WATER RIGHTS CONSIDERATIONS IN RESERVOIR SYSTEM MANAGEMENT

Ralph A. Wurbs
Professor of Civil Engineering
Texas A&M University

INTRODUCTION

Allocation of water resources among different entities is a key aspect of river basin management that becomes particularly important as demands approach and exceed supplies. Streamflow and reservoir storage capacity in major river basins are typically shared by many water users. Water rights systems provide a basis to (1) allocate resources among users, (2) protect existing users from having their supplies diminished by new users, and (3) govern the sharing of limited streamflow and water in storage during droughts when supplies are inadequate to meet all needs. Water rights have historically played a greater role in reservoir system operations in the more arid western states of the United States than in the eastern states with more abundant water resources. However, water rights are growing in importance throughout the nation with increasing demands on limited water resources.

The institutional framework for reservoir system management may involve an hierarchy of water allocation systems. For example, the water resources of the Rio Grande, Colorado, and Columbia River Basins are allocated between nations by treaty. In these and other major river basins, water is allocated among states through river basin compacts and other means. Within individual states, water is shared by river authorities, municipal water districts, cities, irrigation districts, individual farmers, industries, and private citizens through water rights systems. A water district or river authority distributes water to its customers in accordance with contractual commitments.

A water right is the legal right for an entity to store, regulate, and/or divert water for beneficial use. Water rights systems are established primarily at the state level and vary between states. Legal rights to the use of streamflow are generally based on two alternative doctrines, riparian and prior appropriation. The basic concept of the riparian doctrine is that water rights are incidental to the ownership of land adjacent to a stream. The prior appropriation doctrine is based on the concept of protecting senior water users from having their supplies diminished by newcomers developing water supplies later in time. In a prior appropriation system, water rights are not inherent in land ownership, and priorities are established based on dates that water is appropriated. Water law in 29 eastern states is based primarily on the riparian doctrine. The prior appropriation doctrine governs water rights in nine western states. Ten other states, including Texas, originally had riparian systems but later converted to appropriation systems while preserving existing riparian rights. The remaining states, Hawaii and Louisiana, have unique types of hybrid systems (Rice and White 1991; Getches 1997). To assist states in formulating water rights systems, the Water Law Committee of the American Society of Civil Engineers recently published a model water code for riparian rights (Dellapenna 1997) and is in the process of publishing a model code for prior appropriation systems.

The experience of the state of Texas illustrates the issues involved in managing reservoir systems within a water rights framework. During the past three decades, the state has established two surface water rights permitting systems similar to those of other western states (Skillern 1988). One water rights system has been developed in the Lower Rio Grande Valley, and another otherwise statewide system is administered for the remainder of the state. Water rights have become a governing consideration in reservoir management throughout the state. Major efforts are presently underway for expanding capabilities for water management within this institutional setting. The issues and complexities encountered in Texas are representative of other states as well.

The objective of the paper is to use the state of Texas as a case study to outline key considerations in:

- developing and administering a water allocation system
- modeling reservoir/river systems and assessing water availability/reliability within the framework of a allocation system

The paper first describes water allocation in the state

and then highlights issues and complexities identified in a review of the Texas experience.

WATER MANAGEMENT IN TEXAS

Texas is a large state with diverse geography, economy, climate, and water resources. For example, mean annual precipitation varies from 8 inches (20 cm) at El Paso, on the Rio Grande in arid West Texas, to over 56 in (140 cm) in the humid lower Sabine River Basin in East Texas. The major river basins and larger cities of the state are shown in Figure 1.

Texas is illustrative of a full range of small to large reservoirs operated by a variety of entities. Conservation storage capacities totaling 40 million acre-feet (50 billion m^3) and flood control capacities totaling 19 million ac-ft (23 billion m^3) are provided by 189 major reservoirs with individual capacities of 5,000 acre-feet (6,170,000 m^3) or greater. Although there are several thousand smaller reservoirs, the 189 reservoirs with at least 5,000 ac-ft capacity account for over 95% of the storage capacity in the state. Lake Texoma on the Red River and Amistad Reservoir on the Rio Grande are the largest reservoirs in the state with capacities of 5.3 and 5.1 million ac-ft (6.6 and 6.3 billion m^3). Two reservoirs on the Rio Grande, operated by the International Boundary and Water Commission, and 32 U.S. Army Corps of Engineers reservoirs in eight other river basins account for about 43% of the conservation storage capacity and 89% of the flood control storage capacity in the 189 major reservoirs. Nineteen river authorities play key roles in comprehensive development and management of the water resources of all or portions of several river basins. The river authorities contract for storage capacity in federal reservoirs as well as construct and operate nonfederal reservoirs. Water districts, cities, and electric power companies also own and operate a number of the major reservoirs.

Texas participates in five interstate river compacts administered by commissions representing the member states. The rivers and the dates the compacts became effective are Rio Grande (1939), Pecos (1948), Canadian (1952), Sabine (1954), and Red (1980). The purposes of the interstate compacts are to provide for equitable apportionment of water between the states and to facilitate cooperative planning and management.

Population growth and diminishing groundwater reserves are resulting in increasing demands on the surface water resources of the state. Groundwater use has significantly exceeded recharge for many years resulting in water level declines in several of the major aquifer systems. In 1980, about 61% of the water use in the state was supplied from ground water and 39% from surface supply. In 1990, ground water supplied 47% and surface water 53% of the total water use. The shift from groundwater to surface water is expected to continue.

