Water Rights Modeling and Analysis

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Abstract: A generalized model for simulation of surface water management under a prior appropriation water rights system was recently developed and applied to a major river basin in Texas. The water rights analysis model provides capabilities for evaluating institutional as well as hydrologic water availability. The case study provides a perspective on key considerations in water rights modeling and analysis. A river basin should be viewed as an integrated system. Water available to a particular water management entity depends upon the impacts of other water users in the basin. Increases in reservoir yield achieved by system operations should be properly reflected in water rights. Assigning priorities by appropriation date versus type of use and assigning priorities to refilling storage capacity are two other issues which are illustrative of the complexities of administering and modeling water rights.

Introduction

Modeling and analysis of surface water rights is becoming an increasingly important aspect of water resources development and management in Texas. Population and economic growth, combined with depleting groundwater reserves, are resulting in ever-increasing demands on surface water resources. The state has recently implemented a permit system for allocating surface water among users. The amount of water available to particular users or management entities depends upon the impacts of senior rights in the river basin. Effective water management requires an understanding of institutional as well as hydrologic water availability.

This paper discusses the recently implemented surface water allocation system in Texas, a recently developed water rights analysis computer model, and key issues involved in administering and modeling water rights. These topics are addressed from the perspective of a particular illustrative case study. Results of a simulation modeling study of hydrologic and institutional water availability in the Brazos River Basin are presented.

Water Rights

Generally, in the United States, legal rights to the use of streamflow are 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, "first in time is first in right." In a prior appropriation system, water rights are not inherent in land ownership, and priorities are established by the dates that users first appropriate water. Water law in 29 eastern states is based strictly on the riparian doctrine. Nine western states

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have a pure prior appropriation system. Ten western states, including Texas, originally recognized riparian rights but later converted to a system of appropriation while preserving existing riparian rights. Two other states also have hybrid systems incorporating the two doctrines in a somewhat different manner. Getches (1984) and Rice and White (1987) provide overviews of the development and application of basic principles of water law.

Texas Water Law

Surface water law in Texas developed historically over several centuries (McNeeley and Lacewell 1977; Templer 1981). Claims are presently recognized to water rights granted under Spanish, Mexican, Republic of Texas, and United States, as well as State of Texas, laws. Early water rights were granted based on various versions of the riparian doctrine. A prior appropriation system was later adopted and then modified. An essentially unmanageable system evolved, with various types of water rights existing simultaneously and with many rights being unrecorded. The Water Rights Adjudication Act of 1967 merged the riparian water rights into the prior appropriation system. The allocation of surface water now has been consolidated into a unified permit system. The water rights adjudication process required for transition to the permit system was initiated in 1968 and was essentially completed in 1987.

Water rights permits grant to the holder the use of a specified amount of water, at a specific location, and for a specific purpose. Any person, public or private corporation, city, county, river authority, state agency, or other political subdivision of the state may acquire a permit to appropriate water. Texas has more than 12,000 appropriators of surface water. Pursuant to the Water Rights Adjudication Act of 1967, priority dates for existing water rights were established and permits issued based on historical legal rights and actual water use. Applications for permits are now handled through a formal process administered by the Texas Water Commission (TWC). A water use application is approved only 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. Once the right to the use of water has been perfected by the issuance of a permit by the TWC and the subsequent beneficial use of the water by the permittee, the appropriated water is not subject to further appropriation unless the permit is cancelled. A permit may be cancelled if water is not used during a 10-year period.

The legal right to use or sell the water from a reservoir is usually granted to the owner prior to construction. 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, industries, and/or farmers. The river authority holds the permit or water right. The cities, industries, and farmers purchase the water from the river authority without having to obtain a water right permit. The river authority operates the reservoirs to meet its contractual obligations to its customers. The federal government does not get involved with water rights. The nonfederal project sponsors which contract for the conservation

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storage in federal projects are responsible for obtaining the appropriate water rights permits through the TWC.

