of RasterSeries

OBJECTID	Shape *	Raster	Name	VarID	TsTime	StartDate	EndDate
1	Polygon	<Raster	wl_2001	1	1/1/2001	1/1/2001	3/31/2001
2	Polygon	<Raster	wl_2002	1	1/1/2002	1/1/2002	3/31/2002
3	Polygon	<Raster	wl_2000	1	1/1/2000	1/1/2000	3/31/2000
4	Polygon	<Raster	wl_2003	1	1/1/2003	1/1/2003	3/31/2003
5	Polygon	<Raster	wl_2004	1	1/1/2004	1/1/2004	3/31/2004
6	Polygon	<Raster	wl_2005	1	1/1/2005	1/1/2005	3/31/2005

Record: 1 | 0 | Show: All Selected | Records (0 out of 6 Selected)

Fig. 5: RasterSeries raster catalog for storing and indexing raster datasets. Rasters loaded into the catalog are indexed with a "time stamp" and with a variable identifier.

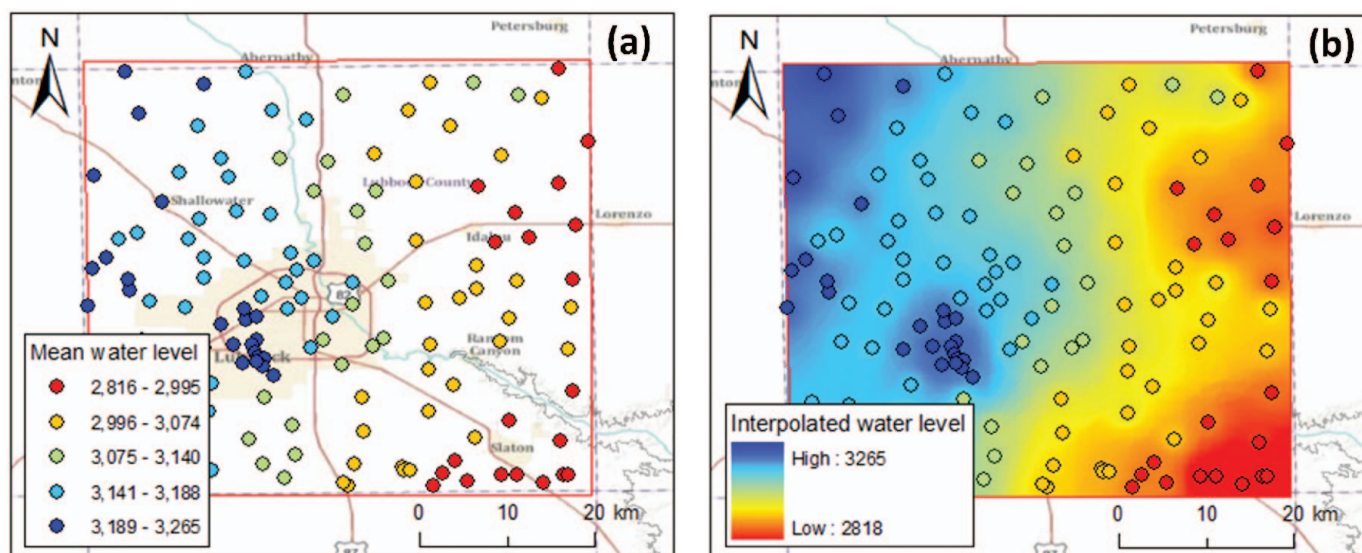


Fig. 4(a): Map of water levels averaged over the winter of 2002 (January 1st through March 31st). The points were created by averaging values from the TimeSeries table and attaching the summary values to the related well features. 4(b): Water level surface interpolated from the summary values.

processing (GP) tools (An ArcGIS tool that can create or modify spatial data). A main advantage of using GP tools is that they can be linked to form models, either via a graphical interface or via scripting. For example the workflow described for creating water level maps can be incorporated into a model that links Groundwater Analyst tools with other GP tools to form a workflow. Figure 6 shows an example of such a model. The orange rectangles represent the tools, blue ovals represent model input parameters, and green ovals represent the output parameters. The “P” value next to some of the input parameters indicate that these parameters will be “model parameters”, meaning the user will have the option to specify these manually when running the model via the model interface. The model incorporates the following tools:

- Make Time Series Statistics (part of Groundwater Analyst) - Inputs to the tool are a set of well features (points) and related time series stored in a separate table. Also, one can specify the start and end dates to define a time range over which time series values will be summarized. The tool output is a new set of point features with the summary values attached to the point.
- IDW (Inverse Distance Weighted, part of the standard ArcGIS

tools) – This is an interpolation tool based on the IDW method. It is important to notice that different interpolation tools are available, and the IDW tool can be substituted with different interpolation tools based on the preferred method. The output of the IDW tool is a raster dataset representing the interpolated water level surface.

- Add to Raster Series (part of Groundwater Analyst) – Takes the output raster from the interpolation tool, loads it to the RasterSeries raster catalog and indexes the raster with the start date and end date values.

Once the model is created, it can be run as a standalone tool, in batch mode, and via scripting. Scripting the model enables users to programmatically iterate on a set of time ranges, thus automating the creation of water level rasters for a selected set of times. For example, one can easily implement a script that will batch process the model for every month in a given set of years. The result would be a monthly water level raster for every month in the selected set of years. Additional tools can be added to the workflow to perform analysis such as the calculations of volume changes within a specified region, or to create visual products such as water level contours.

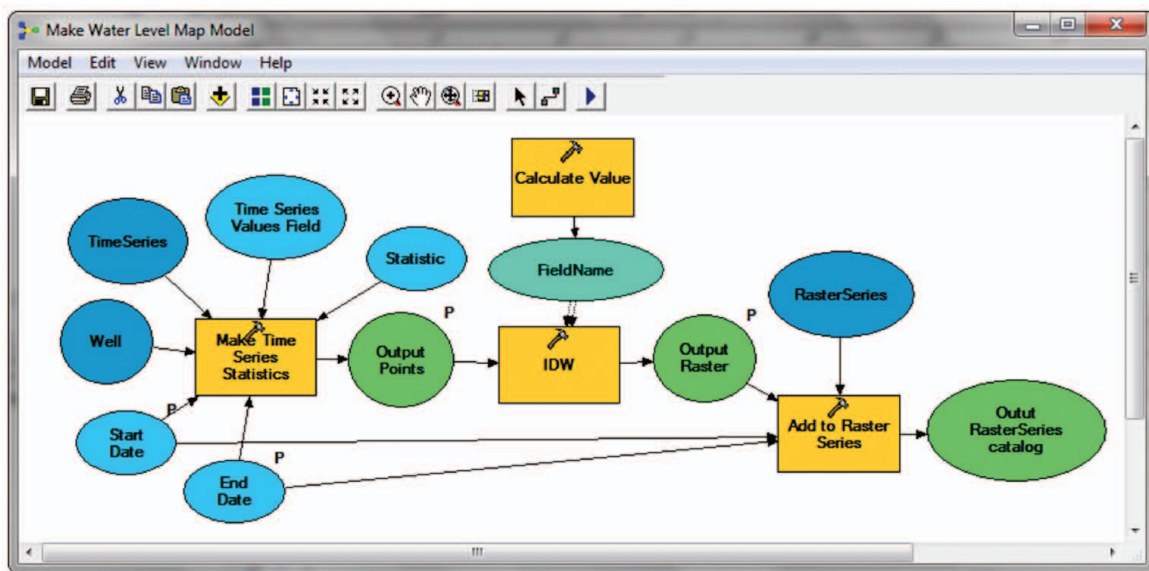


Fig. 6: Example of a model that supports the creation of a water level map. The model includes the following workflow: summarize water level time series over a specified time period and attach the summary values to related well features, interpolate the summary values to create a water level surface, and add the surface to a raster catalog and index the raster with an appropriate “time stamp”.

