A Geodatabase for Groundwater Modeling in MLAEM and MODFLOW

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Abstract

A single geodatabase is created to facilitate groundwater modeling with both the Analytic Element Method (AEM) and the Finite Difference method (MODFLOW). The geodatabase schema follows the Arc Hydro data model and furthers the development of the groundwater data model by including objects for use with MLAEM (Multi-Layer Analytic Element Model). The groundwater geodatabase relies upon hydrogeology features common to previous Arc Hydro data models, which are related to modeling objects specific to either MLAEM or MODFLOW. By sharing common hydrogeology features and establishing common features such as boundary conditions, both MLAEM and MODFLOW model inputs are streamlined from ArcGIS feature datasets readily available from FGDC clearinghouses. Additionally, the groundwater geodatabase structure affords efficient creation of inputs for MLAEM using Python Scripts. Groundwater model results from MLAEM are returned to the geodatabase for storage and visualization.

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Introduction

Freshwater resources are critically important worldwide biologically, ecologically, and economically. Klaus Toepfer, Executive Director of the United Nations Environment Programme at the 4th National Conference on Science, Policy and Environment stated, "*Water issues have become one of the top priorities of the international system." (UNESCO, 2003).* Currently, the Hydro data model available from the ESRI website at the following URL http://support.esri.com/index.cfm?fa=downloads.dataModels.gateway provides an excellent means of organizing and assembling data in a geodatabase which enables water modeling in GIS and related applications to understand surface water systems *(Maidment, 2002; Artur and Zeiler, 2004)*.

However, water issues are related to both surface water and groundwater resources. *"More than 1.5 billion people worldwide and more than 50% of the population of the United States rely on groundwater for their primary source of drinking water. Groundwater is an essential part of the hydrologic cycle and is important in sustaining streams, lakes, wetlands, and aquatic communities." (Alley,et.al,. 2002).*

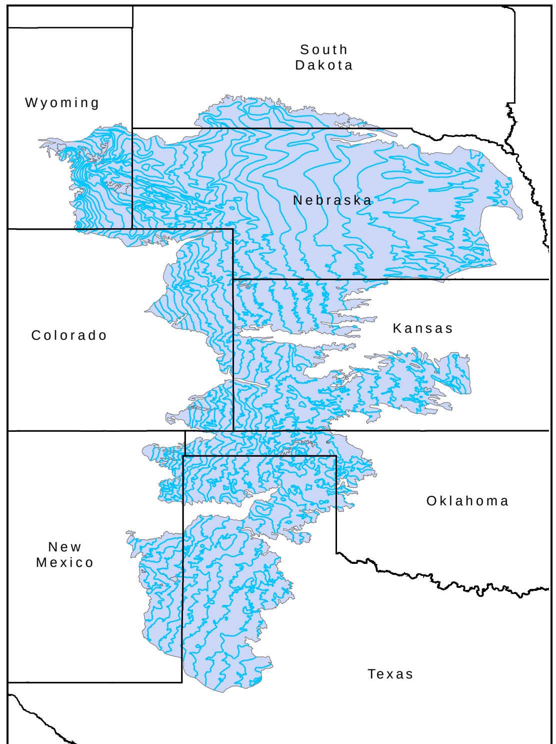


Figure 1. High Plains Aquifer Extents and groundwater elevations (data source: USGS)

In the High Plains region of the United States groundwater is not only the major source of drinking water but also serves as the catalyst for the regional economy which is based on irrigated agricultural production. The High Plains aquifer lies under an eight state region including CO, KS, NE, NM, OK, SD, TX, and WY with a surface area of 174,000 square miles *(see Figure 1)*. *"Approximately 20 percent of the irrigated land in the United States is in the High Plains and about 30 percent of the ground water used for irrigation in the U.S. is pumped from the High Plains aquifer. Irrigation withdrawals in 1990 were greater than 14 billion gallons per day. In 1990, 2.2 million people were supplied by ground water from the High Plains aquifer with total public-supply withdrawals of 332 million gallons per day." (http://co.water.usgs.gov/nawqa/hpgw/HPGW_home.html)*.

While the High Plains Aquifer is fairly well mapped and understood at regional scales *(e.g. Figure 1)* by the USGS and cooperating surveys (e.g. Kansas Geologic Survey) who gather, assemble, model and serve data and information related to the High Plains Aquifer, water continues to decline across most of the region. There are numerous quantifiable and unquantifiable reasons for the continued decline in the aquifer. Many of those reasons are associated with socio-economic and socio-political factors while some dynamic properties of the hydrology of the aquifer are still not well understood. In a recent article in Science, authors contend, *"Future success in understanding the dynamic nature of groundwater systems will rely on continued and expanded data collection at various scales, improved methods for quantifying heterogeneity in subsurface hydraulic properties, enhanced modeling tools and understanding model uncertainty, and greater understanding of the role of climate and interactions with surface water." (Alley, et.al,, 2002).*

Given the geographic extent, continued declining trends and dynamic hydrologic-ecologic-socio-economic system reliant upon the High Plains Aquifer, interdisciplinary research on this spatiotemporal resource is vital and time is of the essence. The Consortium for Research on Groundwater-Based Economies (GRoWE) based at Kansas State University is researching integrated interdisciplinary models of the High Plains Aquifer crossing both natural and social systems. The team has discovered that Kansas has excellent data on wells and well production and usage (perhaps the best in the world over such a region). However, like many data resources these data are stored in multiple databases at different physical locations. Additionally, the databases are not currently in a GIS format although records contain latitude-longitude coordinates allowing import into a GIS system. Each well in the databases is assigned a unique well identification which corresponds with the Hydro data model HydroCode.

The Kansas well records are temporal in nature via annual reporting requirements by the Kansas Department of Agriculture Division of Water Resources with many reports coming from well meter data loggers. This aspect of the data is similar to the temporal data collected at gauging stations used in the Arc Hydro data model. Additional data for the individual wells can also come from a drill log record captured during boring that can allow geologic attributes to be incorporated which provide 3D data modeling of the aquifer formation. This type of data combined with other datasets from the USGS and KGS is critical to modeling the water resource and is currently part of the Groundwater data model (http://support.esri.com/index.cfm?fa=downloads.dataModels.gateway).

Currently, models of the groundwater in the High Plains Aquifer in Kansas produced by the USGS and KGS utilize Kansas well data resources in combination with other common GIS data such rivers and lakes contained in the NHD-National Hydrography Dataset (http://nhd.usgs.gov/). The NHD is also used in the Arc Hydro data model. Both the USGS and KGS model the aquifer using MODFLOW with output results in maps similar to that in Figure 1. MODFLOW is a raster based 3D finite-difference groundwater flow model software application developed by the USGS (http://water.usgs.gov/nrp/gwsoftware/modflow.html). While MODFLOW produces reasonable model results and is widely used in the groundwater modeling community, model results are only scalable to the rectangular cells determined for the model which limits connectivity to other socio-economic and politic thematic data and certain types of relationships relevant to understanding the entire hydro-eco-socio-economic system, particularly when these data are in vector format. The limitations of this type of modeling are well documented in all types of raster or cell-based GIS modeling.

MLAEM, or Multi-Layer Analytic Element Method is a vector based groundwater modeling application which relies upon the Analytic Element Method (AEM) (Strack, 1989; www.strackconsulting.com ; Haitjema, 1995, Steward et.al, 2005). This modeling approach utilizes similar inputs as MODFLOW for modeling groundwater, however it provides scalability down to individual wells due to keeping the input data in a vector format (points, lines, and polygons) during modeling.

To date, the developing Groundwater data model has paralleled the standards set forth in the Hydro data model for surface water and is well suited for integration with traditional MODFLOW models. However, given the need to further quantify and understand the dynamic hydro-eco-socio-economic system of the High Plains Aquifer and existing and developing datasets, a data model capable of allowing AEM (MLAEM) and Finite Difference *and Finite Element Method* (MODFLOW) and potential other modeling approaches is needed.

