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Hydrologic and Institutional Water Availability in the Brazos River Basin

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CHAPTER 1
INTRODUCTION

Statement of the Problem

Effective management of its surface water resources is essential to the continued growth and prosperity of the state of Texas. Rapid population and economic growth combined with depleting ground water reserves are resulting in ever-increasing demands being placed upon the surface water resources. The climate of the state is characterized by extremes of floods and droughts. Reservoirs are necessary to control and utilize the highly variable streamflow. Numerous reservoirs have been constructed to facilitate management of the water resources of the various river basins of the state. Effective control and utilization of the water resource supplied by a stream/reservoir system requires an understanding of the amount of water which can be provided under various conditions. Estimates of reservoir yield are a key element in practically all studies and decisions involving development and management of surface water supplies.

Yield is defined as the amount of water which can be supplied by an unregulated stream, reservoir, or multiple reservoir system during a specified period of time. The stochastic nature of streamflow must be reflected in methods for quantifying yield. The approaches for expressing yield which traditionally have been used in water supply planning and management are firm yield and, to a lesser extent, reliability. Firm yield is the estimated maximum release or withdrawal rate which can be maintained continuously during a repetition of the hydrologic period-of-record. A number of definitions of reliability are cited in the technical literature. A common definition is that reliability is the percentage of time that a stream/reservoir system is able to meet a specified demand. Precise textbook definitions of firm yield and reliability can be formulated for a simple river basin with one reservoir and one water user. However, in actual practice, for a complex multiple reservoir, multiple user system, firm yield and reliability must be defined in terms of the basic assumptions and approaches used in handling various complicating factors.

Water supply planning and management involves complex institutional, environmental, hydrologic, and physical systems. Streamflow, reservoir sedimentation, evaporation, water demands, and other variables pertinent to yield determinations are highly stochastic. Measured historical data is limited in extent and accuracy. The future is always uncertain. Mathematical models only approximate the complexities of reality. Consequently, reservoir yield studies necessarily involve uncertainties and approximations.

The availability of water to particular users depends upon legal rights and contractual commitments as well as physical facilities and hydrologic conditions. Reservoir yield is subject to institutional as well as hydrologic constraints. Evaluation of the relationships between water rights and reservoir yield is particularly important at this time in Texas with the recent completion of the water rights adjudication process.

Scope of the Study

The objective of the study documented by this report was to evaluate and improve state-of-the-art capabilities for estimating reservoir yield. Institutional as well as hydrologic aspects of water availability were investigated. Evaluation of increases in yield achieved by multiple reservoir system operation, rather than separate operation of individual reservoirs, was a major emphasis of the study. The river basin was viewed as an integrated system.

The hydrologic and institutional availability of water was investigated for a case study reservoir system. However, the study approach and computer programs used are generally applicable to any reservoir system. Study findings have pertinent implications for water resources management throughout Texas and elsewhere as well as for the specific river basin studied.

Water availability is dependent upon institutional constraints and capabilities. The study included a review of water law and other institutional aspects of surface water management in Texas.

A literature review was made assessing modeling capabilities for estimating reservoir yield. The reservoir system simulation models HEC-3 and HEC-5 were adopted for use in the case study. These generalized computer programs provide comprehensive capabilities for analyzing the hydrologic aspects of reservoir system operations, but lack the capability to simulate water rights priorities. Consequently, a generalized water rights simulation computer program was developed in conjunction with the study. Other computer programs were used for developing input data and analyzing output from the HEC-3, HEC-5, and water rights models.

A system of twelve reservoirs in the Brazos River Basin provided a case study. Nine multiple purpose flood control and conservation reservoirs are owned and operated by the Fort Worth District (FWD) of the U.S. Army Corps of Engineers (USACE). The Brazos River Authority (BRA) has contracted for most of the water supply storage capacity of the nine federal projects. The BRA owns and operates three other conservation reservoirs. In addition to the 12-reservoir USACE/BRA system, Hubbard Creek Reservoir, owned by the West Central Texas Municipal Water District, was modeled in detail because of its relatively large storage capacity. The numerous other smaller reservoirs in the basin were considered primarily from the perspective of approximating their impacts on the 12 USACE/BRA reservoirs.

Individual reservoir and system firm yields were computed based on alternative conditions of reservoir sedimentation and alternative assumptions regarding multiple reservoir and multiple user interactions. The sensitivity of firm yield estimates to these and other factors was evaluated. A series of yield analyses were made from a strictly hydrologic perspective, without consideration of water rights. Yield analyses were then repeated incorporating water rights constraints. In addition to the firm yield simulations, a basinwide water rights analysis simulation study was performed. The simulations were based on monthly historical period-of-record hydrologic data. The modeling studies provided a basis for evaluating the hydrologic and institutional availability of water in the Brazos River Basin.

Organization of the Report

An overview of water law and institutions in Texas, from the perspective of surface water management, is presented in Chapter 2. Surface water management in the Brazos River Basin is described in Chapter 3. Chapter 4 is a discussion of reservoir system yield analysis models in general and the models used in the present study in particular. The Brazos River Basin simulation studies are documented by Chapters 5 through 9. Chapter 5 describes the compilation of basic data used in the study. A detailed hydrologic yield study is documented by Chapter 6. The analyses outlined in Chapter 6 were performed with HEC-3 and HEC-5 and are from a strictly hydrologic perspective, without consideration of water rights. The water rights analyses, utilizing the TAMU Water Rights Analysis Program, are presented in Chapters 7 and 8. Chapter 7 discusses the results of a simulation of hydrologic and water rights aspects of surface water management in the basin. Firm yields constrained by senior water rights are documented in Chapter 8. Chapter 9 provides a critical evaluation, including sensitivity analyses, of the key factors affecting firm yield estimates. The study summary and conclusions are presented as Chapter 10.

CHAPTER 2
WATER LAW AND INSTITUTIONS IN TEXAS

Streamflow in Texas is highly variable and subject to extremes of floods and droughts. Consequently, reservoirs are necessary to develop dependable water supplies and reduce flooding. Reservoir development and management is accomplished within a complex system of organizations, laws, and traditions. Water is a publicly-owned resource, and its allocation and use are governed by law. An overview of reservoirs, reservoir management agencies, and water law in Texas is presented in this chapter.

Reservoirs in Texas

The water-related resources and activities of the major river basins and coastal basins of the state are described in the Texas Water Plan (TDWR 1984). Reservoir operation is also discussed by Wurbs (1985) along with an inventory of the major reservoirs. Surface water management in the state is facilitated by 187 major reservoirs with storage capacities greater than 5,000 acre-feet, including two reservoir projects presently under construction. The 187 major reservoirs contain conservation, flood control, and total capacities of 40.0 million, 18.5 million, and 58.5 million acre-feet, respectively. Texas has about 5,700 reservoirs with surface areas greater than 10 acres. However, the 187 major reservoirs represent over 95 percent of the total storage capacity in all the reservoirs.

As indicated by Table 2.1, the number of major reservoirs in each of the 15 major river basins range from one in the Lavaca River Basin to 40 in the Brazos River Basin. Seven of the reservoirs are located in the coastal basins. The Trinity River Basin contains 16 percent of the state's total conservation and flood control storage capacity, which is the most of any basin. The Brazos River Basin has the largest number of major reservoirs (40 of the 187) and third largest storage capacity (13 percent) of the 15 major river basins and several coastal basins (Wurbs 1985).

The reservoirs vary tremendously in size. Several hundred thousand natural lakes, farm and stock ponds, flood retarding and stormwater detention structures, recreation lakes, and small water supply reservoirs range in size from less than an acre-foot to 5,000 acre-feet. The 187 major reservoir range in size from 5,000 acre-feet to over 5,000,000 acre-feet.

Surface water management in Texas is greatly influenced by a long-term threat of drought. Water must be stored through many wet years to be available during drought conditions. Although reservoir storage may be significantly depleted within several months, severe drought conditions are characterized as a series of several dry years rather than the dry season of a single year.

The Texas Department of Water Resources (1984) has estimated the dependable yield from all the major reservoirs in the state to be about 11 million acre-feet annually. The present use of surface water is about 64 percent of the firm yield. Most of the remaining firm yield is committed for expanding municipal and industrial needs during the next 20 to 30 years (TDWR 1984).

Table 2.1

NUMBER AND CAPACITY OF MAJOR RESERVOIRS BY RIVER BASIN

Basin	Number of Reservoirs	Controlled Storage Capacity (acre-feet)				
		Conservation			Flood Control	Total
		Active	Inactive	Total		
Trinity	31	7,075,180	271,910	7,347,090	1,820,200	9,167,290
Rio Grande	7	6,120,320	23,400	6,133,720	2,654,000	8,787,720
Brazos	40	3,343,850	564,100	3,907,950	3,940,600	7,848,550
Red	23	3,959,250	9,180	3,968,430	2,972,900	6,941,330
Sabine	12	6,289,790	--	6,289,790	--	6,289,790
Colorado	24	3,690,730	103,110	3,793,840	1,529,620	5,323,460
Neches	10	2,180,270	1,452,000	3,632,270	1,099,400	4,731,670
Sulphur	4	438,820	37,000	475,820	2,640,400	3,116,220
Canadian	2	833,400	43,100	876,500	543,200	1,419,700
Cypress	8	757,490	--	757,490	587,200	1,344,690
San Jacinto	6	592,230	--	592,230	411,500	1,003,730
Nueces	3	977,490	--	977,490	--	977,490
Guadalupe	5	417,580	23,900	441,480	346,400	787,880
San Antonio	4	342,300	--	342,300	12,600	354,900
Lavaca	1	157,900	--	157,900	--	157,900
Coastal Basins	7	280,250	--	280,250	--	280,250
Total	187	37,446,850	2,517,700	39,974,550	18,558,020	58,532,570

Source: Wurbs (1985)

In considering reservoir operation in the state, it is important to realize that water shortage is a regional or local, as well as statewide, problem. A small region of the state may be experiencing drought conditions while the state as a whole is having a relatively wet year. Physical and institutional constraints often prevent transport of water from a surface water system with a surplus supply to a neighboring system experiencing a temporary severe water shortage. Each local and regional water supplier must have the capability to assure its water users an adequate supply during drought conditions in its own area regardless of the statewide situation. A particular entity is in trouble if its reservoir storage capacity is depleted, even if the combined storage capacity in all the reservoirs statewide is practically full of water. On the other hand, however, complex institutional and physical interactions between localities and regions of the state make surface water management a statewide, as well as local and regional, problem.

The relationship between storage capacity and dependable yield varies greatly with geographical location in Texas. McDaniels (1964) illustrated this variation with the following comparison. In humid East Texas, a reservoir may provide a firm annual yield larger than its conservation storage capacity. In subhumid Central Texas, a reservoir may provide a firm annual yield equal to only one-fifth or less of its conservation storage capacity. In semiarid and arid West Texas, a reservoir may provide a firm annual yield varying within a range of one-tenth to one-thirtieth or less of its conservation storage capacity.

Water supply withdrawals at many projects are made through pumping plants with intake structures located in the reservoir. In many other cases, releases are made through outlet works and spillway structures to be withdrawn from the river at downstream diversion and intake facilities. The water may be actually withdrawn at locations several hundred river miles below the dam from which it was released. Travel times of a week or longer are not uncommon. For example, the most downstream water user serviced by the Brazos River Authority is about 200 miles below the most downstream and 640 miles, or two weeks travel time, below the most upstream reservoir from which releases are made. The International Falcon Reservoir is 275 miles, or about one week travel time, above the most downstream water users in the Lower Rio Grande Valley. The most downstream user supplied by the Lower Colorado River Authority is also a week travel time downstream of the closest reservoir from which releases are made.

Water Resources Development and Management Agencies

The 187 major reservoirs in Texas are owned, maintained, and operated by four federal agencies, 43 water districts and river authorities, 39 cities, two counties, a state agency, and 22 private companies. Wurbs (1985) lists the agencies along with the reservoirs they own. Table 2.2 shows the number of reservoirs and storage capacity owned by various types of entities. The U.S. Army Corps of Engineers is the single largest reservoir manager in the state. Federal projects are also owned by the International Boundary and Water Commission, U.S. Fish and Wildlife Service, and U.S. Forest Service. The Bureau of Reclamation and Soil Conservation Service constructed eight of the major reservoirs, but these projects are now owned and operated by nonfederal sponsors. River authorities and water districts own more reservoirs than any other type of entity and have contracted for much of the conservation capacity in the Corps of Engineers reservoirs.

Table 2.2
TYPES OF RESERVOIR OWNERS

Type of Owner	Number of Reservoirs	Storage Capacity (acre-feet)		
		Conservation	Flood Control	Total
Federal Agencies	36	17,358,240	16,518,120	33,876,360
International Boundary and Water Commission	(2)	(5,772,600)	(2,654,000)	(8,426,600)
Corps of Engineers	(32)	(11,559,490)	(13,864,120)	(25,423,610)
Other	(2)	(26,150)	---	(26,150)
Water Districts and River Authorities	57	16,080,060	1,324,600	17,404,660
Jointly Owned by Cities and Water Districts or River Authorities	4	2,539,490	248,300	2,787,790
Cities	48	2,843,470	467,000	3,310,470
Counties	5	54,810	---	54,810
Other State Agencies	1	5,420	---	5,420
Private Companies	36	1,093,060	---	1,093,060
Totals	187	39,974,550	18,558,020	58,532,570

Source: Wurbs (1985)

Water districts are units of local government organized to fulfill specific water resources management functions. Water districts have operational autonomy. They are not dependent on cities or counties for establishing policy or providing controls. Water districts in Texas vary greatly in purpose. They undertake all types of water development and management programs including municipal, industrial, and agricultural water supply, sewage treatment, flood control and drainage, navigation, electric power generation, soil conservation, and recreation.

River authorities are a special type of water district which were created to develop and manage water resources from a basinwide perspective. Some river basins in Texas are served by a single river authority while other basins are served by several authorities. The conservation amendment of the Texas constitution, passed in 1917, enabled the creation of districts such as river authorities. The Brazos River Authority, created in 1929, was the first authority ever set up in the United States to manage the water resources of a major river basin. Each river authority has been created by a separate legislative act, and each has its own primary functions within its general responsibility for the development, control, and management of water resources. River authority activities generally focus on one or more of the following areas: water supply and distribution, flood control, water quality control, navigation, and generation of hydroelectric and/or thermal power. River authorities also provide parks and recreation facilities.

River authorities primarily finance their activities through operational and service fees. In addition, they are eligible for state and federal grants similar to other political subdivisions. Several authorities may levy ad valorem taxes and issue bonds supported by taxes subject to voter approval. All river authorities may issue revenue bonds backed by fees from particular enterprises. River authorities generally do not have to seek voter approval to issue revenue bonds. No river authority receives a line-item appropriation from state or federal tax revenues. River authorities enter into contracts with local interests to sell water or power from authority projects. Under Texas law, a river authority obtains a permit for the right to a specified annual amount of water. The river authority may then sell the right to use the water. Because of larger jurisdictions and specific legislative authority, river authorities can often more effectively finance, construct, and operate dams and reservoirs than cities or local districts.

Although they do not actually construct and operate reservoir projects, the Texas Water Development Board (TWDB) and Texas Water Commission (TWC) play major roles in reservoir development and management. Prior to 1977, the TWDB and TWC were separate agencies. From 1977 through 1986, the staffs of the TWDB and TWC were consolidated into a single agency, the Texas Department of Water Resources (TDWR). The TDWR was abolished and the TWDB and TWC again became separate agencies in 1986. The TWDB has a broad range of responsibilities, which include maintaining a comprehensive state water plan, collecting basic data, interagency coordination, and administration of the water development fund. This fund is used to purchase bonds of eligible governmental entities, such as cities and water districts, which are unable to sell their bonds through commercial channels at a reasonable interest rate. The TWC performs state regulatory functions, including administration of the water rights system.

Federal and Nonfederal Roles

The reservoir management agencies can be categorized as federal agencies, state and local governmental entities, and private companies. Most of the major reservoirs in Texas were constructed by state and local governmental agencies or private industry for conservation purposes. However, two-thirds of the total storage capacity is contained in reservoirs constructed by federal agencies. Most of the federal reservoirs are large multiple purpose flood control and conservation projects.

Federal agencies have constructed 40 major reservoirs and significantly modified two others. Two additional projects are presently under construction. The federal government is responsible for construction of eight of the ten largest and 21 of the 28 reservoirs with capacities exceeding 500,000 acre-feet. Eight federally-constructed projects have been turned over to nonfederal entities for operation and maintenance. The others are operated by federal agencies. The 43 projects with federal involvement contain 52 percent, 99.9 percent, and 67 percent of the conservation, flood control, and total capacities, respectively, of the 187 major reservoirs. Federal involvement in reservoir construction and operation in Texas is summarized in Table 2.3 (Wurbs 1985). The data in Table 2.3 does not include federal grants and loans, such as those provided by the early Works Progress Administration Program, which helped finance several of the nonfederal projects.

The five projects constructed by the Bureau of Reclamation were turned over to local sponsors for maintenance and operation. The Bureau of Reclamation continues to own the projects until the local sponsor has completed payments to the federal government for reimbursable costs. The Soil Conservation Service also has constructed two major water supply reservoirs which are owned, operated, and maintained by nonfederal sponsors. The Corps of Engineers operates and maintains its projects upon completion of construction. Withdrawals or releases from conservation storage are made at the discretion of the nonfederal sponsors.

State and local governmental entities have constructed 109 major reservoirs. These reservoirs contain 45 percent, 0.1 percent, and 31 percent, respectively, of the conservation, flood control, and total storage capacities of the 187 major reservoirs. This does not include the several federally-constructed projects which are maintained and operated by nonfederal sponsors or the conservation storage in federally-maintained and operated reservoirs for which nonfederal sponsors have contracted.

Private companies constructed, own, and operate 36 major reservoirs containing no flood control storage and less than three percent of the total conservation storage of the major reservoirs. The majority of these projects are used for cooling water storage for steam electric power plants.

Institutional Considerations by Project Purpose

Reservoir operation is based upon the conflicting objectives of maximizing the amount of water available for conservation purposes and maximizing the amount of empty space available for storing flood waters to prevent damage at downstream locations. A reservoir is operated only for conservation purposes, or only for flood control, or a certain reservoir volume, or pool, is

Table 2.3
FEDERAL INVOLVEMENT IN RESERVOIR DEVELOPMENT AND MANAGEMENT

Federal Involvement	Number of Reservoirs	Storage Capacity (acre-feet)		
		Conservation	Flood Control	Total
Constructed, Owned and Operated by International Boundary and Water Commission	2	5,772,600	2,654,000	8,426,600
Constructed, Owned and Operated by Corps of Engineers	29	11,062,490	13,732,720	24,795,210
Presently Under Construction by Corps of Engineers	2	368,000	131,400	499,400
Major Modification by Corps of Engineers	2	448,600	248,300	696,900
Constructed by Bureau of Reclamation and Maintained and Operated by Nonfederal Sponsors	5	3,081,100	1,779,000	4,860,100
Constructed by Soil Conservation Service and Maintained and Operated by Nonfederal Sponsors	2	17,850	---	17,850
Constructed by Soil Conservation Service and Owned and Operated by U.S. Fish and Wildlife Service	1	18,150	---	18,150
Constructed, Owned and Operated by Forest Service	1	8,000	---	8,000
Total	44	20,776,790	18,545,420	39,322,210

Source: Wurbs (1985)

designated for conservation purposes and a separate pool for flood control. The conservation and flood control pools in a multipurpose reservoir are fixed by a designated top of conservation (bottom of flood control) pool elevation. Three major reservoirs in Texas are operated for only flood control. Thirty-two reservoirs are operated for both flood control and conservation purposes. The remaining 152 reservoirs are operated for various conservation purposes. The conservation storage capacity is used primarily for municipal, industrial, and agricultural water supply, steam-electric power plant cooling water, hydroelectric power, and recreation.

Flood Control

Essentially all the major reservoirs in Texas containing controlled flood control storage were constructed and are operated by the federal agencies. The federal government has borne all costs associated with flood control. The Corps of Engineers is responsible for flood control operations of its own reservoirs and those constructed by the Bureau of Reclamation. The International Boundary and Water Commission handles the flood control operations of its projects.

Water Supply

About three-fourths of the conservation storage capacity in the major reservoirs is designated for municipal and industrial uses. Municipal and industrial water supply has traditionally been a local responsibility. The federal government confines itself to a secondary role in this area. However, municipal and industrial storage is included in all but two federal reservoirs, subject to nonfederal cost sharing. Although municipal and industrial water supply was already being included in federal reservoirs, the Water Supply Act of 1958 established a uniform policy. Under the provisions of this law, the federal water agencies may provide additional capacity for municipal and industrial water supply in reservoirs to be constructed primarily for federal purposes such as flood control, irrigation, or navigation. Cost allocated to water supply must be repaid, with interest, by nonfederal sponsors over a period of time not to exceed 50 years. Repayment of costs for future water use can be delayed until the water is first used up to the limit of 10 years after completion of construction. No interest is charged during this period. However, no more than 30 percent of the costs of the project may be allocated to storage for future supply. Inclusion of municipal and industrial water supply storage in a federal reservoir requires a contractual agreement with one or more nonfederal sponsors prior to construction. All costs, including construction, operation and maintenance, and major replacement, are allocated to project purposes by a formal cost allocation method. The incremental cost method was used for earlier projects and the separable costs-remaining benefits method was used for most of the later projects in Texas.

The conservation storage in several of the federal reservoirs is used for irrigation as well as municipal and industrial water supply. However, the Bureau of Reclamation has not constructed large federally-subsidized reservoirs devoted primarily to irrigation in Texas like it has in several other western states. In general, nonfederal sponsorship of conservation storage in federal reservoirs has been handled similarly for irrigation and municipal and industrial uses.

Reservoir operation procedures for water supply purposes are based essentially on meeting water demands subject to institutional constraints related to water rights, project ownership, and contractual agreements. The complex organizational framework for water supply operations involves a multitude of water users and suppliers working under various contractual arrangements. Water suppliers may either own and operate reservoirs or contract with other reservoir owners for storage capacity or water use. A number of entities both own and operate their own reservoirs and contract with others for the use of additional capacity.

The Cypress Creek Basin operating agreement illustrates an institutional arrangement for coordinating the operation of reservoirs owned by several entities to the mutual benefit of all. Operation of several reservoirs in the Cypress Creek Basin is governed by an operating agreement entered into in 1972 by the Northeast Texas Municipal Water District, Franklin County Water District, Titus County Fresh Water Supply District No. 1, Lone Star Steel Company, and the Texas Water Development Board. The agreement provides rules for operating reservoirs owned by the participants and provisions for accounting for the waters held in storage. Storage accounts are established for the reservoirs such that basin waters are appropriately divided through exchange of storage, in accordance with existing water rights.

Although most of the surface water used in the state is used within the river basin from which it originates, significant interbasin transfers do occur. For example, Meredith Reservoir on the Canadian River supplies water to nine cities located in the upper Red, Brazos, and Colorado River Basins as well as two cities in the Canadian Basin. The City of Dallas, located in the upper Trinity River Basin, has contracted with the Sabine River Authority for a majority of the water supply from Lake Tawakoni and the recently completed Lake Fork. Dallas has been using Lake Tawakoni water for some time and plans to use Lake Fork in the future. The remaining supply from Lake Tawakoni is used by the City of Terrell in the Trinity Basin, City of Commerce in the Sulphur River Basin, and several small cities in the Sabine Basin. Livingston Reservoir on the Trinity River supplies water to the City of Houston in the San Jacinto River Basin. Large diversions from the Brazos, Colorado, Trinity, and San Jacinto Rivers are made to numerous water users in the several coastal basins. Extensive conveyance and distribution systems are operated to facilitate these diversions.

The storage capacity in several reservoirs on the international and interstate rivers are shared between Texas and neighboring states or Mexico. The five border reservoirs include the three largest reservoirs in the state. The United States and Mexico have divided the storage capacity in the two international reservoirs by treaty. Texas has entered into interstate compacts with neighboring states which divide the storage capacity in the interstate reservoirs.

Steam-Electric Power

Twenty-nine cooling water reservoirs, containing about 2.7 percent of the total conservation capacity of the 187 major reservoirs, provide water for steam electric power plants. With the exception of recreation in some cases, these projects are used solely for steam-electric power plants. Most of the reservoirs are owned by electric companies with several being owned by river authorities or cities. The reservoirs are typically located adjacent to the power plant. Several are off-channel reservoirs with water levels maintained by diversions from a river. Several other multiple purpose conservation reservoirs provide water to steam-electric power reservoirs or directly to the power plants.

Hydroelectric Power

Fifteen of the 21 hydroelectric power projects in Texas are owned and operated by river authorities, which sell the power to electric cooperatives, municipalities, and utility companies. Three of the Corps of Engineers reservoirs and the two International Boundary and Water Commission reservoirs have hydroelectric power plants. Lake Travis constructed by the Bureau of Reclamation also has hydropower, but it was added by the Lower Colorado River Authority. The Western Area Power Administration (WAPA) is responsible for marketing the power generated at the two International Boundary and Water Commission projects. The Southwestern Power Administration (SWPA) markets the power from the Corps of Engineers projects. These are two of several agencies of the Department of Energy which market hydroelectric power from federal projects in various geographical regions of the nation. The SWPA and WAPA sell the power to electric cooperatives, municipalities, and utility companies.

Recreation

Federal and nonfederal entities have been involved to various extents in providing recreation at the major reservoir projects. A few small reservoirs are used only for recreational purposes. However, most recreation occurs at larger multiple purpose projects. The federal water resources development program has strongly emphasized multiple purpose development. Consequently, the federal projects all include public access and recreational facilities. Prior to 1965, recreation was included in federal projects as a fully federal expense. The Federal Water Recreation Act of 1965 established development of the full recreational potential at Federal projects as a full project purpose subject to nonfederal cost sharing. Cities and water districts often include recreational facilities as an incidental use of their water supply reservoirs. Before 1971, most river authorities were not authorized to supply recreation, but were directed not to prevent free public use of their lands. They generally served the public by making land available to other agencies for recreational development or leasing their land for commercial recreation enterprises. However, the River Authority Recreation Act passed by the legislature in 1971 gave the river authorities the authority and responsibility to develop water resources for public recreation purposes and to acquire and improve parkland near public waters.

Water Law

Basic Concepts

A water right is simply the legal right to use water. Water law is the creation, allocation, and administration of water rights. Getches (1984) provides a general overview of the development and application of basic principles of water law. Rice and White (1987) treat water law from an engineering perspective. Jacobstein and Mersky (1966) compiled a water law bibliography covering the period 1847-1965.

Water is categorized by where it is physically contained. Water law in Texas, and most other states, recognizes four distinct classes of water: (1) diffuse surface water, (2) streamflow, (3) percolating groundwater, and (4) underground streams. Separate rules of law have been developed for each category of water.

The law with respect to ownership of subterranean rivers is not settled in Texas. In regard to percolating ground water, Texas courts have followed unequivocally the common law rule that the landowner has a right to take for use or sale all the water he can capture from beneath his land. The state has little control over the use of ground water. Consequently, conjunctive management of ground and surface waters is extremely difficult.

Only water in a watercourse is subject to state ownership in Texas. Diffuse surface water, often called drainage water or runoff, does not become the property of the state until it reaches a watercourse. A landowner may construct a dam on a non-navigable stream on his property to impound and use diffuse surface water, without a permit, as long as the volume of water impounded does not exceed 200 acre-feet. This provision of the law is pertinent to the management of major reservoirs because construction of numerous small dams in a watershed can reduce the amount of runoff that reaches the main river.

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 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.

Historical Development of Surface Water Law in Texas

Texas water law recognizes claims to surface water rights granted under Spanish, Mexican, English, Republic of Texas, and United States as well as Texas state laws. Both the appropriation and riparian doctrines are recognized. The riparian doctrine was introduced into Texas by the Spanish and Mexican governments and then, after independence in 1836, in a somewhat different form by the Republic of Texas. For many years, Texas courts and water agencies ruled that Spanish and Mexican land grants carried extensive riparian water rights, including the right to use water for irrigation. Following more thorough investigations of Spanish and Mexican water law, the courts determined in the Valmont Plantations versus Texas case in 1962 that riparian rights to use water for irrigation did not attach to these land grants, unless specifically included. Few land grants included specific provisions for water rights except in the vicinities of San Antonio and El Paso. Extensive amounts of land, mostly in South and Central Texas, can be traced to Spanish and Mexican grants. Land grants made between 1836 and 1840 by the Republic of Texas also were controlled by Mexican law and have the same water rights. In 1840, the State of Texas adopted the common law of England in which riparian water rights include the right to make reasonable use of water for irrigation or for other extensive and consumptive purposes.

The prior appropriation doctrine was adopted by the state with the Appropriation Acts of 1889 and 1895. After 1895, public lands which transferred into private ownership no longer carried riparian water rights. Water rights are claimed through statutory procedures. At first, appropriation was accomplished through an informal procedure in which a water user simply filed a sworn statement with his county clerk describing his water diversion. Later, certified copies of these claims were recognized by the state, and came to be called "certified filings". Since 1913, more strictly administered procedures have been followed based on administration of a statewide appropriation system by a single state agency. The Board of Water Engineers was established in 1913, renamed the Texas Water Commission in 1962, renamed the Texas Water Rights Commission in 1965, and renamed the Texas Water Commission in 1977. All appropriation statutes recognize the superior position of riparian water rights. Riparian landowners can also acquire appropriative water rights and may claim both types of rights, each without prejudice to the other.

The complications of having various forms of riparian and appropriative water rights existing on the same stream have been a significant difficulty in managing the surface water resources of the state. As late as 1968, no single state agency had a record of the number of riparian water users in any major river basin, the extent of their claims, or the amount of water they were using. Prior to 1967, several unsuccessful legislative attempts were made to more accurately measure riparian rights. A 1917 water rights adjudication attempt was held unconstitutional. In 1955, the legislature adopted a statute requiring all water users, including riparians, to file a statement each March with the Water Commission stating the amount of water used during the preceding calendar year. However, most riparian water users ignored the law and failed to file reports. Penalty provisions were inadequate and were not enforced (McNeeley and Lacewell 1977).

In 1926, the courts divided streamflow into "ordinary normal flow" and "flood flows". Riparian rights are limited to normal flow and therefore are not applicable to flood waters impounded by reservoirs. The ordinary or normal flow of a watercourse is judicially defined as the flow below the line "which the stream reaches and maintains for a sufficient length of time to become characteristic when its waters are in their ordinary, normal and usual conditions, uninfluenced by recent rainfall or surface runoff". Although the courts and water agencies have found this definition to be extremely difficult to apply in actual practice, it has been the basis for correlating riparian and appropriative rights since 1926.

The Wagstaff Act, enacted in 1931, 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." The Rio Grande River was specifically excluded.