The Texas Water Code is based upon the prior appropriation doctrine. However, there is an exception to the "first in time, first in right" rule. The code provides that "any appropriation made after May 17, 1931, for any purpose other than domestic and municipal use, is subject to the right of any city or town to make appropriations of water for domestic or municipal use without paying for the water." This provision was originally enacted by the Wagstaff Act in 1931, and is still commonly referred to as the Wagstaff Act. The implications of the Wagstaff Act have not yet been defined by court cases. The TWC has interpreted the statute as authorizing it to issue new rights to a municipality even if existing nonmunicipal rights are adversely impacted. In a water crisis, a city may be given preference over senior nonmunicipal appropriators. Major appropriations by cities under the provisions of the Wagstaff Act have not occurred to date. However, the statute is expected to become increasingly important as demands on limited water resources intensify.

Although water master operations are common in other western states, the Rio Grande is presently the only river basin in Texas for which a water master has been designated. However, water master operations will likely be established in the other basins in the future. The TWC is presently developing rules and regulations for administering water master operations.

With the exception of the water master operations in the lower Rio Grande Valley, experience in administering water rights in Texas has been limited to date. Few situations have arisen in which junior water rights holders had to curtail diversions during low flow periods to protect senior water rights. Since the adjudication process was just recently completed, the permit system has not been operational very long in the various river basins. Although severe reservoir drawdowns did occur in 1984, the last 20 years have been characterized by relatively abundant precipitation and streamflow as compared to the droughts of the 1950s and earlier periods. The next severe drought will necessitate development of a detailed mechanism for policing water users and curtailing water use in accordance with water rights priorities.

TWC Water Availability Model

The Texas Water Commission (TWC) began development of a water availability model in 1968. Several generations of the model have since been developed, reflecting various improvements and extensions. All the major river basins in Texas have now been modeled. However, the models are continually updated to reflect additional water rights and changed conditions.

The TWC Water Availability Model consists of a set of computer programs and data files for analyzing the allocation of the surface waters of the river basins of Texas based upon the water rights system. The primary purpose of the model is to determine unappropriated streamflow. This information is used by the TWC in the evaluation of applications for permits to appropriate water.

The TWC Water Availability Model is strictly for use within the agency. Although the various input and output data files are readily available to other agencies and individuals, the computer programs have not been generalized for use outside the TWC. The TAMUWRAP model discussed next performs many of the same functions as the TWC Water Availability Model, but is designed to be easily applied by any interested user.

Water Rights Analysis Model

The Texas A&M University Water Rights Analysis Program (TAMUWRAP) is documented by Walls and Wurbs (1988). TAMUWRAP is a generalized computer model for simulating surface water management under a prior appropriation water rights system such as that of Texas. The capabilities of a river basin to satisfy existing water rights and the amount of streamflow remaining for potential additional water rights applicants can be evaluated. TAMUWRAP can be used alone or with other models to perform various types of reservoir yield analyses.

A TAMUWRAP simulation typically will be based on the assumptions of: (1) A repetition of historical hydrology; and (2) the full amounts of all permitted diversions being withdrawn as long as water is available. The model performs water accounting computations for each month of the simulation period. Output includes monthly diversions, diversion shortages, reservoir storage levels, streamflow depletions, and unappropriated streamflows.

System Components

A stream/reservoir/rights system is represented in the model by the following components: (1) Control points; (2) basin hydrology; (3) reservoirs; and (4) water rights.

Control points are specified to indicate the location of streamflow data, reservoirs, and water rights. The computations are based on knowing which of the other control points are located downstream of each control point. Essentially any configuration of stream tributaries can be modeled. Streamflow data must be provided for all control points included in a simulation. Each water right can be assigned a separate control point. Alternatively, water rights can be aggregated such that the water rights assigned to a given control point include all water rights located between that control point and the next upstream control point.

The basin hydrology consists of streamflows and reservoir evaporation rates at each control point for each month of the simulation period. Monthly streamflow input data will normally be naturalized to remove nonhomogeneities caused by the activities of man in a river basin. Net reservoir evaporation rates are adjusted for precipitation. A storage capacity versus water surface area relationship is inputted for each reservoir for use in the evaporation computations.

A water right is represented by the following model input data: (1) Control point location; (2) annual diversion amount; (3) reservoir storage capacity; (4) priority number; (5) type of use; and (6) return flow factor. The diversion amount, storage capacity, priority number, and return flow factor may be zero. The model uses the type of use to assign the proper monthly water use distribution factors. A set of 12 factors, which sum to unity, are provided as input data for each type of use to distribute the annual water right diversions over the year. The priority number typically represents dates. For example, a priority date of May 12, 1965 is inputted as 19650512, which is a larger number than the priority corresponding to any earlier date. The return flow factor is the fraction of the diversion which is returned to the stream at a downstream control point.

