Sustainable Statewide Water Resources Management in Texas

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Abstract: Key integrated components of the Texas sustainable water management enterprise include a regional and statewide planning process, water rights permit system and other water allocation mechanisms, process for establishing environmental flow standards, and water availability modeling system. These statewide endeavors mandated by the Legislature are implemented by a water management community comprised of state, local, and federal agencies, private industry, stakeholders, interests groups, consulting engineering firms, and university researchers. Texas is a large state with a rapidly growing population, declining groundwater supplies, intensifying demands on limited surface water resources, extreme hydrologic variability including severe droughts, and very diverse climate, geography, economic development, and water management practices. The Texas experience is illustrative of fundamental concepts and issues involved in state-level efforts to achieve sustainable water management. **DOI: 10.1061/(ASCE)WR.1943-5452.0000499.** *© 2014 American Society of Civil Engineers.*

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Introduction

Water resources sustainability is the capability to provide for the needs of people and ecosystems without impairing capabilities for continuing to meet future needs. Mays (2007) outlines fundamental concepts of sustainability, describes tools for achieving sustainability, and presents case studies. Fisher (2009) focuses on policy and legal aspects of sustainability. Loucks and Gladwell (1999) investigate the state-of-the-art capabilities for assessing the achievement of sustainability. Jones (2010) and Gleick (2014) highlight the importance of advancing the cause of sustainability throughout the world. These books include extensive reviews of the literature of sustainable water resources management.

Grigg (2008) outlines fundamental concepts of total water management, as promoted by the American Water Works Association, which is defined as stewardship and management of water on a sustainable use basis. Total water management is accomplished within an institutional framework of people, laws, and organizations and combines political, social, economic, environmental, and technical considerations.

Cities, water districts, private companies, and other local entities are responsible for water supply and various other water management functions. The federal government played a dominant role in large-scale water resources planning and development in the United States during much of the 20th century. Since the 1970s, state agencies have become major players. The ASCE Task Committee on State Water Resource Planning Assessment (Viessman and Feather 2006) profiles water-planning activities in each of the 50 states and analyzes general trends. A document known as the *State water plan* had been published by 30 and 62% of the states in 1986 and 2005, respectively. The other states are also engaged in water resources planning and management although not maintaining a formal published water plan. State water-planning processes vary from compartmentalized to integrated, but there is a trend toward more holistic processes.

With intensified demands on limited resources, a more effective allocation of water resources among numerous water users and types of use is a growing concern. The ASCE (2013) outlines issues and practices for sharing water, focusing on interstate and international agreements, and provides an extensive list of references. Getches (2009) describes the law of water rights as administered within the 50 states of the United States. Hawaii and Louisiana have unique water right systems. Variations of the riparian doctrine apply in 29 states in the eastern and central United States. The prior appropriation doctrine governs water rights in nine western states. Ten states, including Texas, originally recognized riparian rights but later converted to a system of appropriation while preserving existing riparian rights. Porter (2014) describes the impacts of water rights in the everyday lives of the citizens of Texas.

Water managers are concerned with the challenges of providing reliable and affordable water supplies for growing populations while preserving the vitality of ecosystems. Richter (2009), O'Keefe (2012), and others note that despite the global recognition of the need to use natural resources sustainably, implementation of policies and practices to protect environmental flows has lagged far behind the intention.

Texas is offered in this paper as an example of state-level policies and practices for achieving effective total water management that are generally illustrative of basic concepts that are relevant throughout the United States and world. Texas is a large state with diverse hydrology, increasing demands on limited water resources, and progressive policies and management capabilities. Integration of water resources planning, allocation, and management functions is a particular notable aspect of the Texas experience.

The paper describes the evolving efforts of a water management community in dealing with intensifying water needs and diverse water issues. Water resources management occurs within an institutional framework that includes a series of laws enacted by the Texas Legislature. Programs mandated by the Legislature are implemented collaboratively by government agencies, private industry, consulting engineering firms, university researchers, stakeholders, special interest groups, and the general public. A water availability modeling system provides analysis capabilities

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required for effective planning, development, allocation, and management of water resources. The paper focuses on the experience of the Texas water management community in implementing the mandates of the following key legislation:

- The Water Rights Adjudication Act of 1967 initiated a 25-year process of consolidating an unmanageable assortment of diverse water rights into a water rights permit system. Treaties, interstate compacts, court cases, and contractual agreements also play important roles in water allocation in Texas.
- Omnibus water management legislation enacted in 1997 called Senate Bill 1 (SB1) instigated a regional and statewide water-planning process and authorized creation of a Water Availability Modeling (WAM) system to support planning and water allocation.
- The 2001 Senate Bill 2 (SB2) authorized the Texas Instream Flow Program (TIFP).
- The 2007 Senate Bill 3 (SB3) created a process for establishing environmental flow standards and incorporating these standards in the WAM system.

Water Resources of Texas

Climate, geography, and water use vary dramatically across Texas from arid western deserts to humid eastern forests, from sparsely populated rural regions to the metropolitan areas of Dallas and Fort Worth (DFW), Austin, San Antonio, and Houston (Fig. 1). The population increased from 20,850,000 in 2000 to 25,388,000 in 2010 and is projected to increase to 29,650,000 by 2020 and 46,324,000 by 2060 [Texas Water Development Board (TWDB) 2012]. Declining groundwater supplies combined with population growth are resulting in intensified demands on limited surface water resources.

The climate of Texas is representative of both the drier western and wetter eastern regions of the United States. Precipitation fluctuates greatly both spatially and over time. Mean annual precipitation increases fairly uniformly from west to east across Texas from 20 to 140 cm, with a statewide mean of 70.9 cm/year. The TWDB maintains a database of mean monthly precipitation for each of 92 one-degree quadrangles that encompass the state. Annual precipitation during 1940–2013 for the wettest and driest quadrangles completely contained in Texas are plotted in Fig. 2 along with the statewide means.

The 15 major river basins and eight coastal basins of Texas are delineated in Fig. 3. Rivers throughout the state exhibit great temporal variability including severe multiple-year droughts and major floods along with seasonal and year-to-year fluctuations. Long-term trends of decreases in flows are evident at some gauging stations, increases have occurred at other gauges, and some sites exhibit no evident long-term flow changes (Wurbs and Zhang 2014). Flow changes vary greatly between daily, monthly, and annual means and between high and low flows.