The Water Rights Adjudication Act was passed in 1967 to remedy the confused surface water rights situation. 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. Pursuant to the act, all unrecorded claims were required to be filed with the Texas Water Commission. Minor exceptions were made for those using only small quantities of water for domestic and livestock purposes. Claims were to be recognized only if valid under existing law and only to the extent of the maximum actual beneficial use of water without waste during any calendar year from 1963 to 1967, inclusive. The deadline for filing was September 1, 1969, but numerous late claims were received and accepted by the Commission. The base period and filing date were extended to 1970 and 1971, respectively, for some riparians, and the filing deadline was extended to September 1974 for those who failed to file because of extenuating circumstances or for good cause (McNeeley and Lacewell 1977).

Statewide 11,600 unrecorded claims were filed claiming more than 7 million acre-feet of water. About 95 percent of the claims were for riparian rights, and the remainder were certified filings which had not been properly recorded previously. 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 (now the Texas Water Commission) initiated a series of administrative adjudications of water rights on a river segment by river segment basis. The adjudication process was essentially complete in 1986.

Davenport (1954) treats the history of water rights in Texas. Templer (1981) provides a detailed discussion of the evolution of Texas water law, with a focus on the adjudication process.

Present Water Rights Permit System

Water rights are granted by a state license, or permit, which grants to the holder the use of a specified amount of water, at a specific location, and for a specific purpose. The laws and regulations governing the permit system are recorded in the Texas Water Code and the Rules of the Texas Water Commission. The Texas Water Code is included in Vernon's Texas Codes Annotated (1972 and 1988). The Texas Department of Water Resources (1984) and Kaiser (1987) provide concise descriptions of the present water rights system.

The Texas Water Commission (TWC) is responsible for administering rights to use the surface waters of the state. The TWC consists of three full-time commissioners appointed by the governor and a professional and administrative staff. The water rights permitting functions of the TWC include determining the amount of water available for appropriation, evaluating permit applications, and granting permits.

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. The Texas Water Code recognizes an appropriator as any person who has made beneficial use of water in a lawful manner. Texas has more than 12,000 appropriators of surface water (Kaiser 1987).

The Water Rights Adjudication Act applies to permit claims through 1969, which are titled certificates of adjudication. For permits after 1969, a more standard procedure is followed. Applications for permits to appropriate water are formally submitted to the TWC. A water use application is approved by the TWC 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. After approval of an application, the TWC 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 TWC 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 cancelled. A permit may be cancelled if water is not used during a ten-year period. Cancellation of unused permits, certified filings, or certificates of adjudication is done through administrative action by the TWC.

Permits may be regular, seasonal, temporary, or emergency in nature. A regular permit is issued in perpetuity so long as the water is used for a beneficial purpose. Seasonal permits are similar to regular permits except that the use of water is limited to certain months or days during the year. A temporary permit is granted for a period of time up to three years and does not give the holder a permanent water right. An emergency permit allows the holder to divert and use water for up to 30 days if emergency conditions exist that threaten public health, safety, and welfare.

The TWC may also grant permits to impound and store water, then determine the actual diversion and use at a later date. Many permits issued to river authorities fall in this category. At a later date, the river authority may locate a customer for the water. The TWC will then issue a water use permit.

A 1985 amendment to the Texas Water Code requires applicants to adopt water conservation practices before they receive a water permit from the TWC. The water user must develop water conservation plans and demonstrate that their techniques either will reduce water consumption, loss, or waste, or will increase recycling or reuse of water.

Streamflow is public property. A water permit holder has no actual title to the water but only a right to use the water. However, a water right is a recognized property right in Texas. A water right can be sold, leased, or transferred to another person. A water right can be conveyed automatically with the title to land, unless reserved in a deed, or can be sold separately from the land. In these cases, the water code provides that the written instruments conveying water rights may be recorded in the same manner as a property deed.

The Texas Water Code and Rules of the Texas Water Commission place certain restrictions on the transfer of water rights. Transfers must be approved by the TWC. A transfer will not be allowed if other water rights would be impaired. The transfer of a water right to another river basin is prohibited if the transfer will materially harm any person in the watershed from which the water was taken. The physical transfer of water from one basin to another is allowed only if there is no prejudice. In this case, the water is transported but not the water right.

Water Rights Priorities

The Texas Water Code is based upon the prior appropriation doctrine. Section 11.027 of the Texas Water Code states: "As between appropriators, the first in time is the first in right." However, there is an exception to the first in time, first in right rule. Section 11.028 provides: "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." 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 crises, a city may take water from another appropriator and use it for domestic purposes even though the other appropriator used the water first. 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.

The prior appropriation doctrine requires that water be used for a beneficial purpose. The Texas Water Code defines beneficial use as the use of such a quantity of water, when reasonable intelligence and diligence are exercised in its application for a lawful purpose, as is economically necessary for that purpose. Section 11.024 of the code lists beneficial uses in order of priority as follows: (1) domestic and municipal uses, (2) industrial uses, (3) irrigation, (4) mining, (5) hydroelectric power, (6) navigation, (7) recreation and pleasure, and (8) other beneficial uses. These priorities are followed when a conflict exists between water use applications. After permits have been issued and water rights perfected, priorities are based on dates, with the previously discussed exception of the Wagstaff Act.

Penalties for Water Rights Violations

The Texas Water Code contains a number of penalties for violations of the substantive and procedural provisions of the law. Violations are considered misdemeanors and are punishable by fines as high as $1,000 or by confinement in a county jail for not more than two years, or both. Examples of misdemeanor violations include: (1) unlawful use of state water without a permit, (2) sale of a water right without a permit, (3) interwatershed transfers, (4) interference with diversion of water on an international stream, (5) willful destruction of ditches, canals, reservoirs, or machinery associated with a water right, (6) allowing Johnson grass or Russian thistle to go to seed on a waterway, (7) throwing garbage into a water canal, (8) obstructing a navigable stream, and (9) willfully wasting water. In addition to the misdemeanor penalties, the Texas Water Code allows a civil penalty to be levied for unlawful use of water. A person who takes state water without a permit, or in violation of a permit, faces a civil penalty of up to $1,000 for each day of the violation.

Water Availability

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 TWC must determine the amount of water available for appropriation at various locations in each river basin of the state.

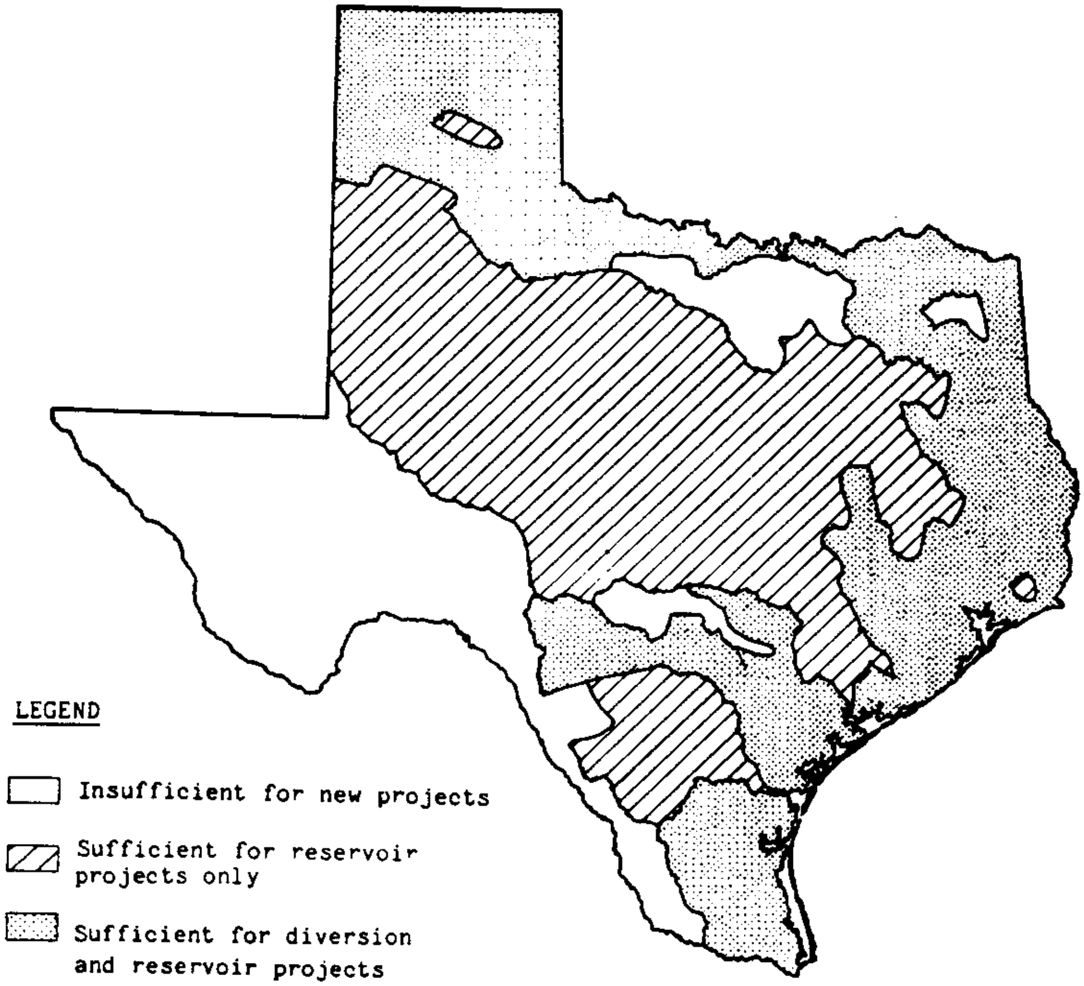
Estimating unappropriated water amounts for a river basin is difficult due to a number of reasons. Streamflow, as well as other hydrologic variables such as precipitation and reservoir evaporation, are highly stochastic. Streamflow at a location varies tremendously from year to year and throughout a given year due to natural variations in precipitation and watershed conditions. The runoff characteristics of a watershed also change with changes in land use and watershed development. Actual water use also varies greatly depending on weather conditions and numerous other factors. Water users normally do not use the full amounts to which they are legally entitled each year. On the other hand, since water withdrawals are not closely monitored, certain users may take more water than they are entitled. Reservoir storage, channel losses, return flows, and seasonal water use patterns also significantly affect water availability.

The TWC has developed computer models for each river basin to estimate the amounts of unappropriated water. Since future streamflow is unknown, the water availability models are based on historical gaged monthly streamflow data. The streamflows are naturalized to remove nonhomogeneities caused by the activities of man in the basin. Missing data in gage records are filled in by regression analyses with records at other gages. The point of diversion for each water right is located on a map. Streamflow at the water right location is estimated by various techniques such as applying drainage area ratios to streamflow at gaged locations. Historical monthly reservoir evaporation rates are applied to computed water surface areas. All water rights holders are assumed to fully use their permitted amounts each year. Return flows and monthly water use distribution factors are estimated based on past records.

The water availability model simulations are based on monthly naturalized historical streamflow, historical reservoir evaporation rates, permitted water use and reservoir storage capacities, and historical return flow and monthly water use patterns. The model computes unappropriated water amounts for each pertinent location for each month of the simulation period.

The computed unappropriated water amounts vary monthly and annually. Since the model is based on historical streamflows, actual future streamflow will result in different amounts of unappropriated water than the model. Precise methods of quantifying the probability or likelihood of various water amounts being available for appropriation have not been developed as part of the modeling effort. The water availability model provides a quantitative basis for estimating unappropriated water. However, considerable judgement is exercised in using the model output to determine whether applications for permits for additional water use are approved.

Many segments of Texas rivers are fully appropriated or have limited water available for appropriation. Some rivers still have significant amounts of water available for future appropriation. Figure 2.1 illustrates general water availability in various parts of the state.



Source: **TDWR (1985) and Kaiser (1987)**

Figure 2.1 Water Availability

Water Rights Administration

The legal right to use or sale 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 sales 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 sales 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 storage in federal projects are responsible for obtaining the appropriate water rights permits through the TWC.

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 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 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.

The International Falcon and Amistad Reservoirs on the Rio Grande River are owned and operated by the International Boundary and Water Commission, United States and Mexico. The TWC is responsible for utilizing the United States share of the conservation storage capacity in the two reservoirs and administering the allocation of the water to users. A water master, who is on the staff of the TWC, works directly with irrigation districts, individual farmers, and municipalities in Texas who hold permits for use of water from the Rio Grande River. The water master administers the water allocation system and determines the required releases to be made from Falcon and Amistad Reservoirs. The International Boundary and Water Commission makes the releases as requested by the water master.

According to Rice and White (1987), ensuring that the water to which seniors are entitled is not taken by juniors is a task which is very simple to describe but quite difficult to carry out. Rice and White (1987) describe the system of calls followed in most western states, including Texas. The prior appropriation water rights on most of the streams of the western states are virtually self-administering. In some cases, long-time neighbors are familiar with one another's priorities and voluntarily restrict their water usage to maintain the priority system. On larger streams, as competition for water becomes intense during drought conditions, voluntary compliance with the priority system often breaks down. A system of "calls" is triggered. A senior water right owner will contact the water commissioner requesting action to stop diversions by junior users. The senior water right owner is said to be "putting a call" on the river. The water commissioner will contact junior water users directing appropriate curtailment of water use. Enforcement actions can be taken as necessary.

With the exception of the water master operations in the lower Rio Grande River Basin, experience in administering water rights in Texas has been limited to date. Few situations have arisen in which junior water rights owners 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 twenty years have been characterized by relatively abundant precipitation and streamflow as compared to the droughts of the 1950's 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.

Reservoirs are necessary to develop dependable water supplies from highly variable streamflow. Water rights involve storage as well as diversions of water. Although many permits are for diversion only, permits often specify a reservoir storage capacity as well as a diversion amount. Reservoir owners must pass inflows through their projects to meet downstream senior water rights. A strict administration of the water rights system would include assuring maintenance of reservoir storage during relatively wet years as well as diversion during dry years for senior water rights. Drought cycles are unpredictable. In Texas, each day without precipitation could be the beginning of the next severe drought, comparable to the drought of the 1950's. Likewise, each reservoir drawdown could be the beginning of a several-year drawdown resulting in an empty reservoir. Consequently, the firm yield of a reservoir is decreased if upstream junior water rights owners make diversions when the reservoir is not spilling. This is assuming that the upstream diversions decrease inflows to the reservoir. Consequently, water availability in dry years is dependent upon water diversions and storage in prior wet years. Maintenance of reservoir storage illustrates the complexities of the water rights system which have not all been clearly worked out to date.

The implementation of a permit system and the adjudication of water rights have resulted in a manageable allocation of water resources. However, the water allocation and accounting system is still not extremely precise. Water diversions are not closely policed and may not be accurately measured and recorded. The impacts of junior diversions at certain locations on senior water rights at other locations in the basin may not be clearly evident. Water rights are expressed in terms of an annual amount, without specifying the monthly or daily diversion rates. Although some recent permits have addressed return flows, most permits do not specify the amount of the diversion to be returned to the stream. The Wagstaff Act may be evoked as drought conditions worsen. Various emergency conditions may develop as shortages become severe. Water rights are associated with individual reservoirs without regard to multireservoir system operations. Hydroelectric power operations can have beneficial as well as adverse impacts on downstream water availability. Consequently, administration of the water rights system during a severe drought can be expected to be complex, with allocation decisions requiring somewhat subjective judgments as well as application of the quantitative criteria associated with the permits.

CHAPTER 3
SURFACE WATER MANAGEMENT IN THE BRAZOS RIVER BASIN

Brazos River Basin

The Brazos River Basin extends from eastern New Mexico southeasterly across the state of Texas to the Gulf of Mexico. The basin has an overall length of approximately 640 miles, with a width varying from about 70 miles in the High Plains in the upper basin to a maximum of 110 miles in the vicinity of the city of Waco to about 10 miles near the city of Richmond in the lower basin. The basin drainage area is 45,600 square miles, with about 43,000 square miles in Texas and the remainder in New Mexico. The basin encompasses about 16 percent of the land area of Texas. Approximately, 9,570 square miles in the northwest portion of the basin, including all the area in New Mexico and a portion of the area in Texas, are noncontributing to downstream streamflows. The Texas Department of Water Resources (1984) as well as several Corps of Engineers reports (USACE 1987) provide descriptions of the Brazos River Basin. The basin map presented as Figures 3.1 and 3.2 is a modified version of a map prepared by the Corps of Engineers (USACE 1977 and 1983).

The 12 reservoirs operated by the U.S. Army Corps of Engineers (USACE) and Brazos River Authority (BRA), and most of the numerous other basin reservoirs, are located in the lower two-thirds of the basin. Three reservoirs of the 12-reservoir system are located on the main stem of the Brazos River and the others are on tributaries. The Leon, Lampasas, San Gabriel, Little River subbasin contains several major reservoirs. Reservoirs of the 12-reservoir system are also located on Aquilla Creek, Bosque River, Navasota River, and Yequa Creek. From its inception at the confluence of the Salt Fork and Double Mountain Fork, the Brazos River flows in a meandering path some 923 miles to the city of Freeport at the Gulf of Mexico. Most of the reservoirs in the basin are located on various tributaries which confluence with the Brazos River all along this length.

In its upper reaches, the Brazos River is a gypsum-salty intermittent stream. Toward the coast, it is a rolling river flanked by levees, cotton fields, and ancient hardwood bottoms. Upon its descent from the high plains and Caprock Escarpment, the Brazos River traverses through a small, semiarid region of gypsum and salt encrusted hills and valleys studded with salt springs and seeps. Natural salt pollution in this area significantly impacts reservoir development and operation in the basin. Waters in the three mainstream reservoirs, Possum Kingdom, Granbury, and Whitney, are unsuitable for municipal water supply without special and costly treatment processes. The quality of the river improves significantly in the lower basin due to dilution by good quality water from tributaries below Whitney Reservoir. An extensive natural salt pollution study is documented by the USACE (1977 and 1983).

The 1980 population of the Brazos River Basin is estimated to be 1,530,000 people (TDWR 1984). Lubbock is the largest city in the basin with a 1980 population of 174,000 or 11.4 percent of the basin total. Lubbock is followed in size by Waco, Abilene, Bryan-College Station, Killeen, and Temple, all of which have populations of 25,000 or more. The overall economy of the basin is based principally on agriculture, agribusiness, varied manufacturing, and mineral production and processing.

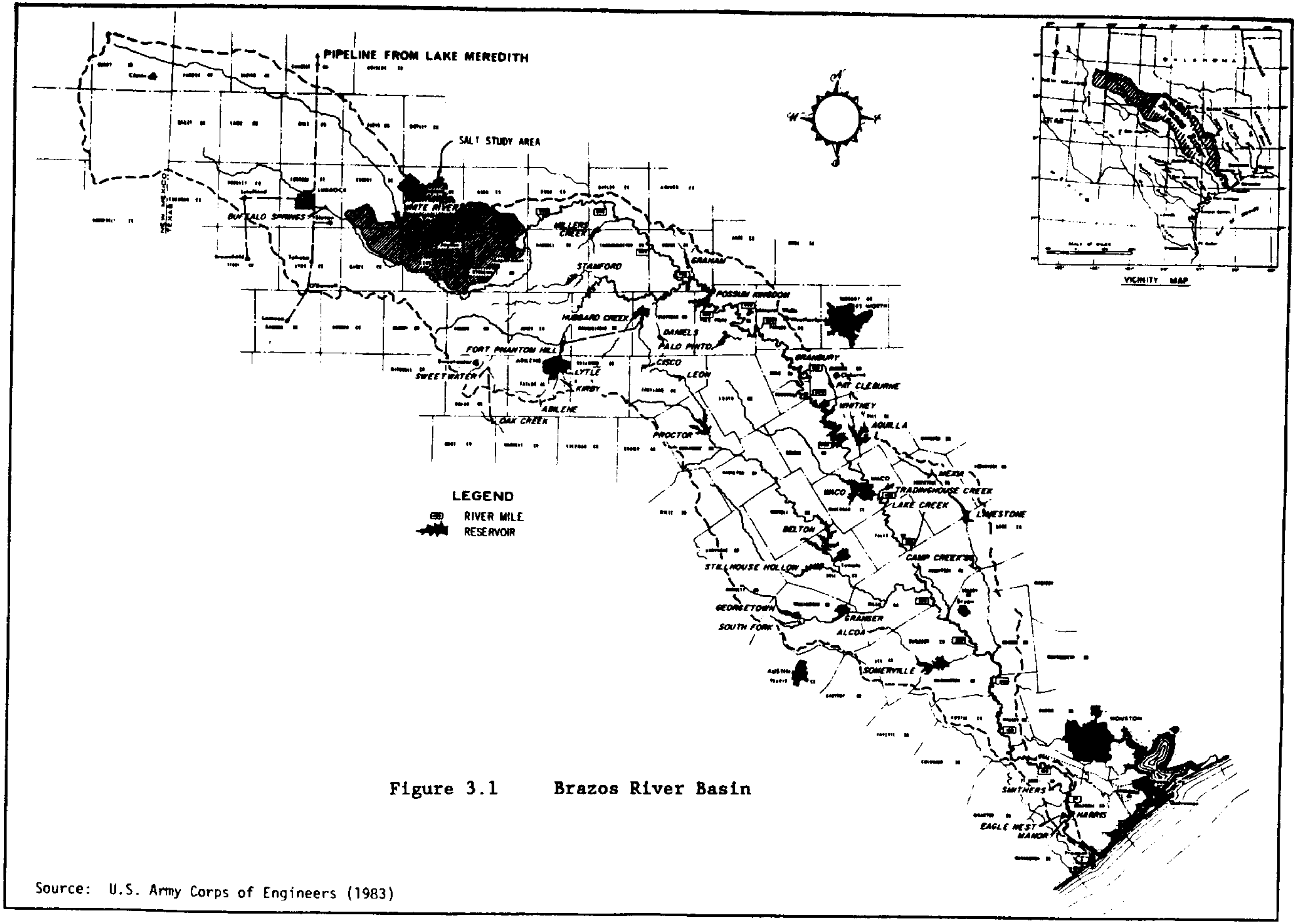


Figure 3.1 Brazos River Basin

Source: U.S. Army Corps of Engineers (1983)

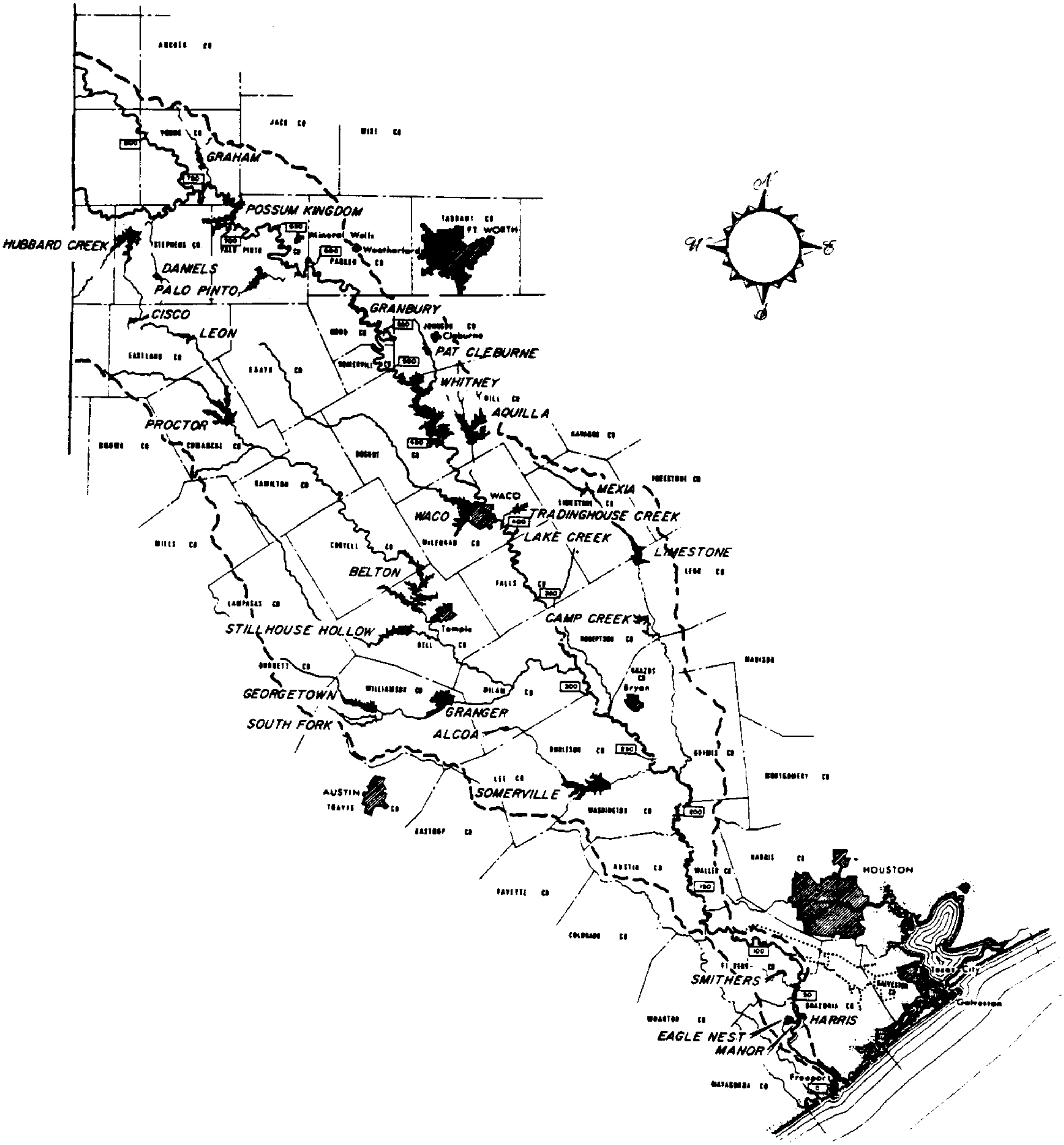


Figure 3.2 Middle and Lower Brazos River Basin

San Jacinto-Brazos Coastal Basin

Brazos River water is diverted for beneficial use in the San Jacinto-Brazos Coastal Basin as well as in the Brazos River Basin. The 1980 population of the San Jacinto-Brazos Coastal Basin was reported at 536,800 people (TDWR 1984). Galveston, with a 1980 population of 61,900 people, is the largest city in the basin, followed by Texas City and Lake Jackson. The economy of the area is based on oil production, petrochemical and other chemical manufacturing, agriculture, agribusiness, commercial fishing, and shipping activities associated with the Ports of Galveston, Freeport and Texas City.

The San Jacinto-Brazos Coastal Basin has a drainage area of 1,440 square miles. There are no major reservoirs with conservation storage to capture runoff in the coastal basin. However, in the eastern part of the coastal basin, the Galveston County Water Authority operates a 12,500 acre-foot capacity off-channel reservoir which stores and regulates water diverted from the Brazos River through the Canal B system. Water supply sources include saline water from the Gulf, groundwater pumped within the basin, and surface water diversions primarily from the Brazos Basin and also from the Trinity River and San Jacinto River Basins. The Canal A and Canal B systems, owned and operated by the Brazos River Authority, and other diversion facilities, owned and operated by the Chocolate Bayou Company and Dow Chemical Company, convey Brazos River water to irrigation and industrial areas in the coastal basin. The Dow Chemical Company diversion facility is operated in conjunction with Harris Reservoir, which is an off-channel reservoir located in Brazoria County in the Brazos Basin. The transbasin diversions from the Brazos River are diverted at several locations in Brazoria and Fort Bend Counties.

Water Use

The amended Texas Water Plan includes a description of past and projected future water use in the Brazos River Basin and San Jacinto-Brazos Coastal Basin. Tables 3.1, 3.2, and 3.3, and 3.4 were developed from Texas Water Development Board data. The year 2010 water use data are from the final Texas Water Plan report (TDWR 1984). The 1974 data are from an earlier draft (TWDB 1977), and the 1984 data are from a computer file of water use by county.

Table 3.1 shows the total 1974, 1984, and 2010 water use by category of use for the entire Brazos Basin. Table 3.2 is a tabulation of the same information, excluding water use in the counties located in the watershed above Possum Kingdom Reservoir. The Table 3.2 data represents in-basin water needs at locations adjacent to and below the twelve Brazos River Authority reservoirs. Total water use in the San Jacinto-Brazos Coastal Basin is tabulated in Table 3.3. All data are for water withdrawals, except steam electric use reflects consumptive use only.

A majority of the water use in the Brazos Basin consists of irrigation in the High Plains from the Ogallala Aquifer. The groundwater irrigation in the extreme upper basin has little impact on operation of the USACE/BRA reservoir system. There are few reservoirs and relatively little surface water use in the upper basin. Surface water from the Brazos River and several of its tributaries upstream of Possum Kingdom Reservoir is too saline for most beneficial uses. The city of Lubbock and several other smaller cities in the upper basin obtain water via pipeline from Lake Meredith in the Canadian River

Table 3.1
WATER USE IN THE BRAZOS RIVER BASIN

(acre-feet per year)

Category of Use	1974 Ground Water	1974 Surface Water	1974 Total	1984 Ground Water	1984 Surface Water	1984 Total	2010 Ground Water	2010 Surface Water	2010 Total
municipal	94,500	129,200	223,700	131,400	173,900	305,300	133,000	497,100	630,100
manufacturing	17,000	214,200	231,200	12,200	169,200	181,400	12,000	624,400	636,400
steam electric	9,200	37,600	46,800	11,300	75,900	87,200	89,800	188,100	277,900
mining	27,500	10,600	38,100	13,600	600	14,200	19,700	11,500	31,200
irrigation	3,782,600	68,000	3,850,600	2,394,100	106,000	2,500,100	3,913,200	356,500	4,269,700
livestock	19,200	45,300	64,500	26,100	38,200	64,200	24,200	47,000	71,200
Total	3,950,000	504,900	4,454,900	2,588,700	563,800	3,152,500	4,191,900	1,724,600	5,916,500

Table 3.2
WATER USE IN THE BRAZOS RIVER BASIN
EXCLUDING THE SUBBASIN ABOVE POSSUM KINGDOM RESERVOIR

(acre-feet per year)

Category of Use	1974 Ground Water	1974 Surface Water	1974 Total	1984 Ground Water	1984 Surface Water	1984 Total	2010 Ground Water	2010 Surface Water	2010 Total
municipal	63,500	73,500	137,000	103,500	97,200	200,700	82,500	367,400	449,900
manufacturing	11,600	208,900	220,500	7,600	164,800	172,400	3,100	609,800	612,900
steam electric	1,600	34,000	35,600	3,300	68,700	72,000	70,200	172,100	242,300
mining	5,700	1,600	7,300	12,000	600	12,600	19,200	10,200	29,400
irrigation	94,300	56,000	150,300	99,700	85,000	184,700	66,100	176,800	242,900
livestock	7,300	35,000	42,300	9,900	26,200	36,100	8,900	37,600	46,500
Total	184,000	409,000	593,000	236,000	442,500	678,500	250,000	1,373,900	1,623,900

Table 3.3
WATER USE IN THE SAN JACINTO-BRAZOS COASTAL BASIN

(acre-feet per year)

Category of Use	1974 Ground Water	1974 Surface Water	1974 Total	1984 Ground Water	1984 Surface Water	1984 Total	2010 Ground Water	2010 Surface Water	2010 Total
municipal	42,100	7,200	49,300	72,480	26,580	99,060	88,300	154,600	242,900
manufacturing	21,800	82,700	104,500	3,220	102,970	106,190	-	287,100	287,100
steam electric	-	-	-	530	1,940	2,480	2,000	-	2,000
mining	2,500	100	2,600	190	2,440	2,630	1,100	-	1,100
irrigation	16,200	155,200	171,400	11,000	176,420	187,420	6,300	205,100	211,400
livestock	200	1,400	1,600	700	470	1,170	500	900	1,400
Total	82,800	246,600	329,400	88,120	310,820	398,940	98,200	647,700	745,900

Basin. About 9,570 square miles of drainage area located in the upper extreme of the basin is noncontributing to downstream streamflows. Consequently, the upper third of the basin accounts for a large portion of the total basin water use but does not play a significant role in the operation of the USACE/BRA reservoir system.