A water right is represented in the model by a single value for each of the aforementioned variables. Therefore, a water right which includes three different uses, such as municipal, industrial, and irrigation, is treated as three separate water rights. A single reservoir may be associated with several water rights with different combinations of priority dates, storage capacities, and other variables. The diversion amount and storage capacity can be assigned different priorities by treating the right as two separate rights, one with zero storage capacity and the other with a zero diversion. Thus, the model provides considerable flexibility in describing water rights.

Model Computations

The water balance computations proceed by month and, within each month, by water right on a priority basis. The water right diversion amount is diverted as long as streamflow or reservoir storage not yet appropriated by senior water rights, is still available. A shortage occurs if sufficient streamflow and/or storage are not available to supply the water right that month. Permitted reservoir capacity is filled to the extent allowed by available streamflow. Reservoir evaporation is computed by multiplying the computed average water surface area during the month by an inputted net evaporation rate. Return flows are computed as a fraction of diversions. An accounting is maintained of storage levels in each reservoir and streamflow still available at each control point.

The naturalized streamflow provided in the TAMUWRAP input data for each control point represents the streamflow which would occur at that location assuming no water users, reservoirs, or other activities of man in the river basin. TAMUWRAP computes streamflow depletions associated with each water right and unappropriated streamflows associated with each control point. The computed total streamflow depletions and unappropriated streamflows for the entire basin for a given month equal the total inputted naturalized streamflow plus computed return flows.

A streamflow depletion represents the streamflow taken by a water right in a given month to meet the target water right diversion and to fill the previously drawn-down reservoir storage capacity. Water rights diversions are supplied by streamflow depletions, as long as streamflow is available, and then by reservoir storage depletions, if reservoir storage is available. Evaporation also depletes reservoir storage. Thus, a streamflow depletion in a given month may include refilling of reservoir storage capacity depleted during previous months.

Unappropriated streamflow represents water still available after all streamflow depletions or the water that flows past the basin outlet into the ocean or other receiving body. The unappropriated streamflow is the water not used by the water rights included in the simulation.

Combined Use with Other Models

Firm yields and yield versus reliability relationships for a specific reservoir or multireservoir system, constrained by other senior water rights in the basin, can be computed using TAMUWRAP with another model, such as HEC-3 or HEC-5. Other reservoir system simulations constrained by senior water rights can be performed as well.

Feldman (1981) describes the various generalized simulation models available from the Hydrologic Engineering Center (HEC) of the U.S. Army Corps of Engineers (USACE). HEC-3 simulates the operation of a reservoir system for conservation purposes such as water supply and hydroelectric power ("HEC-3" 1981). HEC-5 has most of the conservation capabilities of HEC-3 and greatly expanded flood control capabilities (HEC-5 1982). HEC-5 is required for detailed flood control simulations. Either HEC-3 or HEC-5 can be used for the water supply oriented studies discussed here.

HEC-3 and HEC-5 have reservoir system simulation capabilities not included in TAMUWRAP, such as optional routines for computing firm yields or reliabilities for specified yields for individual reservoirs and multireservoir systems. However, these models have no capabilities for simulating a water rights priority system. TAMUWRAP can be readily combined with HEC-3 or HEC-5.

Streamflow depletions and unappropriated streamflows computed with TAMUWRAP are provided as streamflow input data for HEC-3, HEC-5, or other similar models. TAMUWRAP contains an option for providing the streamflow output in the format required for HEC-3 input. The TAMUWRAP-computed streamflow data are manually combined with the other data required for a HEC-3 input file. Streamflow depletions plus unappropriated streamflows represent the water available to specified water rights after all other senior rights have been considered. Thus, HEC-3 is run with streamflow data representing only the streamflow available to the selected water rights.

