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Condensing Water Availability Models to Focus on Specific Water Management Systems

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Abstract: The Texas Water Availability Modeling System is routinely applied in administration of the water rights permit system, regional and statewide planning, and an expanding variety of other endeavors. Modeling water management in the 23 river basins of the state reflects about 8,000 water right permits and 3,400 reservoirs. Datasets are necessarily large and complex to provide the decision-support capabilities for which the modeling system was developed. New modeling features are being added, and the different types of applications are growing. Certain applications are enhanced by simplifying the simulation input datasets to focus on particular water management systems. A methodology is presented for developing a condensed dataset for a selected reservoir system that reflects the impacts of all the water rights and accompanying reservoirs removed from the original complete dataset. A set of streamflows is developed that represents flows available to the selected system considering the effects of all the other water rights in the river basin contained in the original complete model input dataset that are not included in the condensed dataset. The methodology is applied to develop a condensed model of the Brazos River Authority reservoir system based on modifying the Texas Water Availability Modeling System dataset for the Brazos River Basin.

Key words: reservoirs, rivers, water supply reliability

INTRODUCTION

The Texas Commission on Environmental Quality (TCEQ), in collaboration with the Texas water management community, maintains a Water Availability Modeling (WAM) System used in the administration of the state's water rights permit system, regional and statewide planning, and other activities (Alexander Martin and Chenoweth 2009). The WAM System is routinely applied by applicants in preparation of water right permit applications and by TCEQ staff in evaluating the applications. The Texas Water Development Board (TWDB) is the lead agency for regional and statewide planning studies, which represent another major application of the modeling system. River authorities and other water management agencies and their consultants also apply the WAM System in other endeavors not directly mandated by either the TCEQ water rights permitting or TWDB planning programs. The WAM System supports a broad range of water management activities and contributes to the integration of those activities. Modeling capabilities continue to be expanded and the range of applications continues to grow.

WAM System datasets for the larger river basins are complex with numerous reservoirs, water supply diversions, and instream flow requirements. These large, complex models are essential for the water rights permitting applications for which the WAM System was originally developed. However, simplification of datasets is beneficial for other applications that focus on a particular water management system while still considering interactions between that system and other water management entities in the river basin.

This paper presents a methodology for condensing WAM datasets, which has been applied to the Brazos River Basin (Wurbs and Kim 2008). The original Brazos WAM has about 3,750 control points, 670 reservoirs, and 1,700 water rights (HDR Engineering 2001). A much easier-to-use condensed

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dataset with 48 control points and 15 reservoirs is focused on a reservoir system operated by the Brazos River Authority (BRA) and associated water rights. The effects of the numerous other reservoirs and water rights in the river basin are incorporated in the streamflow inflows at the 48 selected control points while properly maintaining the priority system reflected in the water right permits.

The paper begins by describing the TCEQ WAM System, including major new features currently being added as well as basic modeling capabilities that have been routinely applied for several years. The recently developed methodology for condensing input datasets to focus on a particular reservoir system is then presented. The procedure is illustrated by the development and application of a BRA condensed dataset.

TEXAS WATER AVAILABILITY MODELING (WAM) SYSTEM

The TCEQ WAM System consists of the generalized Water Rights Analysis Package (WRAP) river/reservoir system water management model, WRAP hydrology and water rights input files for all of the river basins of Texas, geographic information system tools, and other supporting databases (Wurbs 2005). The WRAP modeling system is generalized for application to river/reservoir systems located anywhere in the world, with input datasets being developed for the particular river basin of concern. For simulation studies in Texas, WRAP input files from the TCEQ WAM System are altered as appropriate to reflect proposed water management plans of interest, which

Table 1. Texas WAM System Models

Fig. 1 Map ID	Major River Basin or Coastal Basin	Period of Analysis	Number of Primary Control Points	Number of Total Control Points	Number of Model Water Rights	Number of Instream Flow Rights	Number of Model Reservoirs
1	Canadian River Basin	1948-98	12	85	56	0	47
2	Red River Basin	1948-98	47	447	489	103	245
3	Sulphur River Basin	1940-96	8	83	85	5	53
4	Cypress Bayou Basin	1948-98	10	189	163	1	91
5	Rio Grande Basin	1940-00	55	957	2,584	4	113
6	Colorado River Basin and Brazos-Colorado Coastal	1940-98	45	2,395	1,922	86	511
7	Brazos River and San Jacinto-Brazos Coastal	1940-97	77	3,830	1,634	122	670
8	Trinity River Basin	1940-96	40	1,334	1,169	23	703
9	Neches River Basin	1940-96	20	318	333	17	176
10	Sabine River Basin	1940-98	27	376	310	21	207
11	Nueces River Basin	1934-96	41	542	373	30	121
12	Guadalupe and San Antonio River Basins	1934-89	46	1,349	860	184	237
13	Lavaca River Basin	1940-96	7	185	71	30	22
14	San Jacinto River Basin	1940-96	16	411	148	13	114
15	Lower Nueces-Rio Grande	1948-98	16	119	70	6	42
16	Upper Nueces-Rio Grande	1948-98	13	81	34	2	22
17	San Antonio-Nueces	1948-98	9	53	12	2	9
18	Lavaca-Guadalupe Coast	1940-96	2	68	10	0	0
19	Colorado-Lavaca Coastal	1940-96	1	111	27	4	8
20	Trinity-San Jacinto	1940-96	2	94	24	0	13
21	Neches-Trinity Coastal	1940-96	4	245	138	9	31

could involve changes in water use or reservoir/river system operating practices, construction of new facilities, or other water management strategies.

WAM System input datasets

The Texas Legislature authorized development of a water availability modeling system in the comprehensive water management legislation enacted as its 1997 Senate Bill 1. The TCEQ and its partner agencies and contractors implemented the WAM System during 1997–2003. Consulting engineering firms and university researchers under contract with the TCEQ performed much of the technical work. Consulting firms developed WRAP input datasets and modeled specified water management scenarios for each of the river basins. The water rights in the datasets are updated by the TCEQ as applications for new permits or revisions to existing permits are approved. Other aspects of the datasets also continue to be refined. The river basin datasets and an array of information regarding the WAM System are available at the TCEQ WAM website.