Observed flows of the Brazos River at the USGS gauge near Waco in central Texas are plotted in Figs. 4 and 5 to illustrate the great variability characteristic of river flows throughout the state. Mean daily flows during January 1900 through June 1914 are shown in Fig. 4. Annual means and the minimum monthly flow in each year of 1900–2013 are plotted in Fig. 5. The effects of multiple-purpose reservoirs with large flood control pools constructed upstream of this site during the 1950s–1960s are apparent in the daily flows of Fig. 4 but are not evident in plots of monthly flows or the annual flows in Fig. 5.

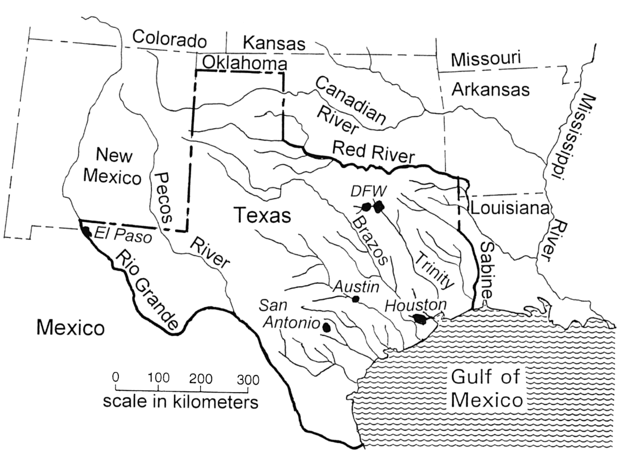

Fig. 1. Map of Texas (reprinted from Wurbs and Zhang 2014, with permission)

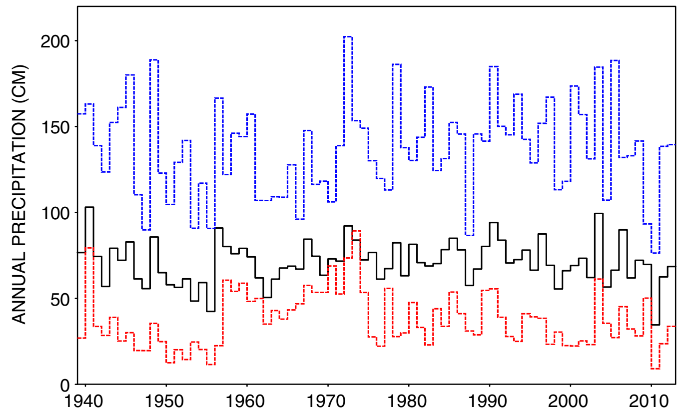

Fig. 2. Mean annual precipitation statewide (solid line) and in the dry western and wet eastern extremes of the state (high and low dotted lines)

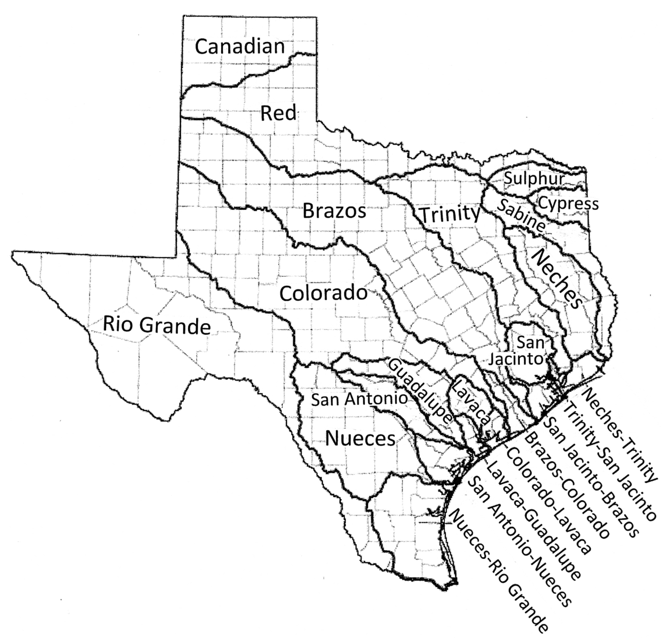

Fig. 3. Fifteen major river basins and eight coastal basins of Texas (reprinted from Wurbs and Zhang 2014, with permission)

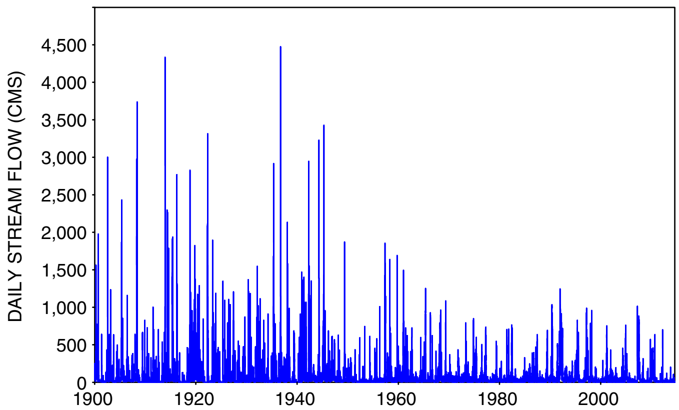

Fig. 4. Gauged daily flows of the Brazos River at Waco

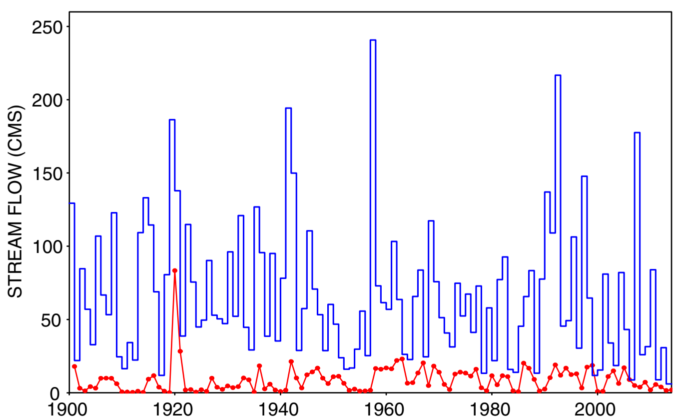

Fig. 5. Annual (solid line) and minimum monthly (dotted line) observed flows of the Brazos River at Waco

Water management in Texas is governed by the need to be prepared for extended droughts. The hydrologically most severe drought on record for most of the state began gradually in 1950 and ended in April 1957 with one of the largest floods on record. Droughts during the 1910s and 1930s were also extended multiple-year dry periods over large areas. The 1995–1996 drought that motivated the enactment of the 1997 SB1 was much more costly than the earlier droughts because of the larger population and economic growth. In terms of annual precipitation, for more than half of Texas, 2011 was the driest year since the beginning of official precipitation records in 1895.