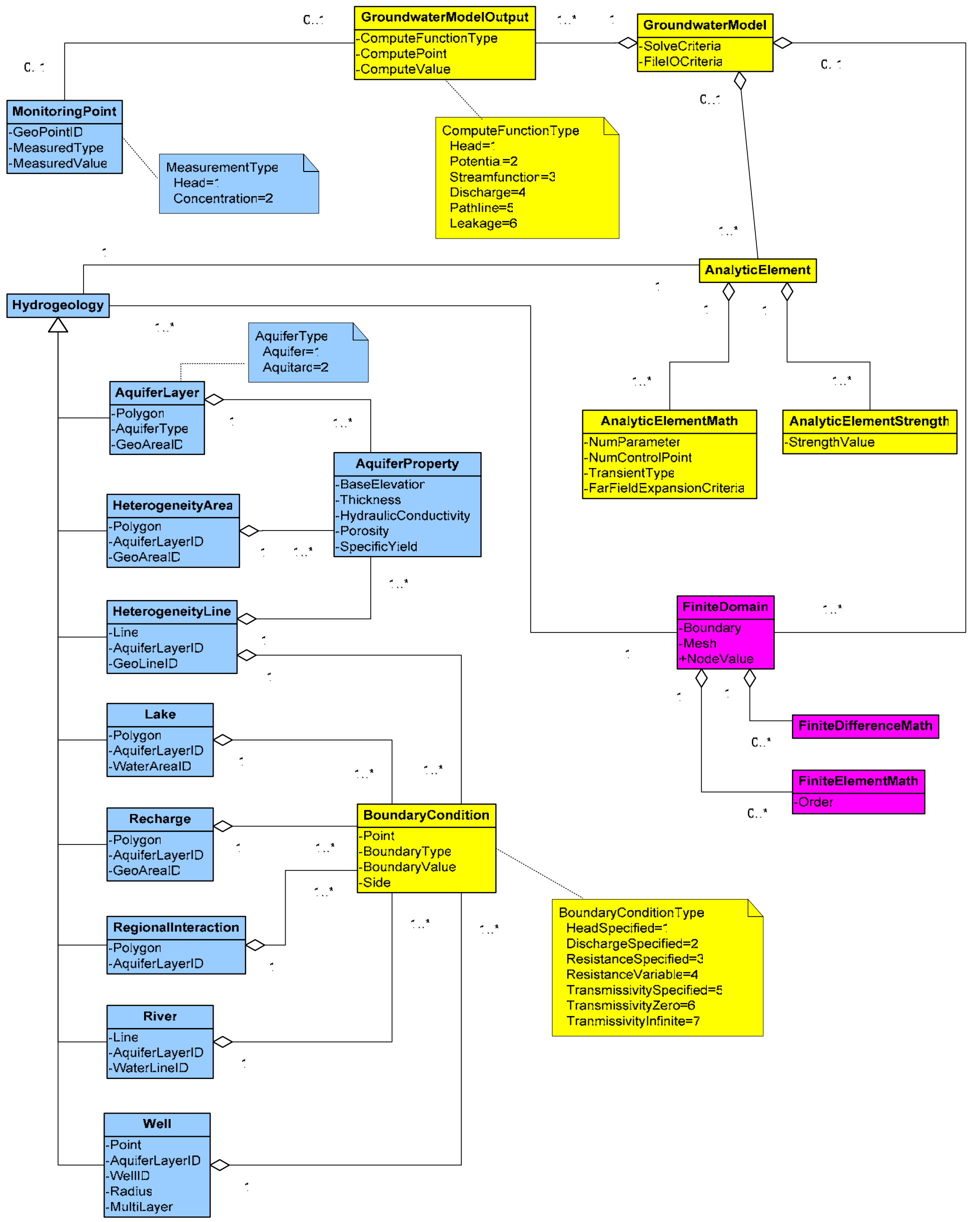
The remainder of this paper describes an alternative groundwater data model hereafter called Groundwater-AEM data model to avoid confusion. The Groundwater-AEM data model and resulting ArcGIS geodatabase follows the Arc Hydro data model and parallels much of the Groundwater data model under development and available at ESRI, and enables modeling with MODFLOW as well as MLAEM.

Groundwater Geodatabase for MLAEM and MODFLOW

The Groundwater-AEM data model shares the design intent of the Arc Hydro data model in that it relies on a group of thematic layers with common spatial representations, has minimal attributes, establishes integrity rules and relationships, is simple and additive in nature so feature classes can be derived from or added to it including elements in existing Arc Hydro geodatabases.

While Arc Hydro is organizes vector and tabular data in 5 main categories of Drainage, Hydrography, Network, Channel, Time Series (Arctur and Zeiler, 2004), the Groundwater-AEM is organized around 3 main categories a Hydrogeology, Model-Math, Time Series. The Groundwater-AEM utilizes a HydrogeologicID to identify groundwater features in exactly the same manner as Arc Hydro uses the HydroID. Individual wells have a unique HydrogeologicID as well as the equivalent HydroCode from ArcHydro.

Both the MLAEM and MODFLOW modeling approaches for the High Plains Aquifer begin with a common set of thematic layers largely contained in the NHD with additional layers from USGS or KGS. They also both rely on well records that are temporal in nature. Common thematic representations exist for features in both models as illustrated in UML diagram in Figure 2 below.



Legend

UML line	Description/Example
Aggregation (———◇)	E.g., an AnalyticElement is composed of AnalyticElementMath and AnalyticElementStrength
Generalization (———▷)	Subclasses inherit attributes of parent classes; e.g., a Well has Hydrogeology
Association (————)	E.g., AnalyticElement is associated with Hydrogeology
Comment Link (..........)	E.g., BoundaryType documents types of BoundaryCondition

Figure 2: Groundwater-AEM Data Model UML Diagram
Note the legend illustrating relationships shown with connecting lines in the diagram and numeric notes that identify multiplicity of relationships (e.g. Hydrogeology feature may contain one or more BoundaryCondition).

As illustrated in the UML diagram (Figure 2) the groundwater objects within the geodatabase contain: a) geometry, b) hydrogeological information, and c) mathematical representation and the mathematical representation are stored independently of the hydrogeology and contain strength parameters and links to boundary conditions. Additionally, the data model incorporates objects necessary for display of solutions, and the data model uses nomenclature that can be understood across the AEM, FDM and FEM communities.

The Groundwater-AEM geodatabase contains feature datasets related to Hydrogeology and to Modeling. The Hydrogeology feature dataset contains information about the geological medium through which groundwater flows and the fluxes induced by interactions with surface objects. The Modeling feature dataset contains information necessary to construct a groundwater model and store output from the groundwater model. In this document, the groundwater model uses the Analytic Element Method, although the relationships necessary for the Finite Difference Method and Finite Element Method are identified in Figure 2.

A summary of the Hydrogeology feature dataset is shown in figure 3. Each object in this dataset is a feature class, meaning that is has a geometry associated with it as indicated by the polygon, line or point to the left of the feature class name. Each feature class may be found in the lower left portion of Figure 2.