Subsurface Analyst – creating workflows for subsurface characterization

Subsurface Analyst is a set of GIS-based tools that support visualization, creation, and editing of 2D and 3D subsurface models. The tools support the creation of workflows starting with visualization and classification of borehole stratigraphy, generation of cross sections, and construction of fence diagrams and volume models. Figure 7 shows a schematic diagram of the different spatial datasets generated and the associated workflow. A typical workflow includes the following steps:

- (a) Creation of point features that represent the location of wells/boreholes. Vertical stratigraphic data (usually represented as intervals along the borehole) is related to the point features through key fields.

- (b) Classification of the stratigraphic data into hydrogeologic units. The data can be visualized as 3D points and lines.
- (c) Creation of 2D cross sections. It is typical to add stratigraphy projected from nearby wells onto the cross section. One can add additional data such as outcrops, surface terrain, and faults to the cross section to help guide the “sketching” of the cross section.
- (d) Surfaces representing top/bottom of hydrogeologic units are interpolated based on the 3D contacts derived from the classified borehole data. Additional points can be included by creating sample points along the “sketched” cross sections.
- (e) 3D fence diagrams and volume models can be derived from the surfaces. Also, 2D cross sections “sketched” in map view can be transformed to 3D features and vice versa.

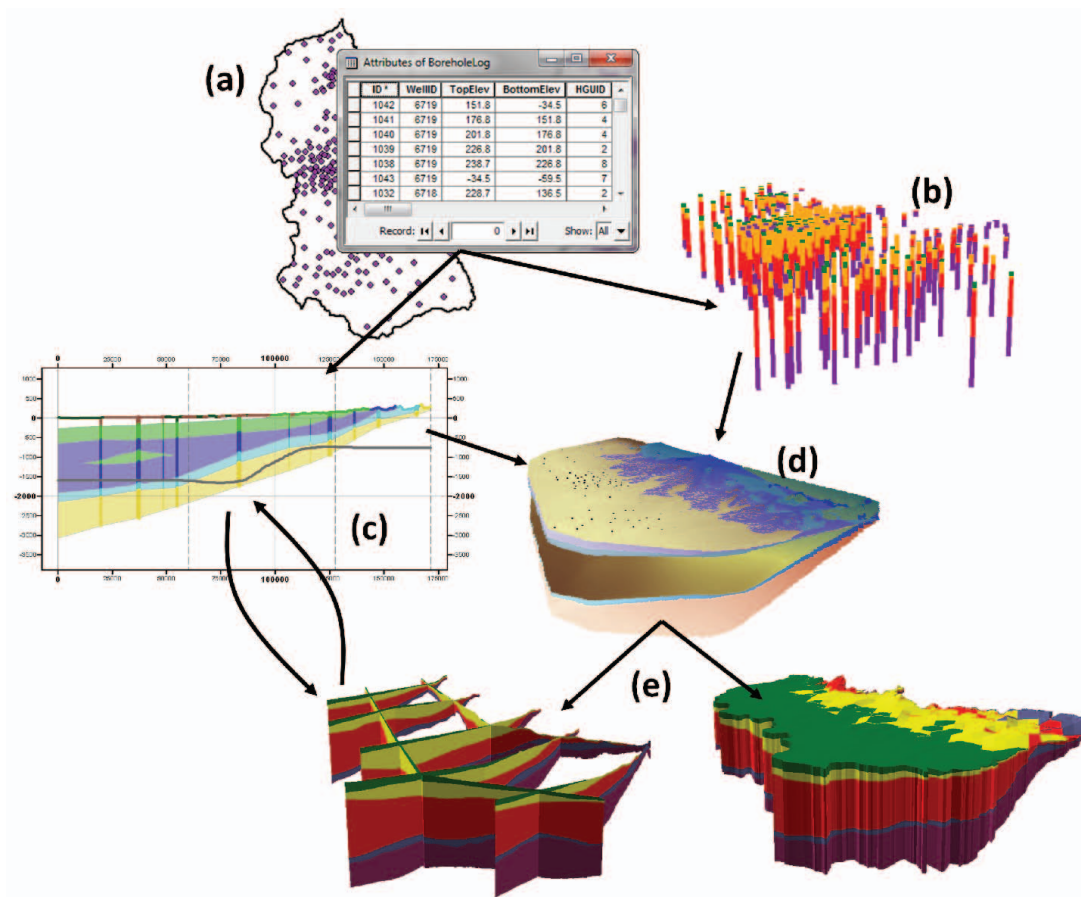


Fig. 7: Workflow for visualizing subsurface data and building 3D subsurface models. (a) Well features and related borehole stratigraphy, (b) 3D features representing borehole stratigraphy, (c) 2D cross sections, (d) surfaces representing hydrogeologic unit boundaries, (e) 3D fence diagrams and volume objects.

The workflow described above (Fig. 7) is a basic set of steps that are common when visualizing subsurface data and constructing 3D models of the subsurface. In many cases additional steps are included to add data from various datasets such as, terrain representation, outcrop maps defining the edge of units outcropping on the surface, and faults projected from the surface downwards. The following sections describe in more detail some of the datasets, tools, and workflows supported by the groundwater data model and Subsurface Analyst tools.

Data used in the examples are from the development of a groundwater simulation model in the Sacramento Valley, California (some of the data were modified due to confidentiality requirements). The base of the model domain is marine sediments that consist of sandstone and shale deposited about a hundred million years ago when an ancient sea formerly covered what is now the Sacramento and San Joaquin Valley. A depositional environment that consisted of a progression of sands, silts, and clay that have accumulated over a history of erosional sequences and volcanic eruption formed a sequence of formations. The formations were classified into five primary hydrogeologic units and these are the basis for developing the 3D subsurface model.

Developing and visualizing a 3D hydrogeologic model

The hydrostratigraphy component of the groundwater data model includes a set of data structures for representing 3D hydrogeologic models. The center of the component is a HydrogeologicUnit table where hydrogeologic units are conceptually defined. Key fields in

this table are the hydrogeologic unit identifier (HGUID) and a horizon identifier (HorizonID). The identifiers serve different purposes: the HydroID is used as a unique identifier within the geodatabase and enables linking different spatial representations of units (e.g. 3D points and lines, boundary polygons, cross sections, and volumes) to a conceptual description of the units defined in the HydrogeologicUnit table. The HorizonID is an index given to each of the units based on our understanding of the layering of the units. A “horizon” represents the top of a stratigraphic unit, and HorizonIDs are numbered consecutively based on the depositional sequence (from the bottom up). Figure 8 shows an example of a HydrogeologicUnit table developed for the case study. Five units are defined starting from the Lone Formation at the bottom to the Riverbank formation at the top. The horizon identifiers indicate the “layering” of the units.

