Texas Water Availability Modeling System

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Abstract: A water availability modeling system was implemented during 1997–2004 by the Texas Commission on Environmental Quality and its contractors, in collaboration with the water management community, under a mandate provided by comprehensive water management legislation enacted by the Texas legislature in 1997. The availability and reliability of water resources are assessed based on simulating river/reservoir system management and water allocation practices using sets of historical naturalized monthly streamflow sequences to represent basin hydrology. The prior appropriation water rights permit system and other institutional mechanisms for allocating streamflow and reservoir storage resources among numerous water users are considered in detail in evaluating basinwide impacts of water management decisions. The generalized modeling system and lessons learned in its implementation in Texas are applicable to river basin management throughout the world.

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Introduction

The Brown–Lewis Water Management Plan enacted by the Texas legislature as its 1997 Senate Bill 1 is a milestone in the history of water resources management in Texas. The designation *Senate Bill 1* is traditionally applied in each legislative session to highlight legislation of the upmost importance. The 1997 Senate Bill 1 and subsequent amending legislation authorized the water availability modeling (WAM) system described in this paper, as well as a regional water resources planning process and other related activities.

The WAM system was developed under the leadership of the Texas Commission on Environmental Quality (TCEQ) in conjunction with administering a water rights permit system and is also applied in the Senate Bill 1 regional and statewide planning activities for which the Texas Water Development Board (TWDB) is the lead agency. The WAM system provides a consistent set of databases and modeling tools for use both in conducting planning studies and in preparing and evaluating water rights permit applications (Sokulsky et al. 1998; Texas 1998).

River authorities, irrigation districts, municipal water districts, cities, private companies, and individual citizens hold about 8,000 permits to use the surface waters of the state. Priorities are set by the dates of appropriation recorded in the permits. The 1997 Senate Bill 1 directed that the TCEQ, in conjunction with developing the WAM system, inform all water right permit holders of the reliabilities associated with their permits. Changes in water use or management practices or development of new water projects require TCEQ approval of either new permits or revisions to existing permits. In evaluating permit applications, the TCEQ determines whether sufficient water is available to supply any proposed new use and evaluates the impacts on all other water users in the river basin. TCEQ procedures require that water management entities and their consultants use the WAM system in preparing water right permit applications, and TCEQ staff use the modeling system in evaluating the applications.

The 1997 Senate Bill 1 also established a program for developing regional water plans that are integrated into a statewide planning process administered by the TWDB. Committees of local water interests have been established to prepare plans for the orderly development, management, and conservation of the water resources of each of 16 regions. The TWDB provides funding, administrative, and technical support to the regional committees. Consulting firms perform much of the technical work. Senate Bill 1 mandated that initial regional plans be completed by 2001 and incorporated into a statewide plan by 2002 (Texas 2002). Continuing planning is organized based on updated plans being reported at cycles not to exceed 5 years. In evaluating applications for water right permits, the TCEQ requires that proposed actions must be consistent with pertinent regional plans. The WAM system is applied in the planning process. River authorities, other water management agencies, and their consultants have broadened WAM applications to also include various types of studies that are not directly mandated by the TCEQ water right permit program or the TWDB Senate Bill 1 planning studies.

The Texas WAM system consists of the Water Rights Analysis Package (WRAP) model, 21 sets of WRAP input files covering the 23 river basins of the state, a geographic information system (GIS), and other supporting databases. The WRAP model is generalized for application anywhere, subject to input files being developed for the river basins of concern. Applications in Texas consist of executing the WRAP model with the WAM system data files altered as appropriate to reflect proposed water management plans of interest that could involve changes in water use or operating practices, construction of new facilities, or other management strategies.

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Generalized Simulation Modeling System

The WRAP modeling system developed at Texas A&M University has been greatly expanded since 1997 for the TCEQ WAM system. Early versions of WRAP date back to the mid-1980s. Model development has been an evolutionary process with extensive interactions between professionals from the agencies and consulting firms applying the model to specific river basins and university researchers responsible for improving the modeling methodology and computer software. The public domain software and documentation (Wurbs 2003a,b) may be downloaded from the Web site ⟨http://ceprofs.tamu.edu/rwurbs/wrap.htm⟩ or obtained from the TCEQ or the Texas Water Resources Institute.

WRAP simulates management of the water resources of a river basin or multiple-basin region under a priority-based water allocation system. The generalized model is designed for assessing hydrologic and institutional water availability and reliability for water supply diversions, environmental instream flows, hydroelectric energy generation, and reservoir storage. Basinwide interactions among numerous water uses and diverse water management facilities and practices may be modeled. River basin hydrology is represented by sequences of monthly naturalized streamflows and reservoir net evaporation less precipitation depths.

WRAP is a set of computer programs. WRAP-HYD provides a set of computational routines for converting gauged streamflows to naturalized flows and compiling sets of net reservoir evaporation less precipitation depths. WRAP-HYD output consists of hydrology input data sets for WRAP-SIM. The program WRAP-SIM performs the river/reservoir system water allocation simulation, and the program TABLES organizes the simulation results and develops frequency relationships, reliability indices, and summary statistics. WinWRAP is a user interface for executing the programs within Microsoft Windows.

