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Space-Time Analysis of the WRAP Model with a Focus on Data Visualization

by

Clark D. Siler, M.S.E.

David R. Maidment, Ph.D.

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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
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Abstract

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Clark D. Siler, M.S.E.
The University of Texas at Austin, 2008
SUPERVISOR: David R. Maidment

The Water Rights Analysis Package (WRAP) is Texas' official water availability model. The output of this computer simulation is a voluminous, structured text file. In its native format, the output file cannot be exposed to geographic information system (GIS) software due to inconsistent formatting between the file's sections. This thesis presents a space-time analysis of the WRAP model and its output while focusing on making the output data available for visualization in a GIS. This analysis reveals that the temporal and spatial nature of the data make possible the display of output data as color-coded maps which can show spatial relationships between data, as well as time series graphs which are useful in revealing temporal trends and events for locations. This visualization is made possible through repackaging the output data from its native format to a set of multivariable geodatabase tables. The means of these forms of visualization are automated through the use of the WRAP Display Tool. This tool was developed specifically for the WRAP output data for use in revealing the maps and time series mentioned.

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Chapter 1. Introduction

In 1996, the state of Texas suffered a particularly hard year of drought. As is often the case in drought conditions, people, animals, and plants were in need of water where not enough was available. Here, decision makers faced a dilemma; they knew how much water was needed without an understanding of where the water could come from or how to get it. For perhaps the first time, many became painfully aware of an existing lack of understanding regarding the state's water availability (Texas Environmental Profiles 2006).

Realizing the need for change, the Texas legislature passed Senate Bill 1, or the "Water Bill," in 1997 after this awakening drought. This bill changed the way that many aspects of planning were performed, including the implementation of a state-wide water availability model. While the water availability model does not specifically solve the state's water need problems—it does not create water—it does track water uses and can be used in predicting future water availability. Armed with this knowledge, decision makers are better prepared to confront challenges that arise.

The Water Rights Analysis Package (WRAP) is the official water availability model for the state of Texas. WRAP is a suite of modeling programs developed by Dr. Ralph Wurbs of Texas A&M University. These programs take hydrological information (such as streamflow, evaporation, reservoir levels, etc.) along with prior appropriation water right data to produce output that is useful in designating water right applications in Texas. In addition, the WRAP output can be used as a basic water availability model to predict quantities of water in river systems under various scenarios. Hence, WRAP is more than just a way to analyze water rights—it is a water availability model.

1.1 MOTIVATION

The Texas Commission on Environmental Quality (TCEQ) is Texas' regulatory environmental agency which is responsible for, among other things, the review, analysis, and approval of water right applications and amendments. TCEQ actively uses WRAP to model water quantities in streams, reservoirs, and watersheds. The WRAP output that TCEQ generates is composed of text files containing much data.

In its native format, WRAP output is difficult to decipher, even with an understanding of its complex structure. This file contains rows and rows of numbers that correspond to modeled output for many variables for each time step of the model at every location used in the model. The result is a large file that is highly cyclical and follows strict formatting.

The output data of WRAP provides an exclusive look into space-time analyses by virtue of its structure and format. In its original format, the WRAP output cannot easily be used to visualize the results of analyses. In other words, after placing considerable efforts and time into each simulation, the results cannot be seen in easy to understand formats; rather, one is given only numbers.

The structure of the output data involves values for many variables for each time step at every location in the simulation. The temporal and spatial aspects of the output lend heavily to the need to perform a space-time analysis of the WRAP output data. The motivation for the study presented in this thesis is to examine the WRAP output and its format in such a way as to enable meaningful presentation of simulation results in formats that incorporate the dual space and time aspects of the output data.

In addition to a space-time analysis, another motivation for this study is to represent the WRAP output data according to such analyses: spatially and temporally. This is best achieved through the use of a geographic information system (GIS) which is designed to make such data visually available as maps and/or time series. With the water availability model's output data available in visual formats, TCEQ will be better able to easily understand the results of simulations and make appropriate decisions.

1.2 PROJECT PURPOSES

Closely linked to the study's motivation are the project purposes. As was stated, simply using WRAP as a water availability model is insufficient if the output data is cryptic and contains information that is hard to readily visualize—data is only useful if it is digestible and can be understood. The purposes of the space-time analysis of the WRAP model's output include:

1. Advancement of data management in attribute series styles – The vast amount of data that is produced with each run of WRAP introduces innovative data management opportunities. These opportunities involve the development of the Arc Hydro II data structure, which is the Arc Hydro data structure with integrated temporal and space components.
2. Visualization of WRAP output data for synthesis and analysis purposes – The visualization method of choice is using a component of the Environmental Systems Research Institute's (ESRI) geographical information system: ArcGIS. This is accomplished through the use of a tool in ArcMap (a mapping component of ArcGIS).
3. Creating pathways for future work by ESRI so similarly structured data is more readily accessible by ArcMap – The visualization and data management advancements developed in the WRAP space-time analysis research can be applied to other collections of data, and may be instrumental in paving the way for future tool development by ESRI.

1.3 CONTRIBUTIONS TO KNOWLEDGE

The project purposes, listed above, can be viewed as contributing to the overall knowledge of water resources engineering. Interestingly, this can be seen by analyzing each alone, or taking them together as a group.

1.3.1 Attribute Series

The way of storing WRAP output data, attribute series, is a contribution to knowledge itself. This is verified by comparing the native format of WRAP output data with the processed multivariable geodatabase format which is the result of the space-time analysis. The first being difficult to access and understand, and the second being in an environment which fosters access and understanding. The attribute series structure is an advancement of both data storage and data access. In addition, the specific application of WRAP output data has lead to the development of an improved way of storing and accessing hydrological data: Arc Hydro II. The inability of Arc Hydro to easily handle the WRAP output pointed to possible improvements in the data model. The result is a work in progress and will incorporate integrated temporal and spatial components.

1.3.2 GIS Visualization

The research presented in this thesis takes advantage of traditional mapping capabilities and recent advancements in the graphing abilities of ESRI's ArcMap. The capability of displaying map and time series data is made possible by the ArcGIS software, but the means of doing so is useful to those who use WRAP as well as those who have any type of space-time data. The research presented in this thesis involves the development and use of the WRAP Display Tool. While this tool was developed for the express use of WRAP data, it can also be used to display other space-time data, providing it is organized similarly to the WRAP attribute series. In this case, ESRI made the visualization possible and the WRAP space-time analysis made the methods of visualization easier.

1.3.3 Future GIS Tools

The combination of the previous two contributions to knowledge enables stunning views of space-time data. The ability of the WRAP Display Tool to act as mediator between the WRAP output data and ArcMap has been noticed by ESRI. Professional associations with ESRI have assisted in the sharing of knowledge of how the WRAP Display Tool is used to make attribute series data available visually. Future GIS tool development by ESRI may result from the sharing of knowledge which has taken place.

1.4 OUTLINE OF THESIS

This thesis contains the space-time analysis of the WRAP model and its output. A brief outline of the various sections follows:

- Technical and Literature Review – To better understand the WRAP model, the technical review covers many aspects of Texas' official water availability model to varying degrees of intricacy. This review includes extensive discussion on naturalized flows and their use in the WRAP model. Included in this section is a literature review which introduces comparative publications that relate to water availability models or data and database management.
- Methodology – Model output can be represented by a structure called the data cube. This section examines the WRAP output data through the lens of the data cube and explores how the native output data is organized and then progresses to methods of representing such in a geodatabase structure. Linking the time series data of the WRAP output file to GIS attribute information results in attribute series. These are discussed as attention is placed on how attribute series can be used to realize the purposes of the project. Finally, an advancement which has resulted from this project, Arc Hydro II, is discussed. This data model's structure is discussed and its similarities and differences from the WRAP output data structure are explored.
- Procedure of Applications – This section explores in great detail the process of taking native WRAP output data and representing it in a GIS environment. This is done by converting the output data from a text file to a collection of geodatabase tables, while preserving metadata in the process. With information in an attribute series, it is exposed to GIS to successfully link the model output data to geographical locations on a map, resulting in a color-coded map display which indicates spatial relationships and values. Furthermore, time series graphs are made possible which can be used to reveal temporal trends in data at locations. Finally, attention is placed on how the benefits of the WRAP Display Tool can be made available to non-WRAP data.

- Example – Discussion leaves the oft-abstract realm and is focused on practical applications of the results of the space-time analysis of WRAP data. This is done through a step-by-step example of how the WRAP Display Tool can be used to access and display the modeled output of a WRAP simulation.
- Conclusion – This section synthesizes the other sections giving a condensed look at what was learned. In addition, recommendations for future work and application of the space-time analysis research are listed.

Chapter 2. Technical and Literature Review

A detailed space-time analysis of the WRAP model's output would be incomplete without first fleshing out the WRAP model—presenting the inner-workings of WRAP. An appreciation for what the modeled output is can be developed after the model's parts are examined. While the WRAP model is subject to frequent revisions and changes, because it is a computer model, the conceptual framework of the model should remain intact. Therefore, the conceptual framework of the model and its various programs is presented in this technical review.

2.1 WRAP PROCESS

The information presented in this section was obtained from the official WRAP documentation. For a more exhaustive discussion, the reader is referred to the current WRAP Users Manual, *Wurbs*, 2008. The Water Rights Analysis Package, or WRAP, is, as its name states, a package for analyzing water rights. This package is a collection or suite of programs that work together with the end goal of producing useful output. The path from initial data to the end result output is followed as each of WRAP's programs is examined. In this process, please refer to Figure 2-1 for both orientation and general descriptions.

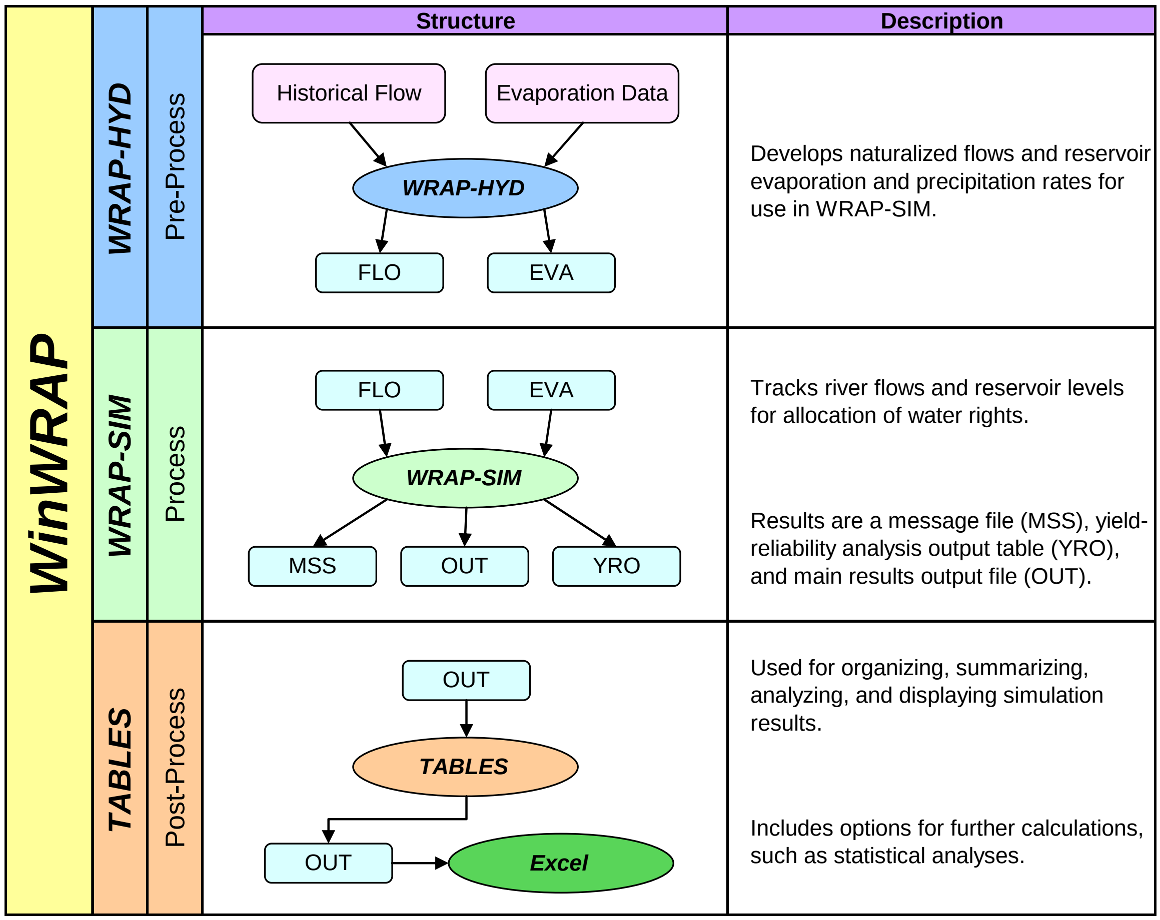


Figure 2-1. Water Rights Analysis Package Procedure

Figure 2-1 presents a simplified outline or flowchart of the WRAP process. This figure shows the input and output for each of the programs comprising WRAP. Please note that this flowchart is simplified and excludes much of WRAP's functionality, including capabilities for modeling salinity and options for extended daily output.

2.1.1 Input and output format

The modular programs of WRAP employ an input file format with a command line user interface (similar to DOS) that many elementary computer programs use. WRAP utilizes an organizational style that is reliant on ASCII text files. These files are rigidly organized, delimited by spaces, and require that the data be exactly placed—a deviation by a single space wreaks havoc on the programs' processing capabilities.

Nevertheless, despite these files' rigid requirements, experienced users are able to navigate the tedious waters of input file manipulation.

2.1.2 WinWRAP

Shown as an overarching yellow banner in Figure 2-1, WinWRAP is a WRAP wrapper which provides a "soft," user-friendly graphical user interface. WinWRAP is shown as being over all other programs because it provides access to the three main components of WRAP: WRAP-HYD, WRAP-SIM, and TABLES, with the user not being subjected to these programs' native command line interface format. While WinWRAP alleviates the need to individually access the other programs, the necessary input files must be organized properly, as they would usually be, before this application can be successfully used.

In the path through WRAP's workings, the user enters WinWRAP either with the input files required for WRAP-HYD or with those for WRAP-SIM. With these files in hand, the user is able to invoke the appropriate programs from a distance through the use of the WRAP wrapper: WinWRAP. The path through WRAP continues as the three pillars of WRAP—WRAP-HYD, WRAP-SIM, and TABLES—are discussed.

2.1.3 WRAP-HYD

As described in Figure 2-1, WRAP-HYD provides an environment for developing necessary input files for WRAP-SIM, namely the file of monthly naturalized flows (FLO) and the file for net evaporation-precipitation depths (EVA). These files are of a hydrological nature, thus the "HYD" in WRAP-HYD.

Because WRAP-HYD is solely used to produce the input files for the subsequent program, its use can be skipped entirely if the FLO and EVA files are already available (e.g. TCEQ has naturalized flows for given times for Texas). As shown in Figure 2-1, the EVA file is both an input and output file for WRAP-HYD; therefore, the unique output is the naturalized flow file. The naturalized flow, FLO, file is used as a base case of flow, from which specific anthropogenic effects are added or subtracted (e.g. diversions, reservoir effects) in the process of modeling available flows for water rights.

In the WRAP path, the user feeds historical flow and evaporation-precipitation data files to WRAP-HYD and obtains the FLO and EVA files as output. These files are then used in WRAP-SIM.

2.1.3.1 Naturalized flows

Naturalized flows are a core of the WRAP simulation. As such, an overview of WRAP's workings would be incomplete with only a superficial mention of this important component. This section discusses what these flows are along with algorithms of how they can be developed and used.

Naturalized flows can be obtained either as ready-made text files from TCEQ, or by using the WRAP-HYD program of the WRAP model. This data is an output from WRAP-HYD and is a required input for WRAP-SIM.

Naturalized flows are measured flows that have been adjusted to remove anthropogenic effects of both management and use (e.g. reservoirs, diversions). The concept of naturalized flows is central to the workings of the WRAP model. In order to best simulate the availability of water for water rights and other purposes, it is useful to have an understanding of how much water is, or was available before any withdrawals, diversions, or storage. This is what naturalized flows provide.

WRAP is an inherently Texas modeling package. This package is the standard for use in TCEQ with their water availability model system. As such, it is safe to assume that the great majority of use of WRAP is for Texas and Texas-related studies. Having thus stated, it is also known that naturalized flows for all of Texas have been calculated by various consulting firms to various degrees of intricacy (and accuracy). Now, considering the globalization of many aspects of modern research, it is natural to question: If WRAP is such a useful tool, why is it not being implemented outside of Texas? Furthermore: If one were to use WRAP outside of Texas, what hindrances would need to be overcome?

TCEQ, as a regulatory body, requires the use of WRAP for its water rights assessments. If other states' regulatory bodies likewise required WRAP, its use would obviously increase outside of Texas. Furthermore, the need for naturalized flows as part of analysis has historically been a hindrance to the spreading of WRAP past Texas' large borders. However, due to WRAP's structure (using WRAP-HYD), naturalized flows can both be calculated for gaged flow sites, and assigned to ungaged sites through the use of algorithms. Nevertheless, the process of creating naturalized flows for large-scale analyses may be too cost intensive for widespread implementation.

The basic method for determining naturalized flows is shown in the following equation (Wurbs 2006).

$$NF = GF + \sum D - \sum RF + \sum EP + \sum \Delta S \tag{2-1}$$

Where:

NF	naturalized flow
GF	gaged flow
D	water supply diversions upstream
RF	return flow upstream
EP	reservoir evaporation minus precipitation
DS	change in storage in upstream reservoirs

This method goes hand in hand with the definition of naturalized flows given earlier: naturalized flows are measured flows that have been adjusted to remove anthropogenic effects of both management and use (e.g. reservoirs, diversions). The terms of the naturalized flow equation are shown graphically in Figure 2-2 as a typical water resources schematic (with the solid circle being the gaged flow location), where the colored terms of the equation coincide with the objects in the figure.

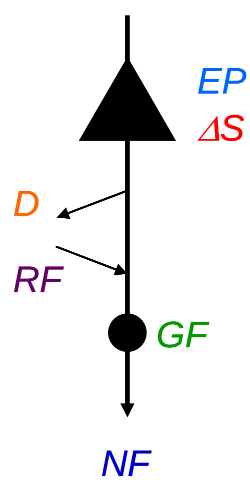


Figure 2-2. Schematic for Naturalized Flows

The GF term, gaged flow, in the naturalized flow equation is somewhat limiting for use in WRAP. WRAP simulation results are for many geographic points which are not necessarily gaged flow points. Naturalized flows, calculated from gaged locations, can be distributed to ungaged locations using the Drainage Area Ratio method (Wurbs 2006). The Drainage Area Ratio is a method where ungaged flow is distributed according to drainage area proportionality, as follows:

$$Q_{ungaged} = R_{DA} Q_{gaged}, \quad R_{DA} = \frac{DA_{ungaged}}{DA_{gaged}} \tag{2-2}$$

Where:

Q_i naturalized flow at either gaged or ungaged site
R_{DA} drainage area ratio
DA_i drainage area

The Drainage Area Ratio equation, (2-2), uses the naturalized flow, as calculated using the naturalized flow equation (or some other method), and the respective drainage areas to obtain an approximation for the naturalized flow at an ungaged location.

