CRWR Online Report 11-06

A Hydrologic Information System for Water Availability Modeling

by

Clark Siler, PhD

August 2011

CENTER FOR RESEARCH IN WATER RESOURCES

Bureau of Engineering Research • The University of Texas at Austin
J.J. Pickle Research Campus • Austin, TX 78712-4497

The Dissertation Committee for Clark D. Siler

certifies that this is the approved version of the following dissertation:

A Hydrologic Information System

for Water Availability Modeling

Committee:

David R. Maidment, Supervisor

Robert Gilbert

Ben Hodges

Norm Jones

Daene McKinney

A Hydrologic Information System

for Water Availability Modeling

by

Clark D. Siler, B.S., M.S.E.

Dissertation

Presented to the Faculty of the Graduate School of

The University of Texas at Austin

in Partial Fulfillment

of the Requirements

for the Degree of

Doctor of Philosophy

The University of Texas at Austin

August 2011

A Hydrologic Information System

for Water Availability Modeling

Clark D. Siler, Ph.D.

The University of Texas at Austin, 2011

Supervisor: David R. Maidment

Texas water availability modeling has undergone a transition from paper-based documents to digital databases and GIS maps. This results in many discrete components: a water rights database, a GIS database, a monthly flow simulation model to quantify water availability, and an environmental flows assessment to quantify how much water should remain in Texas rivers. This dissertation examines how these components can be connected by a conceptual model and automated as a Hydrologic Information System (HIS) for Texas water availability modeling using custom GIS toolsets and data processing. The HIS is defined using three tools that combine components of the conceptual model. These tools automate the processes of water availability modeling and synthesize the conceptual model components. This dissertation also explores how desktop-based Texas water availability modeling can be informed by web services and how a services-oriented architecture for water availability modeling could be constructed. Existing hydrologic information models are used as a guide in creating an Arc Hydro

Web information model as a framework for this activity. This model is demonstrated using scenarios highlighting its capabilities for representing desktop and web-informed analyses. The functionality of Arc Hydro Web is demonstrated via a use case of five associated component studies in the San Jacinto Basin illustrating the functionality of the HIS of water availability modeling in Texas. The shift from desktop-based analyses to web-enabled processing enables certain aspects of water availability modeling being moved to cloud computing. The network aspects of the Texas water availability modeling environment can be informed by web services using a centrally-stored network, negating the current system of having nearly-identical duplicate networks. This could foster communication and sharing of water resources models. It is recommended that Arc Hydro Web be implemented, that aspects of water availability modeling processing become web-enabled through the combination of web processing and web services, and that additional services be developed to meet the needs of web-based water availability modeling.

Table of Contents

List of Figures

List of Tables

Chapter 1. Introduction

Surface water withdrawals and use in Texas and many other states in the western United States are based on the system of prior appropriation where a state agency administers appropriative rights. These water rights are specified by location, quantity of water, time of withdrawal, and purpose of use. The basic engineering problem with surface water appropriation in such a system is to ensure that the available surface water is not over-committed.

The management of water rights and surface water use in Texas necessitates a complex system of data governance. It is essential that the geographic relationships and connectivity between water rights and their respective parameters are understood and managed for proper surface water appropriation. Current practices of water rights data management in Texas utilize the latest advances in computer technologies and data management, but historical water rights data management systems—while similar in scope—were markedly different in practice.

A description of an historical water rights data management system may follow this scenario: A file cabinet sits in a corner of an office. Inside this cabinet rests a collection of water rights data for a state or jurisdiction. These data are all in hard copy form—they are either hand-written or printed on paper—and they include a set of Mylar maps with sticker dots indicating locations of interest (e.g. diversions, water right access points, etc.). If changes need to be made or data need to be verified, the records and maps are pulled out and painstakingly referenced. This whole process is done by hand, and may be prone to a whole cluster of errors. Historically, such cabinets and data management systems were widespread (Renton et al 2008).

Despite digital advances in many realms, similar hard-copy-based water right data management systems still persist in some locations. At an American Water Resources Association (AWRA) GIS in Water Resources Conference, Renton et al, of the California State Water Resources Control Board, highlighted the then-recent transition from a hard-copy-based system to a geographic information system. Figure 1-1 shows an actual image of the hard-copy-based cabinet in California referenced by the Renton presentation (2008, USGS 2008).

Figure 1-1. Water Rights Data in Hard Copy Form
(Showing the California Division of Water Rights Map Room, from Renton et al 2008)

Many in the global hydrologic community have come a long way from cabinets housing maps and hard-copy data. The combination of digital databases and geographic information systems (GIS) have enabled the connection of maps and data in meaningful ways—enabling queries, networks traces, water rights data management, and many other basic hydrologic processes; however, with the concept of Web 2.0—meaning the access of data and applications via the Web from anywhere in the world—much of hard-copy or individually-held data are being made available via web applications and data sharing resources. This paradigm shift is changing the environment of many industries and practices, including hydrology.

This dissertation presents a case study of the San Jacinto Basin in Texas that is used as part of a narrative to describe the transition of a hard-copy-based water resources data management system to a digitally-enabled environment of water rights management. This discussion outlines the conceptual model for water availability modeling in Texas. In its current digitally-enabled environment, a Hydrologic Information System (HIS) for Texas water rights management and water availability modeling is developed, which incorporates the components of Texas water availability modeling conceptual model. These include: water rights data in a database; maps and geographic networks in a geographic information system (GIS); a model for simulating the water availability of water rights under various scenarios, called Water Rights Analysis Package (WRAP); the official water availability model of Texas (WRAP and associated basin input files); an environmental flows assessment process designed to quantify how much water should be left in Texas rivers and not allocated for withdrawals; and tools for accessing and displaying modeled results. Included in this case study are considerations for the recent advances in access to web-based data and processing—termed "the cloud" and cloud computing, respectively. The hydrologic geospatial information model, Arc Hydro Web, is developed and used to show how recent advances in data access and data management can benefit the water resources data management of Texas water rights.

1.1 BACKGROUND

Beginning with the response to a hard year of drought in 1996, the Texas Legislature passed a series of Senate bills which have considerable impact on surface water management in Texas. These three Senate bills have shaped the way that current water resources management and modeling are performed: Senate Bill 1 (in 1997), Senate Bill 2 (in 2001), and Senate Bill 3 (in 2007). These bills, respectively, resulted in the development of basin water availability models for all basins in Texas, established the Texas Instream Flow Program and mandated flow regime recommendations, and created the current environmental flows assessment process and established an Environmental Flows Advisory Group which oversees its implementation—this group is commissioned to work with stakeholders in Texas basins in developing recommendations for environmental flow protection (Texas State Legislature 1997, Texas State Legislature 2001, and Texas State Legislature 2007).

These Senate Bills served as the impetus for the creation of the Texas water rights management conceptual model components. Various tools and processes have been developed in an effort of uniting these data in ways that allow automation and synthesis. The WRAP Display Tool enables access and visualization of Texas water availability model output in GIS. The WRAP Network Tools provide the ability prepare networks of streamlines and water right points for network analyses, perform selective drainage area delineation for water right locations without reprocessing the entire basin, and produce lists of water right holders and mailing addresses from selected points on a map. The Texas Flow Regimes Tool incorporates data extraction, the ability to run multiple models, and the tracking of steps taken. This tool successfully combines web data with multiple models, all housed within a single Excel workbook.

1.2 Research Questions

To address the engineering question of appropriating surface water without over-committing it, it is necessary to first understand the prior appropriation system of water rights and water right management in Texas. The research question associated with this need is:

1. What is the conceptual model for Texas water rights management and water availability modeling?

The components of the Texas water availability modeling conceptual model represent improvements to historical methods of water rights and water resources management; however, to be of most use, they must be combined in a way to allow more meaningful analyses. Such a system of connected data and analysis tools is defined as a Hydrologic Information System (HIS) for Texas water availability modeling. The research question associated with such an information system is:

2. How can the components of the Texas water availability modeling conceptual model be better automated and synthesized to form a more connected whole as a Hydrologic Information System for Texas water availability modeling?

Much of Texas water availability modeling environment procedures are based on desktop analyses (e.g. the data are stored locally and the computations are performed on a desktop computer). Web services demonstrate the advances in access to data and computational models housed on external servers (termed "the cloud"). Such services not only provide access to data, but can be used for web processing as well, as part of a web-based services-oriented architecture where multiple data repositories and processing services are linked to one another. This shift in location—from the desktop to the cloud—suggests the need of an information model suited to meet the needs of such a change. This proposed information model will need to allow for appropriately managing data accesses from the cloud via web services. The research question that stems from this is:

3. *How can desktop-based Texas water availability modeling be informed by web services using an appropriate information model that could lead to a web-based service-oriented architecture?*

While the research questions are posed individually, they are related and represent a systematic process related to an engineering problem of Texas surface water resources: to not over-commit water. The solution to this problem includes an intellectual problem of synthesizing and automating components of the Texas water availability modeling environment via geoprocessing and analytical tools and exploring how such are enhanced and influenced by web services and cloud computing using an appropriate information model (Arc Hydro Web). This dissertation's research questions are answered through an examination of the historical approach to this engineering problem, how the system is benefitted by this research, and what can be done to make the overall process better via an information model that incorporates cloud data access and cloud computing.

1.3 RESEARCH OBJECTIVES

The research questions presented above are answered using the following research objectives of this dissertation:

1. Outline the conceptual model for Texas water rights management and water availability modeling.
2. Define a Hydrologic Information System for Texas water availability modeling;
3. Employ use cases in the San Jacinto Basin in Texas to demonstrate scientific and engineering contributions;
4. Describe a unifying information model for Texas water availability modeling: Arc Hydro Web;
5. Demonstrate that Arc Hydro Web can be used with cloud data access and cloud computing (web processing) to provide support for Texas water availability modeling; and
6. Discuss potential advances in water availability modeling using a services-oriented architecture approach;

1.4 DISSERTATION OUTLINE

This dissertation is organized into five chapters. This chapter presents a brief introduction to water availability modeling in Texas and outlines this dissertation's research questions and objectives. The second chapter provides a literature and technology review of geographic information systems, the history of hydrologic information models, and standards used in this dissertation. The third chapter presents the conceptual model of Texas water availability modeling, defines the Hydrologic Information System (HIS) for Texas water availability modeling, outlines the framework and key data layer groups of Arc Hydro Web, and outlines a reference model of open distributed processing (RM-ODP) used to demonstrate the HIS and Arc Hydro Web information model. The fourth chapter presents five use cases as applications of the solutions to this dissertation's research question (illustrating certain steps in the overall water availability modeling process of Texas). The fourth chapter also includes a look at the overall water availability modeling process from a web or cloud perspective and demonstrates the Arc Hydro Web information model in the cloud. The final chapter revisits each of the research questions to tie them together and make recommendations for the future of Texas water availability modeling.

Chapter 2. Literature and Technology Review

This literature and technology review presents the state of engineering as shown by published papers, research, tools, and standards, as related to the research presented in this dissertation. This chapter is composed of four sections: a discussion on geographic information systems, a history of hydrologic information models, a look at standards organizations and how they can benefit hydrologic analyses, and a summary.

2.1 GEOGRAPHIC INFORMATION SYSTEMS

A geographic information system (GIS) is more than maps on a computer screen. The definition of GIS given by the developer of the industry-standard GIS packages, Environmental Systems Research Institute (ESRI) based in Redlands, California, is as follows: A geographic information system "integrates hardware, software, and data for capturing, managing, analyzing, and displaying all forms of geographically referenced information" (ESRI 2009).

Using the mapping and data management provided by GIS, it is possible to "view, understand, question, interpret, and visualize data in many ways that reveal relationships, patterns, and trends" (ESRI 2009). This portal to data representation facilitates quick and easy assimilation and distribution of data and related analyses.

2.1.1 Geodatabases and RDBMS

The basic data storage and framework for ArcGIS—a suite of ESRI's GIS software products—is the proprietary geodatabase. This portmanteau of "geo" (spatial data) and "database" (data repository) provides an all-in-one packaged collection of geographic data (ESRI 2009b). In addition, the geodatabase is a relational database management system (RDBMS) that can be managed with SQL Server, MySQL, and Oracle. The RDBMS aspect of geodatabases enables the various attributes to be related to one another, even across different tables, feature classes, or other entities. These relationships have cardinality that defines the number of features or attributes that can be related (e.g. relationships may be one-to-one, one-to-many, or many-to-many). Geodatabases can have five components: (1) feature datasets – collections of feature classes with a common coordinate system; (2) tables of attributes; (3) relationships linking tables and feature classes; (4) raster datasets; and (5) metadata documents (Arctur and Zeiler 2004; Zeiler 1999).

One of the fundamental purposes of GIS is to provide representations of the real world. One way that this is accomplished is through the use of geographic data models. Data models, or information models, can be thought of as ready-built structures into which data can be placed. In this sense, a "structure" is a collection of objects and the corresponding relationships between them. Data models can range from simple to incredibly advanced and include such particulars as field names (in tables), relationships between objects, etc. Geographic data models are just one flavor of the data model collection that provide spatial (or "geo") aspects to databases (Zeiler 1999).

2.1.2 Data Cube

Many types of hydrologic and other geo-temporal data—including simulation model output—can be visualized as lying on a vertex of a data cube. The data cube, shown in Figure 2-1, is a 3D representation of data where the dimensions are time, space, and variable—or, in other when, where, and what. Recent representations of the data cube include a "who" aspect, referring to the data source—useful when using web services to obtain data from the cloud. The data cube representation is quite different from a Cartesian coordinate view which shows three distinct coordinates for pinpointing a location in space. Rather, the data cube has this spatial location represented by a single axis: space. In addition, two other dimensions are represented by the other axes: time and variables (Maidment 2002, Siler 2008).

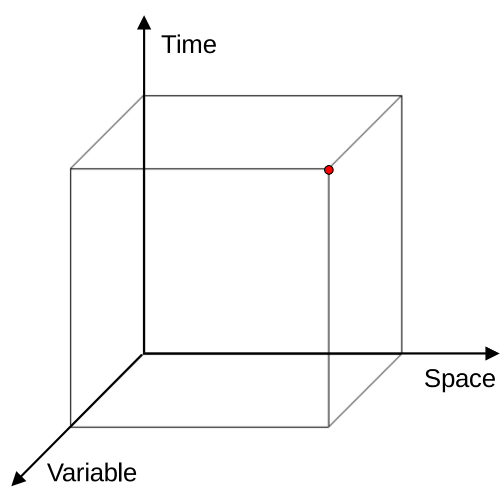


Figure 2-1. Data Cube

Simulated or observed hydrologic data can fall within the data cube structure where, for a specified variable, one can select data for a location and time. For example, consider a basin with many reservoirs. Choosing the percent of reservoir storage value (*variable*) for July 1996 (*time*) at one reservoir (*space*) is akin to designating a unique data cube where the points are determined by the selections (*variable, time,* and *space*). This general structure can be applied to any variable that has data recorded in space and time. An example of the application of this principle is the WRAP Display Tool described in section 3.2.4. The use of the data cube structure allows for a variety of information products, such as maps, time series, or animations (Siler 2008).

2.1.3 ArcToolbox and ModelBuilder

ArcToolbox is a collection of geoprocessing tools that works inside of ESRI's ArcGIS suite of GIS programs. Included are a number of built-in tools (with the number depending on which extensions are enabled/available) and custom-built tools. These tools can be run individually to perform specific functions, or they can be used in a user-friendly modeling environment called ModelBuilder. ModelBuilder provides the ability to combine any number of ArcToolbox tools to be run in series as part of a specific, repeatable chain. In this way, a specific set of geoprocessing steps can be automated in a standardized way, providing a set of steps that are run exactly in the same way each time. ModelBuilder models themselves can be saved as ArcToolbox tools for subsequent use or exported for use by others (Tucker 2000, Cesur 2007).

2.2 HISTORY OF HYDROLOGIC INFORMATION MODELS

2.2.1 Arc Hydro

Arc Hydro is a geospatial and temporal data model for surface water hydrology and hydrogeography which employs the geodatabase schema to connect geospatial and temporal data to support hydrologic analyses. This means that this data model can be used to store both geospatial data as well as time series data. This is done through the use of specialized Arc Hydro geodatabases within a GIS environment—ESRI's ArcGIS, in particular (Maidment 2002).

The Arc Hydro Geodatabase schema includes a collection of features and tables that are related to one another using IDs (integers)—such as HydroID, a universal identifier spanning feature datasets and tables (rather than feature layer IDs)—and codes (text fields)—such as HydroCode which is used to both describe features and relate them to external information systems. These relationships enable one to determine information about geographic locations (e.g. a point on a river), how a location relates to other water features (e.g. the stream that the point lies on or its drainage area), as well as time series data related to the whole. These relationships, along with the relationship between the data model and computational models (or simulation models, if preferred) are shown in Figure 2-2, which is a graphic taken from Maidment's book illustrating Arc Hydro (represented as the collection of components shown in the green outline) as part of a Hydrologic Information System (2002).

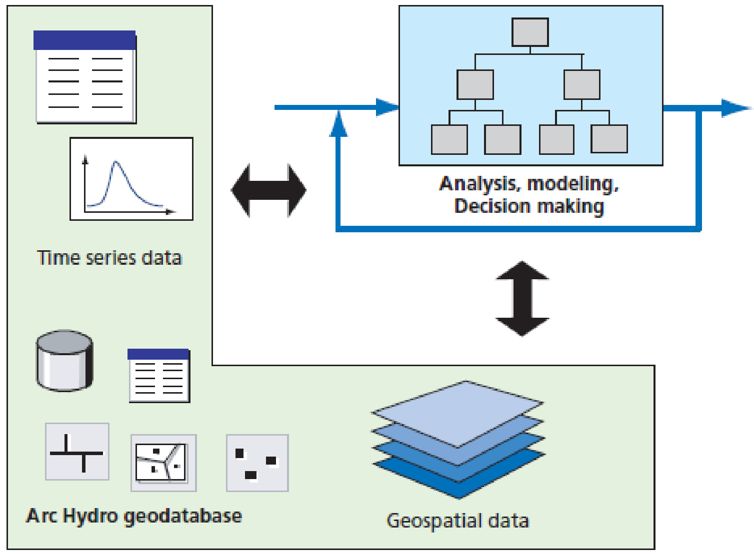


Figure 2-2. Arc Hydro as part of a Hydrologic Information System
(from Maidment 2002)

In addition to the Arc Hydro's data model is a collection of associated tools for use in ArcGIS which has been developed to assist in preparing data for hydrologic analyses and modeling. Starting with a DEM, these tools can be used to create flow direction rasters, delineate watersheds and catchments, define stream paths, calculate an array of watershed parameters, and determine and maintain network relationships, including stream order, and other topological details. Through these processes, raster-based data are transformed to other rasters, as well as pertinent vector data (including points, lines, and polygons).

The relationships that Arc Hydro establishes, enabling the linking of points (junctions), streamlines, and watersheds—which is at the core of Arc Hydro—are well demonstrated in the development of the Hydrologic Atlas of Austria (Furst and Horhan

2008). Using the basic, out-of-the-box functionality of Arc Hydro, meaningful relationships were established between existing hydrologic data. These relationships were integral in the defining of topological relationships among Austria's water resources information which aided in furthering understanding of the water balance.

Recognizing the ability of Arc Hydro to track and manage water flow data, Yi et al (2007) expanded the general use of Arc Hydro (as a surface water data model) to also represent a constructed irrigation water infrastructure system in Northwest China. This application demonstrates the hybrid-nature of Arc Hydro in meeting a variety of water management needs in the hydrologic community.

Arc Hydro can be used to link various models and their respective data together, allowing the output of one model to serve as the input of another. This linking power of Arc Hydro is demonstrated by Whiteaker et al (2006) in an examination of the conversion of rainfall data to flood inundation maps using Arc Hydro as part of an interface data model, which utilizes a geospatial data model and a time series data model to integrate spatial and temporal data, linking GIS and simulation models.

The use of Arc Hydro has predominantly dealt with surface water. Arc Hydro Groundwater extends Arc Hydro to include data related to the subsurface flow of water Arc Hydro Groundwater incorporates the inherently 3D nature of groundwater and hydrogeologic studies (including aquifer analyses, well and borehole data, and faults) for analysis and visualization. In addition, Arc Hydro Groundwater provides the added benefit of visualizing the output of various groundwater flow simulation models (Strassberg et al 2007, Strassberg 2005).

Arc Hydro and Arc Hydro Groundwater share framework datasets to preserve the connectivity that should exist between water resources. The shared Arc Hydro framework involves an integrated geodatabase—as opposed to just a collection of data layers. The collections of features in the Arc Hydro geodatabase have shared relationships which enable the many disparate features to be linked to one another through a shared commonality of structure. Figure 2-3 shows the Arc Hydro Groundwater framework. The green lines in the figure illustrate the relationships between features in the framework, and the features' cardinality is indicated through the use of the 1 and * characters, indicating one-to-many relationships (Strassberg et al 2011).

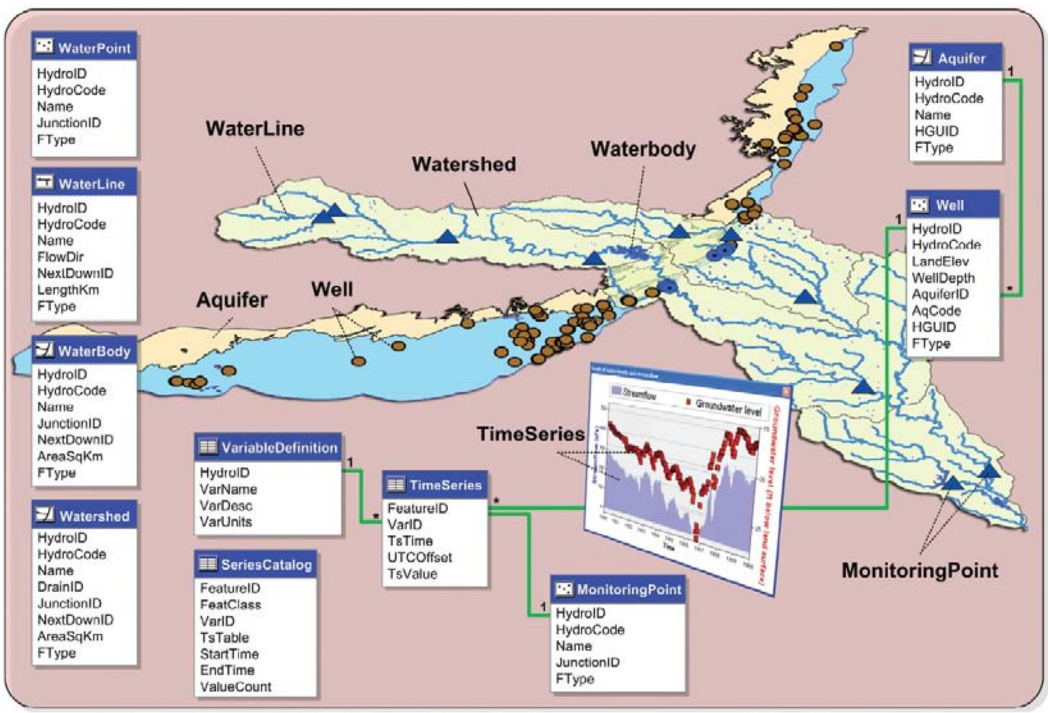


Figure 2-3. Arc Hydro Groundwater Framework

By utilizing this framework, Arc Hydro and Arc Hydro Groundwater applications preserve an approach to data management and representation in a way that enables relationships and a wide range of applications. These relationships enable selective visualization and queries (e.g. “show me all the streams and connected wells in my watershed.”) in ways that utilize the many data that can be related.

The layers and layer types shown in Figure 2-3 are representations of the key thematic layers of Arc Hydro and the Arc Hydro data framework. These layers are a sampling of the types of data to which the Arc Hydro data model can be applied. Figure 2-4 presents a descriptive visual display of the key thematic data layers of the Arc Hydro data model framework (Maidment 2002).

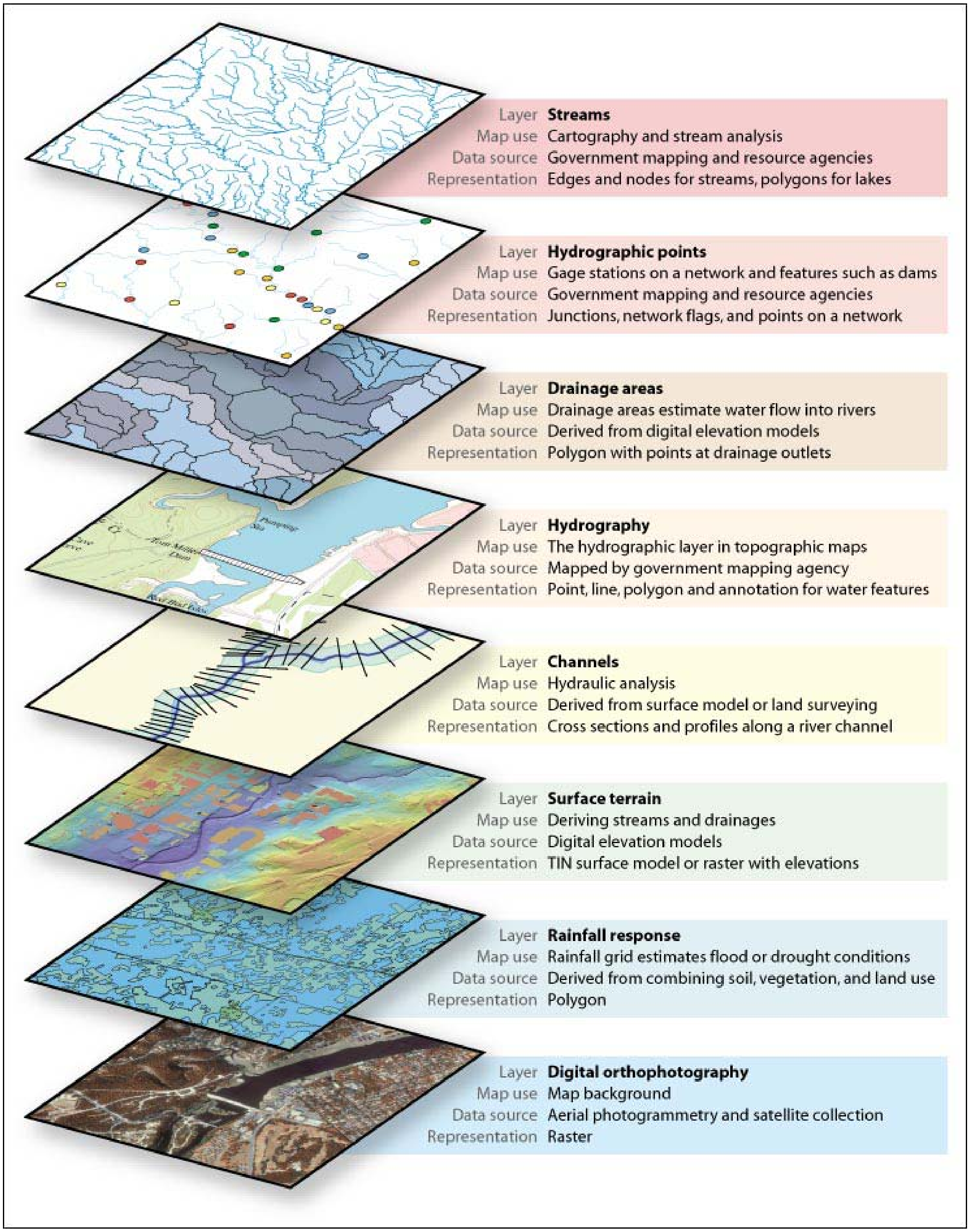


Figure 2-4. Thematic Layers of the Arc Hydro Data Model Framework
(From Maidment 2002)

Figure 2-5 presents a descriptive visual display of the key thematic data layers of the Arc Hydro Groundwater data model framework (Strassberg et al 2011).

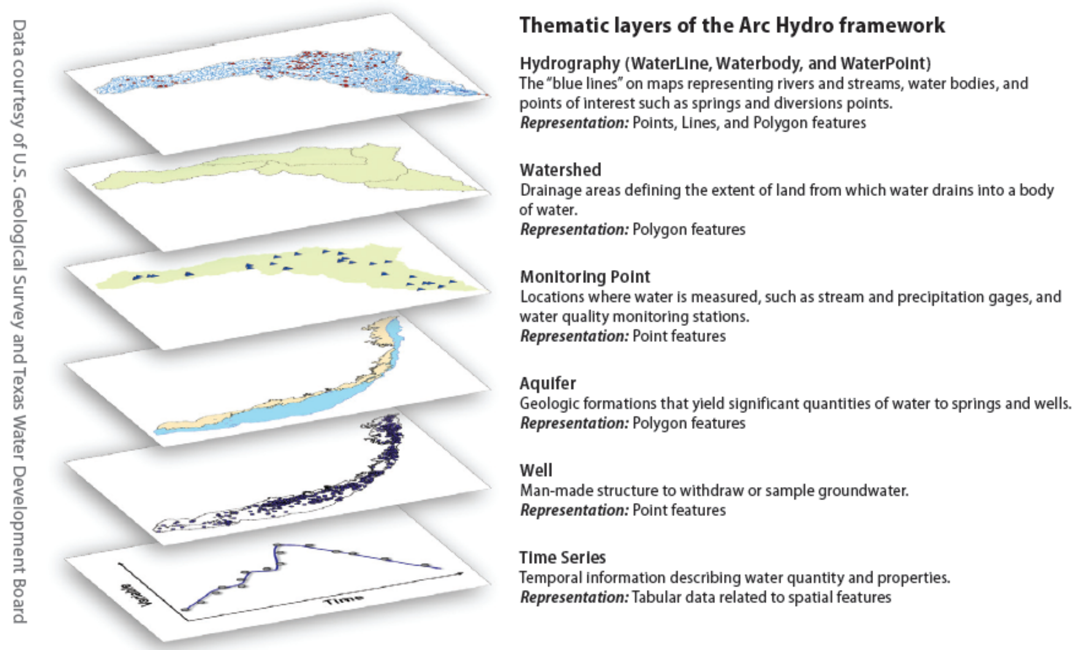


Figure 2-5. Thematic Layers of the Arc Hydro Groundwater Data Model Framework
(From Strassberg et al 2011)

Each of the layers and layer types shown in Figure 2-3 (excepting VariableDefinition and SeriesCatalog) correspond with the key thematic layers shown in Figure 2-4 and Figure 2-5.

In its less than ten-year history, Arc Hydro has been used to meet the varied needs of the hydrologic community in ways that it was explicitly designed. Perhaps more interestingly, it has also been the subject of alterations, modifications, and augmentations that have yielded additional applications across the globe, resulting in new ways of analyzing and visualizing water data and combining water data with geospatial information and useful models.

2.2.2 WRAP Hydro

The Center for Research in Water Resources (CRWR) has been involved with the development of tools and models that are used for the management, processing, and display of Texas water rights data. These include: WRAP Hydro; the WRAP Display Tool; and the WRAP Network Tools (the latter two are discussed further in sections 3.2.4 and 3.2.6).