The first step in the workflow is to classify borehole stratigraphy into hydrogeologic units based on the units defined in the HydrogeologicUnit table. The stratigraphy described in borehole logs is usually considered as “raw” data and in many cases includes detailed information that is observed on the local (borehole) scale, but needs to be aggregated into a set of more general hydrogeologic units. The groundwater data model includes a table for storing and classifying borehole data named BoreholeLog. Once classified, we can create 3D features to visualize the borehole data. Subsurface Analyst includes tools for creating 3D lines (BoreLines) and points (BorePoints) representing borehole data. The lines represent vertical segments along the borehole while the points represent the “contacts” of the borehole with the hydrogeologic units. Figure 9 shows the process of creating

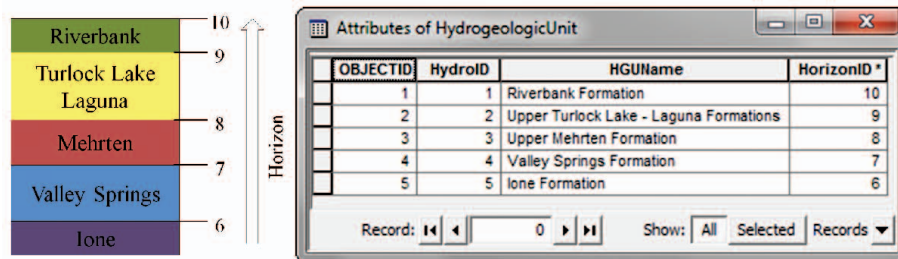


Fig. 8: The HydrogeologicUnit table is a central part of the hydrostratigraphy component, and provides a conceptual representation of hydrogeologic units to which different spatial instances of the units can be related. Units are indexed with a unique identifier (HydroID) and a horizon identifier (HorizonID).

3D BoreLine and BorePoint features. The classified borehole data is stored in the BoreholeLog table. Each record in the table is related with a well (point) feature through the WellID attribute. Subsurface Analyst includes custom tools for combining the spatial features, which provide the X and Y coordinates, with the vertical information (top elevation, bottom elevation, and HGUID) to create 3D geometries that can be visualized in 3D.

Using the tabular borehole data or the 3D points one can interpolate a set of surfaces representing the top/bottom of hydrogeologic units. Subsurface Analyst includes tools for processing the rasters indexed by HorizonID to create 3D fence diagrams (GeoSections) and volume objects (GeoVolumes). The tools work following the “Horizons” method (Lemon and Jones, 2003) where the sections and volumes are built by filling between surfaces from the bottom upwards. Each unit is built by filling between the surface defined by all the lower horizons and the next horizon in sequence. Clip and fill options give control on which surfaces to include in the process and which surfaces are used as clipping planes. Figure 10 shows a number of examples of applying the fill and clip options.

The groundwater data model includes a raster catalog named GeoRasters for storing and indexing rasters describing hydrogeologic units (Fig. 11a). Each of the rasters in the catalog is indexed with a hydrogeologic unit identifier (HGUID) that relates to the definition of the unit in the HydrogeologicUnit table, and is also indexed with a horizon identifier (HorizonID) that defines the 3D ordering of the units. Once the rasters are stored and indexed within the GeoRasters

raster catalog one can use Subsurface Analyst tools to generate 3D fence diagrams and volumes (Fig. 11b and Fig. 11c). The features created are also indexed with a HGUID and HorizonID to enable visualization, symbolization, and querying of specific units within the subsurface model.

Creating 2D cross sections from GIS data

Cross sections are common data products that illustrate the structure of the subsurface along a vertical plane defined by a section line. In many cases it is difficult to view and edit 3D objects, and it is more intuitive to slice through the subsurface along a given plane of interest and edit subsurface features in a 2D view. Thus, creating 2D cross sections makes it easier to edit subsurface features and add your own interpretation on the structure of hydrogeologic units. To create a cross section, we start by defining a section line in map view. Then a 2D vertical view is created to visualize the hydrogeologic units along the section line. It is common to add additional information on the cross section such as stratigraphy or geophysical logs recorded at boreholes along the cross section, or water related properties such as water levels and water quality. The hydrostratigraphy component of the groundwater data model includes a specific set of feature classes and tables for representing 2D cross sections. Common cross section features include: borehole data as vertical lines, cross section panels and panel dividers, and major and minor grid lines. The cross section features are managed by relating them with section line features (line features representing the cross sec-

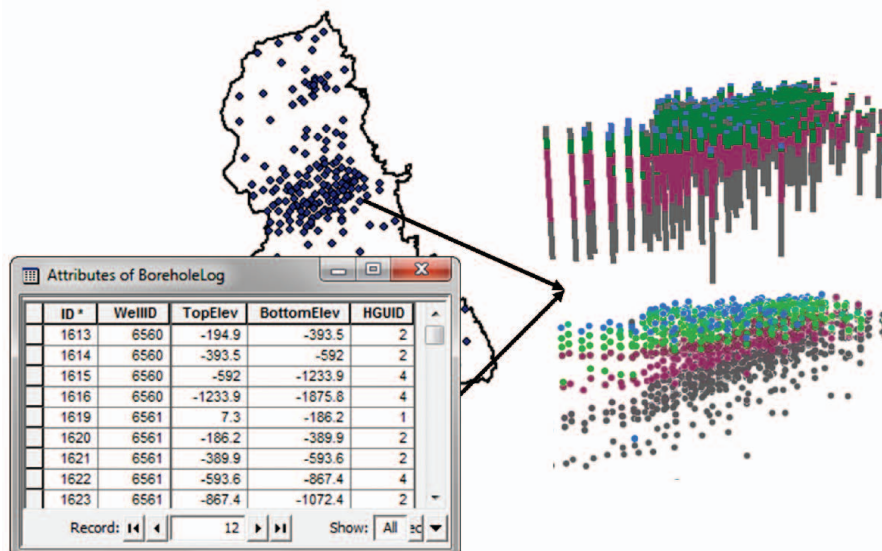


Fig. 9: Process of creating 3D features representing borehole hydrostratigraphy. The borehole data are stored in the BoreholeLog table and are related with point features giving the X and Y coordinates. The combination of the tabular vertical information and the spatial features enable the creation of 3D BorePoint and BoreLine features.

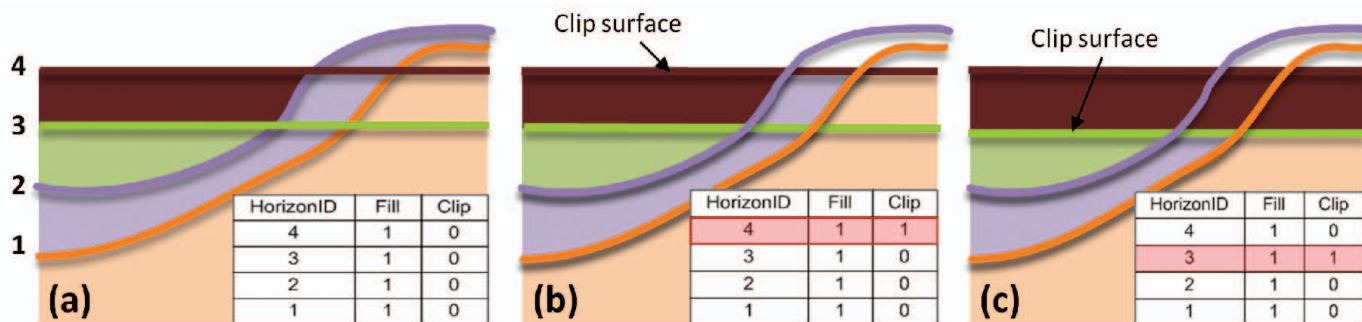


Fig. 10: Examples of applying the horizons method. The clip and fill options provide control on how the 3D hydrogeologic units are constructed. A value of 1 (see table on lower right side) enables the clip/fill options and a value of 0 disables the options. (a) All horizons are filled and no horizons are used as clipping surfaces. (b) All horizons are filled and horizon 4 is used as a clipping surface. (c) All horizons are filled and horizon 3 is used as a clipping surface.