In addition to the Drainage Area Ratio method, (2-2), WRAP has an option for distributing flows using the related but more generic equations (Wurbs 2006):

$$Q_{ungaged} = a\left(Q_{gaged}\right)^{b} + c,$$
$$a = \left(\frac{DA_{ungaged}}{DA_{gaged}}\right)^{N_1}\left(\frac{MP_{ungaged}}{MP_{gaged}}\right)^{N_2}\left(\frac{CN_{ungaged}}{CN_{gaged}}\right)^{N_3}\left(\frac{Other_{ungaged}}{Other_{gaged}}\right)^{N_4} \tag{2-3}$$

Where:

Q_i naturalized flow at either gaged or ungaged site
DA_i drainage area
MP_i mean precipitation
CN_i curve number
$Other_i$ some other parameter
b, c coefficient provided by user (default are 1 and 0, respectively)
N_i coefficient provided by user (default is 1)

Clever manipulation of these equations provides the ability to fit the data that is available. For example, the *N* coefficient could be set to zero in a case where certain parameter(s) were not available. It is plain to see that the Drainage Area Ratio equation is a version of this more generic equation with coefficients chosen wisely.

The coefficients provided in the more generic equation provide significant freedom in calibrating the model against measured flow, say, for further regional use. This would require computations outside of WRAP, but such may prove useful in specific studies.

2.1.4 WRAP-SIM

The “SIM” in WRAP-SIM stands for simulation. This is where the main simulation of WRAP takes place. Water balances for each month of the simulation period are performed using the FLO and EVA files along with information for specific reservoir information, channel losses, specified diversions, instream flow requirements (amounts of flow that are required to be in the stream), and hydroelectric power requirements.

Three main output files are produced as part of a successful modeling session in WRAP-SIM. These files, as mentioned in Figure 2-1, are (Wurbs 2006):

1. MSS – the message file that reports simulation progress and errors in the input data.
2. YRO – the yield-reliability output file.
3. OUT – the main output file which is an extremely specifically formatted file which presents a wealth of data in many variables in a somewhat cryptic format.

It is the WRAP-SIM output (OUT) file upon which the bulk of the space-time analysis research is based. This file is organized in a condensed data management form, and is relatively inaccessible for the WRAP user. Additional assistance for deciphering this file is provided through the use of TABLES.

In the WRAP path, the user provides the WRAP-SIM output files and begins the simulation. As mentioned, a water balance for each time step is performed for each location of interest in the modeling scenario. This process is considerably fast, considering the intricate nature of WRAP’s modeling processes and the large output files produced.

2.1.5 TABLES

The TABLES program is the WRAP users' greatest ally in the quest for accessible water rights data. As discussed, the WRAP-SIM output format can be viewed as significantly non-user-friendly. TABLES provides a way for the user to specify the data, format organization, and format type for the WRAP simulation results. Three common format types available from TABLES are (Wurbs 2008):

1. standard text files of organized and easy to read tables of results,
2. results in text file format for additional use in Microsoft Excel, and
3. results in a binary file of HEC-DSSVue (U.S. Army Corps of Engineers' Hydrologic Engineering Center Data Storage System) format—a format for efficiently storing time series data (Hydrologic Engineering Center 2008).

In addition to providing useful formats for data, TABLES can perform computations including reliability and frequency relationships.

In the WRAP path, the user feeds the WRAP-SIM output file to TABLES and specifies which data is to be displayed, if any further computations are to be done, and the format to which the data is to be written. After the necessary calculations or organizations are performed, the user is able to use the output file at their discretion, according to the output format specified. For example, TABLES provides means for the WRAP user to digest the inaccessible WRAP-SIM output file and display the output in the comfortable data access and manipulation environment that Microsoft Excel provides.

2.1.6 WRAP Conclusion

Prior to WinWRAP, the user was required to invoke each of WRAP's programs in series to obtain desired results. The implementation of WinWRAP has provided additional resource to WRAP users and has enhanced the overall WRAP experience. However, despite the advancements in user experience, the ASCII text input files are still required. The modern, novice WRAP user will typically express frustration at the requirement to have spacing be exact, and may bristle at the lack of friendly forms to input data in a tabular environment. Nevertheless, with training (and patience) the WRAP user can harness the modeling power that WRAP provides.

The output of the WRAP-SIM program is of most value to the WRAP user. This is the file that contains the results of the simulation. It is somewhat unfortunate that this file is rigidly structured and fairly inaccessible to the WRAP user—its structure and size make data acquisition tedious, at best. It is noted that the TABLES program may provide options for gleaning data from this output file, but the TABLES process is not as automated as may be desired; the user would need to input specific formatting data after each simulation run and access the results in various other programs.

After each successful run of WRAP, the user is issued an output file containing only numbers. It is difficult—if not impossible—to understand spatial or temporal trends for locations or regions from this output file alone. While the simulation is of great importance, the ability of understanding the results of the simulation is lacking. In other words, it is difficult to fully grasp the meaning of the output when confronted with only rows and columns of numbers. A successful space-time analysis provides the ability to present this data in a visual format which unveils the simulation results as a map view or time series progression.

2.2 Hydrological Models Review

One of the purposes of the space-time analysis of the WRAP model and its output is to better understand how WRAP output data can be represented geographically and temporally. Before continuing inspection of the WRAP modeled output, a brief look at other hydrological models is presented. The intricate details of each model likely differ widely from one model to the next, yet the methods of displaying the resulting simulation results may provide insight in the space-time analysis of the WRAP model.

The end result of the space-time analysis is to enable display of WRAP output data in the ArcMap GIS format. This is due to the desires of TCEQ – the organization for which the research is being performed. Having data in a format that can be exposed to ArcMap is advantageous if it is in a database structure because this format allows for not only visualization in a GIS, but for mathematical and statistical operations to be performed on the data, as well as having the ability to sort and arrange the data easily, which is not available with the output data in its native format. In addition, ArcMap time series graphs provide options for exporting the graph image, as well as the graph data. In this way, selected data can be easily gleaned from the full collection of data, packaged for display, and exported to a variety of data storage formats for further analysis or sharing.

An updated version of WRAP was made available during the space-time analysis research of WRAP output. Prior to this version, the major output version was a text output file. However, the new version utilizes an additional output format: the US Army Corps of Engineers' Hydrologic Engineering Center (HEC) Data Storage System (DSS) files. This storage system stores the WRAP output in a collection of binary files that can only be read by HEC software, such as HEC-DSSVue. The new version of WRAP includes the option of exporting output to this DSS format, but it does not provide tools for viewing the output itself—this must be done with HEC-DSSVue. The visualization of WRAP output is limited to tabular and time series views. HEC-DSSVue does not support map capabilities (Wurbs 2008, USACE HEC HEC-DSSVue 2008).

The HEC DSS file system is used by other modeling software packages besides WRAP. The Hydrologic Engineering Center's widely-used Hydrologic Modeling System (HEC-HMS) also uses DSS files. HEC-HMS is used to simulate precipitation-runoff processes for both large and small systems. The display provided by this software incorporates both map views and time series display (USACE HEC HEC-HMS 2008). It is foreseeable that an HEC-HMS model could be established for a WRAP simulation scenario which would take WRAP output in DSS format and display it in HEC-HMS. However, such is not practiced at TCEQ, and no trials were performed as part of this space-time analysis to verify the feasibility of doing so.

While HEC-HMS use is widespread, other models with different display options exist. An example of a water resources model which incorporates GIS display (in ArcGIS) is the MIKE BASIN by the DHI Group in Denmark. MIKE BASIN combines hydrologic modeling with ArcGIS to provide many options in modeling, including water availability analysis. Like WRAP, MIKE BASIN is based on a connected network, but MIKE BASIN provides a visual map environment that WRAP lacks by itself. Due to its GIS-centered nature, MIKE BASIN takes advantage of many of ArcMap's display options, including maps, time series, and movie displays of modeled results (DHI Group 2008, Ireson 2006).

2.3 LITERATURE REVIEW

The space-time analysis of the WRAP model and its output is not limited to a strict focus on the model itself. In order to make the data available for space-time viewing the output data must be exposable to a GIS. The geographic display environment used by TCEQ is ESRI's ArcMap; therefore, it is logical to focus attention on the storage systems that are available for use with ArcMap.

An industry standard for data representation can be found in Maidment, 2002. This work discusses the Arc Hydro data model in great detail and provides many water resources examples. The chapter on Time Series is particularly useful in understanding the space-time relationships that can exist in a GIS environment. This chapter also discusses a way of representing variables in space in time, known as the data cube. This structure is explored more fully in this thesis, section 3.1.

A geodatabase structure different than the Arc Hydro data model was selected for the space-time analysis of the WRAP output. As a result of this departure, new methods of data representation were explored. The work of Arctur and Zeiler, 2004, provides useful instruction on the design of geodatabases. Of particular interest is the chapter on Streams and River Networks. This chapter discusses attribute series, which is a term used to describe the case where geographic features have time series associated with them. This is the case with the WRAP output. This work includes applicable discussion in its chapters regarding Geodatabase Design, and Building Geodatabases.

Although superseded by the later work of Arctur and Zeiler, 2004, the geodatabase illustrations and insights provided by Zeiler, 1999, are still applicable to the overall geodatabase aspects of the data transformation tasks required with the space-time analysis presented in this thesis. Of particular relevance are the chapters on Object Modeling and Geodatabases, and Geodatabase Design Guide. In addition, the purposes of the space-time analysis are afforded additional validation by the chapter on How Maps Inform. This chapter reechoes the utility of representing space-time data graphically (or geographically, in this case) as opposed to a tabular view of values.

Chapter 3. Methodology

A space-time analysis of the WRAP model, particularly the output of the WRAP model, is the purpose of this thesis. Previous sections have presented generalized indications on how the output data is organized and structured. This section lays the groundwork for understanding—the data cube—and follows by exposing a sample output file for inspection and analysis.

The ultimate goal of the space-time analysis is to be able to expose the WRAP output data to a geographic information system (GIS), ArcGIS in this case, and make the data visually available. After discussing the output format, attention is turned to the representation of this data in a GIS environment, and the path that was taken to arrive there.

3.1 DATA CUBE

Simulation model output can be visualized as lying on a vertex of a data cube. The data cube, shown in Figure 3-1, is a 3D representation of data where the dimensions are time, space, and variable—or, in other words, what, where, and when. This representation is quite different from a Cartesian coordinate view, which the reader may be more familiar with, 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, if you will, are represented by the other axes: time and variables (Maidment 2002).

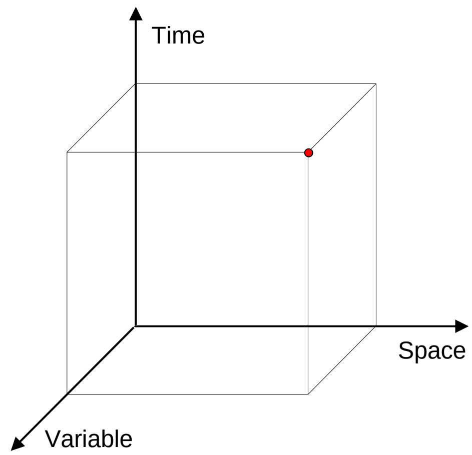


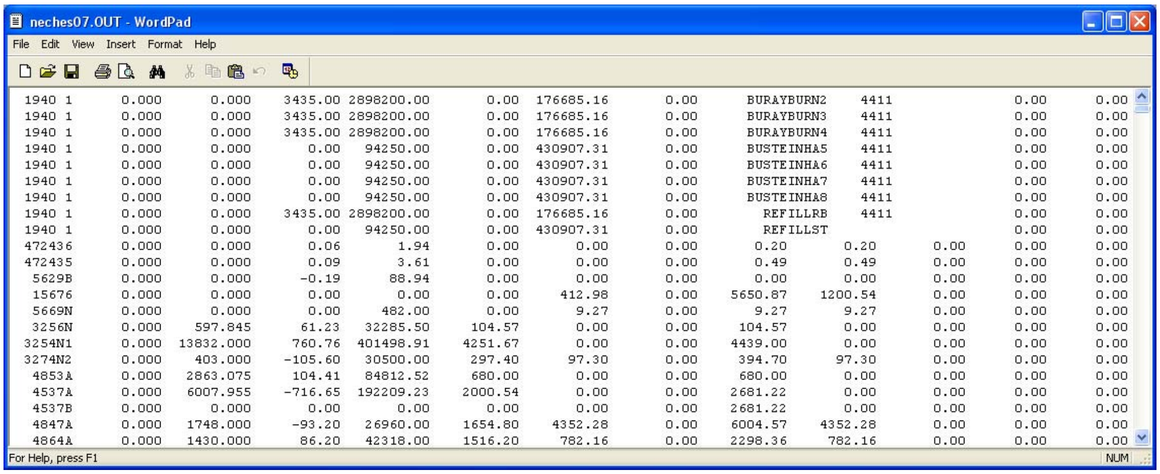
Figure 3-1. Data Cube

WRAP output data falls within the data cube structure where, for a chosen variable, one can select modeled output 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*). Keep in mind, though, percent of reservoir storage is not the only data that is output from the WRAP model—there are many.

Dealing with data cubes (read: collections of data) for one variable over time and space seems relatively straightforward and logical. Such can easily be displayed in a GIS environment as map data or a collection of time series. However, WRAP output introduces a level of complexity because it includes many variables' output for each time and space point. Gaining an understanding of additional complexities provides opportunity for further research into data management and access.

3.2 WRAP Data Organization and Access

The output from a WRAP simulation is a voluminous file with many variables for each location and time step. Hydrological analyses in WRAP usually consist of greater than fifty years of simulation. With increments of one month, the result is already more than 600 distinct time steps. Given the number of locations and variables of an analysis, the output indeed has much information (typical runs produce millions of data values). A snapshot of the resulting output file is shown in Figure 3-2.




```
  1940 1      0.000      0.000   3435.00 2898200.00      0.00 176685.16      0.00    BURAYBURN2    4411                       0.00      0.00
  1940 1      0.000      0.000   3435.00 2898200.00      0.00 176685.16      0.00    BURAYBURN3    4411                       0.00      0.00
  1940 1      0.000      0.000   3435.00 2898200.00      0.00 176685.16      0.00    BURAYBURN4    4411                       0.00      0.00
  1940 1      0.000      0.000      0.00   94250.00      0.00 430907.31      0.00    BUSTEINHA5    4411                       0.00      0.00
  1940 1      0.000      0.000      0.00   94250.00      0.00 430907.31      0.00    BUSTEINHA6    4411                       0.00      0.00
  1940 1      0.000      0.000      0.00   94250.00      0.00 430907.31      0.00    BUSTEINHA7    4411                       0.00      0.00
  1940 1      0.000      0.000      0.00   94250.00      0.00 430907.31      0.00    BUSTEINHA8    4411                       0.00      0.00
  1940 1      0.000      0.000   3435.00 2898200.00      0.00 176685.16      0.00      REFILLRB    4411                       0.00      0.00
  1940 1      0.000      0.000      0.00   94250.00      0.00 430907.31      0.00      REFILLST                               0.00      0.00
  472436      0.000      0.000      0.06       1.94      0.00      0.00      0.00      0.20      0.20      0.00      0.00      0.00
  472435      0.000      0.000      0.09       3.61      0.00      0.00      0.00      0.49      0.49      0.00      0.00      0.00
   5629B      0.000      0.000     -0.19      88.94      0.00      0.00      0.00      0.00      0.00      0.00      0.00      0.00
   15676      0.000      0.000      0.00       0.00      0.00    412.98      0.00   5650.87   1200.54      0.00      0.00      0.00
   5669N      0.000      0.000      0.00     482.00      0.00      9.27      0.00      9.27      9.27      0.00      0.00      0.00
   3256N      0.000    597.845     61.23   32285.50    104.57      0.00      0.00    104.57      0.00      0.00      0.00      0.00
  3254N1      0.000  13832.000    760.76  401498.91   4251.67      0.00      0.00   4439.00      0.00      0.00      0.00      0.00
  3274N2      0.000    403.000   -105.60   30500.00    297.40     97.30      0.00    394.70     97.30      0.00      0.00      0.00
   4853A      0.000   2863.075    104.41   84812.52    680.00      0.00      0.00    680.00      0.00      0.00      0.00      0.00
   4537A      0.000   6007.955   -716.65  192209.23   2000.54      0.00      0.00   2681.22      0.00      0.00      0.00      0.00
   4537B      0.000      0.000      0.00       0.00      0.00      0.00      0.00   2681.22      0.00      0.00      0.00      0.00
   4847A      0.000   1748.000    -93.20   26960.00   1654.80   4352.28      0.00   6004.57   4352.28      0.00      0.00      0.00
   4864A      0.000   1430.000     86.20   42318.00   1516.20    782.16      0.00   2298.36    782.16      0.00      0.00      0.00
```

Figure 3-2. WRAP Output Native Format

The output file is structured in space delimited columns of data. An example of these columns can be seen in Figure 3-2. Running WRAP produces variables of four types: water rights, instream flows, control points, and reservoirs. The vast amount of data in the WRAP data cube has structure that is cyclic. The data representation follows a representation hierarchy of time step, variable type, location, individual variable value (the data cube). An attempt at representing this visually is presented in Figure 3-3. For example, the output cycles through each time step (month); within each month are the four variable type sections (water rights, instream flows, control points, and reservoirs); within each variable type are individual rows for every location; in each row are specific columns for the many variables. This structure repeats again for each time step in the simulation period.

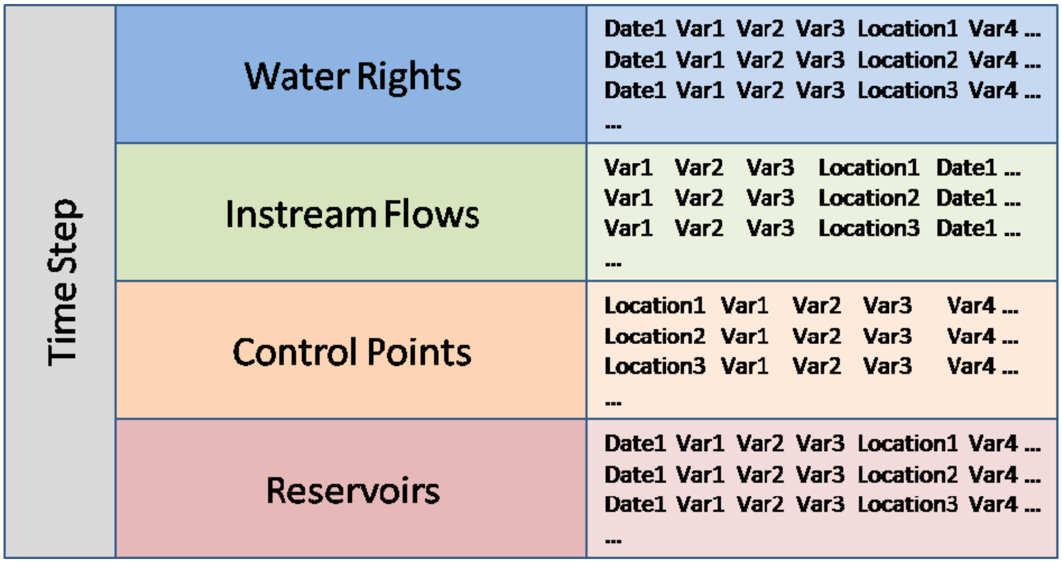


Figure 3-3. Output File Structure

In addition to the complexity of maintaining order among the many variables of each type of variable for each time step is added the difficulties associated with different formatting among the variable type sections. This is illustrated in both Figure 3-2 and Figure 3-3. Figure 3-2 shows the output file on the threshold of a transition between sections. Notice the difference in column spacing on the right-hand side. Notice, further, that the time indication of the preceding section dissolves to a location indicator in the following section. Not only are the variable spacings different, but the order of similar variables is also changed, including where the location code is stored (see Figure 3-3).