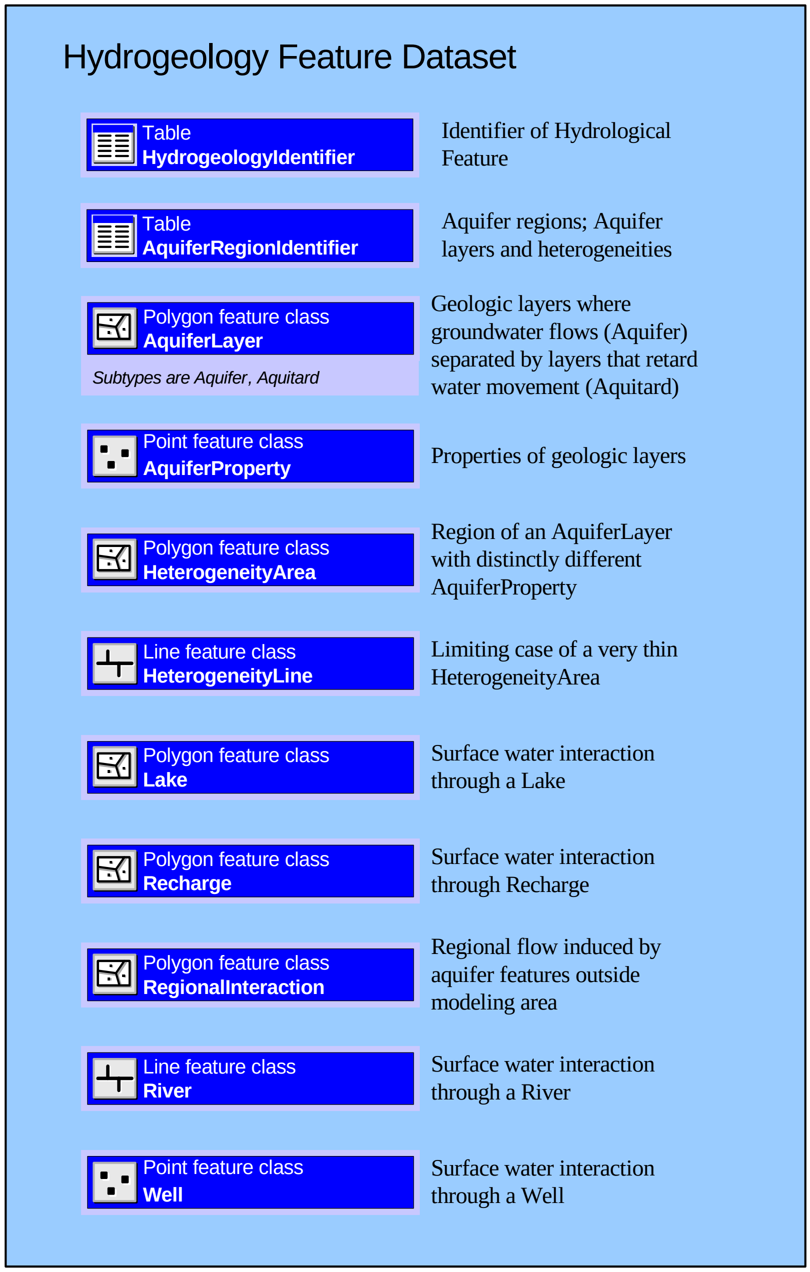


Figure 3: Hydrogeology Feature Dataset

The following graphic, Figure 4, summarizes the Modeling Feature Dataset. Two of the objects are feature classes, with point geometry (GroundwaterModelOutput and Boundary Condition). The others are of type Object Class, meaning information is stored within a table that is not directly associated with a geometrical representation. Once again, each object may be found in the overview shown in Figure 2. Specific details of the data included in each object and the relationship between objects is presented shortly.

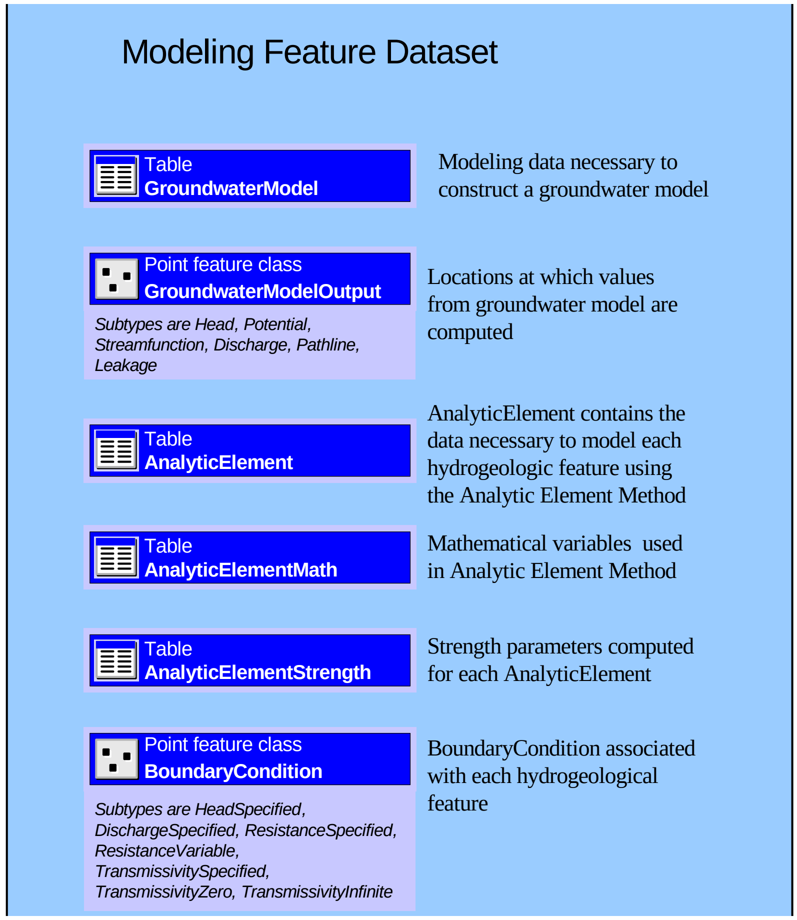


Figure 4: Model Feature Dataset

The Groundwater geodatabase available at ESRI website (available at http://support.esri.com/index.cfm?fa=downloads.dataModels.gateway) does not currently support the Analytic Element Method. The following table illustrates the Hydrogeology feature class comparison between the Groundwater data model and the Groundwater-AEM data model presented here. Please note that both use a Hydrogeology feature dataset.

GroundwaterAEM feature class	ArcHydro Groundwater feature class
Aquifer Layer (polygon)	Aquifer, HydrologicUnit
HeterogeneityArea (polygon)	GeoArea
HeterogeneityLine (line)	GeoLine
AquiferProperty (point)	GeoPoint, BoreLine
Lake (polygon)	WaterArea, TimeSeries
Recharge (polygon)	GeoArea, TimeSeries
RegionalInteraction (polygon)	(no direct feature), GeoPoint, TimeSeries
River (line)	WaterLine, TimeSeries
Well (point)	Well, BoreLine, TimeSeries

The main differences being that the GroundwaterAEM gathers ArcHydro hydrogeological data into objects related to either aquifer regions or surface water interactions. Both ArcHydro Groundwater and GroundwaterAEM geodatabases contain a feature dataset for Modeling. However, Groundwater currently contains only a BoundaryCondition feature class, with similar attributes as GroundwaterAEM. Thus, the modeling feature datasets are compatible, with GroundwaterAEM extending ArcHydro to contain the information necessary for models based upon the Analytic Element Method. The ArcHydro Groundwater geodatabase also contains raster information necessary for display and spatial analysis of modeling results. This is extended in the GroundwaterAEM geodatabase to contain modeling results (GroundwaterModelOutput) either at a set of raster grid points, or at multipoint ComputePoint locations.

The GroundwaterAEM geodatabase model Feature classes and Object classes are presented next, first for Hydrogeology and then for Modeling. All field names are presented for each class, along with the type of data, and default values. It is also indicated whether null values for the field name are allowed, for example, the geometry of a BoundaryCondition could be <null> indicating that it should be associated with a Hydrogeology feature, as opposed to a point along a feature. The Relationship classes are presented after the Feature and Object classes. These relationships indicate the origin and destination classes and the multiplicity of each relationship. The fields used to link two data layers are also included in the Relationship classes.

Feature and Object Classes associated with Hydrogeology

Note that the Hydrogeology Identifier object class contains a unique HydrogeologyID for each of the Hydrogeology Features. Likewise the AquiferRegionIdentifier contains a unique identifier for each aquifer layer or heterogeneity. This enables Hydrogeology Features to be directly linked to their Analytic Element mathematical formulation, and Aquifer Features to be directly linked to their aquifer properties.

Table
HydrogeologyIdentifier

Field name	Data type	Allow nulls	Default value	Domain	Precision	Scale	Length
OBJECTID	Object ID						

Hydrogeology identifier for hydrogeological features

Table
AquiferRegionIdentifier

Field name	Data type	Allow nulls	Default value	Domain	Precision	Scale	Length
OBJECTID	Object ID						

Aquifer region identifier for aquifer layer or heterogeneity

Simple feature class AquiferLayer

Geometry *Polygon*, Contains M values *No*, Contains Z values *No*

Geologic layers where groundwater flows (Aquifer) separated by layers that retard water movement (Aquitard)

Field name	Data type	Allow nulls	Default value	Domain	Precision	Scale	Length	
OBJECTID	Object ID							
SHAPE	Geometry	Yes						
AquiferType	Long integer	No	1		0			Type of AquiferLayer
Description	String	Yes					50	Descriptive text
ArcHydro_GeoAreaID	Long integer	Yes			0			ArcHydro geodatabase representation
SHAPE_Length	Double	Yes			0	0		
SHAPE_Area	Double	Yes			0	0		
HydrogeologyID	Long integer	Yes			0			Hydrogeology identifier
AquiferRegionID	Long integer	Yes			0			Aquifer region identifier

Subtypes of AquiferLayer

Subtype field *AquiferType*

Default subtype *1*

List of defined default values and domains for subtypes in this class

Subtype Code	Subtype Description	Field name	Default value	Domain
1	Aquifer	No values set		
2	Aquitard	No values set		