tion extent in plan view). Each of the cross sections is viewed in a separate data frame (a map element that defines the coordinate system and other display properties within ArcMap) and is represented in a unique coordinate system, as the dimension of the cross section depends on the length of the section line. The feature geometries are also adjusted to reflect a vertical exaggeration commonly applied when visualizing subsurface data. To add GIS data stored in “real world” coordinates [X, Y, and Z] to a 2D cross section one needs to project the data into a 2D coordinate system [S, Z], where S is the length along the section line and Z is the elevation value (with the applied vertical exaggeration). Subsurface Analyst includes a set of tools and wizards that support the creation of the cross section data frames and the associated basic features (grid lines, borehole stratigraphy, and panel dividers). Additional GIS data such as outcrops, elevation, faults, well construction, and water table can be added to the cross sections by projecting the data onto the cross section plane. One can then use the wide suite of GIS based editing tools available in ArcGIS to “sketch” cross section panels reflecting the understanding of the subsurface system. Figure 12 shows an example of the process for creating 2D cross sections:

- We start with a cross section and selected well features adjacent to it. We can use spatial queries (e.g. buffer selection) to select the wells, or manually select the wells from which we want to add data.
- A cross section data frame is created with the basic features (grid lines and panel dividers) on it, and the stratigraphy data from the selected wells.

- Additional information is added to the cross section. In this case we added outcrops from a geologic map overlain with a DEM to get the elevation of the outcrops along the section line, and a salt water interface derived from a raster dataset. Cross section panels are “sketched” using the standard ArcGIS editing tools.

Another workflow for creating 2D cross sections is to “reverse engineer” existing cross sections developed outside the GIS environment. We can take existing cross section images (from reports, geologic atlases, etc.), that were generated with different drawing or CAD software, and by spatially registering the cross section images we can create a new cross section data frame and add the registered image to the data frame. We can then digitize the features that appear in the cross section image to create spatial features that can be managed within a geodatabase. There are a number of advantages for converting the images into GIS features:

- Cross sections can be continuously updated as new data is available (e.g. new boreholes in the vicinity of the cross section). Also, additional data such as water levels, water quality, updated surface terrain models, observed faults, well construction, and many other GIS based datasets can be added to the cross section.
- “Legacy” cross sections can be compared with new ones developed in the same region, and can serve as a guide for developing new cross sections.

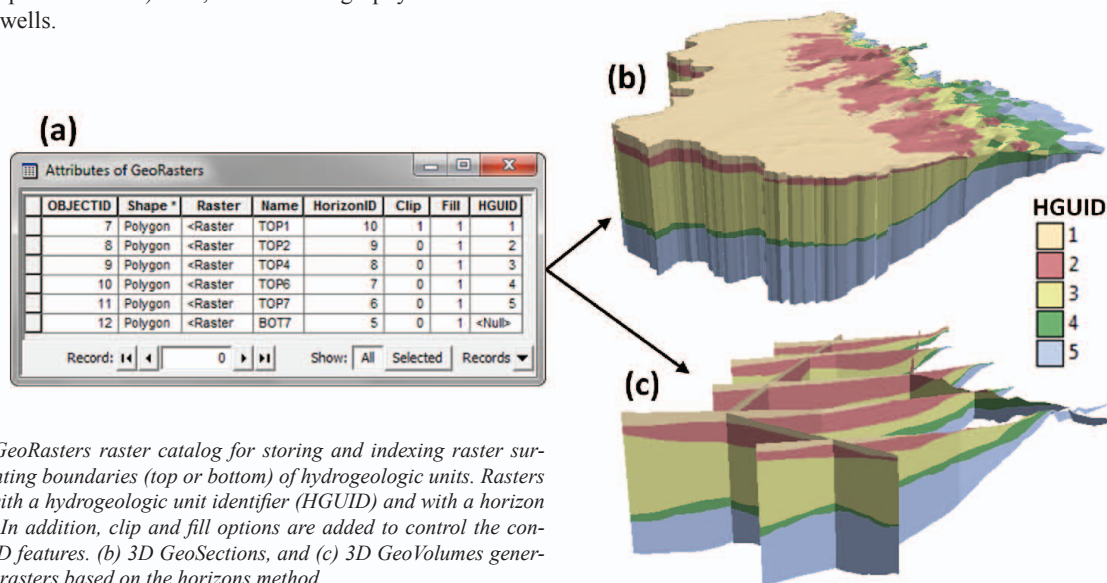


Fig. 11: (a) GeoRasters raster catalog for storing and indexing raster surfaces representing boundaries (top or bottom) of hydrogeologic units. Rasters are indexed with a hydrogeologic unit identifier (HGUID) and with a horizon (HorizonID). In addition, clip and fill options are added to control the construction of 3D features. (b) 3D GeoSections, and (c) 3D GeoVolumes generated from the rasters based on the horizons method.

- The referenced cross sections can be sampled to create “sample points” and these can be included in the interpolation process of a 3D hydrogeologic model. Thus, we include the logic and knowledge of the subsurface structures, as they are captured in the “legacy” cross section, into a 3D model.

Figure 13 shows an example of the process for registering a cross section image. Data shown in the example are taken from a USGS report describing the Virginia Coastal Plain hydrogeologic framework (McFarland and Bruce, 2006). We first georeference the map showing the section lines and digitize line features representing the cross section lines (Fig. 13a). Cross section images are prepared showing the individual cross sections we want to register. In this example a set of cross sections were available in a single PDF file, and these were separated into individual cross section images (Fig. 13b). We can then use a Subsurface Analyst wizard to register the file (Fig. 13c). We use vertical sliding lines to reference the image to the section line (we can use the start and end points of the section line feature to register the x and y coordinates or any other points of reference along the cross section) and horizontal sliding lines to define

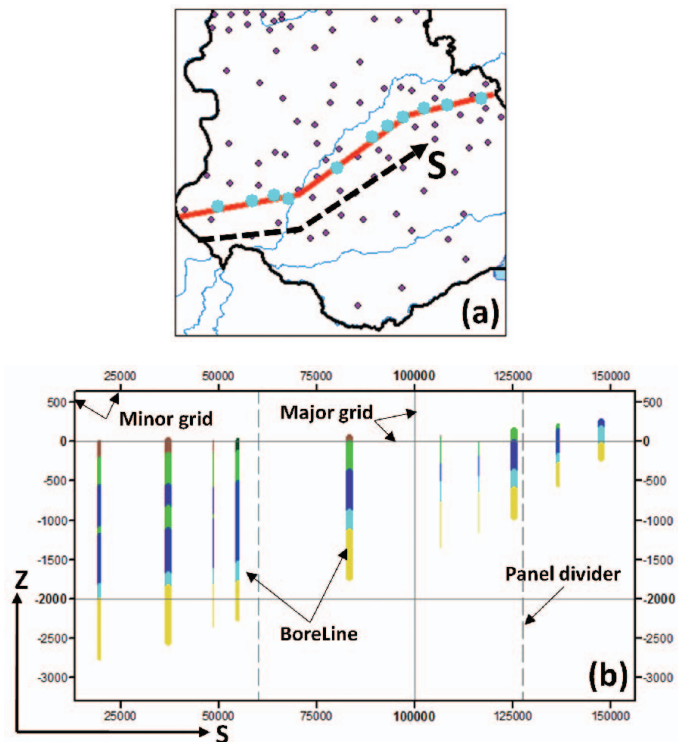
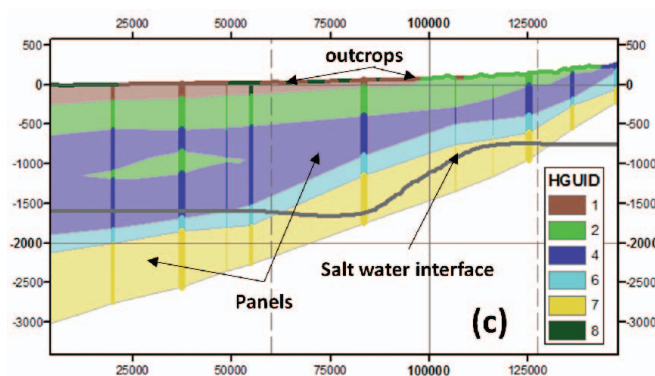