Water resources development and management in Texas is greatly influenced by the need to be prepared for infrequent severe droughts. Typically in the majority of the reservoirs, storage capacity is sized to provide dependable supplies during a severe multiple-year drought, and drawdowns are minimal in wet years. The present water rights system, with current demands and development, has not been tested by a major drought comparable to those of the 1910's, 1930's, and 1950's. The hydrologically most severe drought of record in Texas began in 1950 and ended in April 1957 with one of the largest floods on record. Although severe dry conditions and reservoir drawdowns such as the 1995-1996 drought have occurred periodically, the last several decades have been characterized by relatively abundant precipitation and streamflow compared to the droughts of the 1950's and earlier periods.

Historical Development of Water Rights in Texas

Rights to use streamflow in Texas have been granted historically under Spanish, Mexican, Republic of Texas, and State of Texas laws. Early water rights were based on various versions of the riparian doctrine. The prior appropriation doctrine was adopted in the 1890's, while still maintaining existing riparian rights. An essentially unmanageable system evolved, with various types of water rights existing simultaneously, with many rights being unrecorded. The drought of the 1950's motivated a 20-plus year effort to merge the numerous varied rights into a unified permit system. The 1995-1996 drought provided an impetus for further refinements. Two somewhat similar but yet distinctly different water rights systems have been developed, one in the Lower Rio Grande Valley and another for the rest of the state.

The Rio Grande is unique relative to the other river basins of Texas from several perspectives. It is an international river shared by two nations. The Lower Rio Grande Valley accounts for the majority of the surface water irrigation in Texas. The intensive

agricultural production of the region depends almost exclusively on the Rio Grande with little use of groundwater. Other major irrigation regions of the state rely primarily on groundwater. The water rights system for the Lower Rio Grande was developed separately and has distinct differences from the rest of the state, particularly in regard to the priority system and water master operations.

A map of the entire 356,000 mi^2 (870,000 km^2) Rio Grande Basin is provided as Figure 2. Only about 176,000 mi^2 of the basin actually contributes runoff to the Rio Grande. The non-contributing areas drain into internal closed subbasins. About 50% of the contributing watershed lies in the United States, and about 26% is in Texas. The Texas portion of the Rio Grande Basin encompasses about 18% of the state. Fort Quitman, located 90 miles downstream of the City of El Paso, is a key location in the both the international and state water allocation systems. Fort Quitman is 1,150 river miles above the Gulf of Mexico. The Texas share of the waters of the Rio Grande below Fort Quitman was allocated among numerous water rights holders in conjunction with a massive lawsuit, State of Texas v. Hidalgo County Water Control and Improvement District No. 18, commonly called the Lower Rio Grande Valley Water Case. The lawsuit was filed in 1956, the trial was held in 1964-1966, and the final judgment of the appellate court was filed in 1969. In 1971, the Texas Water Rights Commission adopted rules and regulations implementing the court decision. The assorted versions of riparian and appropriative rights were combined into a permit system. The litigants in the Rio Grande law suit included 42 water districts and 2,500 individuals. More than 90 lawyers appeared before the court. The expense and effort involved demonstrated the impracticality of a purely judicial determination of water rights for the entire state and led to enactment of the Water Rights Adjudication Act of 1967 (Templer 1981).

The present surface water rights system applicable to all of Texas, except for the Rio Grande below Fort Quitman, was established pursuant to the Water Rights Adjudication Act passed by the state legislature in 1967. The stated purpose of the Act was to require a recording of all claims for water rights which were not already recorded, to limit the exercise of those claims to actual use, and to provide for the adjudication and administration of water rights. The adjudication process required to merge all existing rights into a permit system was initiated in 1968 and completed in the late 1980's. All unrecorded claims were required to be filed with the Texas Water Rights Commission. Minor exceptions were made for those using only small quantities of water for domestic and livestock purposes. Claims were recognized only if valid under existing law and only to the extent of the maximum actual beneficial use of water without waste during any year from 1963 through 1967. Statewide 11,600 unrecorded claims were filed. Most were for riparian rights since most appropriative rights were already recorded. More than half the claims were rejected because they showed no water use during the base period. Shortly after receiving the claims, the Texas Water Rights Commission initiated a series of administrative adjudications of water rights by river segment, and permits called certificates of adjudication were issued. The adjudication process was essentially completed in the late 1980's. With the permit system now in place, applications for additional water rights are submitted and processed following prescribed procedures.

Unlike other western states with groundwater permit systems, groundwater rights in Texas are based essentially on the common law rule allowing land owners to pump as much water as they wish from under their land. The water rights permit system applies only to surface water.

Some centralized agency has administered some type of water rights system statewide since 1913. However, the agencies and water rights system have changed over time. The Board of Water Engineers was established in 1913; reorganized as the Texas Water Commission in 1962; and renamed the Texas Water Rights Commission in 1965 with non-water rights functions being transferred to the Texas Water Development Board which had been previously created in 1957. In 1977, the Texas Department of Water Resources was created by combining the Water Rights Commission, Water Development Board, and Water Quality Board. In 1985, the Texas Department of Water Resources was dissolved, and the Texas Water Commission and Texas Water Development Board became separate agencies. The Texas Water Development Board is responsible for developing and updating the State Water Plan and administering an array of financial assistance programs. The Texas Natural Resource Conservation Commission was created in 1993 by merging the Texas Water Commission and Texas Air Quality Board.