The result of the spacing inconsistencies between output file sections is that when the output file is exposed to the GIS—ArcMap, the map display side of ArcGIS—ArcMap is unable to process and display the values. The differences render the file too complex for standard file interpretation functions.

3.2.1 Towards Geodatabase Representation

The desire to represent the modeled output data in a GIS environment coupled with the inability to do so with the native output file format requires a transformation of the data from its original structure to one that can be digested by the GIS. A preferred system of data representation uses databases to store data. Due to their spatial geographic nature, these databases are called geodatabases. This style of data storage works well with ArcMap, but many organizational options are available.

In transforming the data from a text file to a database, time of conversion and size of the resulting database are two major factors in selecting an acceptable geodatabase representation system. An industry standard for representing hydrological data, Arc Hydro was the first choice. Arc Hydro is a system for storing and using GIS data in a Relational Database Management System (RDMS). In this application, an RDMS is an enhanced database which stores GIS data and makes it available for relational and connectional analyses (can be used to show how data relate or are connected to each other) as well as geometric network studies (how values change along a network, e.g. how stream flow changes along a stream network) (Maidment 2002).

The Arc Hydro data model consists of various database tables that are related to each other. A simplified view of how this is applied is shown in Figure 3-4. The main table, TimeSeries, contains the actual data—a collection of variable values. This data is linked to the TSType table which is a table of metadata, or data about data. As shown in Figure 3-4, the TSTypeID index connects the time series table to the metadata table. This connection reveals the variable name, units, and other information related to the variable (Figure 3-4 data is from Arc Hydro Online Support System 2003).

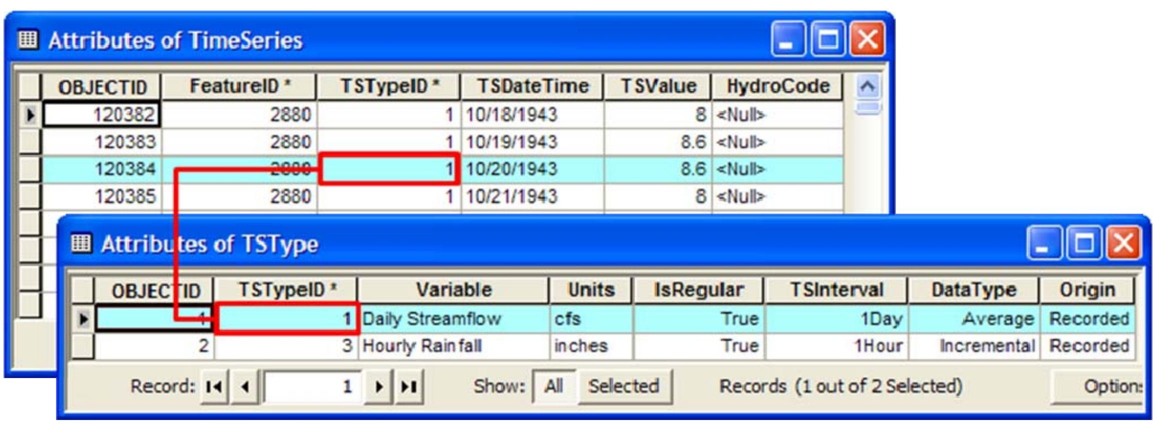


Figure 3-4. Arc Hydro Data Model Representation

While Arc Hydro is a widespread and useful data model, its use presents limitations to representing WRAP model output. In the Arc Hydro data model, the TimeSeries table has one row for each variable value entry. Using WRAP model output in Arc Hydro would require a standard TimeSeries table to contain millions of rows—which may not be unreasonable in some applications. This results in considerable difficulty when working with WRAP output data.

The conflict between Arc Hydro and the WRAP output data relates to time of conversion and processing size. Time and size are two major factors in data transformation, as mentioned above. When a preliminary tool was created which parsed the output file and organized the individual variable values into rows—with one row for each value in Arc Hydro style—the resulting time of conversion and file size were unacceptable.

When a typical WRAP output file was converted, the process took well over one hour, and the resulting geodatabase was larger than 650 MB (as compared to the 35 MB original file size). These results may not have been exorbitant in some applications, the desire to make the conversion process available for fast access to WRAP data demanded that a better way be found; a process that was faster (on the order of minutes) and resulted in a comparably sized resulting file would be ideal. Unfortunately, the industry-accepted Arc Hydro data model was insufficient.

3.2.2 Multivariable Geodatabase Tables

The inability of the Arc Hydro data model to reasonably represent WRAP model output led to an expanded view of traditional Arc Hydro. The difficulties (time and size) seemed to be related to Arc Hydro's structure of having a single value for each row, resulting in millions of rows. The original output file (shown in Figure 3-2) managed space by having multiple variables for each row. Recall that each row was for one of the four types of variables, for a single location, at an individual time step (see Figure 3-3). The output file's structure lent experience and application to a new world of data management in a geodatabase and raised the question: How would the use of a multivariable geodatabase table affect the time and size of data transformation?

The WRAP model output consists of four types of water data: water rights, instream flows, control points, and reservoirs. Each of these types of data has their own set of variables. If a single geodatabase table were to be created from the WRAP output, the result would of necessity contain a field for each of the variables of all four types. If each type had ten variables, the table would have forty variable fields. Not only would this result in difficulty in displaying the entire set of variables, but there may be many rows with multiple empty field values where a location has data for one variable type and not the others.

To combat the difficulties associated with a single table representation for the whole of the WRAP output, multiple geodatabase tables were explored. Working under this scheme, a single table is created for each type of variable. The result is four multivariable geodatabase tables, each related to water rights, instream flows, control points, or reservoirs, shown in Figure 3-5.

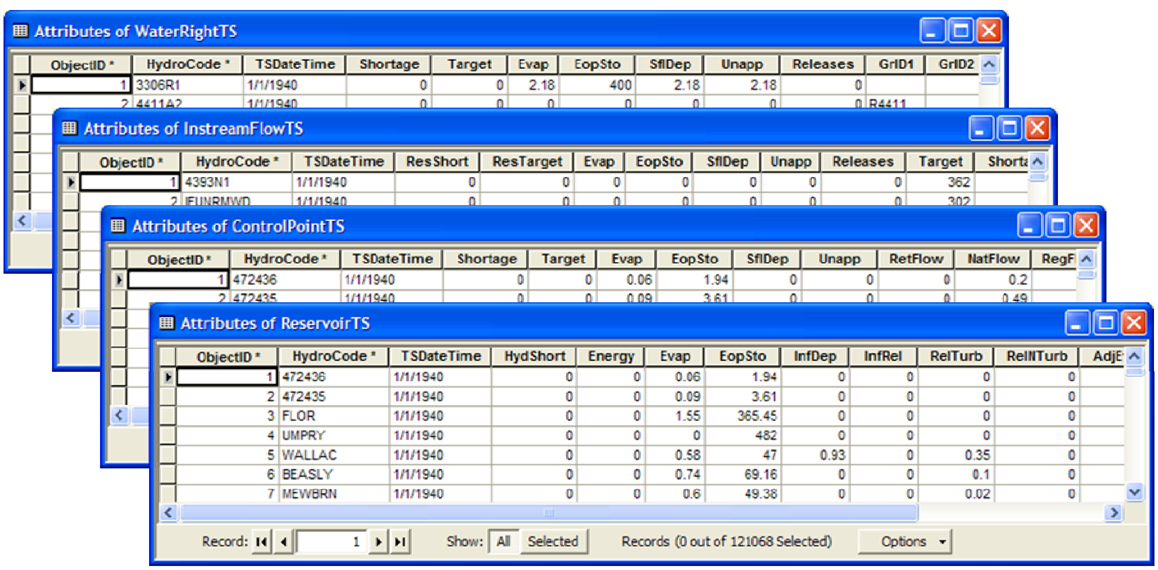


Figure 3-5. Multivariable Geodatabase Tables

By using multivariable geodatabase tables, the output looks similar to the original text version of the output data while being in a geodatabase structure. This lends familiarity to the experienced WRAP user as well as providing the benefits associated with having data in a database. These benefits include tabular data comparison and sorting, application of arithmetic and statistical functions, cross-platform sharing of data, and representation of WRAP data in ArcMap.

The many benefits mentioned above provide a good selling point, but the question remains as to how this new format meets the conditions on time and size. With typical WRAP output of millions of variables with an original file size of 35 MB, the conversion process to multivariable geodatabase tables takes 30 seconds with a resulting size of 40 MB. These results are considerably better than the hour-plus time and 650 MB associated with a typical single-variable-per-row Arc Hydro structure. This comparison is shown in tabular format below.

Type	Size	Process Time
Original WRAP output file	35 MB	n/a
Traditional Arc Hydro	650 MB	>1 hour
Multivariable geodatabase tables	40 MB	30 seconds

3.2.3 Attribute Series

Through the conversion process, the original WRAP model output data structure is transformed from a rigid text file to a set of multivariable geodatabase tables. These collections of data may well be called *attribute series* (Arctur and Zeiler 2004).

In GIS data models, an attribute is data about a location (or locations) which is nonspatial—meaning that attributes deal with data about a place, rather than being descriptive of the location of the place itself. For example, attributes of a reservoir may include its name, the surface area, how full it is (as a percent), and the water surface elevation, and not where the reservoir is. Therefore, an attribute series is a collection of attribute data. Hence, the newly created multivariable time series of WRAP data—which variables are attribute data—can succinctly be called attribute series. These attribute series are a completion of the first project purpose outlined in the Introduction: to advance data management in attribute series.

With the WRAP data in GIS-friendly attribute series, links can be made to geographic information to produce a space-time data layer which has both spatial, geographic data (where the data represents), as well as attribute series data (the variable values themselves. With this space-time data layer, the modeled output from the WRAP model can be represented in a GIS environment in many useful ways.

3.3 ARC HYDRO II

A serendipitous outcome of the space-time analysis of WRAP output is the burgeoning of the Arc Hydro II data format. As discussed in sections 3.2.1 and 3.2.2, the traditional Arc Hydro data model is insufficient for representing the WRAP output data quickly and concisely. The development of the attribute series' multivariable geodatabase tables enables the WRAP data to be represented in a way that complies with the overall project purposes of access, availability, and representation.

The WRAP output presents a data organizational structure that may be similar to other models' output, or to observed and recorded data. Considering other data raises the questions: Can the WRAP space-time analysis results be of benefit to these other data? Is there a data model that can be used to better represent multiple-variable per time step data? There may be a single solution to both questions.

The Arc Hydro II data model is currently under development. This is an expansion on the traditional Arc Hydro data model which provides for enhanced data cube representation. The structure is similar to Arc Hydro, but encourages expansion of either attributes or number of tables. The structure of the Arc Hydro II data model is shown in Figure 3-6. This figure shows three possible tables, with the Variables and TimeSeries tables constituting what is, in the WRAP case, the attribute series.

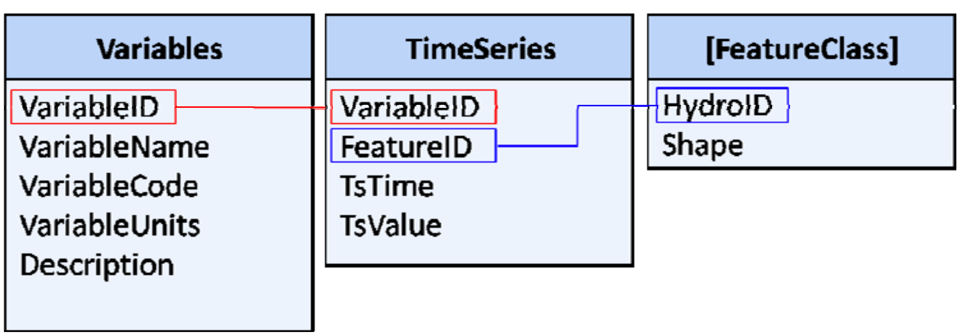


Figure 3-6. Arc Hydro II Data Model Structure

As shown, the TimeSeries table holds the data cube information: the what, where, and when (TsValue, FeatureID, and TsTime, respectively). Variable and location information are not explicitly held in the TimeSeries table, so IDs, or pointers to the data are included (as shown by the connected attributes of the tables in Figure 3-6). The FeatureClass table represents the geographic information (e.g. a GIS feature layer), which, when coupled with the attribute series data, becomes the space-time data layer. With data in this format, the same map and time series access to data is available in a GIS that the WRAP attribute series tables provide.

The Arc Hydro II data model differs from the structure of the WRAP attribute series tables in that Arc Hydro II splits into two tables (Variables and TimeSeries) what the WRAP attribute series has in one. If Arc Hydro II is developed and released as shown in Figure 3-6, size issues may be encountered when using the WRAP output data, similar to those shown in section 3.2.1 through the repetitive use of rows for each variable instance for a given time and location. Nevertheless, the advancements shown in Arc Hydro II data model will likely enable more efficient data storage and access.

Chapter 4. Procedure of Applications

The previous chapter discussed the organization of WRAP output data. In its native format, this data is inaccessible by ArcMap due to its disparate sections with cyclic nature. Attention was given to an intellectual framework regarding the process of overcoming the limitations of the original data structure and preliminary solution ideas. The result being that through successful processing of this data into multivariable geodatabase tables, or attribute series, the result can successfully be exposed to a GIS to meet the second project purpose listed in the Introduction: the visualization of WRAP output data for synthesis and analysis purposes. This chapter discusses in greater detail how the project purposes are realized, including discussion on the WRAP Display Tool which automates the processes through various specific functionalities.

4.1 PROCESSING WRAP OUTPUT DATA

Sections 3.2.2 and 3.2.3 of this document discussed, in some detail, the process of converting the WRAP output data from its native format into a collection of attribute series (multivariable geodatabase tables). The WRAP Display Tool was created to automate the processes related to the overall purposes of data management and display in a GIS. This tool includes an option for converting the WRAP output to a geodatabase.

Guidance is needed to properly parse the output file. Each native WRAP output file has a line that contains numerical information specific to that simulation's output data. This line, shown as the fifth line in Figure 4-1 (reading "1940 57 319 351 177"), is the last of five lines of the output file's metadata listed before the simulation output data begins. Shown in this line are the first year of simulation, the number of years in the simulation, and the number of control points, water rights, and reservoirs in the output file. Combining these numbers with knowledge of the file's structure allows for proper parsing. In other words, when the number of years and components are known, the tool knows where to look to obtain the specific data.

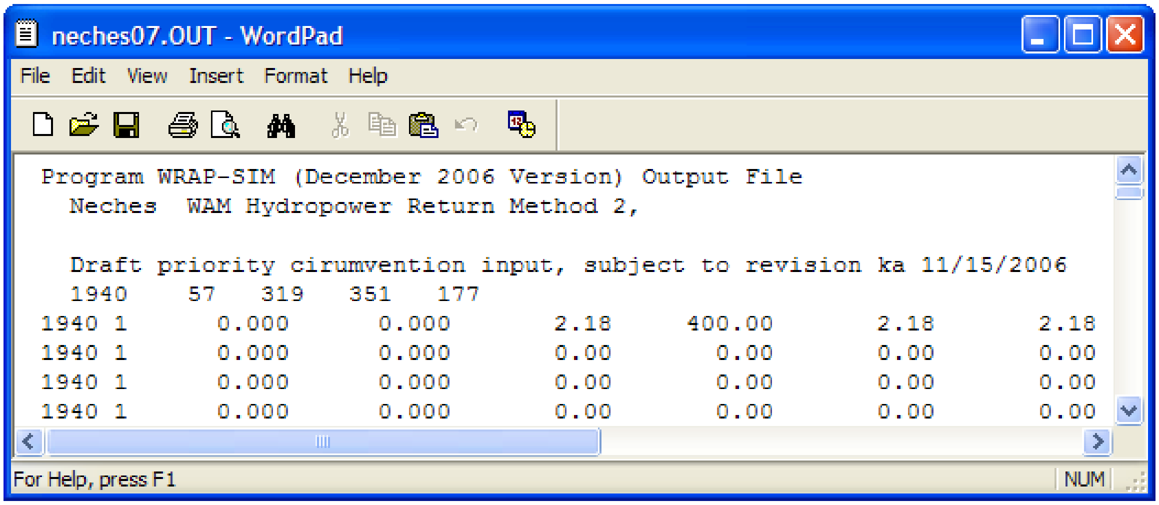


Figure 4-1. WRAP Output File Metadata View

The conversion option of the WRAP Display Tool is primarily responsible for producing a set of attribute series from the original WRAP output file. This is done through a series of steps, listed below:

1. The output file is opened in the computer's memory to allow parsing.
2. The file's metadata (first five lines) are retained for future use, including direction on where to look for specific output data.
3. The rest of the file is parsed, line by line, section by section, where the individual entries (read: variable values) are stored in a collection of multivariable arrays for later recall.
4. Empty template geodatabase tables are opened, which contain the proper number of fields with labels for each type of data (water rights, instream flows, control points, and reservoirs). These templates are the same as those shown in Figure 3-5 save they do not contain the attribute data yet.
5. The template geodatabase tables are systematically populated with the harvested data from the output file. This is done by using a buffer that holds rows' data until it is written to the geodatabase table en masse, improving processing speed.
6. The geodatabase and tables are added to the ArcMap document where their data become available for visual representation.

The WRAP output files, as mentioned before, can contain exorbitant amounts of data. When converting very large output files, care must be taken to not overwhelm the computer’s memory or the maximum size of the geodatabase. To combat this possibility, two direct measures were taken: 1.) Visual Basic .NET was the chosen as the programming environment, and 2.) the file geodatabase organizational structure was chosen over personal geodatabase. These measures are discussed in more detail below.

Due to the expansive use of storing values in memory in the parsing process, the potential to overwhelm the computer’s memory exists, particularly when processing large WRAP output files. Without the possibility to use alternate means of memory, the program would fail and be unable to produce the desired results. It is to avoid this that the Visual Basic .NET programming environment was selected. Doing so opens the use of what is called virtual memory. This allows the processing to continue, even if the computer’s random access memory (RAM) capacity is reached. In this case, the computer makes use of other forms of available memory, such as disk space. When this happens, the process can slow considerably, but it does not fail. Thus, large output files can be converted to attribute series and used in a GIS.

The root of the potential memory problem, large WRAP output files, contributed to the decision to use the file geodatabase structure. Personal geodatabases, which are based on Microsoft Access, may be the more typical or traditional geodatabase for use in GIS. However, these have a maximum size of 2 GB. While this size may meet the needs of most modeled WRAP output, the possibility of exceeding is enough to look for other options.

Introduced with ArcGIS 9.2, file geodatabases provide up to 1 TB in size, along with cross-platform abilities due to their independence from Microsoft. This storage structure uses “an efficient data structure that is optimized for performance and storage” compared to the traditional file geodatabase system (ESRI ArcGIS Desktop Help). The almost limitless storage capability (with regard to WRAP output) coupled with the optimized nature of the file geodatabase structure made it the natural choice for storing the WRAP attribute series.

The WRAP Display Tool provides means for automating the conversion process from the native WRAP output file to a set of multivariable geodatabase tables (attribute series) using the innovative and effective file geodatabase system. Once converted, the output data is accessible in ArcMap for further use and display.

4.2 PRESERVING METADATA

A benefit of the Arc Hydro data model is its use of the TSType table. This table, shown in Figure 3-4, provides a way to track each variable's name, units, interval, and type. Information such as this is useful for GIS displays of data, particularly for axes on time series, and indications of what is displayed in a map. Ambiguity is the result of not having proper labels. However, the attribute series adopted for WRAP representation does not incorporate the use of a TSType table. Therefore, an alternate method was employed to track and manage metadata.