A WRAP simulation study involves assessing capabilities for meeting specified water management and use requirements during a hypothetical repetition of historical hydrology. The overall modeling process includes the following tasks:

1. Sequences of monthly naturalized flows covering the specified period of analysis at selected gauging stations are developed.
2. Naturalized flows are distributed from gauged to pertinent ungauged locations.
3. The water management system is simulated, with water being allocated to each water right in priority order.
4. Simulation results are organized and water supply reliability indices, flow and storage frequency relationships, and other summary statistics are computed.

Task 1 has been completed for all of the river basins in Texas; Tasks 2 and 3 occur each time WRAP-SIM is executed; and the postsimulation program TABLES is used for Task 4.

Input Data and Simulation Results

A standard WRAP input data set contains a file with water management information and three hydrology files: naturalized flows at gauged sites, watershed parameters for distributing naturalized flows from gauged to ungauged sites, and net reservoir evaporation rates. Information describing water use requirements, channel loss rates, water control facilities, and operating rules are provided in a water rights data file. In WRAP terminology, a *water right* is a set of data describing a water use requirement and the reservoir storage and conveyance facilities and operating rules available for meeting the water use requirement.

The spatial configuration of a river basin 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. The modeling process results in three forms of streamflows at each control point: naturalized, regulated, and unappropriated.

A WRAP-SIM simulation begins with naturalized flows. In general, the terms *naturalized, unregulated*, or *unimpaired* 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 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. Input data sets of naturalized flows are developed by adjusting gauged flows to remove the historical effects of upstream reservoirs, diversions, return flows from surface and groundwater sources, and possibly other factors.

Regulated and unappropriated flows computed by WRAP-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 data set. Unappropriated flows are available for further appropriation after all the water rights receive their allocated share. Regulated flows may be greater than unappropriated flows due to instream flow requirements at the site or commitments to other rights at downstream sites.

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 flows that are added to the streamflows. Channel losses are considered in adjusting streamflows for depletions and return flows occurring at upstream locations using channel loss factors F_{CL} provided as input and defined for the reach between two control points as

$$\text{adjustment at downstream site} = (1.0 - F_{CL})\ \text{adjustment at upstream site}$$

Water management and use requirements, policies, practices, and facilities are described in terms of water rights. The model provides flexibility for modeling complex system configurations and operations. Extensive improvements to WRAP have been made in response to various situations encountered as the individual river basins were modeled for the Texas WAM system. The objective was to develop a generalized model providing the flexibility needed to address the diverse water management practices found across the state. Required and optional features for defining water use requirements and management practices include:

- Identifiers for aggregating simulation results for groups of related water rights;
- Locations of system components by control point;
- Priority specifications;
- Diversion, instream flow, and hydroelectric energy targets for 12 months of the year;
- Specifications for varying water use targets as a function of storage or streamflow;

The river/reservoir/use system is simulated with WRAP-SIM.

- Main input file containing water rights data is read.
- Water rights are ranked in priority order.
- Various other data manipulations are performed.
- Flow distribution file containing watershed parameters is read.
- Watershed parameters are determined for incremental watersheds.

Loop repeated for each month in sequential order

- Naturalized flow and net evaporation rates are read.
- Naturalized flows are transferred from gaged to ungaged sites.
- Negative incremental flow array is developed.

Loop repeated for each water right in priority order

- Diversion, instream flow, or hydropower target is set.
- Water availability is determined from available flow array.
- Diversion and reservoir release decisions are made and water balance computations are performed in an iterative loop.
- Available streamflow array is adjusted for effects of water right.
- Simulation results for this water right are recorded.

- Simulation results for this month are recorded.

The program TABLES is used to develop frequency relationships and reliability indices and otherwise organize and summarize simulation results.

Fig. 1. Outline of simulation

- Seasonal or annual limits on diversions, reservoir releases, or streamflow depletions;
- Return flow specifications in various optional formats;
- Conveyance of flow through pipelines and canals;
- Reservoir storage volume versus surface area and elevation relationships; and
- River/reservoir system operating rules including multiple-reservoir system operations, multiple-owner reservoirs, off-channel storage, and constraints on depleting streamflows.

Simulation results may be organized in various formats including the entire time series of monthly or annual values of selected variables, water budgets, frequency statistics, and reliability indices. Results are typically viewed from the perspective of frequency, probability, percent of time, or reliability of meeting water supply, instream flow, hydropower, and/or reservoir storage targets. Exceedance frequency relationships are developed for naturalized, regulated, and unappropriated flows and reservoir storage or storage drawdowns. Volume and period reliabilities may be computed for water supply diversions for individual water rights or the aggregation of selected groups of rights.

Similar energy reliability indices are computed for hydroelectric energy production targets. Volume reliability is the ratio of the water volume supplied to the demand target, or equivalently the ratio of the mean actual rate supplied to mean target rate, expressed as a percentage. Period reliability is the percentage of months in the simulation for which a specified demand target is met; it is an expression of the percentage of time that the demand can be met, or equivalently the likelihood of the demand being met in any randomly selected month. Reliability tables also include tabulations of both the percentage of months and the percentage of years during the simulation for which the amounts supplied equal or exceed specified magnitudes expressed as a percentage of the target.