The 21 WRAP input datasets as of 2008 covering 23 river basins are listed in Table 1 (Wurbs 2010a). The river basins are delineated in Fig. 1. Three of the 21 WAM datasets combine two river basins, and one basin is divided into two datasets. Each dataset includes water rights information in a file with filename extension DAT (called a DAT file) and hydrology data in streamflow (FLO), net reservoir evaporation (EVA), and flow distribution (DIS) files.

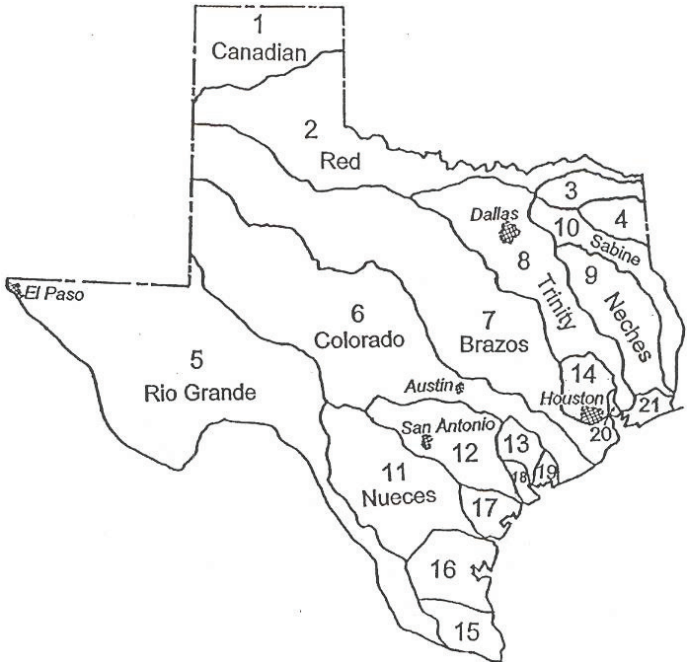

Fig. 1. Texas WAM System River Basins

Authorized use and current use versions of the water rights (DAT) files model two alternative scenarios, reflecting different combinations of premises regarding water use, return flows, and reservoir sedimentation. The authorized use scenario water rights input files are based on the following premises:

- Water use targets are the full amounts authorized by the water right permits.
- Full reuse with no return flow is assumed.
- Reservoir storage capacities are those specified in the permits, which typically reflect no sediment accumulation.
- Term permits are not included.

The current use scenario water rights input files are based on the following premises:

- The water use target for each right is based on the maximum annual amount used in any year during a selected 10-year period.
- Best estimates of actual return flows are adopted.
- Reservoir storage capacities and elevation-area-volume relations for major reservoirs reflect year 2000 conditions of sedimentation.
- Term permits are included.

The TCEQ applies the authorized use scenario in evaluating regular water right permit applications and the current use scenario in evaluating applications for term permits. The holder of a regular water right permit is entitled to continue to use the water forever, though permits may be cancelled if water is not actually used during a 10-year period. A term permit is issued for a set period, usually ranging from one to 10 years, and is generally based on other water rights holders not using their full permitted amounts.

The authorized use versions of the 21 datasets as of January 2008 contained 10,512 water right (WR) records and 662 instream flow (IF) records for 11,174 total model water rights representing almost 8,000 water right permits (Wurbs 2010a). Multiple water rights in the model may represent a single permit. The datasets model the approximately 3,435 reservoirs for which a water right permit has been issued. More than 90% of the total storage capacity of the 3,435 reservoirs is contained in the approximately 210 reservoirs that have conservation capacities exceeding 5,000 acre-feet (ac-ft). The TCEQ continues to periodically update the datasets.

In WRAP terminology, water use requirements, water control infrastructure, and reservoir/river system operating strategies are called water rights. Required and optional features for defining water use requirements and management practices in a DAT file include:

- locations of system components by control point
- priority specifications
- water supply diversion, environmental instream flow,

and hydroelectric energy targets for each of the 12 months of the year and specifications for varying the water use targets as a function of reservoir storage contents or streamflow
- seasonal or annual limits on diversions, reservoir releases, or flow depletions
- return flow specifications in various optional formats
- conveyance of flow through pipelines and canals
- reservoir/river system operating rules including multiple-reservoir system operations, multiple-purpose operations, multiple-owner reservoirs, off-channel storage, and constraints on depleting streamflows
- reservoir storage volume versus surface area and elevation relationships

Several of the river systems shown in Fig. 2 are shared with neighboring states. The Rio Grande is shared with Mexico. For the interstate and international river basins, hydrology and water management in neighboring states and Mexico are considered to the extent necessary to assess water availability in Texas. The models reflect two international treaties and five interstate compacts as well as the two Texas water rights systems administered by the TCEQ. The water rights system allocating the Texas share of the waters of the lower Rio Grande is significantly different from the water rights system for the rest of Texas (Wurbs 2004).

The spatial configuration of a river system is defined in WRAP by a set of control points, with the next downstream control point being specified for each control point. All reservoirs, diversions, return flows, hydropower plants, environmental instream flow requirements, and other system components are assigned control point locations. The 21 datasets contain approximately 13,300 control points (Table 1). About 500 primary control points, most representing gaging stations, have naturalized flows included in WAM System hydrology input files. Hydrology input for a WRAP simulation consists of sequences of monthly naturalized streamflows at all control points and net evaporation less precipitation rates for all reservoirs for the hydrologic period-of-analysis shown in Table 1.

Primary control points are locations, usually gaging stations, for which naturalized flows are provided in a WRAP simulation input FLO file. Naturalized flows at ungaged secondary control points are computed during a simulation. The model includes several alternative methods for transferring naturalized flows from gaged to ungaged sites. Flows may be distributed in proportion to drainage area with or without considering channel losses. SIM also includes an option based on the relationship between precipitation and runoff determined by the Natural Resource Conservation Service. The WAM System datasets include watershed parameters required for these methods in a DIS file.