Fig. 12: Process of creating a 2D cross section. (a) A set of wells are selected in the vicinity of the section line used to create the cross section. (b) Using Subsurface Analyst tools we generate a new cross section data frame with grid lines, panel dividers, and borehole data. (c) Additional data is added to the cross section (outcrops, surface terrain, and a salt water interface) and cross section panels are “sketched”.

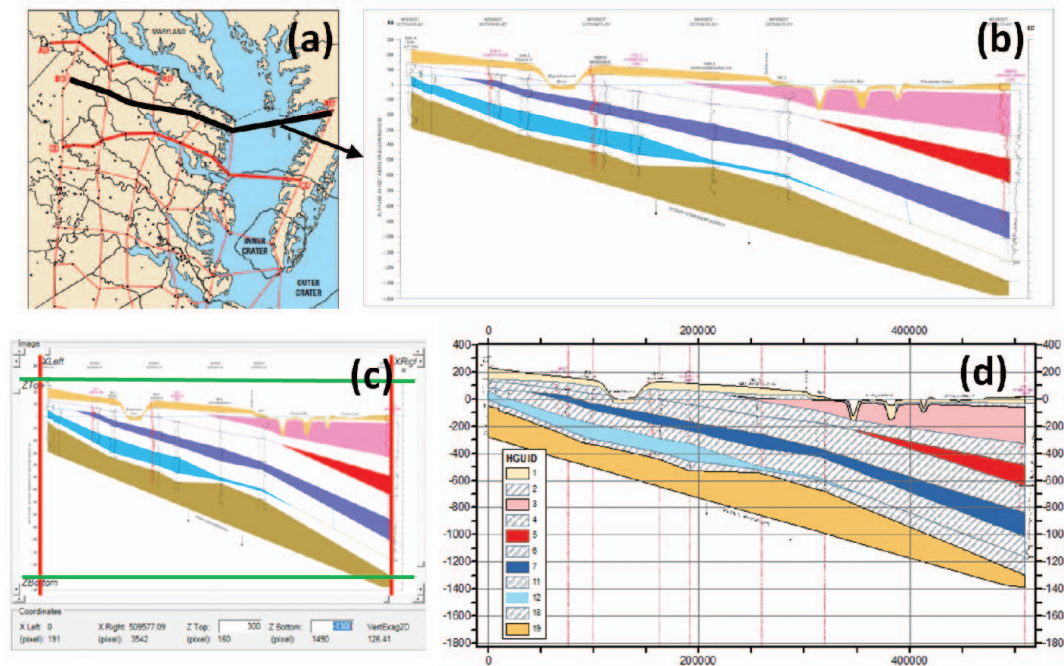


Fig. 13: Process of referencing 2D cross section images. (a) A map of section lines is geo-referenced and section line features are digitized as line features. (b) Individual cross section images are prepared, one image per cross section. (c) The cross section image is registered using vertical and horizontal sliding lines. (d) The registered image is loaded to a cross section data frame and GIS features are digitized. In the example shown the solid colors represent aquifers and the dashed areas in between represent confining units.

top and bottom elevations. The image is then transformed using the reference points defined by the intersection of the sliding lines. Once transformed, the image is loaded into a cross section data frame (which is automatically created by the wizard) and we can then use the ArcGIS editing tools to digitize GIS features representing the cross section (Fig. 13d).

MODFLOW Analyst

One of the primary components of the Arc Hydro Groundwater data model is the Simulation feature dataset. This dataset is used to represent groundwater simulation models in a geodatabase. It can be used with either finite element or finite difference models and supports both 2D and 3D models. The primary components of the Simulation feature dataset are shown in Figure 14. The Boundary polygon defines the model domain and is used to georeference the model grid. The cells and computational points for 2D grids or individual layers of a 3D model are represented using the Cell2D polygon features and the Cell2D point features. The Cell3D multipatch features and the Node3D z-enabled point features are used to represent 3D numerical grids.

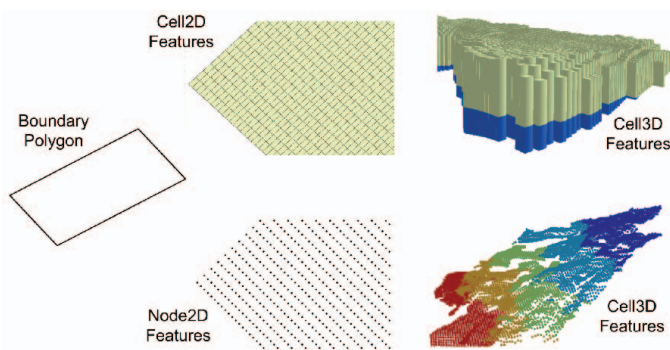


Fig. 14: Simulation feature dataset used to represent groundwater simulation models in a geodatabase.

The MODFLOW data model (Jones & Strasberg, 2008) is an extension of the Simulation feature dataset designed to store complete MODFLOW models (Harbaugh et al., 2000). The MODFLOW data model consists of the feature classes in the Simulation feature data set plus a set of tables. The feature classes define the grid geometry and the tables are used to store the MODFLOW input and output data. MODFLOW is organized into a series of modular units called “packages”. Each package corresponds to a specific process or type of feature that is being simulated. There is a Layer Property Flow (LPF) package that is used to define material properties, including hydraulic conductivity and storage coefficients on a cell-by-cell basis. There is also a suite of packages called “stress packages” that define model sources and sinks including wells, rivers, and drains. For some of the packages, including the Global Package, the LPF package, and the Recharge package, the input data associated with the package is primarily one or more arrays of data representing cell-by-cell values. These arrays are represented in the data model using tables indexed by the cell id and/or the IJK indices. These tables can then be joined with Cell2D or Node2D features to generate map layers. The tables associated with the LPF package are shown in Figure 15. The field names are patterned after the name of the associated MODFLOW variables. The complete MODFLOW data model design is available at <http://www.archydrogw.com/>.

Layer-Property Flow (LPF)

LPFVars		LPFLayers		LPFProperties	
HDRY	Double	Layer	Long Int.	IJK	Long Int.
WETFACT	Double	LAYTYP	Short Int.	HK	Double
IWETIT	Long Int.	LAYAVG	Short Int.	HANI	Double
IHDWET	Short Int.	CHANI	Double	VKA	Double
		LAYVKA	Short Int.	Ss	Double
		LAYWET	Short Int.	Sy	Double
		AM_HK	Double	WETDRY	Double
		AM_HANI	Double	VKCB	Double
		AM_VKA	Double		
		AM_Ss	Double		
		AM_Sy	Double		
		AM_WETDRY	Double		
		AM_VKCB	Double		

Fig. 15: Tables from the MODFLOW data model associated with the Layer Property Flow (LPF) Package.