The file geodatabase system includes a method for maintaining metadata through the use of the extensible markup language (XML). This data structure still allows users to change the metadata, while at the same time having the metadata more behind-the-scenes than using a simple TSType table. In addition, the choice to have the metadata associated with XML should remove some confusion in dealing with the geodatabase tables.

With metadata stored in XML, it can be retrieved and used for the display purposes stated above. The metadata associated with WRAP output attributes is already in place with the template geodatabase tables in section 4.1, so that when the WRAP data is written, the metadata is automatically available. This metadata includes a brief description of the variable and its units.

In addition to attribute metadata, the metadata contained in the first lines of the output file, which is harvested during the output file processing, is written to the tables as a description. While this file metadata is not used in labels when displaying graphs and maps, it may be useful for record keeping of notes or in determining which version of WRAP was used for the simulation.

The metadata that is retrieved and recorded with the attribute series in the multivariable geodatabase tables is shown in Figure 4-2; this is for the reservoir attribute series. Notice that the information displayed is related to attributes, as indicated by the highlighted tab in the figure. Shown is the file metadata, shown under Description, which corresponds to the text in the first four lines of the WRAP output (compare to Figure 4-1). Also shown is a single representation of the attribute metadata, for the Evap (evaporation) field, listed under Definition. This metadata shows the variable description followed by units in parentheses.

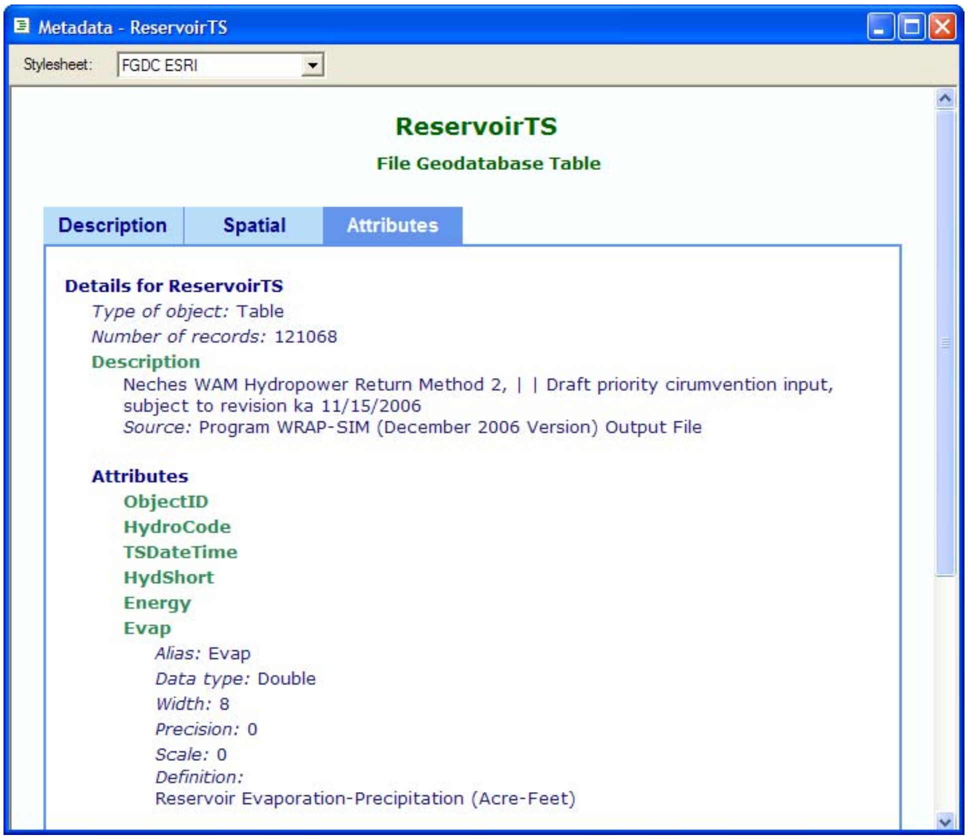


Figure 4-2. WRAP Metadata Presentation

Metadata organized and linked to the attribute series is available for use in displaying the WRAP output data. The two methods of displaying this data are via maps and time series. The next two sections discuss these methods in detail.

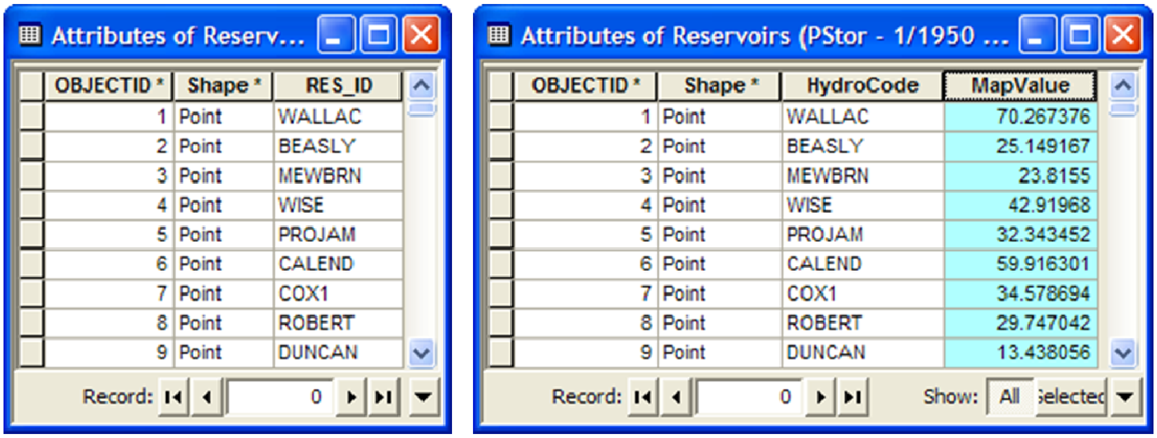
4.3 LINKING TO GEOGRAPHY: MAP DISPLAY

With the output data and metadata transformed and stored in a useful and manageable file format (the attribute series), the first project purpose mentioned in the Introduction is completed. This section discusses the relationship between the first two project purposes in that once a set of attribute series is obtained (first project purpose), the creation and maintenance of a space-time data layer which links attribute data to geographical information in a GIS is possible (second project purpose). The space-time data layer is vital to realizing the second project purpose: the visualization of WRAP output data for synthesis and analysis purposes.

Previous discussion regarded attributes and attribute series. In such, attribute series were defined to be collections of data regarding attributes, with a definite time component. It is essential to have feature data to create a space-time data layer. Feature data is information about locations. Continuing the example from before, feature data for a reservoir would include the latitude and longitude coordinates (where the reservoir is) along with the projection that is used to display the data. Feature data alone, as well as attribute data alone, are insufficient to produce maps to visualize and analyze WRAP data, they must be linked.

A space-time data layer is the result of the marriage of feature data to attribute series data. With data in this format, ArcMap can easily display maps for spatial data analysis. The following is a discussion on how space-time data layers are created.

A visual comparison of feature data and a space-time data layer are shown in Figure 4-3. This figure shows a GIS representation of the feature layer on the left, and the space-time data layer on the right. The feature layer contains spatial data on where reservoirs are, in this case. The space-time data layer has this information as well, but it also has a temporal value field, MapValue (shown highlighted in Figure 4-3).



Attributes of Reserv...

OBJECTID *	Shape *	RES_ID
1	Point	WALLAC
2	Point	BEASLY
3	Point	MEWBRN
4	Point	WISE
5	Point	PROJAM
6	Point	CALEND
7	Point	COX1
8	Point	ROBERT
9	Point	DUNCAN

Record: 0

Attributes of Reservoirs (PStor - 1/1950 ...

OBJECTID *	Shape *	HydroCode	MapValue
1	Point	WALLAC	70.267376
2	Point	BEASLY	25.149167
3	Point	MEWBRN	23.8155
4	Point	WISE	42.91968
5	Point	PROJAM	32.343452
6	Point	CALEND	59.916301
7	Point	COX1	34.578694
8	Point	ROBERT	29.747042
9	Point	DUNCAN	13.438056

Record: 0 Show: All Selected

Figure 4-3. Feature Layer and Space-Time Data Layer Comparison

With the MapValue field, the feature layer becomes a space-time data layer because both spatial and temporal information are represented. For example, the MapValue field shown is populated with a number representing how full (as a percentage) each reservoir was for a given time. The time is recorded in metadata and can be seen, in part, in the feature class name of Figure 4-3; the full name is "Reservoirs (PStor - 1/1950 to 12/1959)."

The data cube of the WRAP output data discussed earlier (and shown in Figure 3-1) is a way of representing the whole of the simulation output. The goal of linking attribute series data to geography, regarding the data cube, is to represent a view of a planar slice of the data cube for a single variable. Such a slice leaves a space-time data representation, shown in Figure 4-4 for a map display. This figure represents a map, which can be seen visually on the right (with graduated variable values visible), or symbolically on the data cube slice as a representation through space as either a single time step or as a statistical representation of data for a time period, shown as the thin and thick lines in the figure, respectively.

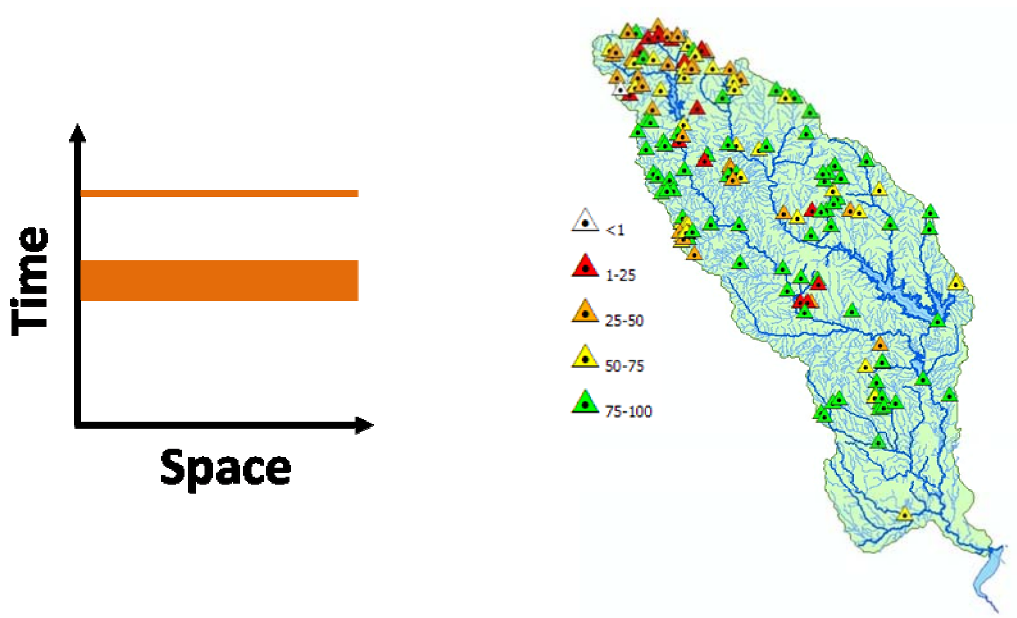


Figure 4-4. Space-Time Plane of Data Cube and Map Display

Before the results of Figure 4-4 can be obtained, the welding link between the attribute series and the feature layer must be made. This is done by properly selecting the variable values from the attribute series for a specified time, performing a statistical operation on the data for each location, if desired, and connecting the results to the feature layer.

Connecting the temporal and spatial data may be easier said than done; there must be a way to relate the attribute series to the feature data. Recall that each type of variable in the WRAP output file has a code that relates its values to a specific location. These are water right IDs, control point IDs, or reservoir names (instream flows are linked to water rights and share an ID). The individual codes are contained in the output file and are retained in the conversion process from the native output file structure to the attribute series tables. With location codes being maintained, the GIS feature data can be made to reflect these codes, where each identifier corresponds exactly to the identifier given in the WRAP output. The end result can be seen in the comparison between a feature layer and space-time data layer in Figure 4-3. The table on the left (the feature layer) has a field named RES_ID. This field is the name assigned to the locations contained in the feature layer, for reservoirs in this case. The table on the right (the space-time data layer) has a field called HydroCode which contains the exact same codes as the RES_ID field, and is used to match to the codes in the HydroCode field from the attribute series (see an attribute series table for reservoirs in Figure 3-5 where HydroCode is the second field). Thus, with HydroCode fields in both the attribute series tables and space-time data layers, whose entries are linkable, calculated temporal values for each applicable location can be applied to the MapValue field of the space-time data layer enabling map displays through standard GIS processes.

The process detailed above would be tedious to perform for multiple analyses if done systematically by hand. Fortunately, the WRAP Display Tool has functions which automate the process. The WRAP Display Tool's Map Display dialog is shown in Figure 4-5. Numerous options are provided for customization of the display results to meet specific individual or institutional needs/requirements. To display a map, one simply selects a feature layer and attribute series, specifies the variable, time period, and statistical operation (if applicable), and the feature layer is transformed into a space-time data layer as the MapValue field is populated with values from the attribute series and the map visually reflects the same.

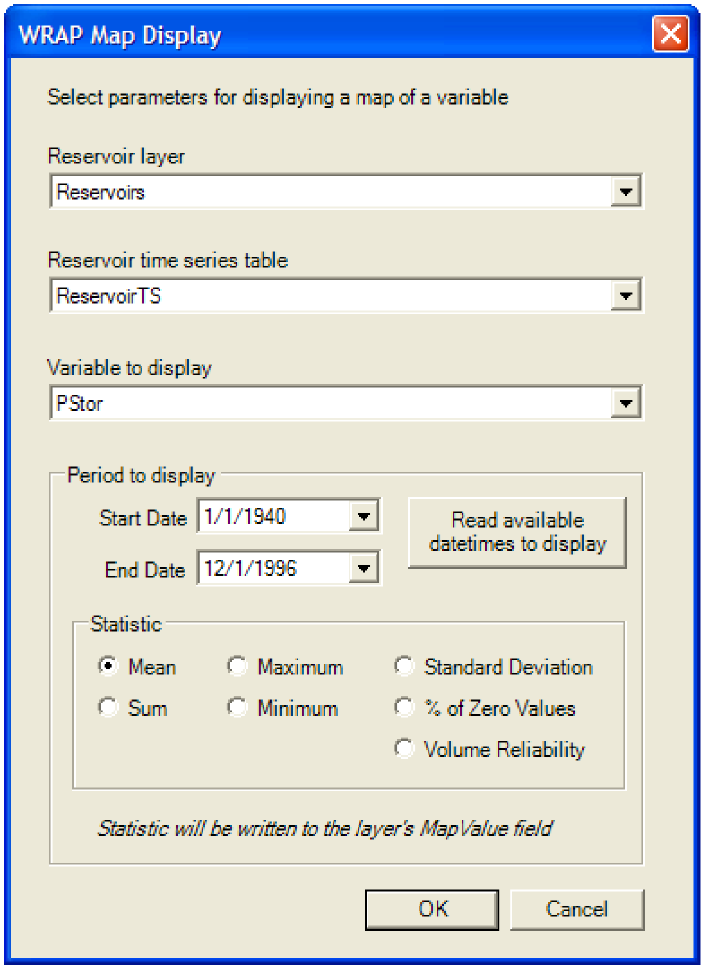


Figure 4-5. WRAP Display Tool's Map Display Dialog

After using the Map Display option of the WRAP Display Tool, the space-time data layer is renamed using metadata to reflect the variable and time period shown. For example, if the feature layer "Reservoirs" were selected, it would become the space-time data layer name "Reservoirs (PStor - 1/1/1940 to 12/1/1996)" if the options in Figure 4-5 were used. The result is a map that may provide superior analysis ability compared to the attribute series alone. In addition, the layer's name reflects the analysis parameters to further assist in record keeping, etc.

4.4 TIME SERIES DISPLAY

Attention is now placed on the creation and display of attribute series data as time series. This is a continuation of the second project purpose mentioned in the Introduction: the visualization of WRAP output data for synthesis and analysis purposes. The previous section covered map display as a means of revealing spatial relationships in the output data, and made a connection between attribute series and the space-time data layer. Attention will return to this connection in this section, but the main focus will be on revealing attribute series data as time series in a GIS, namely ArcMap.

The ability to show time series data in a GIS is greatly enhanced with the use of ArcGIS version 9.2. This version has improved graphing capabilities and provides means for revealing time series from the WRAP output attribute series. In so doing, the graphs created are a representation of the planar slice of the data cube mentioned in the previous section (and shown in Figure 3-1). The resulting slice leaves a space-time data representation shown in Figure 4-6 for a time series display. This figure represents a look at a single variable through time for selected locations (shown as a graph on the right), or symbolically on the data cube slice as either a single location or collection of locations, shown as the thin and thick lines in the figure, respectively.

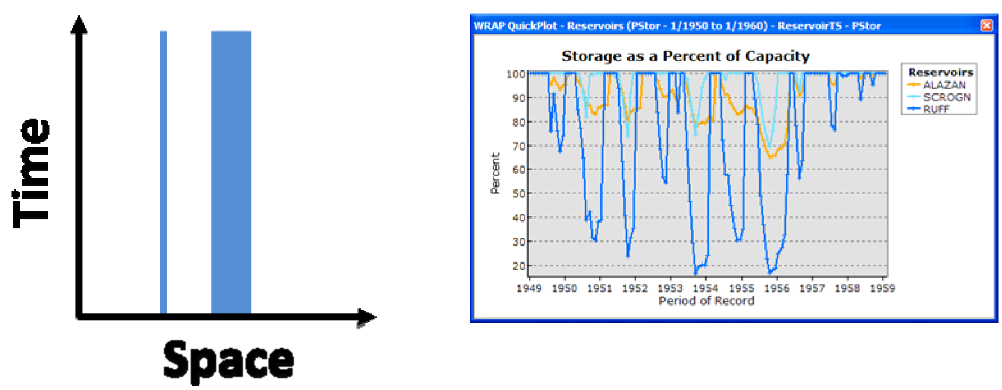


Figure 4-6. Space-Time Plane of Data Cube and Time Series Display

Graphs similar to that shown on the right in Figure 4-6 can be created in ArcMap using ArcGIS' graphing capabilities. These data representations can be made directly from the WRAP attribute series by properly sorting and selecting rows of data for the time period of interest. The internal ArcMap graphing dialog provides options for which variables to show on the axes, as well as other display options. The resulting graph is linked to the attribute table based on what is actively selected. The benefit of this relationship is that if one wishes to show additional time steps, say, they only need to increase the selection set. However, it is limiting in that any subsequent selection or de-selection of data from the attribute series changes the graph. The result is that valuable graphs that take considerable time to produce can be lost by a unintentional selection of a row in the attribute series. Furthermore, because the graph is based on selection, it is difficult to show multiple time series on the same graph, as does the graph in Figure 4-6.

To overcome the limitations of strictly using the as-is graphing options with the WRAP attribute series data, as well as to automate the data selection pre-processing, the WRAP Display Tool employs features to create graphs. These graphs are based on a template so that each graph looks institutionally similar to the others. Being template-based also provides options for changing the template to suit individual display desires. The creation of these graphs happens because of behind-the-scenes programming. Once the appropriate data is specified (including location or space-time data layer, attribute table, variable, and time period), the data sources are queried and the appropriate information is passed directly to the graph. The result is a graph that is not based on an active selection in the attribute series, which enables the graph to be archived and retrieved later, regardless of what data is currently selected; the graph will remain unaltered even if the original attribute series is removed from the map document.

The time series graphs created using the WRAP Display Tool provide more than the attribute series data. The metadata which was preserved during the output file processing (see section 4.2) is displayed in various convenient locations on the graph produced. These can be seen in the graph of reservoir evaporation-precipitation, shown as Figure 4-7. This graph was created using QuickPlot, one of the WRAP Display Tool's time series graphing functions, on a space-time data layer which showed spatial relationships regarding evaporation depth over the entire period of record. This particular graph is chosen because of its relationship to Figure 4-2 which shows metadata for the reservoir attribute series and evaporation variable.