As indicated by Table 3.2, municipal, manufacturing, steam electric, mining, irrigation, and livestock are all significant water uses in the basin below Possum Kingdom Reservoir. Hydroelectric power and recreation are also important uses but are not included in the data because they involve no water diversions or withdrawals. Surface water use exceeds groundwater use. Groundwater is important to reservoir operations both as an alternative water supply source and as a source of return flows to the stream system. Groundwater also provides base flow directly to the streams.

Brazoria and Fort Bend Counties, at the lower end of the Basin, have the largest surface water use of any area in the basin. Most of this water use is for manufacturing, primarily by chemicals and petroleum refining industries, and irrigation. In addition to the fresh water use shown in the tables, 1,275,000 acre-feet of saline water from the Gulf was used in Brazoria County in 1984 for manufacturing purposes.

Significant quantities of water are also diverted from the Brazos River in Brazoria and Fort Bend Counties for transport to the adjoining San Jacinto-Brazos Coastal Basin. Water use in the San Jacinto-Brazos Coastal Basin is tabulated in Table 3.3. A majority of the surface water use represents diversions from the Brazos River Basin through Brazos River Authority, Chocolate Bayou Company, and Dow Chemical Company conveyance facilities. TDWR (1984) data indicate that 87 percent of the surface water used in the San Jacinto-Brazos Coastal Basin in 1980 had been transported from the Brazos River Basin. TWDB (1977) data indicate the percentage was higher in 1974.

A set of control point locations was delineated for purposes of the study, particularly for use in the simulation models discussed in later chapters. TWDB 1984 county water use data is aggregated by control point in Table 3.4. The counties associated with each control point are listed in Table 3.5. The data for each control point represents the water use occurring between that control point and the next upstream control point. The reservoir control points are located at the dams and thus include water use around the reservoir. Water use in the upper basin counties are considered to have little impact on inflows to the reservoir system or reservoir operation and are tabulated separately at the bottom of Table 3.4.

Relative Water Supply and Use Quantities

Various water amounts for 1984 are tabulated in Table 3.6 for comparative purposes in developing a basin overview. The 1984 annual streamflow at the Richmond gage was about five percent of the volume of the precipitation falling on the watershed above the gage. The total surface water withdrawn for beneficial uses in 1984 throughout the basin was about 23 percent of the 1984 streamflow at the Richmond gage or eleven percent of the 1940-1984 mean annual streamflow at the Richmond gage. The total 1984 within basin surface water use, excluding the upper basin above Possum Kingdom Reservoir, was 443,000 acre-feet. An additional 270,000 acre-feet was diverted from the Brazos River

Table 3.4
1984 WATER USE BY CONTROL POINT

	Surface Water Use							Ground Water Use			
Control Point	Municipal	Manufact.	Steam Elec.	Irrigation	Mining	Livestock	Total	Municipal	Manufact.	Steam Elec.	Total Use
					(acre-feet)						
Hubbard Creek	1,096	-	-	195	-	907	2,198	427	-	-	3,232
Possum Kingdom	36,902	2,469	5,328	10,332	-	7,503	62,535	4,215	326	-	362,356
Granbury	4,504	112	1,599	260	201	1,280	7,956	1,258	3	-	9,511
Whitney	3,292	285	4,281	5,378	100	760	14,095	5,196	327	142	21,297
Aquilla	492	25	-	-	-	739	1,256	1,959	214	-	3,511
Waco Reservoir	27,514	2,093	-	3,088	-	2,033	34,729	5,772	562	-	86,641
Waco Gage	-	-	16,119	739	197	1,349	18,404	10,669	1,623	349	-
Proctor	5,050	82	-	25,060	-	2,433	32,625	992	249	-	66,032
Belton	10,447	105	-	1,532	-	1,310	13,394	3,286	10	-	19,205
Stillhouse	1,262	148	-	43	-	419	1,872	788	-	-	3,115
Bell County	33,407	10,200	-	666	-	909	45,182	1,495	94	-	47,031
Georgetown	1	-	-	-	16	212	229	505	193	-	1,139
Granger	3,795	15	-	134	5	1,302	5,251	14,215	232	-	19,956
Cameron Gage	1,680	15,575	8,164	1,487	-	1,184	28,089	2,486	1,192	-	32,656
Limestone	893	-	-	-	-	1,925	2,818	1,959	9	-	5,138
Somerville	-	-	-	59	-	897	956	1,240	-	-	2,862
Bryan Gage	1,675	183	-	4,731	-	2,985	9,574	3,190	16	-	34,547
Richmond Gage	2,331	176	8,297	2,361	-	6,201	19,366	38,323	1,106	2,197	86,441
Coast	859	135,811	30,199	39,556	72	272	206,768	10,185	1,734	599	239,446
In-basin Sub-total	135,200	167,279	73,987	95,621	591	34,620	507,297	108,160	7,890	3,287	1,044,116
Upper Basin	38,692	1,921	1,913	10,334	-	3,572	56,431	23,210	4,282	8,056	2,108,332
In-basin Total	173,892	169,200	75,900	105,955	591	38,192	563,728	131,370	12,172	11,343	3,152,448
Coast (San Jacinto-Brazos Coastal Basin)	23,060	89,330	1,680	153,050	2,120	410	269,650				
Coast Total	23,919	225,141	31,879	192,606	2,192	682	476,418				

Table 3.5
CONTROL POINTS AND THEIR UPSTREAM COUNTIES

Control Point - Upstream Counties

Hubbard Creek Reservoir - Shackleford and Callahan Counties

Possum Kingdom Reservoir - Floyd, Crosby, Garza, Dickens, Kent, King, Stonewall, Knox, Haskell, Throckmorton, Baylor, Young, Stephens, Archer, Scurry, Fisher, Taylor, and Jones Counties

Granbury Reservoir - Jack, Palo Pinto, and Parker Counties

Whitney Reservoir - Hood, Somervill, and Johnson Counties

Aquilla Reservoir - Hill County

Waco Reservoir - Erath, Bosque, and portion of McLennan Counties

Waco Gage - portion of McLennan County

Proctor Reservoir - Eastland, Comanche, and Brown Counties

Belton Reservoir - Hamilton and Coryell Counties

Stillhouse Hollow Reservoir - Mills and Lampasas Counties

Bell County - Bell County

Georgetown Reservoir - Burnett and Travis Counties

Granger Reservoir - Williamson County

Cameron Gage - Milam County

Limestone Reservoir - Limestone and Freestone Counties

Somerville Reservoir - Lee and Bastrop Counties

Bryan Gage - Robertson and Falls Counties

Richmond Gage - Burleson, Washington, Brazos, Leon, Madison, Grimes, Waller, Austin, Fort Bend, and Fayette Counties

Coast - Brazoria and Fort Bend Counties

Note: Water use in Parmer, Castro, Bailey, Cochran, Lamb, Hockley, Swisher, Hale, Lubbock, Lynn, Terry, Borden, Dawson, Mitchell, and Nolan Counties in the extreme upper basin was considered to have insignificant impact on inflows into the reservoir system.

Table 3.6
1984 WATER AMOUNT COMPARISON

Annual Precipitation (acre-feet)

Watershed (excluding 9,566 square mile non-contributing area):	1984	1940-1984 Mean
Above Richmond Gage	50,000,000	52,080,000
Above Waco Gage	26,160,000	26,630,000
Above Cameron Gage	10,250,000	11,320,000

Annual Streamflow (acre-feet)

Gage	1984	1940-1984 Mean
Richmond	2,413,000	5,188,000
Waco	303,000	1,558,000
Cameron	309,000	1,172,000

1984 Basin Water Use (acre-feet)

Subbasin	Surface Water	Ground Water	Total
Above Possum Kingdom	121,000	2,353,000	2,474,000
Brazoria and Fort Bend Counties	207,000	33,000	240,000
Remainder of Basin	236,000	203,000	439,000
Total	564,000	2,589,000	3,153,000

1984 Interbasin Diversions (acre-feet)

From Canadian (Lake Meredith) to Brazos Basin	38,000
From Colorado (Oak Creek Reservoir) to Brazos Basin	2,000
From Brazos to San Jacinto-Brazos Coastal Basin	270,000

1984 Conservation Releases from 12-Reservoir System (acre-feet)

Whitney Hydropower Releases	186,000
Possum Kingdom Hydropower Releases	79,000
All Other Water Supply Releases	329,000

1984 Reservoir Evaporation (acre-feet)

Reservoirs	Gross	Net
12 BRA Reservoirs	557,000	382,000
1,166 Other Reservoirs	337,000	248,000
Total	894,000	630,000

for use in the San Jacinto - Brazos Coastal Basin. About 60 percent of the 794,000 acre-feet total 1984 water use from the Brazos River and its tributaries occurred in the lowermost two counties in the basin (26%) and in the adjoining coastal basin (34%). The total annual surface water use represents a volume equivalent to about 20 percent of the conservation storage capacity of the 40 major reservoirs.

A total of 329,000 acre-feet was released from the 12 BRA reservoirs under water rights permits associated with the reservoirs, excluding water released through hydroelectric power turbines. A portion of the 186,000 acre-feet and 79,000 acre-feet of water released through the hydroelectric plants at Whitney and Possum Kingdom Reservoirs, respectively, was diverted at downstream locations for other beneficial uses. The reservoir releases shown were made under water rights permits associated with the reservoirs. The BRA Canal A and Canal B systems diverted an additional 130,000 acre-feet under separate water rights permits for use in the San Jacinto - Brazos Basin and in the Brazoria and Fort Bend Counties portion of the Brazos Basin.

Reservoir evaporation withdraws more surface water than all the beneficial uses in the basin combined. Total 1984 withdrawals of surface water for beneficial use in the basin and annual gross reservoir evaporation are equivalent to 17 percent and 23 percent, respectively of the conservation storage capacity of the 40 major reservoirs. The evaporation amounts were estimated by water surface area and evaporation rate data discussed in Chapter 5.

Reservoirs in the Brazos River Basin

A total of 1,178 reservoirs located in the Brazos River Basin are included in the dam inventory maintained by the Texas Water Commission. This includes all reservoirs meeting at least one of the following two conditions: (1) storage capacity of 15 acre-feet or greater and dam height of 25 feet or greater or (2) storage capacity of 50 acre-feet or greater and dam height of 6 feet or greater. For purposes of the present discussion, reservoirs are categorized as small or major, depending on whether total controlled storage capacity is less than 5,000 acre-feet. Data presented in this report regarding small reservoirs are based on a computer listing of reservoirs obtained from the Texas Water Commission dam inventory. Additional information for the major reservoirs are available from several sources including Wurbs (1985).

The historical growth in number and capacity of reservoirs is illustrated in Table 3.7. The present inventory of reservoirs is categorized by the decade in which impoundment began. The 1960's was the decade with the largest number of projects constructed, with 524 small reservoirs and 11 major reservoirs being completed. With the two largest reservoirs in the basin being completed in the early 1950's, the 1950's was the decade with the largest storage capacity being added. Ten major and 127 of the existing small reservoirs have initial impoundment dates prior to 1950.

Total controlled storage capacity in the basin is approximately 8,079,500 acre-feet, including 7,849,000 acre-feet and 230,500 acre-feet in the 40 major and 1,138 small reservoirs, respectively. Thus, the 230,500 acre-feet of total normal pool capacity in the 1,138 small reservoirs represents only about 2.85 percent of the total controlled capacity in the 1,178 reservoirs. Twenty-eight

Table 3.7
TOTAL NUMBER AND CAPACITY OF RESERVOIRS IN THE BRAZOS RIVER BASIN BY DATE OF INITIAL IMPOUNDMENT

Initial Impoundment Year	Number of Reservoirs		Controlled Capacity of Major Reservoirs in Acre-Feet		
	Small	Major	Conservation	Flood Control	Total
before 1909	11	0	0	0	0
1910-1919	12	0	0	0	0
1920-1929	50	4	31,000	0	31,000
1930-1939	20	2	86,000	0	86,000
1940-1949	34	4	600,000	0	600,000
1950-1959	161	10	1,271,000	2,012,000	3,283,000
1960-1969	524	11	1,261,000	1,592,000	2,853,000
1970-1979	285	4	417,000	0	417,000
1980-1986	41	5	242,000	337,000	579,000
Total	1,138	40	3,908,000	3,941,000	7,849,000

Notes:

1. Data includes only reservoirs presently existing and included in the TWC dam inventory. Past reservoirs which have been inundated by construction of larger dams downstream or otherwise no longer exist are not included.

2. Major or small refers to whether controlled storage capacity is less than 5,000 acre-feet.

3. Surcharge storage and flood control pools not controlled by gated outlet structures are not included in the capacity data.

4. Inactive storage and total sediment reserve, including sediment reserve in flood control pools, are included in the above values for conservation capacity.

5. The estimated total normal pool capacity of the 1,138 small reservoirs is 230,500 acre-feet.

of the small reservoirs have normal pool capacities of 1,000 acre-feet or greater. A number of dams provide flood-retarding pools with additional uncontrolled capacity not included in the 230,500 acre-feet normal pool capacity. The term controlled storage is used here to mean capacity controlled by gated outlet structures. The major reservoirs contain slightly more controlled flood control capacity than conservation capacity.

The simulation study focused on the system of twelve reservoirs owned and operated by the Fort Worth District (FWD) of the U.S. Army Corps of Engineers (USACE) and the Brazos River Authority (BRA). Hubbard Creek Reservoir was also included with the principal reservoirs modeled due to its relatively large storage capacity. Hubbard Creek Reservoir is owned and operated by the West Central Texas Municipal Water District, whose member cities include Abilene, Breckenridge, Anson, and Albany. The numerous other reservoirs in the basin were addressed in the simulation study primarily from the perspective of evaluating their impacts on the yield of the twelve USACE/BRA reservoirs.

Major Reservoirs

The 40 reservoirs in the Brazos River Basin with controlled storage capacities of 5,000 acre-feet or greater are listed in Table 3.8. The major reservoirs in the basin include 28 reservoirs in addition to the 12-reservoir USACE/BRA system. Eleven reservoirs with storage capacities totalling about 7.0 percent of the total conservation storage of all the major reservoirs are owned and operated by cities for municipal and industrial water supply and recreation. The City of Abilene owns and operates Kirby, Abilene, and Fort Phantom Hill Reservoirs for municipal, industrial, and recreational use. Likewise, Mineral Wells, Cisco, Daniel, Sweetwater, Pat Cleburne, and Graham Reservoirs are owned and operated by the Cities of Mineral Wells, Cisco, Breckenridge, Sweetwater, Cleburne, and Stamford, respectively. Lake Stamford, owned by the City of Stamford, was constructed primarily for supplying cooling water for a steam-electric power plant but also serves municipal uses. Bryan Utilities Lake, owned by the City of Bryan, is used for steam-electric power plant cooling and recreation.

Six reservoirs with storage capacities totalling about 11 percent of the conservation storage in the major reservoirs of the basin are owned and operated by municipal water districts which supply water to member cities and other users. These reservoirs are Mexia, Millers Creek, Leon, White River, Palo Pinto and Hubbard Creek. The corresponding water districts are Bristone Municipal Water Supply District, North Central Texas Municipal Water Supply District, Eastland County Water Supply District, White River Municipal Water District, Palo Pinto Municipal Water District No. 1, and West Central Texas Municipal Water District.

Six reservoirs with a storage capacity totalling about 6.0 percent of the total conservation storage of the major reservoirs in the basin are owned and operated by electric utility companies to provide cooling water for steam-electric power plants. Texas Power and Light Company owns and operates Lake Creek, Tradinghouse, and Twin Oaks Reservoirs for steam-electric power plant cooling. Smithers Reservoir is owned and operated by Houston Lighting and Power for the same purpose. Likewise, Gibbons Creek Reservoir is owned and operated by Texas Municipal Power Agency. Supplemental water is delivered to Gibbons Creek Reservoir from Lake Limestone through contractual arrangements

Table 3.8
MAJOR RESERVOIRS IN THE BRAZOS RIVER BASIN

RESERVOIR	PRIMARY OPERATOR/OWNER	PURPOSES	DATE IMPOUNDMENT BEGAN	DAM HEIGHT	SURFACE AREA CON-FC	CONTROLLED STORAGE CAPCITY			
						CONSERVATION		FLOOD CONTROL	TOTAL
						INACTIVE	ACTIVE		
				(feet)	(acres)	(acre-feet)	(acre-feet)	(acre-feet)	(acre-feet)
Brazos River Basin									
Davis	League Ranch	I	1959	32	580	-	5,400	-	5,400
Mineral Wells	City of Mineral Wells	M	1920	74	650	-	6,760	-	6,760
Kirby	City of Abilene	M	1928	50	740	-	7,620	-	7,620
Abilene	City of Abilene	M,R	1921	51	590	-	7,900	-	7,900
Lake Creek	Texas Power & Light	P	1952	50	550	-	8,400	-	8,400
Camp Creek	Camp Creek Water Company	M,R	1948	49	750	-	8,550	-	8,550
Cisco	City of Cisco	M	1923	96	440	-	8,800	-	8,800
Daniel	City of Breckenridge	M	1948	60	920	-	9,520	-	9,520
Mexia	Bristone MWSD	M	1961	50	1,200	-	10,000	-	10,000
Sweetwater	City of Sweetwater	M	1930	50	630	-	11,900	-	11,900
William Harris	Dow Chemical Company	I	1947	12	1,660	-	12,000	-	12,000
Alcoa	Aluminum Company of America	I,R	1953	50	880	-	14,750	-	14,750
Bryan Utilities	City of Bryan	P,R	1975	62	830	-	15,230	-	15,230
Smithers	Houston Lighting & Power	P	1957	18	2,480	-	18,700	-	18,700
Brazoria	Dow Chemical Company	I	1954	16	1,860	-	21,970	-	21,970
Pat Cleburne	City of Cleburne	M	1964	78	1,550	-	25,300	-	25,300
Millers Creek	North Central Texas MWA	M	1974	75	1,900	-	25,520	-	25,520
Leon	Eastland County WSD	M,I	1954	90	1,590	-	26,420	-	26,420
Gibbons Creek	Texas Municipal Power Agency	P	1981	50	2,490	-	26,820	-	26,820
Twin Oaks	Texas Power & Light	P	1982	56	1,460	-	30,320	-	30,320
Tradinghouse	Texas Power & Light	P	1968	60	2,010	-	35,120	-	35,120
White River	White River MWD	M,Mi	1963	84	1,810	-	37,950	-	37,950
Palo Pinto	Palo Pinto MWD 1	M	1964	96	2,660	-	42,200	-	42,200
Stamford	City of Stamford	M	1953	78	4,690	-	52,700	-	52,700
Graham	City of Graham	M	1929;1958	57;82	2,550	-	53,680	-	53,680
Fort Phantom Hill	City of Abilene	M,R	1938	84	4,250	-	74,310	-	74,310
Georgetown	Corps of Engineers	F,M,R	1980	162	1,310-3,220	14,000	29,200	87,600	130,800
Aquilla	Corps of Engineers	F,M,R	1983	104	3,280-7,000	25,700	33,600	86,700	146,000
Squaw Creek	Texas Utilities Services	P	1977	159	3,230	-	151,050	-	151,050
Granbury	Brazos River Authority	M,A,P	1969	84	1,300	-	153,500	-	153,500
Limestone	Brazos River Authority	M,A	1978	65	14,200	-	225,400	-	225,400
Granger	Corps of Engineers	F.M.R	1980	115	4.400-11.040	44.100	37.900	162.200	244.200
Hubbard	West Central MWD	M,I,Mi	1962	112	16,250	-	314,280	-	314,280
Proctor	Corps of Engineers	F,M,A,R	1963	86	4,610-14,010	32,700	31,400	310,100	374,200
Somerville	Corps of Engineers	F,M,A,R	1967	80	11,460-24,400	25,900	143,900	337,700	507,500
Possum Kingdom	Brazos River Authority	M,A,R,H,Mi	1941	189	14,440	-	569,380	-	569,380
Stillhouse Hollow	Corps of Engineers	F,M,A,R	1968	200	6,430-11,830	34,900	204,900	390,600	630,400
Waco	Corps of Engineers	F,M,R	1965	140	7,270-19,440	65,100	104,100	553,300	722,500
Belton	Corps of Engineers	F,M,A,R	1954	192	12,300-23,600	76,500	365,500	640,000	1,082,000
Whitney	Corps of Engineers	F,H	1951	159	23,560-49,820	245,200	381,900	1,372,400	1,999,500

Source: Wurbs (1985)

with the Brazos River Authority. Squaw Creek Reservoir, owned and operated by Texas Utilities Generating Company, will provide cooling water for the Comanche Peak Nuclear Power Plant currently under construction. Lake Granbury supplies water as needed to Squaw Creek Reservoir.

Dow Chemical Company owns and operates Brazoria and William Harris Reservoirs to provide off-channel storage and regulation of water diverted from the Brazos River for manufacturing use at the industrial complex in southern Brazoria County. The Aluminum Company of America owns and operates Alcoa Lake for manufacturing use and steam-electric power plant cooling. Davis Lake, owned by the League Ranch, is used for irrigation. Camp Creek Lake, owned by the Camp Creek Water Company, is used primarily for recreation.

USACE/BRA Reservoir System

The 12 reservoirs operated by the U.S. Army Corps of Engineers (USACE) and Brazos River Authority (BRA) are listed in Table 3.9.

Corps of Engineers Reservoirs

Nine of the reservoirs were constructed by the Corps of Engineers as components of a comprehensive basin-wide plan of development. Georgetown, Aquilla, Granger, Proctor, Somerville, Stillhouse Hollow, Waco, Belton, and Whitney Reservoirs are each operated by the Fort Worth District for flood control, water supply, and recreation. Whitney Lake serves the additional purpose of hydroelectric power generation. The nine Corps of Engineers projects contain about half of the conservation capacity and all of the flood control capacity of the major reservoirs in the basin. Corps of Engineers personnel operate and maintain the nine federal multiple purpose projects. The Corps of Engineers is totally responsible for flood control operations. Conservation releases are made as directed by the local project sponsor, which for most of the conservation capacity, is the Brazos River Authority. Operation of the Corps of Engineers reservoirs is based on designated pools.

Flood control operations are in effect whenever the water surface rises or is predicted to rise above the top of conservation pool elevation. As long as flood inflows are not expected to exceed the top of flood control pool elevation, flood control operations are based on emptying the flood control pool as quickly as possible without contributing to downstream flooding. Regulation plans include specified maximum allowable discharges at downstream control points (stream gaging stations). Releases cannot be allowed to contribute to streamflows rising above the specified nondamaging levels. Several of the reservoirs have zoned flood control pools in which maximum allowable streamflows are dependent upon reservoir storage levels. The maximum allowable streamflow increases as the flood waters rise above set elevations in the flood control pool.

Aquilla, Belton, Stillhouse Hollow, Georgetown, Granger, and Somerville Dams have gated outlet works with conduits through the embankment in combination with ungated overflow spillways. The uncontrolled spillway crest elevation is the top of the flood control pool. Whitney, Waco, and Proctor Dams have spillways controlled by tainter gates. If the reservoir level rises or is predicted to rise above the top of flood control pool, the tainter gates are operated to minimize downstream flooding while assuring that the design

Table 3.9
PRINCIPAL RESERVOIRS

Fort Worth District (FWD) of U.S. Army Corps of Engineers (USACE) and Brazos River Authority (BRA)

Whitney Lake and Whitney Dam; Brazos River; flood control, water supply, hydroelectric power, and recreation.

Aquilla Lake and Aquilla Dam; Aquilla Creek; flood control, water supply, and recreation.

Waco Lake and Waco Dam; Bosque River; flood control, water supply, and recreation.

Proctor Lake and Proctor Dam; Leon River; flood control, water supply, and recreation.

Belton Lake and Belton Dam; Leon River; flood control, water supply, and recreation.

Stillhouse Hollow Lake and Stillhouse Hollow Dam; Lampasas River; flood control, water supply, and recreation. .

Georgetown Lake and Georgetown Dam; formerly North Fork Lake and North Fork Dam; North Fork San Gabriel River; flood control, water supply, and recreation.

Granger Lake and Granger Dam; formerly Laneport Lake and Laneport Dam; San Gabriel River; flood control, water supply, and recreation.

Somerville Lake and Somerville Dam; Yequa Creek; flood control, water supply, and recreation.

Brazos River Authority

Possum Kingdom Lake and Morris Sheppard Dam; Brazos River; hydroelectric power, water supply, and recreation.

Lake Granbury and DeCordova Bend Dam; Brazos River; water supply and recreation.

Limestone Lake and Sterling C. Robertson Dam; Navasota River; water supply and recreation.

West Central Texas Municipal Water District

Hubbard Creek Reservoir and Hubbard Creek Dam; Hubbard Creek; water supply and recreation.

water surface is not exceeded. The design water surface is set during design to prevent overtopping and structural failure of the dam. Procedures for developing operating schedules for use during extreme flood events which exceed the flood control storage capacity are outlined by the USACE (1959).

The Southwestern Power Administration is responsible for marketing hydroelectric power from Whitney Reservoir. The Southwestern Power Administration sells the electricity to the Brazos Electric Power Cooperative.

The Brazos River Authority (BRA) has contracted for the water supply capacity in each of the Corps of Engineers projects, except Fort Hood military base has 3.2 percent of the conservation storage in Belton Lake and the City of Waco has 12.5 percent of the conservation storage capacity in Lake Waco. The City of Waco is also the primary customer for the 87.5 percent of the Lake Waco conservation capacity controlled by the BRA.

Brazos River Authority System

In addition to controlling the conservation storage in the nine Corps of Engineers projects, the BRA constructed, owns and operates Granbury, Limestone, and Possum Kingdom Reservoirs. The 12 reservoirs are operated as a system to supply downstream municipal, industrial, and agricultural water users as well as users located in the vicinities of the reservoirs. The simulation studies reported herein focus upon this 12-reservoir system.

Possum Kingdom Reservoir, completed in 1941, provides water supply and hydroelectric power. BRA sells the power to the Brazos Electric Power Cooperative. Lake Granbury, completed in 1969, provides cooling water for a gas-fired plant near the lake and to Squaw Creek Reservoir for the Comanche Peak Nuclear Power Plant. Granbury and Possum Kingdom Reservoirs provide make-up water, as needed, to maintain constant operating levels in Tradinghouse Creek and Lake Creek Reservoirs which are owned and operated by utility companies for steam-electric power plant cooling. A desalting water treatment plant is under construction to treat water from Lake Granbury to supplement the water supply for the City of Granbury. Lake Limestone, completed in 1978, will supply water to off-channel cooling lakes for two lignite-fueled power plants being built by the Texas Power and Light Company.

BRA uses Lake Belton to supply water under contracts with the Cities of Temple and McGregor, and through Bell County Water Control and Improvement District No. 1 and two water supply corporations, to several other cities and communities. Water from Lake Whitney is contracted for use by the Cities of Cleburne, Whitney, and Rio Vista. Lake Waco supplies the City of Waco. A reallocation of 8.6 percent of the flood control capacity of Lake Waco to conservation is planned to meet the increasing water needs of the City of Waco and its suburbs. Water from Proctor Reservoir is provided to several cities under a contract between BRA and the Upper Leon River Municipal Water District. Proctor also provides water for agricultural use to individual farmers around the lake and to a corporation of farmers along the Leon River downstream of the dam. Stillhouse Hollow Reservoir supplies water to a number of communities and rural water supply corporations. Somerville Reservoir and the recently completed Georgetown, Granger, and Aquilla Reservoirs are also committed for municipal and industrial water supply.

In addition to the uses cited above, BRA operates the upstream reservoir system to regulate flows for municipal, industrial, and irrigation uses in the lower Brazos Basin and the neighboring San Jacinto-Brazos Coastal Basin. Downstream water customers include a large chemical plant at the mouth of the Brazos River, a canal company with a pumping plant a short distance upstream, and several public utility plants generating electric energy for the lower Brazos Basin and Houston area. BRA owns and operates several canal systems which include pumping stations and about 200 miles of canals. Water is diverted to municipalities and industries in the coastal area south of Houston which includes one of the world's largest petrochemical complexes. Water is also supplied through BRA canal systems for irrigation of rice in Fort Bend, Brazoria, and Galveston Counties.

Reservoir Storage Capacities

The 12-reservoir USACE/BRA system contains all of the controlled flood control storage and about 70 percent of the conservation storage in the basin. In terms of conservation storage capacity, Hubbard Creek Reservoir is the fourth largest reservoir in the basin. Hubbard Creek Reservoir contains about 8 percent of the conservation storage in the basin. The 13 reservoirs contain about 88 percent of the total flood control and conservation storage capacity in the 1,178 reservoirs in the basin. Excluding all reservoirs with capacities less than 5,000 acre-feet and excluding steam-electric cooling reservoirs and dead storage for hydroelectric power and other inactive storage, about 2,666,000 acre-feet of conservation capacity is contained the basin. About 84 percent of this municipal, industrial, and agricultural water supply and active hydropower storage capacity is in the 13 reservoirs.

Pertinent basic data, describing the physical characteristics of the reservoirs and incorporated in the simulation models, are cited in Table 3.10. Reservoir operations are based on the top of conservation and flood control pool elevations tabulated. The inactive pool elevation at Possum Kingdom Reservoir is contractually set to accommodate hydroelectric power operations. Likewise, the inactive pool elevation at Granbury Reservoir is contractually set to accommodate withdrawals of cooling water for a steam-electric plant near the reservoir. The inactive pool at Whitney Reservoir is also dead storage for hydroelectric power. Withdrawals from the inactive pools can physically be made at these three reservoirs. Drawdown limits are set by contractual operating policies, not outlet structures. The other 10 projects can be emptied to the invert of the lowest outlet structure.