Brazos River Basin Study

TAMUWRAP and HEC-3 simulation analyses were a major component of the study of the hydrologic and institutional water availability in the Brazos River Basin documented by Wurbs et al. (1988). The Brazos River Basin extends from eastern New Mexico southeasterly across Texas to the Gulf of Mexico. The basin has a drainage area of 118,000 km^2, of which 111,000 km^2 are in Texas; the remainder are in New Mexico. Brazos River water is diverted for beneficial use in the adjoining San Jacinto-Brazos Coastal Basin as well as in the Brazos River Basin. Almost all the surface water use in the two basins is from the Brazos River and its tributaries. Past and projected future surface water use amounts are cited in Table 1 ("Water" 1984).

Reservoir System

The investigation focused on the system of 12 reservoirs listed in Table 2 and shown schematically in Fig. 1. The numerous other reservoirs in the basin were considered primarily from the perspective of their impacts on the 12 principal reservoirs. Nine of the reservoirs are owned and operated by the U.S. Army Corps of Engineers (USACE), with the Brazos River Authority (BRA) having contracted for most of the water supply storage capacity. The other three reservoirs, which are Possum Kingdom, Granbury, and Limestone, are owned and operated by the BRA. The BRA sells water to a number of cities, industries, irrigators, and other water users. The nine USACE reservoirs contain flood control storage. All 12 reservoirs contain conservation capacity for municipal, industrial, and/or agricultural water supply. Several provide cooling water for steam electric power plants. Pos-

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TABLE 1. Water Rights and Use in Brazos River Basin

Quantity (1)	m³/s (2)
1984 surface water use	
Brazos River Basin	22.1
San Jacinto-Brazos Coastal Basin	12.2
2010 TDWR projected surface water use	
Brazos River Basin	67.5
San Jacinto-Brazos Coastal Basin	25.3
1984 water supply and hydropower releases from 12 USACE/BRA reservoirs	23.2
Permitted water rights diversions	
Priority rights associated with 12 USACE/BRA reservoirs	29.5
All other priority rights	55.4
BRA excess flow permit	25.4

sum Kingdom and Whitney Reservoirs also have hydroelectric power plants. Most of the water released through the turbines is diverted at downstream locations for other beneficial uses. Recreation occurs at all the reservoirs. A majority of the municipal, industrial, and agricultural water use occurs in the lower basin and adjoining coastal basin. Diversions from the river occur at significant distances below the dams and can be met by releases from various combinations of several reservoirs.

The 12-reservoir USACE/BRA system contains essentially all of the flood control and about 70% of the conservation storage capacity in the basin. The 12 reservoirs have conservation capacities totaling 3,437 million m^3. About 28% of the conservation capacity is inactive storage which provides head for hydroelectric power operations.

Water Rights

About 1,040 individual citizens, private companies, cities, and public agencies hold permits to use the waters of the Brazos River and tributaries.

TABLE 2. USACE/BRA Reservoir System Storage Capacity

Reservoir (1)	Storage Capacity (million m³) Conservation (2)	Flood control (3)	Total (4)
Possum Kingdom	703	0	703
Granbury	189	0	189
Whitney	774	1,693	2,467
Aquilla	65	115	180
Waco	188	708	896
Proctor	73	388	462
Belton	552	794	1,346
Stillhouse	291	487	778
Georgetown	46	116	161
Granger	81	220	301
Somerville	198	429	626
Limestone	278	0	278
Total	3,437	4,950	8,387

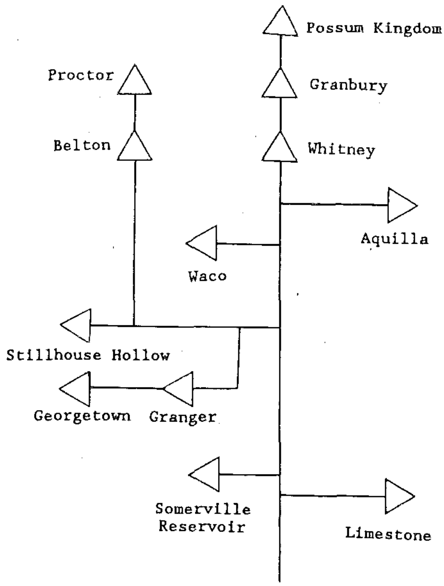

FIG. 1. Schematic of USACE/BRA Reservoir System

The water rights include diversions totalling 84.9 m^3/s and storage capacities totalling 5,634 million m^3 in 598 reservoirs. Of the total permitted annual diversion amount, 51%, 29%, 19%, and 1.0%, respectively, is for municipal, industrial, irrigation, and mining uses. Water rights for releases or withdrawals from the 12 USACE/BRA reservoirs are 29.5 m^3/s or 35% of the basin total. About 19% of the total water rights diversions in the basin have locations upstream of one or more of the 12 USACE/BRA reservoirs. The remaining 46% of the permitted diversions are below the reservoir system.