Water Rights Analysis Package (WRAP)

WRAP simulates water resources development, management, regulation, and use in a river basin or multiple-basin region under a priority-based water allocation system. The model facilitates assessments of hydrologic and institutional water availability and reliability in satisfying requirements for environmental instream flows; municipal, industrial, and agricultural water supply; hydroelectric energy generation; and

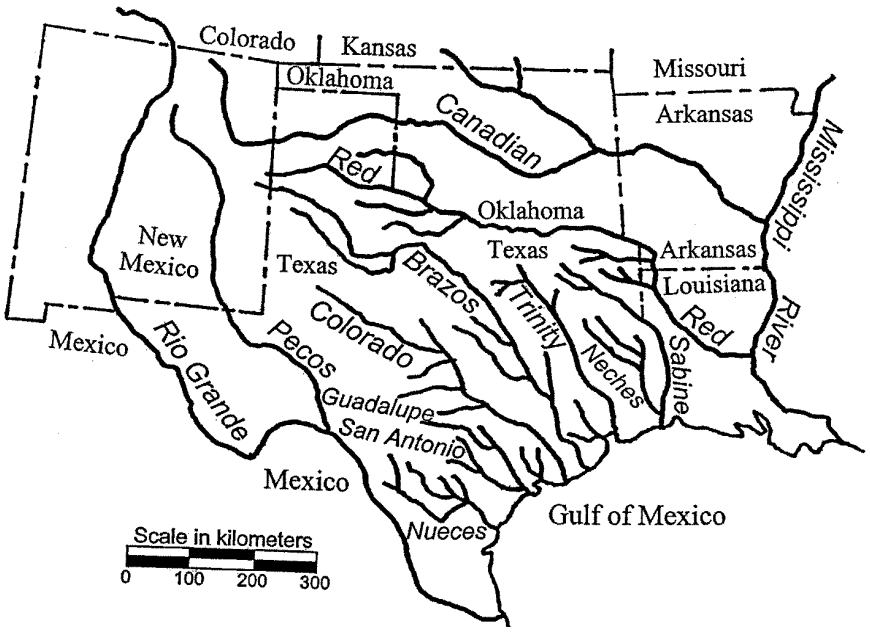

Fig. 2. Major Rivers of Texas

reservoir storage. Basinwide impacts of water resources development projects and management practices are modeled. The public domain software and documentation (Wurbs 2009, 2010a, 2010b, 2010c, and Wurbs et al. 2010a) are available at the following website: http://ceprofs.tamu.edu/rwurbs/wrap.htm.

WRAP computer programs

WRAP is a set of executable programs developed in Fortran. WinWRAP is a user interface for executing the programs on microcomputers within Microsoft Windows®. WinWRAP provides the model-user an environment in which to manage data files and WRAP programs and connect with other software.

Program HYD is a set of routines for converting sequences of monthly gaged streamflows to naturalized flows and compiling sets of monthly net reservoir evaporation less precipitation depths. HYD output consists of hydrology input for SIM. Recently added HYD features are designed to apply procedures, discussed later, for developing condensed datasets.

Program SIM performs the conventional river/reservoir/use system water allocation simulation using a monthly time step. SIMD (D for daily) is a recently expanded version of SIM with submonthly time step, flow forecasting, routing, and flood control simulation features. Program SALT reads a SIM output file and salinity input file and tracks salt loads and concentrations through a river/reservoir system.

Program TABLES organizes the SIM, SIMD, and SALT simulation results and develops frequency relationships, reliability indices, and summary statistics. TABLES organizes simulation results into a variety of user-defined tables and also provides convenient export to Microsoft Excel® or HEC-DSSVue (USACE 2005). WRAP Display is an ArcGIS®-based tool for spatially displaying simulation results (CRWR 2007).

WRAP simulation

WRAP-SIM simulation computations are performed in a water rights priority loop that is embedded within a monthly time-step loop. The WAM System input datasets reflect a monthly interval though the new SIMD also allows a daily or other submonthly computational time step. SIM model execution begins with reading and organizing input data. Water rights are sorted into priority order based on priority numbers and/or other user-defined options. The simulation steps through time. Naturalized flows for primary control points and net evaporation rates for reservoirs are read from the FLO and EVA files. Flows are distributed from primary control points to all other sites based on watershed parameters read from the DIS file. Within each sequential month, water accounting computations are performed as each set of water use requirements (water right) from the DAT file is considered in priority order.

Water allocation and management are modeled by accounting procedures within the water rights priority sequence. An array is maintained of streamflow available for appropriation at all control points. The following tasks are performed as each water right is considered in priority order:

- The diversion, instream flow, or hydropower target is set starting with an annual amount and set of 12 monthly distribution factors provided as input. The target may be further modified as a function of the storage content in any number of specified reservoirs and naturalized, regulated, or unappropriated flow at any control point.
- The amount of water available to the water right from streamflow is determined based on the available streamflow array considering the control point of the water right and all downstream control points.
- Water use requirements are met subject to water availability following specified system operating rules. Water accounting computations are performed to determine the diversion, diversion shortage, end-of-month storage, and related quantities. Reservoirs and hydropower plants necessitate an iterative algorithm since evaporation and hydropower releases are a function of both beginning-of-month and end-of-month storage.
- The available streamflow array is adjusted for that location and all downstream sites to reflect the effects of the water right. Channel loss factors are applied in translating adjustments for streamflow depletions and return flows to flows at downstream sites. Within the priority sequence, the available flow array is used to determine the amount of water available to each individual right. At the end of the month, the available flow array is used to determine regulated and unappropriated flows.

Simulation results consist of time series of the variables computed in the simulation covering the period-of-analysis. The model-user selects the control points, water rights, and reservoirs for which simulation results are recorded. Variables written to the main output file include but are not limited to

- naturalized, regulated, and unappropriated flows, streamflow depletions, and return flows for each selected control point
- channel losses and channel loss credits for each selected control point representing the reach below the control point
- storage, net evaporation, inflows, releases, diversions, and hydroelectric energy at each selected reservoir
- diversion targets and shortages, return flows, available streamflows, streamflow depletions, and storage for each selected water supply right
- hydropower targets, firm energy produced, secondary energy produced, energy shortages, and storage for each

selected hydroelectric power right
- instream flow target and shortage for each selected instream flow right

WRAP includes the post-simulation program TABLES that organizes simulation results in various user-specified formats, including time series of selected variables, water budgets, statistical summaries, and various types of frequency relationships, statistics, and reliability indices. Tables may be created in a format for incorporation in reports. Alternatively, data may be organized in formats convenient for export to Microsoft Excel or HEC-DSSVue.