State Water Allocation System

The Texas Natural Resource Conservation Commission (TNRCC) is one of the largest and most comprehensive state environmental protection agencies in the nation. The TNRCC consists of three full-time commissioners appointed by the governor and a professional and administrative staff of over 3,000 employees. Water rights represent just one of many statewide regulatory responsibilities of the TNRCC.

The TNRCC presently administers about 7,000 active water rights permits including about 1,600 rights in the Lower Rio Grande Valley. Numerous other claims and permits have been canceled due to lack of water use or other reasons. The rights are held by river authorities, cities, municipal water districts, irrigation districts, individual farmers, companies, and private citizens. 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. The water allocation system described next is applicable to the entire state, except there are significant differences for the Rio Grande below Fort Quitman, which are noted in the discussion.

Anyone may submit an application to the TNRCC for a new water right or to change their existing water right at any time. The TNRCC will approve the application if unappropriated water is available, a beneficial use of the water is contemplated, water conservation will be practiced, existing water rights are not impaired, and the water use is not detrimental to the public welfare. After approval of an application, the TNRCC issues a permit giving the applicant the right to use a stated amount of water in a prescribed manner. Once the right to the use of water has been perfected by the issuance of a permit by the TNRCC and the subsequent beneficial use of the water by the permittee, the water authorized to be appropriated under the terms of the particular permit is not subject to further appropriation until the permit is canceled. A permit may be canceled if water is not used during a 10-year period. The Rio Grande has been over appropriated for many years with no new rights for additional water use being granted. However, rights are commonly transferred between users in the Rio Grande Basin.

A water permit holder has no actual title to the water but only a right to use the water. However, a water right can be sold, leased, or transferred to another person. The Lower Rio Grande Valley has been the only region of Texas with an active water market in the past. In 1993, the Texas Legislature established a statewide water bank to be administered by the Texas Water Development Board. Although transfers can be accomplished independently of the water bank, the program was created to encourage and facilitate water marketing, transfer, and reallocation.

The legal right to use or sell the water from a reservoir is usually granted to the owner prior to construction of the project. Many reservoirs are owned and operated by cities to provide water to their citizens for domestic, public, and commercial use. The city holds the permit or water right and sells the water to its citizen customers. Another common case is a reservoir or system of several reservoirs owned and operated by a river authority which sells the water to a number of cities, water districts, industries, businesses, and/or irrigators. The river authority holds the water right permit. The entities that purchase the water from the river authority are not required to hold a water right. The river authority operates the reservoirs to meet its contractual obligations to its customers. The nonfederal project sponsors which contract for the conservation storage in federal reservoirs are responsible for obtaining the appropriate water rights permits through the TNRCC.

Individual farmers, industries, and cities also hold water rights permits not associated with reservoirs. In several of the river basins, a number of reservoir operators, all holding appropriate water rights permits, operate reservoirs in the same basin. Reservoir operators are required to make releases, typically not exceeding inflows, to allow senior downstream users not associated with the reservoir access to the water for which they are legally entitled.

Although water-master operations are common in other western states, the Rio Grande and South Texas water-master offices, which are components of the TNRCC, are the only such programs in Texas. A water-master office has administered water rights and accounted for water use in the Rio Grande Basin since the 1960's.

The South Texas water-master was established in the late 1980's to administer water rights allocations in the Guadalupe, Nueces, and San Antonio River Basins. Plans during the 1980's to establish water-master programs throughout the state have been abandoned due to political considerations. The TNRCC responds to

reports of illegal water use anywhere in the state. However, with the exception of the Lower Rio Grande Valley, water withdrawals are not routinely monitored.

The Texas Water Code is based on the prior appropriation doctrine. For permits issued during the adjudication of existing rights pursuant to the Water Rights Adjudication Act of 1967, priority dates were established based on historical legal rights and actual water use. Since completion of the adjudication process, priorities for additional new rights are based upon the dates that the permit applications are filed. In general, senior water users are legally protected from more junior appropriators taking their water. However, a provision of the Texas Water Code, known as the Wagstaff Act, is an exception to this rule. The Wagstaff Act, originally enacted in 1931, states that "Any appropriation made after May 17, 1931 for any purpose other than domestic or municipal use is subject to the right of any city or town to make further appropriation of the water without paying for the water." The implications of the Wagstaff Act have not yet been defined by court cases. Major appropriations by cities under the Wagstaff Act have not occurred to date. However, the stature is expected to become increasingly important as demands on limited resources intensify.

For the Lower Rio Grande, priorities were set in conjunction with the previously discussed lawsuit. Water rights are divided into three categories. Municipal rights have the highest priority. Irrigation rights are divided into Class A and Class B rights, with Class A rights receiving more storage in Falcon and Amistad Reservoirs storage accounts in the allocation procedure described next. Although this weighted priority system for irrigation rights has little significance during years of plentiful water, its effect in water-short years is to distribute the shortage among all users, with the greater shortages occurring on lands with Class B water rights.

Allocation of the Waters of the Rio Grande

Allocation of the water resources of the Rio Grande Basin is governed by two international treaties and two

interstate compacts. Allocation of the Texas share of the waters to irrigators, cities, and other users is based on state law.