Water rights are associated with specific individual reservoirs. The City of Waco has the water rights for Waco Reservoir. The BRA holds most of the water rights associated with the other 11 USACE/BRA reservoirs. The water rights associated with the 12 reservoirs have different priority dates, and some reservoirs have several rights with different priorities. Priority dates range from 1929 to 1982. Each of the reservoirs are constrained by numerous other rights with senior priorities. Inflows must be passed through a reservoir to meet senior water rights at downstream locations.

The Brazos River Authority (BRA) permits have been modified to reflect system operation. Flexibility is provided in regard to meeting demands by releases from alternative reservoirs and also shifting between types of use, as long as the total of the individual reservoir permitted water rights diversions is not exceeded. The system permits allow operational flexibility but do not increase the total permitted diversion amount from the several reservoirs. The BRA also holds an excess flows permit which allows diversion of up to 25.4 m^3/s from the lower reach of the Brazos River as long as priority water rights are not adversely affected. The excess flows permit has no priority and is not included in the data cited in the preceding paragraph.

The BRA also has an interbasin transfer permit which allows previously permitted diversions to be transported out of the basin, but does not increase the total permitted amount of water which can be diverted from the reservoirs. Other water managers also have rights for interbasin transfers, primarily to the adjoining San Jacinto-Brazos Coastal Basin.

Hydroelectric power is generated with water supply releases and unappropriated flows. There are no water rights for hydroelectric power in the basin.

Basic Data

Basin hydrology, water use, water rights, and reservoir features and operating policies are represented by the input data for the TAMUWRAP and HEC-3 models.

Basin hydrology consists of monthly streamflows and reservoir net evaporation rates. A set of naturalized monthly streamflows at 21 selected gaging stations covering the 85-year period from January 1900 through December 1984 was compiled. Naturalized streamflow data for the period 1940–1976 were available from the TWC. Naturalized streamflows covering the remainder of the 1900–1984 simulation period were developed as part of the study. Streamflow naturalization consists of adjusting gaged streamflows to remove the nonhomogeneities caused by reservoir development and diversions of water for beneficial use. Records began in different years for the various stream gages. The MOSS-IV computer program (Beard 1973) was used to fill in missing streamflow data to cover the period 1900–1984. Monthly net evaporation rates for the period 1940–1984 were available from a computer data file described by Kane (1967). Average values (1940–1984) for each of the 12 months were used in the simulation study for the period prior to 1940.

Reservoir storage capacity versus water surface area relationships for the 35 largest reservoirs in the basin were obtained from agency reports and files. A single generalized storage versus area relationship was developed for the other 563 smaller reservoirs included in the TAMUWRAP simulation. The generalized relationship was developed by averaging storage versus area curves for 10 selected reservoirs.

A water rights data file for the basin was provided by the TWC. The water rights list includes the owner, subbasin location, type of use, annual diversion amount, storage capacity, and priority date for each water right. Return flow factors developed by the TWC were also used in the study.

Water Rights Analysis

The TAMUWRAP simulation is based on historical hydrology and the assumption that the full amounts of all permitted diversions are withdrawn as long as water is available. For each month of the simulation, diversions and refilling of reservoir storage are made for each water right in turn by priority date. Diversions, diversion shortages, and streamflow depletions are computed for each water right for each month. Reservoir evaporation and end-of-month storages are computed for each reservoir. Unappropriated streamflows are computed for each control point. Thus, model output can be extremely voluminous.