Water Management Community

Key agencies responsible for administering the statewide programs discussed in this paper are the TWDB, Texas Commission on Environmental Quality (TCEQ), and Texas Parks and Wildlife Department (TPWD). The TCEQ, with approximately 2,800 employees, is responsible for administering numerous regulatory programs for protecting natural resources and human health, including the water allocation functions highlighted in this paper. The TWDB, with approximately 800 employees, is responsible for statewide planning and programs for financing water projects and promoting efficient water conservation practices. The TWDB has for many years administrated revolving loan programs to assist local and regional entities in financing water projects, which in 2013 were significantly expanded with legislative and voter approval. The TPWD plays a key role in TCEQ and TWDB activities, particularly with regard to protecting and enhancing fish, wildlife, and ecosystems.

Partnering and consensus water planning are key concepts in Texas. State water programs are characterized by close collaboration between the TCEQ, TWDB, TPWD, and between these agencies and the water management community. The TWDB is the lead agency for the SB1 regional and statewide planning efforts, with the TCEQ and TPWD playing supporting roles. The TCEQ administers the water right permit system, but consistency with regional plans is a requirement for approval of water right permit applications. The TCEQ maintains the WAM system developed pursuant to SB1, but the TWDB and SB1 regional planning groups routinely apply the modeling system. The TCEQ, TWDB, and TPWD are partners in implementing the SB2 TIFP and SB3 procedures for establishing environmental flow standards.

Water supply infrastructure is constructed and maintained by numerous cities, municipal water districts, irrigation districts, river authorities, and utility companies. Groundwater conservation districts provide leadership in managing groundwater. Nineteen river authorities are responsible for development and management of the water resources of all or portions of major river basins. River authorities construct and operate their own reservoir projects and contract for storage capacity in federal reservoirs.

Federal involvement in developing the state's water resources includes 32 U.S. Army Corps of Engineers (USACE) reservoirs and 2 International Boundary and Water Commission (IBWC) reservoirs that account for approximately 40 and 90% of the conservation and flood control, respectively, storage capacity of the 200 major reservoirs with storage capacities of at least 6.17×10^6 m^3. River authorities and cities have contracted for the water supply storage capacity of the USACE reservoirs. The USACE is responsible for flood control operations. The Bureau of Reclamation constructed three reservoirs that are now owned by local entities.

Consulting engineering firms provide essential technical support to the water management agencies. University researchers also contribute. For example, the author of this paper and his research group working through the Texas Water Resources Institute (TWRI) of the Texas A&M University System were instrumental in the initial development of the WAM system during 1997–2003 and have continued to expand the modeling system under the sponsorship of the TCEQ and other agencies through the present.

A variety of legislatively established committees facilitate integration of the overall water management community in endeavors administered through the TWDB and TCEQ. For example, the Legislature created the Water Conservation Advisory Council in its 2007 SB3. The 23-member Council represents a comprehensive spectrum of agency programs, water use sectors, and stakeholders in promoting water conservation in planning, water right permitting, and financing programs at the state level and municipal, industrial, and agricultural water supply activities at the local level.

Regional and Statewide Planning

The Texas Legislature traditionally assigns the designation "Senate Bill 1" during each legislative session to legislation of special importance. Motivated by severe drought conditions during 1995–1996, the 1997 SB1 created a regional and statewide water-planning process and authorized the development of the WAM system to support both the planning process and administration of the water rights permit system.

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The original Texas Water Plan was published by the TWDB in 1961 and updated several times during the 1970s–1990s. The 1997 SB1 emphasized the concept of integrating local stakeholder-guided consensus-based planning with statewide TWDB-led planning. A process was established for developing 16 regional plans and a statewide plan at 5-year planning cycles, with a 50-year future planning horizon. Updated plans were completed in 2002, 2007, and 2012, and the current cycle is scheduled for completion in 2017. The various updates of the 16 regional plans and statewide plan are documented by voluminous reports available at the TWDB website along with regulations governing the planning process and other information.

The 16 planning regions are delineated by sets of counties, considering river basins, aquifers, and municipal and agricultural water use areas. Under the SB1 planning process, regional plans are developed under the guidance of committees, representing at least the following 11 interests: public, counties, municipalities, industries, agriculture, environment, small businesses, electric utilities, river authorities, water districts, and water utilities. The 16 planning groups total more than 400 members. The TWDB provides administrative leadership and technical and funding support for the regional planning groups. The TCEQ, TPWD, and consulting firms also provide professional services as needed. The TWDB coordinates with the general public in the process of integrating the regional plans into a statewide plan.

The 2012 State Water Plan (TWDB 2012) is presented in a set of reports available at the TWDB website. Annual water demands of $22.2 \times 10^9\ m^3/year$ in 2010 were distributed among use sectors as follows: agricultural irrigation (56.0%), municipal (26.9%), manufacturing (9.6%), mining (1.6%), consumptive use of stream electric cooling water (4.1%), and livestock (1.8%). Although the population of Texas is expected to increase by 82% between 2010 and 2060 (from 25.4 to 46.3 million), water demands are projected to increase by only 22% because of more efficient agricultural irrigation. Municipal and industrial water use is expected to increase dramatically whereas agricultural use declines. Available water supplies with existing infrastructure and current institutional arrangements will significantly decrease during 2010–2060 because of depletion of groundwater aquifers and reservoir sedimentation. The TWDB (2012) predicts that without implementation of needed new measures, annual economic losses of approximately \$11.9 billion/year would result if then-current (2011) drought conditions approach the 1950–1957 drought of record and as much as \$116 billion annually, with over a million lost jobs, with projected 2060 population growth combined with 1950–1957 drought conditions.