After the implementation of Texas Senate Bill 1, researchers at the Center for Research in Water Resources developed WRAP Hydro—a preprocessing information model and toolset related to Arc Hydro that combines geographic information with modeled data. The purpose of WRAP Hydro is to produce and collect watershed parameters and water rights connectivity data as geospatial inputs for the Water Rights Analysis Package (WRAP)—part of the official water availability model of Texas. In addition to a data model, WRAP Hydro also includes tools that delineated watersheds and accumulated attributes from watersheds to junctions on the stream network (Gopalan 2003, Whiteaker et al 2007).

2.2.3 National Elevation Dataset and National Hydrography Dataset

The United States Geological Survey (USGS) produces elevation data in raster format called the National Elevation Dataset (NED). The NED is currently available as a seamless dataset, containing the best available elevation data for the United States, usually at 1 arc-second resolution (approximately 30 meters), but higher resolution (1/3 or 1/9 arc-second) is available in select locations. The NED is updated every two months, on average, providing fairly-recent elevation data for scientific and other studies (Usery et al 2010).

The National Hydrography Dataset (NHD) represents the surface water of the United States. Whereas the NED is raster-based, the NHD is vector-based (points, lines, and polygons). The NHD contains common surface water features, such as lakes, ponds, streams, rivers, and canals. The design of the NHD is to allow easy use within a GIS. The features of the NHD contain information that is useful to the hydrologic community; NHD contains a flow direction network allowing one to track water downstream, as well as an addressing system that employs reaches (with unique reach codes) and linear referencing (reach route system) so specific attributes can be assigned to individual reaches and one can also know "where they are" on any given river. Closely related to the NHD is the Watershed Boundary Dataset (WBD), which defines the perimeter of drainage areas. The NHD and its companion WBD are the result of many Federal, State, and local agencies working together (Usery et al 2010, Simley and Carswell 2010).

NHDPlus is another product of cooperation (by the U.S. Environmental Protection Agency (EPA) and the USGS). NHDPlus combines the benefits of the National Elevation Dataset (NED), the National Hydrography Dataset (NHD), the Watershed Boundary Dataset (WBD), and the National Land Cover Dataset (NLCD—which is a 30 meter raster representation of 21 different types of land cover) in a 30 meter resolution collection of hydrography data, including a water geometric network that has been painstakingly checked for accuracy and elevation-derived catchments. The "Plus" in NHDPlus is not only because of the added benefits of so many pertinent datasets, but also indicates the added functionality of having statistics and estimates for the flow and flowlines—part of the value-added attributes included with the streamlines. These include minimum and maximum elevations, slopes of flowlines, flow volume, and velocity estimates for each of the flowlines in the stream network (EPA and USGS 2010).

The next step in the NHDPlus arena is the development of the high-resolution National Hydrography Dataset 24K. Whereas the resolution of NHDPlus is 1:100,000-scale, the NHD 24K has 1:24,000- or 1:12,000-scale. The result of this higher resolution is markedly increased detail in the streamlines and corresponding networks. At present, this increase in detail comes at a cost: the finer detailed stream networks are not nearly as cleaned and reliable as those of NHDPlus.

In addition to datasets (collections of data in files or databases) are data models (collections of processes that perform specific functions on data) and data services (xml-based services that are accessed to either obtain data or perform geoprocessing functions on data). The USGS developed a water-quality model called SPARROW (SPAtially Referenced Regressions On Watershed Attributes), which can be used to track the transport of sediment, nutrients, or other substances in rivers. The estimates available in NHDPlus can be supplied as input for the SPARROW model to identify various watershed attributes—both with regard to water (including reservoir retention and in-stream loss factors) as well as land (nutrient delivery from land to stream). This model can use NHDPlus attributes to estimate useful nutrient values at ungaged stream locations (Preston et al 2009).

StreamStats is web-based GIS tool used to quickly and easily acquire hydrologic statistics for both gaged and ungaged stream locations on a water network such as NHDPlus. It is the results of a cooperative effort between the USGS and ESRI (the makers of ArcGIS). Using the Arc Hydro data model and associated tools, StreamStats reports previously published information when a gaged location is chosen, and will delineate a basin, compute basin characteristics, and estimate streamflow statistics for ungaged locations. StreamStats has a Web services aspect which may allow other tools to be developed that rely on StreamStats functionality to, for example, return the same results from a single mouse-click within a GIS instead of a Web browser. This added functionality can streamline GIS-based analyses (Guthrie et al 2009, Ries 2002).

The USGS has developed the Hydrography Event Management Tool that uses events—informational data linked to a network via linear referencing—with the NHD flowlines data. This connection between events and the NHD flowlines allows hydro-related data to be connected to the NHD data while taking advantage of the various benefits of the NHD datasets. When data are connected to the NHD using events, locational information (linear referencing) is stored, creating links between the two data. This tool allows for an alternative way of connecting data to lines. Instead of needing to have nodes, for example, an ID and linear reference value is all that is needed to represent data on a stream network without breaking or otherwise altering the network itself (NHD

2011). This tool is currently only available as a desktop application, but efforts are under way to make its functionality available via web services.

Another Web-based service that combines NHDPlus data with GIS is the WATERS (Watershed Assessment, Tracking & Environmental ResultS) Web Services. The EPA's Office of Water has provided several Web mapping services that use the NHDPlus data, along with its river reach addressing system, to perform various analyses and tasks. (WATERS services are detailed in section 2.3.2.2.) These services work well with ArcGIS, where the user can connect directly to the Web services and use their functionality. Using NHD-based data (with or without other data), users can use the current services to navigate up- or downstream on the network, index features, query NHD features, use WATERS spatial analysis services, and/or obtain count and summary statistics within specified boundaries (USEPA 2010)..

2.2.4 CUAHSI

The Consortium of Universities for the Advancement of Hydrologic Science, Inc. (CUAHSI) is an organization funded by the National Science Foundation which represents more than 100 U.S. universities and is charged with the task of developing infrastructure and services to further hydrologic science and education. CUAHSI introduced WaterOneFlow and WaterML to make data retrieval and publishing easier and straightforward (Whiteaker and To 2008).

WaterOneFlow is a set of Web services used to assist with obtaining hydrologic observations data from online data sources. This transfer process uses the language

WaterML—an XML schema that defines all that is used and needed for the WaterOneFlow services to function. WaterML is related to the Observation Data Model, which is used for storing observations data (Whiteaker and To 2008).

WaterOneFlow and WaterML can be used inside of a Web browser or within another application (e.g. within a GIS). The ability of use within a GIS allows for new possibilities of observations data access and sharing where locations of interest are stored in features, desired variables are specified, the time period of choice is input, and a geodatabase receptacle is indicated, and the associated tool gets the data. If this process uses WaterML, it will be able to use any WaterOneFlow Web service by virtue of complying with a common standard (Whiteaker and To 2008).

CUAHSI has developed HydroDesktop, a free, open-source hydrologic GIS application that utilizes the services and structure of CUAHSI web services. Data access via web services is coupled with plug-ins that provide analysis, visualization, and export options (CUAHSI 2011).

2.2.5 Australian Geofabric

Australia's Bureau of Meteorology is charged by the Australian Government to build a system to house all of the water information in the country. Specifics include the need to accurately monitor, assess, and forecast three main aspects of Australia's water resources: water availability, water use, and water quality. To help in this goal, individuals, organizations, and groups are asked to contribute their respective water information/data to a central hub for subsequent dissemination and widespread use. This collection is planned to represent every hydrologic feature and properly represent the connectivity between the features.

In order to accurately store and deliver the deluge of water data that will be generated and tracked in these efforts, the Bureau of Meteorology is establishing an Australian Water Resources Information System (AWRIS) that will contain data sets representing: hydrology and measurement sites for both surface water and groundwater; a digital elevation model (DEM) at 1 arc-second resolution; and key catchments. Having this information system is only one part of the overall solution, though; in order to have a meaningful way to analyze the water data in the information system, AWRIS will be spatially enabled by the geospatial fabric (Geofabric): a specialized set of geospatial GIS features that makes possible the necessary spatial relationships between key features (e.g. rivers, dams, lakes, aquifers, diversions, watersheds, catchments, gaging stations, and monitoring points). This geographic aspect of data storage and management will reveal the overall water balance—how water is stored, transported, and used throughout the country. In addition to surface water considerations, Australia is using Arc Hydro Groundwater to compile a national groundwater information system (Australian Bureau of Meteorology 2010, Vertessy 2010).

2.2.6 Base Maps

The concept of base maps can be introduced through Google Earth. Google Earth is a “virtual globe” computer application that enables geographic visualization by novice or advanced users. Using a collection of satellite and other aerial photos that provide varying degrees of accuracy—even for one earth location—Google Earth stitches these images (or tiles) together to provide a continuous, interactive map interface the both displays earth images and incorporates GIS data. As the user zooms in or out at a location, the cached images that provide the best or optimal resolution imagery are loaded to optimize understanding and speed of data transfer (To et al 2006, Haitling et al 2009).

Google Earth's genesis is traced to the early 2000's when it was known by another name and owned by another company, Keyhole, Inc. Although it is now a product of Google, its beginnings are perpetuated, at least in part, in the name of the XML-based language (KML: Keyhole Markup Language) used in Google Earth to annotate and connect other data (e.g. data points and lines) to the map view. Since being adopted by Google, Google Earth, and its sister, Google Maps, are becoming ubiquitous. This is seen in the many uses of mapping in the online arenas of direction finding, mapping website visitors' locations, and common instances of users instructing mapping sites to "show me my house." Google Earth also shows up in newscasts and other presentations where sites around the world are displayed, often coupled with related data (e.g. storm tracking showing historical and predicted paths of storms).

Central to Google Earth is the concept of having local data overlaid on data services data. In fact, placing data on top of an underlying map is at the heart of Google Earth; this is seen in the novice user's interaction with the application and how they can use Google Earth to get directions, visualize shopping locations, search for parks, or tour national points of interest. Each of these examples relies on some external data being coupled with the underlying maps, so that when viewed, the user sees a context-rich presentation of the map imagery and data—including points (e.g. location markers) and vector lines (e.g. roads).

Google Earth imagery can be used as base map data in conjunction with other GIS data and analytical tools. In their work on managing the health risks of the mosquito-borne Dengue fever in Nicaragua, Chang et al (2009) use Google Earth images as the starting point of a base map in ArcGIS, on which study-specific GIS data are placed to create neighborhood maps—even showing individual houses—to reveal spatial patterns regarding larval development and outbreak. In this application, ArcGIS was used with the Google Earth-based base maps because of the advantages that the GIS software provided, including ease on inputting GPS-collected data points, increased benefits of visual presentation, and readily available statistical functions.

In a study of flood inundation areas in Japan, Mori and Kameyama (2009) used Google Earth images as a base map. Moving in the opposite direction from Chang et al, Mori and Kameyama exported features available in GIS into Google Earth for analysis. Despite this difference, important analyses were afforded quick study due to the availability of Google Earth's tiled and base-map-ready images.

Since the release of ArcGIS 9.3, ESRI has made a collection of base maps available through their online resource center (ArcGIS Online). These maps are provided as part of a service that displays tiled map images behind GIS information within ArcMap or within map objects as part of web mapping—displaying a map in a webpage (ESRI 2010b).

In addition to the collection of base maps currently available (including world imagery, topography, and street maps), researchers at CRWR are currently collaboratively developing a hydro base map that will show hydro-related objects in a map behind user-specified data—acting as a view into the water landscape. The hydro base map may contain "streams, waterbodies, aquifers, watersheds, and other locational information that provide geospatial context for the observational data" (Dangermond and Maidment 2010). It is hoped that this hydro base map will provide added benefit to engineers and analysts working with water data who desire the rich benefits of joining tiled images with water-specific data. At the time of this writing, a version of the hydro base map is available for use within HydroDesktop. A screenshot is shown in Figure 2-6.

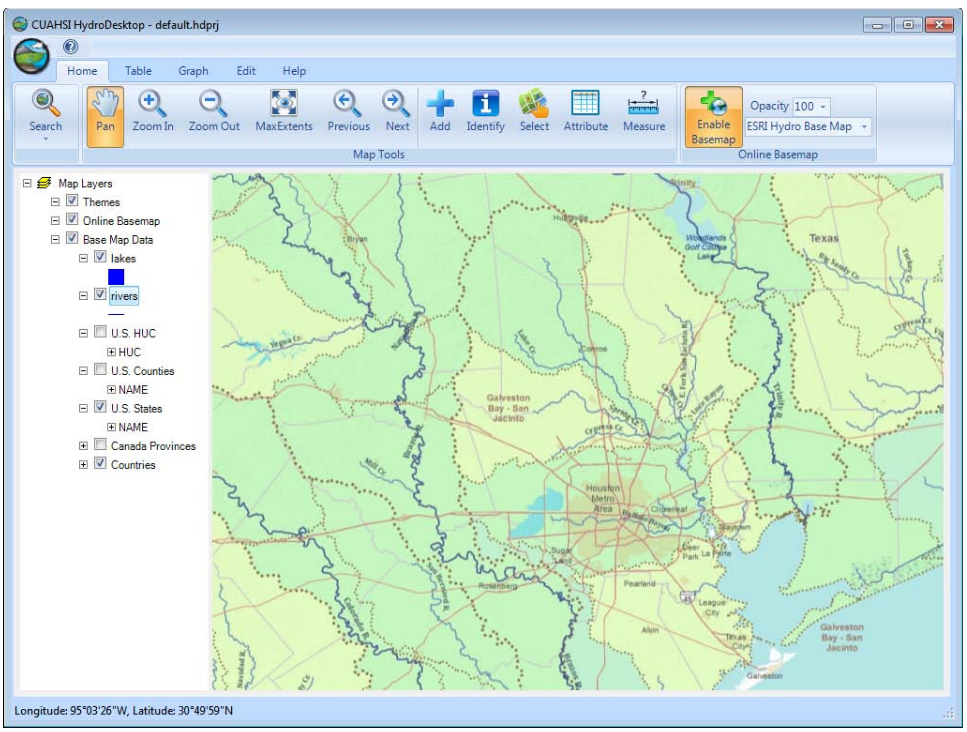


Figure 2-6. Hydro Base Map within HydroDesktop

2.2.7 USGS Water Census

The USGS Water Census is similar to Australia's efforts at gathering all water data to a central information system. While not an information system, the water census draws on water data from a variety of state, local, and national levels and should provide seamless water that spans jurisdictional and political boundaries, providing for more unified analyses. The information that the water census will provide will include water availability and water use trend data over recent decades which will contribute substantially to the forecasting efforts regarding availability of water for a variety of uses (USGS 2007).

In 2002, a committee on USGS water resources research published their findings and recommendations for estimating water use in the United States (USGS 2002). The stated goals of the group were to:

1. *Maintain a comprehensive national water inventory* – this is in addition to the surface and groundwater resources already inventoried. The purpose would be to better understand the effects of spatial and temporal patterns of water use.
2. *Help assure the nation's water supply* – this would be done through science-based assessments of the nation's water supply.
3. *Help preserve water quality and protect ecological resources* – the quality and quantity of water resources are closely related, and both influence aquatic ecosystems.

The goals and recommendations of this committee contribute to the water census of the United States. With the last assessment of the nation's water resources conducted in 1978, the 2007 strategy for the census seems appropriate. This census stems from the realization that water needs are no longer considered only on how humans are affected, but includes the importance of environmental purposes as well. To better understand the intricacies of the water resources in the United States, the water census provides knowledge and understanding to citizens, engineers, natural resources managers, and policymakers. The information that the water census provides is more than a status on water resources; it also includes water availability and water use trend data over recent decades which contributes substantially to the forecasting efforts regarding availability of water for a variety of uses. The water census focuses on the nation's 21 water-resources regions. Drawing on water data from a variety of state, local, and national levels, the National Water Census can be used to provide seamless water data that spans jurisdictional and political boundaries, providing more unified analyses (USGS 2007).

2.3 STANDARDS ORGANIZATIONS

Similar to how spoken languages have structure and rules that facilitate the sharing of information and thoughts, the purpose of standards (and standards organizations) is to ensure that technical barriers are limited and the sharing of information, ideas, or data can progress without the need of translation. When standards are used, progress is facilitated.

The need for standards in communication and the sharing of data is not new. The use of standards is more on the forefront with the increasing availability of communication and sharing media, rates of transfer, and access points. An example of such is the cross-boundary sharing of files over the Internet. Computers and software adhere to international standards to such precision that everyday users are essentially unaware of the very standards that make their regular computing and Internet use possible.

International standards organizations issue standards that the international community can adhere to in order to benefit from others' work as well as to share their own ideas and data. Two international standards organizations that are of import to this dissertation are the International Organization for Standardization (ISO) and the Open Geospatial Consortium (OGC).

2.3.1 International Organization for Standardization (ISO)

Headquartered in Geneva, Switzerland, the ISO was founded in 1947. As the world's leading developer of international standards, the ISO has over 17,000 published standards of various range and application that work to equalize the world as far as transparency and making known what practices and procedures are being used in almost every area of business, industry, and technology (ISO 2008).

One particular standard that is widely used in computer science is the Reference Model of Open Distributed Processing. Called RM-ODP (or by its ISO publication number, ISO/IEC 10746-1:1998), this model provides a framework for how multiple systems (or computers) can interact and share information while working together on a network.

The RM-ODP is a framework for the standardization of open distributed processing (how many computers can interact on a network). This model, shown in Figure 2-7, provides five views of the system and its environment which are complimentary to one another and work together to describe the overall system.

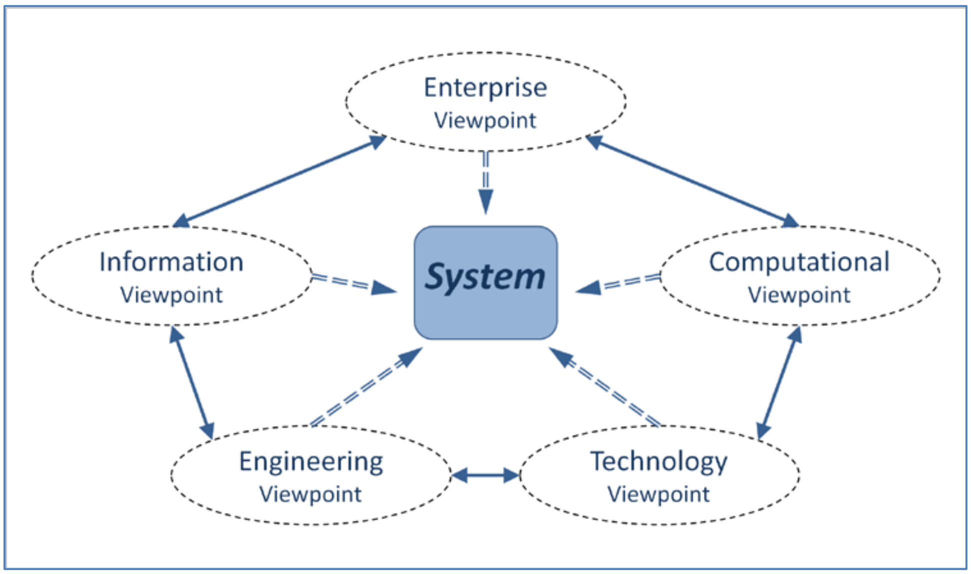


Figure 2-7. RM-ODP: Complimentary View

The five viewpoints shown in Figure 2-7 are explained below:

- Enterprise viewpoint – describes the general view of the effort and outlines its purpose, scope, and objectives; this viewpoint can answer the what, why, who, and when questions through use cases.
- Information viewpoint – describes the information elements and how they will be used, managed, and structured.

- Computational viewpoint – describes how the system will function; this can be done by explaining how each individual part of the system will work.
- Engineering viewpoint – describes how communication occurs between system entities through specific languages and functions.
- Technology viewpoint – describes which technology will be used to implement the system (e.g. specifies the various software, network, and hardware components).

Having established and explained each of the viewpoints in the RM-ODP, developers work toward the type of standardization that enables sharing of products, ideas, and data.

2.3.2 Open Geospatial Consortium (OGC)

Founded in 1994, the Open Geospatial Consortium, Inc. (OGC) is an international consortium of 420 companies, government agencies, and universities striving to develop publicly available interface standards. The overall purpose of the OGC is to make geographic spatial information and services both accessible and useful across a broad spectrum of uses and applications. When properly implemented in application development, the standards and documents that the OGC produces make for "plug and play" applications—even if such applications are created by two completely independent entities (OGC 2011).

As an international standards organization, the OGC has adopted the use of the RM-ODP in its internal development processes. Figure 2-8 shows an OGC image highlighting the viewpoints of the RM-ODP as part of three categories, and showing brief descriptions (OGC 2011b).

Figure 2-8. RM-ODP Grouped View

In addition to working in harmony with other standards organizations, the OGC has an extensive collection of standards. Examples of these standards are expounded upon in the following section.

2.3.2.1 ESRI and OGC Standards

As a leader of GIS technology and services, ESRI aims for interoperability with geo-enabled software and services. As such, it has produced a white paper that outlines a list of OGC and ISO standards it supports (ESRI 2010c). A selected list of such standards and services follows:

- Web Mapping Service (WMS)
- Web Feature Service (WFS)
- Web Coverage Service (WCS)
- Web Processing Service (WPS)
- Geography Markup Language (GML)
- Keyhole Markup Language (KML)

These standards and services are used in sharing all manner of geo-enabled data. Each is described briefly here:

Web Mapping Service (WMS) – The OpenGIS Web Map Service Interface Standard (WMS) provides a way to obtain geo-referenced map images over the Internet. This service responds to two primary requests: GetCapabilities, which returns parameters about the service itself; and GetMap which returns a map according to the specified parameters. The resulting map image(s) that are obtained from a map server can be viewed in an Internet browser or a GIS application like ArcMap. It is important to note that the results are map images, meaning that they do not carry attributes or parameters for the data they represent and they cannot be edited or used in spatial analysis (i.e. one cannot see an attribute table for a river shown in an image) (OGC 2004).

Web Feature Service (WFS) – The OpenGIS Web Feature Service 2.0 Interface Standard (WFS) provides a way to obtain GIS features over the Internet. These are features that can be edited and used in analyses. The WFS allows for multiple operations: discovery operations, which return the service's capabilities (e.g. GetCapabilities and DescribeFeatureType); query operations, which return the feature itself or metadata (e.g. GetPropertyValue, GetFeature); locking operations, which provide ways to modify or delete features; and transaction operations, which are used to create, change, replace, or delete features from the data source. One of the benefits of WFS is that it provides a way to obtain and share features, allowing the requestor to specify which are desired exactly, and obtain only what is wanted, instead of the possibility of getting much more than was desired (OGC 2010).

Web Coverage Service – The Web Coverage Service (WCS) Implementation Standard provides a way to access coverage or gridded data over the Internet (coverage refers to a way of storing thematically associated data; gridded data refers to elevation data, flow direction rasters, etc.). The three main WCS operation types are: GetCapabilities, which returns parameters about the service and its coverages; DescribeCoverage, which returns detailed metadata about a specified coverage; and GetCoverage, which return the coverage or gridded data according to specified parameters (OGC 2010b).

Web Processing Service (WPS) – The Web Processing Service was originally called Geoprocessing Service, but was changed to avoid a confusing acronym, GPS (widely used to denote global positioning system). The previous name helps in defining what a WPS does, though; a WPS combines geoprocessing—or any calculations or computations on geographic data—with web services. A WPS can be thought of as geoprocessing that occurs in the cloud, or on an online server (OGC 2007).

Geography Markup Language (GML) – The OpenGIS® Geography Markup Language Encoding Standard (GML) is an XML-based language and schema that is used to describe and encode geospatial information and data. GML can be used to share geographic information between systems or users independent of the software being used. GML is vital to the services provided by the OGC (OGC 2007b).

Keyhole Markup Language (KML) – Like GML, KML is an XML schema used for visualizing and annotating geographic images originally in Google Earth.

Once data are acquired, GIS users typically employ any number of geoprocessing steps as part of their geographic analyses. Geoprocessing is simply the process whereby geographic data is transformed—typically through the use of a geoprocessing tool—yielding a new dataset as a result. This simple process is illustrated in Figure 2-9. Please note that while the idea of geoprocessing is simple, not all geoprocessing models are; multiple geoprocessing tools can be linked together in ArcMap's Model Builder to perform complex analyses that are quite complicated.

Figure 2-9. Geoprocessing Illustration

2.3.2.2 WATERS: NHDPlus and OGC Standards

WATERS, or Watershed Assessment, Tracking & Environmental ResultS, include a collection of OGC-compliant web, mapping, and database services that function specifically with the NHDPlus dataset (USEPA 2010).

Of the many services that WATERS provides, the following are of particular importance to this dissertation:

- Point Indexing Service – This service provides a function for linking/snapping a point to the National Hydrography Dataset in one of two ways: 1) via the shortest geographic distance; or 2) via raindrop tracing which uses the NHDPlus flow direction grid to trace to the nearest stream along a water path. This service returns the point on the NHD, information about the path to the NHD, and the information associated with the NHD flowline.
- Navigation Service – This service allows for traversing a standard stream network. Requests to this service may include information as to where to begin the traversal, along with descriptors of where and how to stop.
- Navigation Delineation Service – Building upon the Navigation Service, this service utilizes the NHD catchments and their topological connections to delineate drainage areas for the NHD.
- Upstream/Downstream Service – This service can be used as a stand-alone service, but it is fundamental to other WATERS services (including the navigation services, above) and provides standard stream network

traversal and discovery functions. Requests to this service may include information as to where to begin the traversal, along with descriptors of where and how to stop.

The WATERS services listed above can be used for the basic hydrologic task of basin delineation. Note that the downstream-most point of any analysis, while inside of an NHD catchment, will not ultimately be the newly delineated basins outlet point; these services use the NHD on a catchment-level, so the catchment containing the point will either be included or excluded from the delineated basin, depending on the input supplied by the user or service.

CUAHSI's HydroDesktop has an extension, or plug-in, that utilizes the functionality of the WATERS web services. Called EPA Delineation, this tool provides an interface where a user can click anywhere on a map and the web services find the nearest NHD stream (using Point Indexing Service), traverses the NHD stream network (using Upstream/Downstream Service), and delineates a basin from NHD catchments (using Navigation Delineation Service). Figure 2-10 shows a screenshot of HydroDesktop and a basin delineated using the EPA Delineation tool (CUAHSI 2010).

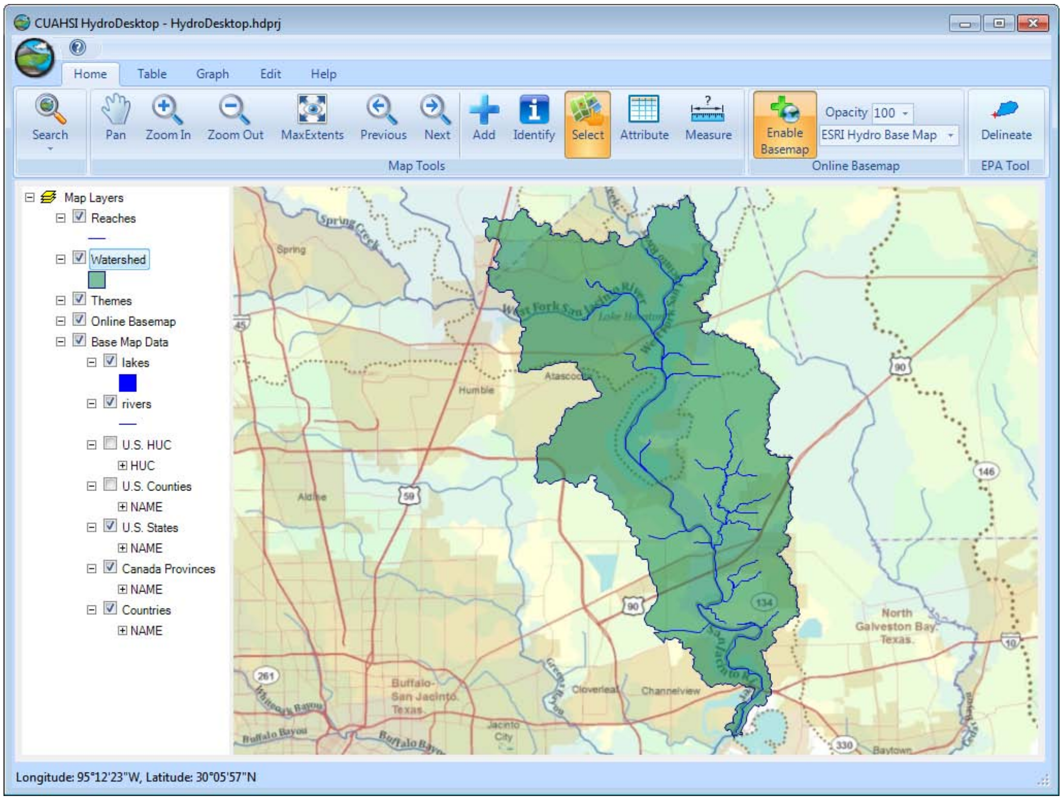


Figure 2-10. WATERS Services in HydroDesktop

2.4 SUMMARY

This literature and technology review presented research, information, and tools relevant to the research presented in this dissertation. Maps are useful in understanding and representing the water rights data of Texas. The combination and analysis of maps and data is facilitated through the use of GIS. The seven information models outlined in this literature and technology review illustrate how the application of water resources questions is not limited in geography to Texas or even the United States; rather, their growth and application represent an interwoven tapestry of water science that can benefit decision makers in dealing with the complex water needs in Texas, the United States, and across the globe. A discussion on standards organizations highlighted the benefits that are obtained when communication is facilitated—between individual users or data providers as well as between users and geoprocessing services.

Despite the benefits that these information models and tools provide, they lack a unifying framework. The data access made possible through innovations in data sharing and online computing (via web services and international standards) requires an updated hydrologic geospatial information model to handle these changes and perpetuate the theme of data availability that the Web 2.0 movement has triggered. This dissertation addresses this need through a case study of water availability modeling in Texas, using Arc Hydro Web, an information model developed with historical information models in mind, that can be used with GIS for storing and representing Texas water resources data and analyses.

Chapter 3. Methodology

3.1 INTRODUCTION

This chapter contains five sections: this introduction; a section on Texas water availability modeling which describes and defines the conceptual model of the Texas water rights management and water availability modeling environment; a section that builds upon the conceptual model discussion in defining a Hydrologic Information System (HIS) for Texas water availability modeling; a section describing how the framework and key data layers of Arc Hydro are adapted—from a Texas water availability modeling standpoint—to meet the changes in availability and access of hydrologic data; and a section outlining a reference model of open distributed processing (RM-ODP) for the Arc Hydro Web information model using the water availability model of Texas.

The section on the Texas water availability modeling conceptual model (section 3.2) addresses the first research question of this dissertation by outlining the participating components in the Texas water availability modeling conceptual model through an historical look at Texas water availability modeling. Furthermore, section 3.2 shows how the tools that were developed to incorporate the various components of the Texas water availability modeling environment are automated and synthesized to form a more connected whole as key aspects of a Hydrologic Information System (HIS) for Texas (along with the data they incorporate). A part of the third research question on web-informed desktop analyses is demonstrated briefly in section 3.2 in the discussion on the Texas Flow Regimes Tool. The third research question is further demonstrated in the presentation of an information model—Arc Hydro Web—for incorporating web and desktop data (section 3.4). Parameters for demonstrating the effectiveness of this information model are presented as an RM-ODP in section 3.5, which is used as an application / example in Chapter 4.