The results of a base simulation (run 1) and two other alternative simulation runs are summarized in Table 3. Run 1 is based on applying priority

TABLE 3. Basin Summary of TAMUWRAP Simulation Results

Quantity (1)	1900–1984 Means (m^3/s)		
	Run 1 (2)	Run 2 (3)	Run 3 (4)
Naturalized streamflow	221.7	221.7	221.7
Permitted diversions	84.9	84.9	84.9
Actual diversions	76.8	76.1	79.4
Shortages	8.1	8.8	5.5
Reservoir evaporation	20.7	21.1	20.7
Return flows	14.0	13.4	14.0
Unappropriated streamflow	138.7	138.5	136.1
Storage change	0.6	0.6	0.6

dates specified by the water rights to both diversions and refilling storage capacity. Run 2 is identical to run 1 except that all municipal rights with priority dates after May 17, 1931, are changed to May 17, 1931. Run 3 is identical to run 1 except that the priorities associated with refilling storage capacity in the major reservoirs are made junior to all diversions.

Table 3 presents basin totals of pertinent quantities expressed as averages over the 85-year simulation period. The naturalized streamflow is provided as input to the model. The other quantities are computed. Shortages are the diversion amounts permitted by the over 1,000 water rights minus the actual diversions as limited by water availability. Evaporation and storage changes associated with the 598 reservoirs are also shown. The unappropriated streamflow represents flows into the Gulf of Mexico or water available for additional water rights permit applicants. The sum of naturalized streamflows and return flows equals the sum of actual diversions, reservoir evaporation, unappropriated streamflow, and reservoir storage change.

Total shortages, averaged over the simulation period, are 9.6%, 10.4%, and 6.5% of the target water rights diversions for runs 1, 2, and 3, respectively. The unappropriated streamflows are 62.6%, 62.5%, and 61.4% of the naturalized streamflows for runs 1, 2, and 3, respectively.

Run 2 tests the sensitivity of the simulation results to evoking the previously discussed Wagstaff Act. As indicated by Table 3, assigning higher priorities to municipal rights has little effect on the basin totals. However, individual water rights are greatly impacted.

Run 3 illustrates the effect of assigning no priority to refilling reservoir storage. Diversions by junior rights are not curtailed to allow replenishment of storage by senior rights. Total shortages are decreased from a mean of 8.1 m^3/s to 5.5 m^3/s. The effects on individual water rights vary greatly. Mean shortages associated with the 12 USACE/BRA reservoirs increase by 62% if water rights priorities are not applied to storage capacity as well as diversions.

Yield Analysis

A yield analysis was performed for the system of 12 reservoirs owned and operated by the USACE and BRA. Streamflow depletions and unappropriated streamflows computed with TAMUWRAP were used as streamflow input data for HEC-3 to compute firm yields and reliabilities constrained by

TABLE 4. Yields for 10 Reservoirs

Quantity (1)	m^3/s (2)
Sum of individual reservoir hydrologic firm yields	27.7
System hydrologic firm yield	
excluding downstream unregulated flows	41.7
including downstream unregulated flows	57.7
Sum of individual reservoir firm yields constrained by senior water rights	21.4
System firm yield constrained by senior water rights	
excluding downstream unregulated flows	25.4
including downstream unregulated flows	33.1
95% reliability system firm yield constrained by senior water rights	
excluding downstream unregulated flows	38.1
including downstream unregulated flows	48.6

senior water rights. A streamflow depletion represents the streamflow taken by a water right in a given month to meet the water right diversion and to fill previously drawn-down reservoir storage to the permitted capacity. Streamflow depletions are the water available to a given water right, considering the impacts of all the other water rights in the basin.

Firm yield is the estimated maximum release or withdrawal rate which can be maintained continuously during a repetition of the hydrologic period of record, based on specified assumptions regarding various factors such as the interactions between multiple reservoirs and multiple users. A number of definitions of reservoir reliability are cited in the literature. A common definition is that reliability is the percentage of time that the reservoir is able to meet consumer demand (McMahon and Mein 1986). In the present study, reliability (R) was estimated from the results of a simulation as $R = n/N$, where n denotes the number of months during the simulation for which a specified yield could be met and N is the 1,020 months in the simulation. An annual yield is combined with a set of 12 monthly distribution factors to reflect seasonal water use variations within the year.

Reservoir yield in Texas has traditionally been quantified in terms of individual reservoir firm yield. Individual reservoir firm yields are computed with selected major upstream reservoirs included in a model with diversions at the upstream reservoirs set equal to their previously computed firm yield. Thus, reservoir inflows consist of unregulated local flows plus spills from upstream reservoirs. The total yield supplied by a river basin or reservoir system is typically viewed as the summation of the individual firm yields for the reservoirs included in the basin or reservoir system. Thus, complex system interactions are greatly simplified for modeling purposes. However, system considerations are extremely important in quantifying water availability in the Brazos River Basin and should be pertinent to other river basins as well.