Outline of Simulation Algorithms

The simulation tasks performed by WRAP-SIM are outlined in Fig. 1. Model execution begins with reading and organizing input data. Water rights are sorted into priority order based on priority numbers input for each water right. In the Texas WAM system, the priority numbers are appropriation dates, but in general the integers can represent any relative ranking of priority. Watershed parameters are typically input for the entire watershed above each control point. Computations convert the parameters to the incremental local subwatersheds used to distribute naturalized flows from gauged to ungauged sites.

The simulation then steps through time. Within each sequential month, water accounting computations are performed as each set of water use requirements (water right) is considered in priority order. Thus, a water rights priority loop is embedded within a monthly time step loop.

Naturalized flows for primary control points and net evaporation rates for reservoirs are read at the beginning of the time step loop. Naturalized flows are distributed from primary control points to all other sites based on watershed parameters. WRAP includes several methods for distributing flows from gauged to ungauged sites. Most applications in Texas have used an option based on the Natural Resource Conservation Service (NRCS) relationship between precipitation depth and runoff volume with watershed characteristics represented by a curve number (CN) (NRCS 1985). Unlike conventional applications of the NRCS method, in the WRAP adaptation, a precipitation depth P is computed for the CN for the gauged watershed and naturalized monthly flow at the gauge. After adjusting P by a mean annual precipitation ratio, it is substituted back into the precipitation-runoff relation with the CN for the ungauged watershed to determine the flow at the ungauged site. If the CN and mean annual precipitation are the same for the gauged and ungauged watersheds, the method reduces to distributing flow in proportion to drainage area.

Incremental watersheds and incremental flows may be used in the flow distribution algorithms. However, for all other aspects of the simulation, all streamflows are total cumulative flows, not incrementals. Naturalized flows usually increase going downsteam. However, situations sometimes occur in which a naturalized flow is less than corresponding naturalized flows at upstream control points. WRAP includes options for adjusting total flows during the simulation algorithms in response to these negative incremental flow situations.

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

1. 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.
2. The amount of water available to the water right from stream flow is determined based on the available streamflow array considering its control point and all downstream control points.
3. 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.

Fig. 2. Major rivers of Texas

4. 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 streamflows at downstream sites. Within the priority loop, 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.

WRAP-SIM has options that involve automatic repetitions of the simulation outlined in Fig. 1. With the yield-reliability option, a selected diversion right starts with a specified amount that is iteratively incremented until the firm yield (100% reliability) is reached. A dual simulation option is useful in modeling multiple rights with different priorities associated with the same reservoir system. Another option sets reservoir storage contents at the beginning of a second simulation equal to the storage at the end of a first pass. However, in Texas WAM system applications, reservoirs are usually assumed full at the beginning of a simulation.

Simulation results can be extremely voluminous. Essentially every variable computed each month for each water right, reservoir, and control point may be output by WRAP-SIM and included in tables developed by the postsimulation program TABLES. Considerable flexibility is provided for the model user to select the amount and format of simulation results.

Modeling River Basins of Texas

Texas encompasses 685,000 km^2 and has a population of 21 million people. Climate, geography, and water management vary dramatically across the state from the arid west to humid east, from sparsely populated rural regions to the Dallas–Fort Worth, Houston, San Antonio, and Austin metropolitan areas. Mean annual precipitation varies from 20 cm at El Paso on the Rio Grande to 140 cm in the lower Sabine River Basin. Population and economic growth combined with depleting groundwater reserves have resulted in increasing demands on surface water resources throughout the state (TWDB 2002). Texas has 15 major river basins and 8 coastal basins. Several of the major 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.

Texas Water Availability Modeling System Datasets

The Texas WAM system consists of the generalized WRAP model, data sets containing hydrology and water rights input files for the river basins of the state, GIS tools, and other supporting databases. The 21 WAM datasets listed in Table 1 cover the entire state subdivided by the river basins shown in Fig. 3. Three of the data sets combine two adjoining basins, and one basin is divided into two data sets. The data sets are available at the WAM Web site maintained by the TCEQ. The water rights in the data sets are updated as the TCEQ approves applications for new permits or revisions to existing permits. Other aspects of the data sets also continue to be refined. The writer developed the information presented in the tables of this paper by running WRAP with the data sets available from the TCEQ WAM Web site as of early 2004. Run times on the writer's Pentium 4 desktop computer range from less than 1 min to about 3 min for each of the 21 river basin models.

The 21 WAM data sets covering the 23 river basins were developed by six consulting engineering firms working for the TCEQ as prime contractors with assistance from several other firms serving as subcontractors. The Sulphur, Neches, San Jacinto, Nueces, San Antonio, and Guadalupe river basins were modeled during 1998–1999, the Rio Grande was completed during 2002–2004, and the other data sets were compiled during 1999–2002. Reports document modeling of individual basins or groups of basins.

The Center for Research in Water Resources at the University of Texas developed a GIS based on ESRI ArcGIS software to determine the drainage area, curve number, and mean annual precipitation for the approximately 13,000 control points included in the WRAP input data sets (Maidment 2002; Goplan 2003). The GIS was also used to develop lists of the next downstream control point below each control point used to define spatial connectivity and the lengths of the stream reaches between the control points used in establishing channel loss factors.