3.2 CONCEPTUAL MODEL OF TEXAS WATER AVAILABILITY MODELING

This section presents the conceptual model of Texas water availability modeling by examining the various components as responses to an historical progression, outlining the tools and processes that have been developed to connect the components of Texas water availability modeling in useful ways. The conceptual model is developed as three smaller pieces for the water availability model, for the WRAP network, and for the instream flows and flow regimes process. These three individual conceptual models are then combined as an overall conceptual model for water availability modeling in Texas.

3.2.1 Texas Water Availability Modeling Transition

Whether considering historical or current management of water rights data in Texas, two components are of primary importance: water rights data, including the various specifics of the right: location, quantity of water, time of withdrawal, and purpose of use, and the associated network the points participate in, be it a geometric network or an inferred topologic network, e.g. tracking which rights are upstream or downstream of each point.

Historically, water right management steps in Texas were similar to those described in the Introduction where water right holders' data were stored on paper sheets (see Figure 1-1) and Mylar maps were referenced to determine topological relationships (which rights were upstream and downstream). This process was painstaking and potentially error-prone.

Despite the difficulties of the historical process, the key is to understand the relationship between the water rights data and the network. It is essential to know the topological connections or order of water rights on the network to determine how one right influences another—this is particularly important when considering the prior appropriation water rights system used in Texas where some water rights are senior to others, meaning that holding a water right is not a guarantee of receiving water, depending on the order rank of the right in relation to other rights on the stream network.

The transition to digitally-managed data via water rights databases eliminated some of the tedium of manual traces of stream networks. The results of this transition include five components in the Texas water availability modeling environment that help describe the character of the intellectual problem addressed in this dissertation; they are:

1. A water rights database has been developed which describes each water right individually. This database is the digital equivalent of the paper records depicted in Figure 1.1;
2. There is a GIS database (geodatabase) for Texas, called StratMap; the development of which directly resulted from Senate Bill 1 to provide a digital basis for water management across Texas (this bill and others are addressed in

following sections). This geodatabase replaces the map equivalent of the paper records represented in Figure 1.1;

3. A computer model, Water Rights Analysis Package (WRAP), exists that simulates monthly flows in Texas rivers over many years—using historical data—to quantify the availability of water for each water right under various scenarios;
4. There is an official water availability model for Texas that includes the WRAP model and associated input files for Texas basins. This model gives probabilistic water reliabilities under various scenarios and is used in surface water appropriation; and
5. There is an environmental flows assessment process designed to quantify how much water should be left in Texas rivers as instream flows and not allocated for withdrawals.

These five components are shown as graphical representations in Figure 3-1, and described in more detail throughout the following conceptual model discussion.

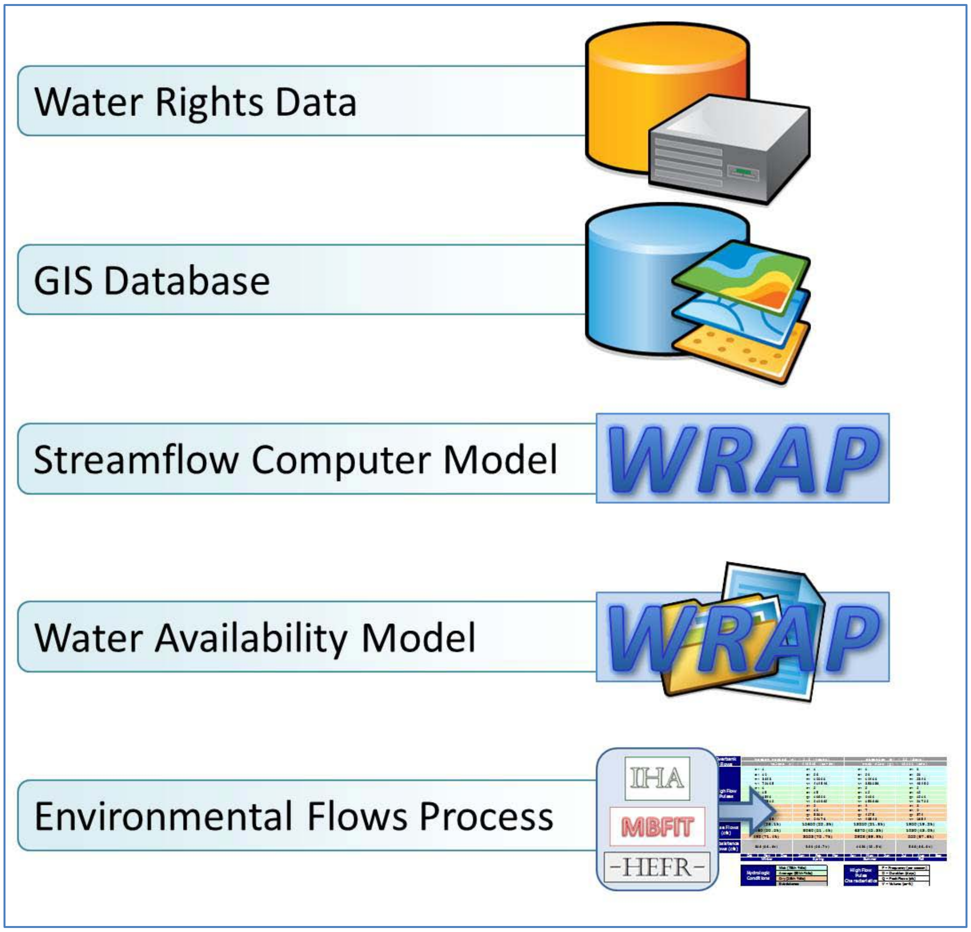


Figure 3-1. Components of Texas Water Availability Modeling

3.2.2 Texas Senate Bills

Beginning with the response to a hard year of drought in 1996, the Texas legislature passed a series of Senate bills which have considerable impact on water management in Texas. These three Senate bills have shaped the way that current water resources management and modeling are performed: Senate Bill 1 (in 1997), Senate Bill 2 (in 2001), and Senate Bill 3 (in 2007). These bills, respectively, resulted in the development of basin water availability models for all basins in Texas, established the

Texas Instream Flow Program and mandated flow regime recommendations, and created the current environmental flows assessment process and established an Environmental Flows Advisory Group which oversees its implementation—this group is commissioned to work with stakeholders in Texas basins in developing recommendations for environmental flow protection (Texas State Legislature 1997, Texas State Legislature 2001, and Texas State Legislature 2007).

3.2.3 Senate Bill 1 and the Texas Water Availability Model

Passed in 1997—after a particularly hard year of drought—Senate Bill 1 changed the way that many aspects of water planning were performed, including the implementation of an official state water availability model, the Water Rights Analysis Package (WRAP) and associated input files for Texas basins. At its core, the water availability model of Texas is geographically-based; the water availability model input files contain hydrologic information and geographic data. The hydrologic information includes such things as naturalized streamflow (the streamflow that would theoretically exist without anthropogenic factors considered), evaporation, reservoir levels, and the prior appropriation water rights data. The geographic data includes the topologic connectivity of water rights in a text-based virtual stream network (Wurbs 2009).

The model side of the Texas water availability model, WRAP, is a suite of advanced computer programs that does more than analyze water rights; it uses the water availability model input files to produce output that is useful in estimating quantities of water in river systems under various scenarios (for a more detailed narrative of the water availability modeling process using WRAP, see section 4.1). This model represents Texas water management by representing water rights, reservoirs, instream flows, and control points in structured input files ingested by the model. All of the real-world hydrologic entities (water rights, reservoirs, diversions, return flows, instream flows, etc.) are assigned control points. For example, water rights are assigned control points at the location on the river where the water is withdrawn, regardless of where the actual water right holder location may be. A single control point can correspond to multiple entities, providing they all are coincident at that stream location; thus there is a one-to-many cardinality between the control points and other points they represent in the model (other points are reservoirs, water rights, and instream flows).

The way that water withdrawal rights are managed may cause some confusion when representing the withdrawal point in a GIS. For example, in addition to specifying one distinct location, water rights can be written to allow water withdrawal from multiple locations. One water right may allow water to be drawn from any location on the boundary of a reservoir. Another could specify withdrawal anywhere along a certain length of river. A third could specify multiple withdrawal locations on different rivers. These varied scenarios require intelligent representation in GIS.

GIS features representing water right withdrawal locations account for various withdrawal possibilities. For example, water rights from reservoirs are represented as a point at the reservoir outlet location; withdrawal along a river length corresponds to upstream and downstream boundary points (with attributes indicating which is which while using the same water right code); multiple withdrawal locations on different rivers are represented as multiple GIS points at each location (where each point has the same water right code with an added code value of 001, 002, and 003, to each of three locations, for example).

The cardinality of WRAP control points is represented in Figure 3-2 where the number of instream flows (IF), reservoirs (RES), and water rights (WR) are shown to exceed the number of control points (CP) that are used in the model to represent the collection of points. This collection of control points define the spatial configuration of a river system by specifying the point itself and its next downstream neighbor; thus the text-based virtual stream network is established through ID relationships—not a geographic (map) display (Wurbs 2009).

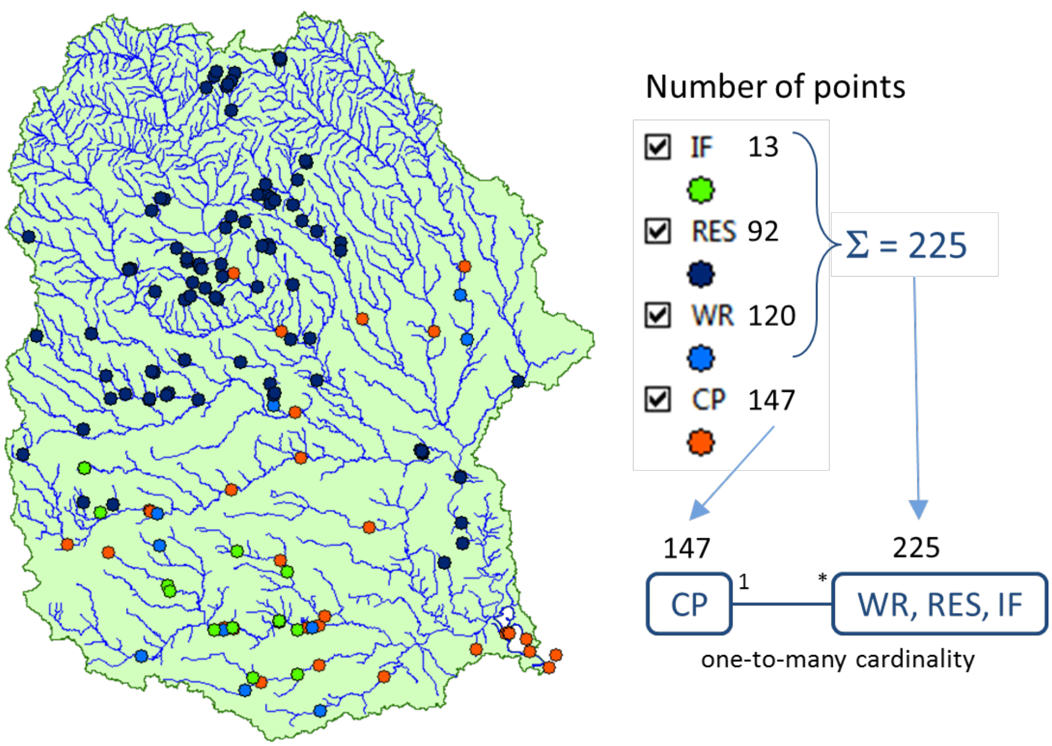


Figure 3-2. Cardinality of WRAP Control Points

The input files of the WRAP model use ID values to maintain connectivity. Each control point has a value assigned to it, NextDownID, that corresponds with the ID number of the next downstream control point. This connectivity is a representation of a stream network. These relationships are recorded in ASCII text files, but they are illustrated in Figure 3-3 where the red lines connect points with their next downstream neighbors. The inset attribute table demonstrates the relationship between the object ID (OID) and the ID of the next downstream point (NextDownID).

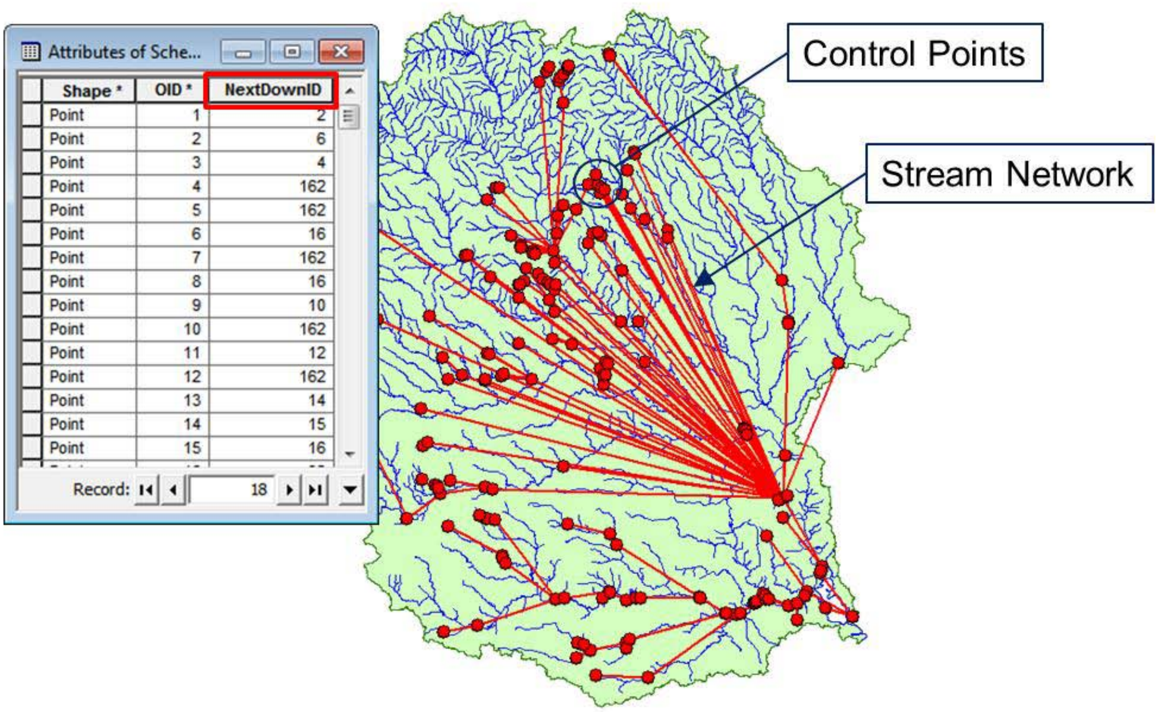


Figure 3-3. Schematic Network Representation of WRAP Points

In addition to the geospatial property of connectivity, the water rights control points in the WRAP model have drainage areas assigned to them. The drainage area values are used in transferring values or properties from one point to another. For example, naturalized streamflows are transferred from locations where streamflow values were recorded to upstream ungaged locations. Figure 3-4 shows drainage areas associated with WRAP points.

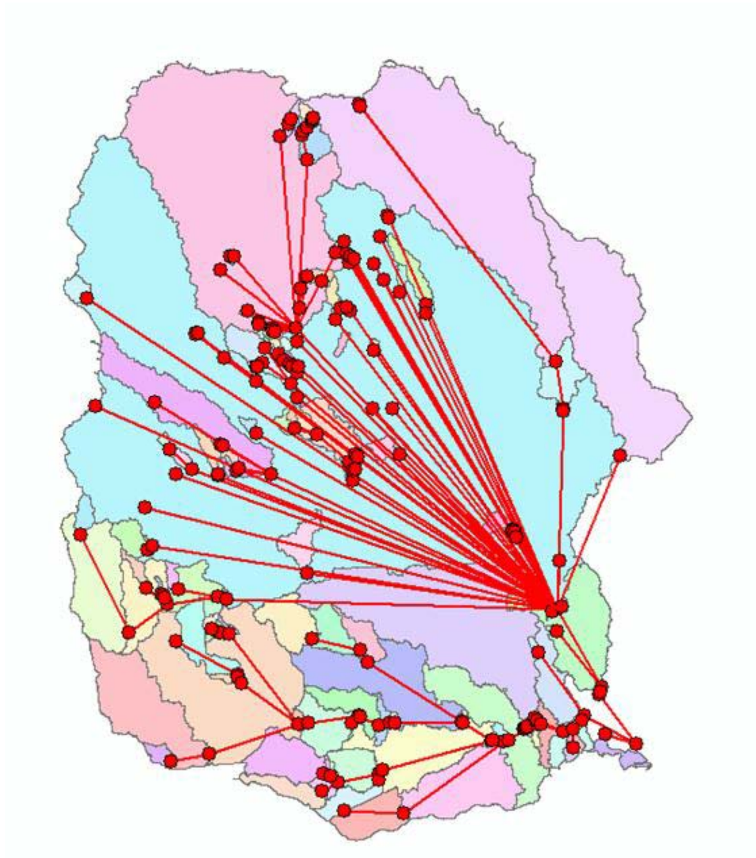


Figure 3-4. Drainage Areas of WRAP Points

The WRAP simulation model, shown as a flowchart descriptive diagram of WinWRAP (the Microsoft Windows user interface to WRAP's three process programs) in Figure 3-5, is used in the current water planning process for the state of Texas, and is composed of a suite of models (Wurbs 2009).

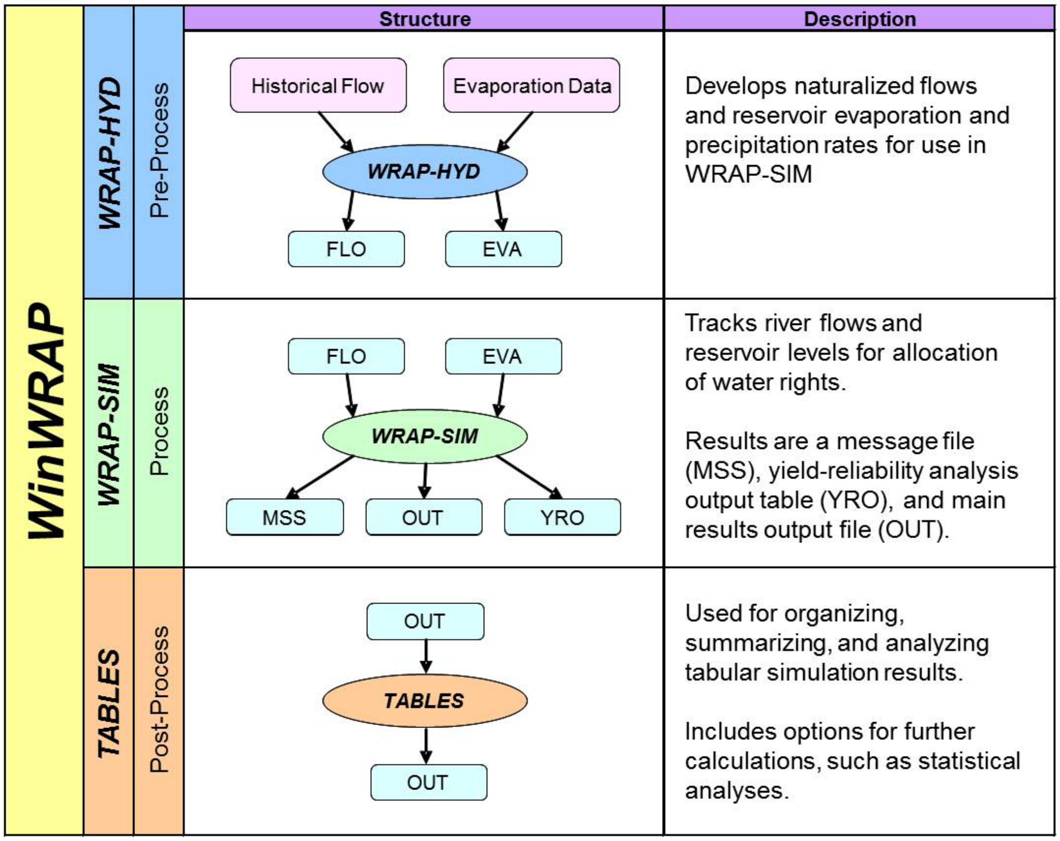


Figure 3-5. Overview of WRAP

It is useful to note that each of the files associated with WRAP (shown in Figure 3-5) are ASCII text files; while they are geographically based, they are not inherently linked to any geographic representation. Despite this, the inputs to WRAP are associated with geospatial properties of the points they represent (e.g. drainage areas).

The WRAP model uses historical streamflow values that have been naturalized (had anthropogenic effects removed). The collection of naturalized flows values are calculated from historic USGS flow values. Because the points in the WRAP model are not necessarily at USGS stream gages (where the naturalized flows have been calculated), the model includes a distribution process where calculated naturalized flows values are applied at ungaged locations using the drainage area ratio method (where the values at ungaged locations are a ratio of the naturalized USGS gaged values based on the relative drainage areas of the ungaged location to the USGS gage location). The process of streamflow distribution is shown in Figure 3-6 as part of an overall graphic representing the conceptual model of the water availability model of Texas. This figure is also used later as part of an illustration demonstrating the overall conceptual model for water availability modeling in Texas.

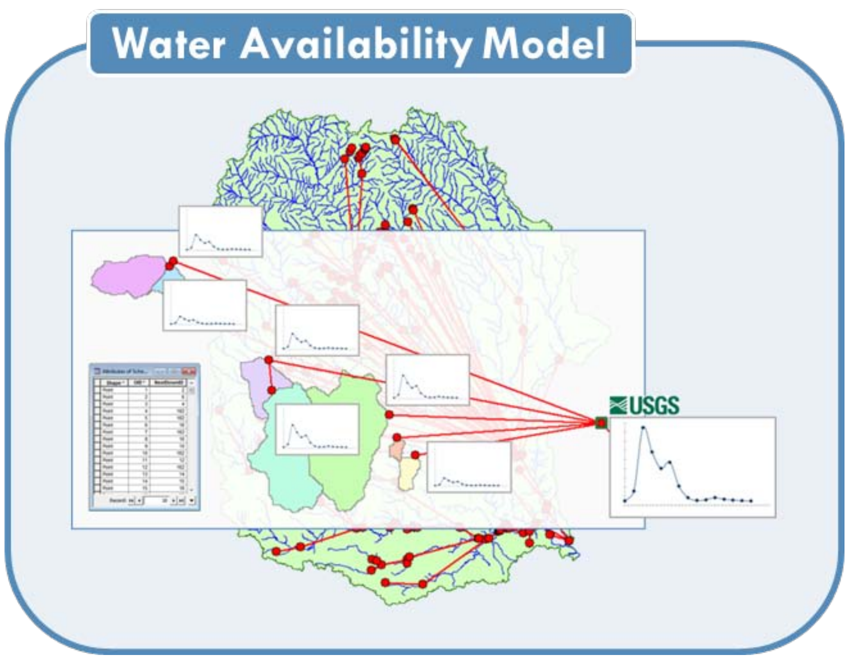


Figure 3-6. Water Availability Modeling Conceptual Model

Figure 3-6 represents how the water availability model captures the schematic network connectivity of points in the basins (represented by the red points and lines), the geospatial properties associated with each point (drainage area in this case), as well as the distribution of naturalized streamflow values from USGS gages to ungaged WRAP-modeled points.

As a review, Senate Bill 1 advanced Texas water rights management to digital representations of hydrographic data—the data can be represented as points on the traditional data cube: what, where, and when—but such remained as ASCII data files and were lacking a visual component.

As part of the WRAP process, geospatial input files for each Texas basin—in ASCII format—are fed into a series of analytic programs, and a single ASCII output file is produced that represents multiple variables of modeled hydrologic data in four categories: water rights, instream flows, control points, and reservoirs. Each of these variables can be thought of as a point on the data cube. This overall process is depicted visually in Figure 3-7, where the structure of the ASCII output file is shown as color-coded groups in the WordPad screenshot.

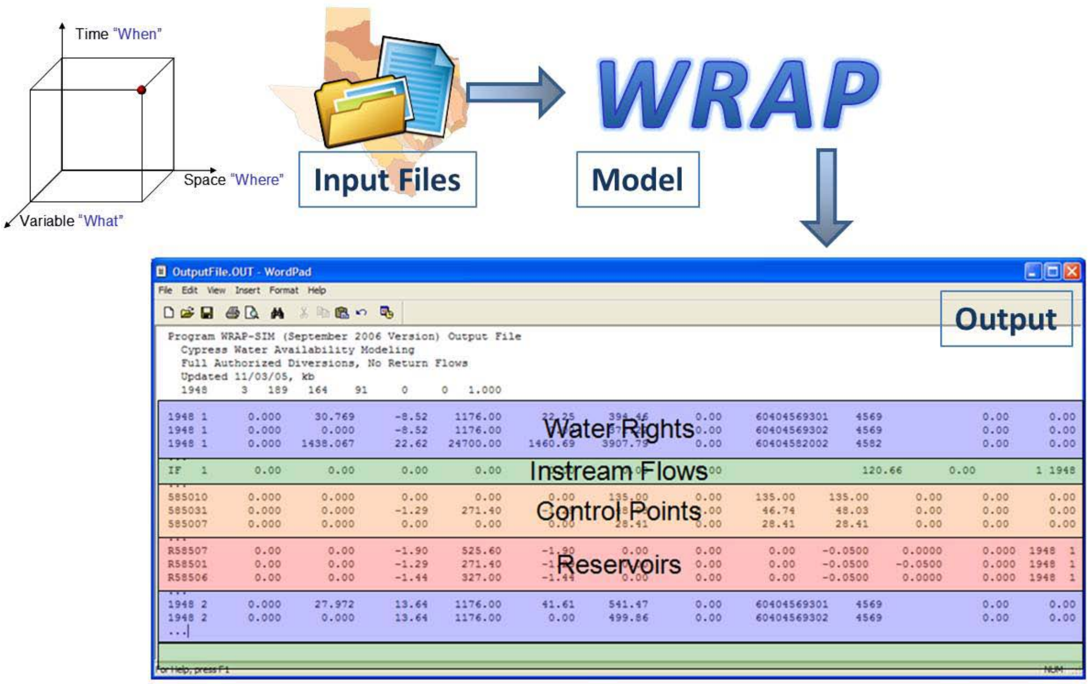


Figure 3-7. Overview of WRAP Process

3.2.4 WRAP Display Tool

The author's master's thesis examined the WRAP model and its output file as part of a space-time analysis, focusing on data visualization using a GIS toolset called the WRAP Display Tool. The repeating nature of the data in the output file enables it to be parsed programmatically and linked to GIS data. This is one of the functions of the WRAP Display Tool, an ArcMap toolset designed to translate the WRAP output into geodatabase tables and provide tools to visualize the data in space and time (Siler 2008).

Each of the variables in the WRAP output file can be considered as a distinct plane in the data cube. The variables can be thought of as a plane—instead of a point—because a single variable can represent time series for any location. On the other hand, specifying a single variable value at a given time and place would be the equivalent of a single point in the data cube.

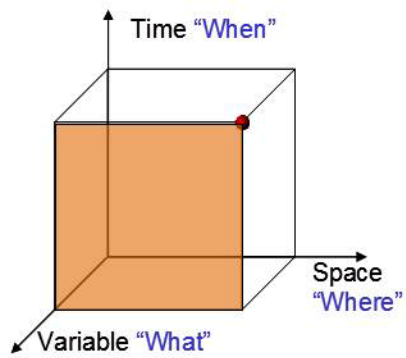
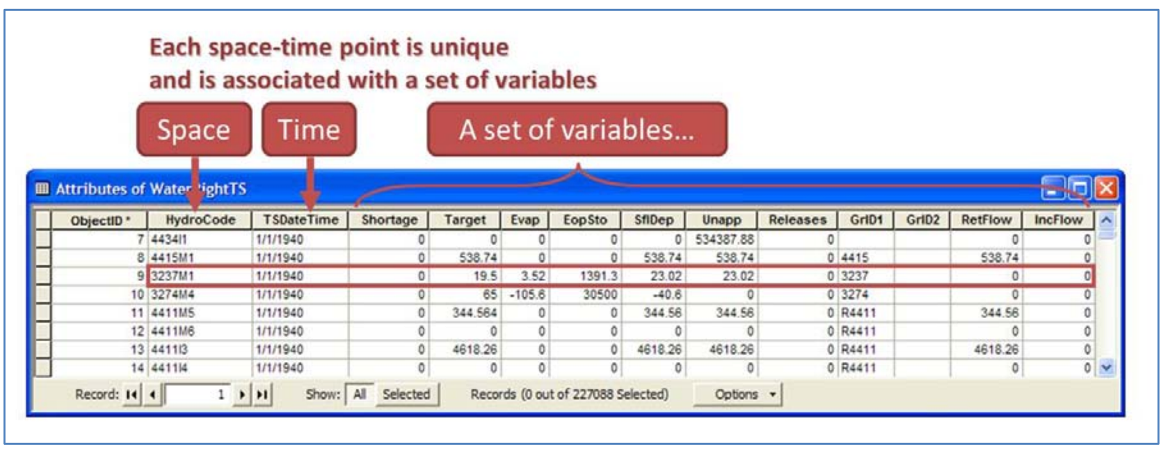


Figure 3-8. WRAP Data Variables as Data Cube Planes

Figure 3-9 shows one of the WRAP Display Tool's functionalities: a geodatabase expansion view of the WRAP ASCII output file shown in Figure 3-7. This geodatabase table is ingestible by ArcMap and represents many variables grouped together by space (HydroCode) and time (TSDateTime), as shown in Figure 3-9.



ObjectID *	HydroCode	TSDateTime	Shortage	Target	Evap	EopSto	SflDep	Unapp	Releases	GrID1	GrID2	RetFlow	IncFlow
7	4434I1	1/1/1940	0	0	0	0	0	534387.88	0			0	0
8	4415M1	1/1/1940	0	538.74	0	0	538.74	538.74	0	4415		538.74	0
9	3237M1	1/1/1940	0	19.5	3.52	1391.3	23.02	23.02	0	3237		0	0
10	3274M4	1/1/1940	0	65	-105.6	30500	-40.6	0	0	3274		0	0
11	4411M5	1/1/1940	0	344.564	0	0	344.56	344.56	0	R4411		344.56	0
12	4411M6	1/1/1940	0	0	0	0	0	0	0	R4411		0	0
13	4411I3	1/1/1940	0	4618.26	0	0	4618.26	4618.26	0	R4411		4618.26	0
14	4411I4	1/1/1940	0	0	0	0	0	0	0	R4411		0	0

Figure 3-9. WRAP Output as a Geodatabase Table

With the data organized as a collection of geodatabase tables, the functionality of GIS is utilized to represent the WRAP data in space or time, with processes automated by the WRAP Display Tool. Figure 3-10 shows a plane of the data cube for a single variable (with Time and Space axes) and corresponding representations of WRAP output data in time and space. The graph on the left is a representation of a model output value for a single point or collection of points (space) over time, and the map on the right represents a model output value at a time step or time period (time) over space.