Forms of streamflow in WRAP

The WRAP modeling process consists of a series of adjustments to streamflow sequences covering the hydrologic period-of-analysis. The Texas WAM System reflects simulation periods that range from 50 to 60 years for the various river basins listed in Table 1 and a monthly time step. The procedure for converting a WAM dataset to a condensed dataset adds another set of flow adjustments. In a condensed dataset, an adjusted set of inflows replaces the naturalized flows described below. The distinction between regulated and unappropriated flow is important in the development and application of condensed datasets.

A WRAP-SIM simulation begins with naturalized flows. In general, the terms *naturalized* or *unregulated* refer to sequences of past streamflows adjusted to represent a specified condition of river basin development that includes either no human impact or some defined level of development. For the Texas WAM System, naturalized flows ideally are river flows that would have occurred historically, in the absence of the water management activities reflected in the water rights input data, but with all other aspects of the river basin reflecting constant present conditions.

Regulated and unappropriated flows computed by SIM reflect adjustments to naturalized flows for water right requirements representing a specified scenario of water resources development and use. Regulated flows are physical flows considering all water rights in the input dataset. Unappropriated flows are available for further appropriation after all the water rights receive their allocated share. Regulated flow in a particular month at a particular control point is never less than the corresponding unappropriated flow but may be greater than the unappropriated flow due to instream flow requirements at the site or commitments to other water rights at downstream control points.

The adjustments that convert naturalized flows to regulated flows include both streamflow depletions and return flows. Streamflow depletions are the quantities of water appropriated to meet water supply diversion requirements and refill reservoir storage. Return flows are added back to streamflows. Channel losses are considered as SIM streamflow adjustments are cascaded downstream.

New WRAP modeling capabilities

The WRAP modeling capabilities that are routinely applied with the TCEQ WAM System consist of using a hydrologic period-of-analysis of about 50 to 60 years and a monthly computational time step to perform water availability and reliability analyses for municipal, industrial, and agricultural water supply; environmental instream flow; hydroelectric power generation; and reservoir storage requirements. The modeling capabilities currently being routinely applied are documented by Wurbs (2010a, 2010b, and 2010c). Work has been underway for several years on the following new and expanded WRAP modeling capabilities that are becoming operational during 2009 and 2010 (Wurbs 2009, Wurbs et al. 2010a):

- features incorporated in the WRAP programs HYD and SIM for developing and applying condensed datasets as described by this paper
- features incorporated in HYD for extending the hydrologic period-of-analysis
- short-term conditional reliability modeling, which provides estimates of the likelihood of meeting water right requirements and maintaining reservoir storage levels during time periods of one month to several months to a year or perhaps longer into the future, given preceding reservoir storage contents
- daily time-step modeling capabilities that include flow forecasting, flow routing methods, disaggregation of monthly water supply and instream flow targets to daily targets, and disaggregation of monthly naturalized flows to daily flows
- simulation of flood control reservoir system operations
- salinity simulation motivated by natural salt pollution in several Texas river basins

METHODOLOGY FOR DEVELOPING A CONDENSED DATASET

Wurbs and Kim (2008) document the development and application of procedures for (1) extending WAM datasets to cover a longer hydrologic period-of-analysis and (2) condensing WAM datasets to focus on a particular water management system while reflecting the effects of all other water rights in the streamflow inflows. Both of these two very different tasks are based on new features in which the program HYD develops a program SIM streamflow input file based on SIM simulation results. The procedures were applied to the WRAP input dataset for the Brazos River Basin from the TCEQ WAM System. The modeling methods developed are applicable to other river

basins as well.

The WAM System datasets for the larger river basins listed in Table 1 contain hundreds of water rights, control points, and reservoirs. These voluminous datasets are necessary to support administration of the water rights permit system by the TCEQ and planning studies conducted by the TWDB and regional planning groups. The datasets are necessarily complex to serve the original purposes for which the WAM System was developed. However, the modeling system is being used in an expanding range of different types of applications. Condensed datasets are advantageous for certain types of applications.

A methodology is presented by Wurbs and Kim (2008) for simplifying WAM System datasets to focus on management of a particular river/reservoir system. Selected water rights, control points, and reservoirs are removed with their effects retained in the adopted stream inflow input data for the condensed dataset. A much simpler dataset is developed for purposes of studying or providing decision support for a particular reservoir/river water management system. WRAP input datasets and corresponding simulation results with dramatically fewer control points, water rights, and reservoirs are much more manageable to use in modeling studies. However, the interactions between numerous water users and water control facilities in a river basin should be preserved in the model. The condensed model allows alternative operating plans for the primary water management system to be simulated based on the premise of assuring appropriate protection of all other water rights.

Development of a condensed dataset serves two purposes. Firstly, the condensed dataset is much easier to apply in certain types of studies focused on a particular water management entity. Secondly, the entity of interest can be segregated and managed in various ways in the WRAP-SIM simulation model while allowing the entity access to only river flows legally available to it considering all other water right permit holders in the river basin.

The accuracy achieved in the development of a condensed dataset is checked by comparing SIM simulation results with the condensed versus original complete dataset. The water supply reliabilities computed for the diversions included in the condensed model should be the same as in the simulation with the original complete dataset. Likewise, the sequences of monthly storage volumes at the common reservoirs and unappropriated streamflows at the common control points will be the same. Near perfect correspondence between simulation results with the condensed versus complete datasets should be expected.

The selected water rights and reservoirs from the complete TCEQ WAM System DAT file that are retained in the condensed DAT file are called the primary system. After creating a condensed dataset, comparing complete TCEQ WAM System versus condensed model simulation results for the primary system reservoirs and water rights requires minimal time and effort. Verifying the condensed dataset is easy and precise. After the development and verification of the condensed WRAP input dataset, then applications of the condensed model may include any number of alternative simulations that reflect different water demands, modified reservoir system operating plans, and other changes in water management strategies associated with the primary system.

Water Rights (DAT) and Hydrology (FLO and EVA) files

A condensed WRAP-SIM input dataset (DAT, FLO, and EVA files) is created by reducing the number of control points, water rights, and reservoirs in a TCEQ WAM System dataset and thus simplifying the modeling system for certain applications. A SIM water rights DAT file for the particular river/reservoir water management and use system of interest, called the primary system, is developed along with a FLO file containing river system inflows that have been adjusted to reflect all other water rights in the original complete WAM dataset, which are referred to as secondary water rights. The effects of the water rights, control points, and reservoirs that are removed from the original WAM DAT file are maintained in the stream inflow input data (FLO file) for the condensed dataset. The condensed dataset also includes an EVA file containing the same net reservoir evaporation-precipitation rates as used with the complete WAM dataset with the same adjustments.