The accumulated storage capacities cited in Table 3.10 are total capacity, including sediment reserves and inactive storage, below the indicated elevation for the topography existing at the indicated year. A portion of this capacity can be expected to have since been lost due to disposition of sediment. The streams have heavy sediment loads, and the reservoirs are efficient sediment traps. The incremental flood control and water supply storage capacities listed in Table 3.10 are exclusive of sediment reserve storage. Sediment reserves in the flood control and conservation pools are also tabulated. Thus, more capacity is actually available than indicated by the incremental data prior to depletion of the sediment reserve.

Elevation versus capacity and area relationships for Possum Kingdom, Whitney, and Belton Reservoirs have been updated based on surveys at the dates

Table 3.10
RESERVOIR DATA

Reservoir	Hubbard	Possum Kingdom	Granbury	Whitney	Aquilla	Waco
Storage Capacity (ac-ft)						
Flood Control	-	-	-	1,372,400	86,700	553,300
Water Supply	297,910	551,860	104,790	50,000	33,600	104,100
Hydroelectric Power	-	-	-	198,000	-	-
Sediment Reserve (ac-ft)						
Flood Control Pool	-	-	-	8,155	6,900	20,600
Conservation Pool	19,840	118,380	48,700	51,645	18,800	48,400
Accumulative Storage (ac-ft)						
Flood Control Pool	-	-	-	1,999,500	146,000	726,400
Conservation Pool	317,750	570,240	153,490	627,100	52,400	152,500
Inactive Pool	-	221,050	52,500	379,100	-	-
Lowest Outlet Invert	3,470	0	2,500	4,250	0	580
Elevation (feet msl)						
Top of Dam	1,208	1,024	706.5	584	582.5	510
Flood Control Pool	-	-	-	571	556	500
Conservation Pool	1,183	1,000	693	533	537.5	455
Inactive Pool	-	970	675	520	-	-
Lowest Outlet Invert	1,136	875	640	449	503	400
Stream	Hubbard	Brazos	Brazos	Brazos	Aquilla	Bosque
Drainage Area (sq mi)	1,085	23,596	25,679	27,189	252	1,652
Gage Station Number	367	376	381	387	389	400
Gage Drainage Area (sq mi)	1,089	23,811	25,818	27,244	308	1,656
Drainage Area Ratio	1.0	1.0	1.0	1.0	1.0	1.0
Date of:						
Initial Impoundment	1962	1941	1969	1951	1983	1965
Accumulative Capacity Data	1962	1974	1969	1959	1983	1965

Reservoir	Proctor	Belton	Stillhouse	Georgetown	Granger	Limestone	Somerville
Storage Capacity (ac-ft)							
Flood Control	310,100	640,000	390,660	87,600	162,200	-	337,700
Water Supply	31,400	372,700	204,900	29,200	37,900	210,990	143,900
Sediment Reserve (ac-ft)							
Flood Control Pool	4,700	15,600	4,100	6,100	16,500	-	9,700
Conservation Pool	28,000	69,300	30,800	7,900	27,600	14,450	16,200
Accumulative Storage (ac-ft)							
Flood Control Pool	374,200	1,091,320	630,400	130,800	244,200	-	507,500
Conservation Pool	59,400	447,490	235,700	37,100	65,500	225,440	160,100
Lowest Outlet Invert	70	11	780	238	222	0	220
Elevation (feet msl)							
Top of Dam	1,205	662	698	861	555	380	280
Flood Control Pool	1,197	631	666	834	528	-	258
Conservation Pool	1,162	594	622	791	504	363	238
Lowest Outlet Invert	1,128	483	515	720	457	325.5	206
Stream	Leon	Leon	Lampasas	San Gabriel	San Gabriel	Navasota	Yequa
Drainage Area (sq mi)	1,259	3,531	1,313	247	709	675	1,007
Gage Station Number	412	418	424	426	431	448	443
Gage Drainage Area (sq mi)	1,261	3,542	1,321	248	738	968	1,009
Drainage Area Ratio	1.0	1.0	1.0	1.0	1.0	0.697	1.0
Date of:							
Initial Impoundment	1963	1954	1968	1980	1980	1978	1967
Accumulative Capacity Data	1963	1975	1968	1980	1980	1978	1967

Table 3.11
STORAGE CAPACITY BELOW TOP OF CONSERVATION POOL

Reservoir	Storage Capacity (acre-feet)					Date	
	Water Rights	Initial or Resurveyed	1984	2010	Ultimate	Initial or Resurveyed	Ultimate
Hubbard Creek	317,750	317,750	308,070	300,730	297,910	1962	2020
Possum Kingdom	724,739	570,240	544,510	477,600	451,860	1941/74	2020
Granbury	155,000	153,490	137,410	113,850	104,790	1969	2020
Whitney	627,092	627,100	599,160	574,520	574,520	1951/59	2010
Aquilla	52,400	52,400	52,210	47,340	33,600	1983	2083
Waco	104,100	152,500	133,750	108,880	104,100	1965	2015
Proctor	59,400	59,400	46,850	31,400	31,400	1963	2010
Belton	457,600	447,490	428,250	372,700	372,700	1954/75	2010
Stillhouse	235,700	235,700	225,310	209,700	204,900	1968	2018
Georgetown	37,100	37,100	36,540	34,540	29,200	1980	2080
Granger	65,500	65,500	64,190	57,070	37,900	1980	2080
Limestone	225,400	225,440	218,050	214,060	210,990	1978	2030
Somerville	160,110	160,100	154,450	146,140	143,900	1967	2017
	3,221,891	3,104,210	2,948,750	2,688,530	2,598,711		

indicated in the table. The area and capacity data for the other projects have not been updated by field surveys since project design and construction.

In the present study, linear interpolation was applied to the initial (or resurveyed) and ultimate storage data to develop estimates for years 1984 and 2010 conditions of sedimentation. Ultimate refers to the condition in which the sediment reserve has been depleted. Storage capacities below the top of conservation pool are tabulated in Table 3.11 for initial (or resurveyed), 1984, 2010, and ultimate conditions of sedimentation. Storage capacities specified in the water rights permits are also included in Table 3.11.

The stream gage stations used to represent reservoir inflows in the simulation studies are also indicated in Table 3.10. In most cases, the stream gage is located conveniently close to the dam site such that adjustments are not necessary. Inflows for Aquilla and Limestone Reservoirs were developed by multiplying gaged streamflows by the drainage area ratios for the dam site and gage.

Contractual Commitments

Water supply contracts have been executed by the USACE and BRA for the water supply storage capacity in each of the nine USACE reservoirs, except the City of Waco has contracted with the USACE for 12.5 percent of the conservation storage capacity of Waco Reservoir and the Fort Hood Army Base has 3.2 percent of the conservation storage capacity in Belton Lake. The BRA has contracted with the USACE for the other 87.5% of the conservation capacity in Waco Reservoir. The City of Waco, in turn, has contracted with the BRA for this capacity. Waco Reservoir is the only reservoir in the BRA system for which the conservation storage capacity is committed to a single user.

As discussed earlier in this chapter, the BRA has contractual commitments to a number of cities, water districts, water supply cooperations, industries, and irrigators. Table 3.12 shows the amount of water in acre-feet/year committed from the various reservoirs for various types of use. System commitments of 256,625 acre-feet/year, or 45% of the total commitments, can be met by combinations of any of the reservoirs. The individual reservoir commitments are also categorized in Table 3.11 by the location of the diversion. Lakeside water use is diverted directly from the reservoir. Downstream diversions are released through the dam to the river to be withdrawn at downstream locations.

All the reservoirs are operated for water supply. Possum Kingdom and Whitney Reservoirs also have hydroelectric power plants. In the past, Possum Kingdom Reservoir was operated primarily for hydroelectric power with water supply being an incidental purpose. The present contract, which will soon expire, between the BRA and the Brazos Electric Power Cooperative provides for releases for hydroelectric power generation upon demand.

The Whitney active conservation pool, which is between elevations 520 feet and 533 feet, provides releases for both water supply and hydroelectric power generation. The water supply contract between the USACE and BRA commits 22.017 percent of the water provided by the active conservation pool to BRA for water supply. The hydroelectric power contract between the Southwestern Power Administration and the Brazos Electric Power Cooperative provides for 30,000

Table 3.12
BRA CONTRACTUAL COMMITMENTS (1988)

Reservoir	BRA Contractual Water Commitments (acre-feet/year)				
	Total	Municipal	Industrial	Irrigation	Mining
Possum Kingdom					
(lakeside)	8,865	1,930	-	35	6,900
(downstream)	54,385	7,840	45,380	990	175
Granbury					
(lakeside)	32,717	3,800	25,003	3,914	-
(downstream)	110	-	-	110	-
Whitney (lakeside)	16,096	16,096	-	-	-
Aquilla (lakeside)	13,896	13,896	-	-	-
Proctor					
(lakeside)	5,349	5,349	-	-	-
(downstream)	12,035	4,835	-	7,200	-
Belton					
(lakeside)	27,472	27,472	-	-	-
(downstream)	18,875	18,500	-	375	-
Stillhouse (lakeside)	35,482	35,400	-	82	-
Georgetown (lakeside)	13,610	13,610	-	-	-
Granger (lakeside)	9,336	9,336	-	-	-
Limestone					
(lakeside)	55,400	4,000	51,400	-	-
(downstream)	3,600	-	3,600	-	-
Somerville (lakeside)	4,494	4,494	-	-	-
System (Little River)	5,000	-	5,000	-	-
System (Richmond)	251,625	-	199,333	52,292	-
Total	568,347	166,558	329,716	64,998	7,075

kilowatts of peaking power and 1,200 kilowatt-hours of annual energy per kilowatt of peaking power, with the energy not to exceed 200 kilowatt-hours per kilowatt in any one month or 600 kilowatt-hours per kilowatt during four consecutive months.

1984 Reservoir Releases

Although reservoir releases vary greatly from year to year, data for a selected year is tabulated to generally illustrate the relative magnitude of actual releases. Recorded releases during 1984 are shown in Table 3.13.

Water Rights in the Brazos River Basin

The water rights adjudication process was recently completed for the Brazos River Basin. The data presented in this chapter, and later in Chapters 7 and 8, are based on a list of water rights furnished by the Texas Water Commission. The list is a printout of a computer file and is entitled "Brazos River Basin, List of Water Rights Including Permits, Certified Filings, Claims and Certificates of Adjudication As Existing on June 30, 1986." The list was compiled prior to final completion of the adjudication process and does not reflect changes made after June 1986. A total of 1,348 entries in the list, include diversions totalling 2,170,428 acre-feet/year and reservoir storage capacities totalling 4,567,202 acre-feet. About 1,040 individual citizens, private companies, cities, and public agencies own the water rights. Many of the water rights owners have just one right, while many other owners have several rights included in the list. Rights held by a single entity for different types of use include a separate citation for each use. Additional information regarding water rights associated with the twelve BRA reservoirs was obtained from the individual permits.

Tables 3.14 and 3.15 show the water rights diversions aggregated by the main reservoir and nonreservoir control points used in the simulation models discussed in later chapters. Each control point represents the water rights at diversion locations between the control point and the next upstream control point. The reservoir control points include the water rights associated with the reservoir as well as upstream rights. Table 3.15 compares the accumulative water rights above a location with the 1940-1976 TWC naturalized streamflows at the location. As discussed in Chapter 4, the naturalized streamflow is measured streamflow adjusted to remove the effects of reservoir regulation and water use. Throughout the basin, water rights greatly exceed the lowest annual flow occurring during the 1940-1976 period. The last column of the table shows water rights in the watershed above a location as a percentage of the mean annual naturalized flow at the location. At the coast, the total basin water rights are divided by the mean annual streamflow at the Richmond gage. Total annual water rights are 37.4 percent of mean annual streamflow.

As previously discussed, Section 11.028 of the Texas Water Code states: "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." Ramifications of the Wagstaff Act during drought conditions have not been precisely defined. However, municipal water rights with priority dates after May 1931 could conceivably have their priority dates changed to May 1931 or otherwise be given priority over nonmunicipal water rights. As indicated by Table 3.14, municipal

Table 3.13
1984 RESERVOIR RELEASES

Reservoir	Conservation Releases (acre-feet)		
	Water Supply	Hydroelectric Power	Total
Possum Kingdom	44,490	78,510	123,010
Granbury	67,000	-	67,000
Whitney	9	186,360	186,370
Aquilla	485	-	485
Waco	28,060	-	28,060
Proctor	12,490	-	12,490
Belton	83,680	-	83,680
Stillhouse	36,980	-	36,980
Georgetown	1,330	-	1,330
Granger	-	-	-
Limestone	64	-	-
Somerville	49,130	-	49,130
Sub-total	323,720	264,880	588,800
Excess Flows Permit	4,440	-	4,440
Transbasin Diversion	820	-	820
Total	328,980	264,880	594,060

Table 3.14
WATER RIGHTS ABOVE CONTROL POINTS

Control Point	Water Rights (acre-feet per year)					
	Municipal	Industrial	Irrigation	Mining	Recreation	Total
Hubbard Reservoir	51,011	1,306	2,125	6,000	-	60,442
Possum Kingdom	365,263	24,945	44,075	15,565	50	449,898
Granbury Reservoir	25,510	48,707	22,042	383	-	96,642
Whitney Reservoir	37,050	23,180	6,772	125	-	67,127
Aquilla Reservoir	13,896	-	41	-	-	13,937
Waco Reservoir	58,855	11	9,365	-	-	68,231
Waco Gage	5,600	12,074	6,849	-	-	24,523
Proctor Reservoir	7,716	3,881	24,243	-	-	35,840
Belton Reservoir	111,363	21,721	11,717	-	-	144,801
Stillhouse Reservoir	71,466	48	4,010	-	5	75,529
Georgetown Reservoir	13,610	-	95	70	-	13,775
Granger Reservoir	14,840	5,203	580	540	-	21,163
Cameron Gage	38,906	56,981	5,731	138	-	101,756
Bryan Gage	6,224	27,112	47,082	-	-	80,418
Limestone Reservoir	16,071	55,065	14	50	-	71,200
Somerville Reservoir	5,758	42,262	99	-	-	48,119
Richmond Gage	99,932	49,745	41,461	200	-	191,338
Coast	160,636	261,934	181,011	-	2,108	605,689
Total	1,103,707	634,175	407,312	23,071	2,163	2,170,428

Source: Compiled from TWC computer data file entitled "Brazos River Basin, List of Water Rights Including Permits, Certified Filings, Claims and Certificates of Adjudication As Existing on June 30, 1986."

Table 3.15
WATER RIGHTS ABOVE CONTROL POINTS COMPARED WITH STREAMFLOW

Control Point	Water Rights (acre-feet per year)				Stream Gage Number	TWC Naturalized Streamflow (ac-ft/yr)		Water Rights % Flow
	Reservoir	Upstream	Total	Accumulative		Mean	Low	
Hubbard Reservoir	56,000	4,442	60,442	60,442	367	98,310	698	61.5
Possum Kingdom	230,760	219,138	449,898	510,340	376	861,520	69,200	59.2
Granbury Reservoir	64,712	31,930	96,642	606,982	381	1,166,340	134,000	52.0
Whitney Reservoir	18,336	48,791	67,127	674,109	387	1,755,920	370,320	38.4
Aquilla Reservoir	13,896	41	13,937	13,937	389	86,620	4,140	16.1
Waco Reservoir	59,100	9,131	68,231	68,231	400	343,140	29,620	19.9
Waco Gage	-	24,523	24,523	780,800	401	1,933,700	434,410	40.4
Proctor Reservoir	19,658	16,182	35,840	35,840	412	114,800	22,540	31.2
Belton Reservoir	132,257	12,544	144,801	180,641	418	518,150	21,810	34.9
Stillhouse Reservoir	67,773	7,756	75,529	75,529	424	251,240	17,710	30.1
Georgetown Reservoir	13,610	165	13,775	13,775	426	65,470	0	21.0
Granger Reservoir	19,840	1,323	21,163	34,938	431	174,980	2,000	20.0
Cameron Gage	-	101,756	101,756	392,864	434	1,328,640	98,450	29.6
Bryan Gage	-	80,418	80,418	1,254,082	439	4,006,580	787,590	31.3
Limestone Reservoir	65,074	6,126	71,200	71,200	448	319,440	8,790	22.3
Somerville Reservoir	48,000	119	48,119	48,119	443	223,060	10,010	21.6
Richmond Gage	-	191,338	191,338	1,564,739	456	5,804,560	898,580	27.0
Coast	-	605,689	605,689	2,170,428	-	-	-	37.4
Total	809,016	1,361,412	2,170,428	-	-	-	-	-

Note: The last column is the total (accumulative) water rights above the control point expressed as a percentage of the mean annual naturalized streamflow at the control point.

water rights total 1,103,707 acre-feet per year or 51% of the total water rights diversions in the Brazos River Basin. In Table 3.16, municipal water rights are categorized based on whether their priority dates are after May 17, 1931. Municipal rights of 914,743 acre-feet per year, or 83% of the total municipal rights of 1,103,707 acre-feet per year, have priority dates later than May 1931 and thus are subject to being changed to May 1931. Thus, the priorities of 42% of the total water rights diversion amount (914,743 ac-ft/yr of 2,170,428 ac-ft/yr) could be increased by implementation of the Wagstaff Act.

Almost half of the water rights permits include reservoir storage capacity as well as diversion rates. As indicated by Tables 3.17 and 3.18, the water rights include storage capacities totalling 4,567,202 acre-feet in 598 reservoirs. Forty-six of the reservoirs have permitted storage capacities of 5,000 acre-feet or greater. Four of these major reservoirs are proposed but not yet constructed. The 12 USACE/BRA reservoirs have permitted capacities of 2,904,141 acre-feet or 64% of the basin total. Hubbard Creek Reservoir contains 7% of the total permitted storage capacity. The 552 reservoirs with storage capacities less than 5,000 acre-feet each have a total permitted capacity of 159,249 acre-feet or 3.5% of the basin total. Table 3.18 tabulates the storage capacity totals for reservoirs located between control points and the total accumulative capacity above each control point. Data for reservoir control points include the capacity of the reservoir as well as upstream reservoirs. For example 18 small reservoirs (permitted capacities less than 5,000 ac-ft) and 4 major reservoirs (including Whitney) with a total permitted capacity of 908,339 acre-feet are located between Whitney Dam and Granbury Reservoir. Including Whitney Reservoir, 206 reservoirs with a combined permitted capacity of 2,744,072 acre-feet are located above Whitney Dam.

Water Rights for the 13 Reservoirs

Water rights in the Brazos River Basin total 2,170,428 acre-feet per year. Water rights for releases from the 12 BRA reservoirs are 753,016 acre-feet annually, or 35% of the total. Annual rights of 279,580 acre-feet, or 13% of the total, are associated with diversions located upstream of Possum Kingdom Reservoir. Diversions above the other BRA reservoirs account for 134,108 acre-feet or 6 percent. The remaining 1,003,724 acre-feet, or 46%, of the annual water rights are located downstream of the reservoir system. Diversions below the Richmond gage account for 605,689 acre-feet of the downstream water rights.

The agencies owning water rights for the water supplied by the 13 reservoirs are cited in Table 3.19, and their water rights are listed. The City of Waco owns the rights for water from Waco Reservoir. The City of Temple and the Fort Hood Army Base hold rights to portions of the water from Belton Reservoir. West Central Texas Municipal Water District owns the water rights associated with Hubbard Creek Reservoir. The Brazos River Authority owns the remaining water rights. The Brazos River Authority has rights of 661,911 acre-feet/year associated with 10 reservoirs and 224,932 acre-feet/year associated with two canal systems. This 886,843 acre-feet/year represents 41 percent of the previously discussed 2,170,428 acre-feet/year basin total. BRA priority dates range from 1926 to 1982.

Water rights are normally for a specified type of water use. However, the BRA permits provide a certain flexibility in regard to the annual amounts of

Table 3.16
MUNICIPAL WATER RIGHTS AFFECTED BY WAGSTAFF ACT

	Number of Rights		Diversions (ac-ft/yr)	
Control Point	Total	After May 31	Total	After May 31
Hubbard Reservoir	11	5	51,011	48,950
South Bend Gage	30	18	123,413	113,092
Possum Kingdom Reservoir	6	5	241,850	237,850
Granbury Reservoir	12	11	25,510	23,830
Whitney Reservoir	4	4	37,050	37,050
Aquilla Reservoir	6	5	58,855	19,755
Waco Reservoir	1	1	13,896	13,896
Waco Gage	1	0	5,600	0
Proctor Reservoir	3	2	7,716	7,716
Belton Reservoir	6	4	111,363	110,549
Stillhouse Reservoir	2	1	71,466	67,706
Georgetown Reservoir	1	1	13,610	13,610
Granger Reservoir	2	2	14,840	14,840
Cameron Gage	6	4	38,906	20,310
Bryan Gage	5	5	6,224	6,224
Limestone Reservoir	5	4	16,071	13,571
Somerville Reservoir	1	1	5,758	5,758
Hempstead Gage	0	0	0	0
Richmond Gage	1	0	99,932	0
Coast	4	4	160,636	160,636
Total	107	77	1,103,707	914,743

Table 3.17
PERMITTED STORAGE CAPACITY IN THE BRAZOS RIVER BASIN

Type Reservoir	Number	Capacity (acre-feet)
USACE/BRA reservoirs	12	2,904,141
Hubbard Creek Reservoir	1	317,750
other existing major reservoirs	29	880,213
proposed major reservoirs	4	305,849
small reservoirs (less than 5,000 ac-ft)	552	159,249
Total	598	4,567,202

Source: Compiled from TWC computer data file entitled "Brazos River Basin, List of Water Rights Including Permits, Certified Filings, Claims and Certificates of Adjudication As Existing on June 30, 1986."

Table 3.18
PERMITTED STORAGE CAPACITY ABOVE CONTROL POINTS

	Number of Reservoirs		Capacity (acre-feet)	
Control Point	Small	Major	Incremental	Accumulative
Hubbard Reservoir	9	2	370,854	370,854
South Bend Gage	112	10	471,638	842,492
P.K. Reservoir	7	3	778,279	1,620,771
Granbury Reservoir	38	3	214,962	1,835,733
Whitney Reservoir	18	4	908,339	2,744,072
Aquilla Reservoir	1	1	52,450	52,450
Waco Reservoir	48	1	115,905	115,905
Waco Gage	4	0	3,855	2,916,282
Proctor Reservoir	143	2	104,332	104,332
Belton Reservoir	42	1	465,529	569,861
Stillhouse Reservoir	15	1	236,678	236,678
Georgetown Reservoir	5	1	37,250	37,250
Granger Reservoir	2	1	65,522	102,772
Cameron Gage	27	0	2,927	912,238
Bryan Gage	21	2	57,360	3,885,880
Limestone Reservoir	9	2	240,915	240,915
Somerville Reservoir	8	2	176,147	176,147
Hempstead Gage	26	5	121,097	4,424,039
Richmond Gage	5	0	1,896	4,425,935
Coast	13	5	141,267	4,567,202
Total	552	46	4,567,202	

Table 3.19
WATER RIGHTS ASSOCIATED WITH THE 13 RESERVOIRS

Permit Number	Location	Diversion Amount (ac-ft/yr)	Storage Capacity (ac-ft/yr)	Type Use	Priority Date
	Brazos River Authority				
1262	Possum Kindom Reservoir	230,750	724,739	multiple	Apr 1938
2111	Granbury Reservoir	64,712	153,490	multiple	Feb 1964
3940	Whitney Reservoir	18,336	627,100	municipal	Aug 1982
3403	Aquilla Reservoir	13,896	52,400	multiple	Oct 1976
2107	Proctor Reservoir	19,658	59,400	multiple	Dec 1963
2108	Belton Reservoir	100,257	457,600	multiple	Dec 1963
2109	Stillhouse Reservoir	67,768	235,700	multiple	Dec 1963
2367	Georgetown Reservoir	13,610	37,100	multiple	Feb 1968
2366	Granger Reservoir	19,840	65,500	multiple	Feb 1968
2950	Limestone Reservoir	65,074	225,440	multiple	May 1974
2110	Somerville Reservoir	48,000	160,100	multiple	Dec 1963
1040	Canal System A	99,932	-	multiple	Jan 1926
1299	Canal System B	75,000	-	industrial	Feb 1939
1299	Canal System B	50,000	-	multiple	Dec 1950
	Brazos River Authority (not included in TWC list)				
1467	Canal System A	12,000	-	multiple	none
2661	Interbasin Transfer	200,000	-	multiple	none
2947	Excess Flow	650,000	-	multiple	none
	City of Waco				
2315	Waco Reservoir	39,100	104,100	muncipal	Jan 1929
2315	Waco Reservoir	19,100	-	municipal	Jan 1958
2315	Waco Reservoir	900	-	irrigation	Feb 1979
	U.S. Department of the Army				
2936	Belton Reservoir	10,000	-	municipal	Aug 1953
2936	Belton Reservoir	2,000	-	municipal	Aug 1954
4130	Stillhouse Reservoir	5	-	recreation	May 1984
	City of Temple				
2938	Belton Reservoir	20,000	-	municipal	Jan 1957
	West Central Texas Municipal Water District				
4213	Hubbard Reservoir	44,800	317,750	municipal	May 1957
4213	Hubbard Reservoir	6,000	-	mining	May 1957
4213	Hubbard Reservoir	2,000	-	irrigation	Aug 1972
4213	Hubbard Reservoir	2,000	-	municipal	Aug 1972
4213	Hubbard Reservoir	1,200	-	industrial	May 1957

Table 3.20
BRA RESERVOIR WATER RIGHTS BY TYPE OF USE

Reservoir	Water Rights Diversions (acre-feet/year) Total	Municipal	Industrial	Irrigation	Mining
			BRA Permitted Diversions		
Possum Kingdom	230,750	175,000	250,000	250,000	49,800
Granbury	64,712	10,000	70,000	19,500	500
Whitney	18,336	25,000	25,000	-0-	-0-
Aquilla	13,896	17,000	18,200	-0-	200
Proctor	19,658	18,000	17,800	18,000	200
Belton	100,257	95,000	150,000	149,500	500
Stillhouse	67,768	74,000	74,000	73,700	300
Georgetown	13,610	16,500	16,400	4,100	100
Granger	19,840	30,000	29,800	5,500	200
Limestone	65,074	69,500	77,500	70,000	500
Somerville	48,000	49,500	50,000	50,000	500
			BRA Diversions Included in Computer Models		
Possum Kingdom	230,760	230,760	-	-	-
Granbury	64,712	10,000	42,550	11,850	312
Whitney	18,336	18,336	-0-	-0-	-0-
Aquilla	13,896	13,896	-0-	-0-	-0-
Proctor	19,658	4,935	2,274	12,449	-0-
Belton	100,257	78,549	21,708	-0-	-0-
Stillhouse	67,768	67,706	-0-	62	-0-
Georgetown	13,610	13,610	-0-	-0-	-0-
Granger	19,840	14,840	5,000	-0-	-0-
Limestone	65,074	10,074	55,000	-0-	-0-
Somerville	48,000	5,758	42,242	-0-	-0-

water which can be withdrawn or released from each reservoir for the various types of use. The permits specify the total annual water right diversion for each reservoir, as tabulated in Table 3.19 and 3.20. As indicated in Table 3.20, maximum limits are also specified for diversions for each type of use. However, the sum of the diversion limits for the various types of use exceed the maximum allowable total diversion. Thus, flexibility is provided in allocation of the total diversion between types of use. However, the TWC water availability model as well as the model studies conducted in the present study require specified diversions for each type of use which sum to the total for the reservoir. The diversions assumed for each type of use in the TWC computer data file are reproduced in the bottom half of Figure 3.20.

The BRA also has a system order in effect since July 1964 which allows the reservoirs to be operated as a system such that releases from tributary and main stem reservoirs can be coordinated. Diversions from individual reservoirs can exceed the amounts specified in the individual permits as long as the sum of the diversions in a year for each use type from all the reservoirs does not exceed the sum of the amounts specified in the individual reservoir permits. Thus, the system order does not change the total annual amount of water which can be withdrawn from the BRA system, but does add operational flexibility in selecting the reservoirs from which to make releases.

The BRA permits have been amended to allow an interbasin transfer of 200,000 ac-ft/yr to the San Jacinto-Brazos Coastal Basin. This is not a right to more water in addition to that included in the permits for the 10 reservoirs. However, it allows the already permitted diversions to be transported to the San Jacinto-Brazos Coastal Basin as well as be used within the Brazos River Basin.

The Possum Kingdom Reservoir permit was amended in January 1987 to allow diversion of 5,240 ac-ft/yr for municipal use in the Trinity River Basin. Again, this 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 reservoir.

The BRA also holds an excess flows permit, granted in June 1974, which allows utilization of flows in the lower reaches of the Brazos River which are in excess of amounts needed to satisfy water commitments from unregulated river flows in lieu of reservoir releases, subject to the provisions of the permit, if other water rights are not adversely affected. The excess flows permit allows the BRA to divert, without priority and as limited by several special provisions, not to exceed 100,000 ac-ft/yr for municipal purposes, 450,000 ac-ft/yr for industrial purposes, and 100,000 ac-ft/yr for irrigation purposes. Irrigation diversions can be used to irrigate not more than 119,078 acres of land.

Possum Kingdom and Whitney Reservoirs have hydroelectric power plants. However, no water rights exist specifically for hydroelectric power. Hydropower is generated by unappropriated flows and water supply releases. Hydroelectric power was aggregated with municipal, industrial, and agricultural water supply in the original Possum Kingdom Reservoir water rights permit which included a diversion of 1,500,000 ac-ft/yr. However, hydropower was treated as incidental to water supply at Possum Kingdom in the adjudication process which resulted in the present permitted diversion of 230,750 ac-ft/yr. Whitney

Reservoir has never had a water right for hydroelectric power. Prior to the BRA obtaining a right for water supply from a relatively small portion of the storage capacity in 1982, no water right permit had ever been granted for Whitney Reservoir.

Senior Rights

Total water rights senior to the rights associated with each of the 12 BRA reservoirs are tabulated in Table 3.21. The senior rights include all rights with priority dates earlier than the rights associated with the reservoir, which are located upstream of the reservoir, such that the diversion affects reservoir inflows, or located at downstream locations at which flows are affected by the reservoir storage and releases. The senior water rights are aggregated by location in three categories: (1) diversions above the reservoir, (2) diversions at locations downstream of the reservoir but upstream of the Richmond streamflow gage, and (3) diversions below the Richmond gage.