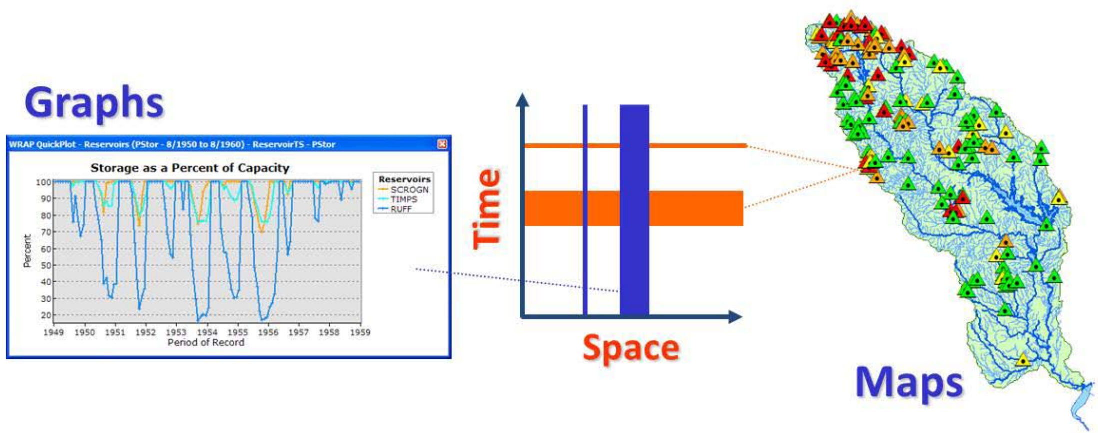


Figure 3-10. WRAP Output as Graphs and Maps

The WRAP Display Tool is successful at representing WRAP data in an adapted version of the Arc Hydro information model which links the water rights database with a GIS network of streamlines, but its flaws are that the WRAP ASCII output itself is space-delimited and extremely sensitive to change. This requires that the WRAP Display Tool be explicitly hard-coded to read the specific output of WRAP, limiting its functionality for other non-WRAP applications. In other words, the WRAP Display Tool follows a specifically-applied information model for the Texas water availability modeling process and its output.

3.2.5 Texas StratMap

In addition to the state's official water availability model, the results of Senate Bill 1 also include the Texas Strategic Mapping Program (StratMap). This collection of GIS base data—which provided a digital basis for water management across Texas and replaced the map equivalent of Figure 1-1—is managed and maintained by the Texas Natural Resources Information System, part of the Texas Water Development Board. This collection of GIS data includes data related to transportation, political boundaries, hydrography, lidar and elevation, soils, and digital imagery (TNRIS 2011).

3.2.6 WRAP Network Tools

With Texas water rights data removed from paper documents and Mylar maps in cabinets and represented digitally in databases and as GIS feature datasets, the data can be synthesized and made available for network analyses. The WRAP input files represent topology—albeit as textual relationships in ASCII text files; in a GIS environment, the water rights data can participate in geometric networks and be subject to various network traces and analyses.

The WRAP Network Tools assist in the task of geographically selecting water rights (and the water right holders, by extension) as part of a process where the Texas Commission on Environmental Quality (TCEQ)—the environmental regulatory agency of Texas—sends notices in the mail to inform water right holders of various water-related specifics (e.g. changes to a water right, general policy changes, etc.). As an ArcMap toolset, the WRAP Network Tools are also used to prepare networks of streamlines and water right points for network analyses, as well as perform selective drainage area delineation for water right locations without needing to reprocess the entire basin—a useful function for WRAP analyses.

In order for network analyses to work properly, the point locations must be coincident with the network of streamlines. As many water right point locations in the TCEQ geodatabase do not lie exactly on the TCEQ network of streamlines when represented in GIS, the WRAP Network Tools documentation prescribes the use of proxy points—points that coincide with the streamlines (i.e. are snapped to the lines) and are related to the water right points via HydroID and JunctionID relationships that use one-to-many cardinality. Once the proxy points are in place, the network itself is broken at each proxy point location to ensure that the points will participate in network analyses. This concept is presented in Figure 3-11 where the blue points represent the water right holders' locations (WaterRights), and the red points represent where the respective proxy points (WRProxyMZ) are snapped to the now-broken network of streamlines. Also shown is a view of the points' attribute tables, illustrating the connection between them and demonstrating the one-to-many cardinality by JunctionID and HydroID relationships.

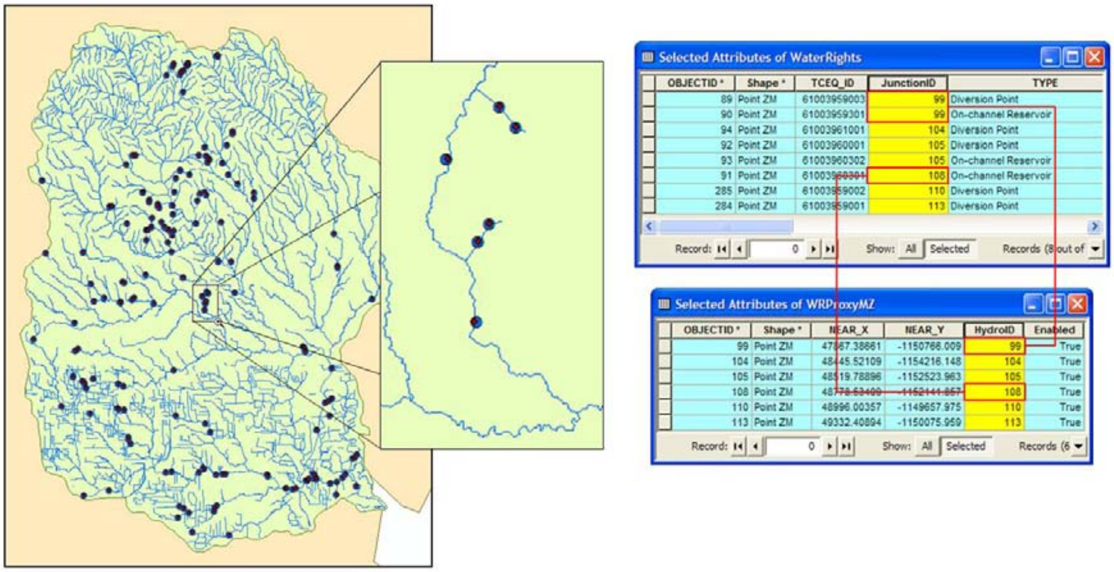


Figure 3-11. WRAP Network Tools Visualization

The WRAP Network Tools synthesize components of the overall Texas water availability modeling conceptual model and automate tasks that were previously time-consuming and error-prone by enabling traces on the Texas water rights network. These tools are used to intelligently select water right holders according to a prescribed set of conditions. However, the process of breaking the streamlines in the network, while useful for the purpose of network analyses, results in a separate network that requires independent update and preservation from a group perspective. In other words, TCEQ, the agency that uses this tool and manages Texas water rights, must have at least two nearly-identical networks—one for water availability modeling and WRAP network analyses, and one for other water-related studies (e.g. water quality)—resulting in lack of productivity from a network maintenance standpoint. Despite the unique network the

WRAP Network Tools process creates, the WRAP network analyses represent a distinct part of the overall water availability modeling conceptual model, shown in Figure 3-12.

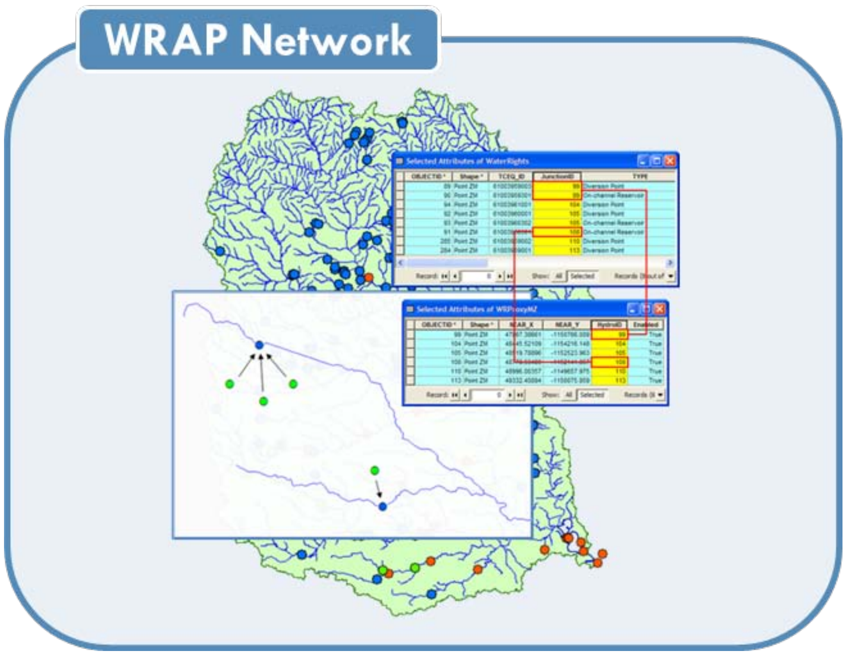


Figure 3-12. WRAP Network Conceptual Model

The WRAP network conceptual model, as depicted graphically in Figure 3-12, is meant to symbolize the interconnectivity of the water availability model points and the water rights database—including the one-to-many cardinality between the WRAP network points and the WRAP points and associated JunctionID/HydroID relationships.

3.2.7 Senate Bill 2 – Texas Instream Flow Program

Building on the advancements established in Senate Bill 1, the Texas Legislature passed Senate Bill 2 in 2001. This bill can be thought of as establishing the necessary science to understand the balance between human and environmental water needs through the use of instream flow recommendations—the base of the Texas Instream Flow

Program. These recommendations are to be the result of joint efforts between the Texas Parks and Wildlife Department (TPWD), the Texas Commission on Environmental Quality (TCEQ), and the Texas Water Development Board (TPWD) (TWDB 2009, Texas State Legislature 2001).

Instream flow is not the flow that occurs in streams; rather, it is water designated to support the entire stream ecosystem and maintain an ecologically sound environment. Instream flows can be thought of as flows that must remain in the stream and are, therefore, unavailable for appropriation as surface water rights. The instream flow recommendations include specifying flow regimes, which are designated flow values and flow timing. So, for example, instead of just specifying a given quantity of water flowing at a location indeterminately over the course of a year, instream flow regimes indicate when certain flow values must be met, and for how long (TWDB 2009).

3.2.8 Senate Bill 3 – Environmental Flows Advisory Group

Flowing naturally from previous Senate bills, the Texas Legislature passed Senate Bill 3 in 2007. Where Senate Bill 2 can be thought of as addressing water science, Senate Bill 3 is concerned with the implementation of water science on basins. This bill created an environmental flows assessment process and established the Environmental Flows Advisory Group—which contains state senators, state representatives, and state agency representatives—that oversees its implementation through the input of the Texas Science Advisory Committee (experts that provide technical guidance), Basin and Bay Area Stakeholder Committees (individuals representing interest groups of the basin), and Basin and Bay Expert Science Teams (technical experts that do the science analyses and support the stakeholder committees). These groups are commissioned to develop recommendations for environmental flow protection, including the use of flow regimes. These recommendations are submitted to the Texas Commission on Environmental Quality (TCEQ) and, if accepted, established as environmental flow standards (TPWD 2009).

3.2.9 Flow Regimes in Texas

As a result of the Texas Senate bills, a need arose for the analysis of flow conditions and the determination of flow regimes in Texas. Flow regimes are can be represented as a matrix that gives magnitude, frequency, duration, and timing of streamflows under various hydrologic conditions. Examples of flow regimes for the Roanoake River (USGS gage 02080500, Roanoke River at Roanoke Rapids, NC) for flows between 1911 and 2004 are shown seasonally in Figure 3-13, and monthly in Figure 3-14.

Overbank Flows	Return Period (R) : 23.5 (years)		Duration (D) : 15 (days)	
	Volume (V) : 999838 (ac-ft)		Peak Flow (Q) : 80400 (cfs)	
High Flow Pulses	F: 1 D: 4 Q: 16750 V: 130225	F: 2 D: 6 Q: 19100 V: 212133	F: 1 D: 6 Q: 18600 V: 172949	F: 1 D: 4 Q: 15275 V: 116227
	F: 3 D: 2 Q: 12000 V: 49587	F: 4 D: 4 Q: 13600 V: 90814	F: 3 D: 3 Q: 13000 V: 75442	F: 2 D: 2 Q: 11600 V: 41812
	F: 4 D: 1 Q: 10200 V: 21025	F: 5 D: 2 Q: 10625 V: 37235	F: 4 D: 2 Q: 10400 V: 36258	F: 4 D: 1 Q: 10000 V: 20232
Base Flows (cfs)	6470(33.4%)	7700(58.5%)	6950(48.5%)	5700(31.4%)
	4520(48.1%)	6250(69.5%)	5750(63.9%)	3850(47.8%)
	3220(62.5%)	4640(80.4%)	4100(79.2%)	2830(64.2%)
Subsistence Flows (cfs)	1760(88.7%)	1600(95.7%)	2070(97.3%)	2040(91.3%)
	Oct Nov Dec	Jan Feb Mar	Apr May Jun	Jul Aug Sep
	Winter	Spring	Summer	Fall

Hydrologic Conditions	
	Wet (75th %ile)
	Average (50th %ile)
	Dry (25th %ile)
	Subsistence

High Flow Pulse Characteristics	
	F = Frequency (per season)
	D = Duration (days)
	Q = Peak Flows (cfs)
	V = Volume (ac-ft)

Figure 3-13. Seasonal Flow Regime Matrix

Overbank Flows	Return Period (R) : 23.5 (years)						Duration (D) : 15 (days)					
	Volume (V) : 999838 (ac-ft)						Peak Flow (Q) : 80400 (cfs)					
High Flow Pulses	F: 1 D: 4 Q: 16750 V: 130225			F: 2 D: 6 Q: 19100 V: 212133			F: 1 D: 6 Q: 18600 V: 172949			F: 1 D: 4 Q: 15275 V: 116227		
	F: 3 D: 2 Q: 12000 V: 49587			F: 4 D: 4 Q: 13600 V: 90814			F: 3 D: 3 Q: 13000 V: 75442			F: 2 D: 2 Q: 11600 V: 41812		
	F: 4 D: 1 Q: 10200 V: 21025			F: 5 D: 2 Q: 10625 V: 37235			F: 4 D: 2 Q: 10400 V: 36258			F: 4 D: 1 Q: 10000 V: 20232		
Base Flows (cfs)	5728 (27.4%)	6265 (32.0%)	7080 (40.9%)	7480 (54.1%)	7720 (61.0%)	7990 (60.0%)	7630 (56.4%)	6840 (48.6%)	6220 (40.6%)	5873 (33.5%)	5500 (32.3%)	5590 (28.0%)
	4000 (40.8%)	4360 (47.9%)	5220 (55.7%)	5920 (66.6%)	6290 (71.7%)	6530 (70.1%)	6280 (68.7%)	5970 (65.1%)	4690 (57.8%)	4070 (51.0%)	3800 (49.6%)	3570 (42.6%)
	2930 (54.3%)	3145 (62.8%)	3730 (70.5%)	4450 (79.0%)	4520 (82.4%)	5120 (80.1%)	5030 (80.8%)	4650 (81.3%)	3410 (75.5%)	2960 (68.4%)	2810 (66.8%)	2690 (57.4%)
Subsistence Flows (cfs)	1840 (83.7%)	1580 (89.1%)	1550 (92.8%)	1640 (95.8%)	1690 (96.5%)	1525 (95.0%)	2010 (96.8%)	2130 (98.9%)	2130 (96.2%)	2075 (92.9%)	2060 (92.0%)	2030 (85.9%)
	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
	Winter			Spring			Summer			Fall		

Hydrologic Conditions	
	Wet (75th %ile)
	Average (50th %ile)
	Dry (25th %ile)
	Subsistence

High Flow Pulse Characteristics	
	F = Frequency (per season)
	D = Duration (days)
	Q = Peak Flows (cfs)
	V = Volume (ac-ft)

Figure 3-14. Monthly Flow Regime Matrix

The flow regime matrices present flow recommendations for many hydrologic conditions (wet, average, dry, and subsistence) for various components (TCEQ 2011):

- Overbank flows – infrequent, high magnitude flow events whose water levels exceed channel banks and result in water entering the floodplain.
- High flow pulses – short duration, high magnitude (within the channel) flow events that occur during or immediately after rainfall events.
- Base flows – represent average flow conditions in the absence of significant precipitation or runoff events.
- Subsistence flows – low flows that occur during times of drought or under very dry conditions.

The process of determining flow regimes for the different rivers of Texas is performed by separate groups, using a collection of models, and is subject to personal interpretation of data and specification of variable values in the overall process. The complexities associated with many options and variable specifications, combined with a lack of transparency and documentation creates flow regime results that can be difficult, if not impossible to reproduce.

The Texas Flow Regimes Tool was developed to assist with calculating flow regimes. It incorporates data extraction, containment of multiple models, and the tracking of steps taken. This tool combines web data extraction (e.g. daily flow values from the USGS) with multiple models, all housed within a single Excel workbook.

Figure 3-15 illustrates the steps of the Texas Flow Regimes Tool. First, the USGS gage number and time period of interest are input. The tool then gathers daily streamflow data via CUAHSI web services. The user can then inspect the data and manipulate input parameters for two models: Indicators of Hydrologic Alteration (IHA) from the Nature Conservancy, or Modified Base Flow Index with Threshold (MBFIT, created by Joe Trungale), which is a modified version of the US Bureau of Reclamations BFI Tool. These models are then run within Excel, where the models' output can then be examined and the user can select which output values to use for further analysis with Hydrology-based Environmental Flow Regime (HEFR). HEFR is a computational approach for creating flow regime matrices that is consistent with the Texas Instream Flow Program. HEFR is run via an Excel Add-In, which uses the user-specified data as input in creating flow regimes.

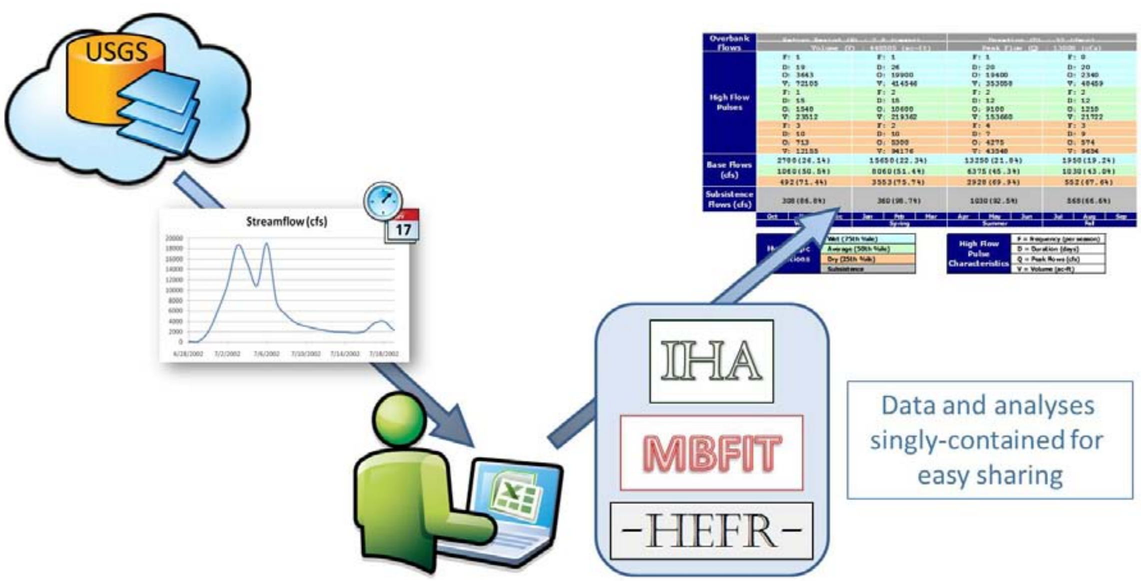


Figure 3-15. Flow Regimes Process

One of the reasons the Texas Flow Regimes Tool was created was to reduce ambiguity in knowing what intermediate steps were taken in the process of determining flow regimes. The Texas Flow Regimes Tool records which input parameters were used, which assists with replicating the process or reviewing what variable values were chosen. This tool demonstrates that multiple models linked together in a single location and workflow process have the benefits of reproducibility. This results in a start-to-finish view of analyses and results that can be fully-transferred and replicated.

Figure 3-16 illustrates the conceptual model of the flow regimes determination process of the overall water availability modeling process in Texas.

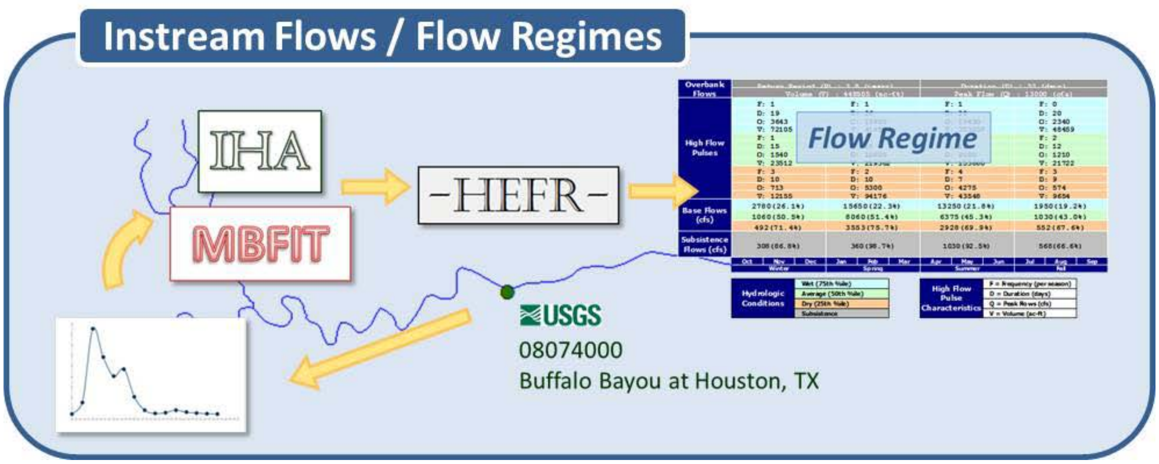


Figure 3-16. Flow Regimes Conceptual Model

3.2.10 Conceptual Model

This section has defined the individual pieces of the conceptual model for Texas water availability modeling. Taken piecemeal, these individual portions of the overall water availability modeling conceptual model may seem to be disparate and not part of an overarching whole; however, when presented together, as in Figure 3-17, these three components can further be analyzed as connections between the distinct parts are shown.

This representation of the water availability modeling conceptual model is composed of the conceptual models for the general water availability model, the WRAP network process, and the instream flows and flow regimes process.

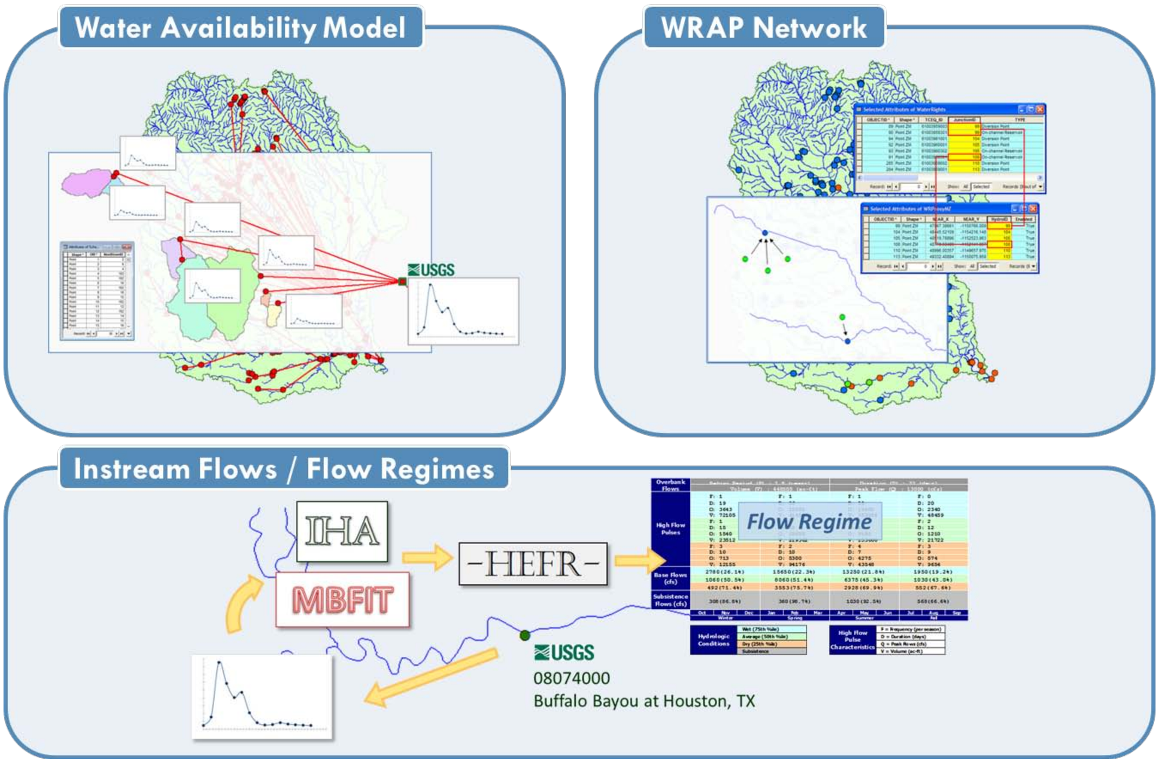


Figure 3-17. Water Availability Modeling Conceptual Model

The conceptual model for water availability modeling as outlined in this section and shown graphically in Figure 3-17 is in fulfillment of the first research question. This outlining was done by examining the various components as a response to an historical progression, outlining the tools and processes that have been developed to connect the components of Texas water availability modeling in useful ways.

In summary, the conceptual model for Texas water availability modeling makes connections between the five components that were historically loosely used together. These components (shown in Figure 3-1) are the water rights database which describes each water right individually; a GIS database for Texas; a computer model (WRAP) which simulates monthly flows in Texas rivers to quantify the availability of water for each water right under various scenarios; an official water availability model for Texas that includes the WRAP model and associated input files for Texas basins; and an environmental flows assessment process designed to quantify how much water should be left in Texas rivers and not allocated for withdrawals.

3.3 HYDROLOGIC INFORMATION SYSTEM FOR TEXAS WATER AVAILABILITY MODELING

While the previous section defined the conceptual model for water availability modeling, this section demonstrates how the tools that were developed to incorporate the various components of the Texas water availability modeling environment are automated and synthesized as a Hydrologic Information System (HIS) for Texas. This HIS includes each of the components described above (and shown in Figure 3-1) along with the three tools discussed: the WRAP Display Tool, the WRAP Network Tools, and the Texas Flow Regimes Tool.

3.3.1 Hydrologic Information System Overview

The Texas water availability modeling environment, as described in this section, works as an HIS where each of the parts of the picture are represented. Figure 3-18 is a demonstration of what a Hydrologic Information System could look like in an Arc Hydro environment.

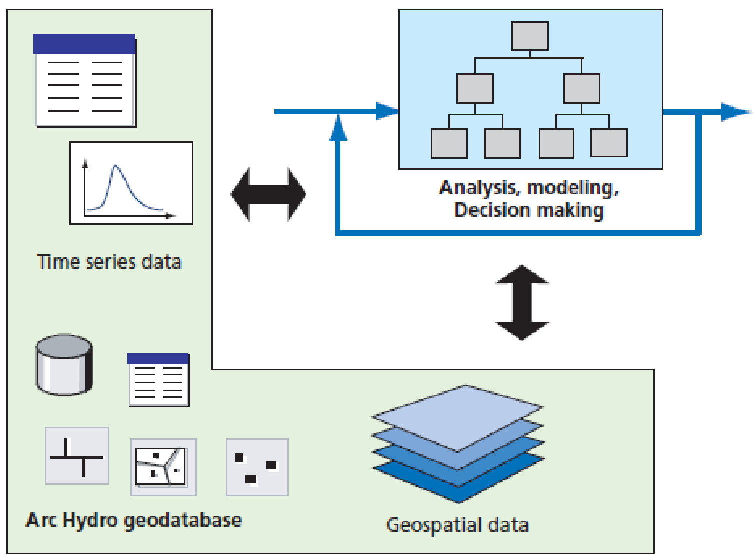


Figure 3-18. Hydrologic Information System Illustration
(from Maidment 2002)

The connections between the representation of an HIS (shown in Figure 3-18) and the Texas water availability modeling environment are explained below:

- The time series data can be found in the water availability model input files, as a result of using the WRAP Display Tool to display the WRAP results, or as part of the environmental flows process;

- The geometric networks used by the WRAP Display Tool, the WRAP Network Tools, and inherently in the Environmental flows process are part of the Arc Hydro geodatabase;
- Geospatial data are seen as GIS representations of the WRAP model—made visible with of the WRAP Display Tool—and as visual representations of the water rights data and streamline networks that the WRAP Network Tools use to automate and synthesize data analyses.
- The analysis, modeling, and decision making aspects are represented by the official water availability model of Texas and the environmental flows assessment process.

3.3.2 Hydrologic Information System Defined

The synthesis and automation of the components of the Texas water availability modeling conceptual model demonstrate an HIS for Texas. This HIS unites the individual components of the water availability modeling conceptual model and related tools. A graphical representation of how the water availability modeling conceptual model components work together as an HIS is shown in Figure 3-19.

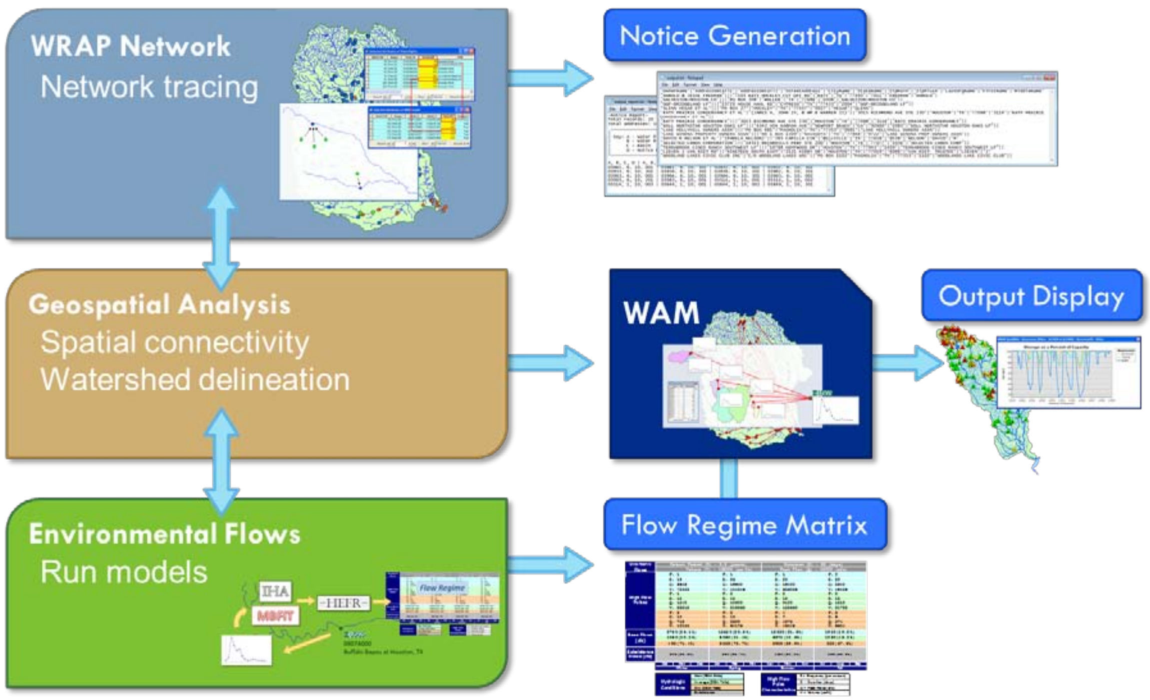


Figure 3-19. Hydrologic Information System for Water Availability Modeling

Figure 3-19 illustrates that geospatial analyses are central to water availability modeling and the starting point for analyses. For example, the spatial connectivity of the water rights network and corresponding drainage areas are central to both the water availability model (WAM, which includes WRAP) and WRAP network analyses.