The methodology for creating a condensed WRAP input dataset from a TCEQ WAM System dataset is based on developing flows at selected control points that represent stream inflow amounts available to the selected primary system. These river flows recorded in the condensed dataset FLO file represent flows available to the primary system modeled in the water right DAT file considering the effects of all the other water rights in the river basin contained in the original complete DAT file that are not included in the condensed DAT file.

The river system inflows in the FLO file for a condensed dataset include streamflow depletions made for the selected water rights less return flows plus unappropriated flows. Hydropower releases and reservoir releases made specifically to meet instream flow requirements are also properly incorporated in the flows. Summation and cascading operations, including channel losses, are applied in developing the FLO input file.

The primary system in the condensed DAT file has access only to the flows in the condensed FLO file, which consist of the monthly streamflows that the primary system appropriated in the complete TCEQ WAM System model plus unappro-

priated flows. Thus, all reservoir storage, water supply diversions, return flows, instream flow requirements, subordination agreements, and other water allocation, control, management, and use associated with the secondary system are reflected in the streamflows incorporated in the FLO file of the condensed dataset.

The methodology for developing the sequences of monthly streamflow volumes and net evaporation-precipitation depths (FLO and EVA files) for a condensed dataset is outlined as follows:

1. The WRAP simulation program SIM is executed with the original complete dataset.
2. Program HYD is used to retrieve the adjusted net evaporation-precipitation depths from the SIM output file and store them in an EVA file for the condensed dataset.
3. HYD is applied to read streamflow depletions, return flows, unappropriated flows, and other pertinent variables from the SIM output file and combine these variables as required to develop the streamflow FLO file for the condensed dataset. Combining the time sequences of flow volumes includes summations and cascading operations that may include channel losses.

The accuracy of the procedure is confirmed by reproducing the sequences of monthly water supply diversions, reservoir storage contents, unappropriated flows, and other pertinent variables contained in the SIM simulation results associated with the primary system reservoirs, diversions, and control points. These SIM simulation results should be same with the condensed dataset versus the original complete dataset. The primary system reservoirs and diversions must be operated the same in both the condensed and complete datasets for the comparison simulations. After completing the comparison to confirm that the dataset is correct, the condensed dataset can be used to simulate alternative river/reservoir system operating rules and water management and use scenarios for the primary system.

Regulated-Unappropriated Flow (RUF) File

With the exception of naturalized and regulated flows, all the variables in the SIM input and simulation results are defined the same in condensed and complete models. However, the regulated flows computed by SIM are defined differently. The optional RUF file described below is needed only for those applications in which knowing the actual regulated flows is important.

The unappropriated streamflows computed by SIM are the

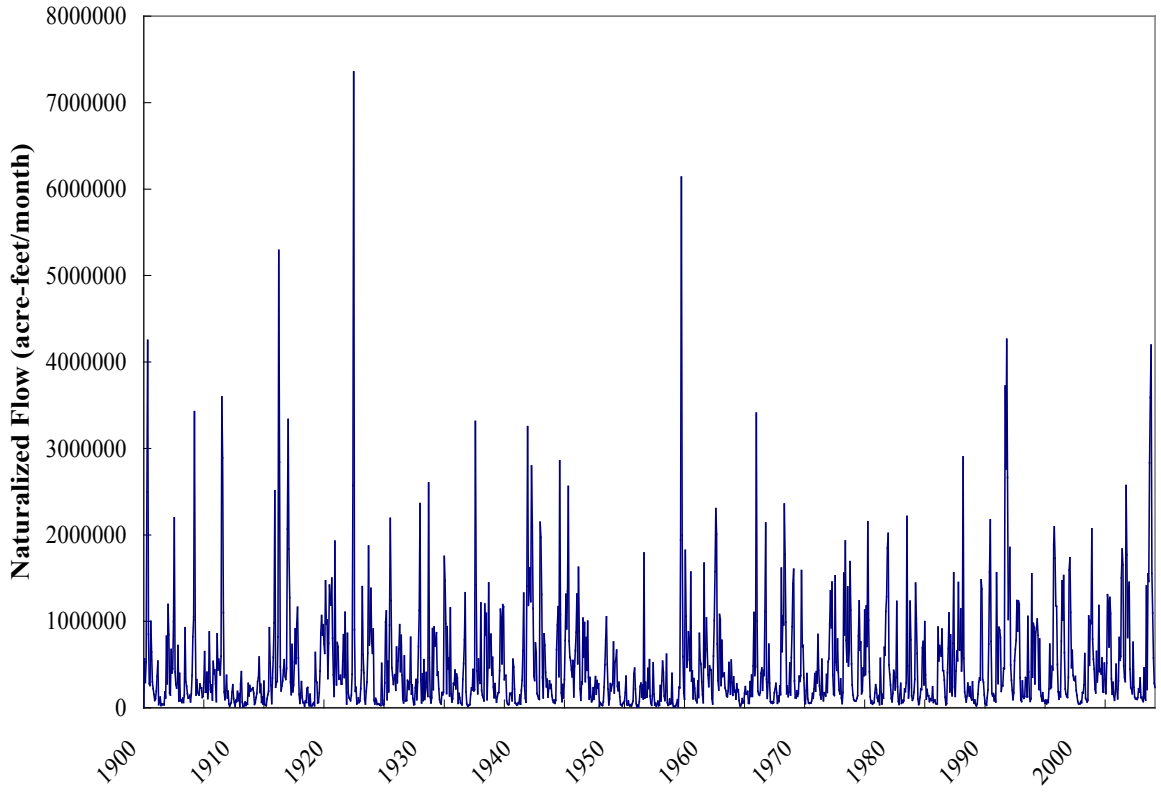

Fig. 3. Naturalized Flows at the Richmond Gage on the Brazos River

same with either a condensed or a complete WAM input dataset. However, the naturalized and regulated flows are defined differently. The streamflows in the FLO file of the original WAM dataset are naturalized flows. However, the streamflows in the FLO file of the condensed dataset are flows reflecting the effects of all of the water rights in the river basin that are not included in the DAT file of the condensed dataset. With a complete dataset, the regulated flows computed by SIM represent the actual flows at a site on a river. With a condensed input dataset, the regulated flows computed by SIM represent the flows that remain unaffected by the water rights omitted from the DAT file.