A 1906 Treaty between the United States and Mexico provides for delivery of 60,000 acre-feet/year of Rio Grande water to Mexico in the El Paso-Juarez Valley above Fort Quitman, Texas. Elephant Butte Reservoir in New Mexico, operated by the U.S. Bureau of Reclamation, and the American and International diversion dams near El Paso, operated by the International Boundary and Water Commission (IBWC), have been constructed to implement the water allocation provisions of the treaty. The treaty further provides that if water is unavailable, the amount allocated to Mexico shall be diminished in the same proportion as water delivered to irrigate lands in the United States. This provision has been invoked in about a third of the years since 1951.

The Rio Grande Compact approved by the legislatures of Colorado, New Mexico, and Texas in 1939 allocated the uncommitted waters of the Rio Grande above Fort Quitman. The Pecos River Compact adopted in 1949 allocates the waters of that tributary between Texas and New Mexico.

The 1944 Water Treaty expanded the International Boundary Commission to the International Boundary and Water Commission (IBWC), provided for the distribution of waters of the Rio Grande from Fort Quitman to the Gulf of Mexico between the two nations, and authorized construction of Amistad and Falcon Reservoirs. The 1944 Treaty also includes provisions for allocation of the waters of the Colorado River.

The International Amistad and Falcon Reservoirs are operated by the IBWC primarily for flood control and water supply for the Lower Rio Grande Valley and also provide hydroelectric power and recreation. Amistad Reservoir contains 3,380,000 acre-feet of conservation storage and 1,740,000 ac-ft of flood control storage. Falcon Reservoir contains 2,670,000 ac-ft of conservation storage and 510,000 ac-ft of flood control storage. In accordance with the 1944 Treaty, the United States has 56.2% and 58.6% of the conservation storage capacity of Amistad and Falcon, respectively, with Mexico owning the remaining conservation storage capacity. The IBWC operates the Anzaldus and Retamal Dams on the lower reach of the Rio Grande to facilitate diversions. The travel time for releases from Falcon Reservoir to reach the most downstream diversion locations is about a week. The Retamal and Anzaldus diversion dams and Falcon and Amistad storage dams are at river miles 133, 170, 275, and 574, respectively, on the Rio Grande above the Gulf of Mexico.

Streamflows into Falcon and Amistad Reservoirs are also allocated between the two countries. Flows on a number of major tributaries named in the treaty are gaged and allocated as specified by the treaty. All other flows not otherwise allocated are divided equally between the two countries. Mexico receives all the flows from several specified Mexican tributaries and two-thirds of the flows from other specified tributaries. The United States receives all the flows from certain U.S. tributaries and one-third of the flows from the other specified tributaries. Computations are performed weekly to allocate the reservoir inflow and evaporation volumes which are combined with recorded releases to determine the amount of water that each country has in storage.

The IBWC is totally responsible for flood control operations. Hydroelectric power generation is essentially limited to using water released anyway for other purposes. The United States share of the water supply storage in Amistad and Falcon Reservoirs is used to meet demands in the lower basin administered by the TNRCC in accordance with the water rights system. Irrigation districts, individual farmers, and cities communicate their water needs directly to the TNRCC Water-Master Office, which in turn schedules releases from the Falcon and Amistad Reservoirs. The IWBC makes releases as directed by the TNRCC Water-master. The Water-master Office maintains a weekly accounting of the amount of water used and the amount of water in reservoir storage allocated to each of the 1,600 water rights accounts. The Waster-master supervises the distribution of all water diverted from the Rio Grande in Texas below Fort Quitman. Most of the water is used in the very productive agricultural region below Falcon Reservoir.

The Water-Master performs computations each week to allocate the United States share of the storage in Amistad and Falcon Reservoirs to each of the 1,600 water rights accounts. The allocation rules include first providing a reserve of 225,000 acre-feet in Amistad and Falcon Reservoirs for domestic, municipal, and industrial uses, which is called the municipal pool. Next, available water is allocated to an operating reserve that fluctuates between 380,000 ac-ft and 275,000 ac-ft, depending on the amount of water in storage. The operating reserve provides for loss of water by seepage and evaporation, adjustments required as the United States-Mexico water ownership computations are finalized each month, and emergency requirements. The remaining water in storage is allocated among all the irrigation allottees. The storage is basically allocated in proportion to annual diversion rights, except the Class A rights are multiplied by a factor of 1.7 to allow them a greater storage allocation than Class B rights. Other provisions include limiting each storage allotment to not exceed more than 1.41 times its authorized diversion right. If an irrigation right does not use water for two consecutive years, its storage account is reduced to zero.

MODELING AND ANALYSIS CAPABILITIES

Effective management of the highly variable water resources of a river basin requires an understanding of the reliability with which various quantities of water can be supplied, under various conditions, within institutional constraints. Two general types of simulation models are envisioned. Long-term planning models support planning studies and preparation and evaluation of permit applications. Drought management models support decisions regarding curtailing water use and other actions during the weeks and months ahead given known storage levels today. Although the second type of model is being considered, efforts to date in the state have focused on the first type. The following discussion of computer modeling capabilities first addresses statewide efforts excluding the Rio Grande, with a later section focusing specifically on modeling the Rio Grande system.