Furthermore, these same aspects (spatial connectivity and drainage areas) are fundamental to analyses for environmental flows. The results of these analyses are fed into the general water availability model, and the produced output can be visualized and used to inform water availability modeling decisions.

The development and definition of a Hydrologic Information System for water availability modeling is a fulfillment of the second research question of this dissertation.

The third research question on desktop-based water availability modeling being informed by web services is briefly addressed through the Texas Flow Regimes Tool. This tool's use of web services to "pierce the cloud" and obtain daily streamflow data to inform environmental flows analyses demonstrates a small aspect of the benefits of web services in Texas water availability modeling analyses. The steps and procedures related to Texas water availability modeling are benefited by web data access and web processing. The next section addresses the second part of this dissertation's third research question through introducing an information model to handle Texas water availability modeling—including those benefitted by web services.

3.4 ARC HYDRO WEB FOR TEXAS WATER AVAILABILITY MODELING

This section builds upon the aspect of web-informed water availability modeling analyses as part of this dissertation's third research question regarding the use of an appropriate information model for desktop- and web-based data.

The long-standing practice of much of computing has been that of working with data on a local level (or over a shared local network in an organization). This localized desktop-centric environment is changing through of the innovations of the Internet, Web 2.0, and the geo-enabling efforts of organizations like the Open Geospatial Consortium (OGC). The Arc Hydro information model is used by many organizations in representing hydrologic data. The key features that are central to Arc Hydro (and Arc Hydro Groundwater) remain essential, but they can be thought of as falling into a more expansive descriptive collection and organization of data in a new application of the Arc Hydro information model: Arc Hydro Web. This information model is presented as a potential framework for data management, storage, and presentation.

3.4.1 Thematic Layers

The framework and key data layers that make Arc Hydro useful are shown in this dissertation to be applicable to meet the changes in availability and access of hydrologic data through the adaptation of Arc Hydro Web, as seen through the lens of Texas water availability modeling.

Arc Hydro and Arc Hydro Groundwater share framework datasets to preserve the connectivity that should exist between water resources. This framework has proven effective at handling various types of hydro-data—from surface hydrology to groundwater applications; however, with the innovations associated with the Web 2.0 movement and the accompanying increase in access to all sorts of data—including hydrologic data—the Arc Hydro data framework benefits from a new look in a Web-accessible environment.

The key thematic layer groups of Arc Hydro Web are introduced, which meets the objective of describing a unifying information model for Texas water availability modeling. Where the presentation of Arc Hydro and Arc Hydro Groundwater use what are called key thematic layers, the Arc Hydro Web structure uses key thematic layer *groups*. A descriptive visual display of the proposed key thematic data layer groups of the Arc Hydro Web information model is shown in Figure 3-20. This figure depicts Texas water availability modeling data in Arc Hydro Web and provides additional data examples as well.

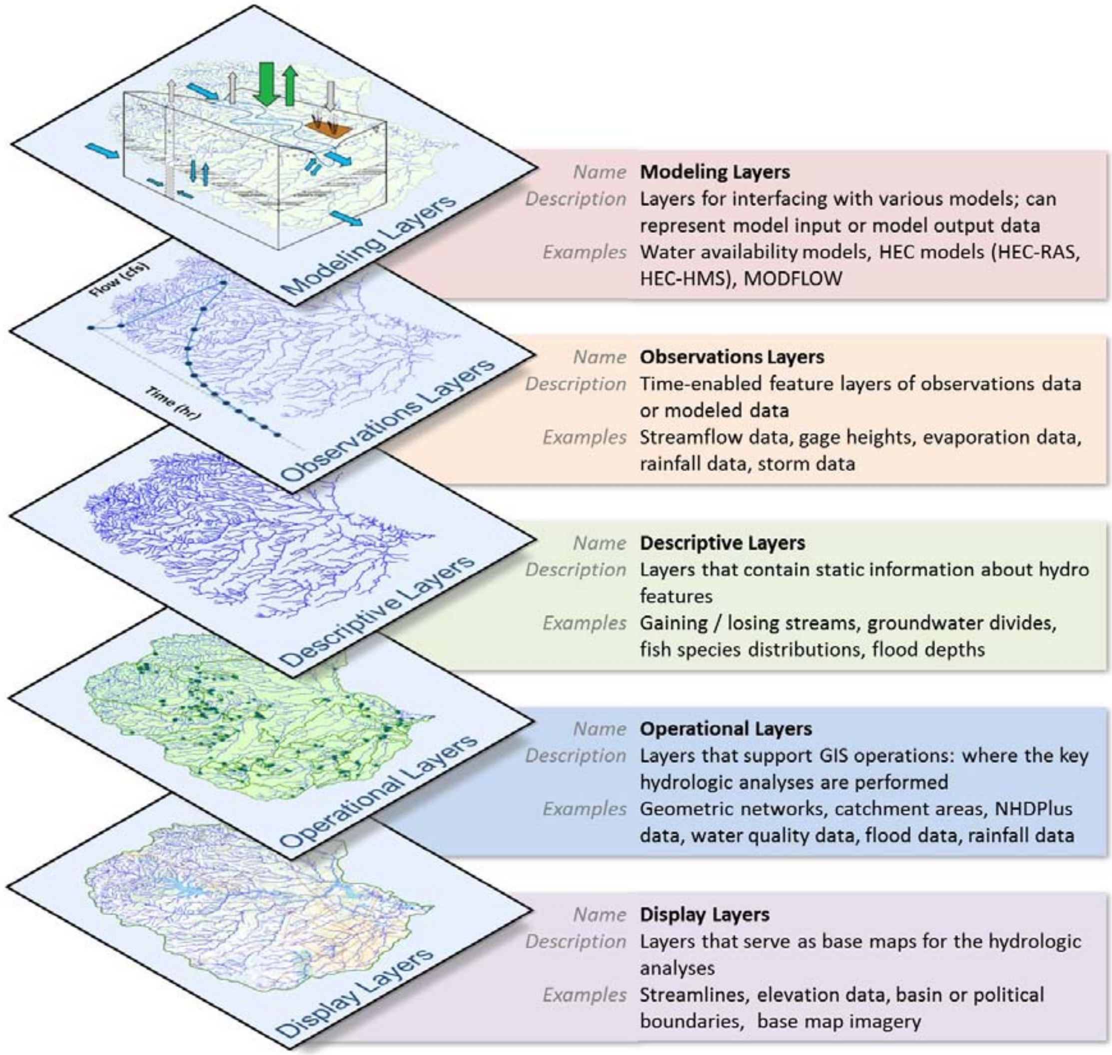


Figure 3-20. Key Thematic Layer Groups of Arc Hydro Web

The key thematic layer groups of Arc Hydro Web can be thought of as an additional grouping structure for hydrologic data. These layer groups aid in the transition from local desktop-centric GIS data storage and analyses, and assist in the incorporation of data from disparate sources, fully embracing the cloud component of hydrologic data over the Internet. Descriptions of each of the layer groups follow, including examples from the Texas water availability modeling system and associated data:

Display Layers – base maps for the analyses. These base maps are either interactive (e.g. hydrography or "blue line" components of topographic maps) or provide locational or contextual information (e.g. orthophotography or satellite imagery indicating land uses and general surroundings). Examples: streamlines, elevation data, basin or political boundaries, base map imagery.

Operational Layers – where hydrologic analyses are performed; may include services that provide data in a format that is ready to use. Examples: geometric networks and associated catchment areas, NHDPlus data, water quality data, flood data, rainfall data.

Descriptive Layers – static information about hydro-features. Examples: gaining/losing streams, groundwater divides, fish species distributions, flood depths.

Observations Layers – time-enabled feature layers of observations data. Examples: streamflow data, gage heights, evaporation data, rainfall data, storm data.

Modeling Layers – layers that interface with hydrologic models. Layers can represent model input or model output data; e.g. water availability models.

3.4.2 Geodatabase Design

The layer groups of Arc Hydro Web have a place in the geodatabase design of the information model. As a descendent of Arc Hydro and Arc Hydro Groundwater, Arc Hydro Web's geodatabase design is similar to its predecessors. Figure 3-21 through Figure 3-23, and associated discussion, present a review of these related geodatabase designs.

Figure 3-21 shows an ArcCatalog view of an Arc Hydro geodatabase and presents the geodatabase design of the Arc Hydro information model. Shown are two views of the geodatabase: collapsed and expanded. The collapsed view shows key thematic layers, or data themes (on the left), and the expanded view gives a more clear picture of the components (on the right)—note the key thematic layers from Arc Hydro (Maidment 2002).

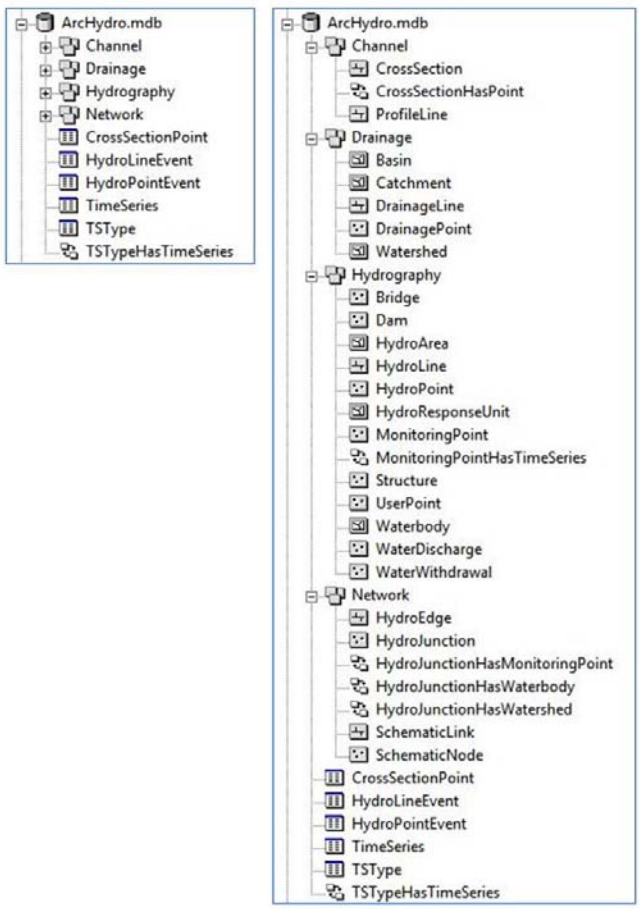


Figure 3-21. Arc Hydro Geodatabase Design
(Collapsed on left, expanded on right)

The geodatabase design of Arc Hydro Groundwater builds upon that of Arc Hydro, as shown in Figure 3-22. This figure, as the previous, presents a collapsed and expanded view of the geodatabase. Figure 3-22 shows that the thematic layers are represented in the Framework theme feature dataset, with supporting thematic layer groups particular to groundwater analyses. This is an illustration of the adaptability of the general Arc Hydro data model (Strassberg et al 2011).

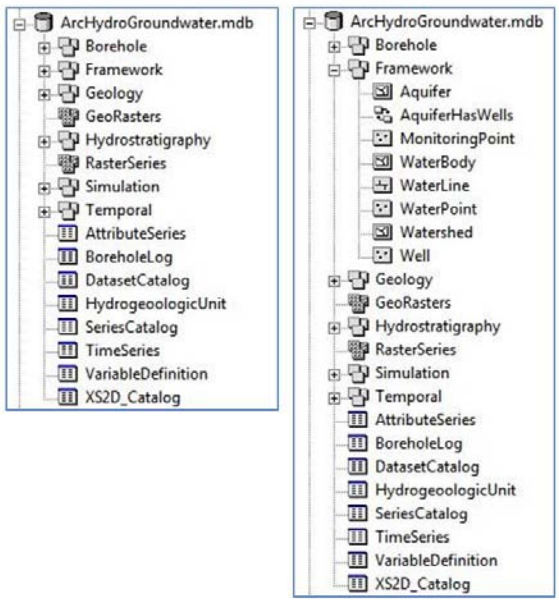


Figure 3-22. Arc Hydro Groundwater Geodatabase Design
(Collapsed on left, expanded showing thematic layers on right)

The thematic layer groups of Arc Hydro Web, illustrated graphically in Figure 3-20, are presented in geodatabase form in Figure 3-23. This figure shows two groups of views of the geodatabase—with collapsed views (on the left) and expanded views (on the right). There are two groups to illustrate that while the feature datasets correspond to the key thematic layer groups depicted in Figure 3-20, the features (and tables) that are used to represent various geographic information systems can range from generic (as represented by the group on the left) to specific (shown in the group on the right).

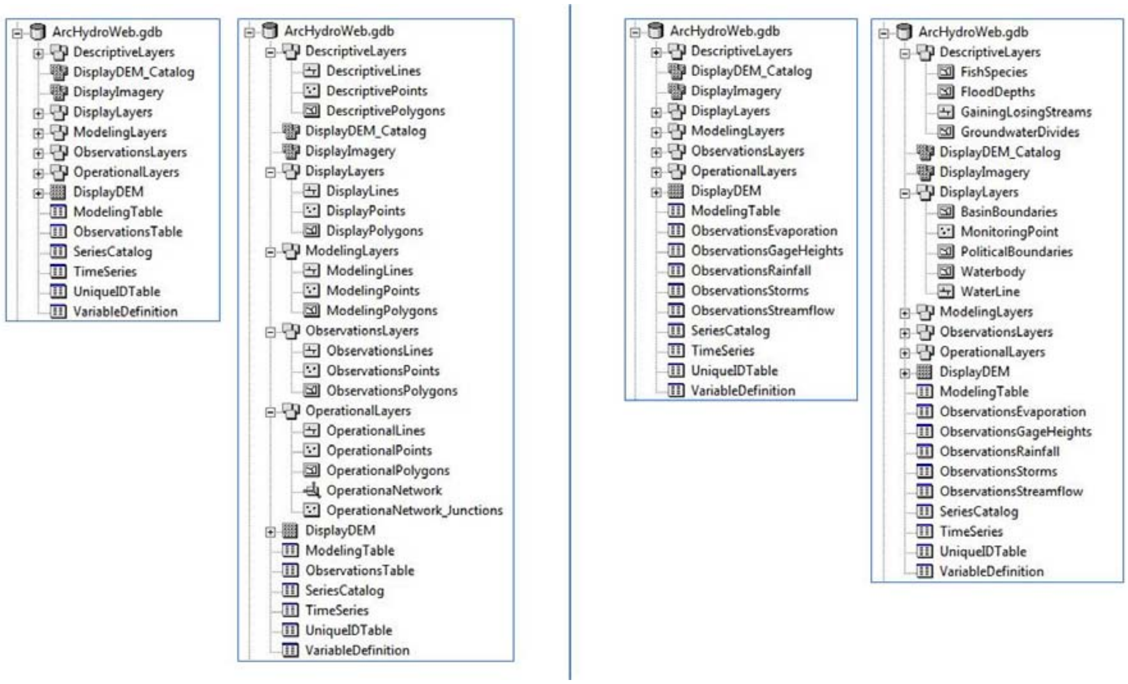


Figure 3-23. Arc Hydro Web Geodatabase Design
(Group on left is generic application, group on right is illustrative)

The collection of key thematic layer groups of Arc Hydro Web encompasses the bulk of key thematic layers of Arc Hydro and Arc Hydro Groundwater. As such, as additional layers are added (perhaps outside of the key thematic layers), they are structured following the general Arc Hydro framework schema with fields for HydroID, VarID, JunctionID, and HydroCode, which provides for the preservation of whatever numbering or labeling the data originally utilized, but allows participation in the Arc Hydro analyses at the same time. For example, if using NHDPlus data served from the cloud (or locally), the original COMID could be maintained while including a HydroID to link to other data in the analysis. A generic framework view of such an arrangement is shown in Figure 3-24.

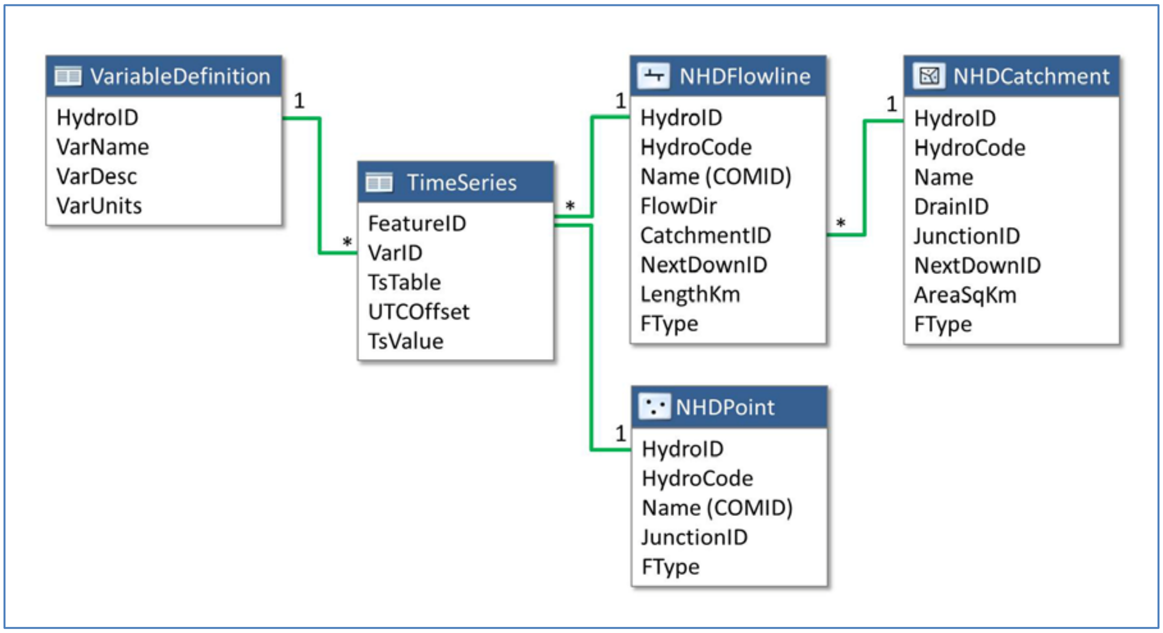


Figure 3-24. Generic Arc Hydro Web Framework Example

The Arc Hydro Web framework (including the key thematic layer groups) is used in section 4.2 to demonstrate the power of Arc Hydro and its Web component, Arc Hydro Web from a Texas water availability modeling viewpoint.

3.5 RM-ODP FOR ARC HYDRO WEB

This section outlines a process for demonstrating the benefits of this dissertation's research questions, particularly the question regarding web-informed water availability modeling and an appropriate information model.

A standard that is widely used in computer science is the reference model of open distributed processing (RM-ODP). This is a framework for the standardization of open distributed processing (how many computers can interact on a network). The purpose of Arc Hydro Web is to couple the benefits of Arc Hydro with the burgeoning availability of online hydro data and online processing services (for application in a Texas water availability modeling environment). Considering the Internet as a large interconnected network presents an opportunity to examine an RM-ODP for Arc Hydro Web. This section presents the RM-ODP as a methodology for evaluating the Arc Hydro Web information model for Texas water availability modeling. This includes presenting use cases for the steps currently used in Texas water availability modeling data processing. These are subsequently expounded to incorporate cloud data access and cloud computing.

Please note that an RM-ODP, by its very nature and structure, can serve as a stand-alone document; however, in the framework of a dissertation—with various sections—much of the detail and many of the components are already expounded and explained (in the Literature and Technology Review, for example). Therefore, in an effort to not repeat previously discussed matter verbatim, this section presents the overall structure of an RM-ODP from a methodology application viewpoint with pointers or references to what was discussed. The five viewpoints of an RM-ODP are applied to the

Arc Hydro Web information model for Texas water availability modeling in the following sections.

3.5.1 Enterprise Viewpoint

The Enterprise Viewpoint of an RM-ODP describes the general view of the effort and outlines its purpose, scope, and objectives. On its own, an RM-ODP can be used to frame a stand-alone document. Considering that this dissertation uses an RM-ODP approach as one of its many parts, the enterprise viewpoint can be thought of as the material presented in Chapter 1; however, the Enterprise Viewpoint includes the useful feature of use cases which present a practical side of what could become a theoretical application. The following use cases outline the methodology that will be used to show the benefit and application of Arc Hydro Web through hydrologic processes. Doing so will demonstrate that Arc Hydro Web supports traditional Arc Hydro analyses and can be used to meet the future needs of Texas water availability modeling regarding web data access and cloud computing.

Current processes of water availability modeling data preparation and analysis consist of several steps that are combined through custom-built tools (e.g. the WRAP Network Tools and Texas Flow Regimes Tool). This Enterprise Viewpoint presents these tools' steps as uses cases; the incorporation of cloud data access and cloud computing are presented subsequently to illustrate how Arc Hydro Web and the cloud can be used to benefit Texas water availability modeling.

The overall process of using the WRAP Network Tools is presented in Table 3-1. These steps are presented to demonstrate all the steps, whereas subsequent use cases highlight certain steps.

Table 3-1. General WRAP Network Tools Process

1.	Create file geodatabase and feature dataset
2.	Import relavent GIS data to geodatabase (e.g. streamlines, water right points, flow direction raster)
3.	Create proxy water right points that are snapped to streamlines
4.	Split streamlines at point locations
5.	Build geometric network using flowlines and proxy points
6.	Set flow direction
7.	Assign ID values to streamlines corresponding to proxy points
8.	Delineate basin(s)
9.	Add additional water rights points, as needed
10.	Re-delineate affected basins
11.	Generate notice reports

Similar to the previous table, Table 3-2 lists the overall steps of using the Texas Flow Regimes Tool.

Table 3-2. General Texas Flow Regimes Tool Process

1.	Specify flow data specifics (USGS gauge and start/end dates of analysis)
2.	Get flow data using web services
3.	Enter or adjust IHA / MBFIT model paramaters
4.	Run IHA / MBFIT models
5.	Specify which model output to use as input for HEFR
6.	Enter HEFR model parameters
7.	Run HEFR
8.	Inspect flow regime matrices

A listing of the five use cases presented as part of this Enterprise Viewpoint is summarized in Table 3-3.

Table 3-3. Summary of Use Cases

Use Case	Description (Tool)
1	Delineate basins, full watershed (WRAP Network)
2	Add water right points (WRAP Network)
3	Re-delineate select basins (WRAP Network)
4	Get flow data (Texas Flow Regimes)
5	Run models (Texas Flow Regimes)

The first three use cases refer to functionality of the WRAP Network Tools, and the final two correspond to the Texas Flow Regimes Tool. The first use case, delineating all basins in a watershed, is outlined in Table 3-4. This table (and subsequent) presents the use case, a description, what data are used, a brief listing of steps involved, and a summary. Each of the use cases are outlined in greater detail in Section 4.2.

Table 3-4. Use Case 1: Delineate Basins, Full Watershed

Overview	
Title	Delineate Basins, Full Watershed (WRAP Network Tools)
Description	Basins are delineated for all water right proxy points on the stream network.
Data Used	• Water Right Proxy Points • Streamlines • Flow Direction Raster
Basic Flow	
Steps	• Delineate basins as raster using ArcToolbox Tools • Convert rasters to polygon using ArcToolbox Tools • Preserve ID relationships
Post Condition	
Summary	A new feature class consisting of delineated basins is created for all water right proxy locations in study area.

The second use case, Table 3-5, covers how additional water right points can be added to the network.

Table 3-5. Use Case 2: Add Water Right Points

Overview	
Title	Add Additional Water Right Points (WRAP Network Tools)
Description	Additional water right points and proxy points are added to the existing geometric network.
Data Used	• Water Right Points • Water Right Proxy Points • Streamlines
Basic Flow	
Steps	• Create water right point(s) • Create proxy water right point(s) • Preserve ID relationships
Post Condition	
Summary	Additional water right points and proxy points are added to the geometric network, preserving ID relationships between all participants.

The third use case, Table 3-6, covers re-delineating affected areas without having to reprocess the entire study area.

Table 3-6. Use Case 3: Re-Delineate Select Basins

Overview	
Title	Re-Delineate Select Basins (WRAP Network Tools)
Description	Basins with new water right and proxy points are re-delineated without reprocessing all basins in the entire study area.
Data Used	• Water Right Proxy Points • Streamlines • Flow Direction Raster
Basic Flow	
Steps	• Delineate basins as raster using ArcToolbox Tools • Convert rasters to polygon using ArcToolbox Tools • Preserve ID relationships
Post Condition	
Summary	An existing feature class of delineated basins is modified by reprocessing only an affected area.

The fourth use case, Table 3-7, outlines how daily flow values are obtained using web services.

Table 3-7. Use Case 4: Get Flow Data

Overview	
Title	Get Flow Data (Texas Flow Regimes Tool)
Description	Daily streamflow values are obtained from the USGS using web services.
Data Used	• USGS Gage Number • Start / End Dates
Basic Flow	
Steps	• Web services are invoked to retrieve flow values
Post Condition	
Summary	Daily streamflow values are obtained via web services according to user-specified parameters.

The final use case, Table 3-8, presents how the tool runs multiple models and describes the interaction between them.

Table 3-8. Use Case 5: Run Models

Overview	
Title	Run Models (Texas Flow Regimes Tool)
Description	A series of models are run according to user-specified input parameters. The output of one model is used as input for the next. The end result is a flow regime matrix.
Data Used	• Streamflow values • Model input parameters
Basic Flow	
Steps	• Model parameters are input and the models are run • Output data is inspected and chosen for input for next model • Subsequent model is run yielding flow regime matrices
Post Condition	
Summary	Multiple models are used in concert (with the output from the first used as input for the latter) to produce flow regime matrices.

The preceding use cases involve selected steps of two tools developed by the author of this dissertation to meet the needs of water availability modeling in Texas. These use cases give insight into the current workings of the water availability modeling process and its Hydrologic Information System and are used later as illustrations of how the Texas water availability modeling process could be benefitted by the Arc Hydro Web information model, coupled with web services and cloud computing.

3.5.2 Informational and Computational Viewpoints

The Information Viewpoint describes the information elements and how they are used, managed, and structured. The five-layer description and presentation of Arc Hydro Web, along with the standard Arc Hydro schema, represent the Information Viewpoint from a methodology standpoint.

Where the Information Viewpoint describes the data structure and organization, the Computational Viewpoint presents how these data can be shared and accessed. From the point of view of current practices, the computing is performed by the desktop computer; however, web services and cloud computing provide an additional look at the computation viewpoint through interacting services (the cloud). The standards and services that are supported by ESRI are discussed and related to one another in section 2.3.2 of the Literature and Technology Review; this discussion of standards and services is a computational viewpoint for cloud-related procedures.

3.5.3 Engineering and Technology Viewpoints

The Engineering Viewpoint describes how communication occurs between system entities through specific languages and functions. The combination of geographic markup language (GML) and web services enable a GIS user to send requests through the cloud to various servers housing the requested data. After first determining which data are available, the GIS user requests the data using a web mapping service (WMS), web feature service (WFS), or web coverage service (WCS)—or any combination—and the requested data are delivered.

The combination of web services and geoprocessing results in geoprocessing services. These services move the location of the geoprocessing from the desktop machine to a server. With such a server made accessible through the cloud, it is possible for multiple servers to communicate with each other, transferring their service products and utilizing any combination of geoprocessing services. Such an environment allows a GIS user to request feature or gridded data from multiple servers, have the data sent to another server that performs some operation (via geoprocessing tools) and return a new dataset to the GIS user.

The technology viewpoint, which describes which technology is used to implement the system (e.g. specifies the various software, network, and hardware components), is outside the scope of this dissertation. This dissertation rests on the basis that the standards mentioned are being employed and recognized by all participants. The discussion on specific software and hardware is left for another analysis.

Chapter 4. Application / Example

This chapter presents the use cases itemized in section 3.5.1. After these are presented and discussed, attention is placed on how web services and cloud computing—coupled with the Arc Hydro Web information model—could benefit water availability modeling in Texas. This chapter uses examples to demonstrate the usefulness of the solutions to the research questions posed in the introduction.

The San Jacinto Basin in Texas is used as a geographic setting for the use cases. Of the 23 major river basins classified in Texas, the San Jacinto is nearly-median by size—total drainage area is 5,600 square miles—but it contains Texas' most populous city, Houston. The basin has 147 WRAP control points, of which 120 are water right features, and 92 are reservoirs. Texas basins are shown in Figure 4-1 with the San Jacinto Basin shown in green.

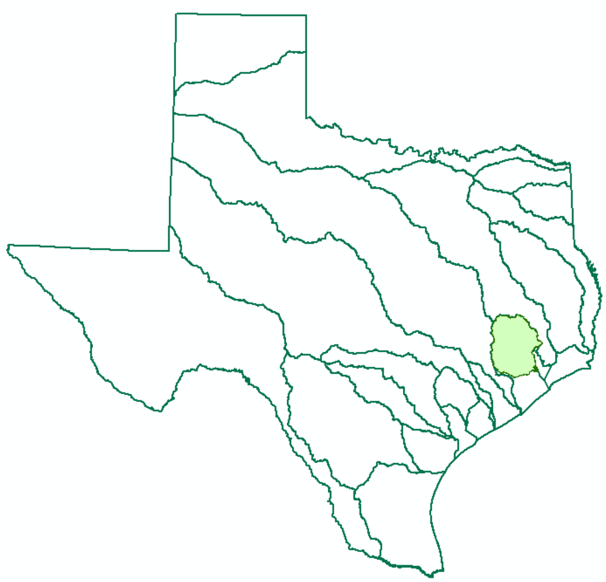


Figure 4-1. San Jacinto Basin Location

4.1 WATER AVAILABILITY MODELING PROCESS NARRATIVE

A theoretical new water right in an existing water availability modeling environment for the San Jacinto Basin is used as a generalized look at the water availability modeling process. This is done to tie the Texas water availability modeling environment to the methodology and associated use cases. This section also demonstrates the tools and other advances that have been developed as part of an effort at automating and synthesizing various water availability modeling components to create a connected Hydrologic Information System for Texas water availability modeling.

While it may not be obvious in the map of the San Jacinto Basin, shown in Figure 4-1, the city of Houston is inside the basin. Consider the hypothetical situation where a country club in Houston wishes to apply for a water right for lawn irrigation purposes. A picture of the GIS view of this scenario is shown in Figure 4-2. This figure shows a world topographic map as a base map image behind a river network—that has black arrows indicating flow direction—and colored water right location points (where the blue points indicate existing water rights and the green point is the proposed water withdrawal point for a new water right).