Senior water rights are tabulated in Table 3.21 based alternatively on (1) the permitted priority dates and (2) the assumption that the priority dates for all rights for municipal use are changed to May 17, 1931 in accordance with the Wagstaff Act. The 12 BRA reservoirs each have rights for multiple uses including municipal. A large portion of the other rights in the basin are also for municipal use. Water rights associated with Waco Reservoir have a priority date of January 10, 1929. Water rights associated with the 11 other BRA reservoirs have priority dates after May 17, 1931. Water rights senior to each reservoir are shown based on the assumption that the 11 reservoirs and all other municipal rights, with priority dates later than May 17, 1931, are changed to May 17, 1931. As indicated by Table 3.21, evoking the Wagstaff Act greatly decreases the water rights senior to the rights associated with the municipal rights of the 11 BRA reservoirs. The senior rights cited in Table 3.21 have earlier priority dates, not the same date, as the earliest right associated with the specified reservoir. With the Wagstaff Act, 83% of the municipal rights or 42% of the total rights in the basin have the same priority date of May 17, 1931.

Table 3.21
SENIOR WATER RIGHTS

Reservoir and Senior Rights Location	Senior Water Rights			
	Without Wagstaff Act		With Wagstaff Act	
	Number	Diversions (ac-ft/yr)	Number	Diversions (ac-ft/yr)
Possum Kingdom Reservoir (priority date 6 April 1938 or 17 May 1931)				
upstream	45	53,337	41	22,279
dam to Richmond gage	23	166,334	18	165,334
below Richmond gage	2		2	60,000
Total	70	279,671	61	247,613
Granbury Reservoir (priority date 13 February 1964 or 17 May 1931)				
upstream	184	445,770	44	24,559
dam to Richmond gage	86	199,878	15	163,054
below Richmond gage	18	504,736	2	60,000
Total	288	1,150,384	61	247,613
Whitney Reservoir (priority date 30 August 1982 or 17 May 1931)				
upstream	420	688,724	44	24,559
dam to Richmond gage	144	252,653	15	163,054
below Richmond gage	27	529,189	2	60,000
Total	591	1,470,566	61	247,613
Aquilla Reservoir (priority date 25 October 1976 or 17 May 1931)				
upstream	0	0	0	0
dam to Richmond gage	102	230,358	14	160,234
below Richmond gage	24	508,168	2	60,000
Total	126	738,526	16	220,234
Waco Reservoir (priority date 10 January 1929)				
upstream	1	7	1	7
dam to Richmond gage	14	162,394	14	162,394
below Richmond gage	0	0	0	0
Total	15	162,401	15	162,401
Proctor Reservoir (priority date 16 December 1963 or 17 May 1931)				
upstream	12	4,802	3	2,207
dam to Richmond gage	141	282,031	21	160,312
below Richmond gage	20	507,872	2	60,000
Total	173	794,705	26	222,519

Table 3.21 (continued)
SENIOR WATER RIGHTS

Reservoir and Senior Rights Location	Senior Water Rights Without Wagstaff Act Number	Diversions	With Wagstaff Act Number	Diversions
Belton Reservoir (priority date 16 December 1963 or 17 May 1931)				
upstream	105	4,802	14	3,719
dam to Richmond gage	48	241,624	10	138,800
below Richmond gage	20	507,872	2	60,000
Total	173	794,705	26	222,519
Stillhouse Hollow Reservoir (priority date 16 December 1963 or 17 May 1931)				
upstream	42	5,811	16	4,452
dam to Richmond gage	38	166,418	8	142,796
below Richmond gage	20	507,872	2	60,000
Total	100	680,101	26	207,248
Georgetown Reservoir (priority date 12 February 1968 or 17 May 1931)				
upstream	3	95	0	0
dam to Richmond gage	55	167,583	8	142,796
below Richmond gage	21	507,984	2	60,000
Total	79	675,662	10	202,796
Granger Reservoir (priority date 12 February 1968 or 17 May 1931)				
upstream	15	1,108	0	0
dam to Richmond gage	43	166,570	8	142,796
below Richmond gage	21	507,984	2	60,000
Total	79	675,662	10	202,796
Limestone Reservoir (priority date 6 May 1974 or 17 May 1931)				
upstream	8	6,071	1	2,500
dam to Richmond gage	21	142,002	5	139,932
below Richmond gage	23	508,168	2	60,000
Total	52	656,241	8	202,432
Somerville Reservoir (priority date 16 December 1963 or 17 May 1931)				
upstream	3	738	0	0
dam to Richmond gage	9	140,049	5	139,932
below Richmond gage	20	507,872	2	60,000
Total	32	648,659	7	199,932

CHAPTER 4
YIELD ANALYSIS MODELS

This chapter consists of a review of approaches for analyzing yield which have been reported in the literature, followed by a description of the generalized computer models adopted for the Brazos River Basin study. Yield is a measure of the amount of water which can be supplied by a stream/reservoir system. The stochastic nature of streamflow and other pertinent variables must be incorporated in yield analysis methods. Yield may be expressed in terms of a firm or dependable yield, percent of time specified quantities of water are available, reliability of meeting various demand levels, risk of shortages, likelihood of various reservoir storage levels occurring, or a tabulation of the amount of water available during each period of a simulation based on specified conditions or assumptions.

Rippl presented his well-known mass diagram technique for determining reservoir firm yield over a century ago (Rippl 1883). Since that time, a variety of mathematical models have been developed to evaluate the amount of water which can be supplied by a unregulated stream, reservoir, or multiple reservoir system. For purposes of the present discussion, the numerous methods for analyzing stream/reservoir system yield are categorized as: (1) statistical analysis of unregulated streamflow, (2) storage probability theory and related methods, (3) mathematical programming or optimization techniques, and (4) simulation of a stream/reservoir system for a specified hydrologic sequence. The first category consists of evaluating the yield which can be provided by an unregulated stream. The other approaches involve reservoir storage capacity. The second and third category are the most mathematically sophisticated. The fourth category is most often adopted for practical application in the planning, design, and management of reservoir projects. System simulation (category 4) models are used to estimate firm yield and reliability as well as other measures of water availability. The TWC Water Availability Model for analyzing water rights, which is discussed later in this chapter, is included in this category. The HEC-3, HEC-5, and TAMUWRAP models used in the present study are also included in the fourth category.

Streamflow synthesis or synthetic streamflow generation models are not included in the above categories but are closely associated with yield analysis models. Streamflow sequences are fundamental input data for the yield models. Streamflow synthesis models are used to fill in missing data and/or extend streamflow records. MOSS-IV was used in the present study to fill in missing streamflows.

Models can also be categorized in regard to capabilities for analyzing yield from an (1) unregulated stream, (2) single reservoir, or (3) multiple reservoir system. A single reservoir is much more complicated to analyze than an unregulated stream. A multireservoir system is much more complicated than a single reservoir.

Review of Approaches for Evaluating Yield

McMahon and Mein (1986) provide a comprehensive treatment of a broad range of yield analysis methods. An overview of yield analysis approaches is presented below, following the categories outlined above.

Yield of Unregulated Streams

One of the simplest and most informative means of quantifying the yield of an unregulated stream is the traditional flow-duration curve, which shows the percentage of time during which specified discharges were equalled or exceeded during the period-of-record at a stream gage. Flow duration curves are developed by counting the number of periods (days or months) during the period-of-record for which flows equalled or exceeded specified levels. The duration or frequency associated with a given discharge is computed by dividing the number of periods it is equalled or exceeded by the total periods in the record. The primary limitation of the flow-duration curve as a method for quantifying yield is that sequencing of flows is not reflected. The relationship does not indicate whether the lowest flows occurred in consecutive periods or were scattered throughout the record.

Low flow frequency curves can be used to estimate the probability of occurrence of a flow event of a given magnitude. These curves are developed by determining the minimum flow during periods of various lengths. The data for each duration can be plotted as a frequency curve.

These and other methods for analyzing the yield provided by unregulated streams are outlined by McMahon and Mein (1986).

Storage Probability Theory and Related Methods

A large group of procedures for analyzing reservoir storage is based primarily on the theory presented by Moran (1959). The objective of stochastic storage analysis methods is to determine the probability distribution of reservoir storage. In terms of practical usefulness, the most important methods in this group are described as probability matrix methods (McMahon and Mein 1986). Other methods are of theoretical interest. Klemes (1981) provides an in depth treatment of applied stochastic theory of reservoir storage.

The stochastic storage theory models assess system performance based on describing inflows by a probability distribution or stochastic process. The methods are typically applied to a single reservoir, rather than a multireservoir system. Modeling is performed in two stages. First, a probability distribution function, if the inflows are assumed independent, or stochastic process, such as a Markov chain, is fitted to the historical streamflow record. Then, simulation or probability techniques are used to develop the storage versus yield function and corresponding reliability estimators. Discrete probabilities are typically used to approximate the continuous distributions of the inflow process. The assumption of first order Markovian processes for representing the inflow process of a reservoir has generally been considered in the literature as adequate for most purposes. The development of models incorporating other approaches result in extremely complex transition probability matrices.

Moran (1959) presents various procedures for determining storage probabilities. Numerous other authors have presented solutions or extensions to the basic models formulated by Moran. McMahon and Mein (1986) outline the basic computational procedures and cite many of the key references. A group of Moran procedures are based on considering either time or both time and volume as continuous variables. Solutions are complex. Another group of procedures treat time and volume as discrete variables, and application is more practical. A reservoir is subdivided into a number of zones and a system of equations developed which approximate the possible states of the reservoir storage. Two main assumptions can be made regarding the inflows and outflows, which occur at discrete time intervals. In a mutually exclusive model, there is a wet period, with all inflows and no outflows, followed by a dry season, with all releases but no inflows. In the more general simultaneous model, inflows and outflows can occur simultaneously. The simultaneous approach is the most practical of the Moran models, but has a number of limitations. Inflows are assumed to be independent, which is not valid for a monthly time period. A constant release rate is typically assumed. A varying release rate can be accommodated if it is storage, not time, dependent. Thus, seasonality of inflows and releases is not considered. Estimates of the probability of the state of the reservoir can be computed either at steady state or as a time dependent function of starting conditions.

Gould (1961) modified the simultaneous Moran-type model to account for both seasonality and auto-correlation of monthly inflows by using a transition matrix with a yearly time period, but accounting for within-year flows by using a monthly behavior analysis. Thus, monthly auto-correlation and seasonal release variations can be included. The Gould method, like other probability matrix methods, computes the probability of reservoir storage levels for a given storage capacity and release rate. Storage probabilities can be computed either at steady state or as a time dependent function of the starting conditions.

Storage probability theory and related methods have been addressed extensively in the research literature. Much of the work represents modifications or extensions of the basic Moran and Gould models. Klemes (1981) and McMahon and Mein (1986) provide concise overviews and cite many significant references. The mathematics of stochastic storage analysis is complex, necessitating significant assumptions and simplifications. Many of the more sophisticated techniques are severely limited from a practical applications perspective. Klemes (1982) has observed: "This theory has evolved into a highly esoteric branch of pure mathematics which, apart from some elements of the jargon, has very little relevance to the original physical problem. It often solves the wrong problems simply because they are mathematically tractable...and that, from the physical point of view, are trivial or irrelevant."

Mathematical Programming

During World War II, the Allies organized interdisciplinary teams to solve complex scheduling and allocation problems involved in military operations. Mathematical programming or optimization models were found to be very useful in this work. After the war, the evolving discipline of operations research or management science continued to rely heavily upon optimization models for solving a broad range of problems in private industry. The same mathematical programming techniques also became important tools in the various systems engineering disciplines, including water resources systems engineering. Reservoir operations have been viewed as an area of water resources planning and management having particularly high potential for beneficial application of optimization models.

The literature related to optimization models in general and application to reservoir operation in particular is extensive. The various optimization techniques are treated in depth by numerous mathematics, operations research, and systems engineering textbooks. Application of optimization techniques to reservoir operation problems has been a major focus of water resources planning and management research during the past two decades. The textbook by Loucks, Stedinger, and Haith (1981) explains the fundamentals of applying optimization techniques in the analysis of water resources systems. Yeh (1982) reviews the state-of-the-art of optimization models applied to operation of reservoir systems. Wurbs, Tibbets, Cabezas, and Roy (1985) provide a state-of-the-art review and annotated bibliography of systems analysis techniques applied to reservoir operation, which is directed toward optimization, simulation, and stochastic analysis methods. A majority of the over 700 references cited in the bibliography focus on optimization techniques.

There is no generalized model for optimizing reservoir operation. Rather, optimization models have been formulated for a variety of specific types of reservoir operation problems. The models have usually been developed for a specific reservoir system. University research projects involving case studies account for most of the applications of optimization techniques to reservoir operations to date. Major reservoir systems for which optimization models have been used to support actual operations decisions include the California Central Valley Project and Tennessee Valley Authority System (Yeh 1982).

Most of the applications of optimization techniques in reservoir systems analysis involve linear programming, dynamic programming, or combining a simulation model with a search algorithm. The numerous other available nonlinear programming techniques have been used relatively little in reservoir planning and operation.

Optimization models are formulated in terms of determining values for a set of decision variables which will maximize or minimize an objective function subject to constraints. The objective function and constraints are represented by mathematical expressions as a function of the decision variables. For a reservoir operation problem, the decision variables might be release rates or end-of-period storage volumes. The objective function to be maximized could be a quantitative measure of economic benefits for various project purposes, hydroelectric energy produced, firm yield, a water quality index , or the length of the navigation season. Likewise, an objective function to be minimized could be expressed as deviations from target discharges, a shortage index such as the squared sum of deviations between target and actual discharges, volume of water released to meet minimum flow requirements, economic costs due to water shortages, expected annual flood damages, or any number of other indices of system performance. Constraints typically include storage capacities, mass balances, and minimum diversion or low flow requirements for various purposes. If the problem can be formulated in the proper mathematical format, linear programming, dynamic programming, and other nonlinear programming algorithms provide readily available solution techniques.

As an example of the application of optimization techniques for yield analysis, reservoir firm yield for a specified inflow sequence can be computed using linear programming. The objective function is to maximize the release rate. Decision variables include end-of-period storages and spills as well as the release rate. Constraints include reservoir mass balances (inflow minus outflow equals change in storage) for each time period (typically monthly) and limiting end-of-period storage to the reservoir storage capacity. All the required mathematical expressions are linear except the storage versus area relationship used in evaporation computations. The storage versus area relationship is approximated as a piece-wise linear function. The linear programming formulation is straight-forward for a single reservoir but much more complex for a multireservoir system.

Reservoir System Simulation

A simulation model is a representation of a system used to predict the behavior of the system under a given set of conditions. Simulation is the process of experimenting with a simulation model to analyze the performance of the system under varying conditions, including alternative operating policies. Many types and forms of simulation models have been used for a variety of purposes. Models for simulating reservoir operation typically consist of a collection of mathematical expressions coded for solution on a computer. A reservoir simulation model typically computes storage levels and discharges at pertinent locations in a reservoir-stream system for various sequences of hydrologic inputs (streamflow, precipitation, and evaporation) and demands for releases or withdrawals for various purposes. Physical constraints, such as storage capacities and outlet and conveyance facility capacities, and institutional constraints, such as maintenance of flows associated with downstream water rights, are also reflected in the models. Simulation models also provide the capability to analyze reservoir system operations using hydrologic and economic performance measures such as firm yield, reliability, hydroelectric energy produced, flood damages, and economic benefits associated with various project purposes.

Modeling flood control operations is significantly different than modeling reservoir operations for conservation purposes such as municipal, industrial, and agricultural water supply, hydroelectric power, navigation, recreation, and maintenance of low flows for water quality. Although optional capabilities for analyzing flood control and conservation operations are combined in some models, other models are limited to one or the other type of operation.

A simulation model for conservation operations is essentially an accounting procedure for tracking the movement of water through a reservoir-stream system. Reservoir releases are determined by the model based on target demands for water supply diversions, instream flows, and/or hydroelectric energy. Diversion and instream flow targets may be specified at downstream control points as well as at the reservoirs. Certain models, such as HEC-3 and HEC-5 discussed later, allow diversions and instream flows to be designated as required or desired with respect to the amount of water in storage. Required demands are met as long as the reservoir storage level is above the top of the inactive pool. Desired demands are met only if the reservoir storage level is above the top of buffer pool.

Modeling reservoir operations is based on a mass balance of reservoir inflows, outflows, and changes in storage, as reflected by the continuity equation:

$$S_2 = S_1 + I - R - E - O$$

where S_2 = reservoir storage at the end of a time period
S_1 = reservoir storage at the beginning of a time period
I = reservoir inflows during time period
R = reservoir releases during time period
E = evaporation during time period
O = seepage and other losses during time period

Seepage and other losses are typically considered negligible. Evaporation is computed by applying an evaporation rate to the average water surface area during the time period. Thus, a reservoir storage capacity versus water surface area relationship must be provided as input data. A time series of reservoir inflows and an operating policy for determining releases must be specified.

If hydroelectric power is being considered, reservoir storage levels and discharges are converted to electrical power in the model using the power equation:

$$P = \gamma Qhe$$

where: P = power (KW or ft-lb/s)
γ = unit weight of water (KN/m^3 or lb/ft^3)
Q = discharge (m^3/s or ft^3/s)
h = effective head (m or ft)
e = efficiency

The effective head (h) is the difference between headwater and tailwater elevations, corrected for hydraulic losses. Tailwater elevation may be expressed as a function of the release rate. The efficiency (e) reflects the power plant energy losses incurred in converting mechanical energy to electrical energy. Energy (kilowatt-hours or foot-pounds) is power multiplied by time.

The fundamental mass balance computations performed by a simulation model are essentially the same for either water supply or hydroelectric power. Hydroelectric power simply entails the additional task of relating reservoir water surface elevation and discharge to power generation for each time interval.

Simulation of conservation operations are typically based on a routing interval of a month, but other intervals may be used. A simulation may be performed with historical period-of-record, critical period, or synthetically generated streamflows. Period-of-record or average monthly evaporation rates can be used.

The information to be obtained from a reservoir simulation will vary depending on the purpose for the study. Model output typically consists of reservoir levels and discharges from the reservoirs and at pertinent downstream locations, as a function of time. System performance in meeting demands can be observed from this output data. A tabulation of reservoir storage levels and discharges may be the only output desired from a simulation. In the case of hydroelectric power, the power produced will be displayed. Firm yield and reservoir reliability can also be determined from simulation studies. Economic as well as hydrologic impacts can be related to discharge and storage levels. A simulation study typically involves numerous runs of a model. A series of runs can be made to compare system performance for alternative reservoir configurations, operating policies, demand levels, or inflow sequences.

Firm Yield and Reliability

Yield is the amount of water which can be supplied from a reservoir in a specified period of time. Quantifying yield is complicated by the stochastic nature of reservoir inflows. Future inflows are unknown and must be estimated based on historical data. Analyses conducted in the planning, design, and operation of reservoirs are typically based on the concept of firm (safe or dependable) yield. Firm yield is the maximum rate of withdrawal which can be maintained continuously assuming the period-of-record historical inflows are repeated in the future. This is the yield which will just empty the reservoir. Linsley and Franzini (1979) outline the traditional Rippl diagram and sequent peak algorithm approaches for estimating firm yield, which are amenable to manual computations. With the advent of computer simulation models, firm yield is now usually computed using a reservoir system simulation model. For a given reservoir storage capacity and inflow sequence, the system is simulated with alternative trial demand levels, in an iterative search for the demand level which just empties the reservoir. The iterative procedure for computing firm yield may be automated within the simulation model. Firm yield computational procedures are outlined by the Hydrologic Engineering Center (USACE, HEC 1975).

Reservoir reliability is an expression of the probability that a specified demand will be met in a given future time period. Reliability (R) is the complement ($R = 1-F$) of the risk of failure (F) or probability that the demand will not be met. Reliability estimates are developed from the results of a reservoir system simulation.

Various definitions of reliability can be formulated for alternative time periods. Computational procedures are dependent upon the manner in which reliability is defined. For example, reliability may be defined as the percentage of months during a simulation for which demand is met. Thus, the reliability would represent the likelihood of demand being met in a randomly selected month in the future. Alternatively, reliability could be defined as the likelihood that demand can be met continuously during a 50-year simulation period. These two approaches for defining reliability are discussed below.

Reliability estimates can be formulated based on either a period or volumetric basis. Period reliability can be defined as the proportion of time that the reservoir/stream system is able to meet demands. Reliability (R) is computed from the results of a simulation as:

$$R = n/N$$

where n denotes the number of time periods (typically months) during the simulation for which demands could be met and N is the total number of time periods in the simulation.

Volumetric reliability is the ratio of the volume of water supplied to the volume demanded. The shortages occurring in each period of a simulation are totalled and divided by the total volume of the demands over the simulation period. By definition, firm yield and smaller yields have a period and volume reliability of 100%. Yields greater than firm yield have a reliability of less than 100%.

Period and volumetric reliabilities were computed in the Brazos River Basin study based on a 85-year hydrologic period-of-record simulation using a monthly time period.

Reliability estimates can also be formulated in terms of the likelihood that demand can be met continuously during a long multiyear period. This type of reliability analysis typically requires streamflow sequences many times longer than the period-of-record. Consequently, synthetic streamflow generation techniques, discussed later in this chapter, have been developed to provide sufficient data for reservoir reliability studies. Synthetic streamflow generation involves synthesis of equally likely streamflow sequences with a length equal to the time period over which the reservoir is being analyzed. With a large number of equally likely alternative inflow sequences routed through a reservoir using a simulation model, the number of times that demands are met, without incurring a shortage due to an empty reservoir, can be counted. The reliability is estimated as the percentage of the inflow sequences for which demands are met without incurring a shortage. For example, a large number (say 100) of monthly streamflow sequences of a specified length (say 50 years) can be synthesized using a model such as MOSS-IV. Firm yields could then be computed for each of the 100 streamflow sequences and the number of times the computed firm yield equalled or exceeded various levels counted. The reliability associated with a given firm yield value would be the number of streamflow sequences for which the firm yield value was equalled or exceeded divided by 100.

A reservoir reliability study using synthetically generated streamflow sequences was not included, but would be a logical extension of the present Brazos River Basin study. However, a comprehensive reliability analysis would require a great amount of time and effort relative to the scope of the yield study documented in Chapters 5 through 8 of this report.

Firm yield and reliability are discussed above from the perspective of supplying water for various beneficial uses. The concepts are equally applicable to hydroelectric power. Firm power is maximum rate of energy production which can be maintained continuously assuming the period-of-record historical inflows are repeated in the future. Firm power and reliability associated with various levels of power production are computed with a simulation model similarly to firm yield and reliability for water supply.

Streamflow Synthesis

Streamflow synthesis models are used to develop input data required for simulation models. Synthesis of streamflow data from historical gaged streamflow records includes filling in missing data and extending the length of the data. Missing data is typically reconstituted by a regression analysis based on flows during preceding periods at the location and flows during the current and preceding periods at nearby locations.

Extension of limited historical data by synthetic streamflow generation may be necessary to provide an adequate basis for analyzing reservoir capacity-yield-reliability relationships. Development of the field of stochastic or operational hydrology has focused primarily upon problems of reservoir planning and operation. Synthetic streamflow generation models accept period-of-record monthly streamflow as input. Monthly streamflow sequences of any specified length are synthesized based on preserving the statistics of the input data. Markov models, such as MOSS-IV (Beard 1973) and LAST (Lane and Frevert 1985), preserve the mean, standard deviation, and lag-1 autocorrrelation coefficient. Estimation of reservoir reliability using synthetically generated streamflow sequences is based on the concept that preservation of the statistical parameters results in a set of streamflow sequences which are equally likely to occur. The historical streamflow represents one sequence which could possibly occur in the future. The synthetically generated streamflow sequences represent alternative sequences which have the same likelihood of occurring in the future. The validity of synthetic streamflow generation models in representing the likelihood of extreme low flow conditions is an aspect of this approach to estimating reservoir reliability which is generally considered to be particularly questionable. Bras and Rodriguez-Iturbe (1985) provide an indepth treatment of stochastic hydrology. Goldman (1985) provides a presentation of synthetic streamflow generation from a practical application perspective.

Specific Simulation Models

The HEC-3, HEC-5, and TAMUWRAP simulation models applied in the Brazos River Basin study are described later in this chapter. Several other major generalized stream/reservoir system simulation computer programs are cited below.

Early Simulation Models. Simulation modeling of major river basins began in the United States in 1953 with a study by the Corps of Engineers of the operation of six reservoirs on the Missouri River (Manzer and Barnett 1966). The International Boundary and Water Commission simulated a two-reservoir system on the Rio Grande River in 1954. A simulation study for the Nile River Basin in Egypt in 1955 considered alternative plans with as many as 17 reservoirs or hydropower sites. Pioneering research in developing reservoir system simulation methods was accomplished in conjunction with the Harvard Water Program (Maass, et at. 1966). Hufschmidt and Fiering (1966) discuss the simulation modeling work of the Harvard Water Program and application to multipurpose planning in the Lehigh River Basin.

TWDB Models. The Texas Water Development Board (TWDB) began development of a series of surface water simulation models in the late 1960's in conjunction with formulation of the Texas Water Plan (TWDB 1974 and TDWR 1984). The present RESOP-II, SIMYLD-II, AL-V, and SIM-V computer programs evolved from earlier versions.

The Reservoir Operating and Quality Routing Program (RESOP-II) is designed for performing a detailed analysis of the annual yield of a single reservoir. A quality routing option adds the capability to route up to three nondegradable constituents through a reservoir and to print a frequency distribution table and a concentration duration plot for the calculated end-of-month quality of the reservoir (Browder 1978).

SIMYLD-II provides the capability for analyzing water storage and water transfer within a multireservoir or multibasin system (TWDB 1974). SIMYLD-II simulates the operation of a system subject to a specified sequence of demands and hydrologic conditions. The model simulates catchment, storage, and transfer of water within a system of reservoirs, rivers, and conduits on a monthly basis with the object of meeting a set of specified demands in a given order of priority. If a shortage occurs such that not all demands can be met for a particular time period, the shortage is located at the lowest priority demand node. SIMYLD-II also provides the capability to determine the firm yield of a single reservoir within a multireservoir water resources system. An iterative procedure is used to adjust the demands at each reservoir of a multireservoir system in order to converge on its maximum firm yield at a given storage capacity assuming total system operation. While SIMYLD-II is capable of analyzing multi-reservoir systems, it is not capable of analyzing a single reservoir as accurately as RESOP-II. Consequently, SIMYLD-II and RESOP-II are both used in an interactive manner to analyze complex systems.

The Surface Water Resources Allocation Model (AL-V) and Multireservoir Simulation and Optimization Model (SIM-V) simulate and optimize the operation of an interconnected system of reservoirs, hydroelectric power plants, pump canals, pipelines, and river reaches (Martin 1981, 1982, 1983). SIM-V is used to analyze short-term reservoir operations. AL-V is for long-term operations. The models combine simulation and optimization. The steady-state operation of a surface water system is represented as a network flow problem. The out-of-kilter linear programming algorithm is used to analyze capacitated networks. Hydroelectric benefits are incorporated by solving successive minimum-cost network flow problems, where flow bounds and unit costs are modified between successive iterations to reflect first-order changes in hydroelectric power generation with flow release rates and reservoir storage.

PRISM. The Department of Geography and Environmental Engineering at John Hopkins University performed a study sponsored by the Office of Water Research and Technology on the operation of reservoirs in the Potomac River Basin and water supply management in the Washington, D.C. Metropolitan Area (Palmer, et al. 1980 and 1982). The first year of the study focused on the formulation and solution of optimization models, and the second year focused on development of the Potomac River Interactive Simulation Model (PRISM). PRISM provided a much more detailed representation of the water supply system than the optimization models.

PRISM simulates the operation of the four reservoirs and the allocation of water within the Washington Metropolitan Area. Input data include: (1) weekly streamflow into each reservoir and weekly flow of the Potomac River, (2) weekly water use demand coefficients for each of three water supply agencies, (3) an allocation formula for distribution of water to jurisdictions, and (4) rules and constraints for operating the reservoirs in the system. The model determines on a weekly basis the supply of water available to each of the three jurisdictions resulting from previous decisions made in response to information on the state of the system.

PRISM is designed for use in a batch mode, where decision strategies are specified by the user prior to model execution, or in an interactive mode. When operating in the batch mode, PRISM performs the function of the regional water supply manager in strict accordance with rules provided by the model user. The interactive model allows participants to engage in a dialogue with the model as it is being executed, thereby changing model parameters and overriding prespecified decision rules. The interactive model represents an attempt to include, in a formal analytical modeling exercise, the process by which water supply management decisions are made.

MIT Simulation Model. Strzepek and Lenton (1978) describe the Massachusetts Institute of Technology (MIT) River Basin Simulation Model and its application to the Vardar/Axios Basin in Yugoslavia and Greece. A users manual is provided by Strzepek, et al. (1979). The generalized computer program provides the capability to evaluate the hydrologic and economic performance of a river basin development system. Existing and proposed reservoirs, hydroelectric power plants, thermal power stations, irrigation areas, and diversions and withdrawals for municipal, industrial, and other uses are represented in the model as a system of arcs and nodes. The model computes the monthly flows at all nodes in the basin, given the streamflows at the start nodes. System reliability in meeting water demands is assessed. Irrigation, hydroelectric power, and municipal and industrial water supply benefits are computed and compared with project costs. Benefits are divided into long-term benefits and short-term losses.

Trent River System Model. Sigvaldason (1976) describes a simulation model developed to assess alternative operation policies for the 48-reservoir multipurpose water supply, hydropower, and flood control system in the Trent River Basin in Ontario, Canada. The model was originally developed for planning but has also been used for real-time operation. In the model, each reservoir was subdivided into five storage zones. Time based rule curves were prescribed to represent ideal reservoir operation. The combined rule curve and storage zone representation is similar to HEC-5. Ranges were prescribed for channel flows, which were dependent on water-based needs. Penalty coefficients were assigned to those variables which represented deviations from ideal conditions. Different operational policies were simulated by altering relative values of these coefficients. The development and use of the model were simplified by representing the entire reservoir system in capacitated network form and deriving optimum solutions for individual time periods with the out-of-kilter algorithm. This optimization submodel for achieving optimal responses during individual time intervals is similar to the approach used in the Texas Water Development Board models except for differences in the objective functions.

SSARR Model. The Streamflow Synthesis and Reservoir Regulation (SSARR) model was developed by the North Pacific Division of the USACE primarily for streamflow and flood forecasting and reservoir design and operation studies. Various versions of the model date back to 1956. A program description and user manual (USACE, NPD 1975) documents the present version of the computer program. Numerous reservoir systems, including the Columbia River Basin in the United States and Mekong River Basin in Southeast Asia, have been modeled with the generalized computer program by various agencies, universities, and other organizations.

The SSARR computer program simulates the hydrology of a river system. The model is comprised of three basic components: (1) a watershed model for synthesizing runoff from rainfall and snowmelt, (2) a streamflow routing model, and (3) a reservoir regulation model for analyzing reservoir storage and outflow.

