Simulation Modeling of River/Reservoir System Water Allocation and Management

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Introduction

The Water Rights Analysis Package (WRAP) is a generalized modeling system for simulating and analyzing water resources development, management, allocation, and use in river basins located anywhere in the world. WRAP is designed for assessing reliabilities in meeting water supply, hydroelectric power, and environmental flow needs. Reservoir operations for flood control can also be simulated. The modeling system is routinely applied in Texas in the United States to support administration of water allocation systems, regional and statewide planning, and other water management activities. The Texas Water Availability Modeling (WAM) System consists of WRAP and input datasets for all the river basins of the state. WRAP has also been applied in several other countries but not to the extent as in Texas. WRAP capabilities continue to be expanded to address an expanding range of water management concerns.

Effective water management requires an understanding of the amount of water available at various levels of reliability under various conditions. Water availability depends upon river basin hydrology, constructed facilities, institutional water allocation systems, management practices, and the characteristics of water demands. Hydrology in Texas and elsewhere is characterized by great variability including extremes of severe droughts and floods. Thus, the availability of stream flow and reservoir storage and associated water supply capabilities must be expressed in terms of flow and storage frequency and supply reliability.

The modeling strategy implemented in WRAP consists of simulating a specified scenario of water resources development, management, and use during a postulated repetition of natural river basin hydrology. Reliability and frequency metrics are developed from the results of the simulation. The system being simulated may range in complexity from a single water user supplied by a single reservoir to complex systems of numerous multiple-purpose reservoirs and water users. Long-term reliability and frequency analyses may be performed in planning studies and evaluating water right permit applications. Short-term reliability and frequency analyses support drought management, including water allocation, and operational planning studies.

The published and unpublished literature on modeling and analysis of river/reservoir systems is massive and complex. Wurbs (1996 and 2011) reviews the literature and compares WRAP and other similar generalized surface water management modeling systems.

Water Rights Analysis Package (WRAP) Modeling System

Development of WRAP at Texas A&M University began in the late 1980's sponsored by a cooperative research program of the U.S. Department of the Interior and Texas Water Resources Institute (TWRI). WRAP has been greatly expanded since 1997 under the auspices of the Texas Commission on Environmental Quality (TCEQ) in conjunction with implementing a statewide Water Availability Modeling (WAM) System. The Texas Water Development Board (TWDB),

U.S. Army Corps of Engineers, and other agencies have also sponsored improvements to WRAP. The TCEQ continues to sponsor further expansions and refinements to WRAP. The software and documentation are available free-of-charge. The modeling system is documented by a set of manuals published as TWRI technical reports (Wurbs 2009, 2013a, 2013b, 2013c, 2013d; Wurbs and Hoffpauir, 2013) available at the TWRI website (http://twri.tamu.edu). The software and manuals are available at the author's WRAP website (http://ceprofs.tamu.edu/rwurbs/wrap.htm). The TCEQ maintains a WAM website with information about application of WRAP in Texas along with WRAP input datasets for all the river basins of Texas.
http://www.tceq.state.tx.us/permitting/water_rights/wam.html

WRAP Modeling and Analysis Capabilities

WRAP simulates capabilities of river/reservoir systems in meeting specified water management and use requirements for sequences of naturalized stream flows and reservoir net evaporation less precipitation rates. Water management is combined with natural hydrology. Water managers are concerned with future not past hydrologic conditions. However, since the future is unknown, historical hydrology is used to capture the hydrologic characteristics of a river basin. The water management and use scenario might be actual current water use, projected future conditions, the premise that all permit holders use their full authorized amounts, or some other scenario of interest. Interactions between numerous water users, diverse types of use, and complex water management strategies can be modeled. Optional auxiliary WRAP features include simulating salinity. Simulation results are organized in a variety of formats including time series tabulations and plots, summary tables, water budgets, frequency relationships, and various types of reliability indices.

In the conventional long-term simulation mode, a specified water management/use scenario is combined with naturalized flows and net reservoir evaporation rates covering the entire hydrologic period-of-analysis in a single simulation. In the short-term conditional reliability modeling mode, the period-of-analysis hydrology is divided into many sequences, and the simulation is automatically repeated with each hydrologic sequence starting with the same specified initial storage condition (Wurbs et al, 2012). For example, a 1940-2014 hydrologic period-of-analysis is divided into 75 annual simulation sequences. Short-term term water availability is conditioned upon preceding reservoir storage contents. The conventional long-term simulation mode supports planning studies and administration of the water rights permit system. The short-term analyses support drought management and operational planning.