In the case of the stress packages, the package input data are typically not defined using an array corresponding to the entire grid. Rather, the data are associated with a subset of the grid cells. For example, the input to the well package is a list of well instances where each instance lists the IJK indices of the corresponding cell and the pumping rate of the well. For transient simulations, one set of values is listed for each stress period (simulation interval). The input to these packages is stored in tables which include the cell ids, the stress period id, and the attributes associated with the particular stress package (water level, conductance, etc.). A subset of the stress package tables is shown in Figure 16. These tables can be joined with Node2D, Cell2D, Node3D or Cell3D features to display the locations of the stress package objects in the model domain.

List-based stress packages

RIV		CHD		WEL	
IJK	Long Int.	IJK	Long Int.	IJK	Long Int.
SPID	Long Int.	SPID	Long Int.	SPID	Long Int.
Stage	Double	Shead	Double	Q	Double
Cond	Double	Ehead	Double	Qfact	Double
Rbot	Double	Shdfact	Double	IFACE	Long Int.
IFACE	Long Int.	Shdfact	Double	SourceID	Long Int.
Conduct	Double	SourceID	Long Int.	LinearScale	Double
SourceID	Long Int.				
LinearScale	Double				

DRN		GHB		HFB6	
IJK	Long Int.	IJK	Long Int.	IJK1	Long Int.
SPID	Long Int.	SPID	Long Int.	IJK2	Long Int.
Elevation	Double	Bhead	Double	Hydchr	Double
Cond	Double	Cond	Double	Factor	Double
IFACE	Long Int.	IFACE	Long Int.	SourceID	Long Int.
Conduct	Double	Conduct	Double		
SourceID	Long Int.	SourceID	Long Int.		
LinearScale	Double	LinearScale	Double		

Fig. 16: A selected set of list-based stress package tables from the MODFLOW data model.

MODFLOW Analyst Tools

MODFLOW Analyst (MA) includes a suite of tools for managing data in the MODFLOW data model. The tools are organized into four primary categories: import tools, visualization tools, data building tools, and export tools.

Import Tools: The first step for working with a MODFLOW model inside Arc Hydro Groundwater is to load the data into a geodatabase. A MODFLOW simulation is stored in multiple input files, most of which are in ASCII format. There is an index file called the “name file” that contains a list of each of the input files associated with the simulation. There is an additional file called the “MODFLOW world file” that must be prepared by the user using one of the MA geoprocessing tools.

cessing tools before importing the simulation. This file is used to georeference the model grid and it contains the coordinate system, the XY coordinates of the grid origin, and the angle at which the grid is rotated. Once this file is prepared, the entire set of input files associated with the simulation can be imported in a single step using the *Import Georeferenced MODFLOW Model* tool. The tool reads the inputs associated with the grid geometry and creates the boundary polygon, the Cell2D features, and the Node2D features. The tool then reads each of the individual package files, creates a corresponding set of tables, and loads the package data into the tables.

Visualization Tools: Once the MODFLOW files are loaded into the geodatabase, one of the more common tasks is to create map layers to visualize the MODFLOW input and output. This is accomplished using a set of MA tools that join the MODFLOW tables with Cell2D and Node2D features to create map layers, or with Cell3D and Node3D features or to create 3D views. Some example map layers are described in the following section.

Data Building Tools: There is a subset of tools in MA that can be used to modify MODFLOW data or to build new MODFLOW data from GIS datasets. This includes tools for modifying cell properties (hydraulic conductivity for example) by overlaying a set of polygons on the model domain or deriving properties or cell elevations from a raster generated by interpolating values from point locations. MA also includes tools for building stress package inputs from GIS features. For example, a stream network can be intersected with the Cell2D features to generate a set of river reaches for input to the MODFLOW river package. Time series data can also be used to populate time-varying inputs for transient simulations.

Export Tools. If the MODFLOW data is modified using some of the data building tools, the modified data must be exported to native MODFLOW input files so that the MODFLOW simulation can be

re-executed using the new data. The MA tools include a separate geoprocessing tool for each of the MODFLOW packages that exports the data from the tables associated with the package to native MODFLOW input files in ASCII format.

As is the case with the GA and SA tools, MA tools are primarily built as geoprocessing tools. This means that they can be used individually from the ArcGIS interface, they can be called from scripts (e.g. Python), they can be embedded in source code using almost any programming language, or they can be sequenced in the ArcGIS Model Builder to build complex workflows to automate repetitive tasks. In the following sections, we illustrate two use cases of the MA tools. The first use case involves using individual tools to build map layers for visualization, and the second use case illustrates how MA tools can be used to build a complex workflow for automating the process of analyzing the impact of a candidate well on an aquifer system as part of a well-permitting process.

Creating Map Layers

One of the more common use cases for MA is the construction of map layers illustrating portions of the MODFLOW inputs or solution. Figure 17 shows a sample map layer created from a MODFLOW model of the Edwards Aquifer in central Texas. This map layer was generated using the Make MODFLOW Feature Layer tool in MA. The tool allows the user to select any of the tables in the MODFLOW data model for display. The user also selects one of the feature classes (Cell2D, Node2D), and the features in the selected feature class are joined to the table using the cell id fields. The join is further modified by limiting the features to those that are in the active model domain using the MODFLOW IBOUND array. The result of the operation is a temporary map layer that can be symbolized and added to layout view in ArcMap to generate a high-quality map for inclusion in a model report.

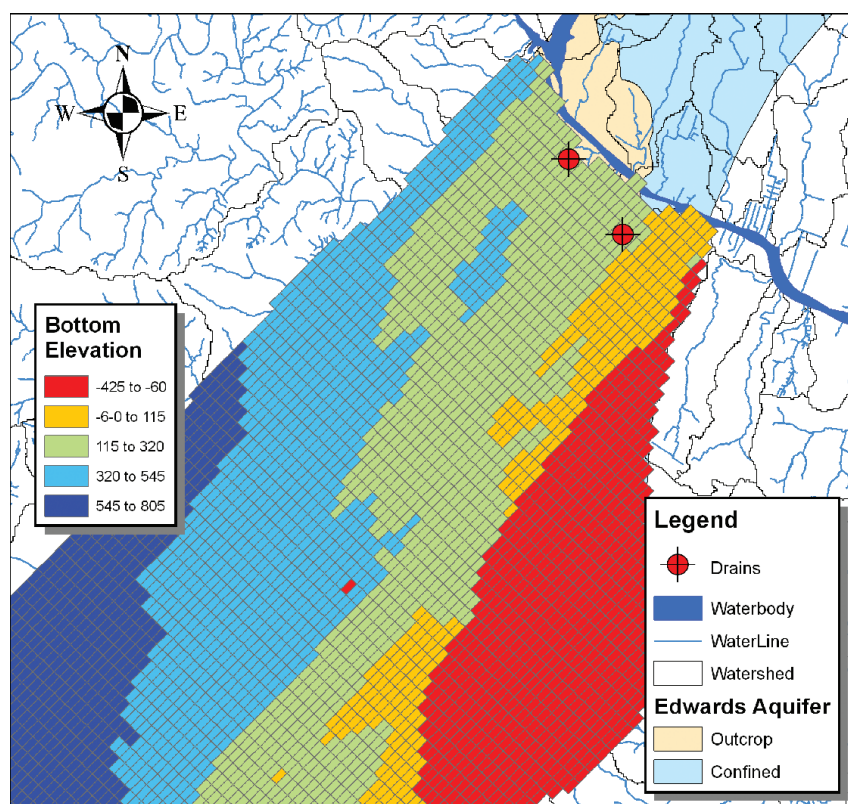


Fig. 17: A map layer illustrating bottom elevations for a selected layer of a MODFLOW grid and drain cells corresponding to two springs.