SWD Model. A generalized reservoir regulation model developed by the Southwestern Division (SWD) of the USACE is described by Hula (1979). Application of the model to the Arkansas River System is described by Coomes (1979) and Copley (1979). The division and district offices in the five-state Southwestern Division have routinely applied the model for a number of years. The Reservoir Modeling Center in the Tulsa District is presently simulating the Brazos River Basin reservoir system. The SWD model simulates the daily sequential regulation of a multipurpose reservoir system. The model performs the same types of hydrologic and economic simulation computations as HEC-5. The SWD model uses a one-day computation interval whereas HEC-5 uses a variable time interval. Details of handling input data and various computational capabilities differ somewhat between the two models.

Hydrologic input data includes daily uncontrolled streamflows at each reservoir and river control point and daily evaporation at each reservoir. Economic input data includes: stage-damage curves; stage-discharge curves; stage-area curves; cropping patterns; crop values; navigation costs relative to discharge; dredging requirements relative to discharge and duration; recreation benefits as a function of pool elevation, season, and pool fluctuation; hydroelectric power value, and costs for purchasing thermal electric power as a function of season and time of day. Input data describing the physical characteristics of the reservoir-stream system include: reservoir elevation-area-capacity curves; reservoir discharge capacity; hydroelectric power plant capacity; tailwater rating curves; and Muskingum routing coefficients. Reservoir release requirements and constraints are based on controls at the reservoir and downstream control points. Hydrologic information provided by the model includes: monthly and annual frequency plots of maximum and minimum reservoir storage and control point discharge; duration plots of reservoir pool elevation and control point discharge; and water supply and low flow shortages. Economic output includes flood damages, recreation benefits, power value, cost of purchased power, dredging costs, and navigation costs.

TWC Water Availability Model. The Texas Water Commission (TWC) began development of a water availability model in 1968 (Murthy, Liu, and Crow 1975). Several generations of the model have 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 a river basin under the water rights system. The primary purpose of the model is to determine unappropriated streamflows. This information is used by the TWC in the evaluation of applications for permits to appropriate water.

A stream/reservoir/rights system is simulated based on historical period-of-record monthly streamflow and evaporation data. Diversions and diversion shortages are computed for each water right for each month of the simulation. Unappropriated flows are determined at locations throughout the basin for each month of the simulation. The model contains an algorithm for allocating water based on permitted priorities and physical constraints.

Models Used in the Present Study

Based on a review of agency practices and the published literature, a set of generalized computer programs developed by the Hydrologic Engineering Center (HEC) of the U.S. Army Corps of Engineers was selected for use in the Brazos River Basin study. Model formulation involved developing input data files for the computer programs. MOSS-IV was used to fill in data missing from the streamflow record. HEC-3 and HEC-5 were used to simulate the reservoir system and compute firm yields. STATS was used to perform various statistical analyses of streamflow and reservoir content data.

HEC-3 and HEC-5 provide comprehensive reservoir system simulation capabilities, with the important exception of water rights. The models cannot simulate water rights priorities. The TWC Water Availability Model is a complex set of computer programs developed for TWC use and has not been released for application outside of the agency. A literature review revealed no other generalized water rights models. The enormously extensive literature on modeling reservoir operations includes surprisingly little reference to water rights. Consequently, TAMUWRAP was developed, in conjunction with the study, for simulating and analyzing water rights. The results of a TAMUWRAP simulation provide input data to HEC-3 for computing firm yields and reliabilities constrained by senior water rights.

Feldman (1981) discusses the various generalized computer simulation programs available from the Hydrologic Engineering Center. The HEC programs used in the present study are briefly described and pertinent references cited below. The Texas A&M University Water Rights Analysis Program (TAMUWRAP) is also described.

HEC-3 Reservoir System Analysis for Conservation

HEC-3 is documented by a user's manual (USACE, HEC 1981) and programmer's manual (USACE, HEC 1976). HEC-3 simulates the operation of a reservoir system for conservation purposes such as water supply, low-flow augmentation, and hydroelectric power. Flood control operations can be modeled in some respects, but not to the degree of detail as HEC-5. The program can accept any configuration of reservoirs, diversions, hydroelectric plants, and stream control points. Input data includes reservoir characteristics, operating criteria, streamflow, and reservoir evaporation rates. The simulation consists of routing streamflows through the system for each computational time period. The model operates the reservoirs to meet specified flood control and conservation operating criteria. Reservoir storages, releases, diversions, streamflows, and shortages are computed for each time period during the simulation . Optional capabilities are available for computing water supply or hydropower firm yields for single reservoirs or multireservoir systems. Economic values can be computed for meeting selected targets, based on input data relating benefits and/or costs to selected streamflow or storage parameters.

HEC-5 Simulation of Flood Control and Conservation Systems

HEC-5 performs the same basic computations using essentially the same input data as HEC-3. HEC-5 has most of the conservation capabilities of HEC-3 and greatly expanded flood control capabilities. For example, unlike HEC-3, HEC-5 performs flood routing and expected annual damage computations. Hydropower modeling capabilities are also more extensive in HEC-5 than HEC-3. HEC-3 has several conservation related options not available in HEC-5. For example, HEC-5 firm yield computations are limited to a single reservoir, whereas HEC-3 can compute system firm yield for a multireservoir system. Although the April 1987 microcomputer version of HEC-5 was tested in the present study, most HEC-5 runs were made with the March 1986 mainframe version. HEC-5 is documented by a users manual (USACE, HEC 1982 and 1986). Other references on use of HEC-5 and associated utility programs include USACE, HEC (1979, 1982, 1985a, 1985b, 1985c, 1986).

MOSS-IV Monthly Streamflow Simulation

MOSS-IV is an improved version of HEC-4 (USACE, HEC 1971), modified for the Texas Water Development Board (Beard 1973). MOSS-IV fills in gaps in monthly streamflow data based on measured streamflow at other nearby gage stations. The program uses a multiple linear regression algorithm based on the transformed incremented logarithm of monthly streamflows. A random component is included in order to reproduce the distribution of random departures from the regression model as they are observed in the basic data. The missing dependent value to be estimated is related to values for the same month at all of the stations where such values exist or values for the preceding month if current-month values do not exist. The value for the preceding month at the dependent-variable station is always used as one of the independent variables in the regression study.

MOSS-IV also provides the capability for generating sequences of hypothetical streamflows of any desired length having the statistical characteristics of inputed measured streamflow data. Synthetic streamflow generation is based on a lag-1 Markov model. Goldman (1985) discusses synthetic streamflow generation from the perspective of methods incorporated in HEC-4 and MOSS-IV.

STATS Statistical Analysis of Time Series Data

The computer program STATS is designed to reduce large volumes of daily or monthly data to a few meaningful statistics or frequency relationships. STATS will perform the following analyses: (1) duration curves, (2) annual maximum events, (3) annual minimum events, (4) departures of monthly and annual values from respective means, and (5) annual volume-duration exchange of high and low events.

TAMU Water Rights Analysis Program (TAMUWRAP)

TAMUWRAP was developed as a part of the study and is documented by a program description and users manual (Walls and Wurbs 1988). The generalized computer model provides the capability to simulate a stream/reservoir/rights system of essentially any normal configuration.

The system configuration is represented in the model by a set of any number of control points. Input data includes: naturalized monthly streamflows at each control point covering the simulation period; diversion amount, storage capacity, priority date, type use, return flow factor, and control point location of each water right; control point location and storage versus area relationship for each reservoir; monthly reservoir evaporation rates for each control point; and monthly water use distribution factors for each type of water use. Several water rights can be associated with the same reservoir. Reservoir storage versus area relationships can be input as a table, which is linearly interpolated by the program, or alternatively as a set of coefficients for an equation coded in the program.

For each month of the simulation, TAMUWRAP performs the water accounting computations for each water right in turn on a priority basis. The computations proceed by month and, within each month, by water right with the most senior water right in the basin being considered first. TAMUWRAP computes diversions and diversion shortages associated with each water right. Permitted reservoir capacity is filled to the extent allowed by available streamflow. Reservoir evaporation is computed and incorporated in the water balance. Return flows are computed as a fraction of diversions and reenter the stream at the next downstream control point. An accounting is maintained of storage levels in each reservoir and streamflow still available at each control point.

TAMUWRAP output includes diversions, diversion shortages, reservoir storage levels, streamflow depletions, and unappropriated streamflows. Streamflow depletions associated with a given water right consist of withdrawals from the system for beneficial use plus streamflow used to refill depleted storage capacity. Streamflow depletions and unappropriated streamflows computed with TAMUWRAP can be provided as input to HEC-3 or HEC-5 to compute firm yields and reliabilities.

CHAPTER 5
BASIC HYDROLOGIC DATA

The results of hydrologic and water rights simulation modeling studies are presented in Chapters 6, 7 and 8. Basic input data incorporated in the simulation models are described in the present chapter. Input data are further discussed in Chapters 6 and 7.

Reservoir Storage Characteristics

The Brazos River Authority (BRA) and Fort Worth District (FWD) of the U.S. Army Corps of Engineers (USACE) provided data from their files regarding the physical characteristics of the 13 principal reservoirs included in the yield study. Texas Water Development Report 126 (TWDB 1973) provides information regarding the physical characteristics of 36 major reservoirs in the Brazos River Basin.

Pool elevations and storage capacities for the 13 reservoirs included in Table 3.10 were provided by the BRA and FWD. Water surface elevation versus area, storage capacity, and outlet discharge capacity relationships were also provided by the BRA and FWD. Reservoir storage capacities change over time due to sedimentation. Sediment reserve capacities are tabulated in Table 3.10. Water surface elevation versus area and storage capacity tables were obtained for both initial, at the time of initial impoundment, and ultimate, at the predicted time for depletion of the sediment reserve, conditions. The sediment reserves tabulated in Table 3.10 correspond to the difference between initial and ultimate area and capacity tables. Belton, Whitney, and Possum Kingdom Reservoirs also have elevation versus area and storage relationships updated by surveys made since initial impoundment. For purposes of the present study, linear interpolation was applied to the FWD and BRA initial (or resurveyed) and ultimate condition elevation versus area and storage tables to develop tables for years 1984 and 2010 conditions of sedimentation.

The sediment volume estimates developed by the FWD and BRA are based on data provided by Texas Board of Water Engineers (now the Texas Water Development Board) Bulletin 5912 (TWDB 1959). TWDB Bulletin 5912 contains empirically developed curves which provide average annual sediment rates as a function of watershed size and land use. Data is also provided to reflect land treatment measures. The distribution of sediment volume within the reservoir pool is based on methods presented by Borland and Miller (1958).

Detailed data were compiled for the 13 reservoirs listed in Tables 3.9 and 3.10. Less extensive data for the numerous other reservoirs in the basin were obtained from TWDB Report 126, Texas Water Commission (TWC) dam inventory data file, and TWC water rights data file.

Reservoir Evaporation Rates

Monthly gross and net reservoir evaporation rates for the period January 1940 through December 1984 were obtained on magnetic tape from the Texas Natural Resources Information System (TNRIS). This data file is described by Texas Water Development Board (TWDB) Report 64 (Kane 1967). Additional information regarding reservoir evaporation data sources is provided by TWDB Report 192 (Doughtery 1975). Net reservoir surface evaporation is the actual evaporation loss rate minus the effective rainfall rate, which is rainfall over the reservoir site less the amount of runoff under preproject conditions. The data are provided on a one-degree quadrangle basis. For reservoirs extending across quadrangle boundaries, the evaporation data for the adjoining quadrangles were averaged in the present study. The evaporation data extends back to January 1940. Average values (1940 through 1984) for each month are used in the simulation models for the period prior to January 1940.

Net reservoir evaporation rates during the period 1940-1965 for quadrangle F-11 are tabulated in Table 5.1 (Kane 1967). This quadrangle covers a portion of the central Brazos River Basin, including Waco, Belton, and Whitney Reservoirs. Annual net evaporation rates range from 0.21 feet to 5.17 feet. July net evaporation rates range from 0.14 feet to 0.99 feet over the 26-year period.

Water Rights

The Texas Water Commission provided a list of water rights, with pertinent data, in the Brazos River Basin. Other basic data developed by the Texas Water Commission in their water availability modeling studies were also provided. Water rights data are discussed in detail in Chapters 3 and 7.

Streamflow

Gaged Monthly Streamflow Data

A total of 141 stream gage stations in the Brazos River Basin are described in TDWR Report 244 (Dougherty 1980) and included in the Texas Natural Resources Information System (TNRIS) computer data base. Most of the stream gage stations are maintained by the U.S. Geological Survey. The 23 stations selected for inclusion in the simulation studies are listed in Table 5.2 Figure 5.1 shows the locations of the 23 stream gage stations along with the 13 reservoirs operated in the simulation models. TDWR Report 244 contains a map on which the stream gages are numbered. These numbers are adopted herein to refer to the gage stations. Period-of-record gaged monthly streamflows for the 23 stations were obtained on magnetic tape from the Texas Natural Resources Information System.

Hydrographs of monthly gaged streamflow at the Richmond (23-456), Waco (9-400), and Cameron (17-434) gages are plotted in Figures 5.3, 5.4, and 5.5, respectively. Monthly streamflows are seen to be highly variable.

Naturalized Streamflow

Homogeneous time series of natural streamflow data are a fundamental requirement for a reservoir system simulation study. The streamflow input data should reflect the stochastic characteristics of the natural hydrologic cycle. However, the streamflow data should represent constant conditions of watershed development. Significant nonhomogeneities may be caused by the activities of man. Consequently, streamflow data is adjusted to remove significant man-induced effects.

Table 5.1
NET EVAPORATION RATES (FEET/MONTH) FOR QUADRANGLE F-11

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
1940	.03	-.07	.28	-.02	.09	.10	.28	.53	.50	.36	-.40	-.13	1.55
1941	.05	-.13	.03	.07	.12	.02	.36	.52	.43	.07	.27	-.02	1.79
1942	.15	.13	.35	-.26	.04	.21	.43	.47	.05	.14	.14	.00	1.85
1943	.08	.23	.04	.23	.37	.25	.42	.64	.25	.22	.21	-.04	2.90
1944	-.26	-.22	-.01	.14	-.48	.37	.62	.52	.57	.51	-.22	-.05	1.49
1945	-.02	-.10	-.32	-.17	.27	.13	.24	.03	.66	.01	.25	-.03	0.95
1946	-.15	-.07	-.07	.18	-.30	.29	.59	.41	.52	.37	-.28	.17	1.66
1947	-.15	.20	-.08	.06	-.11	.40	.60	.52	.52	.53	.14	-.08	2.55
1948	-.13	-.10	.10	.11	-.03	.42	.49	.69	.57	.51	.30	.18	3.11
1949	-.24	.00	.04	-.07	.16	.22	.43	.40	.49	-.07	.41	-.05	1.72
1950	.00	-.17	.28	.02	.10	.23	.39	.57	.27	.43	.42	.27	2.81
1951	.28	.04	.37	.40	.32	.31	.99	1.15	.30	.47	.30	.24	5.17
1952	.09	-.02	.13	-.12	.01	.54	.45	.79	.72	.67	-.18	-.18	2.90
1953	.10	-.02	-.12	-.13	-.17	.52	.46	.43	.37	.06	.19	-.18	1.51
1954	-.02	.26	.25	.11	.09	.64	.80	.79	.81	.21	.22	.24	4.40
1955	.03	-.09	.08	-.08	.03	.17	.37	.41	.33	.59	.49	.21	2.54
1956	.05	-.08	.10	.22	.14	.38	.82	.77	.70	.54	.14	.11	3.89
1957	.09	-.05	-.14	-.83	-.16	.18	.63	.32	.28	-.12	-.17	.18	0.21
1958	.03	-.05	.10	-.06	.08	.33	.45	.28	-.10	.16	.17	.11	1.50
1959	.18	-.08	.22	-.13	-.16	-.03	.14	.31	.24	.07	.27	-.01	1.02
1960	-.05	.01	.09	.08	.24	-.03	.44	.24	.46	-.12	-.03	-.31	1.02
1961	-.20	-.12	-.02	.26	.19	-.09	.19	.46	.17	.28	.08	.01	1.21
1962	.04	.05	.18	-.04	.28	-.03	.60	.68	.24	.11	.08	.05	2.24
1963	.10	.10	.13	-.10	.05	.32	.52	.67	.43	.53	.17	.05	2.97
1964	.03	.03	.04	.08	.18	.35	.67	.43	.18	.35	.09	.15	2.58
1965	.02	-.08	-.02	.16	-.43	.30	.69	.68	.28	.35	-.03	-.04	1.88

NOTE: Negative values indicate effective rainfall exceeds gross lake surface evaporation rate.

Source: TWDB Report 64

Table 5.2
STREAMFLOW GAGES

Gage	Gage Number	Report 244 Map Number	Stream	Near City	Drainage Area (sq mile)	Record Began
1	08086500	367	Hubbard	Breckenridge	1,089	May 55
2	08088000	369	Brazos	South Bend	22,673	Oct 38
3	08089000	376	Brazos	Palo Pinto	23,811	Jan 24
4	08090800	379	Brazos	Dennis	25,237	May 68
5	08091000	381	Brazos	Glen Rose	25,818	Oct 23
6	08093100	387	Brazos	Aquilla	27,244	Oct 38
7	08093500	389	Aquilla	Aquilla	308	Jan 39
8	08095000	394	Bosque	Clifton	968	Oct 23
9	08095600	400	Bosque	Waco	1,656	Sep 59*
10	08096500	401	Brazos	Waco	29,573	Oct 98
11	08099500	412	Leon	Hasse	1,261	Jan 39
12	08102500	418	Leon	Belton	3,542	Oct 23
13	08104000	422	Lampasas	Youngsport	1,240	Nov 24
14	08104100	424	Lampasas	Belton	1,321	Feb 63
15	08104700	426	Gabriel	Georgetown	248	Jul 68
16	08105700	431	Gabriel	Laneport	738	Aug 65
17	08106500	434	Little	Cameron	7,065	Nov 16
18	08109000	439	Brazos	Bryan	39,515	Aug 99*
19	08110000	443	Yequa	Somerville	1,009	Jun 24
20	08110500	448	Navasota	Easterly	968	Apr 24
21	08111000	449	Navasota	Bryan	1,454	Jan 51
22	08111500	452	Brazos	Hempstead	43,880	Oct 38
23	08114000	456	Brazos	Richmond	45,007	Jan 03*

*Note: Gages 9, 18, and 23 have missing records during the periods Oct 81-Feb 82 (gage 9); Jan 03-Feb 18 and Jan 26-June 26 (gage 18); and Jul 06-Sep 22 (gage 23).

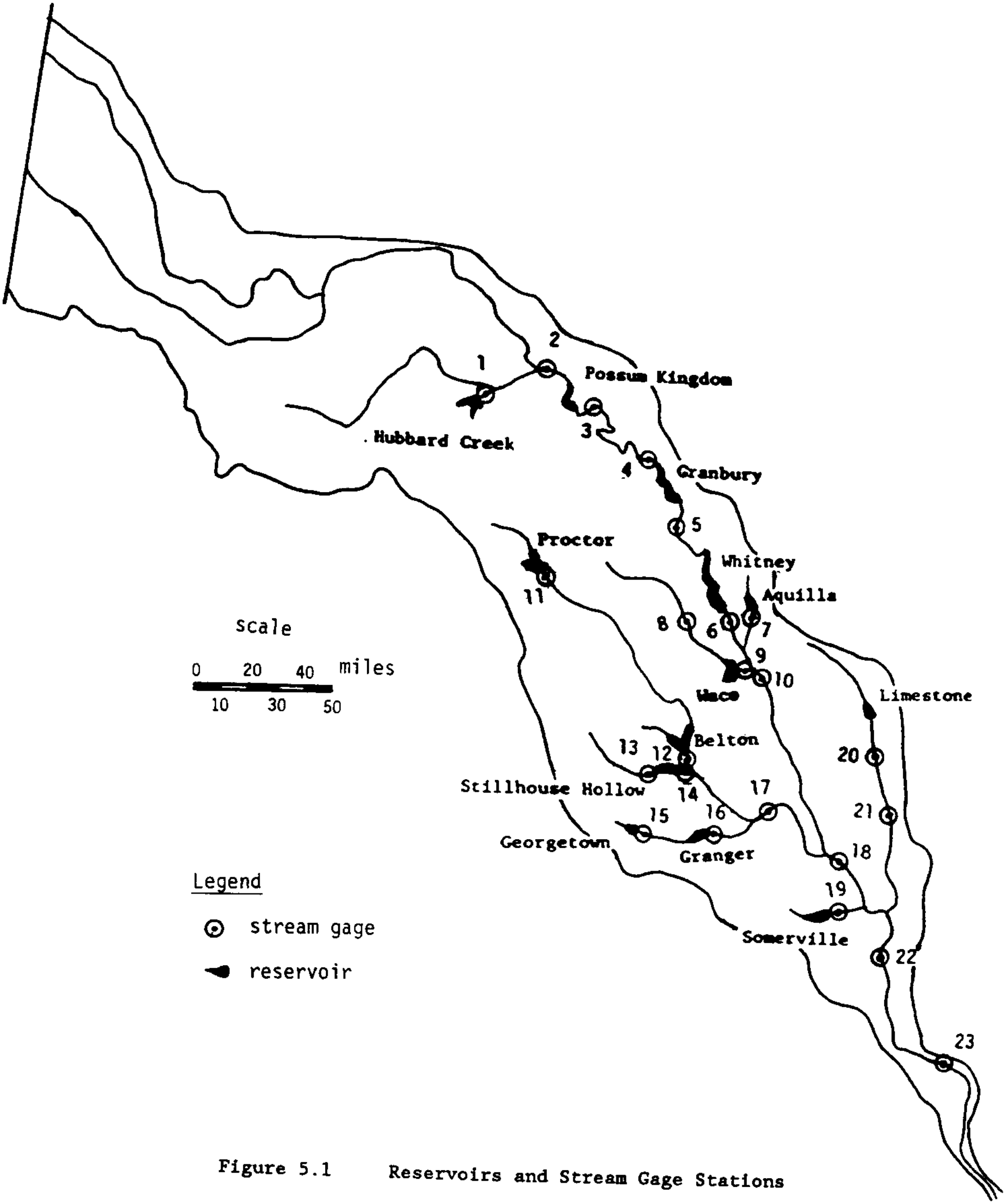


Figure 5.1 Reservoirs and Stream Gage Stations

Two alternative monthly streamflow data sets were used in the study. An initial data set, termed the Texas A&M University (TAMU) unregulated streamflow, was developed by adjusting for the effects of major upstream reservoirs. Another monthly streamflow data set, termed the Texas Water Commission (TWC) naturalized streamflow, was developed by the Texas Water Commission for their water availability model for the basin. The TWC naturalized streamflows include adjustments for water use diversions, return flows, and Soil Conservation Service flood water retarding structures, as well as for the major reservoirs reflected in the TAMU unregulated streamflow. The TWC naturalized streamflows are monthly data covering the period 1940 through 1976.

Prior to obtaining the TWC naturalized streamflow data from the TWC, the possibility of further naturalization of the TAMU unregulated streamflow data was investigated. A great amount of effort was concluded to be required to compile and manipulate the necessary water use and return flow data to further naturalize streamflows. Since many inadequacies exist in historical reported water use and return flow data, streamflow naturalization is necessarily approximate.

The TWC naturalized streamflow is considered to be the best data set available for the simulation study. The major impacts of man's activities are reflected in the naturalization process. It is also advantageous for the present reservoir system simulation studies to be consistent with the TWC water availability modeling studies. The 1940-1976 TWC naturalized monthly streamflow was adopted for the present study. The TAMU unregulated streamflow was used for the time periods 1977 - 1984 and before 1940, which are not covered by the TWC data.

TAMU Unregulated Streamflow

The measured streamflow data were adjusted to remove the effects of the reservoirs in the basin included in the TNRIS data base. Thus, 21 of the 23 water supply reservoirs in the basin which have conservation capacities of 10,000 acre-feet or larger were considered. Aquilla and Limestone Reservoirs were not included. Nine of these reservoirs also have flood control storage capacity. The several reservoirs used primarily for cooling water for electric power plants were not included. The 21 reservoirs included in the streamflow adjustments are listed in Table 5.3 and shown schematically in Figure 5.2 along with the stream gage stations. Monthly reservoir storage content data were obtained on magnetic tape from the TNRIS.

The objective of the adjustments was to make the streamflow data more homogeneous. The resulting data represent streamflows which would have occurred in the absence of the selected reservoir projects. Streamflows at each station were corrected to remove the effects of upstream reservoirs based on the following water balance equation:

$$S_2 = S_1 + I - R - E$$

where S_2 denotes storage at the end of the current month and S_1 denotes storage at the end of the previous month, and I, R, and E denote inflow, releases, and net evaporation, respectively, during the current month. The

Table 5.3
RESERVOIRS INCLUDED IN UNREGULATED FLOW COMPUTATIONS

Reservoir	Gage Number	Stream	Record Began	Evaporation Quadrangle
White River	08080910	White	Apr 64	D6
Millers Creek	08082800	Millers	Jul 74	D9
Sweetwater	08083200	Bitler	Jan 36	E7
Fort Phantom Hill	08083500	Elm	Jul 40	E8
Stamford	08084500	Paint	Jul 53	D8
Hubbard Creek	08086400	Hubbard	Sep 62	E8, E9
Graham	08088400	Salt	Mar 58	D9
Possum Kingdom	08088500	Brazos	Mar 41	E9
Palo Pinto	08090300	Palo Pinto	Apr 64	E9
Granbury	08090900	Brazos	Oct 68	E10
Pat Cleburne	08091900	Nolan	Apr 65	E10
Whitney	08092500	Brazos	Dec 51	E10, F10
Waco	08095550	Bosque	Feb 65	F10
Leon	08099000	Leon	Jan 55	E9
Proctor	08099400	Leon	Jan 63	E9, F9
Belton	08102000	Leon	Mar 54	F10
Stillhouse Hollow	08104050	Lampasas	Sep 66	F10, G10
Somerville	08109900	Yequa	Feb 66	G11
Mexia	08110300	Navasota	Jul 61	F11
Georgetown	08104650	Gabriel	Mar 80	G10
Granger	08105600	Gabriel	Jan 80	G10

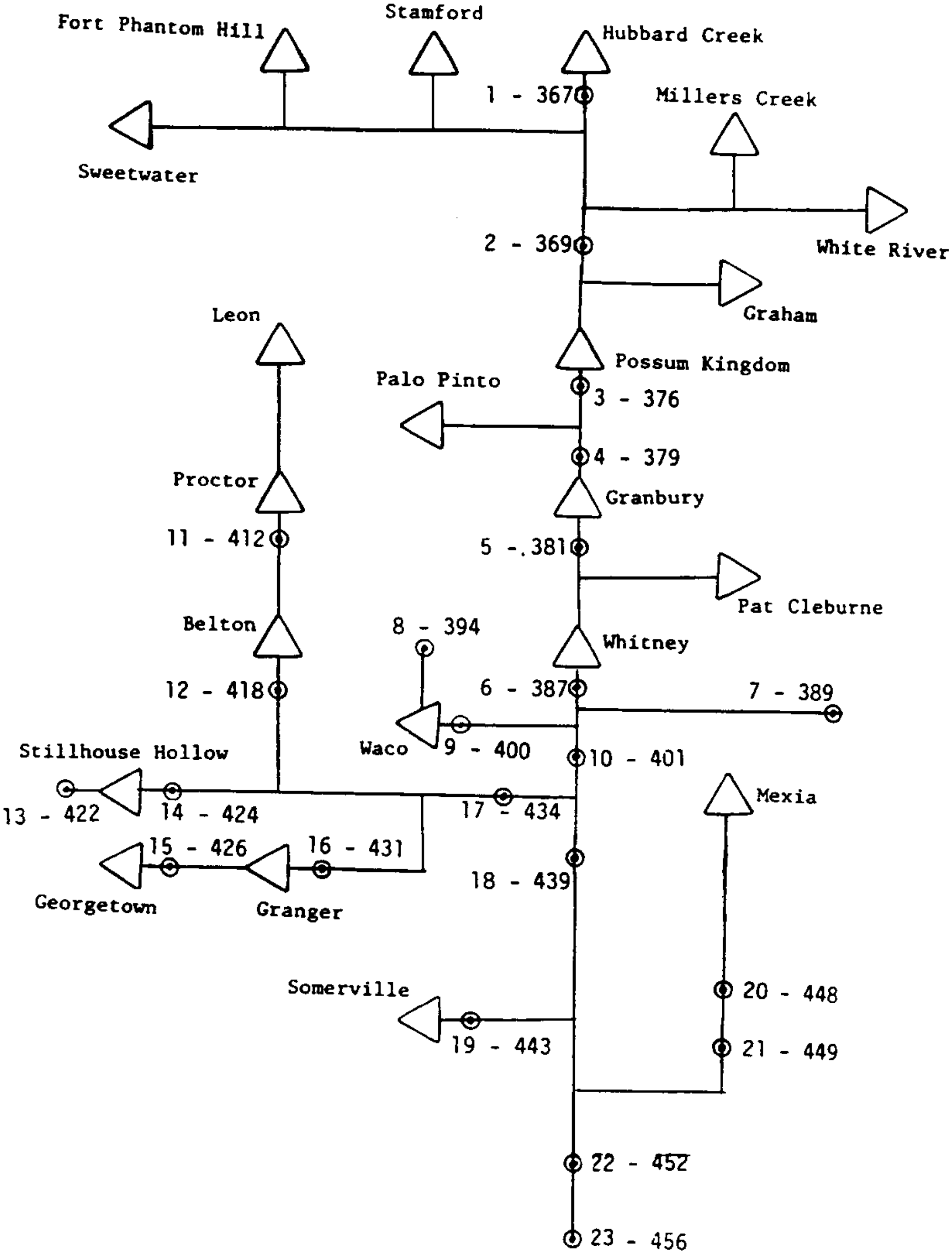


Figure 5.2 Reservoirs Included in Unregulated Flow Computations

water balance equation is rearranged to obtain the following correction factor to be added to the measured streamflow at downstream stations:

$$\text{Correction Factor} = I - R = S_2 - S_1 + E$$

A computer program was coded to manipulate the measured streamflow, reservoir content, and net evaporation rate data files and perform the required computations. Reservoir storage versus surface area tables were provided as input data. Evaporation was computed as the net evaporation rate multiplied by the average of the water surface areas at the beginning and end of the month.

The monthly flows at the Richmond gage (gage 23) were further adjusted by adding diversions measured at the BRA Canal A near Fulshear and Richmond Irrigation Company Canal near Richmond. The Richmond gage is the most downstream gage included in the analysis and the only gage affected by the canal diversions. These two canals are the only diversions included in the adjustments. These are the only canal gages in the Brazos River Basin included in TDWR Report 244 (Dougherty 1980).