WRAP and the Texas WAM System employ a monthly step time. However, recent versions of the modeling system also include capabilities for daily simulations (Wurbs and Hoffpauir, 2013a). The daily WRAP is applicable to all aspects of river/reservoir system management. However, its development has been motivated largely by the need for expanded capabilities for modeling environmental flow requirements and issues (Wurbs and Hoffpauir, 2013b). The WRAP daily modeling system includes the following additional features: disaggregation of monthly naturalized flows to daily; flow routing and forecasting; disaggregation of diversion, hydropower, and instream flow targets; simulation of pulse flow environmental flow requirements; and simulation of reservoir flood control operations. A daily simulation may include flood control operations of any number of reservoirs based on allowable flows at any number of downstream gauges. Flood control pools are emptied as quickly as feasible subject to making no releases that contribute to flows at downstream gauges exceeding allowable limits.

Input Data and Simulation Results

The spatial configuration of a river system is defined 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. Essentially any configuration of stream tributaries and conveyance systems may be modeled. There are no limits on the number of control points, reservoirs, or water rights that may be included in a dataset.

Hydrology input for the simulation model consists of sequences of naturalized stream flows at primary control points and net evaporation less precipitation rates for all reservoirs. Primary control points are locations, usually gauging stations, for which naturalized flows are provided in a simulation input dataset. Naturalized flows at secondary control points are computed during a simulation based on several alternative methods for transferring flows from gauged to ungauged sites. Flows may be distributed in proportion to drainage area with or without considering channel losses. WRAP includes another option based on the Natural Resource Conservation Service relationship between precipitation and runoff (Wurbs, 2013d). The hydrologic period-of-analysis should be sufficiently long, reflecting a full range of fluctuating wet and dry periods, to allow simulation results to be used to develop frequency relationships, reliability indices, and other statistics that characterize the water resources.

Observed historical stream flows are adjusted to develop a homogeneous set of flows representing a specified condition of river basin development. The extent of the adjustments varies depending on circumstances. For relatively undeveloped watersheds, little or no adjustments may be necessary. In extensively developed river basins, adjusting for the effects of all human activities is not feasible. Naturalized flows are typically developed by adjusting recorded flows at gauging stations to remove the impacts of major upstream reservoirs, diversions, return flows from surface and ground water sources, and possibly other factors. A watershed precipitation-runoff model may be used to develop adjustments for changes in land use and vegetative cover or to develop actual natural stream flows.

Channel losses are also included in modeling the effects of diversions, return flows, and reservoirs on stream flows at downstream locations. Channel losses may also be considered in distributing naturalized flows from primary to secondary control points.

Water resources development, management, allocation, regulation, and use requirements, policies, practices, and facilities are described in terms of water rights. WRAP provides flexibility for simulating complex system configurations and operations. Extensive improvements to the generalized modeling system were made in response to various situations encountered as each river basin was modeled for the Texas WAM System, providing flexibility needed to address diverse water management practices. Features for defining water use requirements and management practices in a simulation input dataset 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, stream flow, or other variables

- 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
- operating rules including multiple-reservoir system operations, multiple-purpose operations, multiple-owner reservoirs, off-channel storage, and constraints on depleting stream flows
- reservoir storage volume versus surface area and elevation relationships

Simulation results include time series of any 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. The 40 variables written to the main simulation results output file include but are not limited to:

- naturalized, regulated, and unappropriated flows, stream flow 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
- reservoir storage volume, surface elevation, net evaporation, inflows, releases, diversions, and hydroelectric energy generated at each selected reservoir
- diversion targets and shortages, return flows, available stream flows, stream flow depletions, and reservoir 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

The WRAP modeling system includes flexible comprehensive post-simulation capabilities for organizing simulation results in various user-specified formats including time series tabulations or plots of selected variables, water budgets, statistical summaries, and various types of frequency relationships and reliability indices.

Texas Water Availability Modeling (WAM) System

Texas is a large (685,000 km^2) state located in the south-central United States with climate and water management practices that are representative of both the drier western and wetter eastern regions of the country. Climate, geography, and water management vary dramatically across the state from the arid western desert to humid eastern forests, from sparsely populated rural regions to the metropolitan areas of El Paso, Dallas, Fort Worth, Austin, San Antonio, and Houston shown in Figure 1. Mean annual precipitation varies from 20 cm at El Paso on the Rio Grande to 142 cm in the lower Sabine River Basin at the state border with Louisiana. The population increased from 5.82 million people in 1930 to 25.4 million in 2010 and is projected to increase to 46.3 million by 2060 (Texas Water Development Board, 2012). Population and economic growth combined with depleting groundwater reserves have resulted in increasing demands on surface water resources throughout the state. Environmental flow needs are major concerns as well as municipal, industrial, and agricultural needs Wurbs (2014).