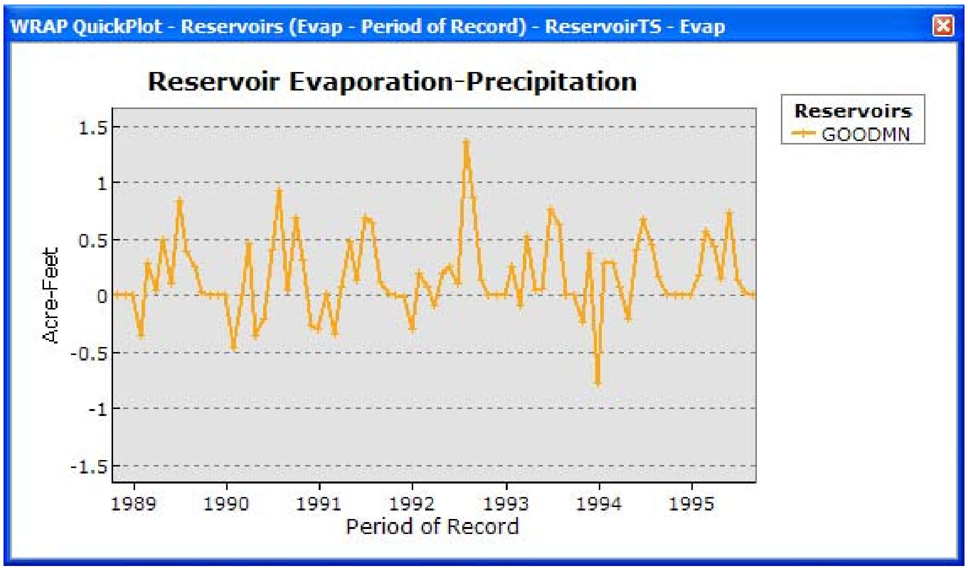


Figure 4-7. Time Series Graph Showing Metadata Use

Metadata features are shown in four main areas of the graph display of Figure 4-7. (Compare the metadata shown to that of Figure 4-2 for full appreciation):

1. Graph Banner – the blue section at the top of the graph shows the process by which this graph was created (from the WRAP QuickPlot tool), the space-time data layer used to spatially select the location (Reservoirs (Evap - Period of Record)), the attribute series table used for the data (ReservoirTS), and the code for the selected variable from this table (Evap).
2. Graph Title – the bolded title of the graph displays the variable description from the attribute series variable metadata (Reservoir Evaporation-Precipitation).
3. Ordinate Title – the title of the y-axis reports the units description from the attribute series variable metadata (Acre-Feet)
4. Graph Legend – due to the selectable nature of the WRAP Display Tool interface, the location related to the time series data can be preserved and displayed, as it is here for the GOODMN reservoir.

In addition to the benefits of preserving and displaying metadata on the time series graphs, the WRAP Display Tool functions allow easy additions of multiple series on the same graph. This is a feat that is difficult to do using the prepackaged graphing utilities of ArcMap (due to the selection-based nature). This feature can be seen in Figure 4-6 where the storage percentages for three reservoirs are shown for easy comparison.

The WRAP Display Tool has two dialogs for creating graphs: Quick Plot and Time Series Display. The results of using these tools are similar—both produce time series graphs—but their bases are slightly different. The Quick Plot tool is linked to the space-time data layer and the attribute series and produces a graph and subsequent additional series based on clicking on locations on the map. The Time Series Display tool is predominantly linked to the attribute series. The interfaces for these tools are shown side-by-side in Figure 4-8, with the Quick Plot tool on the left and the Time Series Display tool on the right.

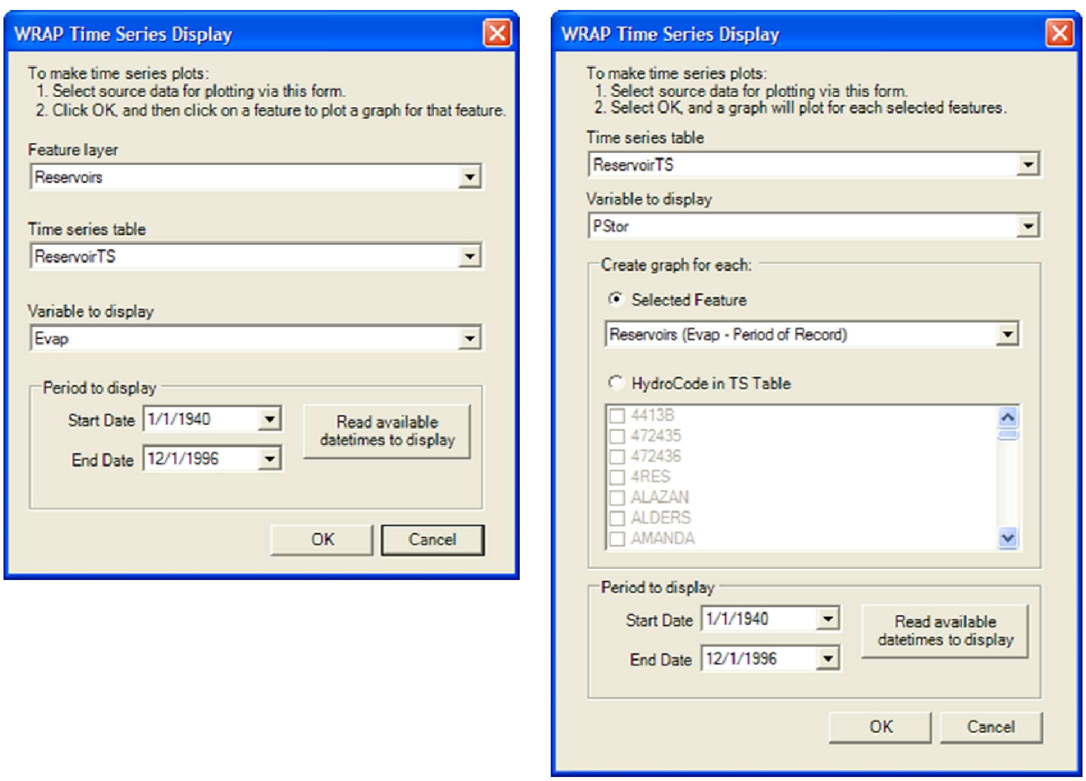


Figure 4-8. WRAP Time Series Tools – Quick Plot and Time Series Display

Additional specifics on the tools include:

Quick Plot

- Links space-time data layer to attribute series through the HydroCode field.
- Graphs created by clicking on a feature after specifying information.
- Multiple series can be shown on the same graph through subsequent selections (mouse clicks).

Time Series Display

- Links feature and attribute tables by creating a graph for selected map features.
- An individual graph is produced for each selected location.
- Can plot based solely on attribute table by selecting from the codes of the table.

The Quick Plot and Time Series Display tools provide similar yet distinct options for creating time series graphs based on attribute data. The selection process can be based either on map features or attribute table entries. The functionality provided through these tools, coupled with map display capabilities, fulfills the second project purpose. After time series graphs are produced, WRAP output data can be visualized for synthesis and analysis, making simulation data more available for comprehension and understanding.

4.5 NON-WRAP DATA

The space-time analysis of the WRAP output data provides methods of sophisticated data representation through attribute series tables (multivariable geodatabase tables). While in this data format, the data is available for exposure to ArcMap, which provides means for representing the data as graduated maps or time series graphs. These options are automated through using the WRAP Display Tool.

The benefits provided through this space-time analysis are not limited only to WRAP model output. The WRAP Display Tool's functions for map or graph display of data can be applied to any other data providing there is a HydroCode field in the attribute series tables and feature layers.

This research has initiated new thinking on ways to link space and time data for beneficial display in a GIS environment. Discussion and further research are ongoing into more general applications of the WRAP space-time analysis and display.

Chapter 5. Example

This chapter serves as an example of the space-time analysis of the WRAP output data through inspection of the input and output of the WRAP Display Tool. The following example uses, predominantly, ArcMap under the ArcGIS 9.2 version with service pack 3. An introductory overview of the GIS document is followed by a systematic presentation of the functions and options of the WRAP Display Tool. These data representation techniques and options are available as a result of the data storage and organization provided through the space-time analysis of the WRAP data.

5.1 Geography Overview

The case site for this example is the Neches Basin in eastern Texas. This basin is the ninth largest of Texas' twenty-three river and coastal basins, and is shown in green in the GIS view of Figure 5-1.

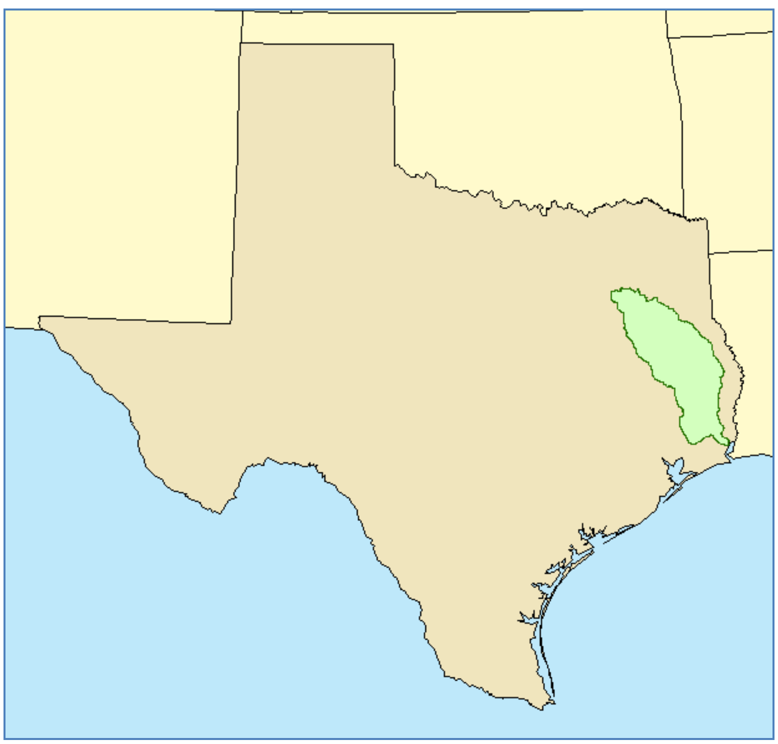


Figure 5-1. GIS View of Neches Basin in Texas

The river networks of the Neches Basin, with large reservoirs being visible, are shown in Figure 5-2. This figure is a screenshot of ArcMap, and shows standard toolbars (top) with the WRAP Display Tool. Also shown are the layers (left) that are or can be used in typical WRAP post-simulation analyses. These include geographic information on the sites (water rights, instream flows, control points, and reservoirs) for which WRAP was simulated, geography (rivers, streams, and lakes), and boundaries (basin, and states).

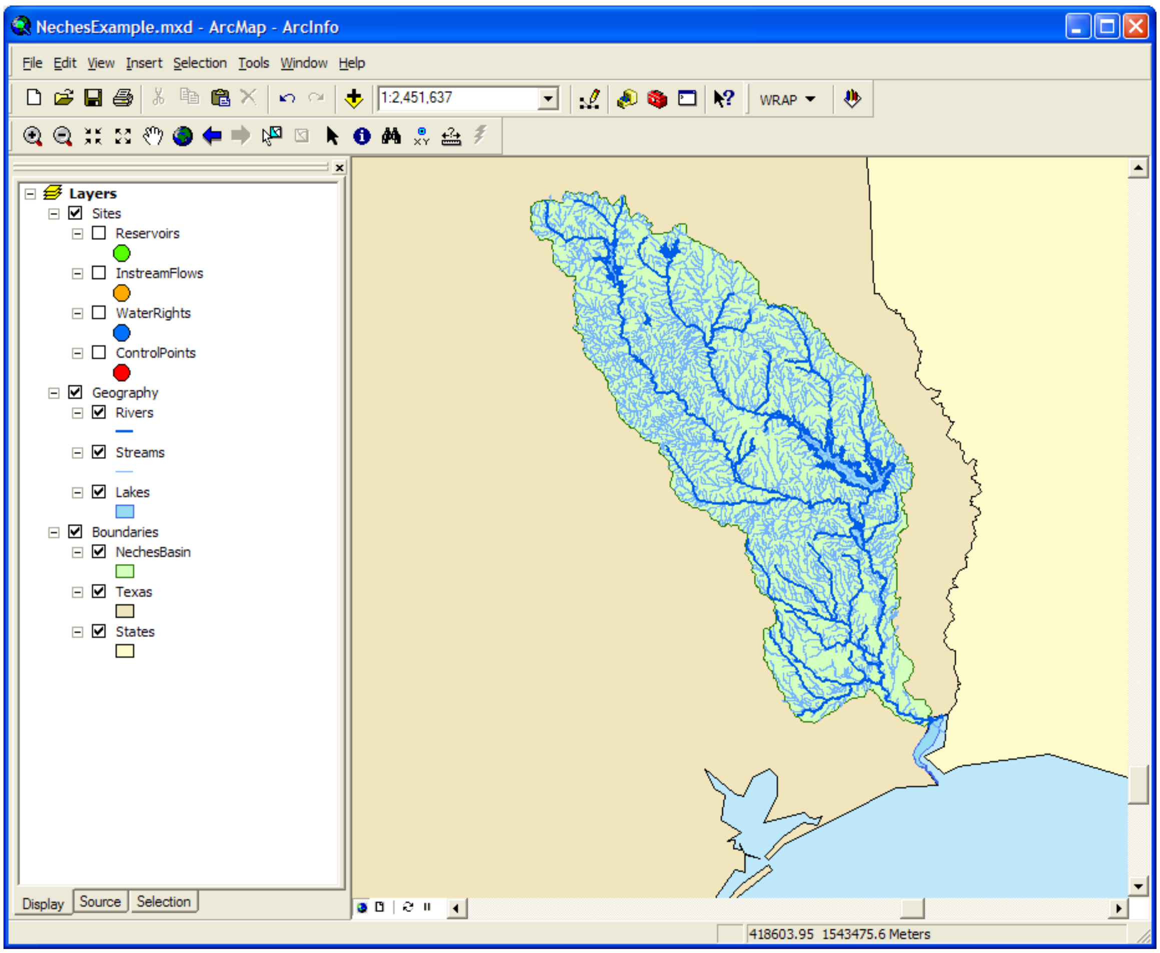


Figure 5-2. River Networks of the Neches Basin (GIS)

The geographic representations of WRAP sites are shown as tiled images in Figure 5-3. This collection of images shows where individual sites are located of each of the variable types used in WRAP simulations, indicated by colored circles. Also shown are labels of the types of variables represented in each individual image.

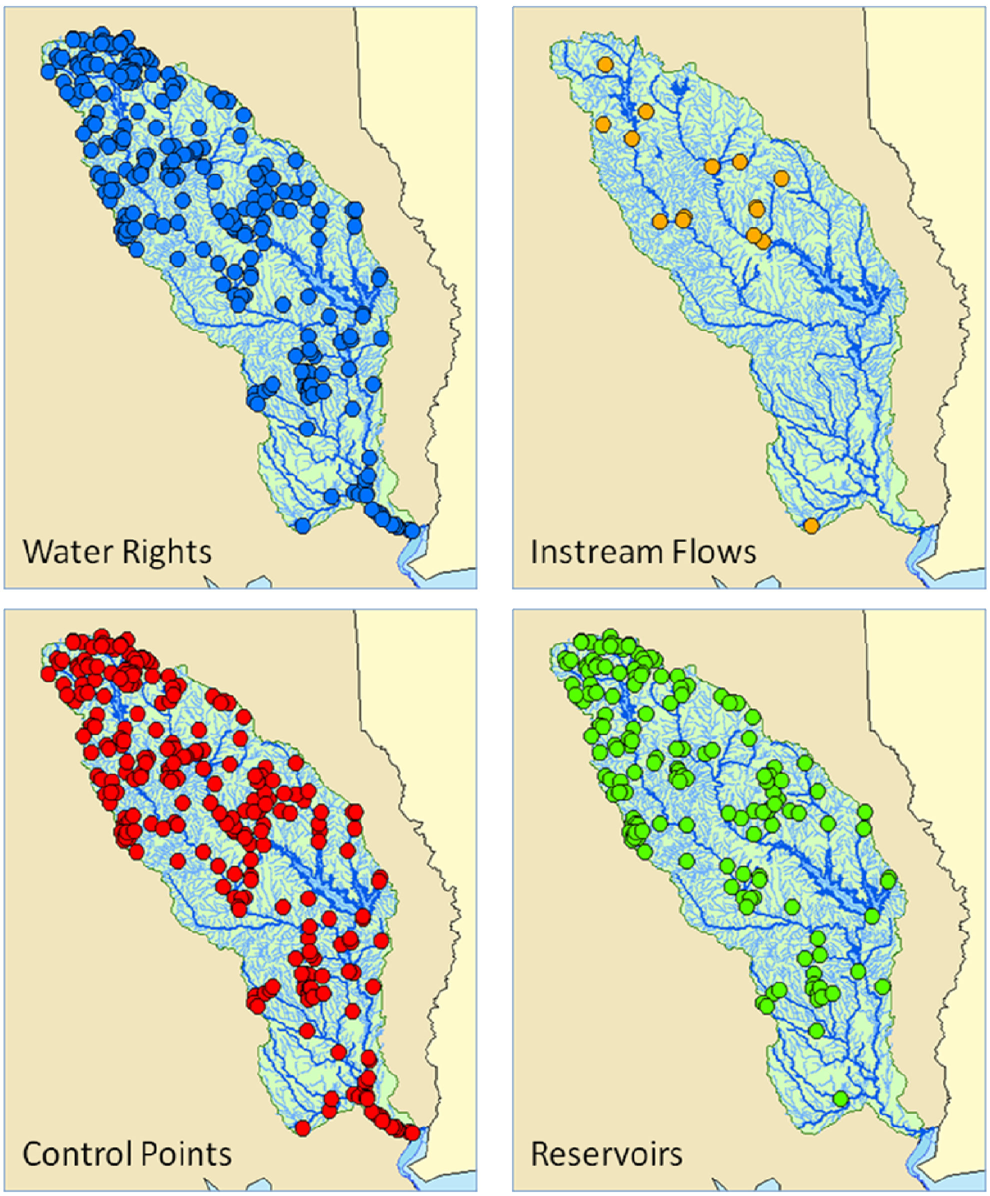


Figure 5-3. WRAP Sites by Type

Whereas the preceding set of figures shows WRAP sites individually, Figure 5-4 shows the accumulation of WRAP sites. The site layer order, shown to the left in the figure, was chosen to give a representation of the layers' nature. For example, note in Figure 5-3 that instream flows represent the fewest modeled locations; in Figure 5-4, instream flows are shown on top of the other layers (as indicated by the layer's order in the visibility hierarchy on the left-hand side). The desired effect of this figure is to represent that multiple values can be represented at one point: a control point can be related to control point values, water right values, reservoir values, or instream flow values.