Simple feature class HeterogeneityArea

Geometry *Polygon*, Contains M values *No*, Contains Z values *No*

Region of an AquiferLayer with distinctly different AquiferProperty

Field name	Data type	Allow nulls	Default value	Domain	Precision	Scale	Length	
OBJECTID	Object ID							
SHAPE	Geometry	No						
AquiferLayerID	Long integer	No	1		0			AquiferLayer where feature exists
Description	String	Yes					50	Descriptive text
ArcHydro_GeoAreaID	Long integer	Yes			0			ArcHydro geodatabase representation
SHAPE_Length	Double	Yes			0	0		
SHAPE_Area	Double	Yes			0	0		
HydrogeologyID	Long integer	Yes			0			Hydrogeology identifier
AquiferRegionID	Long integer	Yes			0			Aquifer region identifier

Simple feature class HeterogeneityLine

Geometry *Polyline*, Contains M values *No*, Contains Z values *No*

Limiting case as a very thin HeterogeneityArea

Field name	Data type	Allow nulls	Default value	Domain	Precision	Scale	Length	
OBJECTID	Object ID							
SHAPE	Geometry	No						
AquiferLayerID	Long integer	No	1		0			AquiferLayer where feature exists
Description	String	Yes					50	Descriptive text
ArcHydro_GeoLineID	Long integer	Yes			0			ArcHydro geodatabase representation
SHAPE_Length	Double	Yes			0	0		
HydrogeologyID	Long integer	Yes			0			Hydrogeology identifier
AquiferRegionID	Long integer	Yes			0			Aquifer region identifier

Simple feature class AquiferProperty

Geometry *Point*, Contains M values *No*, Contains Z values *No*

Properties of geologic layers

Field name	Data type	Allow nulls	Default value	Domain	Precision	Scale	Length	
OBJECTID	Object ID							
SHAPE	Geometry	Yes						
Base	Double	Yes			0	0		Elevation of base
Thickness	Double	Yes			0	0		Thickness of geological media
HydraulicConductivity	Double	Yes			0	0		Hydraulic conductivity of geologic media
Porosity	Double	Yes			0	0		Porosity of geological media
SpecificYield	Double	Yes			0	0		Specific yield of geological media
Description	String	Yes					50	Descriptive text
AquiferRegionID	Long integer	Yes			0			Aquifer region identifier

Simple feature class **Lake** — Surface water interaction through a Lake

Geometry *Polygon*; Contains M values *No*; Contains Z values *No*

Field name	Data type	Allow nulls	Default value	Domain	Precision	Scale	Length	Description
OBJECTID	Object ID							
SHAPE	Geometry	No						
AquiferLayerID	Long integer	No	1		0			AquiferLayer where feature exists
Description	String	Yes					50	Descriptive text
ArcHydro_WaterAreaID	Long integer	Yes			0			ArcHydro geodatabase representation
SHAPE_Length	Double	Yes			0	0		
SHAPE_Area	Double	Yes			0	0		
HydrogeologyID	Long integer	Yes			0			Hydrogeology identifier

Simple feature class **Recharge** — Surface water interaction through Recharge

Geometry *Polygon*; Contains M values *No*; Contains Z values *No*

Field name	Data type	Allow nulls	Default value	Domain	Precision	Scale	Length	Description
OBJECTID	Object ID							
SHAPE	Geometry	Yes						
AquiferLayerID	Long integer	No	1		0			AquiferLayer where feature exists
Description	String	Yes					50	Descriptive text
ArcHydro_GeoAreaID	Long integer	Yes			0			ArcHydro geodatabase representation
SHAPE_Length	Double	Yes			0	0		
SHAPE_Area	Double	Yes			0	0		
HydrogeologyID	Long integer	Yes			0			Hydrogeology identifier

Simple feature class **RegionalInteraction** — Regional flow induced by aquifer features outside modeling area

Geometry *Polygon*; Contains M values *No*; Contains Z values *No*

Field name	Data type	Allow nulls	Default value	Domain	Precision	Scale	Length	Description
OBJECTID	Object ID							
SHAPE	Geometry	Yes						
AquiferLayerID	Long integer	No	1		0			AquiferLayer where feature exists
Description	String	Yes					50	Descriptive text
SHAPE_Length	Double	Yes			0	0		
SHAPE_Area	Double	Yes			0	0		
HydrogeologyID	Long integer	Yes			0			Hydrogeology identifier

Simple feature class **River** — Surface water interaction through a River

Geometry *Polyline*; Contains M values *No*; Contains Z values *No*

Field name	Data type	Allow nulls	Default value	Domain	Precision	Scale	Length	Description
OBJECTID	Object ID							
SHAPE	Geometry	No						
AquiferLayerID	Long integer	No	1		0			AquiferLayer where feature exists
Description	String	Yes					50	Descriptive text
ArcHydro_WaterLineID	Long integer	Yes			0			ArcHydro geodatabase representation
SHAPE_Length	Double	Yes			0	0		
HydrogeologyID	Long integer	Yes			0			Hydrogeology identifier

Simple feature class **Well** — Surface water interaction through a Well

Geometry *Point*; Contains M values *No*; Contains Z values *No*

Field name	Data type	Allow nulls	Default value	Domain	Precision	Scale	Length	Description
OBJECTID	Object ID							
SHAPE	Geometry	No						
AquiferLayerID	Long integer	No	1		0			AquiferLayer where feature exists
Description	String	Yes					50	Descriptive text
ArcHydro_WellID	Long integer	Yes			0			ArcHydro geodatabase representation
Radius	Double	Yes			0	0		Radius of well
MultiLayer	Long integer	Yes	0		0			Multiple layers for screened interval
HydrogeologyID	Long integer	Yes			0			Hydrogeology identifier

Feature and Object Classes Required for Modeling

Note that the GroundwaterModel contains a unique identifier that gets placed into the AnalyticElement that reside within the model, and within the GroundwaterModelOutput for the model. Likewise, an AnalyticElementID gets placed within the AnalyticElementMath and AnalyticElementStrength associated with the analytic element.

Table
GroundwaterModel

Modeling data necessary to construct a groundwater model

Field name	Data type	Allow nulls	Default value	Domain	Precision	Scale	Length	
OBJECTID	Object ID							
FileDirectory	String	Yes					50	File directory for file I/O
FileName	String	Yes					50	File name for i/O
SolveMaxIteration	Long integer	Yes			0			Maximum number of iterations for solve
SolveErrorTolerance	Double	Yes			0	0		Maximum error tolerance for solve
Description	String	Yes					50	Descriptive text

Simple feature class
GroundwaterModelOutput

Geometry *Multipoint*
Contains M values *No*
Contains Z values *No*

Modeling data necessary to construct a groundwater model

Field name	Data type	Allow nulls	Default value	Domain	Precision	Scale	Length	
OBJECTID	Object ID							
SHAPE	Geometry	Yes						
ComputeFunctionType	Long integer	No	1		0			Type of function to compute
ComputeFunctionTime	Double	Yes	0		0	0		Time to compute value of function
GridLeft	Double	Yes			0	0		Left boundary of grid if geometry is <null>
GridBottom	Double	Yes			0	0		Bottom boundary of grid if geometry is <null>
GridRight	Double	Yes			0	0		Right boundary of grid if geometry is <null>
GridTop	Double	Yes			0	0		Top boundary of grid if geometry is <null>
GridInterval	Long integer	Yes			0			Number of grid intervals if geometry is <null>
Description	String	Yes					50	Descriptive text
GroundwaterModelID	Long integer	Yes			0			Groundwater model idntifier

Subtypes of GroundwaterModelOutput

Subtype field *ComputeFunctionType*
Default subtype *1*

List of defined default values and domains for subtypes in this class

Subtype Code	Subtype Description	Field name	Default value	Domain
1	Head	No values set		
2	Potential	No values set		
3	Streamfunction	No values set		
4	Discharge	No values set		
5	Pathline	No values set		
6	Leakage	No values set		