The Texas Commission on Environmental Quality (TCEQ), Texas Water Development Board (TWDB), their partner agencies, and contractors consisting of university researchers and consulting engineering firms implemented the original WAM System pursuant to comprehensive

water management legislation enacted by the Texas Legislature in 1997 (Wurbs, 2005). The modeling system is routinely applied by applicants, or their consultants, in preparation of water right permit applications and by TCEQ staff in evaluating the permit applications. The TWDB is the lead agency for regional and statewide planning studies that represent another major application of the WAM System. River authorities and other water management entities also apply the WAM System in endeavors not directly mandated by the TCEQ water rights permitting or TWDB planning programs. The WAM System supports a broad range of water management activities and helps to integrate these activities (Wurbs, 2014).
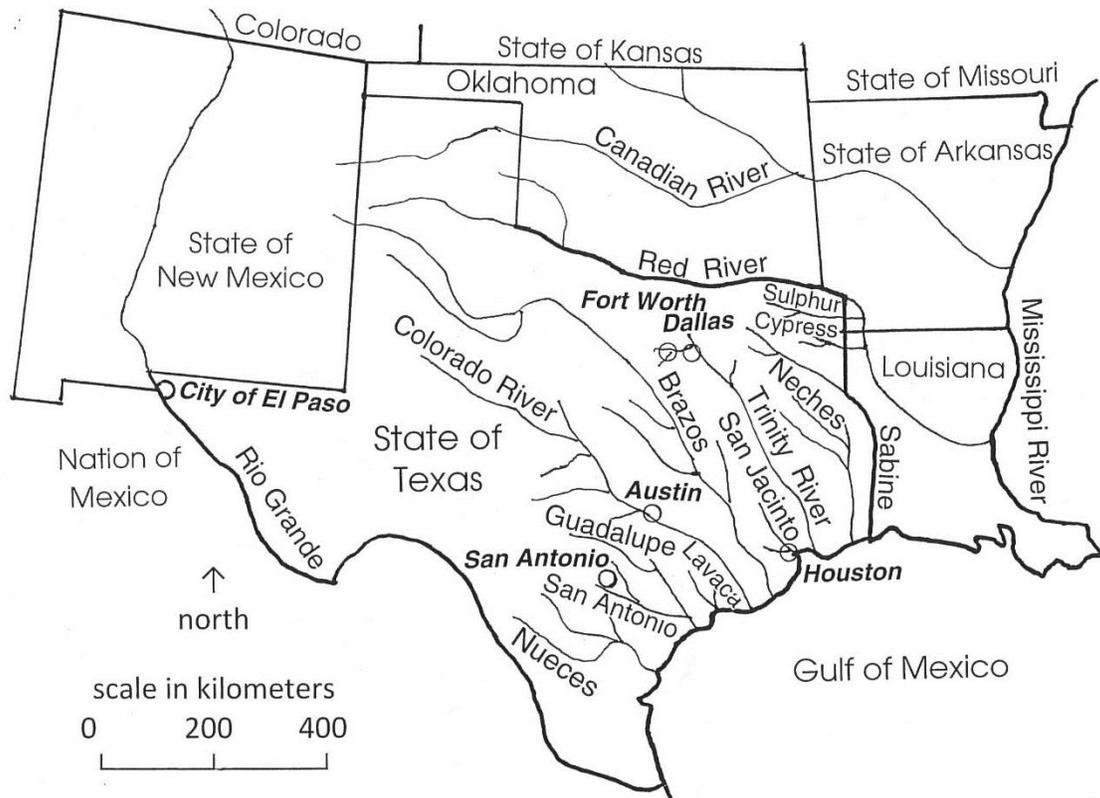
Figure 1. Major rivers and largest cities in Texas.

WRAP is generalized for application to river/reservoir systems located anywhere in the world, with model-users developing input datasets for the particular river basins of concern. In Texas, publicly available WAM System WRAP input datasets are altered as appropriate to reflect proposed water management plans of interest. The 15 major river basins and eight coastal basins of the state are modeled with the 20 datasets listed in Table 1 that include 3,400 reservoirs, water right systems with 6,000 water right permits, five interstate compacts, two treaties between the United States and Mexico, contacts for local use of water supply storage in federal reservoirs, and various other constructed facilities and institutional water allocation systems. The water rights permit system allocating the Texas share of the water resources of the Rio Grande Basin is very different than the water rights permit system for the remainder of the state. Wurbs and Zhang (2014) present summary results for WRAP/WAM simulations of all the river basins of Texas.