TWC Naturalized Streamflow

The Water Use Section, Basin Modeling Unit, of the Texas Water Commission provided naturalized monthly streamflows for the period 1940 through 1976 at 22 of the 23 gaging stations. The gage on Aquilla Creek (7-387) was not included because the TWC naturalization process resulted in no changes from gaged streamflow at this location. The data for the selected stations were computed by manipulation of the water availability model data base. The water availability modeling studies, including streamflow naturalization, are described by the Texas Water Commission (TDWR 1981). The streamflow naturalization process included adjustments for all major reservoirs, 409 Soil Conservation Service flood retarding dams, water use, and return flows. Adjustments for reservoirs involved routing the streamflows through each reservoir using the water balance equation. Water use associated with the over 1700 water rights in the basin were considered. Gaps in the streamflow records were filled in using the MOSS-IV computer program.

Synthesized Streamflow

The period-of-record for each gaging station is indicated in Table 5.2. The Brazos River gage at Waco (gage 10) has flow measurements dating back to October 1898. Ten gages extend back to 1924 or before. All of the gages were reconstituted to cover the period January 1900 through December 1984, using the alternative computer programs HEC-4 and MOSS-IV. Although initial runs were made with HEC-4, MOSS-IV was later adopted as the program to be used in the study. These programs reconstitute missing monthly streamflows by a regression analysis based on flows at other stations during the current or preceding month. HEC-4 and MOSS-IV allow passes with up to 10 stations, with the regression analysis correlating all the stations included in a pass. In the final MOSS-IV run adopted for the simulation studies, the 23 stations were grouped into the following four passes for the purpose of the regression analyses to fill in missing streamflows: gages 1, 2, 3, 4, 5, 6, 8, 10, 17 (first pass); gages 8, 9, 10, 11, 12, 13, 14, 15, 16, 17 (second pass); gages 10, 17, 18, 19, 20, 21, 22, 23 (third pass); and gages 5, 6, 7, and 10 (fourth pass). Selected stations are included in more than one pass to relate the passes together.

The input data to the MOSS-IV program consisted of the TWC naturalized monthly streamflow for the period 1940 through 1976 and the TAMU unregulated streamflow for the period 1900 through 1939, for the 23 gage stations. MOSS-IV reconstituted missing data for the 1900 through 1939 period.

Comparison of Gaged, TAMU Unregulated, and TWC Naturalized Streamflow

The gaged monthly streamflows at Richmond (gage 23-456) are tabulated in Table 5.4. Gaged, TAMU unregulated, and TWC naturalized annual flows are compared in Tables 5.8, 5.9, and 5.10. TWC naturalized streamflows at the Richmond, Waco, and Cameron gages are presented in Tables 5.5, 5.6, and 5.7. Flow duration curves computed with the 1940 - 1976 monthly flows are plotted as Figures 5.6, 5.7 and 5.8. The flow duration curves are repeated showing only flows exceeded at least 30 percent of the time to more clearly differentiate between the alternative data sets. A detailed statistical analysis, not included in the present report, was performed to evaluate and compare the gaged, TAMU unregulated and TWC naturalized data sets for the 23 gaging stations. The TAMU unregulated and TWC naturalized streamflows are very similar, implying that most of the streamflow change is due to evaporation and storage effects of the major reservoirs in the basin, rather than water withdrawals for beneficial use.

Natural Streamflow Variability

Streamflow in the Brazos River Basin is highly variable and subject to extremes of floods and droughts. Consequently, reservoirs are required to provide flood protection and dependable water supplies. The last 20 years has been a period of relatively abundant precipitation and streamflow. Although record reservoir storage depletions occurred throughout the state in 1984, this year and the preceding 20 years had relatively abundant precipitation compared to weather conditions in the early 1960's, early 1950's, and earlier severe dry periods. Most of the reservoirs were constructed, and water demands have greatly increased, during the past 20 years. Consequently, the existing reservoir system, with present levels of water demand, has never been tested by a drought comparable to that of the 1950's or earlier severe dry periods.

Mean annual precipitation in the basin is tabulated in Table 5.11 for the period 1900 through 1984. The data was developed from the annual weather summaries for Texas published each year by the National Weather Service. Basin mean annual precipitation was computed as an arithmetic mean of values for precipitation stations located in the watersheds above the selected stream gages. The 41 precipitation gages with records of 50 years or longer, as listed in Table 5.12, were used to compute the annual means. The subbasin above the Waco streamflow gage contains 28 precipitation gages. The Little River subbasin above the Cameron streamflow gage contains 8 precipitation gages. The watershed above the Bryan gage includes these two subbasins plus three more precipitation gages in the incremental watershed below the Waco and Cameron streamflow gages. The Watershed above the Richmond gage includes all 41 precipitation gages, including two additional precipitation gages below the Bryan streamflow gage.

If a dry year is arbitrarily defined as a year with an annual precipitation less than 75 percent of the mean for the basin above the Richmond gage, the dry years were 1901, 1910, 1917, 1924, 1934, 1943, 1948, 1951, 1954, 1956, and 1963. The driest year on record, 1956, was followed by one of the largest floods on record in 1957.

Runoff rates vary greatly geographically over the basin, as well as over time, both seasonally and from year to year. Tables 5.13 and 5.14 illustrate the natural streamflow variability in the basin. Tables 5.13 and 5.14 are based on the Texas Water Commission naturalized streamflows which cover the period 1940 through 1976.

A portion of the extreme upper basin does not contribute to downstream flows. The noncontributing area is excluded from the drainage areas used to compute the mean annual streamflow, in inches of depth over the watershed above the gage, shown in Table 5.13. Mean annual runoff varies from 0.59 inches for the watershed above gage 369, which is located on the Brazos River just above Possum Kingdom Reservoir, to 6.19 inches at gage 448, which is located on the Navasota River below Limestone Reservoir.

Table 5.13 shows the range between extreme low and high annual naturalized flows at the selected gage stations. The early 1950's is indicated to be the low streamflow years during the 1940-1976 period covered by the data. Gage 401 on the Brazos River at Waco has a continuous record from 1899 to the present. As indicated by Table 5.13 the naturalized flow of 434,410 acre-feet (corresponding to a gaged flow of 412,650 acre-feet) in 1952 was the lowest annual flow during the 1940-1976 period at the Waco gage. However, measured annual flows at gage 401 of 421,440 acre-feet in 1910 and 303,920 acre-feet in 1917 are lower than the 1952 flow.

The records of gaged monthly flows indicate that the gages on the main stem of the Brazos River from Whitney Reservoir downstream to the coast and the gage on the Little River near Cameron have had no months of zero flow during their periods of record. The other gage stations each have several months of zero flow on record. The TWC naturalized streamflows include zero monthly flows for almost all of the gages.

The flood plain of the Brazos River between Whitney Dam and Richmond is underlaid by alluvial deposits that contain large amounts of groundwater. Cronin and Wilson (1967) estimated that the discharge of groundwater into the Brazos River between Waco and Bryan was about 0.3 to 0.55 cfs per mile. A rough estimate of 0.425 cfs per mile applied to the 350 river miles between Whitney Dam and the Richmond gage results in a total of 149 cfs or 108,000 acre-feet per year at the Richmond gage. This extremely approximate estimate of base flow can be compared with the mean and low flows of 6,400,580 acre-feet per year and 898,580 acre-feet per year at the Richmond gage, as tabulated in Table 5.9. Thus, most of the streamflow is direct runoff from precipitation rather than base flow from groundwater.

Table 5.14 illustrates the natural seasonal variability of streamflow. The monthly means for the TWC naturalized streamflows are tabulated as a percentage of annual means. Flows in May are several times higher than August flows.

Table 5.4
MEASURED STREAMFLOW AT RICHMOND GAGE

YEAR	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC	TOTAL
1923	79600	221000	435000	1400000	616000	406000	99100	45500	190000	296000	632000	1870000	6290200
1924	727000	894000	1380000	765000	632000	909000	88800	46100	108000	83800	41000	45100	5719800
1925	44100	34400	30900	27000	514000	52700	31900	42400	290000	991000	1120000	95800	3274200
1926	539000	186000	955000	2190000	1240000	462000	372000	272000	340000	383000	203000	701000	7843000
1927	292000	544000	679000	961000	421000	838000	378000	104000	58600	599000	81500	82400	5038500
1928	85500	318000	298000	214000	295000	815000	161000	264000	105000	37600	40800	231000	2864900
1929	328000	96100	296000	708000	1130000	2360000	322000	57500	393000	861 0	555000	97800	6429500
1930	214000	408000	238000	134000	2600000	582000	128000	58000	118000	916000	212000	935000	6543000
1931	713000	783000	867000	378000	416000	218000	96500	59500	45000	176000	152000	180000	4083000
1932	1750000	1470000	972000	165000	928000	425000	550000	124000	1150000	163000	68400	106000	7871400
1933	282000	270000	434000	220000	383000	330000	39700	153000	114000	57200	48400	34100	2365400
1934	330000	514000	787000	1330000	183000	35900	13600	8670	30800	37480	155000	229900	3655350
1935	207600	443500	197300	208800	3309000	1416000	415400	153000	561500	329000	285100	1213000	8739200
1936	201400	144500	118400	79580	1196000	832500	1087000	91160	453900	1443000	466200	784600	6898240
1937	850100	380700	582700	237700	108200	265200	115700	51590	120100	170000	177500	430700	3490190
1938	1140000	1047000	509100	1188000	1158000	605000	346000	355600	76700	48050	38300	40000	6551750
1939	165200	155100	158600	71260	542700	452800	201800	38010	44290	32820	34770	57790	1965140
1940	43750	150100	42590	192200	306300	641900	1307000	244500	107400	66170	1406000	3251000	7758910
1941	1188000	1357000	1587000	1054000	2507000	2089000	1041000	274700	303500	786100	664900	158300	13910500
1942	147100	103000	89300	2081000	1956000	1287000	333700	96710	819800	726300	410300	246500	8296710
1943	351300	167800	266200	317300	223000	226200	151900	107000	61510	89100	56190	91460	2108960
1944	677800	955000	1132000	338200	2804000	1029000	136000	66550	252200	83530	335800	791400	8600480
1945	1327000	927500	1285000	2493000	757800	561600	433900	445600	362600	478900	131900	490600	9695400
1946	695400	875200	1312000	511200	1601000	844900	213500	69690	175300	318100	1045000	565800	8227090
1947	1027000	323700	812400	433400	853900	357700	101800	363900	143800	57940	91760	213900	4781200
1948	120100	257300	360000	165500	282100	123700	184800	34960	68470	39400	34430	37140	1697900
1949	77590	241900	486100	767800	837700	490600	216300	62080	72840	277700	216900	277200	4023710
1950	285500	758000	181400	482300	402400	662700	169300	209900	263200	149100	54070	52900	3670770
1951	56340	66900	61220	74640	73860	248000	59300	51910	78360	48610	35070	37700	891910
1952	33380	54840	79170	334400	355700	212900	56160	36930	36260	12470	24780	230000	1466990
1953	275900	121500	245800	75020	1646000	113800	61120	49240	116000	212000	199500	553100	3668980
1954	138500	53020	27390	49330	435000	171800	53270	56940	24650	36700	51550	29510	1127660
1955	35790	239800	58940	268000	266500	349900	104600	74530	53520	670200	66630	48180	2236590
1956	59130	119500	64780	53170	318900	46790	44080	39130	35840	39530	76390	62780	960020
1957	42000	50790	223200	1075000	4747000	3472000	979000	201800	98530	1769000	1047000	504100	14208420
1958	585800	813900	853900	356200	1564000	295900	388800	114500	297200	252000	130200	104300	5756700
1959	86780	322500	133900	864600	525300	331700	253500	139200	77870	1455000	599500	657400	5447250
1960	1016000	706000	389300	212800	477600	416500	329100	110800	69540	468500	1058000	1603000	6857140
1961	2237000	1932000	867400	338800	174000	926400	985200	330500	753400	366500	367800	414800	9693800
1962	245800	217200	147100	112900	188000	304400	180500	272300	446400	300500	146400	380200	2941700
1963	224800	218300	110200	163600	80170	185800	119900	33800	34030	52400	63630	66370	1353000
1964	53810	117100	213900	97930	163200	148800	82900	33840	151200	181500	247900	167200	1659280
1965	482200	1016000	383200	437000	2668000	1187000	323400	227900	109000	128000	417500	481800	7861000
1966	238100	420900	401300	679300	2266000	325400	119500	228200	668200	310300	90010	84870	5822080
1967	71240	47400	33130	125500	174700	172900	84430	80180	76430	63930	274000	177600	1381440
1968	1116000	723200	931000	965000	2233000	1668000	21061000	167300	231900	194300	177000	552200	10009900
1969	159900	517100	788400	1281000	1454000	440100	172400	97220	116700	74810	146300	276800	5524730
1970	335000	290600	1369000	784200	619000	427500	91790	81410	179900	376600	102400	54490	4711890
1971	69620	38980	47800	56390	101800	52630	44130	157200	113200	257700	376800	757200	2073450
1972	482800	224900	135400	67900	473900	145700	106300	86780	59980	79400	308300	199100	2370460
1973	463900	512000	896500	1244000	917700	1421000	377900	165900	134300	1400000	581700	451500	8566400
1974	746500	458200	219100	126700	314000	72250	63400	88790	1181000	504100	1926000	901500	6601540
1975	698800	1302000	572400	611700	1403000	1264000	533100	259800	129100	107000	94590	109100	7084590
1976	103900	125000	151800	675800	1124000	649400	766400	181000	134600	342500	358600	1088000	5701000
1977	455700	1096000	489200	1909000	1216000	604500	123000	89460	103800	60320	58530	61960	6167470
1978	165300	237600	188400	53860	67660	135000	60420	104600	177200	41300	147600	141000	1519940
1979	640499	578999	777699	1109999	1618999	2037999	633799	395600	293200	116100	96430	186500	8385830
1980	446200	367700	161400	321000	954299	239900	98520	68390	69990	53160	51980	79350	2911890
1981	97900	106400	120400	91630	213800	1750999	706699	134100	251400	874499	912499	145100	5405430
1982	118600	110400	169300	319300	1218999	842399	786899	108700	61250	65190	138300	196800	4135140
1983	234400	642299	706699	306800	806099	379900	110500	226200	143400	60010	53630	111700	3770640
1984	64620	63340	183900	76160	123100	92870	80270	74090	44570	843699	447800	518400	2412720

Table 5.5
TWC NATURALIZED STREAMFLOW AT RICHMOND GAGE

YEAR	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC	TOTAL
1940	43976	150997	45001	209548	318990	657362	1320467	258867	112489	70380	1408473	3255069	7851618
1941	1189657	1358422	1591596	1266864	2856408	2117006	1171726	387614	320755	741664	633601	171345	13808657
1942	138664	106386	100112	2163586	1976882	1315929	349137	114780	870746	724499	410836	246702	8517257
1943	328192	115141	227930	313063	225381	274431	131331	80376	56736	89281	54389	88487	1984736
1944	675071	972129	1164008	380078	2870616	1087980	177003	71858	270827	122422	326727	782663	8901381
1945	1314261	918398	1373239	2577330	776318	592044	564652	433917	356608	562637	129236	476471	10075109
1946	656274	881757	1316512	511211	1626102	884193	213759	89761	324147	267807	1041066	593514	8406103
1947	980470	302440	818026	435876	1032983	348400	92893	343523	125338	78053	68988	230198	4877188
1948	97098	243492	355698	157975	319772	246313	282725	9911	53819	46964	33019	26318	1873102
1949	65005	242636	496706	799104	1119330	510606	207987	33181	106798	280284	197292	263316	4322245
1950	281871	754912	172117	541216	598156	662993	259970	198180	297482	123189	38680	31651	3960416
1951	18104	47982	61778	69729	196926	394752	28535	25522	71131	32519	24250	25599	996828
1952	24715	51635	79567	391628	471904	207097	40462	-10421	27166	12751	65309	251026	1612838
1953	287200	125812	267723	109659	1820737	101092	338656	1378[illegible]	124591	608415	227626	557612	4606973
1954	139906	55161	28822	160228	550552	153441	24656	56238	26721	43289	89671	33668	1362354
1955	38259	262026	84983	321477	636243	432482	145989	94662	238198	627362	68962	36240	2986883
1956	38665	100277	43026	48741	414157	48623	-30626	19805	23593	30546	58511	103265	898582
1957	11777	280832	234245	2084998	6287410	1832446	554077	179194	117941	1656314	1073391	473159	14984783
1958	559531	893872	792966	440331	1573516	320604	436016	115713	366806	232980	112817	87341	5932483
1959	63800	311416	119459	857249	565527	558958	314718	158669	70541	1727569	461646	666113	5875656
1960	1049794	677206	389198	262205	482585	441132	476921	119427	52093	635480	1009248	1573115	7158404
1961	2332307	2017644	723806	310738	213197	1144171	1037876	255303	801014	373201	401264	408124	10018645
1962	232641	198177	137245	131537	195089	576561	357268	155117	579444	301383	158028	359245	3381734
1963	184636	203507	103649	296241	264912	222023	90159	38831	44617	58332	128495	62861	1698264
1964	70544	192850	254870	168276	178774	212895	42589	73437	353925	123100	412293	126416	2209970
1965	489058	1107503	376944	488674	3612810	976685	165813	156363	176159	209707	406416	464739	8630871
1966	202307	424729	376946	1228295	2161466	346610	107390	360910	785750	283620	75531	60004	6412548
1967	73919	53112	67016	182236	258724	368964	218501	63639	178684	88152	269606	161037	1963592
1968	1786690	624448	1121785	962188	2413795	1837206	1008770	184476	267208	133814	214084	629642	11074102
1969	161086	595608	984395	1469572	1663197	298874	114790	131166	232134	175060	182772	406353	6405007
1970	302566	405031	1635968	687272	741261	340319	81085	47522	219236	401988	96630	61097	5019975
1971	56176	61461	70754	98688	241781	164659	285792	497591	243169	463751	282441	876670	3342931
1972	429865	257743	153056	114888	591795	181532	100823	209017	185217	189243	408604	179923	3001706
1973	562309	585689	987513	1406165	934616	1468424	396223	167279	188012	1452452	530471	434728	9113881
1974	802246	412033	204725	167651	355110	149465	81383	258747	1715264	960608	1948485	767572	7623188
1975	518270	1408973	478689	884386	1778513	1137465	536945	286317	173062	102862	90439	86118	7280038
1976	71536	110470	148333	882118	1272240	881466	785452	174678	239809	523725	378898	1131854	6400679

Table 5.6
TWC NATURALIZED STEAMFLOW AT WACO GAGE

YEAR	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC	TOTAL
1940	4103	9573	6687	109202	122246	450797	167106	255596	73907	15663	414227	409812	2038918
1941	134375	493213	286808	528895	1631087	897667	323943	305102	117806	690019	232153	59360	5700425
1942	69629	29245	29721	1409424	672850	582054	50531	55095	368698	528756	105658	71972	3973631
1943	42436	27952	76194	109517	87718	97994	14170	2402	25730	15365	4902	7910	512290
1944	36064	140026	150572	117736	808326	132363	56302	18845	67827	66631	28748	57763	1681202
1945	169093	296161	640325	930006	167339	174584	398180	33384	18813	198291	33851	43782	3103807
1946	92824	189999	212067	90397	251944	150916	20604	59370	265621	144018	202476	228975	1909210
1947	117357	68704	158826	146992	550557	96816	19986	8195	17990	47304	17829	98513	1349068
1948	31550	114594	82702	21474	133978	168896	173725	6587	24531	20709	11401	4881	795028
1949	9975	69028	101918	123914	757808	325907	56963	9875	103772	106366	31669	10213	1707407
1950	27218	119915	21537	139652	270255	76621	272217	132559	237624	51862	7922	6312	1363694
1951	-290	14605	10745	-3378	155195	306337	24177	28265	39219	5378	7918	1424	589597
1952	2142	6890	3817	103280	184177	-6188	6687	3979	9805	1544	51942	66335	434409
1953	21754	7919	65725	50316	359939	-12166	281381	105241	12400	298492	30717	10561	1232289
1954	5036	4333	3765	125901	456742	105845	20071	32283	13272	26581	38163	4378	836368
1955	3292	18343	27326	29814	477026	263339	79151	42595	343322	539310	27273	13804	1864593
1956	11354	9600	5251	18404	263663	26188	-4781	10430	16677	30139	34142	55729	476796
1957	3469	266946	55129	1307401	3386755	807002	134817	32267	42052	278538	318344	93552	6726271
1958	86494	113839	185813	207603	773218	79930	258961	55699	108254	16232	15645	15170	1928859
1959	10820	30817	14351	28484	88016	303632	156246	41768	24777	963973	61775	146979	1871637
1960	333802	151084	89132	97987	99621	40947	233016	31002	10464	283643	70291	190712	1631701
1961	584563	425927	152854	49599	59928	532188	421904	69613	95252	173792	153212	111556	2830387
1962	45516	28004	31778	48350	36060	445583	259065	121933	566880	171173	66932	67827	1889101
1963	23122	17612	23794	143462	169198	218903	25906	8988	17963	28227	66537	7286	750999
1964	23338	85970	69188	89164	41728	106652	-3886	40045	142551	16712	238524	25290	875277
1965	68303	243173	78904	87309	1289582	116328	21618	52603	76923	95199	66378	31196	2227415
1966	7576	48773	46042	626816	695993	125350	34465	141738	656136	95319	33640	17721	2529568
1967	15815	11479	21050	92103	74591	229430	188629	39540	93114	73070	37541	45401	921784
1968	644251	191799	589565	310405	934929	278953	238786	59097	23567	23326	36251	41542	3372471
1969	24215	50992	233933	297058	1101937	131979	37068	53285	177957	111090	69591	145494	2524598
1970	92231	139145	661773	221926	209223	68994	-4358	1730	46239	53325	2944	11926	1395099
1971	13668	20277	11998	44798	123944	110711	126908	369122	177821	426234	77277	371777	1884536
1972	146414	62907	31847	51965	143467	42113	44498	150842	153868	115137	172367	41895	1157339
1973	138024	134885	202346	515012	193553	449103	135290	67398	60610	109920	47377	23378	2076896
1974	50294	25602	25634	59866	50402	81092	34700	104100	470795	481376	556545	102800	2043226
1975	111211	433441	106639	319863	371656	290521	90249	70643	66270	12456	17818	7667	1898435
1976	8507	19855	20387	158980	234772	138549	303772	42528	127071	201404	97990	110790	1464606

Table 5.7
TWC NATURALIZED STREAMFLOW AT CAMERON GAGE

YEAR	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC	TOTAL
1940	4388	21762	5402	106948	118956	246884	402078	19386	8181	4586	506145	610241	2054956
1941	315147	455510	480003	373800	726577	362913	284331	63609	64541	91268	32561	31877	3282135
1942	23846	21362	19308	427215	430913	399963	50155	37508	364387	195116	105257	79760	2154788
1943	57605	38049	63879	80962	60671	21726	13368	5490	17995	14576	7584	11928	391832
1944	135389	250819	293809	105395	1069596	348395	61593	25529	56155	22821	52077	168097	2589675
1945	297651	273472	364959	728066	203110	199216	78377	36743	27722	109165	39130	91505	2449115
1946	139822	208039	286221	149336	297140	130625	28713	14321	69124	32108	196051	142491	1693990
1947	291221	104192	195156	143136	154322	50546	16168	10461	7379	4937	9113	16014	1002645
1948	11129	31184	29099	35675	76567	22878	35321	7103	10312	2578	1925	2991	266762
1949	15008	24935	79493	329562	131031	80173	19306	6838	3426	9248	8275	14088	721383
1950	7108	57257	10894	63452	68325	53879	33000	3715	62222	3689	1959	2454	367954
1951	3050	5574	18060	5764	34419	55116	1790	615	9706	1439	1184	1613	138330
1952	1802	2565	4934	66787	149146	40929	6460	869	502	366	9991	49078	333429
1953	36987	21598	31561	42979	310823	20736	14403	8410	23365	180943	29690	139698	861193
1954	12701	7657	4756	9198	34445	1128	143	447	1220	3309	21849	1601	98454
1955	4184	37800	15764	51580	177683	106830	21201	26523	31358	11883	1927	2315	489028
1956	4092	11168	2139	3215	159299	7162	1059	4949	1382	2323	17122	18281	232191
1957	4039	5408	52103	944297	925432	430507	66308	40896	21260	563207	218611	112749	3384816
1958	88857	459030	268836	136316	378538	122405	41796	15972	70034	26415	20837	16739	1645774
1959	14459	30561	17437	52320	41106	78974	53290	29136	27448	761404	154422	240569	1501125
1960	342389	232249	123205	80075	52231	27091	21415	13748	10839	324455	127847	422691	1778414
1961	558782	606079	230296	99409	62070	226197	220046	50633	119073	117796	58033	74814	2423227
1962	41782	38679	30501	61858	38340	88158	35474	13353	77928	63142	55630	60798	605643
1963	20599	45822	21615	26597	76886	26840	17267	5780	9874	15434	26844	6159	299717
1964	13559	33177	50979	69129	47606	125682	17912	31909	177326	38855	116271	34986	757591
1965	235010	371593	144710	116717	1375818	185895	66700	43259	62373	61899	178655	130817	2973446
1966	71354	125933	98675	383795	299451	87771	26374	83118	153036	39694	21201	19072	1409473
1967	16627	13240	15629	29984	97668	55167	22306	9471	35639	32376	85747	49275	463129
1968	743214	179911	418555	230663	479554	239561	202423	39774	33630	14990	31390	60004	2673668
1969	26100	77689	127470	334914	263767	58127	27962	37194	21084	47719	32543	101581	1156140
1970	83835	167589	514247	172828	240240	130807	29983	18812	80362	48478	13505	14566	1513261
1971	13626	13560	27307	35133	65310	35661	166003	58750	18516	90487	54781	154422	733555
1972	75479	47453	28559	24840	86488	48580	20984	12523	8518	68808	47472	32950	502654
1973	109339	101142	146974	199863	159652	92215	70970	17947	37124	293125	112373	47977	1388700
1974	78362	44100	34646	22724	118619	27082	21845	136335	286631	245973	397204	121340	1534861
1975	126045	408957	128671	146516	590059	265944	134068	69101	32022	25301	16988	18897	1962568
1976	9078	18393	26734	277346	240457	98781	247854	46316	45202	77998	67029	172838	1324026

Table 5.8
COMPARISON OF ANNUAL FLOWS AT RICHMOND GAGE

Year	Annual Flow in acre-feet			Percent of Gaged	
	Gaged	TAMU Unregulated	TWC Naturalized	TAMU Unregulated	TWC Naturalized
1940	7,758,910	7,410,388	7,851,618	95.5	101.2
1941	13,910,500	14,346,378	13,806,657	103.1	99.3
1942	8,296,710	8,505,618	8,517,257	102.5	102.7
1943	2,108,960	2,106,135	1,984,736	99.9	94.1
1944	8,600,480	8,878,290	8,901,381	103.2	103.5
1945	9,695,400	10,058,334	10,075,109	103.7	104.0
1946	8,227,090	8,886,366	8,406,103	108.0	102.8
1947	4,781,200	5,381,676	4,877,188	112.6	102.0
1948	1,697,900	1,892,009	1,873,102	111.4	110.3
1949	4,023,710	4,064,956	4,322,245	101.0	107.4
1950	3,670,770	4,426,907	3,960,416	121.0	107.9
1951	891,910	1,042,432	996,828	116.9	111.8
1952	1,466,990	1,648,562	1,612,838	112.4	110.0
1953	3,668,980	4,419,181	4,606,973	120.4	126.1
1954	1,127,660	1,418,617	1,362,354	126.0	121.0
1955	2,236,590	2,802,870	2,986,883	125.3	134.0
1956	960,020	842,231	898,582	88.0	93.6
1957	14,209,420	13,825,945	14,984,783	97.3	106.0
1958	5,756,700	5,909,958	5,932,483	103.1	103.1
1959	5,447,250	5,836,004	5,875,656	107.1	108.1
1960	6,857,140	7,110,624	7,158,404	104.1	104.4
1961	9,693,800	9,901,227	10,018,645	102.1	103.4
1962	2,941,700	3,590,161	3,381,734	122.0	115.1
1963	1,353,000	1,551,270	1,698,264	115.1	126.0
1964	1,659,280	2,057,165	2,209,970	124.1	133.2
1965	7,861,000	8,860,428	8,630,871	114.0	110.8
1966	5,822,080	6,311,361	6,412,548	108.4	110.1
1967	1,381,440	1,794,160	1,963,592	130.1	142.1
1968	10,009,900	11,030,169	11,074,102	110.2	111.0
1969	5,524,730	6,285,600	6,405,007	114.1	116.0
1970	4,711,890	5,083,781	5,019,975	108.1	107.0
1971	2,073,450	3,420,179	3,342,931	165.1	161.2
1972	2,370,460	3,058,040	3,001,706	129.0	127.0
1973	8,566,400	9,078,366	9,113,881	106.1	106.4
1974	6,601,540	7,524,622	7,823,188	114.1	119.0
1975	7,084,590	7,093,489	7,280,038	100.1	103.1
1976	5,701,000	6,308,629	6,400,579	111.1	112.3
1977	6,167,470	6,396,303	-	104.0	-
1978	1,519,940	2,267,881	-	149.2	-
1979	8,385,830	8,864,448	-	106.0	-
1980	2,911,890	3,940,466	-	135.3	-
1981	5,405,430	6,337,486	-	117.2	-
1982	4,135,140	4,359,863	-	105.4	-
1983	3,770,640	4,298,145	-	114.1	-
1984	2,412,720	3,110,466	-	129.1	-