Simple feature class
BoundaryCondition

Geometry *Point*
Contains M values *No*
Contains Z values *No*

BoundaryCondition associated with each hydrogeological feature

Field name	Data type	Allow nulls	Default value	Domain	Precision	Scale	Length	Description
OBJECTID	Object ID							
SHAPE	Geometry	Yes						
BoundaryType	Long integer	No	1		0			Type of boundary condition
BoundaryValue	Double	Yes			0	0		Value of boundary condition
BoundaryValue2	Double	Yes			0	0		Extra value for boundary condition
BoundaryValue3	Double	Yes			0	0		Extra value for boundary condition
BoundaryValue4	Double	Yes			0	0		Extra value for boundary condition
TransientType	Short integer	Yes	0		0			Steady (0) or Transient (1)
Side	Short integer	Yes	1		0			Left (1) or right (0) side for boundary condition
Description	String	Yes					50	Descriptive text
HydrogeologyID	Long integer	Yes			0		E	Hydrogeology identifier

Subtypes of BoundaryCondition

Subtype field *BoundaryType*
Default subtype *1*

List of defined default values and domains for subtypes in this class

Subtype Code	Subtype Description	Field name	Default value	Domain
1	HeadSpecified	No values set		
2	DischargeSpecified	No values set		
3	ResistanceSpecified	No values set		
4	ResistanceVariable	No values set		
5	TransmissivitySpecified	No values set		
6	TransmissivityZero	No values set		
7	TransmissivityInfinite	No values set		

Table
AnalyticElementMath

Mathematical variables used in Analytic Element Method

Field name	Data type	Allow nulls	Default value	Domain	Precision	Scale	Length	Description
OBJECTID	Object ID							
NumParameter	Long integer	No	0		0			Number of parameters
NumControlPoint	Long integer	Yes	0		0			Number of control points
TransientType	Short integer	Yes	0		0			Steady (0) or transient (1)
FarFieldTolerance	Double	Yes			0	0		Far field tolerance
FarfieldDistance	Double	Yes			0	0		Far field distance
Description	String	Yes					50	Descriptive text
AnalyticElementID	Long integer	Yes			0			Analytic element identifier

Table
AnalyticElement

Mathematical variables used in Analytic Element Method

Field name	Data type	Allow nulls	Default value	Domain	Precision	Scale	Length	Description
OBJECTID	Object ID							
HydrogeologyID	Long integer	Yes			0			Hydrogeology identifier
GroundwaterModelID	Long integer	Yes			0			Groundwater model identifier

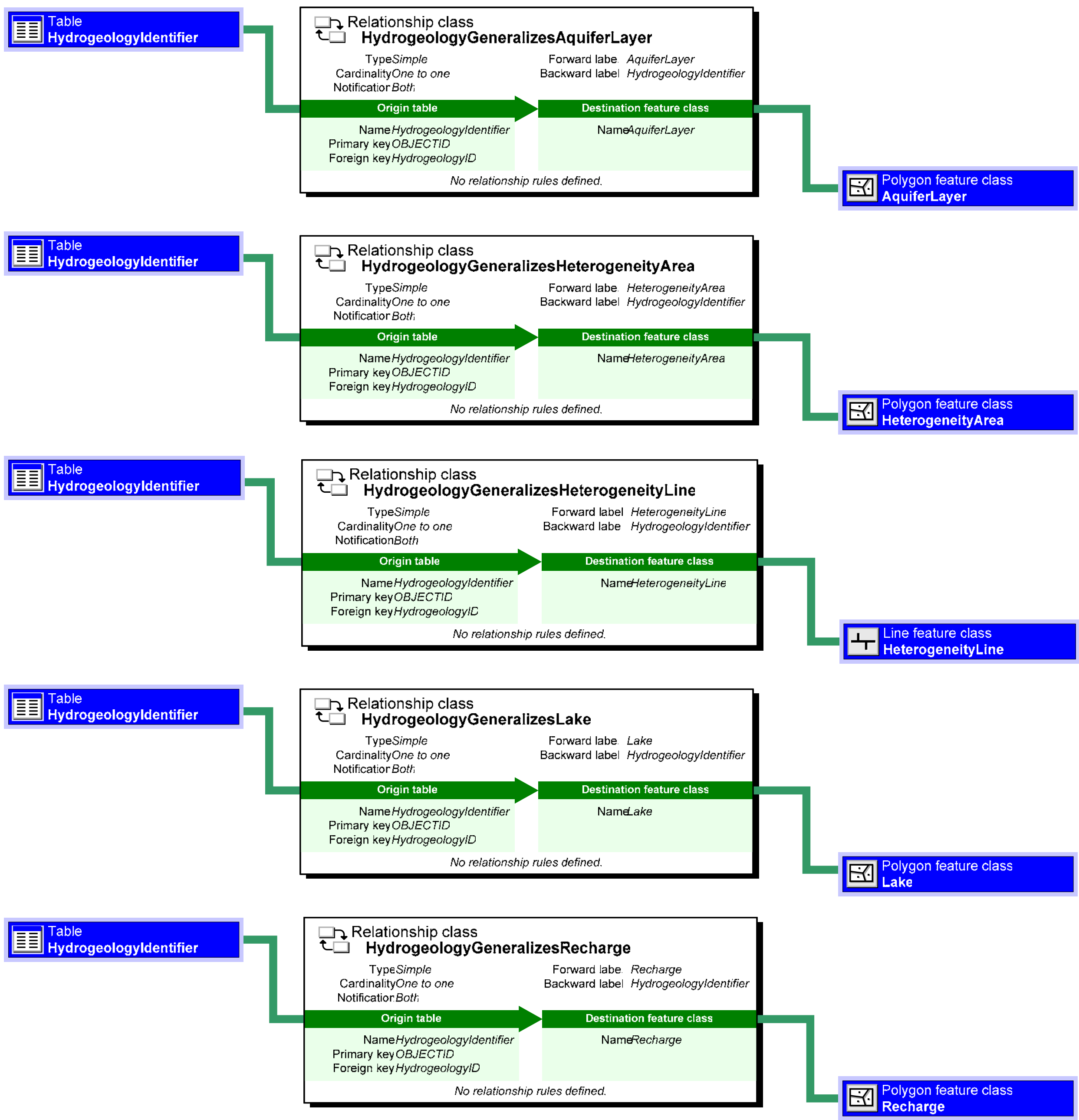
Table
AnalyticElementStrength

Strength parameters computed for each AnalyticElement

Field name	Data type	Allow nulls	Default value	Domain	Precision	Scale	Length	Description
OBJECTID	Object ID							
StrengthValue	Double	No			0	0		Value of strength parameter
AnalyticElementID	Long integer	Yes			0			Analytic element identifer

Relationship Classes

Note that the class to the left is related to the class on the right via these relationships, which are automatically assigned by ArcGIS. Please note that the Foreign key is filled with the OBJECTID from the class on the left, which enables the object that is created to identify its parent class. Relationship classes also indicate multiplicity; all relationships used here are either 1-to-1 or 1-to-many.



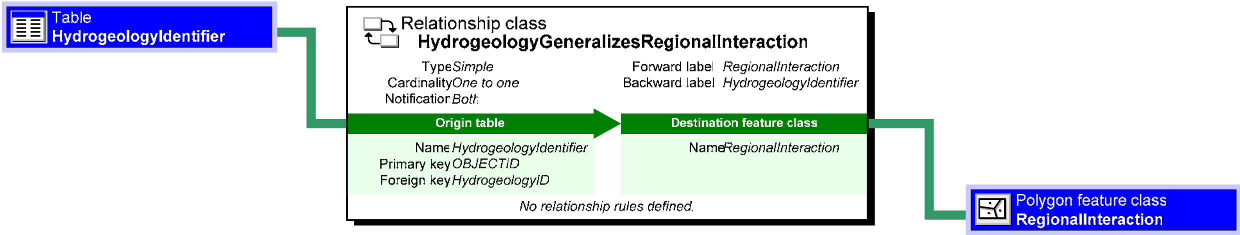


Table
HydrogeologyIdentifier
Relationship class
HydrogeologyGeneralizesRegionalInteraction
Type Simple
Cardinality One to one
Notification Both
Forward label RegionalInteraction
Backward label HydrogeologyIdentifier
Origin table
Destination feature class
Name HydrogeologyIdentifier
Primary key OBJECTID
Foreign key HydrogeologyID
Name RegionalInteraction
No relationship rules defined.
Polygon feature class
RegionalInteraction