The regional planning groups have identified 562 proposed water supply projects with an estimated cost of approximately \$53 billion to meet projected future needs during droughts. Approximately 34% of the projected 2060 shortages are expected to be met through water conservation and reuse, 17% from new reservoirs, and 34% from other surface water supplies, leaving significant projected unmet future needs. Four regional planning groups were able to identify strategies for meeting all of their projected 2060 water needs, but the other 12 planning groups were not able to identify feasible strategies for supplying all future water needs.

Groundwater Management

Approximately 80% of Texas is underlain by 9 major and 21 minor aquifers. Agricultural irrigation currently accounts for 80% of groundwater use. Municipalities now account for approximately 15% of groundwater use, which supplies approximately 35% of municipal water demands.

Depleting groundwater reserves caused by excessive pumping is a major problem. Groundwater use accounted for more than 70% of total water use in 1970 and approximately 50% in 2010. The TWDB projects that present groundwater supplies of $10.0 \times 10^9\ m^3/year$ will decline by 30% to $7.0 \times 10^9\ m^3/year$ by 2060. Declines in aquifer levels have motivated more-efficient water use practices and shifting to a greater reliance on surface water.

The Gulf Coast and Ogallala Aquifers account for the largest volume declines in groundwater supplies. Before the 1970s, the City of Houston and its vicinity relied almost totally on the Gulf Coast Aquifer. However, overpumping of groundwater resulted in major subsistence problems, with the ground surface lowering by several meters. Thus, Houston and neighboring cities and industries are shifting from groundwater to near-total reliance on surface water. Historically, irrigated agriculture in the High Plains Region of northern Texas supplied by the Ogallala Aquifer accounted for a very large portion of the total statewide water use. However, water table declines in the Ogallala Aquifer combined with scarce surface water supply alternatives have resulted in significant decreases in irrigation that are projected to continue in the future.

Groundwater is managed in an entirely different fashion than surface water in Texas. Groundwater rights in Texas have historically been based on the common law rule allowing land owners to pump as much water as they wish from under their land. However, increased state regulation of groundwater is evolving over time primarily through the establishment of local groundwater conservation districts.

In 1949 and 1985, the Texas Legislature passed laws authorizing the creation of groundwater conservation districts with local county-level voter approval. The 1949 legislation allows local residents to petition the state to have a district created. The 1985 amendment authorizes the TCEQ to initiate the formation of districts for areas with critical problems. Local voters can still veto a proposed district, but if they do, state funding for water projects can be withheld. Twelve districts existed before 1985. As of 2014, 102 groundwater districts cover all or part of 184 of the state's 254 counties. The primary purposes of the districts are to encourage water conservation and protect water quality. Legislatively mandated duties of the groundwater conservation districts include permitting water wells, developing a comprehensive management plan, and adopting the necessary rules to implement the management plan.

Most districts focus their efforts toward prevention of waste, water conservation education, recharge projects, and data collection. Some regulate pumping. The districts tread a narrow path between private ownership of groundwater and state responsibility to protect the water resource. Texans are reluctant to allow anyone to tell them how much water they can pump from under their own land. Governmental regulation of pumping has been driven by necessity, as depleting aquifers resulted in major problems.

The Harris-Galveston Coastal Subsidence District and Edwards Underground Water Authority have developed the strongest permitting systems to regulate groundwater use. The Subsidence District was created in 1957 in response to severe subsidence in the low-lying, urbanized coastal region containing the cities of Houston and Galveston caused by overdrafting groundwater. The Edwards Aquifer Authority was created in 1993 largely because of a federal court ruling protecting endangered species under the Endangered Species Act. The Edwards is a limestone aquifer shared by San Antonio, several smaller cities, and extensive irrigated farming interests. Springs fed by the Edwards Aquifer maintain the flow of several rivers and support ecosystems that include endangered species.

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Surface Water Allocation

Water allocation systems for the 15 major river basins and eight coastal basins of Texas delineated in Fig. 3 and simulated in the WAM system described later in this paper include:

- A water rights permit system administered by the TCEQ, which includes approximately 6,000 active permits, with the allocation mechanisms for the Lower Rio Grande being very different from those for the remainder of the state;
- 1903 and 1944 treaties between Mexico and the United States allocating the waters of the Rio Grande between the two nations and agreements implementing the treaties;
- Five interstate compacts with neighboring states with different allocation mechanisms;
- Water supply storage contracts between the federal government and nonfederal entities for conservation storage capacity in each of 32 federal multiple-purpose reservoirs; and
- Various other agreements between water management entities.

Water right systems serve to equitably apportion water resources among users; protect existing water users from having their supplies diminished by new users; govern the sharing of limited water during droughts when supplies are inadequate to meet all needs; and facilitate efficient water use. Effective water allocation becomes particularly important as demands exceed reliable supplies.

Water rights in Texas evolved over several centuries into an unmanageable assortment of poorly recorded and often conflicting rights. The severe drought during 1950–1957 motivated a massive lawsuit in the Lower Rio Grande, which demonstrated the impracticality of a purely judicial adjudication of water rights statewide. Thus, the Water Rights Adjudication Act was enacted by the Texas legislature in 1967 to require a recording of all claims for water rights, limit the exercise of those claims to actual use, and provide for the adjudication and administration of water rights. All riparian water rights were merged into the prior appropriation permit system, creating two variations. One permit system is designed for managing the use of water from International Amistad and Falcon Reservoirs on the Rio Grande, and the other is applicable to the remainder of Texas. The water rights adjudication process required for transition to the permit system was initiated in 1968 and completed by about 1990.

Water rights are granted by a state license, or permit, which allows the holder to divert a specified amount of water annually at a specific location, for a specific purpose, and to store water in reservoirs of specified capacity. Any organization or person may submit an application to the TCEQ for a new water right or to change an existing water right at any time. The TCEQ will approve the permit application if unappropriated water is available, existing water rights are not impaired, efficient water conservation will be practiced, and proposed actions are consistent with regional water plans. During the 1967–1990 adjudication process, priority dates were established on the basis of historical water use. Since then, priorities are based on the dates that the permits are administratively approved. A permit holder has no actual title of ownership of the water but only a right to use the water. However, a water right can be sold, leased, or transferred to another person.