The present study focused on two complicating aspects of estimating yields: (1) System operations; and (2) the impacts of other senior rights in the basin. The study focused on two aspects of system operations: (1) Coordinated operation of multiple reservoirs; and (2) coordination of reservoir releases with unregulated flows entering the river downstream of the dams.

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Table 4 presents yields for a system of 10 reservoirs computed using alternative approaches. The 10 reservoirs include all those listed in Table 2 except Waco and Whitney. The storage in Waco Reservoir is essentially totally committed to the City of Waco. The conservation storage capacity in Whitney Reservoir is divided between hydroelectric power and water supply by contractual agreements, with a majority of the storage capacity being allocated to hydropower. The other 10 reservoirs, which are included in Table 4, are largely system reservoirs. Water demands at downstream locations can be met by releases from several or all of the reservoirs. The firm yields constrained by senior water rights presented in Table 4 are based on the aforementioned TAMUWRAP run 1.

The firm yield was computed with HEC-3 for each of the 10 reservoirs based on reservoir inflows consisting of TAMUWRAP-computed streamflow depletions for the water rights associated with the reservoir plus unappropriated flows at the reservoir location. The individual reservoir firm yields constrained by senior water rights sum to 21.4 m^3/s.

System firm yields were also computed with HEC-3 with streamflow data consisting of streamflow depletions and unappropriated flows from TAMUWRAP. System firm yield involves the 10 reservoirs releasing for a diversion at a common downstream location. Multireservoir release decisions are made by the model based on balancing the percentage of depletion of the conservation pools of each reservoir. System firm yields of 25.4 m^3/s and 33.1 m^3/s, respectively, are obtained excluding and including the unregulated flows entering the river below the most downstream dams. Thus, the system firm yields, excluding and including unregulated flows, are 119% and 155% of the corresponding sum of individual reservoir firm yields.

Multireservoir system operation is beneficial because the critical drawdown periods for the individually operated reservoirs do not perfectly coincide. Operated individually, one reservoir may be completely empty and unable to supply its users while significant storage remains in the other reservoirs. At other times, the other reservoirs may empty. System operation balances storage depletions.

Utilization of unregulated flows entering the river below the most downstream dams is another key aspect of system operation. The naturalized streamflow data at all the control points incorporated in the simulation models have months of zero discharge. Thus, unregulated flows have zero firm yield. However, unregulated flows in the lower basin are of significant magnitude most of the time. When combined with reservoir releases during low-flow periods, the unregulated flows greatly increase the overall stream/reservoir system firm yield.

Firm yield, by definition, has a reliability of 100% based on a hydrologic period-of-record simulation. Yields greater than firm yield have reliabilities less than 100%. However, yield levels significantly larger than firm yield result in shortages only a relatively small percentage of the time. For example, a demand of 38.1 m^3/s, which is 150% of the firm yield, has a reliability of 95%.

Hydrologic firm yields were computed neglecting the impacts of all other water users and reservoirs except the 12 USACE/BRA reservoirs and Hubbard Creek Reservoir, which is located on a tributary which is confluent with the Brazos River just upstream of Possum Kingdom Reservoir. Hubbard Creek Reservoir was included in the HEC-3 computations due to its rela-

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tively large storage capacity. Individual reservoir firm yields were computed considering the impacts of any of the 13 reservoirs located upstream of the reservoir for which the firm yield is computed. Inflows to the reservoir consists of spills from the next upstream reservoir plus incremental flows from the watershed between the reservoirs. The firm yields of the upstream reservoirs are diverted at the upstream reservoirs. Thus, the hydrologic firm yields for the 10 reservoirs reflect the impacts on inflows of three other large reservoirs but do not reflect the impacts of the numerous other smaller reservoirs included in the water rights simulation. As indicated in Table 4, the individual reservoir firm yields for the 10 USACE/BRA reservoirs total 27.7 m^3/s. System firm yields were also computed with the 10 reservoirs releasing for a common downstream diversion. The other three reservoirs were included in HEC-3 as nonsystem reservoirs with diversions equal to their individual reservoir firm yields. The resulting 10-reservoir system firm yields, excluding and including downstream local flows, are 41.7 m^3/s and 57.7 m^3/s, respectively. Thus, consideration of the impacts of senior water rights significantly reduces reservoir yields.