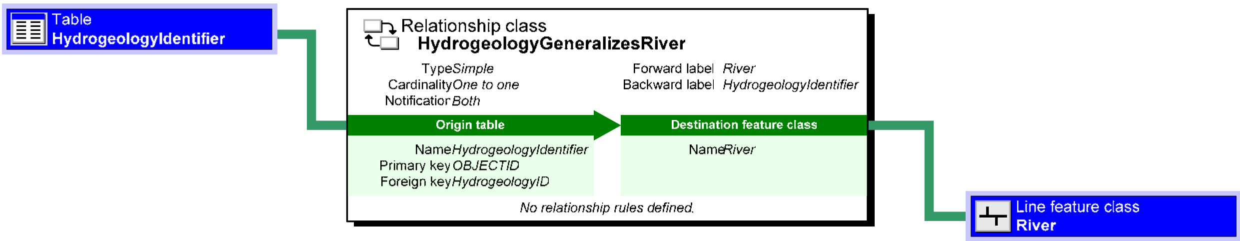


Table
HydrogeologyIdentifier
Relationship class
HydrogeologyGeneralizesRiver
Type Simple
Cardinality One to one
Notification Both
Forward label River
Backward label HydrogeologyIdentifier
Origin table
Destination feature class
Name HydrogeologyIdentifier
Primary key OBJECTID
Foreign key HydrogeologyID
Name River
No relationship rules defined.
Line feature class
River

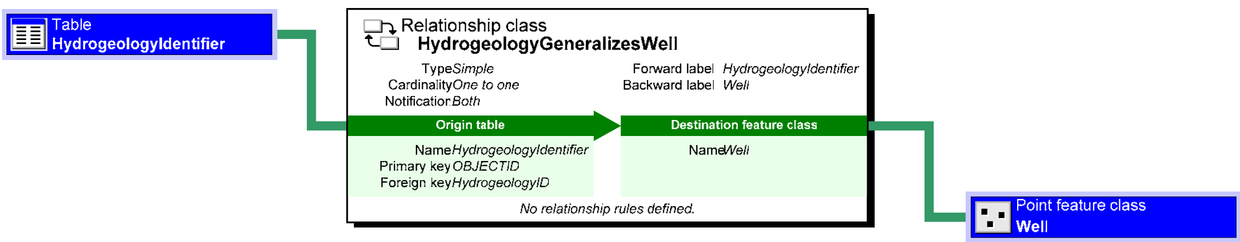


Table
HydrogeologyIdentifier
Relationship class
HydrogeologyGeneralizesWell
Type Simple
Cardinality One to one
Notification Both
Forward label HydrogeologyIdentifier
Backward label Well
Origin table
Destination feature class
Name HydrogeologyIdentifier
Primary key OBJECTID
Foreign key HydrogeologyID
Name Well
No relationship rules defined.
Point feature class
Well

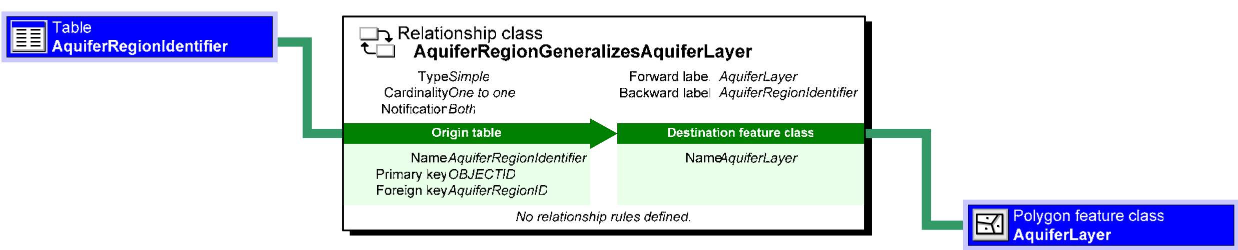
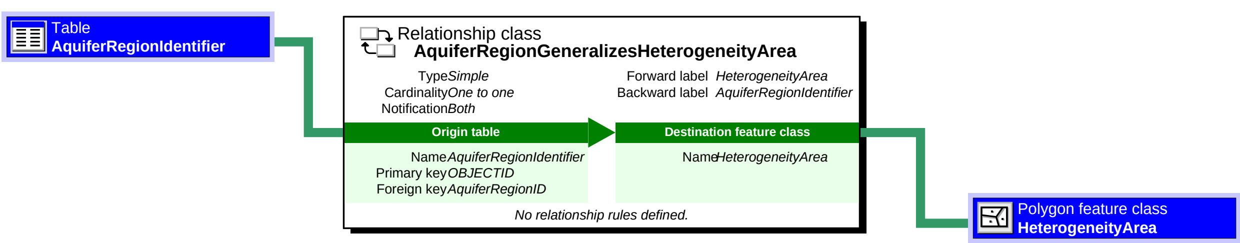


Table
AquiferRegionIdentifier
Relationship class
AquiferRegionGeneralizesAquiferLayer
Type Simple
Cardinality One to one
Notification Both
Forward label AquiferLayer
Backward label AquiferRegionIdentifier
Origin table
Destination feature class
Name AquiferRegionIdentifier
Primary key OBJECTID
Foreign key AquiferRegionID
Name AquiferLayer
No relationship rules defined.
Polygon feature class
AquiferLayer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AquiferRegionIdentifier
Relationship class
AquiferRegionGeneralizesHeterogeneityArea
Type Simple
Cardinality One to one
Notification Both
Forward label HeterogeneityArea
Backward label AquiferRegionIdentifier
Origin table
Destination feature class
Name AquiferRegionIdentifier
Primary key OBJECTID
Foreign key AquiferRegionID
Name HeterogeneityArea
No relationship rules defined.
Polygon feature class
HeterogeneityArea

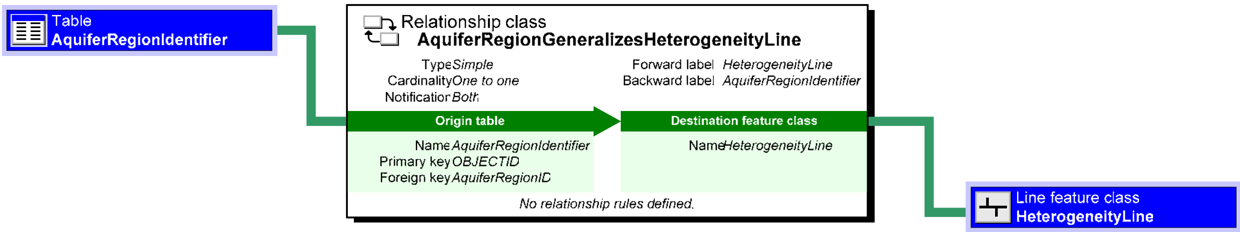


Table
AquiferRegionIdentifier
Relationship class
AquiferRegionGeneralizesHeterogeneityLine
Type Simple
Cardinality One to one
Notification Both
Forward label HeterogeneityLine
Backward label AquiferRegionIdentifier
Origin table
Name AquiferRegionIdentifier
Primary key OBJECTID
Foreign key AquiferRegionID
Destination feature class
Name HeterogeneityLine
No relationship rules defined.
Line feature class
HeterogeneityLine

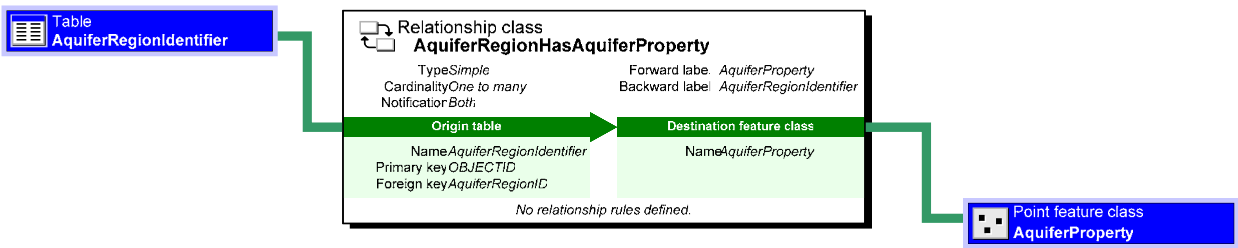


Table
AquiferRegionIdentifier
Relationship class
AquiferRegionHasAquiferProperty
Type Simple
Cardinality One to many
Notification Both
Forward label AquiferProperty
Backward label AquiferRegionIdentifier
Origin table
Name AquiferRegionIdentifier
Primary key OBJECTID
Foreign key AquiferRegionID
Destination feature class
Name AquiferProperty
No relationship rules defined.
Point feature class
AquiferProperty