Environmental Flows

In the past, the TCEQ has used special permit conditions to require consideration of instream uses, freshwater inflows, water quality, and fish and wildlife habitat, with requirements defined in terms of minimum flow limits imposed upon the particular permit. More sophisticated environmental flow standards have recently been established pursuant to SB2 and SB3.

SB2 enacted into law by the Texas Legislature in 2001 established the Texas Instream Flow Program jointly administered by the TCEQ, TWDB, and TPWD. SB2 directed the agencies to collect data and conduct studies to develop methods for determining flow conditions necessary to support a sound ecological environment. The TWDB maintains the TIFP website where relevant reports and information are compiled for convenient access. The TCEQ, TPWD, and TWDB have developed methods for performing environmental flow studies, which have been reviewed by the National Research Council (2005). The TIFP studies consider a wide range of environmental variables such as habitat, hydrology, biology, geomorphology, water quality, and stream system connectivity, dictating a multidisciplinary collaboration.

Many years will be required to perform detailed studies for all of the river systems of the state under the TIFP. Recognizing the need to expeditiously determine appropriate amounts of water to set aside for the environment, the Texas Legislature in its 2007 SB3 created an accelerated process for establishing environmental flow standards for selected priority river systems by using existing information and the best available science. The schedules set by the SB3 process preclude completion of more detailed TIFP studies before establishing flow standards, but TIFP studies can facilitate future refinements of the environmental flow standards.

The SB3 regulatory process results in environmental flow standards, which are incorporated in the WAM system (Wurbs and Hoffpauir 2013a). Flow standards consist of metrics and rules that vary with location, season, and hydrologic condition that govern decisions to curtail diversion and/or storage of stream flows by junior water rights. The standards are defined in terms of flow regimes that describe the magnitude, frequency, duration, timing, and rate of change of flows required to maintain a sound ecology. A flow regime includes subsistence flows, base flows, within-bank high-flow pulses, and overbank high-flow pulses.

The process will require many years to fully implement statewide, but flow standards have been established during 2011–2014 by the TCEQ on the basis of on recommendations of science teams and stakeholder committees for the following selected priority river systems: Sabine and Neches Rivers and Sabine Lake Bay; Trinity and San Jacinto Rivers and Galveston Bay; Colorado and Lavaca Rivers and Matagorda and Lavaca Bays; Guadalupe, San Antonio, Mission, and Aransas Rivers and Mission, Copano, and San Antonio Bays; Nueces River and Corpus Christi and Baffin Bays; and Brazos River and estuary system.

The SB3 regulatory process is based on regional public participation, statewide agency oversight, and technical support by the science and engineering community. Local stakeholders and technical experts develop recommendations regarding the appropriate environmental flow regime for particular river basin and bay systems. The TCEQ, TWDB, and TPWD provide administrative leadership and technical and funding support. The committees described in the following paragraphs are responsible for specified components of the process. Information compiled during this process is maintained at a TCEQ website.

An advisory group provides general oversight, investigates public policy implications, and oversees the appointment of committees. The advisory group is composed of one member each from the TCEQ, TWDB, and TPWD, three members of the Texas Senate, and three members of the House of Representatives. A science advisory committee is composed nine scientists and engineers from consulting firms and universities with diverse experience in hydrology, hydraulics, biology, geomorphology, geology, water quality, and other technical areas pertinent to the evaluation of environmental flows.

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A basin and bay area stakeholder committee (BBASC) is appointed for each priority river system. Each BBASC consists of at least 17 members who reflect an equitable balance of interest groups. Each BBASC must establish a basin and bay expert science team (BBEST). The BBEST is responsible for developing a recommended flow regime for its particular river system considering only environmental needs without regard to needs for human water uses. The BBASC reviews the BBEST report and develops an environmental flow regime on the basis of a comprehensive consideration of all water needs, including human and ecosystem needs.

The TCEQ is responsible for adopting flow standards for each river basin and bay system that are adequate to support a sound ecological environment to the maximum extent reasonable, considering other public interests and other relevant factors. The flow standards are adopted through the TCEQ rule-making procedures based on recommendations of BBESTs and BBASCs. The TCEQ evaluation of recommended standards includes public review and comment.

The environmental flow standards are incorporated in the WAM system with a priority based on the date the TCEQ receives the environmental flow regime recommendations from the applicable BBEST. Thereafter, the TCEQ may not issue a permit for a new appropriation or amendment to an existing water right permit that increases the amount of water authorized to be stored or diverted if any environmental flow standard would be impaired. In amending existing permits, this restriction applies only to the increase in amount of water to be stored or diverted.

WAM System

Effective water management requires detailed assessments of water availability and supply reliability, which depend on complex institutional considerations and natural hydrology and constructed infrastructure. Implementation of the Texas WAM system highlights the importance of the following institutional dimensions of water availability modeling: (1) modeling water rights, contractual agreements, treaties, interstate compacts, and other complex institutional aspects of water resources development, management, allocation, and use is important; and (2) effective implementation of the modeling system required a partnership effort of a water management community that includes the Legislature, water users, government agencies, consulting firms, and university researchers.

The Texas WAM system consists of the Water Rights Analysis Package (WRAP) developed at Texas A&M University (TAMU) and WRAP input data sets for all the river basins of the state (Wurbs 2005). The TCEQ as lead agency, TWDB, TPWD, and contractors consisting of university researchers and 10 consulting engineering firms initially implemented the WAM system during 1997–2003 pursuant to the 1997 SB1. The generalized WRAP modeling system has continued to be expanded and improved at TAMU under the sponsorship of the TCEQ and other agencies. The TCEQ continues to update WAM input data sets as new and revised water right permits are approved, hydrology data accumulates, and modeling capabilities are expanded.