Key Issues in Evaluating Water Availability

The amount of water which can be supplied by a water management entity depends upon institutional as well as hydrologic constraints. The impacts of other water users in the basin can be modeled based on the assumption that all water rights holders will continuously take the full amount of water to which they are legally entitled. Basin hydrology can be represented by adjusted historical streamflows and evaporation rates. In applying this general modeling approach in the case study, several key aspects of evaluating water availability were identified as being particularly significant. These modeling considerations can be categorized as involving: (1) Basic hydrology and water use data; (2) reservoir system operations; and (3) policies and procedures for administering water rights.

Basic data compilation is a major component of the modeling effort. Modeling and analysis of water rights, like other types of modeling studies involving reservoir operation and surface water management, are based on representing unknown future streamflows by assuming a repetition of historical hydrology. Streamflow data must be adjusted to remove nonhomogeneities and fill in missing data. Historical water use and return flow data required for simulating present and future conditions of development, as well as naturalizing streamflows, are limited in availability. Changes in reservoir storage capacity due to sedimentation also complicates modeling.

Water rights permits in Texas are written for individual reservoirs, not multireservoir systems. However, as illustrated by the case study, coordination of releases between reservoirs and with downstream unregulated flows can significantly increase reservoir yields. For the USACE/BRA system, the increases in estimated firm yield can be achieved by properly crediting existing operating policies rather than changing operating policies. The permits were modified several years ago to allow a certain flexibility in system operation, but the total permitted diversions were not increased. The BRA also has an excess flows permit for withdrawals of unregulated flows from the lower reach of the Brazos River as long as priority water rights are not affected. However, the excess flows permit has no priority. Expanded con-

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sideration of system operations in both the administration and the modeling of water rights is a major area of needed additional work.

Administration of a water rights system during drought conditions requires subjective judgments as well as quantitative criteria and, consequently, is difficult to model precisely. Water users are not closely monitored, and diversions may not always be in accordance with permits. Modeling uncertainties also result from two particular aspects of the priority system in Texas discussed next.

Water rights permits include priority dates. The priority allocation system is based on these dates. However, a provision of the Texas Water Code, originally enacted as the Wagstaff Act, allows municipalities to appropriate water previously appropriated by other users under certain circumstances. This provision of the Texas Water Code has not been thoroughly tested in court and its implications are not perfectly clear. However, under drought conditions, municipalities could possibly be given priority over other senior nonmunicipal appropriators. Consequently, the priority system is subject to change as drought conditions worsen.

Reservoir operation in Texas is based on providing long-term storage as protection against infrequent but severe droughts. Water rights permits include storage capacity as well as diversion amounts. 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 firm yield is adversely affected. Each day without precipitation can be the beginning of the next severe drought in Texas. Likewise, each drawdown can 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. However, forcing junior appropriators to curtail diversions to maintain inflows to an almost full reservoir, or even an almost empty one, is difficult. If the junior diversions are not curtailed, the reservoir may later refill anyway without any shortages occurring. Handling of the storage aspect of water rights is not yet precisely defined in Texas.

Conclusions

Effective management and utilization of the water resource provided by a stream/reservoir system requires an understanding of the amount of water which can be supplied under various conditions. Water availability is subject to institutional as well as hydrologic constraints. With the continually increasing demands on surface water resources and the recently implemented permit system, water rights are becoming an increasingly important aspect of water resources development and management in Texas. TAMUWRAP provides a broad range of water rights modeling and analysis capabilities. The generalized model can be used to evaluate the quantity of water which can be supplied by a reservoir system, considering the impacts of other senior water rights in the basin.

A river basin is a complex, integrated system. The amount of water available to a particular water management entity depends upon the impacts of other water users in the basin. System operations can significantly increase yields and should be an important consideration in administering a water allocation system. Assigning priorities by appropriation date versus type of

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use and assigning priorities to refilling storage capacity are two other issues illustrative of the complexities of administering and modeling water rights.

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