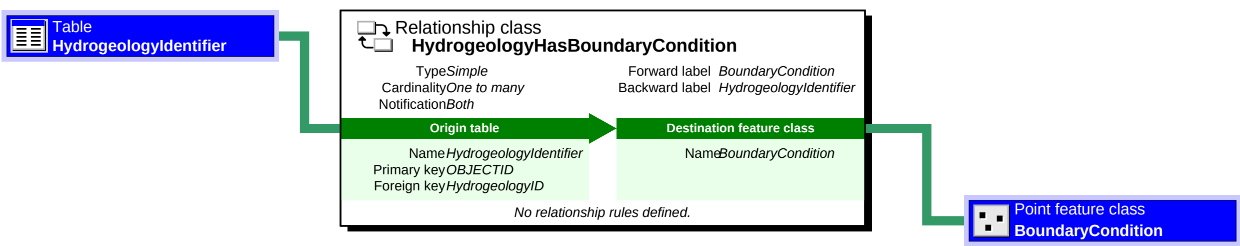


Table
HydrogeologyIdentifier
Relationship class
HydrogeologyHasBoundaryCondition
Type Simple
Cardinality One to many
Notification Both
Forward label BoundaryCondition
Backward label HydrogeologyIdentifier
Origin table
Name HydrogeologyIdentifier
Primary key OBJECTID
Foreign key HydrogeologyID
Destination feature class
Name BoundaryCondition
No relationship rules defined.
Point feature class
BoundaryCondition

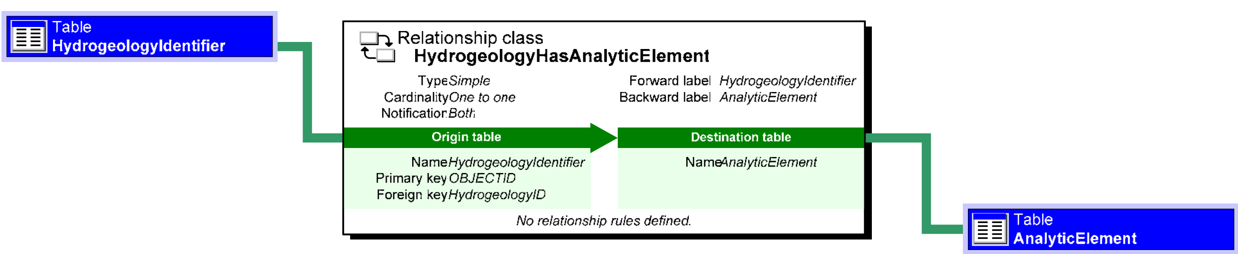


Table
HydrogeologyIdentifier
Relationship class
HydrogeologyHasAnalyticElement
Type Simple
Cardinality One to one
Notification Both
Forward label HydrogeologyIdentifier
Backward label AnalyticElement
Origin table
Name HydrogeologyIdentifier
Primary key OBJECTID
Foreign key HydrogeologyID
Destination table
Name AnalyticElement
No relationship rules defined.
Table
AnalyticElement

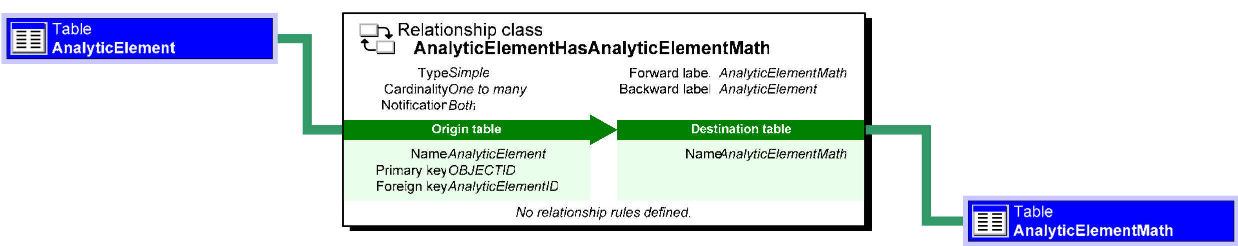


Table
AnalyticElement
Relationship class
AnalyticElementHasAnalyticElementMath
Type Simple
Cardinality One to many
Notification Both
Forward label AnalyticElementMath
Backward label AnalyticElement
Origin table
Name AnalyticElement
Primary key OBJECTID
Foreign key AnalyticElementID
Destination table
Name AnalyticElementMath
No relationship rules defined.
Table
AnalyticElementMath

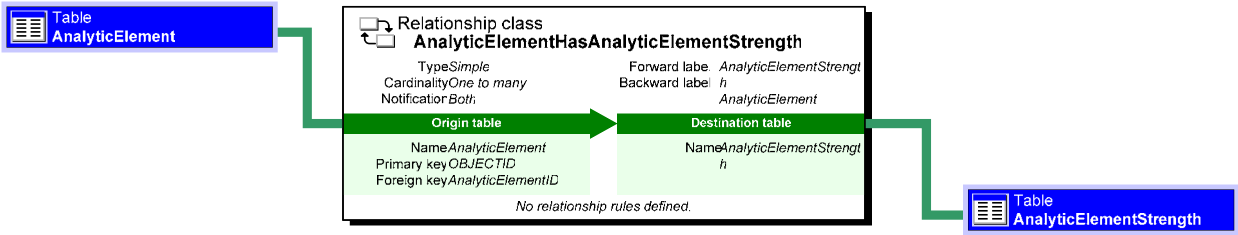


Table
AnalyticElement
Relationship class
AnalyticElementHasAnalyticElementStrength
Type Simple
Cardinality One to many
Notification Both
Forward label AnalyticElementStrength
Backward label AnalyticElement
Origin table
Destination table
Name AnalyticElement
Primary key OBJECTID
Foreign key AnalyticElementID
Name AnalyticElementStrength
No relationship rules defined.
Table
AnalyticElementStrength

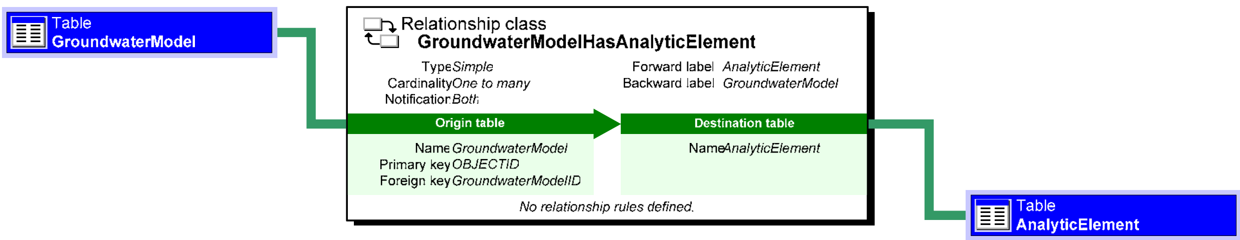


Table
GroundwaterModel
Relationship class
GroundwaterModelHasAnalyticElement
Type Simple
Cardinality One to many
Notification Both
Forward label AnalyticElement
Backward label GroundwaterModel
Origin table
Destination table
Name GroundwaterModel
Primary key OBJECTID
Foreign key GroundwaterModelID
Name AnalyticElement
No relationship rules defined.
Table
AnalyticElement

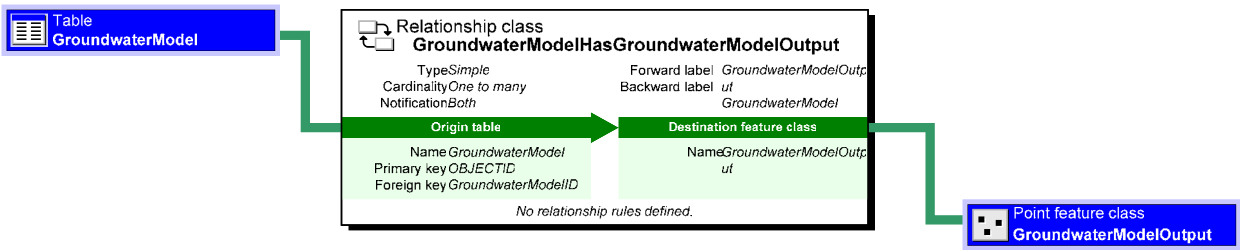


Table
GroundwaterModel
Relationship class
GroundwaterModelHasGroundwaterModelOutput
Type Simple
Cardinality One to many
Notification Both
Forward label GroundwaterModelOutput
Backward label GroundwaterModel
Origin table
Destination feature class
Name GroundwaterModel
Primary key OBJECTID
Foreign key GroundwaterModelID
Name GroundwaterModelOutput
No relationship rules defined.
Point feature class
GroundwaterModelOutput

Creating MLAEM Elements using GroundwaterAEM Geodatabase

The following table illustrates how the geodatabase stores information related to existing elements in MLAEM (Multi-Layer Analytic Element Method). Note that Curvilinear elements must have straight geometry, as ArcGIS does not support parabolic shapes.