Table 1. River Basin Models in the Texas WAM System

Major River Basin or Coastal Basin	Area in Texas	Area Outside Texas	Number of WAM			Reservoir Storage Capacity
			Control Points	Water Rights	Reser-voirs	
Major River Basins	(km^2)	(km^2)				(10^6 m^3)
Brazos River	115,000	6,660	3,830	1,634	670	5,758
Canadian River	32,900	90,700	85	56	47	1,192
Colorado River	108,000	5,100	2,395	1,922	511	5,878
Cypress Bayou	7,280	259	189	164	91	1,078
Guadalupe-San Antonio	26,500	-0-	1,349	860	237	997
Lavaca River	5,980	-0-	185	71	22	290
Neches River	25,900	-0-	318	333	176	4,818
Nueces River	43,900	-0-	542	373	121	1,284
Red River	63,400	61,000	447	489	245	4,965
Sabine River	19,200	6,040	376	310	207	7,873
San Jacinto River	14,500	-0-	411	148	114	787
Sulphur River	9,220	492	83	85	53	930
Trinity River	46,500	-0-	1,334	1,169	703	9,254
Rio Grande	125,000	347,000	957	2,584	113	16,149
Coastal Basins						
Lavaca-Guadalupe	2,590	-0-	68	10	-0-	-0-
Neches-Trinity	1,990	-0-	245	138	31	40
Nueces-Rio Grande	27,000	-0-	200	104	64	140
San Antonio-Nueces	6,860	-0-	53	12	9	2
Trinity-San Antonio	648	-0-	94	24	13	6
Colorado-Lavaca	2,440	-0-	111	27	8	67

The 20 WAM input covering 15 major river basins and eight coastal basins are listed in Table 2. Each dataset includes alternative versions modeling authorized use and current use scenarios The datasets are available at the previously cited TCEQ website. The water rights in the datasets are updated as the TCEQ approves applications for new permits or revisions to existing permits. The datasets also continue to be refined with addition of expanded WRAP capabilities. Incorporation of expanded environmental flow standards is currently a major focus.

Conclusions and Lessons from the Texas Experience

Effective water resources development, allocation, management, regulation, and use require comprehensive detailed capabilities for assessing water availability and reliability. Stream flow and other hydrologic variables are extremely variable and stochastic. Numerous water users share limited water resources used in diverse ways and managed within the framework of complex constructed infrastructure and institutional systems and diverse management practices. The WRAP/WAM modeling system significantly contributes to water management in Texas. The public domain WRAP software and documentation are readily accessible for application to river/reservoir systems located anywhere in the world. The Texas experience in implementing water allocation and planning processes and associated modeling capabilities are applicable elsewhere as well.

With growing demands on limited water resources, effective allocation and management of stream flow and reservoir storage have become increasingly important in Texas. The WRAP/WAM System provides capabilities for assessing institutional as well as hydrologic water availability and supply reliability. The modeling system supports preparation and evaluation of water right permit applications, other water allocation endeavors, regional and statewide planning studies, and operational planning studies. The modeling system supports a broad range of water management activities and helps to integrate those activities.

Developing and applying computer models have typically been viewed in terms of the engineering and scientific concepts and methods incorporated in the models. However, modeling has important institutional as well as technical dimensions. Lessons learned from development and application of the Texas WAM System demonstrate the importance of the following two institutional dimensions of water availability modeling.

- Modeling water rights, contractual agreements, treaties, interstate compacts, and other complex institutional aspects of water resources development, management, allocation, and use may be a key consideration in implementing a modeling system.
- Effective implementation of a modeling system may require a partnership effort of an entire water management community that includes political officials, legislative processes, water users, government agencies, consulting firms, and university researchers.

The following general observations characterize the Texas experience in implementing a water availability modeling system.

- Severe droughts motivate political concern, improvements in water management, and implementation of computer modeling systems.
- Partnerships and consensus building are key aspects of water resources planning and management. Likewise, a water management community may work together to effectively implement a shared modeling system. Development and application of the Texas WAM System was an institutional partnership effort.
- Administration of water allocation systems has become a central focus of river basin management. Regulatory (water allocation) and planning functions are integrally related. Shared modeling tools can facilitate integration of planning and regulatory functions.
- Modeling systems include computer programs, databases, organizations, people, and decision-making processes. Compilation and management of voluminous data is a central governing concern. A modeling system is constructed rather than just a model.
- Model development is a dynamic evolutionary process. As long as a generalized computer simulation model such as WRAP continues to be applied, its development is never completed. Model development is a process of continual expanding and improving.
- Water availability modeling is essential for effective water management.

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