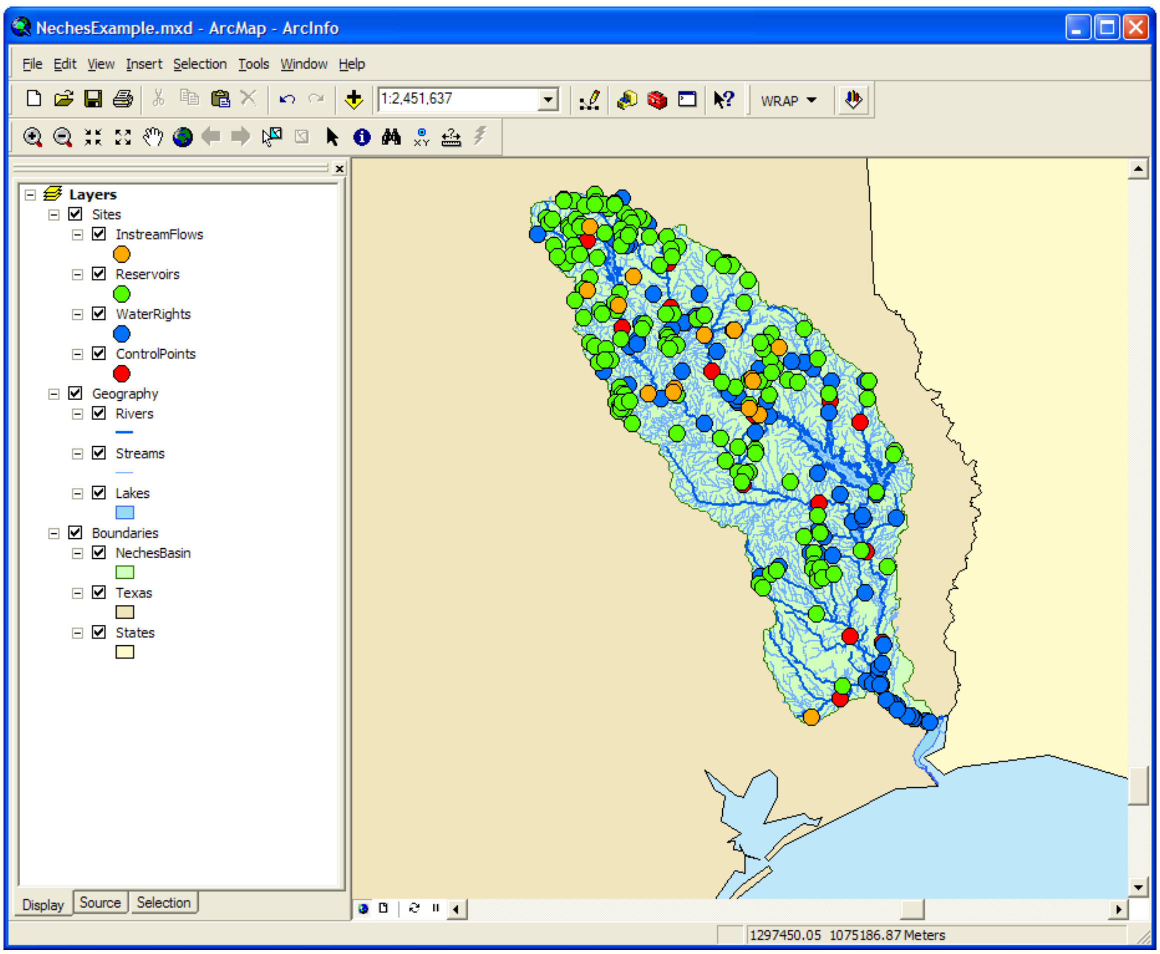


Figure 5-4. WRAP Sites Cumulatively

5.2 Tool Operations

The WRAP Display Tool is used in this example to process and display the results of a WRAP simulation for the Neches Basin. The tool is shown in Figure 5-5. This figure is an ArcMap view of the tool with its various functions shown. These consist of:

- Convert OUT to GDB – this option is used for converting the native WRAP output ASCII text file into an attribute series multivariable geodatabase table.
- Display Map – this option is related to four types of display for the variable types associated with the WRAP output—water rights, control points, reservoirs, and instream flows—and is used to display the simulation results as a map with graduated color symbols at specific locations.
- Display Time Series – two options for displaying time series are available: the Quick Plot tool (shown as the icon to the left of the word "WRAP" in the figure), and the Time Series Display option. Both options produce a time series of WRAP output values as specified.

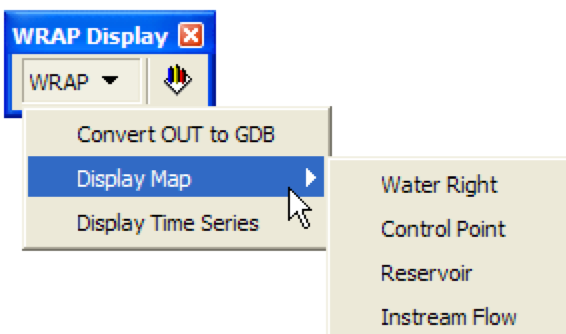


Figure 5-5. WRAP Display Tool

5.3 Convert OUT to GDB

Having had a brief introduction to the map document, its various layers, and the WRAP Display Tool, attention is now turned to the space-time analysis and display options which make the simulation results visible as maps and time series. This begins with the process that makes visual access to WRAP data possible—the conversion of the output file to a multivariable geodatabase. This conversion is based on a precise understanding of the cyclic nature of the WRAP output file data and the specific spacing between variable columns in this file. With this information known, two files are required for the conversion process: the WRAP output file and the WRAP beginning-ending storage (BES) file. These files are shown together in Figure 5-6, with the standard WRAP output file being overlaid by a view of the BES file.

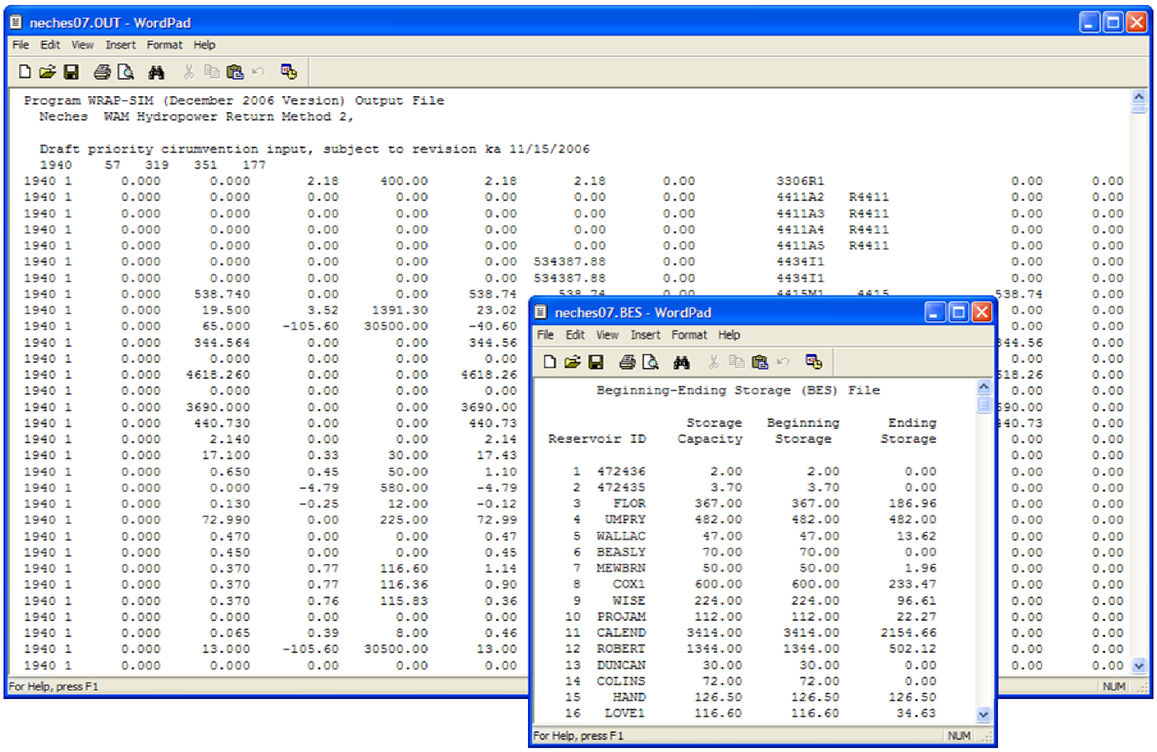


Figure 5-6. WRAP Output File with BES File Overlaid

The WRAP output file shown in Figure 5-6 is the traditional output from a simulation in WRAP, and is the same file that has been discussed in previous chapters. The beginning-ending storage file is an optional output file that is produced by WRAP and contains, for each reservoir in the simulation, the storage volume (in acre-feet). Also listed in this file are the beginning and ending storages, as far as the simulation is concerned. Of interest to the conversion process between the native WRAP output and the attribute series tables is the storage capacity values. These capacity values are stored and later used in computing a reservoir variable for how full reservoirs are (as a percent).

When the Convert OUT to GDB option is selected from the WRAP Display Tool in ArcMap (see Figure 5-5), the dialog shown in Figure 5-7 appears. This simple-looking window is the gateway to making WRAP output available for display in a GIS.

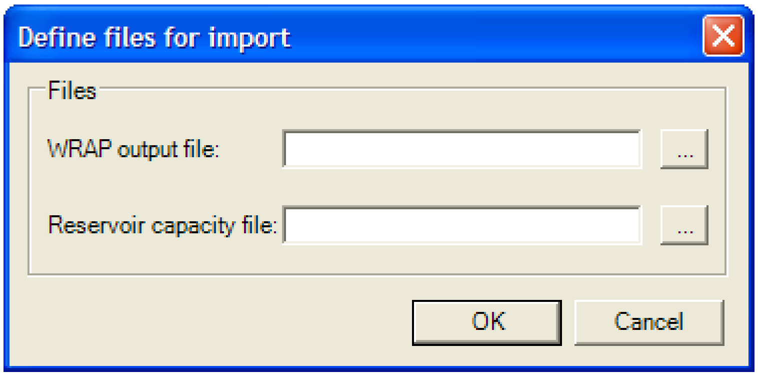


Figure 5-7. Convert OUT to GDB Dialog

After specifying the path to the requested files in Figure 5-7 and specifying the location to store the resulting file geodatabase containing the attribute series tables, the multivariable geodatabase tables are added to the map, as shown in Figure 5-8. These are shown highlighted in the ArcMap table of contents view (on the left). This is the result of successfully extracting WRAP output data and converting it to the attribute series tables.

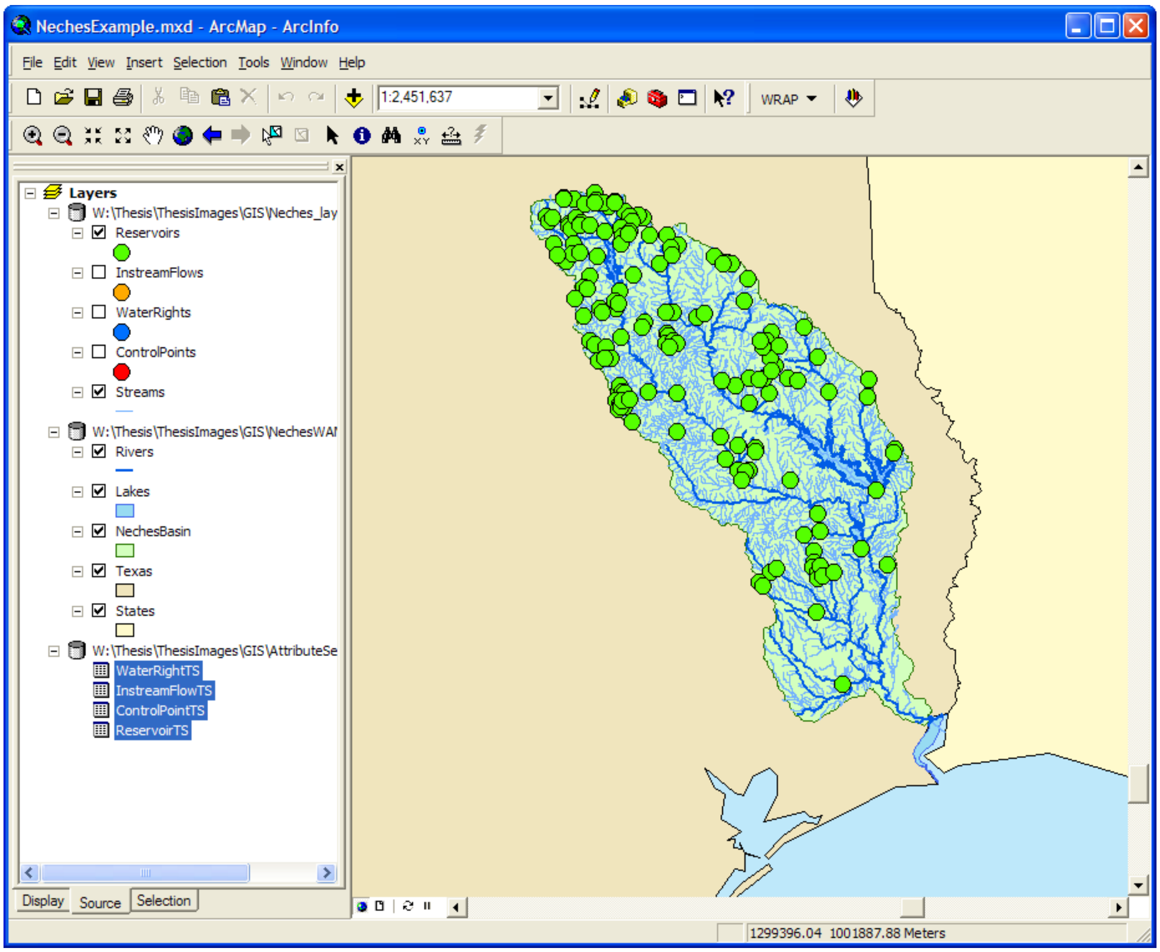


Figure 5-8. GIS of WRAP with Attribute Series Tables Added

The attribute series tables produced as a result of the conversion process are shown in Figure 5-9. This figure is a repeat of Figure 3-5, and shows the database representation of the WRAP output data. Due to their geodatabase representation, these attribute series' data can be displayed as maps and time series when exposed to ArcMap.

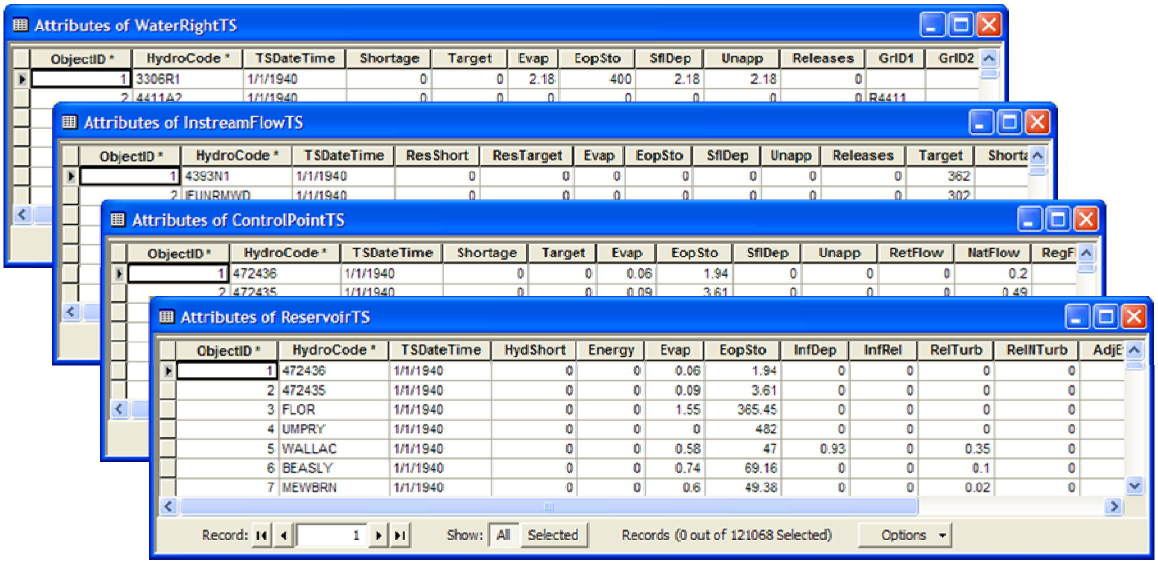


Figure 5-9. Attribute Series Tables

5.4 MAP DISPLAY

The WRAP Map Display dialog is a result of invoking the one of the map display options shown in Figure 5-5. This dialog, shown in Figure 5-9, is used to link an attribute series table to a geographic layer and produce both a map representation of specified data and a space-time data layer. This dialog is used to specify these features (the geographic layer and the attribute series table), the time period of interest, and the statistical operation to be performed for each location on the resulting data. Note that the options specified are for the reservoir variable PStor, percent storage, for the ten-year period of the 1950's, with the mean, or average, value to be displayed.

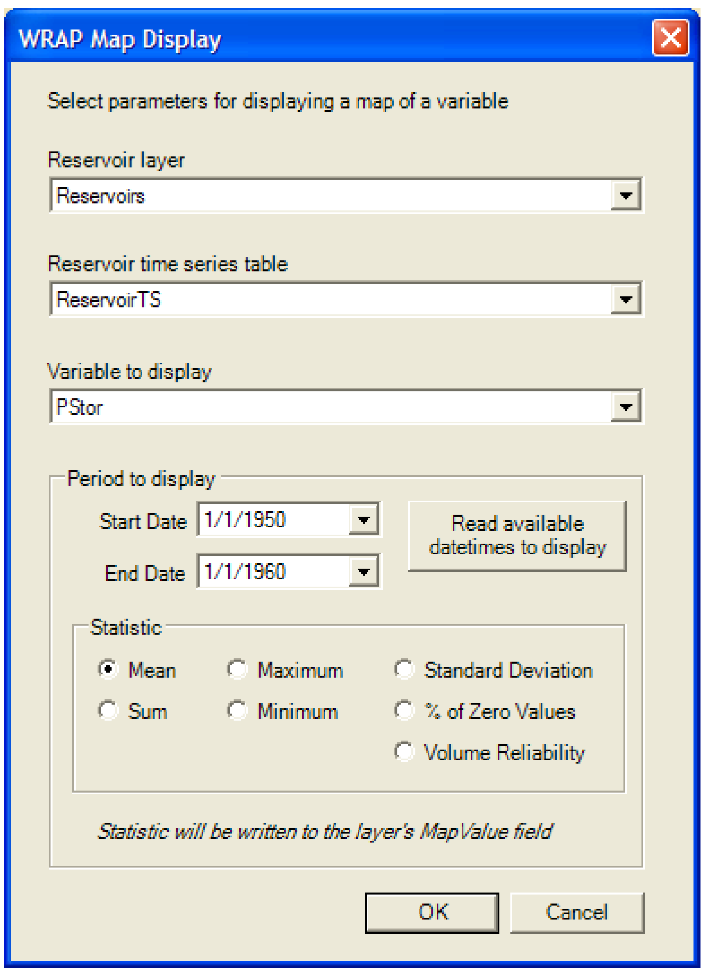


Figure 5-10. WRAP Map Display Dialog

After having specified the proper information in the map display dialog, the results are shown on the map. An example is shown in Figure 5-11. The view of ArcMap shown in this figure is illustrative of features resulting from the map display operation. Most obvious is the map which is displayed. This map shows the average reservoir storage for the 1950's, as specified in the map display dialog (see Figure 5-10) as graduated colors on symbols at reservoir locations. These colors correspond to ranges of values shown in the ArcMap table of contents, under the Reservoirs layer, with value breaks occurring every quarter.