GroundwaterAEM Geodatabase	***Boundary Condition***	***MLAEM Representation***
Aquifer Layer: Aquifer		Aquifer
Aquifer Layer: Aquitard	HeadSpecified ResistanceSpecified ResistanceVariable TransmissivitySpecified	Aquitard + Polygon
Aquifer Layer: Aquitard	ResistanceSpecified	Well-Area Element
HeterogeneityArea	TransmissivitySpecified	Variable Area Element + Polygon + Doublet
HeterogeneityArea	TransmissivitySpecified	Constant strength quadrilateral area element
HeterogeneityLine	TransmissivitySpecified TransmissivityZero TransmissivityInfinite	String of Curvilinear Elements
HeterogeneityLine	TransmissivitySpecified TransmissivityZero TransmissivityInfinite	Double Root
Lake	ResistanceSpecified ResistanceVariable	Variable Area Element + Polygon + Doublet
Lake	ResistanceSpecified ResistanceVariable	Constant strength quadrilateral area element
Recharge	DischargeSpecified	Rain

Recharge	DischargeSpecified	Constant strength quadrilateral area element
Recharge	DischargeSpecified	Variable Area Element + Polygon + Doublet
RegionalInteraction	HeadSpecified	Reference
	DischargeSpecified	Uniflow
River	HeadSpecified	String of Curvilinear Elements
	DischargeSpecified	
	DischargeSpecified:Left side	
	ResistanceSpecified	
	ResistanceVariable	
	TransmissivityInfinite:DischargeSpecified	
River	HeadSpecified	Linesink
	DischargeSpecified	
	ResistanceSpecified	
	ResistanceVariable	
River	HeadSpecified	Double Root
Well	HeadSpecified	Well
	HeadSpecified:MultiAquifer	
	DischargeSpecified	
	DischargeSpecified:Transient	
Unsupported geometry		Given Pond
Unsupported geometry		Given ellipse

The following are examples illustrating how to utilize the GroundaterAEM geodatabase structure to create data for MLAEM.

Aquifer and Aquitard Layers

AnalyticElement

OBJECTID	Hydrogeolo	Groundw ate
1	1	1
2	2	1
3	3	1

AquiferLayer

AquiferTyp	Descriptio	ArcHydro_(	SHAPE_Leng	SHAPE_Area	Hydrogeolo	AquiferReg
1	Bottom Aquifer	0	81116.90608190000	410809325.19900000000	1	1
2	Separating Layer	0	81073.71654350000	410383242.31700000000	2	2
1	Top Aquifer	0	81050.47100690000	410124647.58900000000	3	3

AquiferProperty

OBJECTID	Base	Thickness	HydraulicC	Porosity	SpecificYi	Descriptio	AquiferReg
1	210.00000000000	10.00000000000	0.00340000000	0.30000000000	0.30000000000	Bottom Aquifer general ¦	1
2	220.00000000000	1.00000000000	0.00000010000	0.30000000000	0.30000000000	Global data for aquitards	2
3	221.00000000000	5.00000000000	0.00010000000	0.30000000000	0.30000000000	Top aquifer global data	3

AquiferRegionalIdentifer

OBJECTID	Descriptio
1	Bottom Aquifer
2	Separating Layer
3	Top Aquifer

GroundwaterModel

OBJECTID	FileDirect	FileName	SolveMaxIt	SolveError	Descriptio
1	.\	GeoAEM-mlaem.dat	5	0.00000100000	Basic model for mlaem input

HydrogeologyIdentifier

OBJECTID	Descriptio
1	Bottom Aquifer Hydrogeology ID
2	Separating layer Hydrogeology ID
3	Top Aquifer Hydrogeology ID

Wells

The following files are required in addition to those for Aquifer layers to test wells

AnalyticElement

OBJECTID	Hydrogeolo	Groundw ate
1	1	1
2	2	1
3	3	1
4	7	1
5	4	1
6	5	1
7	6	1

BoundaryCondition

OBJECTID	BoundaryTy	BoundaryVa	Boundary_1	Boundary_2	Boundary_3	Transi	Side	Descriptio	Hydrogeolo
1	1	221.00000000000	0.00000000000	0.00000000000	##########	0	1	Dew atering w ell	5
2	2	0.01000000000	0.00000000000	0.00000000000	##########	0	1	steady discharge	4
3	2	0.02000000000	100.00000000000	0.00000000000	##########	1	1	Transient Dischar	6
4	2	0.12000000000	0.00000000000	0.00000000000	##########	0	1	Total discharge	7

HydrogeologyIdentifier

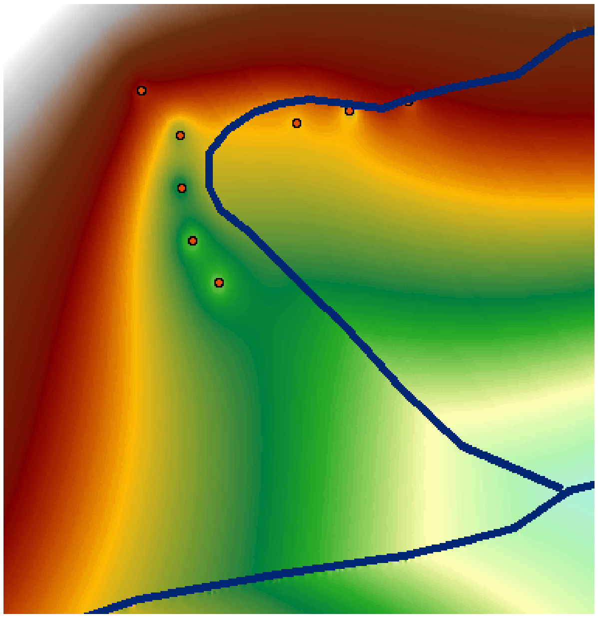
OBJECTID	Descriptio
1	Bottom Aquifer Hydrogeology ID
2	Separating layer Hydrogeology ID
3	Top Aquifer Hydrogeology ID
4	Given Well
5	Head Spec. Well
6	Transient w ell
7	Multi-layer w ell

Well

OBJECTID	AquiferLay	Descriptio	ArcHydro_W	Radius	MultiLayer	Hydrogeolo
1	1	Given	0	0.30000000000	0	4
2	1	Head Spec.	0	0.30000000000	0	5
3	1	TWell	0	0.30000000000	0	6
4	1	Multi	0	0.30000000000	1	7

Results Implementing Groundwater-AEM with MLAEM

The following image illustrates a surface showing groundwater levels near the municipal well field for the city of Manhattan, Kansas. Blue lines indicate the Big Blue River (flowing from the north to south) and the Kansas River (from west to east). River data was obtained from GIS data available in the National Hydrography Dataset (nhd.usgs.gov). Data for wells (red/orange dots) were obtained from the WIMAS dataset available at DASC at the Kansas Geological Survey (www.kgs.ku.edu). Groundwater contours illustrate the drawdowns associated with pumping and the influence between groundwater and surface water.



Conclusions and Future Developments

As illustrated in the municipal well field example above, the Groundwater-AEM data model and geodatabase enables geodatabase features and attributes to be modeled using the MLAEM application as well as receipt and visualization of MLAEM results in ArcGIS. The Groundwater-AEM data model shares the design intent of the Arc Hydro data model and existing UML standards from that model and it relies on a group of thematic layers with common spatial representations, has minimal attributes, establishes integrity rules and relationships, is simple and additive in nature so feature classes can be derived from or added to it including elements in existing Arc Hydro geodatabases which are all key components of successful data models (Arctur and Zeiler, 2004). The following future developments are suggested to enhance utilization of the GroundwaterAEM Geodatabase presented here:

1. To implement GUIs capable of fully automating filling the GroundwaterAEM geodatabase from user input.

2. To implement scripts to fully automating filling the GroundwaterAEM geodatabase from standard GIS repositories (e.g., the Federal GeoDatabase Clearinghouse, FGCD).

3. To automate the utilization of the GroundwaterAEM geodatabase with other types of modeling tools.

Acknowledgments

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