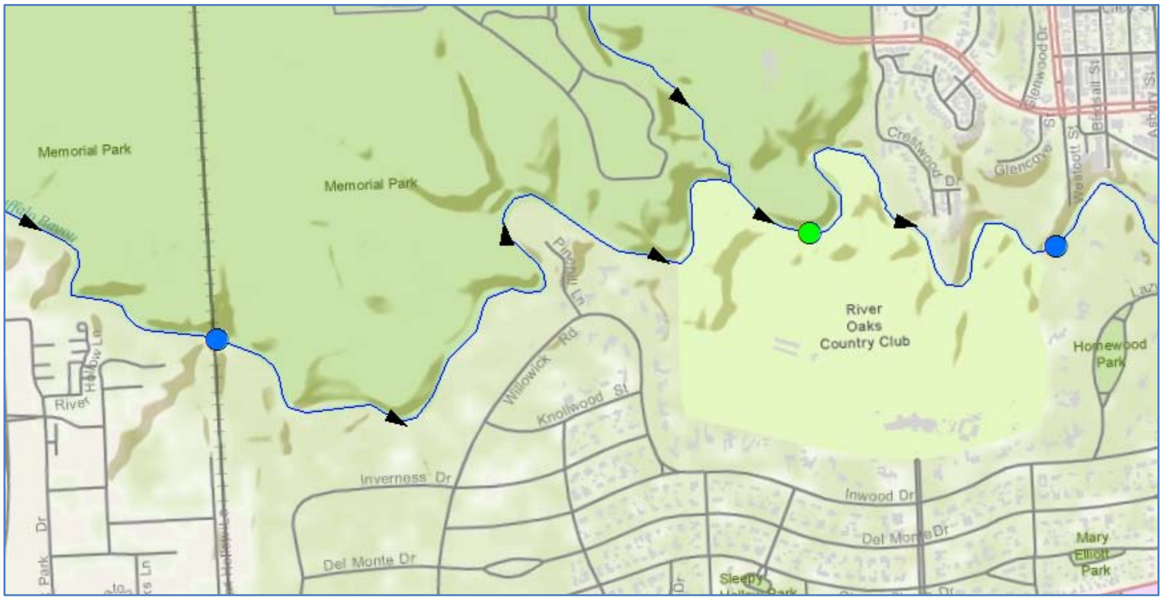


Figure 4-2. New Water Right Location

The streamline shared by the three points shown in the figure is the Buffalo Bayou—one of Houston's main waterways. There is a USGS stream gage (08074000, Buffalo Bayou at Houston, TX) just downstream of the area shown in Figure 4-2. The USGS reports that this gage has a drainage area of 336 square miles, and the average of recorded daily flow values is 473 cubic feet per second (USGS 2011). While not shown in this figure, there are sixteen water right points downstream of the proposed new water right and sixteen water right points upstream.

The application process for a water right diversion point permit is done through TCEQ, and application parameters include the watercourse, the location of the withdrawal point (in latitude and longitude), the location of the county seat, the zip code, the diversion type (e.g. directly from stream, from an on-channel reservoir, etc.), the requested diversion quantity (flow rate), and the drainage area above the diversion point.

These varied parameters are necessary for record keeping and water availability modeling purposes. Modeling purposes of application data include: the location is input in the database so it can be related topologically to existing water rights, the diversion type is input as a parameter in the WRAP model, as are the flow rate and drainage area.

Once the model parameters are input into the WRAP input files (which are space-delimited files set up following strict protocols), the WRAP process is initiated for two run types: full appropriation and limited appropriation.

Under full appropriation, input files containing historical naturalized flow values (approximately 40 years of recorded flow values that have had the anthropogenic effects removed) are used as the water availability model is run. The model run uses all perpetual basin water rights—including the proposed water right—withdrawing their full permitted volumes without returning any flow to river to determine if sufficient water is available for all rights. If 75 percent of the requested water withdrawal volume can be satisfied 75 percent of the time, the request passes the requirements of the full appropriation run and can be considered as a perpetual water permit.

Under the limited appropriation model run, all water rights—perpetual water rights and temporary or short term water rights—are included and return flows are considered. If 75 percent of the requested water withdrawal volume can be satisfied 75 percent of the time, the request passes the requirements of the limited appropriation run and can be considered as a temporary water permit.

The results of the WRAP modeled runs are highly condensed ASCII text files that contain variables for each point used in the analysis for each time step of the analysis. For example, a WRAP run including 100 points using a monthly time step for 40 years (standard in WRAP) would have 100 (points) x 40 (years) x (12 months) = 48,000 individual values for each of WRAP's many variables (more than 40 variables for a collective four types of output). Each of these output values are assembled as text values inside a single text file. The WRAP Display Tool was created to make this data more accessible by converting it to geodatabase tables and enabling the display of the variables as time series or maps in GIS. To continue with the narrative of the country club's application for a water right permit, Figure 4-3 shows a time series of the naturalized flow values—displayed using the WRAP Display Tool—at the new permit point location over the 40-year WRAP period of analysis. Similar time series graphs could easily be produced for any of WRAP's output variables.

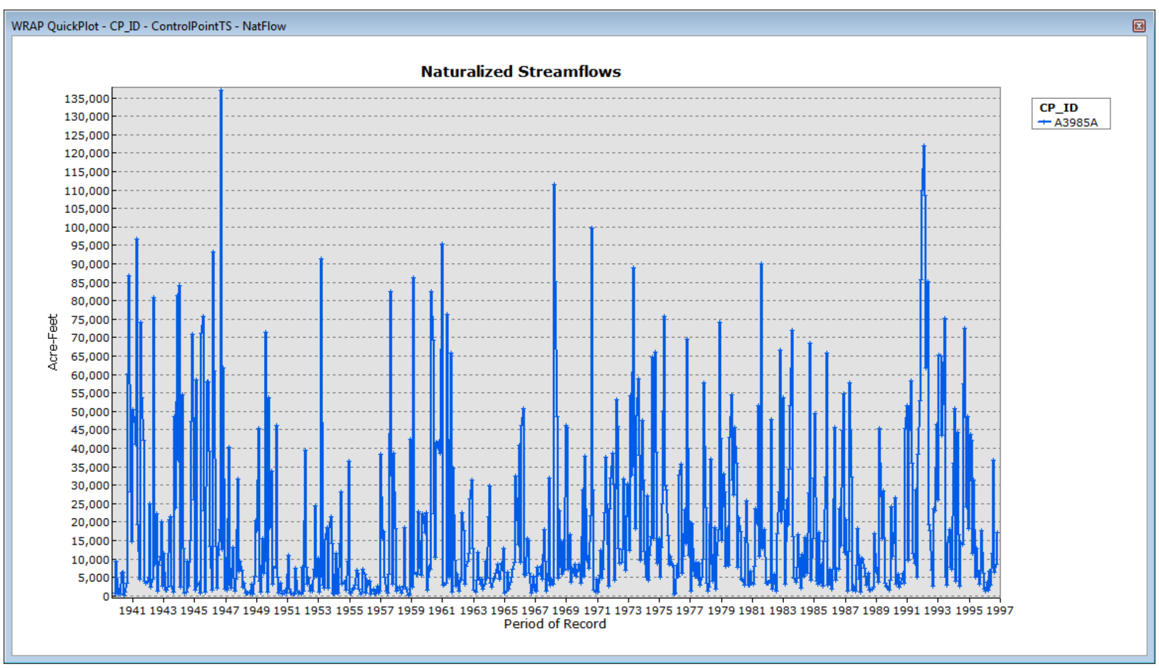


Figure 4-3. Naturalized Streamflows on the Buffalo Bayou

Texas Senate Bills 2 and 3 implemented environmental considerations for streams and rivers in Texas of instream flows and flow regimes. The expert science teams tasked with determining flow regimes for Texas rivers must combine myriad data and analyses in order to make informed decisions. To assist with these labors, the Texas Flow Regimes Tool was created to enable web data extraction and combine input data, multiple models, and their respective output, all within a single Excel workbook. The Texas Flow Regimes Tool presents a fully-transferrable and replicatable start-to-finish view of analyses and results of Texas environmental flows considerations and flow regimes. This discussion on the Texas Flow Regimes Tool fits into the water right permit application narrative in that the tool serves as a behind-the-scenes support to the overall process; the instream flows and flow regimes values are taken into effect as the application is considered.

Assuming that the permit application was approved for this country club in Houston, it may be necessary for the TCEQ to inform various other water right holders in the basin of the change. The WRAP Network Tools were developed by the author of this dissertation to enable and automate the task of geographically selecting those affected by such a change and synthesize various official TCEQ database tables and GIS representations of water rights to create a list of affected rights and appropriate address labels necessary for mailing related correspondence. Thus the WRAP Display Tool, the WRAP Network Tools, and Texas Flow Regimes Tool connect GIS and water right databases in ways that lead to an automated and synthesized Hydrologic Information System for Texas water availability modeling.

4.2 USE CASES

Use cases are used to illustrate current steps taken as part of Texas water availability modeling. These use cases demonstrate the theoretical and practical insight provided by this dissertation research, as listed in the research objectives and summarized in section 4.2.6. The first three use cases are in a GIS environment and demonstrate the structure of the Arc Hydro Web information model; the latter two use cases are in an Excel environment and show web data access and model automation.

Figure 4-4 shows the San Jacinto Basin with GIS data organized according to the Arc Hydro Web information model format. This area is used in the following use cases to demonstrate the WRAP Network Tools.

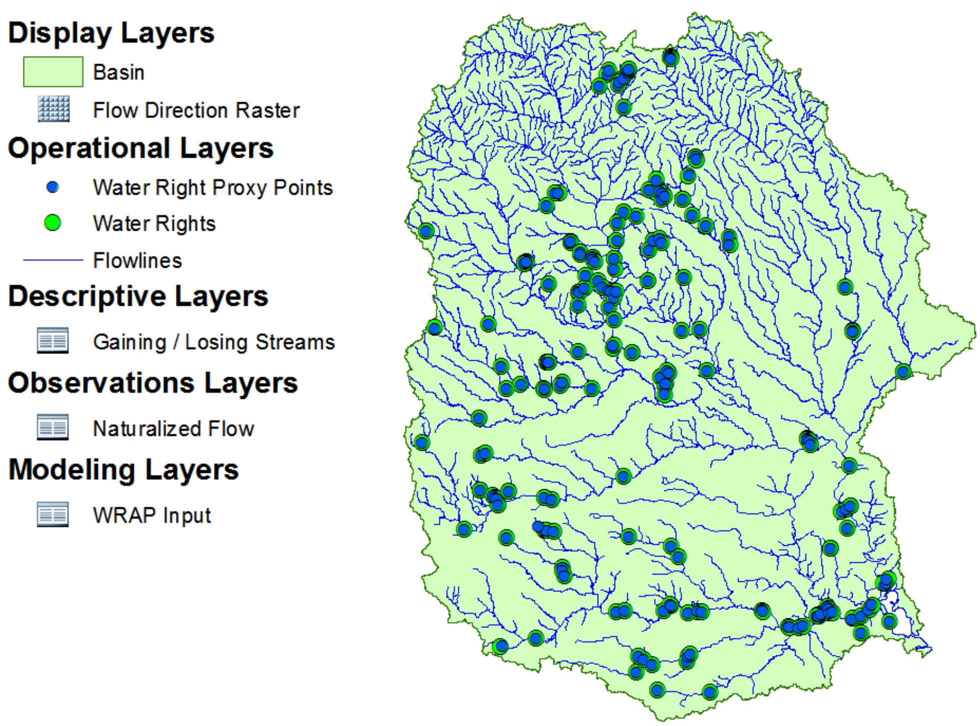


Figure 4-4. San Jacinto Basin with Arc Hydro Web

4.2.1 Use Case 1: Delineate Basins, Full Watershed

Before discussing the steps used in delineating all basins in the study area, it is useful to mention the general data organization. The general WRAP Network Tools process involves organizing relevant GIS data, creating proxy water right points that are snapped to the streamlines, preparing the network for analyses, setting the flow direction, and transferring the HydroID values of the water right proxy points (which correspond to the JunctionID values of the water rights points) to the streamlines. These steps are assisted by the WRAP Network Tools and corresponding documentation. The end result are water right points, water right proxy points, and streamline segments that participate in a geometric network and are related to one another via HydroID and JunctionID relationships, illustrated in Figure 4-5. With the data thus organized, all the basins in the study area can be delineated using the WRAP Network Tools.

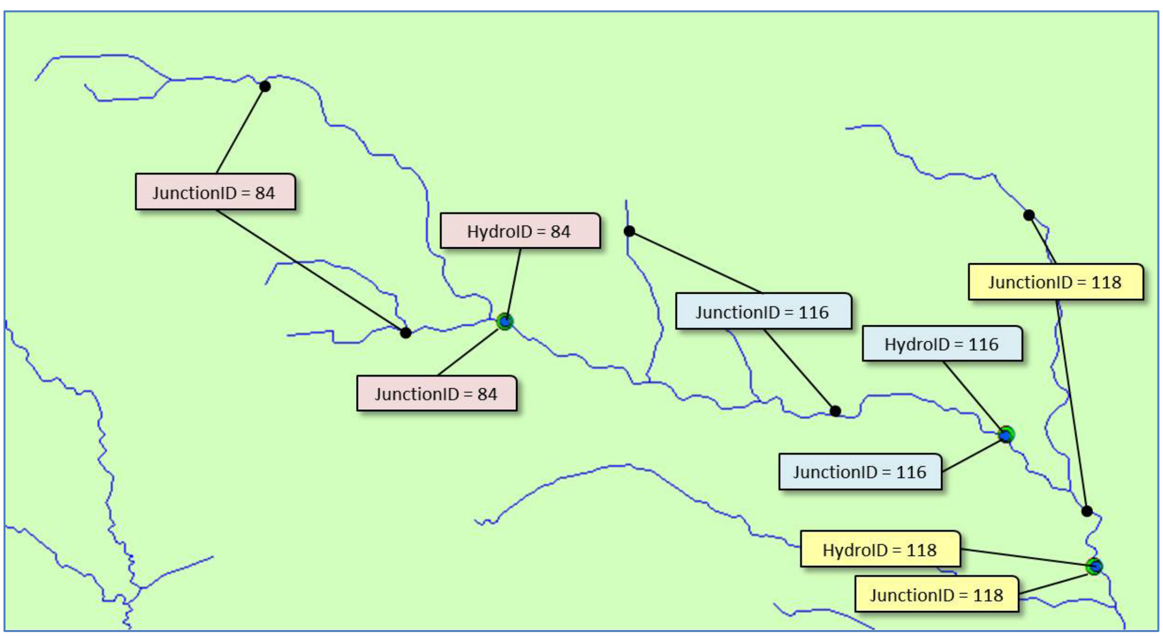


Figure 4-5. HydroID and JunctionID Relationships

The WRAP Network Tools have a geoprocessing tool that combines multiple steps of standard ArcToolbox geoprocessing tools. These steps are presented in the following list:

- The **Watershed** ArcToolbox tool takes the streamline as input and produces a watershed raster according to a specified flow direction raster. The JunctionID field values of the streamline are preserved as ID values for the resulting rasters.
- The **Raster to Polygon** ArcToolbox tool creates vector features from the raster watersheds, storing the JunctionID values as its own field.
- With the feature in a geodatabase, the shape area is automatically calculated.

The benefit of the WRAP Network Tools delineate function is that it delineates upstream drainage areas for all water right proxy points, combining multiple steps into a single function. Drawbacks are that the underlying network's streamlines are broken to accommodate the prescribed HydroID / JunctionID relationships, which may result in the necessity of maintaining multiple nearly-identical stream networks.

The result of such an analysis using the WRAP Network Tools to delineate drainage areas for each proxy water right point is shown in Figure 4-6, which looks similar to Figure 4-4 but with the addition of a heavier-outlined *Watersheds* feature class.

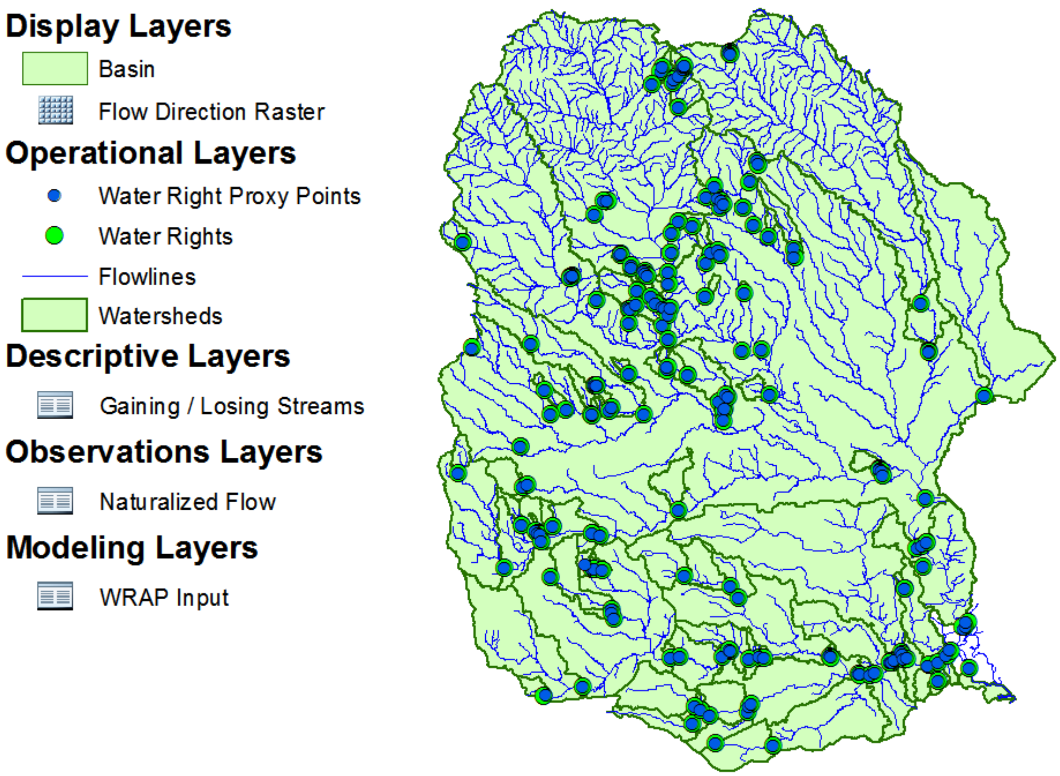


Figure 4-6. All Basins Delineated

4.2.2 Use Case 2: Add Water Right Points

It is not expected that a network of water rights, flowlines, and delineated basins should remain static through time; additional water right points may need to be added. This use case presents steps for how this is done in the Texas water availability modeling environment.

With the point and line feature classes participating in a geometric network, the task of creating new points is fairly straightforward. The Arc Hydro Tools, a toolbar for ArcGIS, facilitates the process through the use the UniqueID Manager. The UniqueID Manager is a function that updates a table in the geodatabase that tracks which HydroID value was previously used and increments subsequent additions accordingly. Figure 4-7 shows a delineated basin where a new water right location is desired.

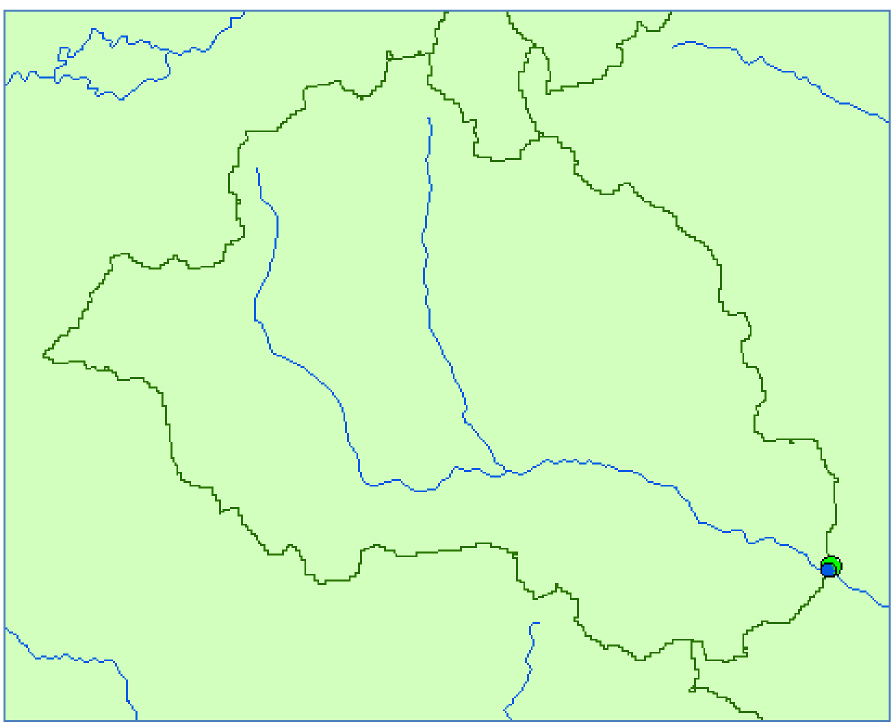


Figure 4-7. New Water Right Point Location

The following list outlines steps that are used to create an additional water right point and corresponding proxy water right point; the process relies heavily on existing functionality of ArcMap's Editor Toolbar functions:

- Start an editing session in ArcMap with the Target feature class set as the proxy water right points, the Task set as "Create New Feature," and the snapping settings set to snap the new point to the streamline.
- The Sketch Tool is used to click on the location (on the streamline feature) for the new water right proxy location; the HydroID value is automatically populated via the Arc Hydro Tools UniqueID Manager.
- Still editing, change the Target feature class to the water rights point feature class.
- Use the Sketch Tool to click on the actual water right location (does not need to be on the streamline feature), setting the JunctionID to match the previously assigned HydroID.
- Stop editing, choosing to save the edits.
- Use the Set Flow Direction tool on the WRAP Network Tools to set the flow direction of the newly split streamline (adding a point automatically splits the line).
- Use the WRAP Network Tools to assign IDs to the lines.

After following these steps, results similar to those shown in Figure 4-8 are expected. This figure shows the previously delineated drainage area with two points; one for the water right location and one for the proxy location on the streamline network. These updated features are now prepared sufficiently for further basin delineation (discussed in the next use case).

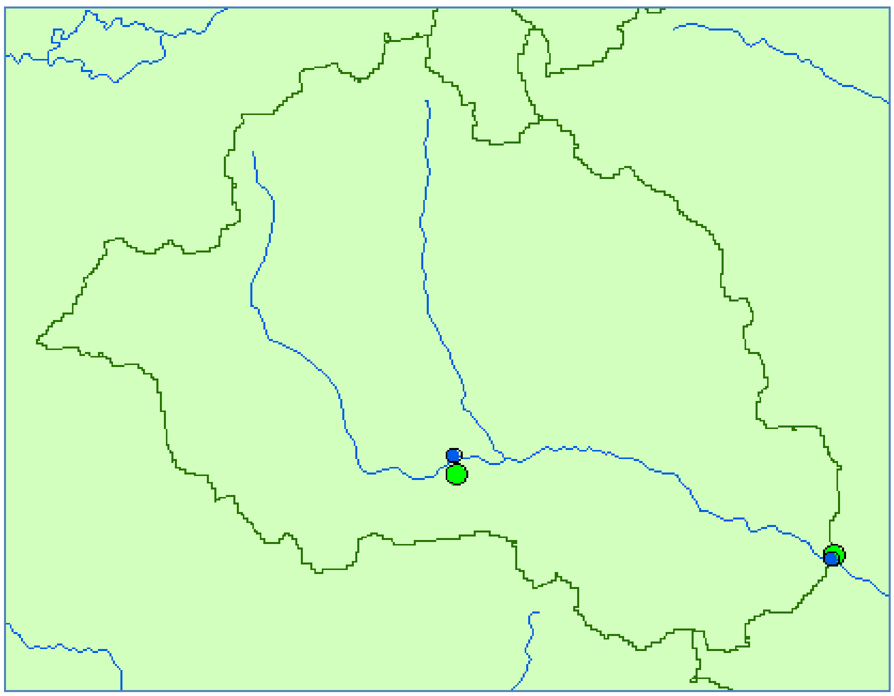


Figure 4-8. New Water Right Points Added

4.2.3 Use Case 3: Re-Delineate Select Basins

The process outlined in the first use case can be applied for delineating smaller sets of basins. The WRAP Network Tools basin delineation function looks for selections and asks if delineation is desired for the entire feature class or the selected subset. Besides looking for a selection and asking the user to specify the desired outcome, the process is exactly the same as in the first use case.

Following the creation of a new water right point, the WRAP Network Tools can intelligently delineate a selected basin, leaving the rest of the study area basins alone, thus saving processing time. The result of such a procedure is shown in Figure 4-9.

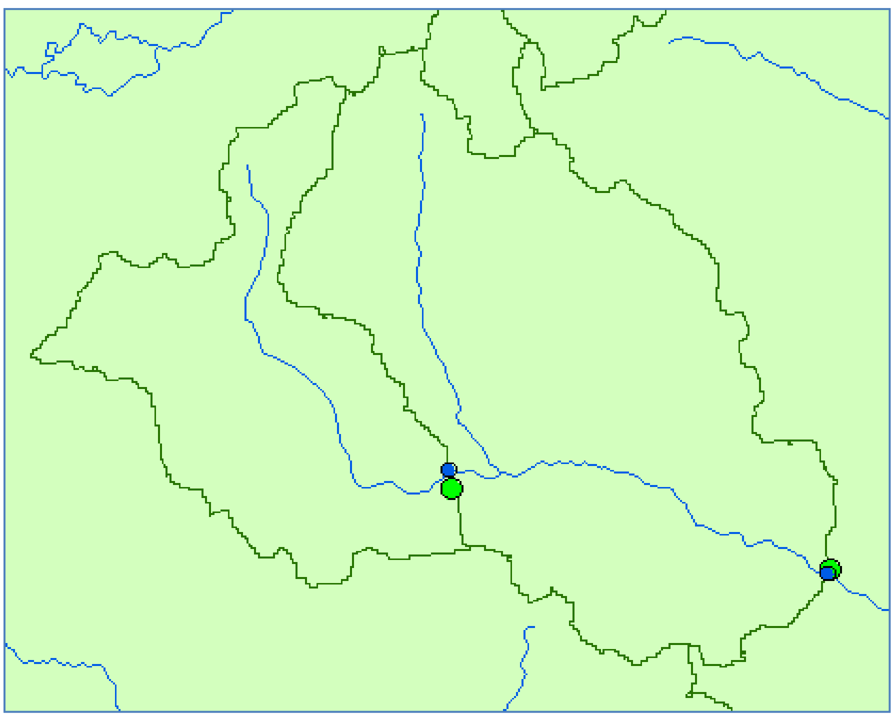


Figure 4-9. Basin Delineated for New Point

4.2.4 Use Case 4: Get Flow Data

The final two use cases are in an Excel environment. While they do not utilize GIS, they do involve web data access. The Texas Flow Regimes Tool uses user-specified data to retrieve daily flow values from USGS gages via web services. The flowchart of steps for this use case follows:

- User enters the USGS gage number from which flow values are desired.
- The dates of analysis are entered (e.g. start data and end date).
- The tool gets the data via a “get values” call to a web services and places it in an Excel workbook for further analysis.

The Excel-based user interface where these values are entered is shown in Figure 4-10. Not shown is a “Get Data” button that executes the data retrieval when clicked.

Data Download Specifics	
USGS gauge station:	08068000
Dates of Analysis (must be on or after 1/1/1900):	
Start Date:	1/1/1940
End Date:	12/31/1996
Data Retrieved:	4/21/2011 8:30

Figure 4-10. Get Flow Data Dialog

Once the flow data are downloaded and stored in the Excel workbook, they are available for further analysis and as input for various models.

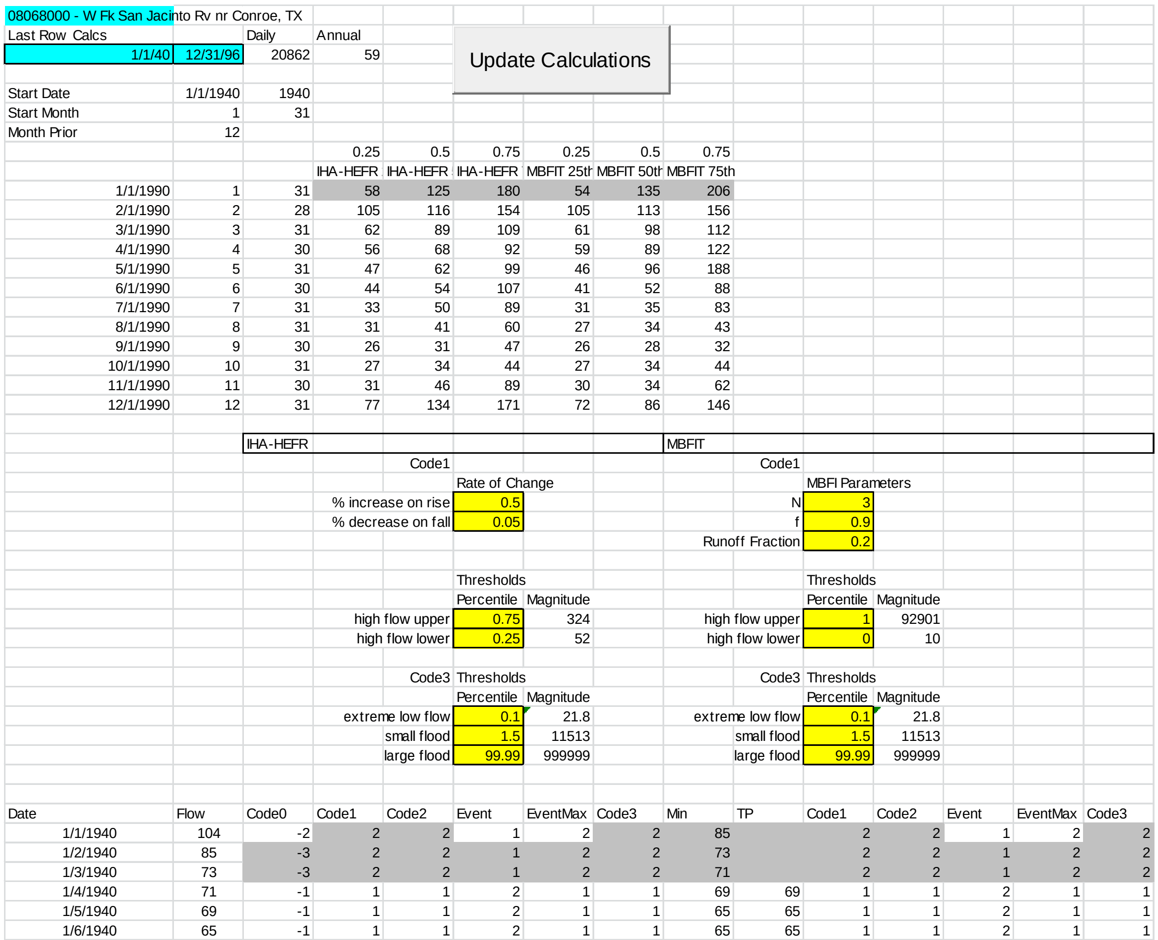
4.2.5 Use Case 5: Run Models

The final use case uses the results of the previous and combines multiple models together to determine a flow regime matrix for the study area. This process uses three models: the Nature Conservancy's Indicators of Hydrologic Alteration (IHA); Joe Trungale's Modified Base Flow Index with Threshold (MBFIT), a modified version of the US Bureau of Reclamations BFI Tool; and Hydrology-based Environmental Flow Regime (HEFR).