The TWDB, regional planning groups, and their consultants apply the WAM system in SB3 planning studies. Capabilities for supplying water needs under alternative future-use scenarios are assessed with alternative proposed projects and management strategies. The TCEQ requires that water right permit applicants or their consultants apply the WAM system to evaluate reliabilities associated with their proposed plans and the effects on the reliabilities of all other water rights. The TCEQ staff uses the model to evaluate water right permit applications. The WAM system is also used by water agencies and consulting firms to support other planning and management efforts that are not directly associated with the water right permitting and SB1 planning activities.

The TCEQ issues or modifies many water right permits each year and also rejects many applications. For some river reaches, water is available for further appropriation. However, major reaches of most rivers, particularly in dry west Texas and populous urban areas elsewhere, are overappropriated, and the TCEQ will not issue permits for additional use. Marketing or transferring of existing water rights among users is encouraged. The majority of water transfers have consisted of cities purchasing water rights from farmers or agricultural irrigation districts. Water Availability Modeling analyses are required for permit applications for transferring water rights between users even if the total amount of appropriated water is not increased.

WRAP Modeling System

Water Rights Analysis Package is generalized for application anywhere in the world, with input data sets being developed for the particular river systems of concern. For applications in Texas, publically available WAM data sets are altered to reflect proposed water management plans of interest, which could involve changes in water use or system operating practices, construction of new facilities, or other water management strategies. The public domain modeling system facilitates assessments of hydrologic and institutional capabilities for satisfying requirements for water supply, hydroelectric energy generation, environmental flows, flood control, and reservoir storage. In WRAP terminology, water use requirements, water control infrastructure, and operating strategies are called water rights. Basinwide impacts of proposed actions are modeled.

The routinely applied WRAP modeling system documented by Wurbs (2013a, b, c) uses a monthly computational time step. Recently added daily modeling features expand capabilities for simulating SB3 environmental flow standards and their impacts on water supply capabilities (Wurbs and Hoffpauir 2013a, b). The daily modeling system includes flow forecasting and routing, disaggregation of monthly naturalized flows and water demands to daily, simulation of flood control reservoir operations, and tracking high-flow pulses of specified frequencies for environmental flow standards along with subsistence and base flows. A salinity simulation component is also available (Wurbs 2009).

A specified water management scenario is combined with historical hydrology. The WRAP system simulates capabilities of river and reservoir systems in meeting water demand targets for given sequences of naturalized stream flows and reservoir net evaporation rates. Historical natural hydrology is used to capture the hydrologic characteristics of a river basin. The water management and use scenario may 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.

WAM System Data Sets

The 20 WAM data sets listed in Table 1 model the 23 river basins delineated in Fig. 3. The Guadalupe and San Antonio River basins are combined in a single model, and the Brazos and Colorado WAMs include adjoining coastal basins. The hydrology files of the 20 data sets include sequences of monthly naturalized flows covering hydrologic periods of analysis of at least 50 years at a total of 500 primary control points, most of which are sites of gauging stations, and watershed parameters for synthesizing natural flows at almost 13,000 ungauged sites based on the flows at the

Table 1. Summary of Means from Current Use Scenario WAM Simulations

River basin	Area in Texas (10^6 km)	Mean precipitation (cm/year)	Reservoir Capacity (10^6 m^3)	Reservoir Contents (% cap)	Use target (10^6 m^3/year)	Reliability (%)	Natural flow (10^6 m^3/year)	Regulated flow (% nat)
Brazos and coastal	114,750	74.8	4,956	83.0	1,875	93.3	8,942	84.2
Canadian	33,320	49.5	1,086	69.4	116	95.4	268	59.0
Colorado and coastal	106,910	62.2	5,812	74.3	2,759	82.5	3,849	61.2
Cypress	7,586	120.0	1,083	85.9	612	78.0	2,068	87.9
Guadalupe and San Antonio	26,244	82.0	934	79.8	519	90.9	2,740	92.9
Lavaca	5,980	100.9	207	92.6	76.0	82.4	1,062	93.7
Neches	25,737	123.6	4,512	98.2	767	81.2	7,680	89.5
Nueces	43,253	63.0	1,184	53.0	786	87.4	800	68.0
Red	62,929	64.9	3,267	85.0	1,062	97.2	6,228	90.3
Rio Grande	127,912	40.8	4,318	49.0	2,750	81.7	1,357	6.84
Sabine	19,606	121.3	4,980	97.2	679	98.7	4,093	93.3
San Jacinto	10,194	118.5	725	91.2	642	83.2	2,801	49.3
Sulphur	9,272	118.4	887	86.9	299	99.2	3,197	86.9
Trinity	46,395	100.0	9,078	79.1	8,166	86.9	8,182	72.8
Colorado-Lavaca	2,432	101.7	8.92	82.6	44.6	65.1	371	97.1
Lavaca-Guadalupe	2,585	100.6	0.00	0.00	0.28	69.1	489	102.6
Neches-Trinity	1,992	125.9	71.6	34.2	258	67.4	502	91.4
Nueces–Rio Grande	27,045	64.2	140	34.5	15.0	38.0	1,423	105.9
San Antonio–Nueces	6,869	89.0	1.83	76.9	0.59	89.4	697	100.0
Trinity–San Jacinto	640	122.2	6.02	65.5	12.5	78.4	223	105.1
Entire state	681,650	79.0	47,400	79.8	21,440	86.5	56,970	80.9

primary control points. Net evaporation rates are provided for reservoirs. The data sets also include channel loss factors.

The data sets model approximately 6,000 water right permits and 3,400 reservoirs. More than 90% of the total storage capacity of the 3,400 permitted reservoirs is contained in the 200 reservoirs that have conservation capacities exceeding 6.17×10^6 m^3. 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 and Texas water rights.

The WRAP water rights input data sets for two scenarios, authorized use and current use, are used in the water rights permitting process. The TWDB has developed data sets based on projected future water use scenarios for use in planning studies along with the authorized- and current-use scenario data sets. The TCEQ uses the authorized-use scenario data sets in evaluating regular permit applications and the current-use data sets for term permits. Regular permits are for perpetuity. Term permits are valid only for a specified period, typically ranging from 1 to several years.