Statewide Reservoir/River System Modeling

Under the prior appropriation doctrine, an application for a water use permit can be approved only if water is available and its use does not impair vested water rights. Thus, the TNRCC must determine the amount of water available for appropriation at various locations in each river basin of the state. The impacts of proposed water management plans on existing water rights must be evaluated.

Water availability models for eight of the major river basins (Brazos, Colorado, Guadalupe, Lavaca, Nueces, San Antonio, San Jacinto, Trinity) were developed during the 1970's and 1980's in conjunction with the water rights adjudication process. The models consist of computer programs and data files for analyzing allocation of the surface waters of each river basin under the water rights system. The primary purpose of the models was to determine unappropriated streamflows. Data from past runs of the models are still used along with other information to evaluate permit

applications. However, the Fortran programs are no longer operative and have not been executed in recent years.

The Water Rights Analysis Package (Wurbs and Dunn 1996) is a recently developed generalized river/reservoir system simulation model based on the Texas water rights permit system. This model has been applied to three river basins (Brazos, San Jacinto, Lavaca) to update previous water availability analyses.

Senate Bill 1 enacted by the Texas Legislature in 1997 is having a major impact on water resources planning and management in the state. The Act provides for development of comprehensive regional plans for water management which are to be incorporated into a statewide plan. Another provision of Senate Bill 1 authorizes the TNRCC to expand modeling capabilities in support of water rights administration functions. Funds have been appropriated and a schedule mandated to develop models for 22 river basins, which cover the entire state except for the Rio Grande Basin. Models for six basins must be completed by December 1999, and the remaining 16 basins completed by December 2001.

The models developed in the past as well as the model development effort currently underway involve a water availability modeling process consisting of two phases:
(1) development of monthly naturalized streamflow sequences for pertinent locations covering the hydrologic period-of-analysis, and
(2) simulation of the water rights/management system, for the input sequences of naturalized flows, to determine reliability indices, unappropriated flows, and related information.

Naturalized or unregulated flows represent natural hydrology without the effects of reservoirs and human water use. Models developed in the past have incorporated monthly naturalized flow sequences covering a period of typically about 1940 to 1980. Models currently being developed will likely use a hydrologic period-of-analysis of about 1940 to the present.

Each water right is represented by an annual water use requirement distributed nonuniformly over the 12 months of the year, associated return flow specifications, priority date, reservoir storage capacity, and location. Model input also includes reservoir operating rules and storage capacity versus surface area relationships.

The models simulate capabilities for meeting water demand requirements, reflecting current water rights and reservoir facilities, during each month of a hypothetical assumed repetition of historical hydrology, represented by naturalized flow and evaporation rate sequences covering the historical period-of-analysis. Model output includes an array of information including reliability indices for satisfying water rights requirements and unappropriated flows still remaining after the water rights are satisfied.

Modeling the Rio Grande System

The IBWC and others have performed various modeling studies over the past several decades. The Lower Rio Grande Valley Development Council, Valley Water Policy and Management Council, and Texas Water Development Board are currently conducting a comprehensive study of the Lower Rio Grande Basin to develop an integrated water management plan. Participates in the study include Turner Collie & Braden, Inc., Perez/Freese & Nichols, Inc., Freese & Nichols, Inc., other consulting firms, and Texas A&M University. Modeling capabilities are being investigated as one component of this study.

The Valley Water Management and Policy Council recently contracted with the consulting engineering firms of R. J. Brandes Company and Michael Sullivan & Associates to develop models for simulating the operation of Falcon and Amistad Reservoirs in accordance with the international and Texas state allocation systems. They are nearing completion of two models called the Reservoir Operations Model (ROM) and the Conditional Probability Model (CPM).

The Reservoir Operations Model (ROM) was developed by modifying SIMYLD-II to incorporate (1) the previously discussed rules for allocating Amistad and Falcon inflows and storage between Mexico and the United States pursuant to the 1944 Treaty and (2) water use requirements reflecting the allocation of the United States share of streamflow and storage in accordance with the state water rights system. SIMYLD-II is a generalized model for simulating reservoir/river system operations and water allocation developed by the Texas Water Development Board (1972). SIMYLD-II computations are based on a network flow linear programming formulation and solution algorithm. Various studies including firm yield analyses are being

performed using the ROM with a monthly time step and 1945-1996 period-of-analysis.

The Conditional Probability Model (CPM) is designed to estimate the probability of meeting demands during the next season or year given known storage levels today. The ROM is executed for many different starting storage levels to develop input for the CPM. ROM simulations have been made for each year of the 1945-1994 period using historical monthly inflows and evaporation rates. For each year with each specified starting storage level, the ending storage level of the reservoirs and number of months that specified demands could not be met are recorded. This matrix of data is input to the CPM to estimate probabilities of failure to meet demands during the next year conditioned upon the storage level at the beginning of the year.

KEY ISSUES AND COMPLEXITIES

Allocating a highly variable water resource to numerous water management entities and users is necessarily complex. The issues and considerations noted below are illustrative of the complexities of managing reservoir systems within the institutional framework of a water rights system.

Allocation of Water Among Users

The prior appropriation concept of protecting early water users from having their supplies diminished by newcomers is achieved in two ways.

- Permits are not granted to new water users if senior rights would be adversely affected.
- During droughts, junior appropriators must curtail their water use if senior appropriators are otherwise adversely affected.