The hydrologic period of analysis is tabulated as the third column in Table 1. For most of Texas, the most hydrologically severe drought on record begin in 1951 and ended with a major flood in April 1957. The simulation periods adopted include the drought of record and other shorter-duration severe droughts as well as a full range of fluctuating wet and dry periods. The number of primary control points and total number of control points are listed in the fourth and fifth columns in Table 1. Primary control points are sites for which naturalized flows are provided as an input file. For all other control points, naturalized flows are computed within the WRAP-SIM simulation using watershed parameters from an input file. Most primary control points are USGS gauging stations.

Naturalized flows were developed by adjusting recorded flows to remove the impacts of upstream reservoirs, water supply diversions, return flows, and in some cases other factors. The TCEQ and TWDB collect data on diversions and return flows from cities, water districts, and other users. Wastewater treatment plant effluent discharges and irrigation return flows to stream systems include water supplied from groundwater as well as surface water sources. Although the completeness and accuracy of these data have historically been erratic, considerable effort has been

Table 1. Texas Water Availability Modeling System Models for Authorized Use Scenario

Map ID number in Fig. 3	River basins	Period of analysis	Number of: Primary control points	Total control points	Model water rights	Reservoirs	Total storage capacity (Mm^3)	Mean natural flow (Mm^3/year)	Permit divert target (Mm^3/year)	Volume reliability (%)
1	Canadian River Basin	1948–1998	12	85	56	47	1,190	235	203	88
2	Red River Basin	1948–1998	50	443	447	240	4,970	19,200	762	85
3	Sulphur River Basin	1940–1996	6	77	82	51	930	3,080	465	99
4	Cypress Bayou Basin	1948–1998	22	158	132	85	1,080	2,150	525	98
5	Rio Grande Basin	1940–2000	77	974	2,562	90	16,150	5,350		
6	Colorado River Basin and Brazos-Colorado Coastal	1940–1998	45	2,263	1,591	503	5,880	3,700	2,270	76
7	Brazos River and San Jacinto-Brazos Coastal	1940–1997	77	3,818	1,606	650	5,760	7,850	2,990	88
8	Trinity River Basin	1940–1996	40	1,329	1,176	702	9,250	8,490	7,250	59
9	Neches River Basin	1940–1996	20	304	327	175	4,820	7,690	2,170	95
10	Sabine River Basin	1940–1998	27	373	308	206	7,870	8,500	2,930	99
11	Nueces River Basin	1934–1996	41	544	376	122	1,280	1,070	2,235	30
12	Guadalupe and San Antonio River basins	1934–1989	46	1,334	853	233	997	2,590	7,880	40
13	Lavaca River Basin	1940–1996	7	176	71	22	290	1,200	391	51
14	San Jacinto River Basin	1940–1996	16	386	164	111	787	2,720	559	96
15	Lower Nueces-Rio Grande	1948–1998	16	119	70	42	126	307	57.8	44
16	Upper Nueces-Rio Grande	1948–1998	13	78	35	22	14	198	12.4	20
17	San Antonio-Nueces	1948–1998	13	49	12	9	2	697	2.32	87
18	Lavaca-Guadalupe Coastal	1940–1996	1	68	10	-0-	-0-	194	5.63	40
19	Colorado-Lavaca Coastal	1940–1996	2	105	26	10	67	167	66.5	48
20	Trinity-San Jacinto Coastal	1940–1996	9	83	21	14	6	223	17.7	89
21	Neches-Trinity Coastal	1940–1996	2	216	134	31	40	749	219	80

expended by the agencies in recent years to better organize available data. The TCEQ maintains a detailed database of information contained in the water right permits.

The 21 WRAP input data sets contain the 3,365 reservoirs for which a water right permit has been issued. Permits are required to store more than 246,800 m^3 (200 acre-ft). Over 90% of the total capacity of the 3,365 reservoirs is contained in the 211 reservoirs that have conservation capacities exceeding 6,170,000 m^3 (5,000 acre-ft). Modeling is complicated by numerous reservoirs, but most of the storage is contained in a few large reservoirs. Modeling complex operating rules for multiple-reservoir and multiple-owner systems has been a major concern in expanding the WRAP model and implementing the WAM system.