If the map layer includes multiple grid layers or stress periods, a definition query can be used to highlight individual grid layers and stress periods without having to generate a new map layer for each case. In the example shown in Figure 17, two sets of features are included in the map. Cell2D features illustrate bottom elevations for a selected model layer, and Node2D features illustrate the locations of two springs on the north end of the model simulated using the Drain package.

The *Make MODFLOW Feature Layer* tool can also be applied to Cell3D and Node3D features. The example shown in Figure 18 is from a large regional groundwater flow model developed for a region encompassing Sacramento, California. The site consists of complex geology represented in the model using multiple grid layers with spatially varying hydraulic properties. The Cell3D features help illustrate the complex relationship between ancestral streams (shown in blue) and the surrounding hydrogeologic units.

Automated Well Permitting

The second use case for the MA tools involves an automated well permitting process. As fresh water becomes increasingly scarce, many government agencies tasked with managing water resources have employed a formal legal and administrative process for granting new groundwater withdrawal permits. The steps involved in reviewing each application may be complex and include non-technical factors such as a demonstration of need and a detailed plan of how the water will be utilized. In addition, the impact of the new withdrawal on the aquifer system is typically analyzed to determine how much drawdown will occur as a result of the new well and what affect the well will have on other groundwater users, neighboring streams, rivers, and on salt-water intrusion. This impact is often estimated with the aid of a groundwater simulation model. The challenge with using a groundwater model for well permitting is that the process of updating and modifying a model must be done carefully and requires the expertise of a trained modeler. It can also be a time consuming process, leading to a significant backlog of permit appli-

cations. The process can be made highly efficient using Arc Hydro Groundwater and the MA tools.

The Virginia Department of Environmental Quality (VA-DEQ) utilizes a pair of models to evaluate groundwater withdrawals as part of a permitting process that is regulated by state law (VA-DEQ, 2006). The Virginia Coastal Plain Model is a ten-layer MODFLOW model that covers the Eastern counties in Virginia (Harsh and Lacznaiak, 1990). A SEAWAT model (three-dimensional variable-density groundwater flow model commonly used to model saltwater intrusion in coastal aquifers) called the Eastern Shore Model is used to analyze candidate wells on the Eastern Shore region (Sanford et al., 2009). In order to perform analysis associated with groundwater permit applications, including running the MODFLOW and SEAWAT models to analyze the impact of candidate wells, a set of GIS-based workflows were developed using the MA tools.

Virginia Coastal Plain MODFLOW Model

We have implemented and deployed an automated system using Arc Hydro Groundwater and the process described above to analyze candidate wells using the Virginia Coastal Plain Model. The associated ArcGIS workflow developed using the Model Builder utility is shown in Figure 19.

Most of the wells in the Virginia's Coastal Plain draw from deep, confined aquifers. By state law, the piezometric head is not allowed to drop below a "critical surface" defined by 80% drawdown from the original pre-pumping conditions and the top of each confined aquifer. Furthermore, the area of impact for a well is defined as the region surrounding the well where the drawdown is equal to or greater than one foot. Permittees are required to mitigate any adverse effects to existing lawful withdrawals within the area of impact. The results of a sample run using a hypothetical well (does not correspond to an actual candidate well) are shown in Figure 20. The cells within the area of impact are highlighted in Figure 20(a) and the area of impact contour is illustrated in Figure 20(b).

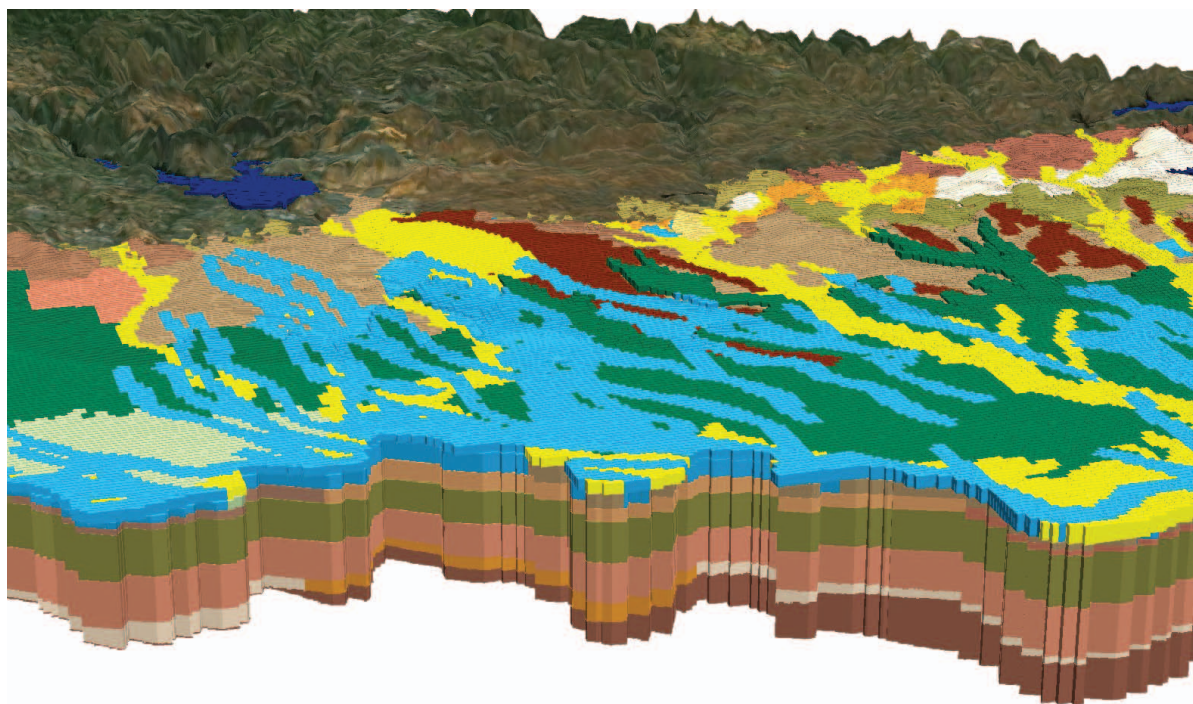


Fig. 18: Cell3D features from a multi-layer MODFLOW model rendered in ArcScene.

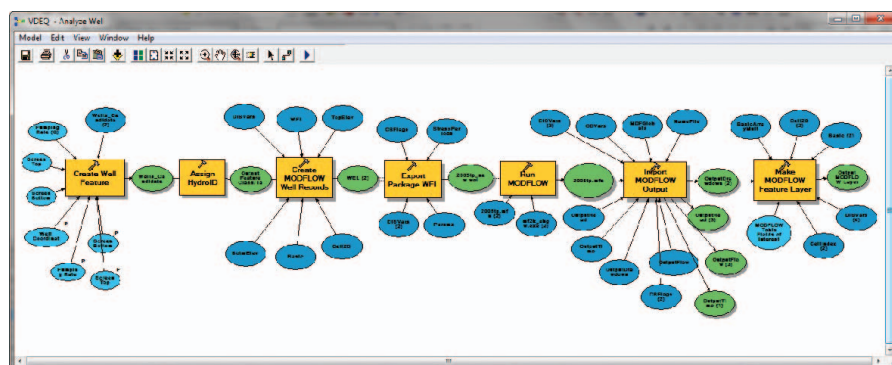


Fig. 19: Automated GIS workflow for analyzing a candidate well for the VA-DEQ model.