Although Texas and other states are viewed as adopting the prior appropriation doctrine, strictly speaking a pure prior appropriation system is probably not feasible and perhaps does not exist.

In dealing with the uncertainties of managing a stochastic water resource, although the effect may be extremely small, developing additional supplies for new users always affects the inflows and thus water supply reliability of existing reservoirs located downstream on the same stream. Also, in drought situations involving insufficient water supply, the shortages will be shared, to some degree, by water users regardless of the relative seniority of their rights. Temporary demand management measures will be implemented. Sharing of water during drought will likely 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. Although the issue is being addressed, detailed drought contingency plans do not exist at this time for most of Texas. Although regions of the state have experienced significant water shortages in recent years, the water rights system has not yet been tested and refined by a major drought comparable to the 1930's and 1950's.

The relationship between basing priorities on seniority (date) of use versus type of use is also not clearly defined. Except for the Lower Rio Grande, water rights priorities in Texas are set by the priority date specified in each permit. Relative priorities for types of use stated in the Texas Water Code have been interpreted to mean that types of use are to be considered if multiple applications for the same water are being considered simultaneously. After permits are issued, the filing dates govern priority. However, though not yet thoroughly tested, the Wagstaff Act appears to allow cities to take water from more senior non-municipal water rights. The Rio Grande allocation system explicitly gives municipal use priority over other uses in the formula for allocating storage in Amistad and Falcon Reservoirs.

Assigning water rights priorities to maintaining reservoir storage levels relative to diversion rights is another important issue. Reservoir operation in Texas is based on providing long-term storage as protection against infrequent but severe droughts. The right to store water is as important as the right to divert water. If junior appropriators located upstream of a reservoir diminish inflows to the reservoir when it is not spilling, reservoir dependable yield is adversely affected. Each drawdown could potentially be the beginning of a several-year critical drawdown which empties the reservoir. Thus, protecting reservoir inflows is critical to achieving the purpose of the reservoir, which is to provide a dependable water supply. On the other hand, forcing appropriators, with rights junior to the rights of the reservoir owner, to curtail diversions to maintain inflows to an almost full, or even an almost empty, reservoir is difficult and often is not the optimal use of the water resource. If junior diversions are not curtailed, the reservoir will likely later refill anyway, without any shortages occurring.

Although water right permits often include reservoir storage, handling of the storage aspect of water rights is not yet precisely defined in Texas except for the Rio Grande. The Rio Grande is simpler in this regard because essentially all of the water users are supplied by two large storage reservoirs operated jointly. In other major river basins, hundreds of small reservoirs and several large reservoirs are owned and operated by various entities in the same basin.

With the exception of the Rio Grande, water rights permits in Texas are for individual reservoirs. However, in some cases, multiple reservoirs are operated in combination to meet common demands. For example, the Brazos River Authority (BRA) operates a system consisting of four of its own reservoirs and the conservation pools of nine federal reservoirs. All of the diversion rights held by the BRA were granted in conjunction with individual reservoirs. The BRA permits have been modified to allow multiple-reservoir releases to meet common downstream diversion requirements as long as the total of the diversions specified in the individual reservoir permits are not exceeded. Flexibility has also been provided for shifting between types of water use as well. Significant complexities arise in attempts to relate individual reservoir water rights to multiple-reservoir system operations. Innovative strategies are needed for incorporating multiple-reservoir system operations into water rights permits.

Unregulated local inflows entering a river below any dams and/or uncontrolled reservoir spills may be adequate to meet water needs much of the time without reservoir releases. In the Rio Grande, during periods of high flows, users are allowed to divert *no charge water* without having their allotments charged. In the Brazos River Basin, an *excess flows* permit allows the Brazos River Authority to divert water from the lower reach of the river without releasing from their reservoirs as long as other water rights holders are not adversely affected.

Although some recently issued water rights have addressed return flows, most permits do not specify the amount of the diversion to be returned to the stream. Return flows can significantly impact the availability of water to downstream users. This issue is currently being addressed particularly in the Trinity River Basin where plans for reuse of municipal wastewater effluent for urban irrigation in the Dallas-Fort Worth metroplex in the upper basin will affect Trinity River flows including inflows to a major downstream reservoir.

Instream flow needs and related environmental issues are important considerations in formulating and evaluating water rights permits. Maintaining specified instream flow requirements is a part of the operating policies of a number of reservoirs. Instream uses include maintenance of aquatic habitat and species, protecting or improving water quality, public recreation, preservation of wetlands, and providing freshwater inflows for bays and estuaries. The Texas Water Code requires that the TNRCC consider existing instream uses and water quality issues in the water rights permitting process. In recent years, establishment of diversion restrictions to maintain instream flows is an integral part of evaluating water availability. Determining instream flow requirements and the impacts of water rights permits on instream flows are complex tasks.

Hydroelectric power operations can have beneficial as well as adverse impacts on downstream water availability. Although hydroelectric plants typically have water rights permits, some federal hydroelectric projects do not. For these projects, hydroelectric energy is generated by unappropriated or unused flows and water supply releases.

From the perspective of hydrology and water resources management, ground water and surface water are two interrelated phases of the hydrologic cycle. Use of one resource often has significant impacts on the other. However, there is little governmental control over the use of ground water in Texas. Consequently, conjunctive management of ground and surface water resources is extremely difficult. Depleting groundwater reserves are forcing the state to move toward greater groundwater regulation and shift to a greater reliance on surface water.