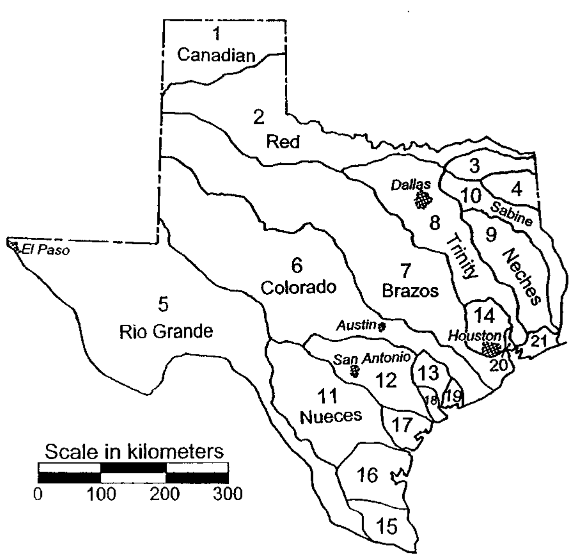

Fig. 3. Texas water availability modeling system river basins

Storage capacities for all of the reservoirs are cited in their water right permits. Most of the larger reservoirs have undergone sediment surveys since construction. In developing the WAM data sets, elevation-storage-area tables for most of the 211 reservoirs having conservation storage capacities of at least 6,170,000 m^3 were assembled for both initial and estimated year 2000 conditions of sedimentation. Generalized storage-area relationships were adopted in each river basin for the numerous smaller reservoirs. The TWDB maintains a database of reservoir evaporation and precipitation rates for each of 75 1-degree quadrangles covering the state for each month from 1940 to the present.

Water Availability Modeling Simulations

Along with compiling the WRAP input data sets, the TCEQ contractors performed simulations for alternative scenarios reflecting combinations of premises regarding water use, return flows, and reservoir sedimentation. Eight defined scenarios were simulated for all of the river basins, and other scenarios were added for particular basins. The following two scenarios are routinely adopted for both water right permit applications and planning studies.

- The authorized use scenario is based on the following premises:

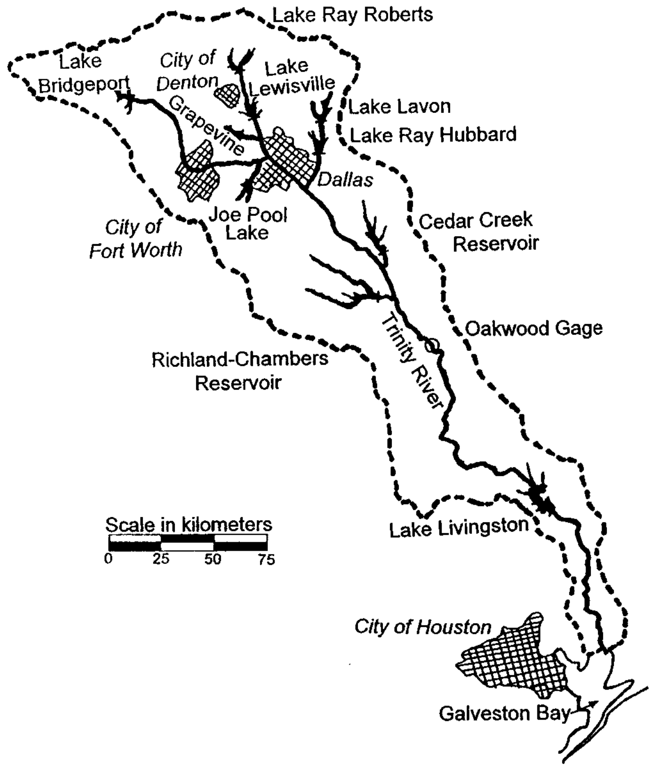

Fig. 4. Trinity River Basin

1. Water use targets are set at the full amounts authorized by the permits.
2. Full reuse with no return flows is assumed.
3. Reservoir storage capacities are those specified in the permits, which typically reflect no sediment accumulation.
4. Term permits are not included.

- The current use scenario is based on the following premises:
  1. The water use target for each water right is set based on the maximum annual amount actually used in any year during a recent 10-year period.
  2. Best estimates of actual return flows are adopted.
  3. Reservoir storage capacities and elevation-area-volume relationships for major reservoirs are adjusted to reflect year 2000 conditions of sedimentation.
  4. Term permits are included.

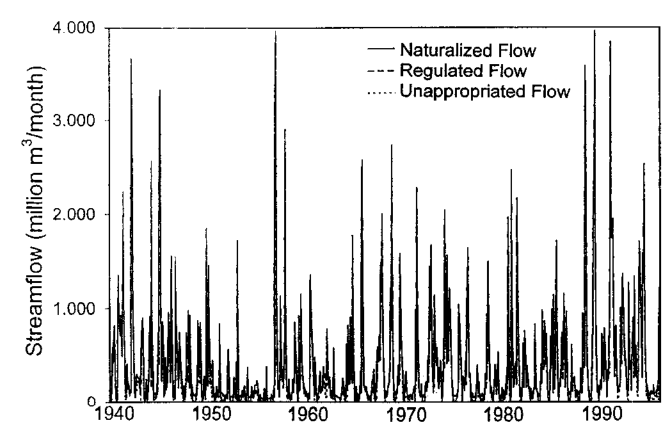

Fig. 5. Naturalized, regulated, and unappropriated flows at Oakwood Gauge on Trinity River

Table 2. Flow Frequency at USGS Gauge on Trinity River near Oakwood for Current Use Scenario

Statistic	Naturalized flows (Mm^3/month)	Regulated flows (Mm^3/month)	Unappropriated flows (Mm^3/month)
Mean	437	365	338
Standard deviation	624	527	538
Exceedance frequency			
Minimum	0	4	0
98%	0	43	0
95%	4	58	0
90%	17	68	0
75%	57	88	45
50%	201	153	138
25%	559	414	397
10%	1,120	866	866
Maximum	4,110	3,930	3,930

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 canceled if water is not actually used during a 10-year period. A term permit is issued for a set period of time, usually ranging from 1 to 10 years.