The basic condensed dataset methodology focuses on unappropriated river flows rather than regulated flows. However, a regulated-unappropriated flow (RUF) file with filename extension RUF may be created using program HYD. A RUF file contains deviations between regulated and unappropriated flows from the simulation results for the original dataset that are used within a SIM simulation with a condensed dataset to estimate regulated flows based on adjusting unappropriated flows.

The RUF file and accompanying flow adjustment options are not needed in various applications in which regulated flows are not of concern. However, the estimates of regulated flows provided by the RUF options may be required in applications for which environmental instream flow requirements or flood control operations are included in the condensed DAT file. A RUF file is not necessarily required if all instream flow requirements and flood control operations are associated with only the secondary system. Salinity simulations require a RUF file. Also, a RUF file may be useful simply to provide general information regarding river flows.

The regulated-unappropriated flow RUF file contains the differences between the regulated flows less unappropriated flows from the simulation results of the original complete dataset. These data are used to perform flow adjustments that allow conventionally defined regulated flows to be included in the SIM simulation results for the condensed dataset.

Incorporation of regulated flows, as normally defined in WRAP-SIM simulations, into a condensed model using the RUF file feature is complicated by the differences between regulated and unappropriated flows being caused by both secondary (FLO file) and primary system (DAT file) water rights. The RUF file feature is necessarily approximate in certain situations because of the combined effects of secondary and primary water rights on river flows. SIM includes a set of options for creating and applying the RUF file adjustments in different situations.

Condensed WRAP input dataset

A condensed dataset consists of required DAT, FLO, and EVA files and an optional RUF file. The DAT file contains the information that describes the primary system water rights including reservoirs, water supply diversions, return flows, instream flow requirements, and other features of water rights. The DAT file water rights may be modified in various ways during studies that apply the condensed dataset. However, only the streamflows recorded in the FLO file are available to the primary system described in the DAT file. The optional RUF file contains adjustments used by SIM to estimate regulated flows based on simulated unappropriated flows. Reservoir surface net evaporation less evaporation rates are contained in the EVA file.

BRAZOS RIVER AUTHORITY SYSTEM CONDENSED MODEL

The BRA sponsored development of the Brazos River Authority Condensed (BRAC) datasets designed to provide a much simpler model that facilitates operational planning studies and other decision support endeavors for the BRA reservoir system (Wurbs and Kim 2008). Alternative versions of the BRAC model were developed for the authorized use and current use scenarios with hydrologic periods-of-analysis of 1900–2007 and 1940–2007 by condensing the TCEQ WAM System authorized use and current use datasets for the Brazos River Basin and San Jacinto-Brazos Coastal Basin, referred

Table 2. Size of Brazos WAM and Condensed Datasets

Complete WAM versus Condensed Water Use Scenario	Brazos WAM		Condensed	
	Authorized	Current	Authorized	Current
Number of primary control points	77	77	48	48
Number of secondary control points	3,753	3,757	0	0
Number of WR record water rights	1,634	1,725	114	112
Number of instream flow rights	122	144	0	0
Number of reservoirs	670	711	15	14

to here as the Brazos WAM. The Brazos WAM has a hydrologic period-of-analysis of 1940–1997, which was extended to 1900–2007 by Wurbs and Kim (2008). The 1900–2007 monthly naturalized flows at the U.S. Geological Survey (USGS) gaging station on the lower Brazos River near Richmond are plotted in Fig. 3.

The condensed datasets are useful for a broad spectrum of different types of WRAP-based studies and decision-support activities. For example, Wurbs and Lee (2009) applied the BRAC datasets in a study of the effects of natural salt pollution in the Brazos River Basin. Unlike the application noted below, the salinity study required the use of the RUF file.

The BRA is currently sponsoring conditional reliability modeling studies that use the BRAC datasets to develop storage frequency statistics for individual reservoirs and groups of reservoirs for storage at various times over the period of a year, given specified initial preceding storage levels (Wurbs et al. 2010b). One of the several variations of the model used in these analyses consists of a version of the BRAC dataset described as follows. The BRAC DAT file developed based on the TCEQ WAM System current use scenario dataset is further adjusted to reflect actual water use and system operations during the relatively dry year 2008. The resulting DAT file is combined with condensed FLO and EVA files developed from the TCEQ WAM System authorized use scenario dataset. Thus, the primary system is operated based on year 2008 water demands based on the premise that all water rights included in the secondary system appropriates the full amounts authorized in their water right permits. With the focus on developing storage statistics, the RUF file was not needed for this particular application.

Brazos River Basin

The 45,600-square-mile Brazos River Basin extends from New Mexico southeasterly across Texas to the Gulf of Mexico as shown in Fig.s 1 and 2. The upper extreme end of the basin in and near New Mexico is an arid flat region that rarely contributes to streamflow. Climate, vegetation, topography, land use, and water use vary greatly across the basin. Mean annual precipitation varies from 16 inches in the upper basin in the High Plains to over 50 inches in the lower basin in the Gulf Coast Region.