Daily data sets incorporating environmental flow standards established through the SB3 process are being developed at TAMU under the sponsorship of the TCEQ. Daily models supplement rather than replace the monthly models. Strategies for applying the monthly and daily models in combination are being investigated, including a strategy outlined by Wurbs and Hoffpauir (2013a) based on summing daily environmental flow targets computed in a daily simulation to series of aggregated monthly quantities incorporated in the monthly WAM input.

Statewide WAM Summary Overview

Wurbs and Zhang (2014) applied the current-use scenario data sets with a monthly time step to explore changes in river flows and water budgets. The simulation results summarized in Tables 1 and 2 cover all of Texas but include only the Texas share of the water resources of the Rio Grande and interstate rivers as defined by international treaties and interstate compacts.

The means of reservoir storage, water supply diversions, and naturalized and regulated flows at the basin outlets are shown in Table 1 along with the totals for the entire state. Mean reservoir storage contents are shown as a percent of conservation storage capacity. Water supply reliability is the volume supplied expressed as a percent of the demand volume. Statewide, 86.5% of the current water demand could be supplied during a hypothetical repetition of historical hydrology. Regulated flow is expressed as a percent of naturalized flow in Table 1 for comparison. Figs. 4 and 5 highlight the extreme variability of river flows throughout Texas that is not portrayed in the long-term means of Tables 1 and 2.

The Trinity WAM has 700 reservoirs with a total water supply storage capacity of $9{,}078 \times 10^6$ m^3, which is the largest storage capacity of the 20 river basin models listed in Table 1. The 46 reservoirs with capacities greater than 6.17×10^6 m^3 (5,000 acre-ft) contain 97.8% of the water supply storage capacity of the 700 reservoirs. The large reservoirs in the upper basin are owned by the cities of Dallas and Fort Worth, Tarrant Regional Water Authority, Trinity River Authority, and USACE. Lake Livingston on the lower Trinity River is operated by the Trinity River Authority to supply water by pipeline to the city of Houston located in the San Jacinto

Table 2. River System Water Budgets Aggregated to Statewide Budget

Water budget component	+ or −	Quantity (10^6 m^3/year)
Naturalized flows at coast or state borders	Inflow	56,970
Water supply diversions	Outflow	18,550
Return flows from surface and ground water use	Inflow	10,500
Reservoir surface net evaporation-precipitation	Outflow	3,010
Net of all other gains and losses	Inflow	180
Regulated flows at coast or state borders	Outflow	46,090

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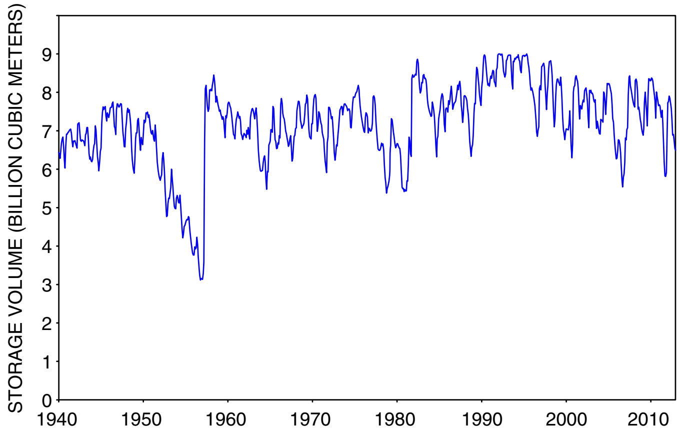

Fig. 6. Total 1940–2013 simulated end-of-month storage contents of 700 reservoirs in the Trinity River basin

River basin. The total storage contents of the 700 reservoirs for each month of the simulation combining the current water use scenario and 1940–2013 hydrologic period of analysis are plotted in Fig. 6. The 1950s drought ending with the April 1957 flood is evident in the storage plot.

The statewide water budget of Table 2 was compiled from the current-use scenario WAM simulations of the individual river basins of Table 1 (Wurbs and Zhang 2014). The quantities in Table 2 sum to zero when added or subtracted, as indicated in the middle column. Naturalized flow is the only quantity that represents natural conditions. The other variables all reflect the effects of development. Net reservoir evaporation is attributable to reservoir construction. Return flows include water supply withdrawals from both surface and groundwater.

The $56{,}970 \times 10^6\ \mathrm{m}^3/\mathrm{year}$ long-term mean of naturalized stream flows that would flow from Texas under natural undeveloped conditions is 11.8% of the mean volume of precipitation falling on the state. If historical hydrology is hypothetically repeated in combination with current conditions of water resources development and use, the mean regulated flow from Texas is 80.9% of the flow under natural undeveloped conditions. Current water supply demands are 37.6% of WAM naturalized flow.

Lessons Learned and Unresolved Issues

This paper begins with a simple definition of sustainability. However, actually assessing the present and future water needs of people and ecosystems, the capabilities for supplying these needs, and the impairments to meeting the needs is complex. Endeavors in Texas to manage and use water resources in a sustainable manner illustrate basic concepts that are also relevant in other regions of the world. Likewise, key issues that are still unresolved in Texas illustrate important concerns elsewhere.

Groundwater and surface water are very different from the perspectives of physical hydrology, legal and institutional systems, and water management strategies. The karst limestone Edwards Aquifer responds relatively quickly to precipitation and pumping, and its regulation is governed by protecting spring flows. However, other aquifers of the state have been drawn down by many decades of overpumping and require a long time to recharge.

Groundwater is legally the property of the land owner. Major problems of overpumping have forced a movement toward greater regulation, which has been countered with strong landowner and political opposition. Conjunctive management of surface and groundwater is hindered. Because Texas has not been able to create a statewide permit system to manage groundwater like those in many other states, the alternative strategy adopted has been local control through creation of groundwater conservation districts.

The state has successfully implemented a statewide surface water rights permit system administered by a single agency, the TCEQ, which also provides staff support for five interstate compact commissions. The International Boundary and Water Commission administers the allocation of the waters of the Rio Grande pursuant to 1903 and 1944 international treaties, and the TCEQ administers the water rights for the Texas share of the reservoir storage and river flow.