The mean naturalized flow either into the Gulf of Mexico or leaving Texas at a state line is shown in the ninth column in Table 1. The totals of the water supply diversion targets from the authorized use scenario data sets are listed in the tenth column. The volume reliabilities in the eleventh column are the percentages of the total authorized diversion targets supplied in the simulation. The diversion targets are lower and reliabilities are higher for the current use scenario.

Major reaches of rivers, particularly in the dry west Texas and populous urban areas elsewhere in the state, are overappropriated. Reliabilities for supplying permitted water use are unacceptably low, and the TCEQ will not issue permits for additional use. Marketing or transferring of existing water rights among users is encouraged. For other river reaches, water is available for further appropriation. The TCEQ continues to issue or modify many water right permits each year.

Trinity River Basin

The Trinity River Basin is used as an example to illustrate the modeling system. With the Dallas–Fort Worth Metroplex located in the upper basin, the Trinity has the highest population of any basin in Texas. The Trinity Basin contains 6.8% of the land area and 24% of the population of Texas. Surface water supplies 90% of the total water use with the remainder supplied from groundwater. Permitted withdrawals from the Trinity River and tributaries are for municipal (58%), industrial (35%), irrigation (7%), and other (0.2%) uses.

The 10 largest reservoirs, which are shown in Fig. 4, account for 89% of the total conservation storage capacity of the 702 reservoirs included in the model. Lake Livingston on the lower Trinity River, owned by the Trinity River Authority (TRA) and the City of Houston, is the largest reservoir in the basin. The lake

Table 3. Storage-Frequency Relationships for Selected Reservoirs for Current Use Scenario

	Percent of time storage is equaled or exceeded						
	Maximum	10%	25%	50%	75%	90%	Minimum
Reservoir	Reservoir storage in million m^3						
Lewisville	758	758	736	646	530	364	2
Ray Roberts	983	906	716	418	232	162	21
Grapevine	199	199	182	145	85	51	17
Ray Hubbard	598	598	598	570	525	458	98
Livingston	2,150	2,150	2,150	2,150	2,150	2,130	1,810

contains about 24% of the total water supply storage capacity in the basin and provides water to Houston and other users in the San Jacinto River Basin and adjoining coastal basins. The TRA controls storage in several reservoirs that supply users throughout the Trinity Basin. Dallas Water Utilities, Tarrant Regional Water District, and North Texas Municipal Water District are major water suppliers in the upper basin.

The simulated flows of the Trinity River at Oakwood presented in Fig. 5 and Table 2 illustrate the great variability, ranging from zero flow to major floods, characteristic of rivers in Texas. As shown in Fig. 4, the USGS gauge near the city of Oakwood is located on the Trinity River upstream of Lake Livingston but downstream of the other large reservoirs. The percentage of months during the 1940–1996 simulation for which the end-of-month storage content equaled or exceeded indicated amounts are tabulated in Table 3 for several reservoirs. Fig. 5 and Tables 2 and 3 are from the current use scenario simulation.

Reliabilities associated with water rights held by the Dallas Water Utilities (DWU) are summarized in Tables 4 and 5. The DWU, which supplies water for Dallas and over 30 other neighboring municipalities and water supply corporations, owns Lake Ray Hubbard and has contracted for water supply storage capacity in Lakes Lewisville, Grapevine, and Ray Roberts, which are multiple-purpose flood control, water supply, and recreation projects owned and operated by the U.S. Army Corps of Engineers (USACE). Storage contracts with the USACE and water right permits to divert water from Lake Lewisville are held by both the DWU and the City of Denton. Likewise, the DWU, the City of Grapevine, and Park City share Lake Grapevine. The DWU also purchases water imported from the Sabine and Neches river basins.

DWU storage and diversion rights associated with Lakes Grapevine and Hubbard have appropriation dates of July 6, 1948, and February 2, 1955, respectively. Rights attached to Lake Ray Roberts have a 1975 priority. The DWU holds multiple storage and diversion rights associated with Lake Lewisville with priorities of 1924, 1948, and 1975. The 1924 rights date back to DWU ownership of the old Lake Dallas that was inundated with construction of the federal project in 1948. The 1975 rights are from a reallocation of flood control storage capacity to water supply in Lake Lewisville in conjunction with construction of Ray Roberts upstream.

Reliabilities in Table 4 from the authorized and current use simulations indicate a severe overappropriation of water. Actual use is much less than authorized by the water right permits. Table 5 provides reliability indices for DWU diversions for the current use scenario. Reliabilities are governed by the record 1951–1957 drought and severe droughts in 1962–1964 and 1980–1981.

Lessons Learned and Current Issues

The Texas WAM system is illustrative of the complexities of assessing water supply capabilities. Issues addressed and lessons learned in Texas are pertinent elsewhere as well.