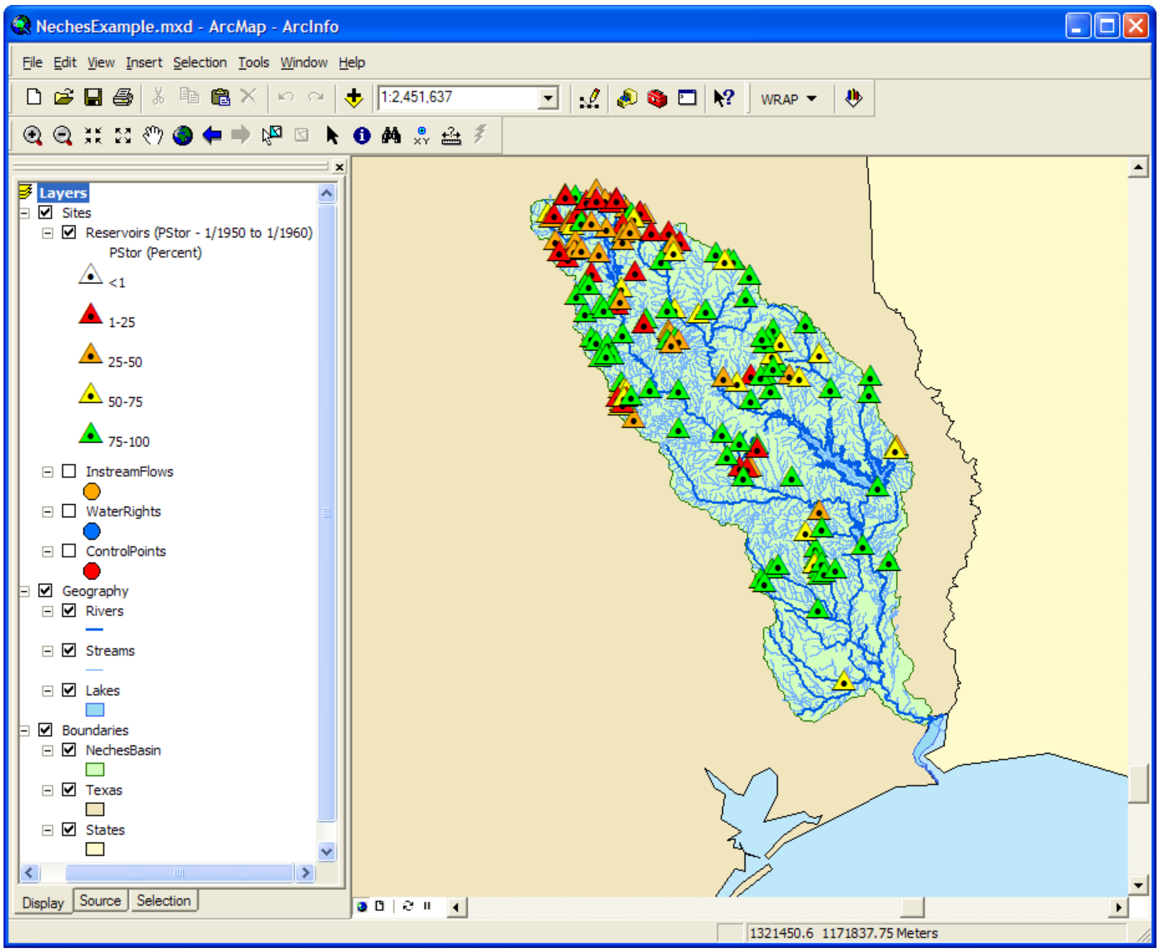


Figure 5-11. Map Display of WRAP Output

Also shown in Figure 5-11 are the selected variable, the units presented, and the period of analysis. These are all shown with the layer name. Before invoking the map display tool, the layer was named Reservoirs. Afterwards, though, the layer name is augmented to maintain information regarding the variable and time of analysis. Below the name is shown the variable code and units (units in parentheses). This information is useful in quickly determining what the map view represents—both in time and value.

The map display options provide invaluable insight into spatial relationships between sites. For example, Figure 5-11 shows that reservoirs in the upstream portions of the Neches Basin experienced lower relative volumes than those downstream. Of course, the variable shown may not give an accurate view of spatial relationships, especially in cases where smaller reservoirs may be more susceptible to lower levels in times of need. However, the map display option still provides a quick and useful look at WRAP output.

The visual representation resulting from the map display option is highly preferable to the original tabular text output format for fast relational understandings. Consider the difficulty in a similar data comparison given only a complex tabular text file: one would need to locate values for the area and time of interest, calculate an average value for each, and mentally visualize how the resulting values relate to each other. It is clear to see that the map display options opens doors in accessibility of data from a visual standpoint, all with a fast interface.

5.5 TIME SERIES GRAPHS

The fast and automated access to WRAP output data is not limited to the map display options. The WRAP Display Tool provides two options for quickly accessing the output data as time series on a graph. These options are the Quick Plot tool and the Time Series Display dialog. Both of these options use similar inputs, but the resulting time series information is slightly different. The following sections examine these tools.

5.5.1 Quick Plot Tool

The Quick Plot tool offers a point-and-click method for producing time series graphs, based on map selections from the ArcMap document. This tool is activated by clicking on the Quick Plot icon of the WRAP Display Tool toolbar, shown in Figure 5-12.

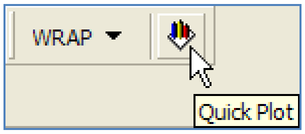


Figure 5-12. Quick Plot Tool Icon

Selecting the Quick Plot icon produces the Quick Plot dialog shown in Figure 5-12. As with the map display options, this tool uses attribute series table data along with geographic information and variable and temporal selections. The link between geography and attribute series information is essential because of the spatial component of this tool.

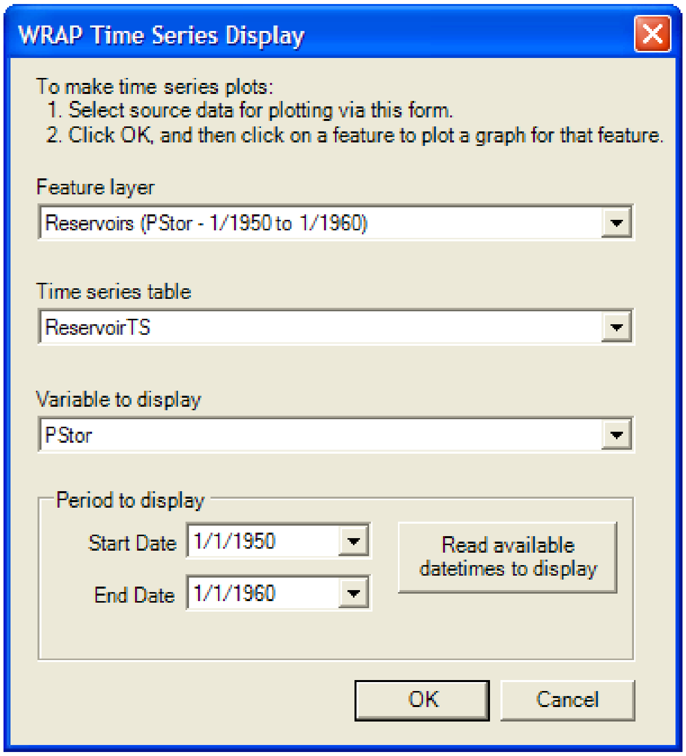


Figure 5-13. Quick Plot Tool Dialog

With the Quick Plot tool activated, a simple click on a point feature produces a time series graph corresponding to the input specified in the Quick Plot tool dialog. Figure 5-14 shows both the GIS document, the location (indicated by the arrow cursor), and the resulting time series graph. The graph gives information regarding the feature layer, attribute series, and variable in the graph banner. Also shown is the reservoir code for the series, shown in the legend.

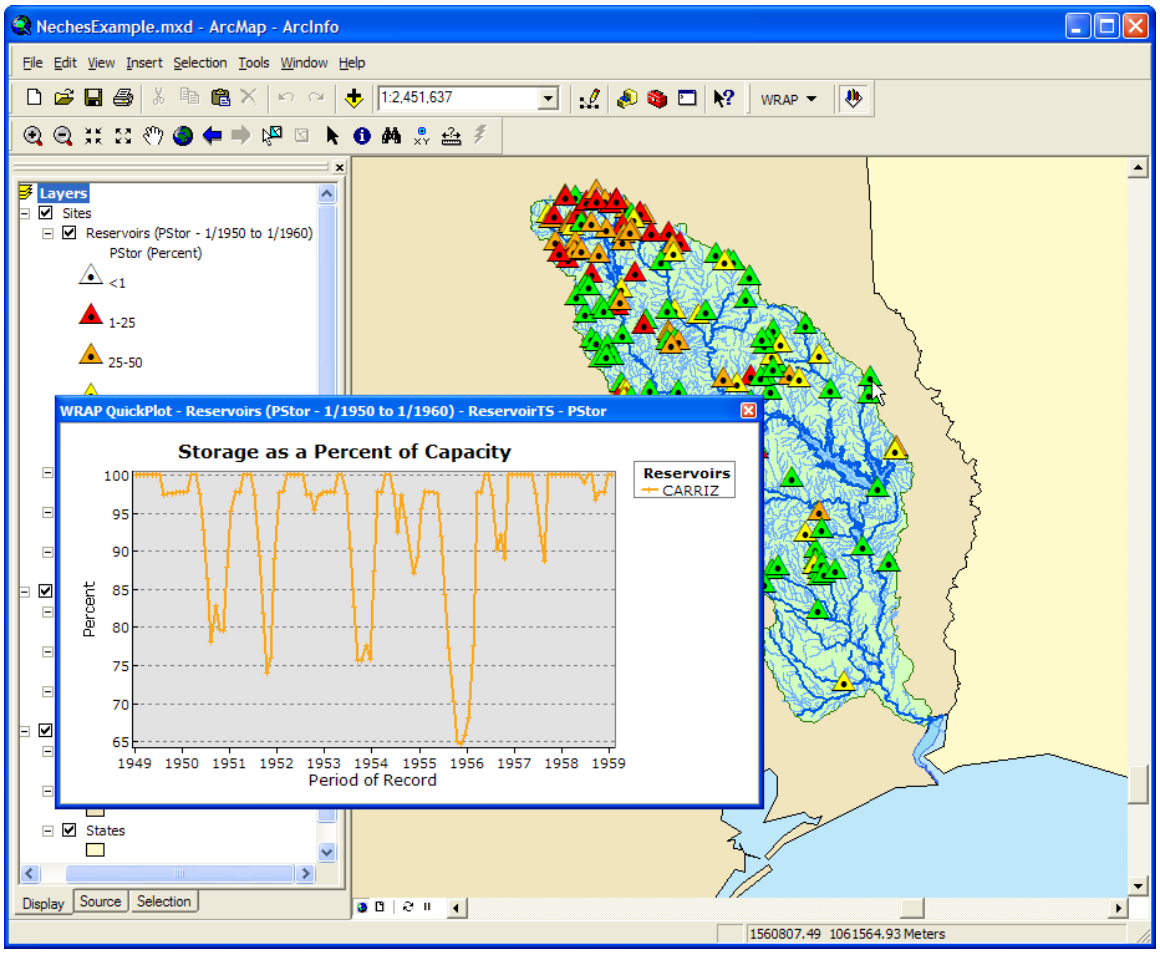


Figure 5-14. Quick Plot Graph and GIS Document

The Quick Plot tool is used to produce quick plots of time series using a map interface. An added benefit of this tool is its use in comparing time series for multiple locations. Continuing the example for the Neches Basin, after creating the time series graph in Figure 5-14, one simply needs to click on another point to have its time series added to the graph. The result of this is shown in Figure 5-15. Shown in the time series from before, with an additional series added for another reservoir, the NEWTON reservoir, just upstream of the CARRIZ, in this case.

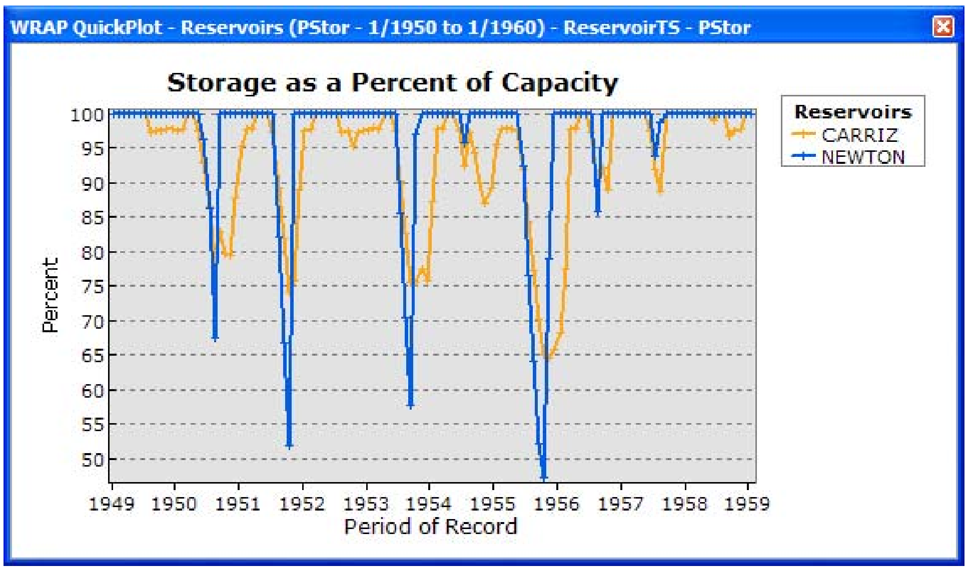


Figure 5-15. Multiple Time Series on a Graph

The ability to have multiple series on a single graph opens ways of comparison that may have been difficult if the series were on separate graphs. Furthermore, when used together with the map display functions of the WRAP Display Tool, additional comparisons can be quickly done. For example, if adjacent reservoirs have the same map display value (as the CARRIZ and NEWTON reservoirs do in this example) for a time period, the Quick Plot tool can be used to see how similar or different the values were. Figure 5-15 shows that while these two reservoirs were both in the 75-100 percent full category, the shapes of the time series are markedly different: one having sharp, shorter intervals of drawdown (NEWTON) and the other having more gradual, longer duration drawdown periods. This can indicate differences in reservoir size, management, or some other aspect that would have been difficult to observe from the data alone.

5.5.2 Time Series Display

The time series display option offers the advantages of plotting from selected features as well as from a complete list of locations. This section continues the Neches Basin example and shows how the time series display option can be used to produce useful time series graphs. In fact, the two reservoirs from the previous section are used for the time series display option as well. These are shown in the GIS display of Figure 5-16.

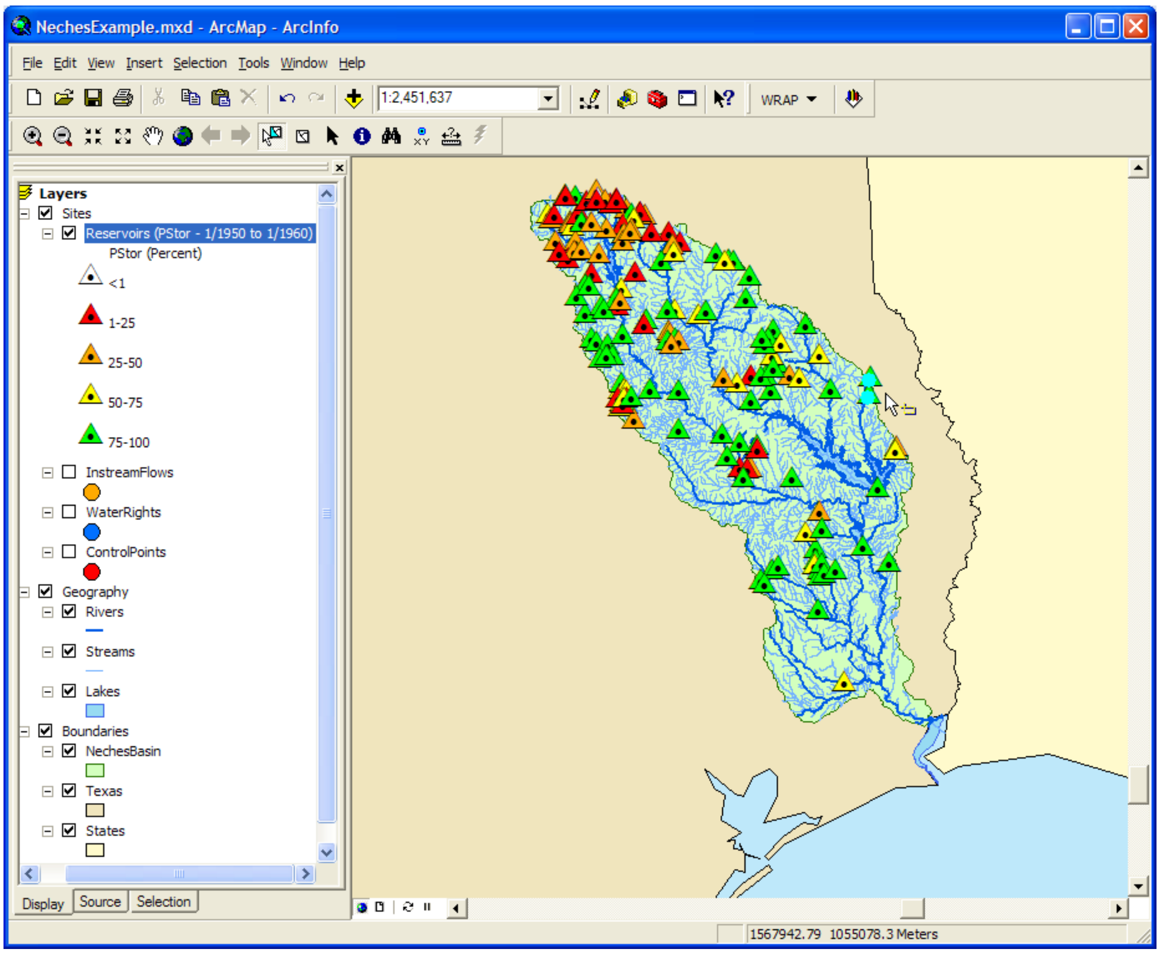


Figure 5-16. Time Series Display Selected Locations

Consider the imaginable case where certain sites have been selected using ArcMap's Select Features option (as shown in Figure 5-16). Consider further that individual time series graphs of a variable and time span are desired for these locations. The time series display option allows for this using the dialog shown in Figure 5-17. This dialog is produced by selecting *Display Time Series* from the WRAP Display Tool (see Figure 5-5). The dialog shows inputs associated with the same locations as the two adjacent reservoirs used in the previous section.