More than 1,000 water districts, cities, companies, and individuals hold water right permits to use the waters of the Brazos River and its tributaries. Based on the Brazos WAM, water rights associated with the 13 reservoirs shown in Fig. 4 account for 74% of the conservation storage capacity of the 711 permitted reservoirs and 33% of the permitted annual water supply diversion volume in the basin. The BRA owns and operates Possum Kingdom, Granbury, and Limestone

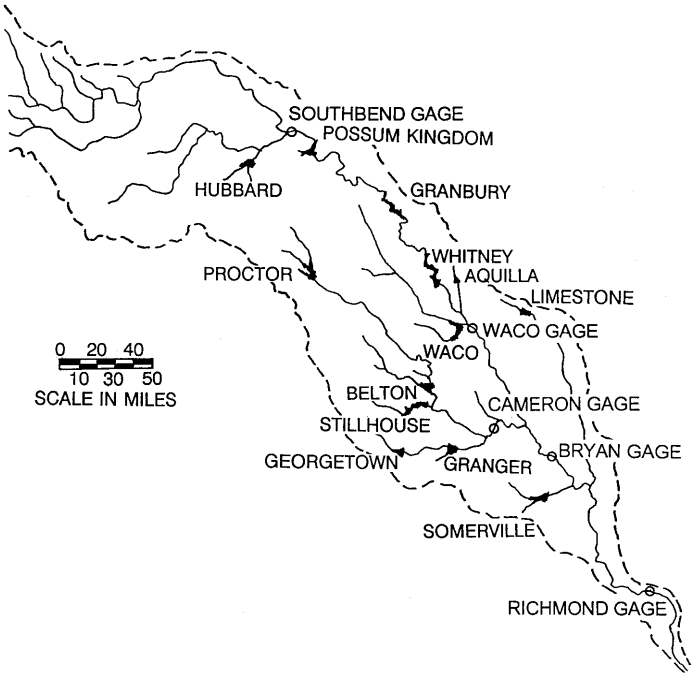

Fig. 4. Brazos River Basin

reservoirs and has contracted with the U.S. Army Corps of Engineers for the conservation storage capacity of nine federal multiple-purpose reservoirs. A significant portion of the water diverted from the Brazos River is actually used in the adjoining San Jacinto-Brazos Coastal between the City of Houston and Galveston Bay.

Brazos River Authority Condensed (BRAC) Datasets

The large complex Brazos WAM dataset is necessary for the planning and water right permitting applications for which the WAM System was developed. However, a much simpler model focused on the BRA reservoir system facilitates BRA operational planning studies. Wurbs and Kim (2008) developed and applied a methodology for simplifying WAM System datasets to focus on management of a particular reservoir system. Selected water rights, control points, and reservoirs are removed with their effects retained in the adopted stream inflow input data file for the condensed dataset. The BRAC datasets developed based on modifying the Brazos WAM authorized use scenario and current use scenario datasets contain 48 primary control points and no secondary control points. BRAC authorized use and current use scenario datasets contain 15 and 14 reservoirs, respectively, with a permitted but not constructed project included in the authorized but not the current scenario. The stream inflows at the 48 control points reflect the effects of the numerous water rights, reservoirs, and control points removed from the Brazos WAM dataset.

The relative size of the Brazos WAM versus BRAC data-

sets is compared in Table 2. The Brazos WAM authorized use scenario dataset contained 1,634 water right *WR* records, 122 instream flow records, 670 reservoirs, and 3,830 control points, as of 2009. The Brazos WAM current use dataset is slightly larger. Naturalized flows are input in a FLO file for 77 primary control points and distributed within SIM to the other ungaged secondary control points as specified by 3,138 flow distribution records in a DIS file.

The condensed datasets designed to focus on operation of the BRA reservoir system include the 15 largest reservoirs in the river basin and associated water rights (Wurbs and Kim 2008). The 15 reservoirs include one proposed (Allen's Creek Reservoir), 12 existing BRA reservoirs, and two other reservoirs (Hubbard Creek and Squaw Creek reservoirs). The proposed Allen's Creek Reservoir is included in the authorized use scenario but is not included in the current use scenario. The 12 BRA reservoirs shown in Fig. 4 include Possum Kingdom, Granbury, and Limestone reservoirs owned by the BRA and nine federal multiple-purpose reservoirs owned by the U.S. Army Corps of Engineers for which the BRA has contracted for the water supply storage capacity. The condensed dataset has 48 primary control points and no secondary control points. With no secondary control points, there is no flow distribution DIS file. The impacts of the 655 reservoirs and numerous water rights removed from the Brazos WAM dataset are reflected in the FLO file river flows developed for the condensed SIM input dataset.

The condensed datasets were developed using the WRAP programs SIM and HYD as outlined earlier in this paper. The resulting BRAC datasets consist of SIM input files with filename extensions DAT, FLO, EVA, and RUF. Four versions of the condensed datasets were initially developed representing authorized use and current use scenarios of water resources development and management and 1900–2007 and 1940–2007 hydrologic periods-of-analysis. The condensed dataset DAT files continue to be modified for particular studies as previously noted. The SIM input files comprising the basic condensed datasets are described as follows:

- The authorized use and current use DAT files contain water rights and related information for 15 and 14 reservoirs, respectively, and associated water supply diversions. This information was excerpted from the Brazos WAM DAT files. All but 48 of the original 3,800 control point records are omitted. Thus, the next downstream control point identifiers and channel loss factors are modified for the adopted 48 control points.
- FLO files with alternative 1940–2007 and 1900–2007 sets of monthly flows at 48 control points represent conditions of river system development that include all of the water rights and associated reservoirs in the original complete Brazos WAM DAT files except the 15 reservoirs and associated diversions contained in the condensed DAT files.
- EVA files contain alternative 1940–2007 and 1900–2007 sets of monthly net evaporation-precipitation depths for the 15 reservoirs. Adjusted net evaporation-precipitation depths are obtained from the SIM output OUT file.
- RUF files contain alternative 1940–2007 and 1900–2007 sets of differences between the regulated flows less unappropriated flows from the SIM output file for complete Brazos WAM simulation. The optional RUF files allow conventionally defined regulated flows to be included in the BRAC simulation results.

The DAT files for the condensed datasets are developed by excerpting pertinent water rights and associated data records from the original DAT file, excerpting pertinent records providing reservoir data, and modifying remaining control point records to reflect removal of many of the control points. With removal of control points, channel loss factors for the stream reaches removed are aggregated for the combined longer reaches between the remaining control points. Various other organizational refinements have no effect on simulation results.

A number of the water rights included in the BRAC datasets have diversion return flows that are returned back to the river in the Brazos WAM dataset at control points that have been removed in the BRAC datasets. The return flows are returned in the BRAC dataset at the next downstream control point that was not removed. Channel losses associated with the return flows may be affected. The decrease in channel loss could be offset by increasing the return flow factor. However, this ploy was not applied for the Brazos since the impacts on channel losses of reassigning return flow locations were negligible.