Administration of a Water Allocation System

Texas is illustrative of two general approaches adopted in different western states for administering water rights permit systems, namely with and without water-master operations. The Rio Grande Water-Master Office maintains a precise accounting of water use, working closely with the irrigators, cities, and other water users in the Lower Rio Grande Valley. For the majority of the state, there is no water-master operation to maintain a water use accounting system.

According to Rice and White (1991), the prior appropriation water rights systems in most western states are virtually self-administering. This is true of Texas. Upon request, the TNRCC takes enforcement action statewide to stop reported unauthorized diversions or water use in violation of water rights permits. However, water diversions are not closely monitored and may not be accurately measured and recorded. Many water rights holders have no meters to measure their diversions. The impacts of junior diversions at certain locations on senior rights at other locations in the basin may not be clearly evident. Monitoring of withdrawals is relatively unimportant as long as everyone has plenty of water but become important during drought when shortages begin to occur. Monitoring and curtailment of water use occurred in several areas during the 1995-1996 drought.

With completion of the adjudication process in the late 1980's, the state planned to eventually establish water-master operations in all the major river basins. The South Texas Water-Master Program was initiated in the late 1980's with responsibilities for the Guadalupe, Nueces, and San Antonio River Basins. However, statewide, many water users were reluctant to have requirements imposed upon them for installing meters and monitoring and regulating diversions. Political pressures have prevented the establishment of water-master offices in other river basins.

Assessment of Water Availability/Reliability

Since streamflows, evaporation rates, reservoir sedimentation rates, water use, and other factors are highly variable, and the future is unknown, water availability must be viewed from a reliability, likelihood, or percent-of-time perspective. Tradeoffs occur between the amount of water to commit for beneficial use and the level of reliability that can be achieved. Beneficial use of water is based on assuring a high level of reliability. However, if water commitments are limited as required to assure an extremely high level of reliability, the amount of streamflow available for beneficial use is constrained, and a greater proportion of the water flows to the ocean or is lost through reservoir evaporation. The optimal level of reliability varies with type of water use. Municipal supplies are typically viewed as requiring particularly high reliability.

Water management decisions necessarily require qualitative judgment in determining acceptable levels of reliability for various situations. Previous studies have demonstrated that reliabilities are not very sensitive to changes in diversion amounts. Typically, the amount of water supplied by a reservoir/river system can be increased significantly by accepting somewhat higher risks of shortages or emergency demand reductions. Reservoir yield versus reliability estimates are not highly precise and can vary significantly with incorporation of different but yet still reasonable assumptions in a model.

The concept of firm yield has traditionally been used in water supply planning and management in Texas. Firm yield is defined as the maximum annual diversion rate that can be maintained continuously during a hypothetical repetition of historical period-of-record hydrology based on specified modeling assumptions. However, the strategy of committing water to different users at different levels of reliability has been pursued to some extent in recent years. Certain water users are curtailed if reservoir storage drops below prespecified levels. This strategy is common in other western states but relatively new in Texas.

Water availability is constrained by water quality as well as water quantity. Beneficial use of streamflow is severely limited by natural salt contamination from geologic formations underlying the upper watersheds of several major Texas river basins, including the Brazos, Canadian, Colorado, Pecos, and Red Rivers (Wurbs 1996). At many locations, water availability is governed by highly variable salinity levels rather than streamflow amounts. The larger reservoirs with high salinity levels include Lake Texoma on the Red River (the largest reservoir in Texas), Possum Kingdom, Granbury, and Whitney Reservoirs on the Brazos River, and Lake Meredith on the Canadian River. Quantification of the impacts of salinity on water supply reliabilities has really not been incorporated into the process of evaluating applications for water rights permits. Expanded modeling and analysis capabilities are needed to incorporate water quality considerations in reservoir system reliability analyses.

Reservoir/River System Models

As previously discussed, major efforts are underway to develop expanded modeling capabilities for evaluating the water supply capabilities of reservoir/river systems. Under the provisions of Senate Bill 1, water availability/reliability models for the 22 river basins of

the state, excluding the Rio Grande, are to be completed by December 2001. Reservoir system simulation models are also being developed and applied in a comprehensive study of the Lower Rio Grande. The focus is on simulation models that combine current water rights and reservoir system operating policies with sequences of monthly naturalized flows and evaporation rates representing historical period-of-record hydrology. Drought management models for predicting the likelihood of meeting demands during the next season or year given current reservoir storage levels are also being investigated. The remainder of this section highlights several key issues related to the modeling effort.

A set of generalized simulation models and databases conveniently accessible to the entire water management community is envisioned for the future. Computer programs and data files can easily be made public through the internet as well as other distribution mechanisms. The motivation for the current model development effort is to expand decision support capabilities for the TNRCC water rights administration functions, including planning studies and evaluation of permit applications, and support of water allocation actions during drought conditions. However, the software and databases used by the TNRCC to evaluate water rights permit applications may also by used by water agencies and consulting firms in performing various feasibility studies as well as for preparing permit applications for submittal to the TNRCC.