Institutional Dimensions of Water Availability Modeling

Institutional considerations are important from two perspectives. First, water allocation systems and management practices must be modeled in detail to meaningfully evaluate water availability. Water supply capabilities are governed by institutional as well as hydrologic considerations. Second, for a modeling system to be effective, its implementation often must be a shared effort of a water management community, not just a few technical experts. The importance of broad involvement of many entities in water resources planning and management has long been recognized in general. The concept is valid for model building as well.

The Texas WAM system models a water rights system with

Table 4. Comparison of Authorized and Current Use Scenarios for Water Rights Associated with Four Reservoirs and Basin Totals

		Authorized use simulation			Current use simulation		
Reservoir	City water utility	Storage capacity (Mm^3)	Diversion target (Mm^3/year)	Volume reliability (%)	Storage capacity (Mm^3)	Diversion target (Mm^3/year)	Volume reliability (%)
Lewisville	Dallas	679	679	77.2	674	252	97.4
	Denton	85	72	39.5	84	4	100.0
	Total	764	751	73.5	758	256	97.5
Ray Roberts	Dallas	730	730	11.5	727	257	74.5
	Denton	257	257	25.4	256	13	100.0
	Total	987	987	15.1	983	270	75.8
Grapevine	Dallas	105	105	63.6	105	93	83.3
	Grapevine	32	32	40.0	32	9	84.3
	Park City	62	62	91.4	62	15	100.0
	Total	199	199	68.4	199	117	85.5
Ray Hubbard	Dallas	605	224	94.3	598	101	100.0
Trinity River Basin totals		9,250	7,250	59.4	8,980	2,860	76.2

Table 5. Reliabilities for Diversion Rights Held by Dallas Water Utilities for Current Use Scenario

Source of water supply	Lewisville Reservoir	Ray Roberts Reservoir	Grapevine Reservoir	Hubbard Reservoir
Diversion target (10^6 m^3/year)	252	257	92.9	101
Mean shortage (10^6 m^3/year)	6.48	65.5	15.5	0.0
Volume reliability (%)	97.4	75.5	83.3	100
(a) Percentage of months with diversion equaling or exceeding				
100 % of target	79.5	43.6	81.9	100
95% of target	96.9	73.0	82.0	100
90% of target	96.9	73.1	82.0	100
75% of target	96.9	73.4	82.6	100
50% of target	97.1	74.3	82.9	100
(b) Percentage of years with diversion equaling or exceeding				
100 % of target	1.8	0.0	61.4	100
95% of target	94.7	56.1	63.2	100
90% of target	96.5	59.6	68.4	100
75% of target	96.5	70.2	80.7	100
50% of target	98.2	75.4	86.0	100

about 8,000 active permits that evolved historically over many decades, five interstate river basin compacts, treaties between Mexico and the United States, and a myriad of agreements between reservoir owners, water suppliers, and water users. These institutional systems are integrated with complex physical systems of reservoirs and conveyance facilities and associated operating practices. A major challenge in expanding the generalized WRAP simulation model during implementation of the Texas WAM system was to provide flexible capabilities for modeling the diverse range of water management practices found across the state.

Partnerships and consensus building are key aspects of water management and likewise are important in creating a modeling system. Implementation of the Texas WAM system was administered by the TCEQ in collaboration with the TWDB and Texas Parks and Wildlife Department, as mandated by the Texas legislature. A Workgroup of Water Use Interests was established to advise on policy issues that arose during the model development process. The USACE sponsored expansion of modeling methodologies through their congressionally authorized Texas Water Allocation Assessment Project. Ten consulting engineering firms and researchers at two universities performed most of the technical work. University research that had been under way for over a decade prior to enactment of the 1997 Senate Bill 1 provided a foundation on which to build the modeling system.

Water allocation systems have become a key focus of river basin management. The Texas WAM system has contributed to integration of planning and regulatory functions. The same modeling tools are applied in local, regional, and statewide planning studies and in the preparation and evaluation of water right permit applications.

Assessing Water Supply Capabilities

Important trade-offs exist between the amount of water committed for beneficial use and the level of reliability that can be achieved. Beneficial use of water is based on ensuring a high level of reliability, particularly for municipal supplies. However, if water commitments are limited as required to ensure an extremely high level of dependability, much of the water resource flows to the ocean or is lost through reservoir evaporation much of the time. The Texas WAM studies indicate that reliabilities are not very sensitive to changes in demand targets. Conversely, the amounts that may be supplied change greatly with relatively small changes in reliability requirements. The amount of water supplied from Texas river systems can be increased significantly by accepting higher risks of shortages or emergency demand reductions.

Reliability estimates provided by the WAM system provide meaningful information but are subject to interpretation. Shortages in the model represent a general index of supply failures that could involve emergency demand management measures, negotiation of resource reallocations, or similar actions. Although the Texas water rights system and the WRAP model are based on protecting senior water rights, in actual situations involving insufficient water supply, users share the shortages to some degree regardless of the relative seniority of their rights. Water allocations during drought depend on political negotiations, alternative demand management and supply augmentation measures available to different entities, and other factors in addition to the water rights permit system.