The condensed dataset should adopt the same net evaporation-precipitation depths for the 15 reservoirs as used in the original complete dataset SIM simulation. SIM includes a routine for adjusting net evaporation-precipitation depths for the precipitation runoff from the portion of the watershed inundated by the reservoir. Therefore, net evaporation-precipitation depths are obtained from the output file for the complete simulation rather than using the original evaporation-precipitation depth input dataset.

River flows developed for the 48 BRAC control points consist of 1940–2007 or 1900–2007 sequences of monthly volumes of the following variables obtained from the simulation results output file created by SIM with the original complete input dataset. The computations are performed with HYD.

- Streamflow depletions made by each of the water rights associated with the 15 reservoirs are included in the flows being developed. These flow volumes are placed at the control point of the streamflow depletion and at all downstream control points. Channel losses are con-

Table 3. Comparison of Means of Flows in FLO Input

USGS Gaging Station	Brazos WAM	Condensed Datasets	
		Authorized	Current Use
	(ac-ft/yr)		
Cameron gage on Little River	1,318,302	81.5%	83.9%
Waco gage on Brazos River	1,942,324	85.6%	87.5%
Richmond gage on Brazos River	5,850,224	77.8%	78.2%

sidered in cascading the streamflow depletions downstream.

- Return flows from the diversion component of the streamflow depletions are subtracted from the flows. These flow volumes are placed at the control point at which the return flow is returned to the stream and at all downstream control points. Channel losses are considered in cascading the return flows downstream.
- Unappropriated flows at each of the control points are added to the flows. Since unappropriated flows are cumulative total flows, these flows are not cascaded downstream.
- Any releases from the 15 selected reservoirs made specifically for instream flow requirements are subtracted at the control point of the reservoir and cascaded downstream in the normal manner, which includes consideration of channel losses.

The BRAC inflows are the portion of the naturalized flows still available to the primary system water rights after the secondary water rights have appropriated their appropriate quantities of the streamflow. Naturalized flows are the same in the authorized use and current use scenario versions of the complete WAM dataset but differ in the condensed datasets. The 1940–1997 means are compared in Table 3 for three of the gaging station locations shown in Fig. 4. The 1940–1997 means of the Brazos WAM naturalized flows at the three control points are tabulated in ac-ft/yr. The corresponding 1940–1997 means of the inflows in the FLO files of the condensed inflows are shown in Table 3 as a percentage of the Brazos WAM naturalized flows. At the Richmond gage control point, the mean FLO file inflows for the authorized use and current use scenarios are 77.8% and 78.2% of naturalized flows.

SUMMARY AND CONCLUSIONS

The TCEQ Water Availability Modeling (WAM) System has significantly contributed to water management in Texas over the past several years. Capabilities are provided for assessing institutional as well as hydrologic water availability and supply reliability. The modeling system supports preparation and evaluation of water right permit applications, regional and statewide planning studies, and various other water management activities.

The primary reason for developing condensed datasets is to provide a much simpler model that can be conveniently and effectively applied in studies dealing with a particular river/reservoir water management system. Condensed datasets also provide a mechanism for allocating water between a primary system of concern and all of the other water rights in the river basin that can be useful in certain types of modeling applications.

The control points, reservoirs, and water rights included in a condensed dataset are called the primary system. The control points, reservoirs, and water rights that are not included in the primary system comprise the secondary system. The effects of all secondary water rights on river flows available to primary water rights are reflected in the inflow streamflows. The inflows provided in the flow input file of a WAM System dataset are naturalized flows. The inflows contained in the flow file of a condensed dataset represent the river flows available to the primary system considering all the other secondary water rights.

REFERENCES

Alexander Martin K and Chenoweth T. 2009. Determining surface water availability. In: Sahs MK, editor. Essentials of Texas Water Resources. Austin: State Bar of Texas, TexasBarBooks Department. p. 213-222.

[CRWR] Center for Research in Water Resources (TX). 2007. WRAP display tool, users manual and operating instructions. Prepared for the Texas Commission on Environmental Quality, University of Texas at Austin, Austin, Texas.

HDR Engineering, Inc. 2001. Water availability in the Brazos River Basin and the San Jacinto-Brazos Coastal Basin Prepared for Texas Natural Resource Conservation Commission, Austin, Texas.

Wurbs RA. 2004. Water allocation systems in Texas. International Journal of Water Resources Development. 20(2):229-242.

Wurbs RA. 2005. Texas Water Availability Modeling System. Journal of Water Resources Planning and Management. 13(2):270-279.

Wurbs RA. 2009. Salinity simulation with WRAP. College Station: Texas A&M University System, Texas Water Resources Institute. Technical Report-317. 84 p.

Wurbs RA. 2010a. Reference manual for the Water Rights Analysis Package (WRAP) Modeling System. 7th ed. College Station: Texas A&M University System, Texas Water Resources Institute. Technical Report-255. 320 p.

Wurbs RA. 2010b. Users manual for the Water Rights Analysis Package (WRAP) Modeling System. 7th ed. College Station: Texas A&M University System, Texas Water Resources Institute. Technical Report-256. 207 p.

Wurbs RA. 2010c. Fundamentals of water availability modeling with WRAP. 5th ed. College Station: Texas A&M University System, Texas Water Resources Institute. Technical Report-283. 99 p.

Wurbs RA. Hoffpauir RJ, Olmos, HE, Salazar AA, Kim TJ, and Schnier ST. (2010a). Conditional reliability, submonthly time step, and flood control features of WRAP. College Station: Texas A&M University System, Texas Water Resources Institute. Technical Report-284. 242 p.

Wurbs RA, Hoffpauir RJ, and Schnier ST. (2010b). Application of expanded WRAP modeling capabilities to the Brazos WAM. College Station: Texas A&M University System, Texas Water Resources Institute. Technical Report-389.

Wurbs RA, Kim TJ. 2008. Extending and condensing the Brazos River Basin Water Availability Model. College Station: Texas A&M University System, Texas Water Resources Institute. Technical Report 340. 493 p.

Wurbs RA, Lee CH. 2009. Salinity budget and WRAP salinity simulation studies of the Brazos River/Reservoir System. College Station: Texas A&M University System, Texas Water Resources Institute. Technical Report-352. 327 p.

[USACE] U.S. Army Corps of Engineers. 2005. HEC-DSSVue HEC Data Storage System Visual Utility Engine, User's Manual. CPD-79, Davis (CA): Hydrologic Engineering Center. 490 p.