The flow of steps for this use case is as follows:

- Using daily streamflow values as input, IHA and MBFIT input parameters are entered in an Excel worksheet which can automate the updating of calculations (shown in Figure 4-11).
- After running these two models, the modeled results are inspected and the user selects which model's output values are desired for input into the next model, HEFR.
- Visual Basic code copies the applicable output data from the specified model and prepares it for input into HEFR (see Figure 4-12).
- HEFR is initiated, where the user specifies various input parameters, runs the model, and receives feedback and results, including flow regimes matrices (see Figure 4-13).

While the Texas Flow Regimes Tool does not have a well-polished graphical user interface, it is effective and performing its tasks and the behind-the-scenes code that enables the process provides simplicity to an otherwise complex process. The IHA and MBFIT Excel interface is shown in Figure 4-11 for daily streamflow data at a USGS gage within the San Jacinto Basin.



08068000 - W Fk San Jacinto Rv nr Conroe, TX														
Last Row Calcs		Daily	Annual											
1/1/40	12/31/96	20862	59		Update Calculations									
Start Date	1/1/1940	1940												
Start Month	1	31												
Month Prior	12													
			0.25	0.5	0.75	0.25	0.5	0.75						
			IHA-HEFR	IHA-HEFR	IHA-HEFR	MBFIT 25th	MBFIT 50th	MBFIT 75th						
1/1/1990	1	31	58	125	180	54	135	206						
2/1/1990	2	28	105	116	154	105	113	156						
3/1/1990	3	31	62	89	109	61	98	112						
4/1/1990	4	30	56	68	92	59	89	122						
5/1/1990	5	31	47	62	99	46	96	188						
6/1/1990	6	30	44	54	107	41	52	88						
7/1/1990	7	31	33	50	89	31	35	83						
8/1/1990	8	31	31	41	60	27	34	43						
9/1/1990	9	30	26	31	47	26	28	32						
10/1/1990	10	31	27	34	44	27	34	44						
11/1/1990	11	30	31	46	89	30	34	62						
12/1/1990	12	31	77	134	171	72	86	146						
		IHA-HEFR						MBFIT						
				Code1					Code1					
					Rate of Change					MBFI Parameters				
				% increase on rise	0.5				N	3				
				% decrease on fall	0.05				f	0.9				
									Runoff Fraction	0.2				
					Thresholds					Thresholds				
					Percentile	Magnitude				Percentile	Magnitude			
				high flow upper	0.75	324			high flow upper	1	92901			
				high flow lower	0.25	52			high flow lower	0	10			
				Code3	Thresholds				Code3	Thresholds				
					Percentile	Magnitude				Percentile	Magnitude			
				extreme low flow	0.1	21.8			extreme low flow	0.1	21.8			
				small flood	1.5	11513			small flood	1.5	11513			
				large flood	99.99	999999			large flood	99.99	999999			
Date	Flow	Code0	Code1	Code2	Event	EventMax	Code3	Min	TP	Code1	Code2	Event	EventMax	Code3
1/1/1940	104	-2	2	2	1	2	2	85		2	2	1	2	2
1/2/1940	85	-3	2	2	1	2	2	73		2	2	1	2	2
1/3/1940	73	-3	2	2	1	2	2	71		2	2	1	2	2
1/4/1940	71	-1	1	1	2	1	1	69	69	1	1	2	1	1
1/5/1940	69	-1	1	1	2	1	1	65	65	1	1	2	1	1
1/6/1940	65	-1	1	1	2	1	1	65	65	1	1	2	1	1

Figure 4-11. Interface for IHA and MBFIT in Excel

The HEFR interface is a graphical user interface which provides constraints and specific selection options. The interface is shown in Figure 4-12.

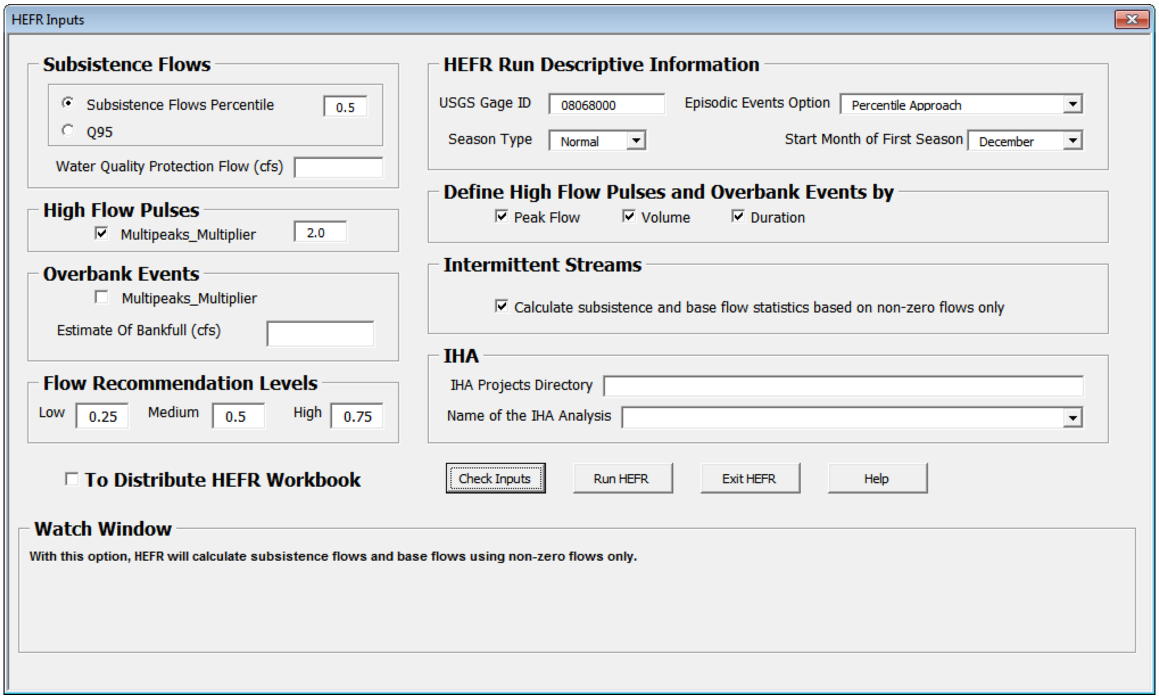


Figure 4-12. HEFR Interface

The results of the analyses are flow regime matrices, one of which—for seasons—is shown in Figure 4-13.

Overbank Flows	Return Period (R) : 0 (years)		Duration (D) : 0 (days)	
	Volume (V) : 0 (ac-ft)		Peak Flow (Q) : 0 (cfs)	
High Flow Pulses	F: 0	F: 0	F: 0	F: 0
	D: 26	D: 33	D: 68	D: 26
	Q: 4040	Q: 5845	Q: 4165	Q: 4975
	V: 47592	V: 45351	V: 38566	V: 39592
	F: 0	F: 0	F: 0	F: 0
	D: 19	D: 19	D: 22	D: 21
	Q: 2950	Q: 1520	Q: 1740	Q: 1240
	V: 29798	V: 18711	V: 15590	V: 10957
	F: 0	F: 0	F: 0	F: 0
	D: 13	D: 12	D: 13	D: 8.5
	Q: 1255	Q: 646	Q: 583	Q: 280
	V: 10810	V: 6816	V: 7307	V: 3763
Base Flows (cfs)	168(52.5%)	105(57.2%)	72(29.0%)	53(42.3%)
	118(61.5%)	79(66.6%)	46(41.4%)	33(56.2%)
	79(72.3%)	56(79.1%)	34(52.5%)	28(64.3%)
Subsistence Flows (cfs)	N/A	N/A	19(82.3%)	13(90.5%)
	Dec Jan Feb	Mar Apr May	Jun Jul Aug	Sep Oct Nov
	Winter	Spring	Summer	Fall

Flow Levels	High (75th %ile)
	Medium (50th %ile)
	Low (25th %ile)
	Subsistence

High Flow Pulse Characteristics	F = Frequency (per season)
	D = Duration (days)
	Q = Peak Flow (cfs)
	V = Volume (ac-ft)

Figure 4-13. Flow Regime Matrix

In addition to running these models, the Texas Flow Regimes Tool records which input parameters were used for each model, which assists with replicating the process or reviewing what variable values were chosen. This tool demonstrates that multiple models linked together in a single location and workflow process have the benefits of reproducibility. This results in a start-to-finish view of analyses and results that can be fully-transferred and replicated.

4.2.6 Summary of Use Cases

The five use cases presented in this chapter tell part of the story of the overall water availability modeling process in Texas. These examples demonstrate various advances and implementations of custom tools to assist with geoprocessing or data processing. Practical insights and engineering benefits of each of the use cases are summarized below:

Use Case 1: Multiple geoprocessing tools are combined in a process that delineates drainage area for any number of specified points. This functionality combines out-of-the-box tools as a custom-built tool for Texas water availability modeling. Attribute data (JunctionID and HydroID values) are tracked and copied/transferred appropriately to assist with automated delineation. This use case demonstrates that the work, tools, or functions of others can be combined in workflow processing. Thus, distinct unrelated steps can be combined to meet the specific needs of another analysis.

Use Case 2: The WRAP Network Tools benefit from the properties of geometric networks in ArcMap. When point and line feature classes both participate in a geometric network, adding a point on the line automatically splits the line at that point. These new features are automatically included in the network. However, the flow direction value is not preserved. The WRAP Network Tools process capitalizes on the practices of ArcMap and Arc Hydro and adds the functionality of copying HydroID values from points to lines to enable automated delineation. This use case demonstrates the benefit gained by using the automation or processing provided by built-in functionality. This saves time and effort by not having to build such from scratch. Also, relationships can be created and maintained using shared ID values of features.

Use Case 3: The delineation process of the WRAP Network Tools is written to intelligently ascertain what is desired by looking for selected features to re-delineate. Re-delineating previously-delineated areas without having to reprocess the entire basin may save considerable time—particularly for large and complicated study areas. This use case demonstrates the advantages achieved by selectively choosing the work that is required and avoiding unnecessary analyses.

Use Case 4: Web services are used in the Texas Flow Regimes Tool to reduce the time and effort required of navigating to a website, entering data parameters (e.g. start/end date), selecting, copying, and pasting results—while making sure they are in the right format and location. While this use case demonstrates a simple example of a web service, it is shown to be beneficial and leads to questions of how else water availability modeling can benefit from web services and web processing.

Use Case 5: The automated steps of the Texas Flow Regimes Tool are another instance of workflow processing benefitting analyses. In this case, the interfaces between three models are automated in an easy-to-use manner. Furthermore, the input parameters are automatically recorded, providing benefits of replication of analyses and verification of results. This use case demonstrates the benefits of linking multiple models and recording decisions made along the way.

4.3 TEXAS WATER AVAILABILITY MODELING THROUGH THE CLOUD

The preceding section of use cases establishes a processing framework where task steps are outlined and left available for further analysis. With the exception of accessing daily USGS streamflow values via web services with the Texas Flow Regimes Tool, the bulk of the WRAP Network Tools and the Texas Flow Regimes Tool is desktop-centric. This section demonstrates that Arc Hydro Web can be used with cloud data access and cloud computing to provide support for Texas water availability modeling.

4.3.1 WRAP Network Tools in the Cloud

In addition to its usefulness in water availability modeling processing, the WRAP Network Tools has limitations, especially when looking to the future of hydrologic computing and data access. The three main limitations of this GIS toolset are 1) its current documentation specifies a reliance on local data; 2) its processing is dependent on a stream network that is systematically broken at each proxy water right point, resulting in the necessity of having at least two nearly-identical stream networks housed within a single organization; and 3) the geoprocessing is performed on a local, desktop scale. This section addresses how Texas water availability modeling desktop processing could be benefitted with use of the cloud.

Before addressing Texas-specific cases, the following elaboration of Open Geospatial Consortium standards helps lay a foundation of web services understanding. When web services can communicate via a common language, such as geographic markup language (GML), GIS users are able to send requests through the cloud to various servers housing the requested data. For example, after first determining which data are available, the GIS user requests the data using a web mapping service (WMS), web feature service (WFS), or web coverage service (WCS)—or any combination of these services—and the requested data are delivered. The latter-end of this description—of the GIS user receiving the data that were requested through the cloud—is depicted in Figure 4-11.

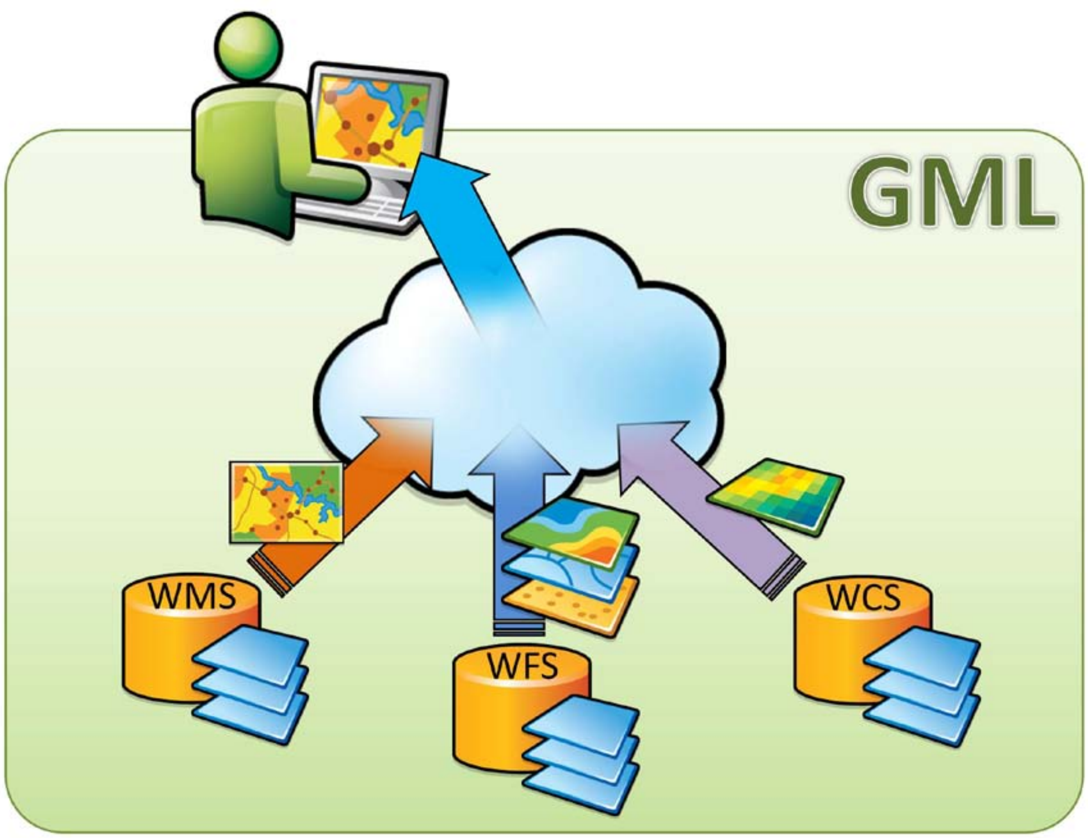


Figure 4-14. Web Services and GML Illustration

Figure 4-11 shows three images of databases and data (on the bottom) representing the servers corresponding to the three web services types: WMS, WFS, and WCS. The cloud represents the Internet, and the green rounded-rectangle labeled “GML” suggests that the entire process is made possible by a common language, GML.

When web services are combined with geoprocessing, the result is geoprocessing services, or Web Processing Services (WPS). Web Processing Services move the location of the geoprocessing from the desktop machine to the server. Such a transition may be useful to organizations that share data and wish to likewise centralize their geoprocessing operations. Once the idea of a geoprocessor is removed from the local environment, it is natural to consider what is possible if the server were made accessible through the cloud.

Such a mental shift could transform the representation shown in Figure 4-14 such that instead of a GIS user requesting data from an external server, multiple servers could communicate with each other, transferring their service products and utilizing any combination of Web Processing Services. Such an environment could lead a GIS user to request feature or gridded data from multiple servers, have the data sent to another server that performs some operation (via geoprocessing tools) and returns a new dataset to the GIS user.

Figure 4-15 illustrates the tail end of this process where the GIS user has already requested multiple web services to provide their data to a third server through the cloud—a Web Processing Service server (labeled WPS in the figure)—which in turn returns the new output dataset to the GIS user, all in a GML environment.

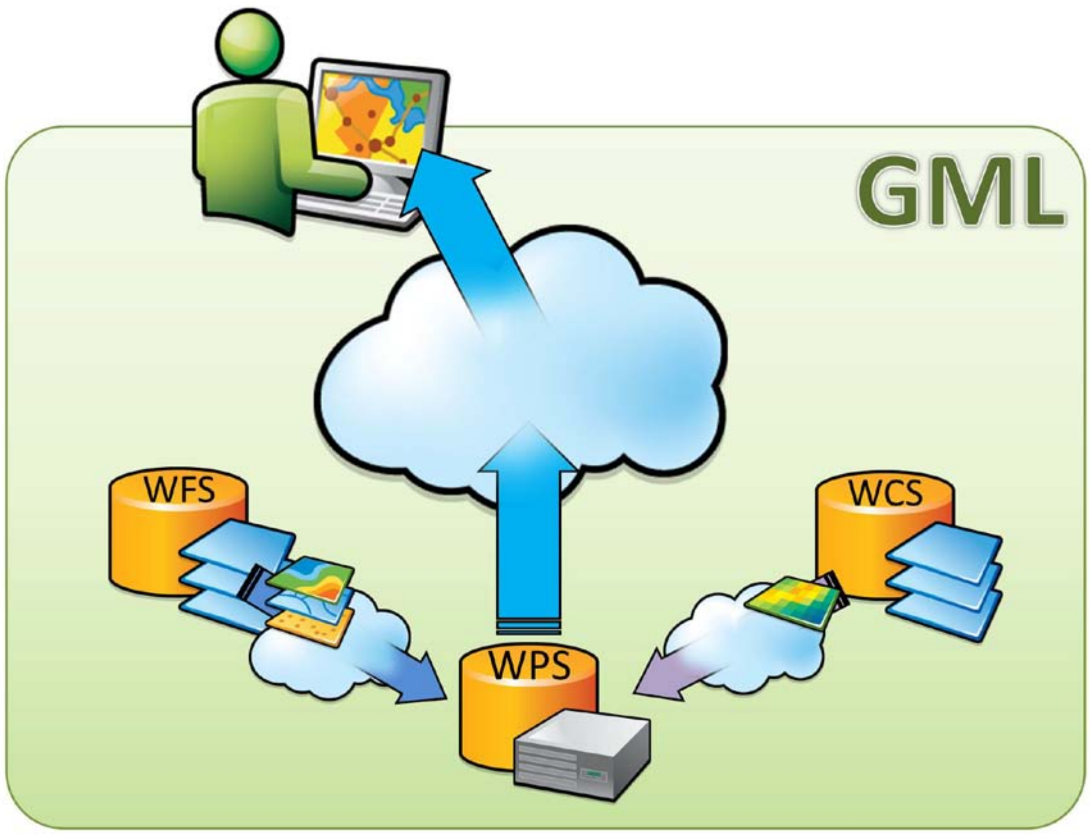


Figure 4-15. Web Processing Service Illustration

Figure 4-14 looks similar to Figure 4-15, but is used to illustrate the difference between services providing data (e.g. WFS and WCS) and WPS. Web Feature Services provide features to users (either desktop users or servers) and Web Processing Services perform calculations or other geoprocessing on data.

Many applications rely on cloud data—with or without the users' knowledge. Many hydrologic base maps are becoming available for use within ArcMap and other applications. Figure 4-16 presents a zoomed-in view of ArcMap showing part of the San Jacinto Texas Basin, with certain data served from the cloud via web services (indicated by the cloud images in the legend).

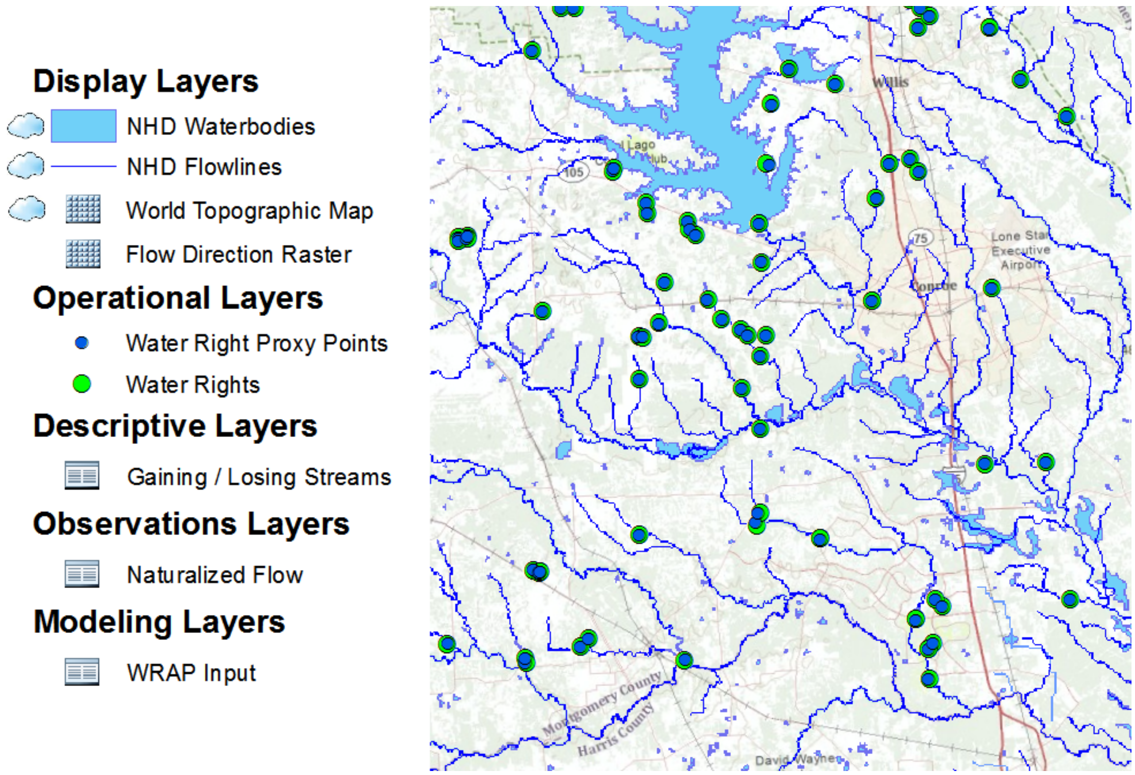


Figure 4-16. San Jacinto Basin with Cloud Data

The cloud-served base maps in Figure 4-16 come from an ArcIMS Server (Arc Internet Map Server) and ArcGIS Online. While base maps are just images—they cannot be used in analyses—data service providers via ArcIMS Servers have feature data that can be served from the cloud which can be used in analyses.

Serving features from the cloud leads to the next limitation: locally-served networks. The WATERS Services include access to the NHD flowline network. Just as that organization serves their network data for others' use, an organization or entity can maintain a single network and serve it to users, along with web services to add points to the network, thus allowing for a single network to be shared among users for various purposes (e.g. water rights analyses and TMDL analyses using the same network).

Web processing services (or cloud computing) provide basin delineation in HydroDesktop using the NHDPlus network capabilities. This is an example of how processing is outsourced from the desktop to the server through the cloud. This is just one example—that is remarkably similar to what the water availability modeling process needs—that illustrates that similar web processing services can be established within an organization's GIS server to provide geoprocessing in the cloud, working in harmony with the cloud-served data discussed previously.

An example of where cloud processing can be used in concert with local water rights data is the Hydrography Event Management Tool combined with the WATERS services. These services can replicate aspects of the WRAP Network Tools in the cloud (NOTE: the Hydrography Event Management Tool is currently a desktop-only application, but its processing capabilities may soon be a web service). Consider water right locations being stored locally as proxy points on a cloud-served NHD flowlines feature class. A tool similar to the Hydrography Event Management Tool could be used to determine where each point lies on the NHD flowlines network, storing the corresponding NHD identifiers (COMID and ReachCode) in the point feature class, along with a calculated linear reference number—indicating where on the stream segment (0-100) the point is. A graphic representing the relationship between the NHD flowline and the water right proxy points is shown in Figure 4-17. This figure shows the flowline network and proxy water right points as a GIS map view behind two attribute tables (one for each) with the ID relationships highlighted with connected red boxes and the linear referencing value shown on the point's attribute table in a yellow box.

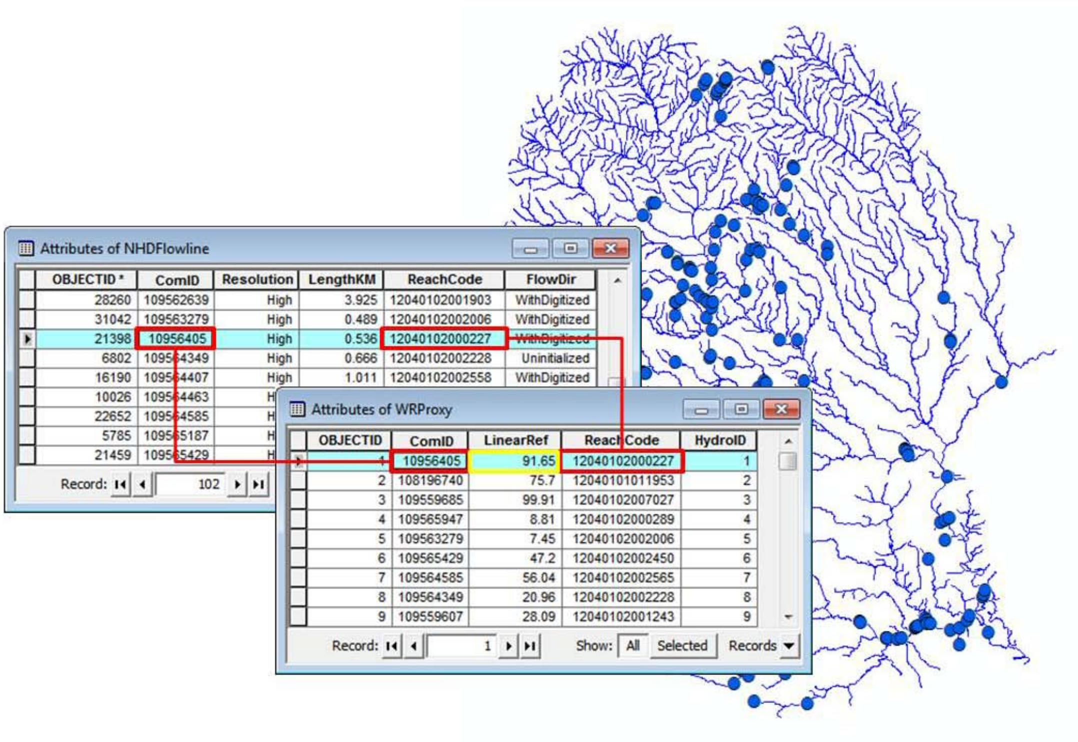


Figure 4-17. Linear Referencing Example

With locations and relationships between the desktop-stored points and cloud-served flowline network, both could be passed to a collection of services similar to the WATERS services that take locations on the NHD flowline network and return delineated watersheds for each. While this example remains partially hypothetical, it demonstrates that the relational and delineation capabilities of the WRAP Network Tools can be mimicked through cloud data access and web processing.

This discussion on WRAP Network Tools in the Cloud has served as a specific example of one aspect of the overall Texas water availability modeling and how it can be informed by web services to perform meaningful analyses and yield useful results. The principles of using web services (including web processing services) may be applied to many aspects of Texas water availability modeling. This discussion is a partial fulfillment of this dissertation's third research question, with the discussion continuing in the following section on flow regimes.

4.3.2 Texas Flow Regimes in the Cloud

The Texas Flow Regimes Tool pierces the cloud with its use of web data services. Convenient as web data harvesting and in-one-place storage of hydrologic models as part of a processing framework are, there remains the fact that this tool combines three models in one location. When models are updated—and models are never-endingly updated—it becomes necessary to publish updates to the Texas Flow Regimes Tool and ensure that all who use it have the same updated versions—for all three models.

The example of the WRAP Network Tools in the cloud is applicable here: just as a single geoprocessing service is considered to handle basin delineation with WRAP networks, the models that exist within the Texas Flow Regimes Tool can likewise exist in the cloud. If models are transformed to web processing services, the difficulties of ensuring similar versions of a desktop-based workbook become obsolete; models as web processing services can be updated and maintained at a single server location, eliminating the need to disseminate updates to all users. Furthermore, just as users can communicate with web processing services via their desktop computer, web processing services can communicate with each other, thus providing the all-in-one connectivity that marks one of the benefits of the Texas Flow Regimes Tool.

Currently, the output of the Texas Flow Regimes Tool is text combined with colors in an array—it lacks a geographic component. The consideration of options for displaying the flow regimes results of combined web processing services geographically should be pursued. With the information already existing in the cloud, it is reasonable to imagine a web mapping service or web feature service that could serve flow regimes data geographically in a GIS.

This discussion is an application of this dissertation's third research question regarding a web-based services-oriented architecture for water availability modeling and its associated benefits. A service-oriented architecture, using a simple definition, can be thought of as a method of utilizing different available services in support of analyses or functions. The transition from desktop analyses and data storage to cloud computing—including the use of web geoprocessing services—is an example of a service-oriented architecture for water availability modeling in Texas. Using shared online data for analyses, along with passing such data to web processing services for online analyses, is the basis of a service-oriented architecture. Benefits of such an architecture include: synthesis among different groups as different data and results are shared; improvements in model maintenance as a single, centralized instance of a model is updated instead of requiring countless users to maintain desktop versions of a model/process; and further synthesis of models and data as the community of such are expanded, allowing for more ease of access to meaningful and robust hydrologic tools and analyses.

4.4 SUMMARY

This chapter presents an evolutionary look at Texas water availability as it examines the current process of a water permit application through a narrative and then steps through the first three use cases that closely examine how the components of the Texas water availability modeling environment are being automated and synthesized to form a more connected whole as a Hydrologic Information System for Texas water availability modeling (in satisfaction of this dissertation's second research question).

The evolutionary journey of Texas water availability modeling continues as further use cases—the final two—introduce ways that desktop water availability modeling analyses can be informed via web services. This exploration is magnified as Arc Hydro Web is used with cloud data access and cloud computing to provide support for Texas water availability modeling. From obtaining daily flow values via the cloud to outsourcing data storage and data processing to web processing services, this dissertation has shown how current Texas water availability modeling practices can be informed by web services (in satisfaction of this dissertation's third research question).

Chapter 5. Conclusion

5.1 WATER AVAILABILITY MODELING SUMMARY

Water availability modeling in Texas has embraced the transition from paper-based documents and maps to a digital system of databases and GIS maps. This fundamental change enables ease of access to data, automation of analytical processes, and synthesis of disparate data in meaningful ways (e.g. enabling queries, network traces, water rights data management, and other basic hydrologic processes). Many of the advances in Texas water availability modeling and associated analyses have impacted desktop processes—doing work on a desktop computer using locally stored data and computer programs. The digital advances associated with the transition from paper-based data storage and analysis to digital-based data storage and analysis are further augmented through the concept of Web 2.0 where data is becoming accessible via web services from anywhere in the world, and geoprocessing analyses can be performed online, or in the cloud.

This dissertation presents a case study in the San Jacinto Basin of Texas that illustrate the intellectual problem resulting from the need to not over-commit water: synthesizing and automating components of the Texas water availability modeling environment via geoprocessing and analytical tools and exploring how such are enhanced and influenced by web services and cloud computing using the Arc Hydro Web information model.