Eastern Shore SEAWAT Model

The Eastern Shore SEAWAT model consists of 370 rows, 102 columns, and 46 layers. The model simulation begins in 1901 and runs to 2050. When candidate wells are analyzed on the Eastern Shore both the drawdown and the change in salinity are analyzed. A set of automated workflows similar to the one illustrated in Figure 19 were developed for the Eastern Shore model. The drawdown for a particular well is analyzed by converting the SEAWAT model to a steady-state flow model. The model is run without the candidate wells and the heads are computed. Then the model is run a second time with the candidate wells included in the model at the appropriate pumping rate and the heads are computed again. The drawdown for the candidate wells is calculated by comparing the two head solutions. If the drawdown is too great the candidate wells may be rejected. The change in salinity caused by candidate wells is analyzed by performing a transient SEAWAT simulation. First, the starting concentrations for chloride were updated to be the calculated concentrations at the end of 2009 from the original Eastern Shore Model. Then a fifty-year run is conducted without the candidate wells to establish the baseline concentrations. The model is run a second time with the candidate wells included. The concentrations at the end of the fifty-year run for both models are then compared to determine the effect of the candidate wells on water quality.

Conclusions

This paper provides an overview of the Arc Hydro Groundwater data model, its associated tools, and the workflows they support. The data model is designed to support archiving, visualization, and analysis of groundwater data within a GIS. The data model is based on a framework data model that can be expanded with surface water and groundwater components. The Arc Hydro Groundwater Tools include three sets of tools: Groundwater Analyst, Subsurface Analyst, and MODFLOW Analyst.

The groundwater data model supports the representation of temporal datasets in different formats. There is a custom table design for representing time series values. The design enables mapping of the time series by indexing values and relating them to spatial features that can be mapped within a GIS. In addition, the data model contains classes for storing and indexing raster surfaces representing continuous phenomena. Based on these data structures, Groundwater Analyst tools support the creation of custom workflows to automate tasks such as the creation of water level and water quality maps. The workflow starts with spatial features (points) representing wells and tabular time series data (e.g. water levels related to the features). Custom tools are used to summarize the time series over a given time period, and the summary values are combined with the

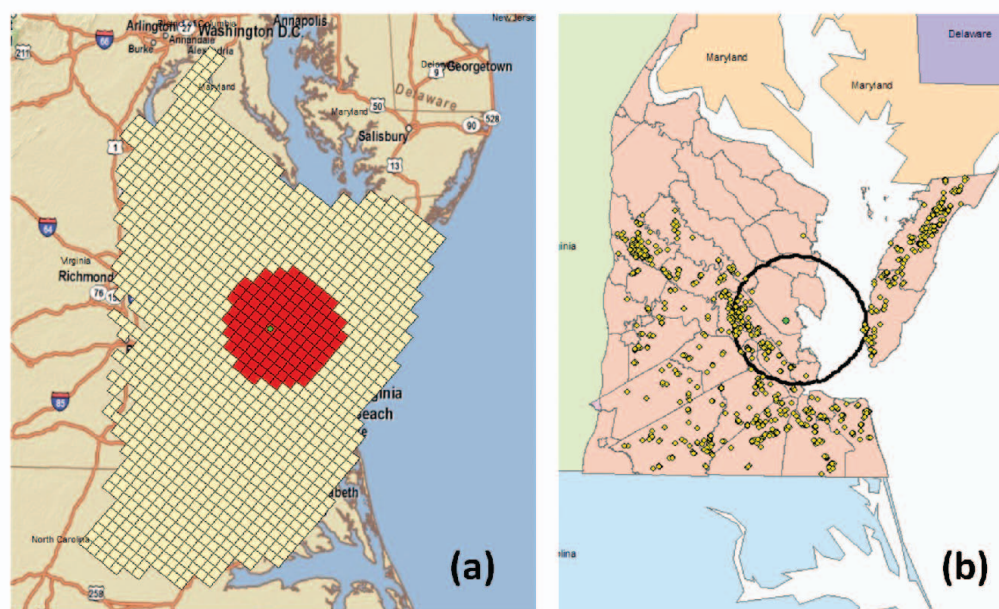


Fig. 20: The Virginia Coastal Plain Model. (a) MODFLOW cells indicating a candidate well and the area of impact simulated. (b) Permitted wells and area of impact (one foot drawdown) contour.

related well features to create a new layer showing the summary values and their locations. These can then be interpolated using interpolation tools to create continuous surfaces of the mapped phenomena. The surfaces are indexed with a time stamp and variable identifier that enables querying and animating the surfaces and calculating changes between surfaces over time. Finally, derived products such as contours and flow direction arrows can be created from the surfaces and added to the map.

The hydrostratigraphy component of the data model includes a set of data structures for representing 3D hydrogeologic models. The center of the component is a HydrogeologicUnit table where hydrogeologic units are conceptually defined. The units defined in the table are indexed with a unique identifier (HydroID) and a horizon identifier (HorizonID). The HydroID is used as a unique identifier within the geodatabase and enables linking different spatial representations of units (e.g. 3D points and lines, boundary polygons, cross sections, and volumes) to the conceptual description defined in the HydrogeologicUnit table. The HorizonID is an index defining the 3D layering of the units. Subsurface Analyst tools enable the creation of workflows for developing 3D hydrogeologic models, starting from classifying borehole hydrostratigraphy represented in tabular format, creating 3D points and lines for visualizing the borehole data, storage and indexing of surfaces representing the top/bottom of hydrogeologic units, and the creation of fence diagrams and volume objects.

In addition, Subsurface Analyst tools enable the creation of 2D cross sections based on GIS features. The cross sections are based on section lines, which are line features representing the cross section in plan view. The cross sections are created in unique coordinate systems. Regular GIS data defined in [X, Y, Z] coordinates are projected on the cross section plane and transformed to an [S, Z] coordinate system, where S is the length along the section line and Z is elevation (also accounting for vertical exaggeration). This paper presents two workflows for creating cross sections: one uses GIS features to setup a new cross section data frame, then GIS data (borehole stratigraphy, outcrops, faults, terrain, etc.) are added to the cross section, and cross section panels are sketched. The second workflow starts with a cross section image. The image is registered to a section line feature and in the vertical dimension, and a new cross section data frame is created based on the registered image. The registered image is added to the data frame and is used as a background for digitizing cross section features. This workflow enables the conversion of “legacy” cross sections (e.g. from reports/geologic atlases) into GIS features that can be easily updated as new

data is acquired. In addition, the GIS features can be incorporated into the development of 3D hydrogeologic models.

The MODFLOW Analyst tools make it possible to import, visualize, modify, and export data associated with MODFLOW-based groundwater simulation models. The tools can be used to generate high-quality map layers for model reports illustrating both 2D and 3D model inputs and outputs. Since the tools are built as geoprocessing tools, complex workflows for repetitive tasks can be quickly constructed using the ArcGIS Model Builder utility. This process has been used to automate the running of MODFLOW simulations associated with the well-permitting process in the state of Virginia. The system has resulted in a substantial increase in efficiency and reduced error.

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