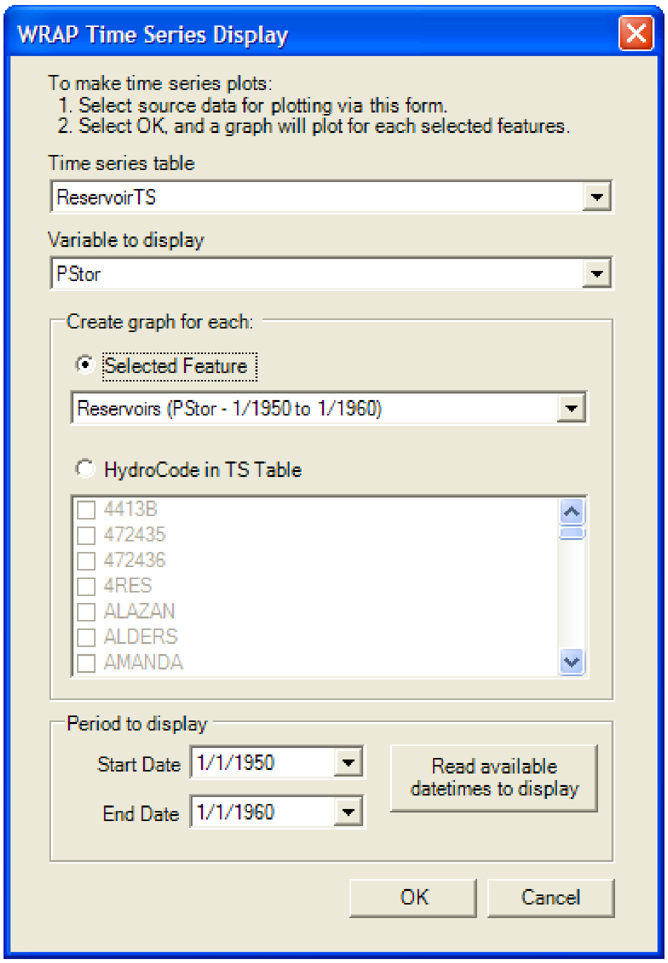


Figure 5-17. Time Series Display Dialog

The time series display dialog (Figure 5-17) allows one to select the option to graph from selection or from selected codes from the attribute table. Each of these options has advantages. The selection based option is preferable if individual graphs are desired for locations identified using ArcMap's *Select by Attributes* or *Select by Location* functions, for example. Graphing from selected codes from the attribute table is preferable where only the location code is known. This option also provides access to time series graphs from WRAP attribute series without having any geographic files at all—one simply needs to choose the attribute series, variable, and period to display.

The Neches Basin example continues by creating time series graphs for the two reservoirs' storage, using the same locations as before. Using the selected reservoirs of Figure 5-16 and the settings of Figure 5-17 yields two time series graphs—one for each location. These graphs are shown cascaded in the GIS view of Figure 5-18.

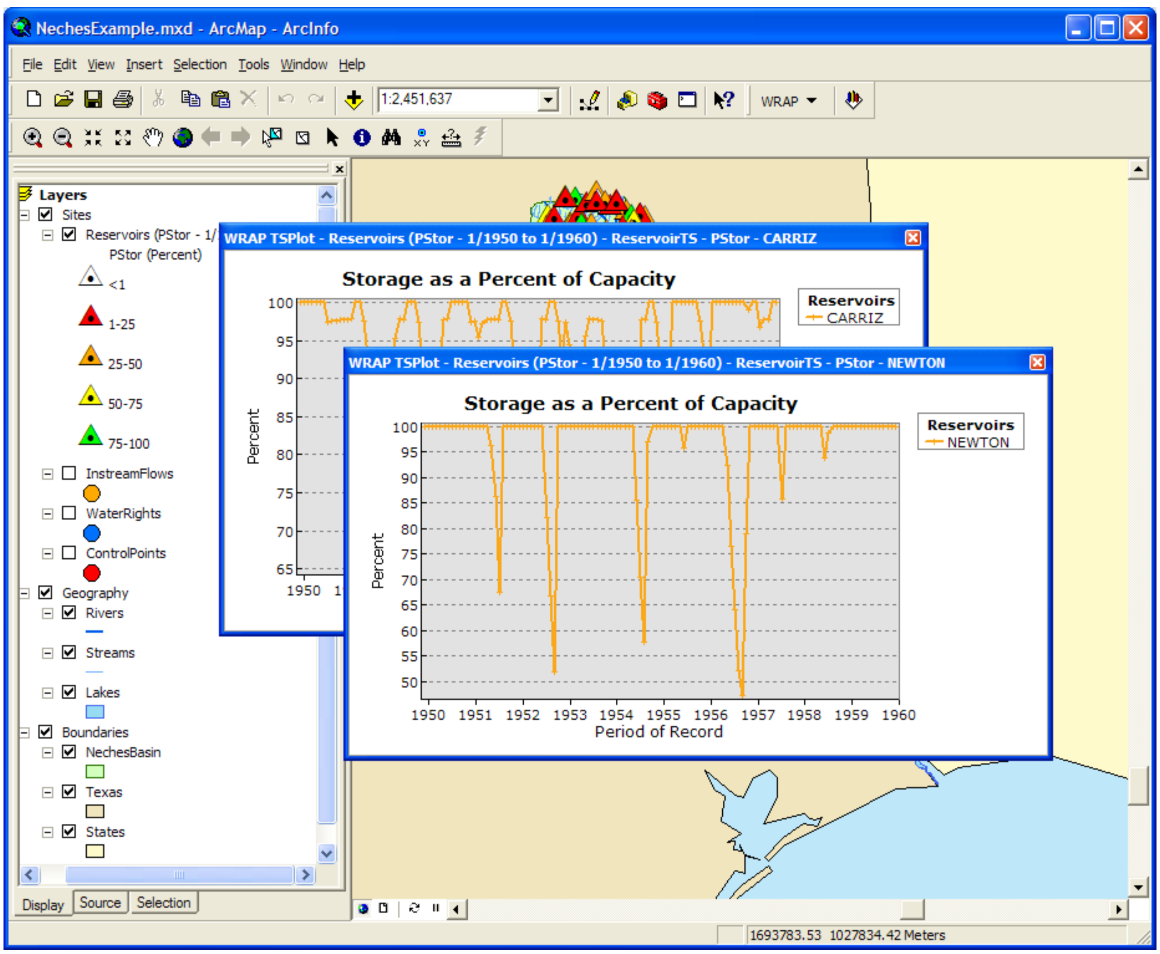


Figure 5-18. Cascaded Time Series Display Graphs

Using the time series display option gives individual graphs for each location selected—either selected geographically or from a list of available locations. This is different from the Quick Plot tool, which stacks multiple time series on a single graph. The time series graphs from the time series display option (from Figure 5-18) are shown individually in Figure 5-19. Compare these representations to that of Figure 5-15 for a comparison.

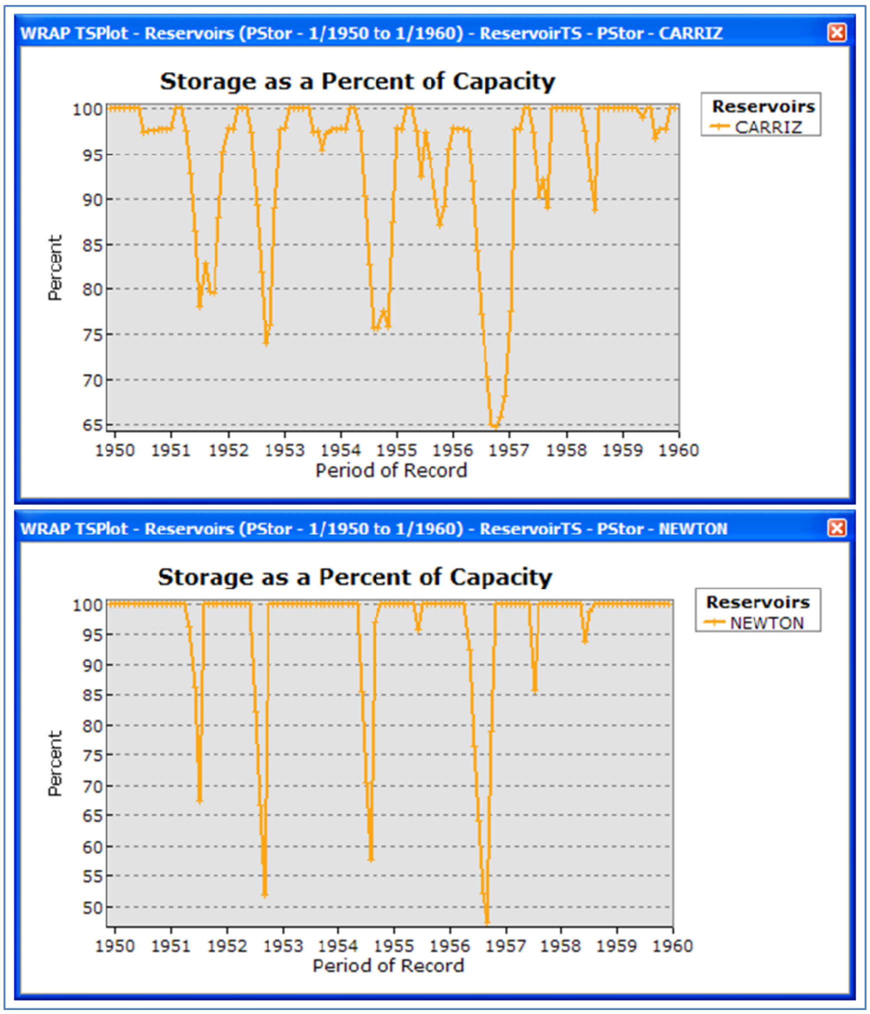


Figure 5-19. Graphs from Display Time Series Option

5.5.3 Managing Graphs

Regardless of the method of creation, graphs created using the WRAP Display Tool are archived and can be accessed at a later time. This is due to ArcMap's management of time series graphs.

The Graph Manager can be accessed, as shown in Figure 5-20, to recall previous graphs, delete unneeded graphs, or load previously saved graphs. Shown are the graphs created in the previous two sections (see Figure 5-15 and Figure 5-19). This handy feature enables a history of graphs and their display to be maintained for future use.

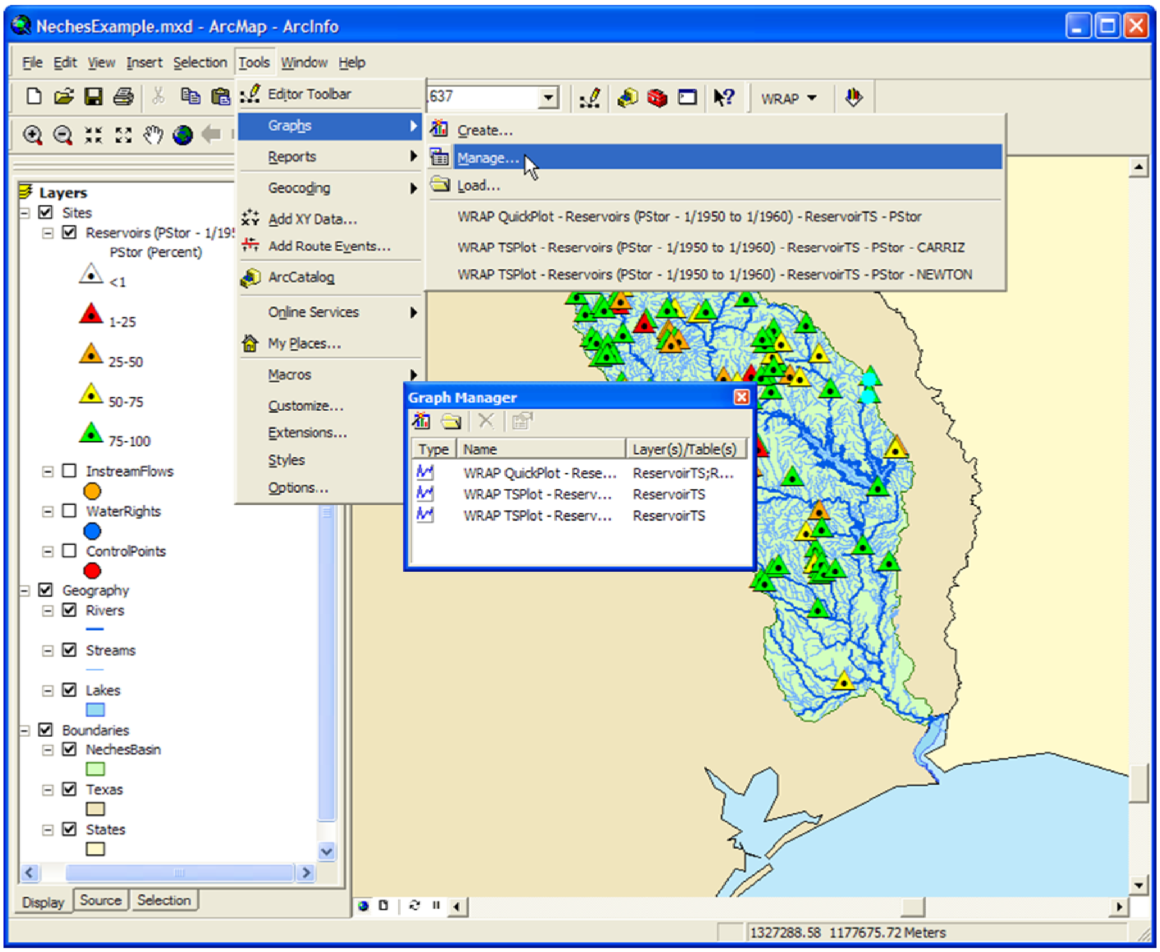


Figure 5-20. Graph Manager of ArcMap

5.6 EXAMPLE SUMMARY

This Example chapter has included a guided tour of the space-time analysis of the WRAP output data for the Neches Basin in eastern Texas. This tour included an examination of the automated steps made possible by the WRAP Display Tool, coupled with the innovative data structure and storage format provided through the multivariable geodatabase tables (attribute series).

The examples and steps of this chapter have shown that previously inaccessible (by ArcMap) data has become available for a number of useful presentation options in a GIS, due to the conversion of structured ASCII text output files into attribute series tables. These tables, when exposed to ArcMap, are structured for display through use of maps or time series.

The map display options, automated through the WRAP Display Tool, provide fast visual access to the otherwise cryptic output file data. Geographic representations of data can reveal spatial relationships and trends otherwise shrouded from view with the data in its native format.

Time series graphs have long been used by scientists to examine the results of simulations or observed data. Data in attribute series tables is pre-packaged for time series representation. The graphing utilities provided in ArcGIS 9.2 are automated through the WRAP Display Tool to provide options for displaying time series—either as multiple series on a single graph, or multiple graphs of single series. Furthermore, the map interface of selecting locations for plotting time series graphs offers fast access to time series graphs that are, quite literally, just a mouse-click away.

The synthesis of the options made possible through the space-time analysis of WRAP data provides innovative means and methods of viewing simulation output data; the combined effect is greater than the individual parts. Thus, successful space-time analysis enables data access and presentation to be facilitated through superior data management and automated map and time series options.

Chapter 6. Conclusion

From its initial widespread use after the devastating drought of 1996, the Water Rights Analysis Package (WRAP) has been used as Texas' official water availability model for assigning and reevaluating water rights. The history of the output file produced by WRAP has been fairly steady, with only minor changes occurring. Despite the passage of time, this output has remained in a rigidly structured ASCII text file that is both cumbersome and difficult to apply in a geographic information system.

The space-time analysis performed on this output data has paved pathways of access and synthesis of the vast amount of data contained in the output file. This analysis involved a detailed look at the organization and structure of the WRAP output data file, as well as a working understanding of what the various variable values represented. With knowledge of the precise structure of the WRAP output file, work was made on altering the format of the data to make it ingestible by a GIS. Initial attempts at conversion yielded a new format that took an exorbitant amount of time and produced a multi-fold increase in size. These factors produced sufficient motivation to find a more excellent way of converting and storing the output data from its native format to a GIS-friendly format.

A structure, organization, and storage system needed to be developed which could be used to quickly process the large output file and store it in a compact fashion. This format needed to be exposable to ArcMap to enable useful displays of the data as different views of the traditional data cube.

Geodatabase representation of data is a preferable organizational structure for use with ArcMap. Therefore, the WRAP output data could be transformed from its native text file format to geodatabase format and be ingestible by ArcMap. The Arc Hydro data model, a data model useful for many hydrological applications, proved inefficient for representing the WRAP data. This is due to the way that space-time data is maintained in Arc Hydro. WRAP output initially has multiple variable values listed for a single location at a single time step. The result is one row of the output file that has multiple data for a time and place. To represent a single row of the original output format in Arc Hydro would require ten or more rows in the resulting geodatabase. This would require a significant increase in size of the resulting file structure as well as an increase in processing time.

To combat the large space and processing time associated with conversion, a modified version of Arc Hydro was developed which involves a multivariable geodatabase table. This format looks remarkably similar to the original data format—it has many variables stored in each row associated with a location and time step. This results in much faster processing time and comparable-sized converted files.

Having a database representation of WRAP data was accomplished by programmatically parsing the output file, line-by-line, and harvesting and organizing the output data in a transformation process that took as input the WRAP output file, and yielded a collection of attribute series tables (multivariable geodatabase tables) in a file geodatabase structure. Determining a structure to accomplish these goals had multiple iterations, yet the end goal was realized. With data in this format, the WRAP simulation results are exposable to GIS for geographic and temporal display of data. The structure of the converted attribute series tables screams to be applied for further understanding.

Geodatabase organization of WRAP data provides a foundation for both geographic (map) and temporal (time series) representation. This data structure and the realization of space-time representation are a direct completion of the first two project purposes: advancing data management in attribute series styles, and making possible the visualization of WRAP output data for synthesis and analysis purposes. These purposes are accomplished using the data management and display features of ArcMap.

With the data organized effectively in geodatabase format, ArcMap is used to achieve the desired display results. While the visualization available using ArcMap is possible, it involves multiple steps. To facilitate visualization, a tool was developed, the WRAP Display Tool, which automates the steps required to convert the native WRAP output file to a geodatabase and display the values as maps or time series graphs.

6.1 RECOMMENDATIONS

The selective representation of data from the attribute series is made possible through the mapping and graphing utilities of ArcGIS and its components. However, useful as these methods are, the processes of arriving at useful results can be tedious and time consuming, particularly if multiple representations are desired. Despite this, the processes are automated through behind-the-scenes programming, resulting in a GIS toolbar, the WRAP Display Tool, which can be used in processing and displaying WRAP output results. The need for independent development of a GIS tool, coupled with the useful space-time visualization made possible by the tool, lends weight to the suggestion for development of a more general display tool, developed, perhaps, by ESRI, the makers of ArcGIS.

The WRAP Display Tool can be used with non-WRAP data, but the tool demands specifics that may be tedious to users unfamiliar with deep workings of ArcGIS. In addition, this tool was developed using ArcGIS 9.2, with a specific service pack. The specificity of this development environment may be a breeding ground for problems given seemingly small changes to the ArcGIS environment. For example, a small change to a single ESRI library item in a version change could disable the WRAP Display Tool. For this purpose, a general tool, developed by ESRI, would benefit from advanced indications of version changes and their implications.

In working toward this recommendation, information has been shared with individuals at ESRI, meetings have been conducted, and dialog is ongoing as to the future development of a generally applicable time series and mapping tool. The development of such a tool would enable holders of space-time data to represent their data as maps and time series with little difficulty.

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Vita

Clark David Siler was born in Aurora, Colorado on 29 Jan 1978, the son of Don and Kay Siler, and is the fourth of six children. After graduating from Platteview High School in rural Omaha, Nebraska in 1996, he devoted two years of his life to the Lord Jesus Christ as a full-time missionary for the Church of Jesus Christ of Latter-day Saints. Thereafter, Clark completed general courses and graduated Cum Laude with an Associates of Science degree at Utah Valley State College in Orem, Utah in 2003. He then focused his attention on civil engineering while studying at Brigham Young University in Provo, Utah. He graduated Summa Cum Laude with a Bachelors of Science degree in civil engineering with a minor in mathematics in 2005. During his undergraduate studies he worked as a teaching assistant, a surveying lab instructor, and a research assistant. After graduation Clark worked as a software tester and documentation specialist for the Environmental Modeling Research Laboratory with their Watershed Modeling Software, WMS. He attended the University of Texas at Austin where he intends to obtain a Master's of Science in Environmental and Water Resources Engineering degree in May, 2008. He plans on continuing his educational and research pursuits with Dr. David Maidment and the researchers of the Center for Research in Water Resources at the University of Texas at Austin. Clark is blessed with an amazing and beautiful wife, Maryann. They have two wonderful children, David and Rebecca, and plan on welcoming another child into their family in July 2008.

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

This thesis was typed by the author.