Five components resulted from the transition from paper- to digital-based data in Texas water availability modeling; these are used to describe the character of the intellectual problem addressed in this dissertation. These five components include a water rights database describing each water right individually, a GIS database for Texas, a computer model to simulate monthly flows in Texas and quantify water availability, an implementation of the water availability model for a particular basin, and an environmental flows assessment process to quantify how much water should remain in Texas rivers. These components form the conceptual model of water availability modeling in Texas.

When the Texas water availability modeling conceptual model is combined with tools and procedures that have been developed to synthesize and automate water availability modeling tasks, a picture of a Hydrologic Information System (HIS) for Texas water availability modeling is formed. This HIS includes the various data in the water availability modeling conceptual model and the tools and procedures that were created to display the connections and functionality inherent in the HIS.

5.2 REVIEW OF RESEARCH QUESTIONS

This section reviews this dissertation's research questions that are answered through the research objectives. Three sections correspond to the three research questions, with the research objectives being identified and illustrated in the research questions' summaries.

5.2.1 Conceptual Model for Texas Water Rights Management

The first research question of this dissertation addresses the engineering question of not over-committing surface water in Texas. To begin to answer this question, it is necessary to first understand the prior appropriation system of water rights and water right management in Texas. The research question associated with this need is:

1. What is the conceptual model for Texas water rights management and water availability modeling?

Two components of the Texas water availability modeling environment are of primary importance: water rights data (including the various specifics of the right: location, quantity of water, time of withdrawal, and purpose of use), and the associated network the points participate in (be it a geometric network or an inferred topologic network, e.g. tracking which rights are upstream or downstream of each point). These components—and their inherent relationship—are central to all subsequent analyses that occur.

This dissertation uses an historical account of water availability modeling—including the influence of drought and Senate bills—and the transition from paper-based records to a digital-based system, to demonstrate the importance of five key components in the Texas water availability modeling conceptual model. These components are the water rights database which describes each water right individually; a GIS database for Texas; a computer model (WRAP) which simulates monthly flows in Texas rivers to quantify the availability of water for each water right under various scenarios; an official water availability model for Texas that includes the WRAP model and associated input files for each Texas river and coastal basin; and an environmental flows process designed to quantify how much water should be left in Texas rivers and not allocated for withdrawals. These components are connected in an overall conceptual model for Texas water availability modeling. This is done through a response to an historical progression that satisfies the first research objective.

5.2.2 Hydrologic Information System for Texas Water Availability Modeling

The second research question builds upon the components of the conceptual model and asks:

2. How can the components of the Texas water availability modeling conceptual model be better automated and synthesized to form a more connected whole as a Hydrologic Information System for Texas water availability modeling?

A Hydrologic Information System (HIS) can be defined as a means of connecting geospatial data and associated time series with hydrologic analyses and modeling. The pieces representing different tasks of the conceptual model of Texas water availability modeling are connected through tools and processes. The HIS for Texas water availability modeling includes the components of the conceptual model along with three tools that automate and synthesize the water availability modeling process. These tools are the WRAP Display Tool for visualizing WRAP output, the WRAP Network Tools for performing network analyses and processing additional WRAP points, and the Texas Flow Regimes Tool that is used to determine flow regimes which define instream flows for environmental flows analyses.

The ways that these three tools connect the components of the Texas water availability modeling environment defines a Hydrologic Information System, in fulfillment of this dissertation's second research objective.

5.2.3 Texas Water Availability Modeling Informed by Web Services

The third research question of this dissertation considers that much of the procedures in Texas water availability modeling are based on desktop analyses (i.e. the data are stored locally and the computations are performed on a desktop computer). The process of determining flow regimes in Texas—using the Texas Flow Regimes Tool—utilizes web services to automate the task of obtaining daily streamflow values from the web. This change in data origination and format may require a change in the information model. Web-informed processes can involve more than accessing data from the cloud via web services; they may include a web-based services-oriented architecture where multiple data repositories and processing services are linked to one another. The research question associated with these considerations is:

3. *How can desktop-based Texas water availability modeling be informed by web services using an appropriate information model that could lead to a web-based service-oriented architecture?*

This dissertation employs the use of a reference model of open distributed processing (RM-ODP) and five associated use cases to illustrate key results of this dissertation's research questions and objectives. The first three use cases demonstrate the advances to desktop-based water availability modeling that the tools of the Hydrologic

Information System provide. The fourth and fifth use cases describe how the Texas Flow Regimes Tool uses web services for online data acquisition and subsequent use in hydrologic models. Each of the use cases is analyzed to demonstrate the engineering advances they represent in fulfillment of this dissertation's third research objective.

The process of web data access serves as a departure from historic desktop-centric data storage and access. Through a process of user involvement and interaction, web services are called on the fly, passed user-specified particulars, and corresponding data is retrieved for subsequent analyses. This is an example of how Texas water availability modeling is being informed by web services.

The presentation of an appropriate information model for web-informed analyses is preceded by a review of hydrologic information models in the Literature and Technology Review chapter of this dissertation. It is shown that these information models lack a unifying framework. The Arc Hydro Web information model is presented as an implementation of lessons learned from the past and a more structured web-enabled information model that can be applied in the Texas water availability modeling environment and Hydrologic Information System. It builds upon the Arc Hydro information model tradition and uses five key thematic layers:

- Display Layers as base maps (e.g. streamlines, elevation data, basin or political boundaries, base map imagery).
- Operational Layers where hydrologic analyses are performed (e.g. geometric networks and associated catchment areas, NHDPlus data, water quality data, flood data, rainfall data).

- Descriptive Layers with static information about hydro-features (e.g. gaining/losing streams, groundwater divides, fish species distributions, and flood depths).
- Observations Layers with time-enabled feature observations (e.g. streamflow data, gage heights, evaporation data, rainfall data, storm data).
- Modeling Layers to interface hydrologic models (e.g. water availability models).

The Arc Hydro Web information model is used to show how Texas water availability modeling can be benefitted by web services. Examples describe a unifying information model for Texas water availability modeling. This demonstration of Arc Hydro Web is in fulfillment of this dissertation's fourth research objective.

The network aspects of the Texas water availability modeling environment can be informed by web services. The example is presented of using a centrally-stored network for multiple purposes, negating the current system of having nearly-identical duplicate networks for different departments of an agency to use for different analyses. The use of a single network—served and accessed through the cloud—could foster communication among different agency teams as well as be helpful in data management and quality control (through reducing redundancies of network duplicities). Furthermore, an examination of current web services and web processing capabilities demonstrates that much of the current functionality of Texas water availability modeling can be performed with web services. These web-enabled capabilities provide support for Texas water availability modeling in fulfillment of this dissertation's fifth research objective.

As the water availability modeling environment of Texas is benefitted through the Arc Hydro Web information model, it is useful to envision how advances in web data access and web processing apply to a services-oriented architecture. This dissertation illustrates the benefits and power of desktop data storage and processing, the advantages to incorporating web data into analyses, and suggests a means of utilizing web data and web processing services to replicate the desktop procedures in the cloud. This discussion fulfills this dissertation's sixth and final research objective.

This dissertation presents a desktop-based process of achieving some of the relational and delineation capabilities of the WRAP Network Tools through cloud data access and web processing. This example is hypothetical because the full functionality of web processing services required to structure a fully capable services-oriented architecture are still being developed. However, this will not occur until the ubiquity of web services and web data enable the full replication of the suite of data and processing afforded in the Texas water availability modeling Hydrologic Information System.

5.3 REVIEW OF RESEARCH OBJECTIVES

Although each of the research objectives were mentioned in the previous discussion on the research questions, they are repeated here to provide a concise summary. The following list is the research objectives, as presented in the Introduction, with a brief summary of how they were fulfilled immediately following each:

1. Outline the conceptual model for Texas water rights management and water availability modeling.

The conceptual model is outlined as a response to an historical progression of water availability modeling in Texas and includes three component models that together form the overall conceptual model.

2. Define a Hydrologic Information System for Texas water availability modeling;

The Hydrologic Information System (HIS) is defined using three tools that combine components of the conceptual model: the WRAP Display Tool, the WRAP Network Tools, and the Texas Flow Regimes Tool. These tools automate the processes of water availability modeling and synthesize the conceptual model components.

3. Employ use cases in the San Jacinto Basin in Texas to demonstrate scientific and engineering contributions;

As part of the Enterprise Viewpoint of the RM-ODP, five use cases are used to demonstrate the functionality and results of HIS tools (WRAP Network Tools and Texas

Flow Regimes Tool). Each of these use cases demonstrates a specific practical contribution to engineering.

4. Describe a unifying information model for Texas water availability modeling: Arc Hydro Web;

The Arc Hydro Web information model is presented and described. It is based on the Arc Hydro information model and has five key thematic layer groups: Display Layers as base maps; Operational Layers where hydrologic analyses are performed; Descriptive Layers with static information about hydro-features; Observations Layers with time-enabled feature observations; and Modeling Layers to interface hydrologic models.

5. Demonstrate that Arc Hydro Web can be used with cloud data access and cloud computing (web processing) to provide support for Texas water availability modeling;

Using existing tools and web services, Arc Hydro Web is shown to handle some of the current functionality of Texas HIS tools. These web-enabled capabilities provide support for Texas water availability modeling.

6. Discuss potential advances in water availability modeling using a services-oriented architecture approach;

Looking to the future, this dissertation illustrates how utilizing web data and web processing services to replicate traditional desktop procedures in the cloud can advance water availability modeling in Texas.

5.4 CONTRIBUTIONS TO KNOWLEDGE

The contributions to knowledge in the field of geospatial hydrology and water resources management that this dissertation provides are outlined in two sections: a section on the conceptual model and Hydrologic Information System, and a section on the Arc Hydro Web information model and potential of relocating geoprocessing from the desktop to the cloud.

5.4.1 Conceptual Model and Hydrologic Information System

This dissertation outlines the conceptual model of water availability modeling in Texas. With the conceptual model outlined, it is easier to see how the various components relate to one another. Furthermore, tools that have been developed help link various components of the conceptual model as a Hydrologic Information System. These tools include:

- WRAP Display Tool – this tool combines GIS representations of water availability modeling features with output from the WRAP model enabling automated visualization of output variables as time series or as maps.
- WRAP Network Tools – these tools combine the official water rights database(s) with GIS representations of water availability modeling features in order to perform network traces and analyses, manage flow directions, establish and maintain relationships between GIS features,

delineate watersheds, and generate appropriate notices for water right holders.

- Flow Regimes Tool – this singly-contained Excel workbook combines the overall environmental flows process with water availability modeling by utilizing web data access (via web services) to obtain USGS flow values, housing multiple models, tracking input variable choices, automating input data preparation for the HEFR model, and displaying the resulting flow regimes.

These tools taken individually or collectively represent contributions to knowledge by their adroit linking of water availability modeling components. In addition, these tools enable additional functionality and analysis outside of their specified purposes as a result of the ways that they synthesize once disparate datasets. For example, the WRAP Network Tools are being used in QA/QC of maps and databases by performing network traces on GIS data and comparing the resulting generated reports to the water rights databases to determine which entries in the official database are lacking detail or are otherwise inconsistent. Furthermore, the WRAP Network Tools are used to quickly generate maps for specified areas based on network connectivity—a process that once would take a week or more being done in minutes. Finally, these tools can be combined to assist with flood analyses in a number of ways (e.g. by accessing flow values as well as doing network analyses to geographically represent various scenarios).

5.4.2 Arc Hydro Web Information Model and Geoprocessing

Arc Hydro Web presents an information model that can be used with web services and web processing to relocate water availability modeling and associated analyses from the desktop to the cloud. Examples of benefits of such relocation include the following:

- Water availability modeling steps and data may become accessible via web services (including web data services and web processing services).
- The results of such a relocation of processing may foster collaboration across departments or fields as communication increases as data and steps become transparent and readily discernable.
- Nearly-identical networks and databases may be eliminated as tools and processes use existing, shared networks in the cloud (as opposed to requiring multiples as different organizations follow different data management protocols).
- The public may be empowered with access to hydro-knowledge via web applications (e.g. “What is the drainage area of this location?”).

The potential for web-based water availability modeling data and processing—as presented in this dissertation—is a contribution to knowledge that can become a reality in the near future.

5.5 FUTURE AND CONCLUSION

This dissertation outlined ways that water availability modeling in Texas has been benefitted through linking separate components (through specific tools and procedures), as a conceptual model and Hydrologic Information System. These connections and tools are enabling useful analyses and expanding understanding. The proposed structure of the Arc Hydro Web information model may enhance data representation and analysis, including the implementation of web data access and web services. The accounts from the history of Texas water availability modeling illustrate cases where the use of the Arc Hydro Web information model would be beneficial. Furthermore, the advances presented in this dissertation can influence data sharing and data access. Consider an organization where many individuals contributed to the benefit of a shared hydrologic network; such an environment would negate the need for multiple instances of nearly-identical networks and could increase productivity and communication as a shared network serves as a sort of round table where professionals meet to discuss new ideas and potential applications for the data.

While such a vision may at present be blue sky thinking, it is clear that harnessing the recent innovations associated with web services and cloud computing, while building upon the best practices of the past, can result in a future of easy accessible hydro-data through the web, expanding geoprocessing capabilities in the cloud (including combining geoprocessing services from multiple web geoprocessing providers), and the combination of such data and services in new and exciting ways for use in water availability modeling applications and other hydrologic analysis scenarios.

References

Arctur, D. and M. Zeiler. (2004) Designing Geodatabases: Case Studies in GIS Data Modeling. ESRI Press, Redlands, California.

Australian Bureau of Meteorology. (2010) “Australian Hydrological Geospatial Fabric (Geofabric) Products Users Guide.” Version 1.0.

Beran, B., and M. Piasecki. (2009) “Engineering new paths to water data.” Computers & Geosciences, 35:753-760.

Braden, J., D. Brown, J. Dozier, P. Gober, S. Hughes, D. Maidment, S. Schneider, P. Schultz, J. Shortle, S. Swallow, and C. Werner. (2009) “Social science in a water observing system.” Water Resources Research, 45:W11301.

Cesur, D. (2007) “GIS as an information technology framework for water modeling.” Journal of Hydroinformatics, 9:123-134.

Chang, A., M. Parrales, J. Jiminez, M. Sobieszczyk, S. Hammer, D Copenhaver, and R. Kulkarni. (2009) “Combining Google Earth and GIS mapping technologies in a dengue surveillance system for developing countries.” International Journal of Health Geographics, 8:49

Cole, S., and R. Moore. (2009) “Distributed hydrological modelling using weather radar in gauged and ungaged basins.” Advances in Water Resources, 32:1107-1120.

Cutore, P., G. Cristaudo, A. Campisano, C. Modica, A. Cancelliere, and G. Rossi. (2007) “Regional Models for the Estimation of Streamflow Series in Ungauged Basins.” Water Resources Management, 21:789-800.

CUAHSI (2010) “EPA Delineation.” HydroDesktop Help. http://his.cuahsi.org/hdhelp/extensions/EpaTools/EPA-Delineation.html

CUAHSI (2011) “HydroDesktop” CUAHSI HIS. http://his.cuahsi.org/hydrodesktop.html

Dangermond, J., and D. Maidment. (2010) “Integrating water resources information using GIS and the web.” AWRA 2010 Spring Specialty Conference.

EPA (2010) “WATERS Services: Standardized interfaces to perform common analyses of water program data.” United States Environmental Protection Agency. http://www.epa.gov/waters/doc/factsheets/WATERS%20Services%20Fact%20Sheet.pdf

EPA and USGS. (2010) “NHDPlus User Guide.” Horizon Systems Corporation: ftp://ftp.horizon-systems.com/NHDPlus/documentation/NHDPLUS_UserGuide.pdf

ESRI (2008) “ArcGIS 9.2 Desktop Help: What is a geometric network?” http://webhelp.esri.com/arcgisdesktop/9.2/index.cfm?TopicName=What_is_a_geometric_network%3F

ESRI (2009) “What Is GIS? Overview.” http://www.esri.com/what-is-gis/

ESRI (2009b) “Geodatabase: Overview.” http://www.esri.com/software/arcgis/geodatabase/

ESRI (2010) “ArcGIS Resource Center: Data Models.” http://resources.arcgis.com/content/data-models

ESRI (2010b) “ArcGIS Online Map Services.” http://www.esri.com/library/fliers/pdfs/arcgisonline-map-services.pdf

ESRI (2010c) “Esri Supported Open Geospatial Consortium, Inc and ISO/TC 211 Standards.” http://www.esri.com/library/whitepapers/pdfs/supported-ogc-iso-standards.pdf

Furst, J. and T. Horhan. (2009) “Coding of watershed and river heirarchy to support GIS-based hydrological analyses at different scales.” Computers & Geosciences, 35:688-696.

Gao, Y., R. Vogel, C. Kroll, N. Poff, and J. Olden. (2009) “Development of representative indicators of hydrologic alteration.” Journal of Hydrology. 374:136-147.

Garbrecht, J., F. Ogden, P. DeBarry, and D. Maidment. (2001) “GIS and Distributed Watershed Models. I: Data Coverages and Sources.” Journal of Hydrologic Engineering, 6:506-514.

Goodall, J., J. Horsburgh, T. Whiteaker, D. Maidment, and I. Zaslavsky. (2008) “A first approach to web services for the National Water Information System.” Environmental Modeling & Software, 23:404-411.

Gopalan, H. (2003) “WRAPHydro Data Model: Finding Input Parameters for the Water Rights Analysis Package.” Thesis, The University of Texas at Austin. CRWR Online Report 2003-03. http://www.crwr.utexas.edu/reports/2003/rpt03-3.shtml

Graham, S., J. Famiglietti, and D. Maidment (1999) “Five-minute, 1/2 degree, and 1 degree data sets of continental watersheds and river networks for use in regional and global hydrologic and climate system modeling studies.” Water Resources Research, 35:583-587.

Guthrie, J., C. Dartiguenave, and K. Ries III. (2009) “Web Services in the U.S. Geological Survey StreamStats Web Application.” Proceedings of the 2009 International Conference on Advanced Geographic Information Systems & Web Services, 60-63.

Haiting, L., P. Qingshan, and L. Yanhong. (2009) “Data Security Analysis of WebGIS Based on Tile-Map Technique.” Proceedings of the 2009 International Symposium on Web Information Systems and Applications, 190-193.

Hickey, J. (2006) "Regime Prescription Tool, HEC-RPT, User's Manual, Version 1.0." US Army Corps of Engineers, Institute for Water Resources, Hydrologic Engineering Center (HEC), CPD-84.

ISO (2008). "ISO in Brief." http://www.iso.org/iso/isoinbrief_2008.pdf

ISO/IEC 10746-1:1998, "Information technology -- Open Distributed Processing -- Reference model: Overview."

Kepler Project (2010) "The Kepler Project." https://kepler-project.org/

Koch, H., and U. Grunewald. (2009) "A Comparison of Modelling Systems for the Development and Revision of Water Resources Management Plans." Water Resources Management, 23:1403-1422.

Li, J., and D. Wong. (2010) "Effects of DEM sources on hydrologic applications." Computers, Environment and Urban Systems, 34:251-261.

Maidment, D. (1995) "Research in hydrologic science in the USA." Journal of Hydrology, 172:1.

Maidment, D., Ed. (2002) *Arc Hydro: GIS for Water Resources*. ESRI Press, Redlands, California.

Maidment, D. (2008) "Bringing Water Data Together." Journal of Water Resources Planning and Management, 134:95-96.

Maidment, D., Ed. (2009). "CUAHSI HYDROLOGIC INFORMATION SYSTEM: 2009 Status Report." http://his.cuahsi.org/documents/HISOverview2009.pdf

Maidment, D., V. Merwade, D. Kim, T. Whiteaker, and M. Muste. () "Vision and Progress: Data models for multi-dimensional representation of the river processes."

Mori, M, and T. Kameyama. (2009) "GIS analysis of flood damage using Google Earth." River Basin Management V (5th International Conference on River Basin Management), 105-112.

National Hydrography Dataset (2011). "Hydrography Event Management Tool." http://nhd.usgs.gov/tools.html#hem

The Nature Conservancy (2010). "Indicators of Hydrologic Alteration IHA Software." http://www.nature.org/initiatives/freshwater/conservationtools/art17004.html

OGC (2004). "OGC Web Map Service Interface." OGC 03-109r1

OGC (2007). "OpenGIS Web Processing Service." OGC 05-007r7.

OGC (2007b). "OpenGIS Geography Markup Language (GML) Encoding Standard." OGC 07-036

OGC (2010). "OpenGIS Web Feature Service 2.0 Interface Standard." OGC 09-025r1.

OGC (2010b). "OGC WCS 2.0 Interface Standard - Core." OGC 09-110r3.

OGC (2011). “OGC Standards and Specifications.” http://www.opengeospatial.org/standards

OGC (2011b). “Water Information Services Concept Development Study Report.” OGC 11-013.

OpenMI Association (2010) “What is OpenMI.” http://www.openmi.org/reloaded/about/what-is-openmi.php

OpenMI Association (2010b) “Publications & Documents: OpenMI Manuals and Guidelines.” http://www.openmi.org/reloaded/about/publications-documents.php#3

Poff, N., J. Allan, M. Bain, J. Karr, K. Prestegaard, B. Richter, R. Sparks, and J. Stromberg. (1997) “The Natural Flow Regime.” BioScience, 47:769-784.

Potter, K. (2001) “A simple method for estimating baseflow at ungaged locations.” Journal of the American Water Resources Association, 37:177-184.

Preston, S., R. Alexander, M. Woodside, and P. Hamilton. (2009) “SPARROW MODELING—Enhancing Understanding of the Nation’s Water Quality.” U.S. Geological Survey, Fact Sheet 2009-3019. http://pubs.usgs.gov/fs/2009/3019/pdf/fs_2009_3019.pdf

Renton, F., J. Kapellas, and L. Anguino (2008) “Indexing Water Rights data to the National Hydrography Dataset.” American Water Resources Association Spring Specialty Conference: GIS and Water Resources V. http://www.awra.org/proceedings/0803pro_toc.html

Ries III, K. (2002) “STREAMSTATS: A U.S. Geological Survey web site for stream information.” Hydroinformatics 2002: Proceedings of the Fifth International Conference on Hydroinformatics.

Rowland, E., R. Hotchkiss, and M. Barber. (2003) “Predicting fish passgae design flows at ungaged streams in eastern Washington.” Journal of Hydrology, 273:177-187.

Sheppard, S., and P Cizek. (2009) “The ethics of Google Earth: Crossing thresholds from spatial data to landscape visualization.” Journal of Environmental Management, 90:2102-2117.

Shiau, J., and F. Wu. (2009) “Regionalization of natural flow regime: Application to environmental flow optimization at ungaged sites.” River Research and Applications, 25:1071-1089.

Siler, C. (2008) “Space-Time Analysis of the WRAP Model with a Focus on Data Visualization.” Thesis, The University of Texas at Austin. CRWR Online Report 2008-02. http://www.crwr.utexas.edu/reports/2008/rpt08-2.shtml

Siler, C. (2009) “WRAP Network Tools.” Unpublished research at the Center for Research for Water Resources.

Siler, C. (2010) “Texas Flow Regimes Hybrid Data Access and Modeling Tool.” Unpublished research at the Center for Research in Water Resources.

Simley, J., and W. Carswell. (2010) “The National Map—Hydrography.” U.S. Geological Survey, Fact Sheet 2009-3054. http://pubs.usgs.gov/fs/2009/3054/

Singh, K. (1995) “Prediction of River Discharge at Ungaged Sites with Analysis of Uncertainty.” Journal of Water Resources Planning and Management, 121:284-285.

Stanislawski, L. (2009) “Feature pruning by upstream drainage area to support automated generalization of the United States National Hydrography Dataset.” Computers, Environment and Urban Systems, 33:325-333.

Strassberg, G. (2005) “A geographic data model for groundwater systems.” Dissertation, The University of Texas at Austin.

Strassberg, G., N. Jones, and D. Maidment. (2011) *Arc Hydro Groundwater: GIS for Hydrogeology*. ESRI Press, Redlands, California.

Strassberg, G., D. Maidment, and N. Jones. (2007) “A Geographic Data Model for Representing Ground Water Systems.” Ground Water, 45:515-518.

Tarboton, D., J. Horsburgh, D. Maidment, T. Whiteaker, I. Zaslavsky, M. Piasecki, J. Goodall, D. Valentine, and T. Whitenack. (2009) “Development of a Community Hydrologic Information System.” 18th World IMACS/MODSIM Congress, Cairns, Australia 13-17July 2009, http://mssanz.org.au/modsim09

TNRIS (2011). “The Strategic Mapping Program (StratMap).” Texas Natural Resources Information System, Texas Water Development Board. http://www.tnris.state.tx.us/Programs/Stratmap/Index.aspx

TCEQ (2010). “Texas Commission on Environmental Quality: Environmental Flows Resources.” http://www.tceq.state.tx.us/permitting/water_supply/water_rights/eflows/resources.html

TCEQ (2010b). “Texas Commission on Environmental Quality: Tools & Guidance.” http://efis.crwr.utexas.edu/tools_guidance.html

TCEQ (2011). “Use of Hydrologic Data in the Development of Instream Flow Recommendations for the Environmental Flows Allocation Process and the Hydrology-Based Environmental Flow Regime (HEFR) Methodology, Third Edition.” http://www.tceq.texas.gov/assets/public/permitting/watersupply/water_rights/eflows/hydrologicmethods04202009.pdf

Texas EFIS (2010). “MBFIT.” http://efis.crwr.utexas.edu/hydrology.html

Texas State Legislature (1997) “Senate Bill 1.” http://www.legis.state.tx.us/tlodocs/75R/billtext/html/SB00001F.htm

Texas State Legislature (2001) “Senate Bill 2.” http://www.capitol.state.tx.us/tlodocs/77R/billtext/html/SB00002F.htm

Texas State Legislature (2007) “Senate Bill 3.” http://www.legis.state.tx.us/tlodocs/80R/billtext/html/SB00003F.htm

To, E., D. Tarboton, and D. Maidment. (2006) “Introduction to Google Earth.” Class assignment for GIS in Water Resources course at the University of Texas at Austin. http://www.ce.utexas.edu/prof/maidment/giswr2006/Ex1/Ex12006Google.doc

TPWD (2009) “Texas Parks and Wildlife Department: 2008 Annual Report.” http://www.tpwd.state.tx.us/publications/pwdpubs/media/pwd_bk_e0100_003_01_09.pdf

Tucker, C. (2000) Using ArcToolbox. Environmental Systems Research Institute, Inc, Redlands, California.

TWDB (2009), “Texas Water Development Board: Texas Instream Flow Program.” http://www.twdb.state.tx.us/publications/shells/TIFP_0308_L.pdf

United States Department of Agriculture (USDA). (1986) “Urban Hydrology for Small Watersheds.” Technical Release 55 (TR-55). http://www.cpesc.org/reference/tr55.pdf

United States Environmental Protection Agency. (USEPA, 2010) “WATERS Web, Mapping, and Database Services.” http://www.epa.gov/waters/geoservices/index.html

Usery, EL., D. Varanka, and M. Finn. (2010) “A 125 Year History of Topographic Mapping and GIS in the U.S. Geological Survey 1884-2009” (parts 1 and 2) United States Geological Survey. http://nationalmap.gov/ustopo/125history.html, http://nationalmap.gov/ustopo/125history_part_2.html

USGS (2002). Estimating Water Use in the United States. National Academy Press, Washington, D.C.

USGS (2007). “Facing Tomorrow’s Challenges—U.S. Geological Survey Science in the Decade 2007–2017.” U.S. Geological Survey, Circular 1309. http://pubs.usgs.gov/circ/2007/1309/

USGS (2008). “USGS National Hydrography Dataset Newsletter.” Vol. 7, No. 6. http://nhd.usgs.gov/newsletters/News_April_08.pdf

USGS (2011) “USGS 08074000 Buffalo Bayou at Houston, TX.” http://waterdata.usgs.gov/usa/nwis/uv?08074000

Vertessy, R. (2010) “Recent advances towards regular and systematic reporting on Australia’s water resources.” Groundwater 2010 Conference. http://www.groundwater2010.com/documents/P3RobVertessy.pdf

Vogl, A., and V. Lopes. (2009) “Impacts of water resources development on flow regimes in the Brazos River.” Environmental Monitoring and Assessment, 157:331-345.

Warwick, J., and S. Haness. (1994) “Eficacy of ARC/INFO GIS Applications to Hydrologic Modeling.” Journal of Water Resource Planning and Management, 120:366-381.

Weiskel, P., R. Vogel, P. Steeves, P. Zarriello, L. DeSimone, and K. Ries III. (2007) “Water use regimes: Characterizing direct human interaction with hydrologic systems.” Water Resources Research, 43:W04402.

Whiteaker, T. (2004) “Geographically Integrated Hydrologic Modeling Systems.” Dissertation, The University of Texas at Austin. CRWR Online Report 2004-04. http://www.crwr.utexas.edu/reports/2004/rpt04-4.shtml

Whiteaker, T., and E. To. (2008) “CUAHSI Web Services for Ground Water Data Retrieval.” Ground Water, 44:136-138.

Whiteaker, T., D. Maidment, H. Gopolan, C. Patino, and D. McKinney. (2007) “Raster-network regionalization for watershed data processing.” International Journal of Geographic Information Science, 21:341-353.

Whiteaker, T., O. Robayo, D. Maidment, and D. Obenour. (2006) “From a NEXRAD Rainfall map to a Flood Inundation Map.” Journal of Hydrologic Engineering, 11:37-45.

Wurbs, R. (2006) “Methods for Developing Naturalized Monthly Flows at Gaged and Ungaged Sites.” Journal of Hydrologic Engineering, 11:55-64.

Wurbs, R. (2009) “Water Rights Analysis Package (WRAP) Modeling System Users Manual.” Texas Water Resources Institute, TR-256.

Yi, S., Z. Chang, and L. Li. (2007) “An ArcHydro-feature based data model of water resources system of irrigation district in northwest China.” Geoinformatics 2007: Geospatial Information Technology and Applications, 6754:Q67541Q.

Zeiler, M. (1999) Modeling Our World: The ESRI Guide to Geodatabase Design. ESRI Press, Redlands, California.

Zheng, C., J. Lin, and D. Maidment. (2006) “Internet Data Sources for Ground Water Modeling.” Ground Water, 44:136-138.

VITA

Growing up in rural Nebraska, outside of Omaha, Clark David Siler had no plans or aspirations for higher education. After graduating from Platteview High School in 1996, he devoted two years of his life in service to God and others as a full-time missionary for the Church of Jesus Christ of Latter-day Saints. During this time of service, Clark decided that education could be a key to happiness, success, and a way to continue serving throughout life. Clark completed general courses and graduated Cum Laude with an Associates of Science degree from Utah Valley State College in Orem, Utah in 2003. He then focused his attention on civil engineering and hydrology while studying at Brigham Young University in Provo, Utah. He graduated Summa Cum Laude with a Bachelors of Science degree in civil engineering and a minor in mathematics in 2005. He attended the University of Texas at Austin where he obtained a Master's of Science in Environmental and Water Resources Engineering degree in May, 2008. Clark is blessed with an amazing and beautiful wife, Maryann. They have four wonderful children.

Permanent address: 2427 Temple View Ln., South Jordan, UT 84095

This manuscript was typed by the author.