The adopted modeling process for planning studies and evaluation of water rights permit applications consists of two phases: (1) developing of monthly naturalized streamflows covering the hydrologic period-of-analysis at all relevant locations and (2) simulation of current water management reflected by existing reservoir facilities and water rights for an assumed repetition of historical hydrology represented by the sequences of naturalized flows and reservoir evaporation rates. The array of information provided by model results include reliability indices for satisfying the water rights requirements included in the model and unappropriated flows still available for additional rights. Proposed new water rights and reservoir operating plans can be incorporated in the model to assess the impacts on existing rights as well as reliabilities associated with the proposed new project.

Methodologies for developing sequences of naturalized streamflows are being investigated. Naturalized flows at streamflow gaging stations are developed by adjusting the observed historical flows to remove the effects of reservoirs, diversions, return flows, and other past water control activities. Regression techniques are used to fill in missing records and extend record lengths based on flows at other gages. Naturalized flows at gages are then transferred to ungaged locations of water rights. The author is working with the TNRCC on a study of methods for developing naturalized montly streamflow sequences, particularly methods for determining flows at ungaged locations.

A reservoir/river system model is used to simulate allocation of input naturalized flows, for each monthly time step, to meet current diversion, instream flow, and storage requirements in accordance with the water rights priority system. The 7,000 water rights in effect in the 23 river basins (Rio Grande and 22 others) vary by basin from just a few in smaller basins to over a thousand in three of the larger basins. For example, recent simulation studies for the Brazos River Basin using the generalized Water Rights Analysis Package (WRAP) model (Wurbs and Dunn 1996) simulated present water management requirements associated with 1,200 water rights and 600 reservoirs during an assumed repetition of historical hydrology represented by naturalized flows and evaporation rates for each month of a 1940-1984 period-of-analysis. A recent WRAP simulation of the San Jacinto River Basin involved 105 water rights with two large reservoirs, about 70 small reservoirs, and a 1940-1980 hydrologic period-of-analysis.

The TNRCC is presently investigating various alternative reservoir/river system water allocation models for use in modeling the 22 river basins. Flexible capabilities are required for simulating the water rights priority system, reservoir system operating policies, and numerous water use requirements. The many areas of potential improvements in modeling capabilities include better representation of channel losses and surface/subsurface interactions, multiple-reservoir system operations, return flows, instream flow requirements, water quality constraints, and reliability indices. Improved strategies for using simulation results to assess water availability/reliability and support decsion-making processes are important.

Data compilation and management is a key fundamental aspect of the overall modeling effort. Time series data compiled from field observations include streamflow, precipitation, reservoir evaporation rates, storage

contents, water use diversions, and return flows. Computed time series data include naturalized streamflows and unappropriated streamflows. Watershed parameters are required to transfer naturalized flows from gaged to ungaged locations. Storage-area relationships and other information are needed for modeling the numerous reservoirs. The water rights database is of course also fundamental to the modeling process. Software for managing time series, spatial, and other types of data and methodologies for collecting these data are extremely important components of the modeling and analysis process which are receiving considerable attention.

CONCLUDING REMARKS

Water rights and associated institutional considerations play key roles in governing reservoir system operations. With growing demands on limited water resources, water rights have become increasingly important in Texas and elsewhere. The establishment of systematic approaches for administering water rights, for both the Rio Grande and the remainder of the state, has been a major thrust of water management in Texas since the 1960's. A current emphasis is on expanding modeling and analysis capabilities to support administration of the water rights system. Water allocation policies and practices vary between states. However, the Texas experience is illustrative of the complexities and issues encountered in developing and managing water allocation systems in general. Lessons learned and capabilities developed in Texas should have broader applicability throughout the nation.

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Ralph Wurbs is a Professor in the Environmental, Ocean, and Water Resources Division of the Civil Engineering Department at Texas A&M University. He is presently participating in both the statewide water availability modeling studies and the Rio Grande study discussed in the paper.

Figure 1. River Basins of Texas

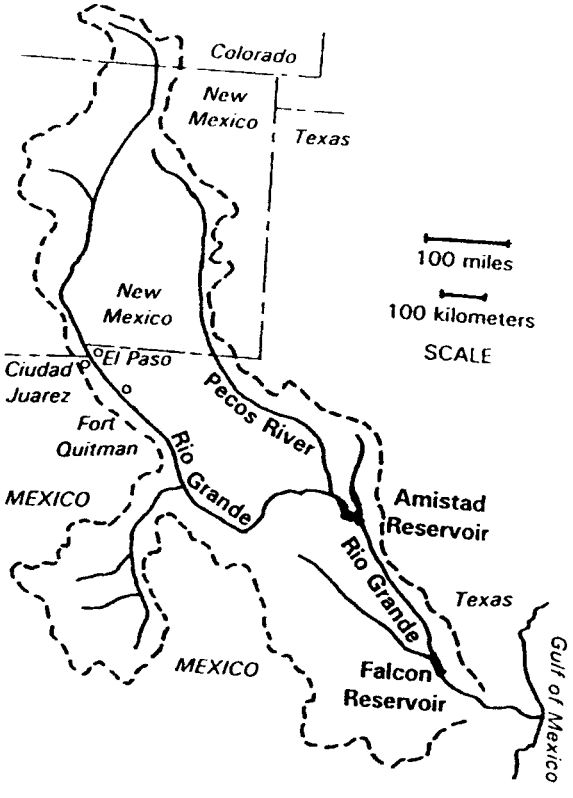

Figure 2. Rio Grande Basin