In evaluating permit applications, the TCEQ has applied criteria that municipal supplies should have a WAM-estimated reliability of 100%, and for agricultural supplies, at least 75% of the permitted demand should be met at least 75% of the time. These guidelines are subject to exceptions and future refinement. A key issue involves proposals for using water supply sources with relative low reliabilities that are backed up by other sources of supply such as groundwater. The TCEQ relies on the regional planning studies administered by the TWDB to assess acceptable levels of reliability for individual components of complex multiple-source water supply systems. The WAM system also is being used to assess trade-offs in converting a portion of a firm (100% reliability) supply to a commitment of larger amounts of interruptible (lower reliability) supply. Criteria for defining unacceptable levels of impact of a proposed plan on the reliabilities of other water users throughout a river basin are also evolving as experience is acquired in applying the modeling system. Again, planning and regulatory efforts are interconnected in this regard.

Water Right Issues

The WAM system provides capabilities for investigating a myriad of water management issues. Several key concerns currently being addressed in WAM studies are highlighted below.

Dallas, Austin, and other entities are pursuing bed and bank permits to reuse wastewater treatment plant effluents for urban irrigation and industrial uses. A *bed and bank* permit allows use of the river to convey return flows for diversion at a downstream location without losing access to the return flows. Although water right permits granted in the future will likely include provisions regarding return flows, most existing permits do not. A water right permit holder is not obligated to return flows to a stream. However, upon return of flows to the river system through wastewater treatment plant effluents or other means, the flows become the property of the state. Reuse is commonly recognized as a sound management strategy to be encouraged. However, proposals for bed and bank permits to facilitate reuse are being strongly opposed by various entities because downstream water users and ecosystems have grown to rely upon the contributions to streamflow resulting from wastewater treatment plant discharges.

Historically, environmental flow needs have not been adequately protected. However, pursuant to policies established since the mid-1980s, preservation of instream flows for fish and wildlife and inflows to bays and estuaries has become a major concern. A few recently issued water supply permits include provisions for maintaining instream flows, but most existing permits do not. Work continues on improving methods for determining instream flow needs and developing mechanisms for incorporating instream flow requirements into the water rights permit system. Studies comparing naturalized and regulated flows from the WAM system have been conducted to categorize the impacts of water development by stream reach throughout the state.

Reservoir storage priorities are another key issue. A single priority date has traditionally been assigned in each water right permit granting the right to both store and divert water. Reservoir operation in Texas is based on providing long-term storage as protection against infrequent severe droughts. If junior appropriators located upstream of a reservoir diminish inflows when the reservoir is not spilling, its dependable yield is adversely affected. Each drawdown could possibly be the beginning of a long drought that empties the reservoir. Thus, protecting reservoir inflows is critical to providing a dependable water supply. However, forcing those appropriators that have rights junior to the rights of the reservoir owner to curtail diversions, and thus maintain inflows to an almost full or even an almost empty reservoir, is difficult and not necessarily the optimal use of the water resource. If junior diversions are not curtailed, the reservoir will likely later refill anyway, without failures to meet water supply demands. Reservoir storage priorities significantly affect WAM reliability results, primarily in trade-offs between individual water rights rather than basin totals.

Developing permitting mechanisms for multiple-reservoir/river system operating plans is also being addressed. Water right permits have always been granted for individual reservoirs rather than multireservoir systems. Several major multireservoir systems have component reservoirs that were constructed over several decades with multiple water rights established at different times. Many major water users are supplied by reservoirs located at great distances upstream. Unregulated flows entering the river below the dams significantly contribute to available streamflow at diversion sites. WAM studies have clearly demonstrated the benefits of system operation.

Continuing Model Expansion Efforts

In conjunction with the Senate Bill 1 planning studies, the TWDB is sponsoring a ground water availability modeling effort that involves application of the USGS MODFLOW model to analyze yields for selected major aquifers. The important interconnections between ground and surface-water resources have been addressed to a limited extent in implementing the TCEQ WAM system. For example, WAM system models for the Nueces, San Antonio, and Guadalupe river basins contain sets of naturalized flow adjustments for changes in spring flows associated with management plans for the Edwards Aquifer obtained from a TWDB groundwater model. Further integration of groundwater and surface-water modeling efforts are expected in the future.

Ongoing efforts at Texas A&M University to further expand the generalized WRAP model are focusing on the following improvements. A conditional reliability version of WRAP will provide capabilities to assess reliabilities for meeting short-term water needs during the next month to a year, which are highly dependent on initial storage contents. Daily time step modeling capabilities are being developed that include options for synthesizing daily naturalized flows from the WAM system monthly naturalized flows based on daily variation characteristics determined from observed daily flows. Salinity tracking capabilities are being incorporated to assess the impacts on water availability of natural salt pollution problems that are prevalent in several of the river basins.

Summary and Conclusions

The Texas experience in implementing a statewide WAM system illustrates the issues involved both in allocating and managing water resources and in developing and applying a modeling system to support planning and regulatory activities. Water availability modeling is complex, requiring considerable effort in compiling voluminous data sets and representing diverse water management practices, but is essential for effective water management. Administration of water rights and integration of water resources planning and water allocation regulatory functions have become a central focus of river basin management. A water management community must work together to implement an effective modeling system. The Texas WAM system provides flexible assessment capabilities for a broad range of water resources planning and management activities. The modeling system is significantly contributing to improved water management.

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