The general concept of the prior appropriation doctrine has been well established over the past century in the western states. Protection of existing water users is important as population and economic growth intensifies demands for water resources. However, strictly applying the first-in-time rule to all aspects of water management is not feasible. For example, water right permits in Texas combine water supply diversions and reservoir storage. Protecting reservoir inflows is critical to providing a dependable water supply. However, forcing appropriators, with rights junior to the rights of reservoir owners, to curtail diversions to maintain inflows to partially full reservoirs is likely not the optimal use of water resources. If junior diversions are not curtailed, reservoirs will likely later refill anyway without failures to supply water needs.

Water resources management consists largely of managing extreme variability and uncertainty. Long-term mean river flows may be relatively large, but much of the flow occurs during infrequent flood events. Dams with large storage volumes are essential to develop dependable water supplies and mitigate flood risks. Water management in Texas is based largely on preparing for a future drought comparable with that of 1950–1957. Although past and current periods of dry weather have resulted in economic losses greatly exceeding those of 1950–1957, the state has never experienced extended hydrologic drought conditions comparable to 1950–1957 combined with present population and economic development. A more severe drought will occur sometime in the future, but its timing is unknown.

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 often lost through reservoir evaporation. Texas WAM studies indicate that quantities that may be supplied change greatly with relatively small changes in reliability requirements. The amount of water supplied from Texas river/reservoir systems can be increased significantly by accepting higher risks of shortages or emergency demand reductions.

In evaluating new permit applications, the TCEQ applies criteria that municipal needs should always be supplied in the WAM simulation. For an agricultural irrigation permit, at least 75% of the demand should be supplied at least 75% of the time in the simulation for the permit application to be approved. Adverse effects on the reliabilities associated with existing senior water right permits must be negligible. Many old permits do not meet these criteria. Although the WAM system provides very useful quantitative information, the criteria and conditions defining acceptable reliability levels are policy decisions that greatly affect the quantity of water available.

The Lower Colorado River Authority water right permit includes a water management plan that is periodically updated and

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recently intensely scrutinized. The Brazos River Authority (BRA) submitted an application to the TCEQ for a systemwide water right permit in 2004 that also includes a water panagement plan. After extensive studies and public review, this BRA system permit application is expected to be approved in 2015. These water management plans include the concept of combining firm and interruptible water supplies. The river authorities have contracts with agricultural irrigation users that allow curtailments of water deliveries to protect municipal and industrial customers as reservoir levels drop below specified trigger levels.

In the past, water right permits were granted for individual reservoirs rather than multiple-reservoir systems. Several major multiple-reservoir systems have component reservoirs with water rights established at different times and diversions occurring at many downstream and lakeside locations. Water Availability Modeling studies have demonstrated the benefits of multiple-reservoir system operations that may not be adequately recognized in the original water right permits.

Access to return flows is also an issue. State policies and practices encourage reuse. Return flows are not required in most water right permits. However, treatment plant effluent becomes state water upon discharge into a river. Permit applications allowing cities to divert their own return flows from the river farther downstream have been opposed by downstream water users and environmental advocates with concerns regarding reducing river flows.

Environmental flow needs have not been adequately protected in the past. The 2001 SB2 mandated a statewide effort to assess environmental flow needs and establish strategies for meeting these needs. With recognition that many years that will be required to achieve optimal standards, the 2007 SB3 established a procedure to establish environmental flow standards in an expedited manner for selected priority river systems. Environmental flow requirements incorporated into the water right permit system during 2011–2014 will be periodically reviewed and improved in the future as additional information is developed. The environmental flow standards established pursuant to SB3 have priorities set on the date the appointed expert science teams submitted recommendations to the TCEQ. Water availability for future water right applicants is significantly affected, but existing water right permit holders are not affected.

Water availability depends on water quality and quantity. The Permian Basin geologic region in the upper watersheds of the Pecos, Colorado, Brazos, and Red Rivers contribute large salt loads to these rivers, which constrain water use from several major reservoir systems in Texas. Brackish groundwater is also a potentially significant resource. Desalination of brackish surface and groundwater will continue to grow in importance in the future. Seawater desalination has not been practiced in Texas in the past, other than through experimental research and development projects, but is included in the inventory of potential future measures.

Climate change caused by global warming is being extensively explored by scientists and water managers worldwide. The naturalized flows in the WAM system show no evident trends of long-term change in the past (Wurbs and Zhang 2014), but the future is highly uncertain. Hydrology and water management are characterized by great variability and uncertainty even without long-term climate change. Climate change adds more uncertainty. Water management entities that have reservoir storage capacities and water right permits needed to deal with the great variability and uncertainty that already exists will be better prepared to deal with the effects of future climate change than those that do not (Wurbs et al. 2005).

The TCEQ Lower Rio Grande Watermaster allocates storage in and releases from Amistad and Falcon Reservoirs. The TCEQ South Texas Watermaster monitors water rights in the Nueces, San Antonio, Guadalupe, and Lavaca River basins, and adjoining coastal basins. Watermaster operations in the Brazos River basin will begin in 2015. For the remainder of Texas, TCEQ administers curtailment actions as necessary during droughts, but local offices have not been established to perform detailed monitoring and accounting. TCEQ is investigating the feasibility of expanding local water master operations throughout the state.

Understanding water availability and supply reliability is essential for effective water management. The WAM system significantly contributes to water management in Texas. Model implementation required an institutional partnership effort of a water management community.

The Texas experience illustrates the integration of water allocation and planning functions. Water allocation has become an important aspect of water management. Consistency with regional plans is required for approval of water right permit applications. The same modeling system is applied in local, regional, and statewide planning studies and in the preparation and evaluation of water right permit applications.

Conclusions

With growing demands on limited resources, sustainable water management is an important challenge in Texas, as in many other regions of the world. The water management community of Texas must deal with extreme hydrologic variability, declining groundwater reserves, rapid population growth, and diverse climate, economic development, and water management practices in the different regions of the state. Water management endeavors mandated by SB1, SB2, and SB3 enacted by the Legislature in 1997, 2001, and 2007 build upon a long history of water resources development, allocation, and management. Partnerships and consensus building are key aspects of water resources planning and management in Texas. The water management community has achieved significant success in implementing the legislatively mandated programs described in this paper along with defining issues yet to be fully resolved. Water management guided by the goal of sustainability is a complex multiple-dimensioned long-term evolving process.

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