Table 5.9
COMPARISON OF ANNUAL FLOWS AT WACO GAGE

Year	Annual Flow in acre-feet			Percent of Gaged	
	Gaged	TAMU Unregulated	TWC Naturalized	TAMU Unregulated	TWC Naturalized
1940	2,003,570	2,036,267	2,038,918	102.0	102.1
1941	4,965,660	5,732,670	5,700,425	115.4	115.1
1942	3,831,550	3,943,540	3,973,631	103.0	104.0
1943	738,920	500,669	512,290	68.1	69.3
1943	1,472,020	1,651,409	1,681,202	112.2	114.2
1945	2,835,030	3,075,364	3,103,807	109.1	110.1
1946	1,808,160	1,885,563	1,909,210	104.3	106.1
1947	1,361,740	1,338,830	1,349,068	98.3	99.1
1948	737,470	787,502	795,028	107.1	108.1
1949	1,540,300	1,647,823	1,707,407	107.1	111.0
1950	1,197,430	1,352,578	1,363,694	113.1	114.1
1951	610,680	582,360	589,597	95.4	97.0
1952	412,650	430,742	434,409	104.4	105.3
1953	432,510	1,224,589	1,232,289	283.1	285.0
1954	761,420	814,349	836,368	107.1	110.0
1955	1,424,510	1,798,487	1,864,593	126.3	131.1
1956	649,280	453,840	476,796	70.1	73.4
1957	6,151,850	6,657,818	6,726,271	108.2	109.3
1958	1,864,540	1,899,938	1,926,859	102.1	103.3
1959	1,572,870	1,832,874	1,871,637	117.0	119.1
1960	1,459,370	1,604,427	1,631,701	110.0	112.0
1961	2,639,660	2,783,641	2,830,387	105.5	107.2
1962	1,627,110	1,858,597	1,889,101	114.2	116.1
1963	670,760	684,175	750,999	102.1	112.1
1964	582,220	817,981	875,277	140.5	150.3
1965	1,680,290	2,192,212	2,227,415	130.5	133.1
1966	2,139,400	2,485,294	2,529,568	116.2	118.2
1967	626,760	863,368	921,764	138.1	147.1
1968	3,006,640	3,357,044	3,372,471	112.1	112.2
1969	1,936,150	2,492,019	2,524,598	129.0	130.4
1970	1,311,110	1,533,267	1,395,099	117.0	106.4
1971	1,042,860	2,092,884	1,864,536	201.1	179.1
1972	802,910	1,283,166	1,157,339	160.0	144.0
1973	1,911,350	2,122,328	2,076,896	111.0	109.1
1974	1,339,000	1,918,892	2,043,226	143.3	153.1
1975	1,721,810	1,816,234	1,898,435	105.5	110.3
1976	1,057,090	1,504,459	1,464,606	142.3	139.1
1977	1,861,470	2,088,229	-	112.2	-
1978	340,850	1,147,901	-	337.1	-
1979	1,479,820	1,667,057	-	113.1	-
1980	563,450	1,287,423	-	228.5	-
1981	1,974,480	2,522,094	-	128.0	-
1982	1,269,840	2,504,606	-	197.2	-
1983	406,130	1,517,461	-	374.0	-
1984	303,070	772,127	-	255.0	-

Table 5.10
COMPARISON OF ANNUAL FLOWS AT CAMERON GAGE

Year	Annual Flow in acre-feet			Percent of Gaged	
	Gaged	TAMU Unregulated	TWC Naturalized	TAMU Unregulated	TWC Naturalized
1940	2,054,350	2,054,350	2,054,956	100.0	100.0
1941	3,280,800	3,280,800	3,282,135	100.0	100.0
1942	2,150,180	2,150,180	2,154,788	100.0	100.2
1943	389,420	389,420	391,832	100.0	101.0
1944	2,584,280	2,584,280	2,589,675	100.0	100.2
1945	2,443,240	2,443,240	2,449,115	100.0	100.2
1946	1,689,000	1,689,000	1,693,990	100.0	100.3
1947	998,350	998,350	1,002,645	100.0	100.4
1948	261,030	261,030	266,762	100.0	102.2
1949	712,810	712,810	721,383	100.0	101.2
1950	363,350	363,350	367,954	100.0	101.3
1951	133,230	133,230	138,330	100.0	104.0
1952	327,952	327,952	333,429	100.0	102.1
1953	835,610	835,610	861,193	100.0	103.1
1954	73,087	92,731	98,454	127.1	135.0
1955	274,780	467,077	489,028	170.1	178.1
1956	216,220	216,685	232,191	100.2	107.4
1957	3,244,730	3,363,659	3,384,816	104.1	104.3
1958	1,614,040	1,635,853	1,645,774	101.4	102.1
1959	1,450,690	1,479,590	1,501,125	102.1	103.5
1960	1,740,640	1,764,633	1,778,414	101.4	102.2
1961	2,385,510	2,407,549	2,423,227	101.0	102.1
1962	547,420	586,013	605,643	107.0	111.0
1963	201,030	257,833	299,717	128.3	149.1
1964	647,770	711,644	757,591	110.1	117.1
1965	2,905,700	2,930,402	2,973,446	101.1	102.3
1966	1,331,540	1,366,925	1,409,473	103.1	106.1
1967	379,370	390,906	463,129	103.0	122.1
1968	2,284,140	2,609,875	2,673,668	114.3	117.1
1969	1,012,770	1,103,290	1,156,140	109.0	114.2
1970	1,424,410	1,464,031	1,513,251	103.1	106.2
1971	427,860	612,031	733,555	143.0	171.4
1972	378,960	455,173	502,654	120.1	132.6
1973	1,142,550	1,341,895	1,388,700	117.4	122.0
1974	1,188,100	1,460,675	1,534,861	123.0	129.2
1975	2,061,360	1,906,154	1,962,568	92.5	95.2
1976	1,195,070	1,284,759	1,324,026	108.1	111.1
1977	1,507,640	1,541,994	-	102.3	-
1978	192,960	125,435	-	65.0	-
1979	1,594,690	1,834,435	-	115.0	-
1980	505,490	587,996	-	116.3	-
1981	1,171,790	1,415,279	-	121.1	-
1982	506,720	552,751	-	109.1	-
1983	579,470	630,770	-	109.1	-
1984	309,450	376,355	-	122.0	-

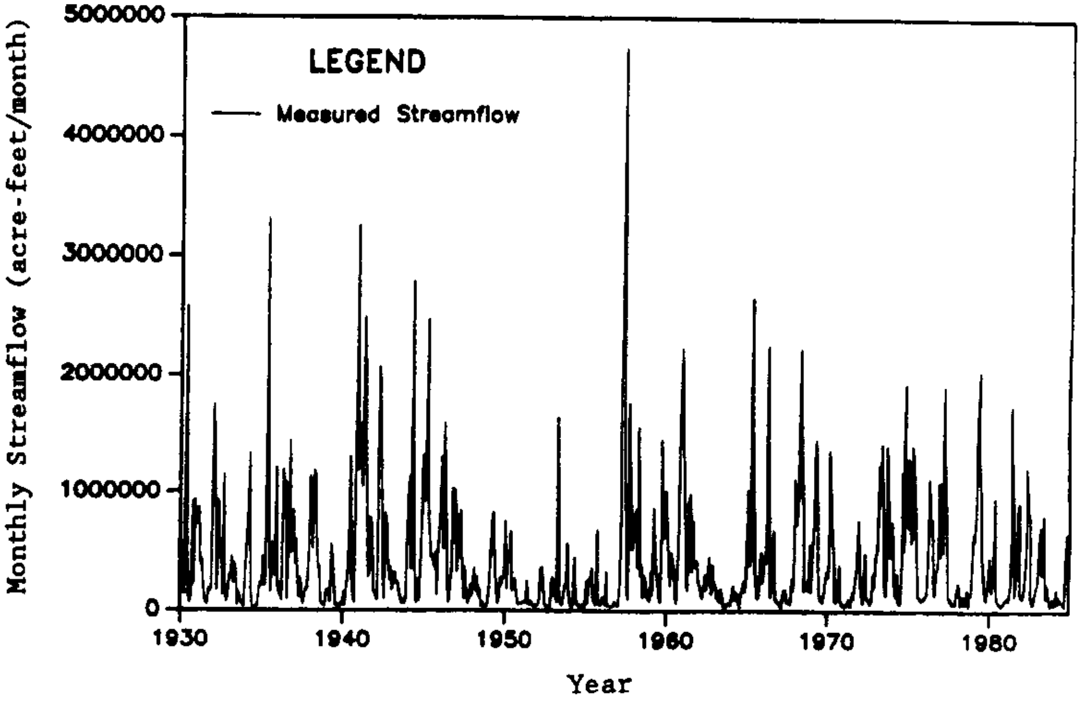


Figure 5.3 Monthly Streamflow Hydrograph at Richmond Gage

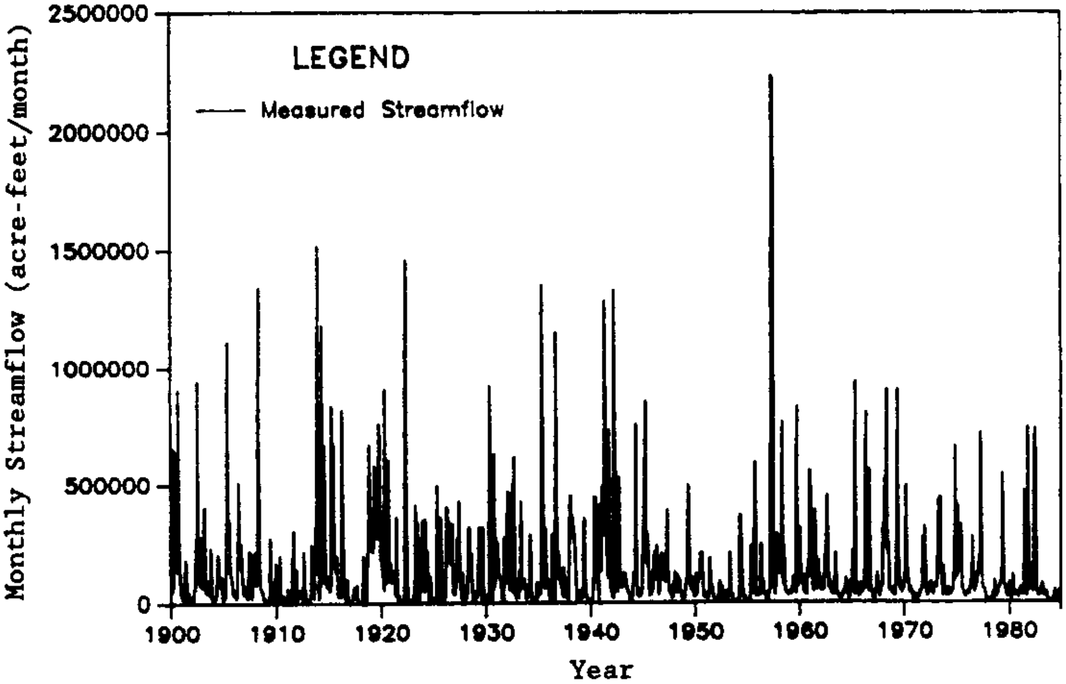


Figure 5.4 Monthly Streamflow Hydrograph at Waco Gage

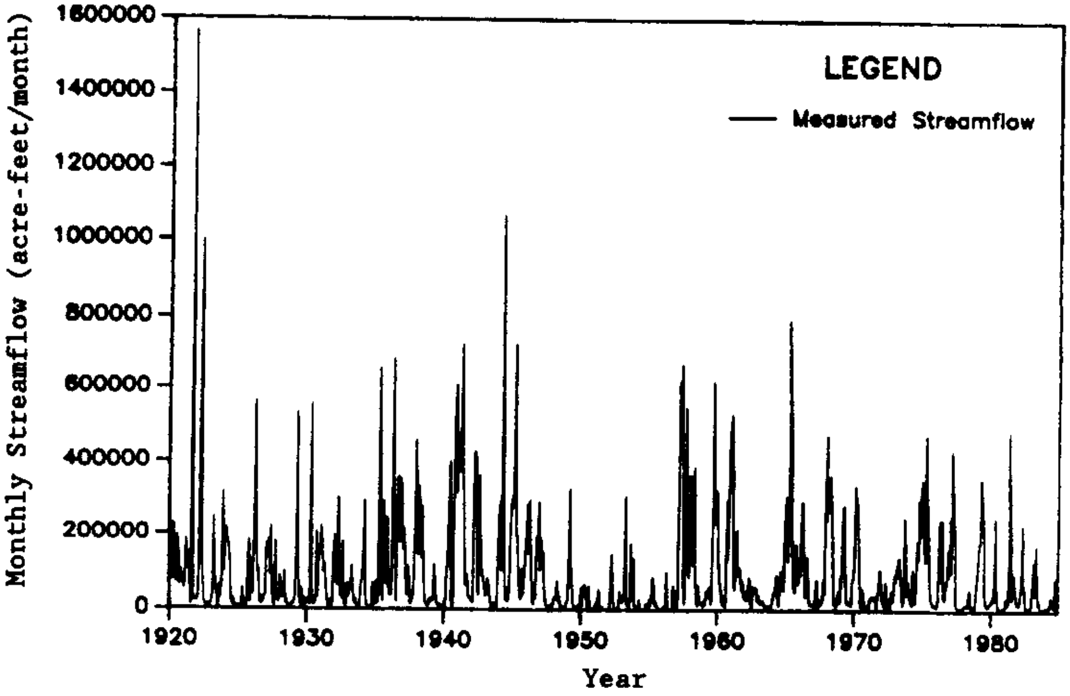
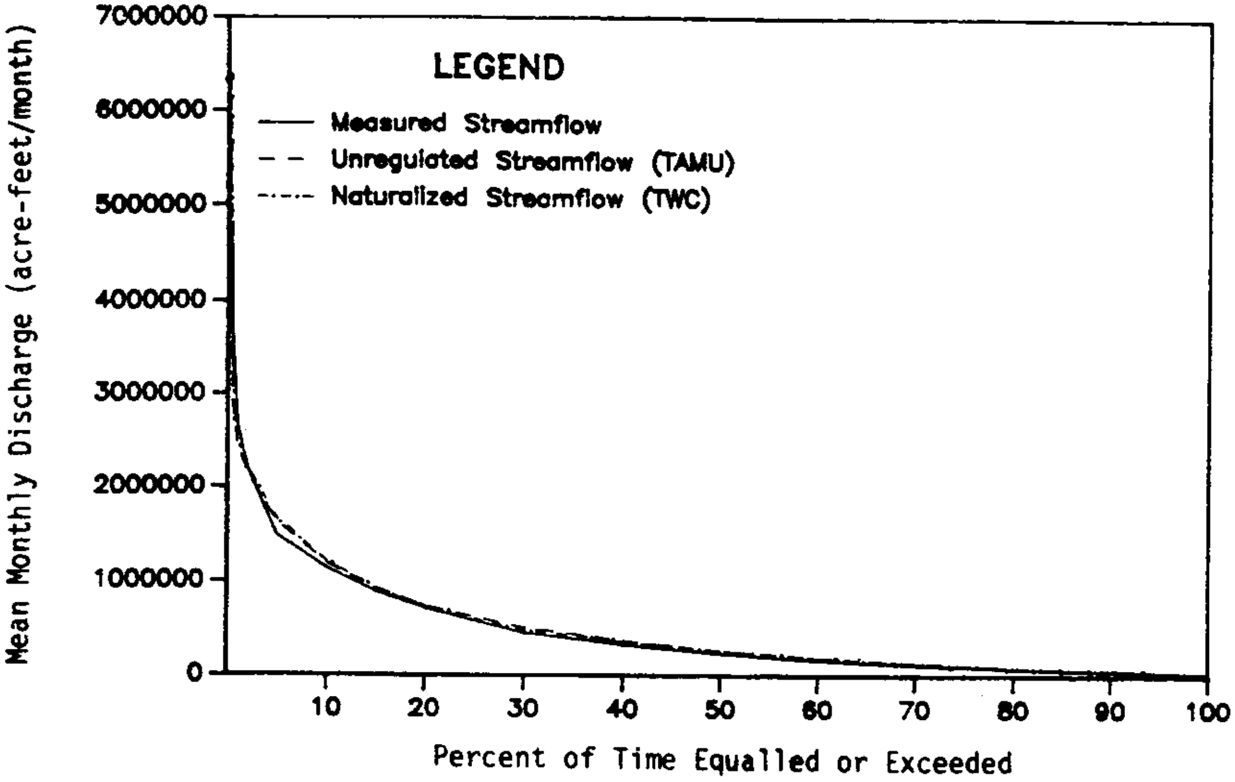


Figure 5.5 Monthly Streamflow Hydrograph at Cameron Gage



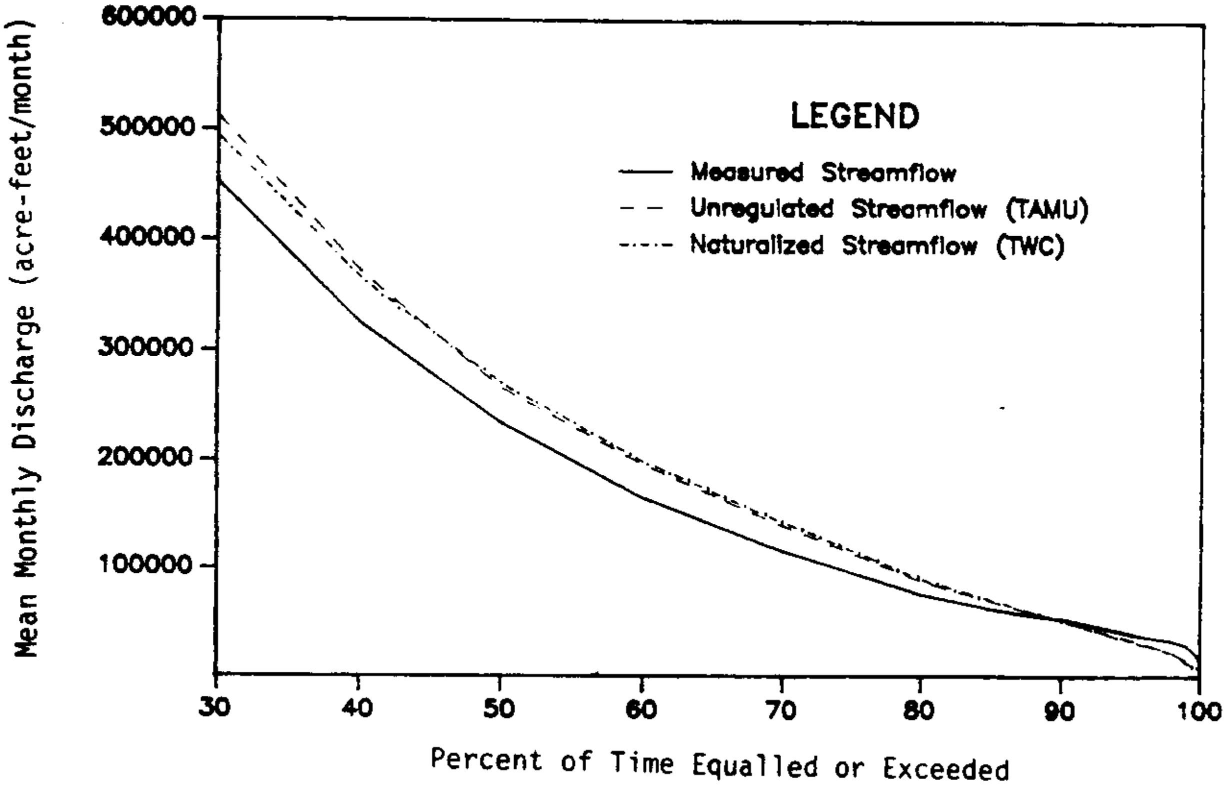


Figure 5.6 Flow Duration Curves at Richmond Gage

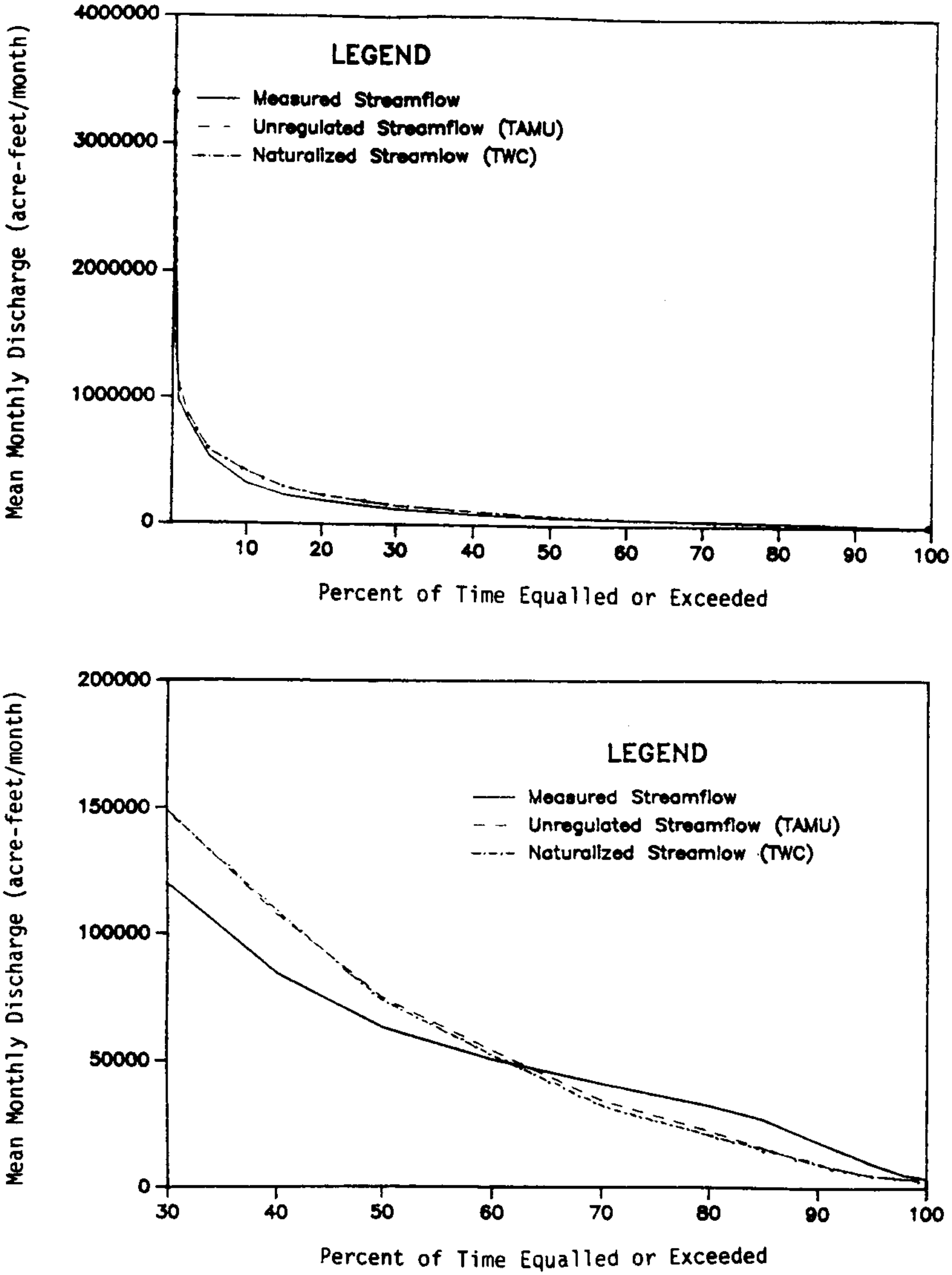
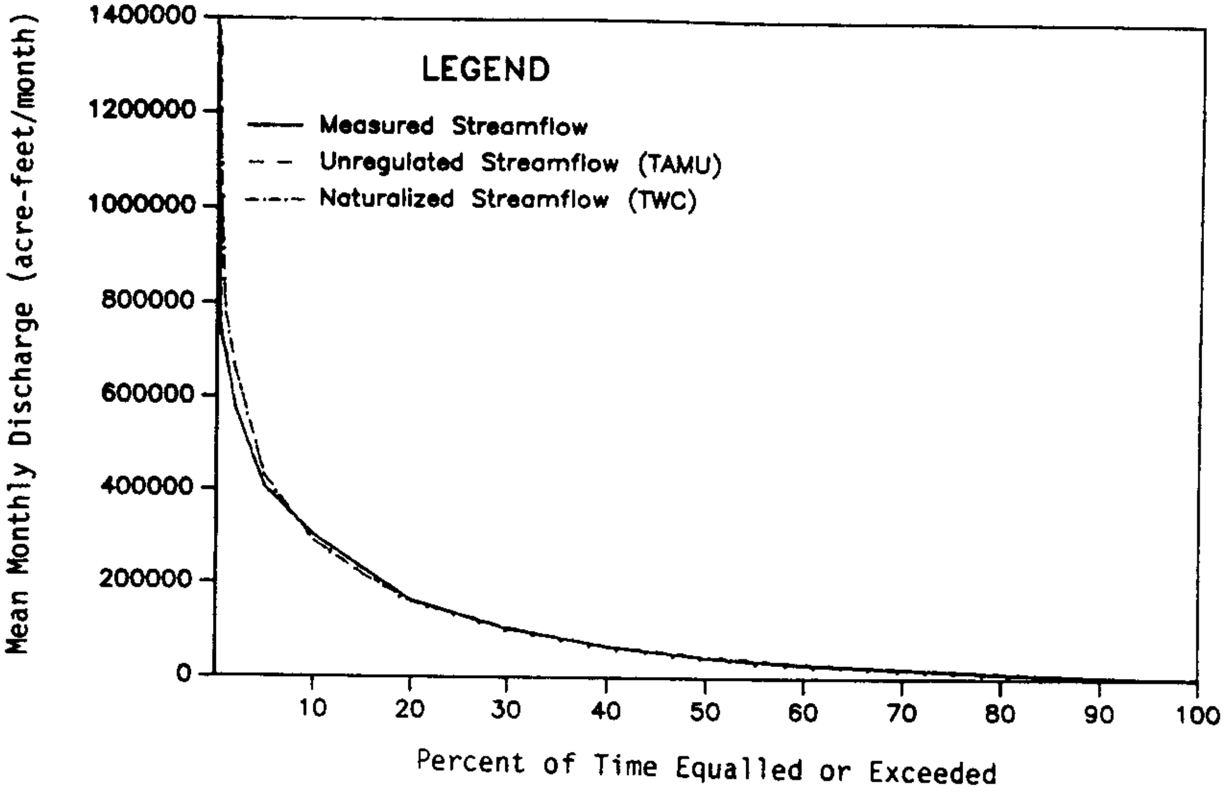


Figure 5.7 Flow Duration Curves at Waco Gage



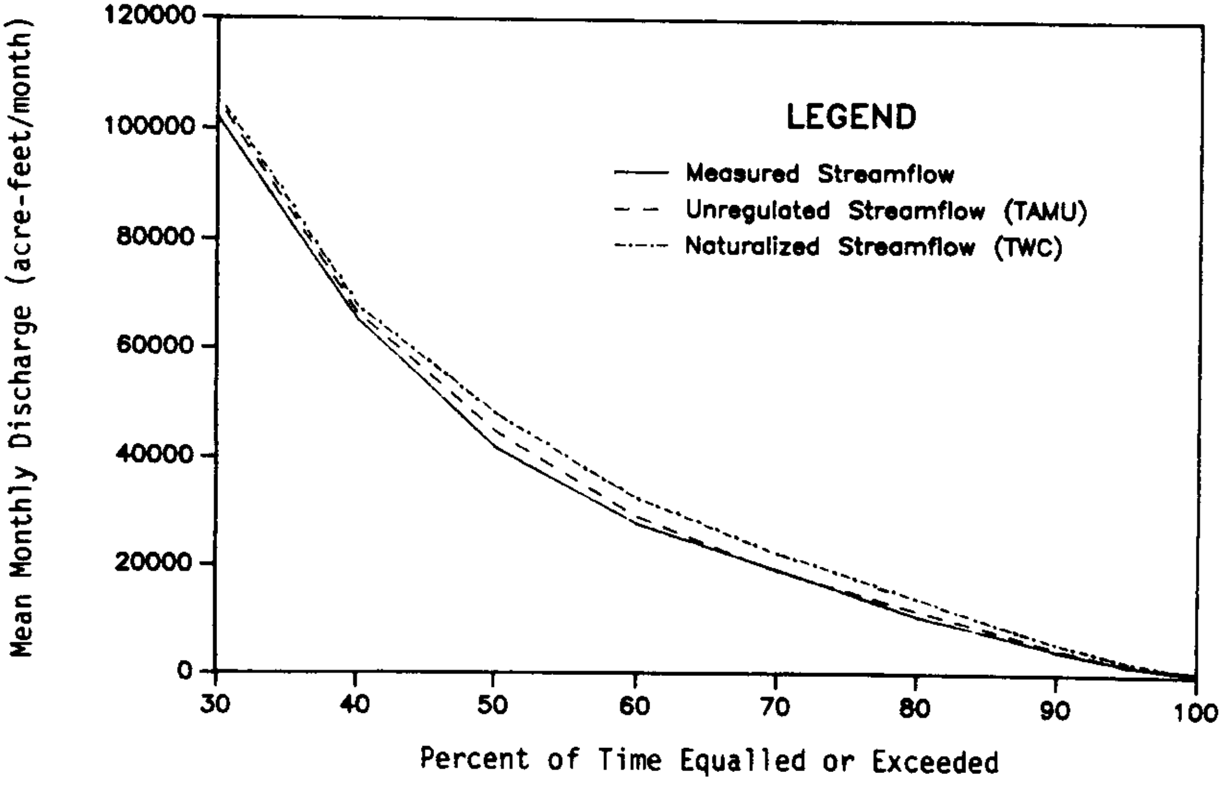


Figure 5.8 Flow Duration Curves at Cameron Gage

Table 5.11
MEAN ANNUAL PRECIPITATION

(INCHES)

	Watershed Above Stream Gage At			
Year	Waco	Cameron	Bryan	Richmond
1900	37.42	35.47	38.88	41.83
1901	17.83	15.80	17.76	18.23
1902	33.53	27.97	34.16	35.83
1903	27.54	31.55	30.38	31.59
1904	28.20	32.44	29.44	30.74
1905	44.03	37.13	44.10	44.74
1906	34.90	28.62	33.47	33.58
1907	30.22	32.42	33.16	35.01
1908	35.79	32.61	36.05	36.41
1909	21.89	21.18	22.84	23.31
1910	18.38	21.72	20.69	21.02
1911	27.99	25.38	27.57	28.75
1912	22.32	22.65	23.03	23.54
1913	32.75	39.76	35.10	36.25
1914	36.42	35.04	36.70	37.69
1915	31.67	27.00	31.51	31.92
1916	23.09	25.38	23.94	24.36
1917	14.86	15.03	15.35	15.51
1918	23.46	23.21	24.29	24.76
1919	39.70	44.58	41.81	44.02
1920	32.91	35.70	34.00	35.01
1921	21.06	25.36	23.81	25.53
1922	24.79	32.25	28.33	29.80
1923	31.98	35.11	33.46	35.39
1924	18.83	20.83	20.16	21.08
1925	21.23	22.33	21.59	22.49
1926	32.91	32.68	33.89	34.99
1927	22.24	28.91	25.08	25.89
1928	22.79	26.15	24.04	24.69
1929	22.44	26.88	24.47	26.04
1930	25.00	29.41	26.85	27.44
1931	23.74	31.49	25.67	26.20
1932	33.96	37.80	35.31	35.43
1933	21.07	25.00	22.32	23.01
1934	16.47	23.75	19.47	20.94
1935	31.15	36.33	33.49	34.58
1936	25.67	35.89	28.73	29.34
1937	22.56	28.99	25.03	25.34
1938	24.55	30.67	26.42	26.94
1939	20.34	26.09	22.15	22.30
1940	25.87	41.81	30.81	31.87
1941	43.53	37.80	42.33	43.41
1942	28.89	39.62	31.75	32.03
1943	17.10	21.53	18.85	19.81
1944	29.08	38.15	32.89	33.64
1945	25.16	37.61	29.53	30.95
1946	26.32	35.86	29.39	30.89
1947	21.82	20.66	22.58	23.58
1948	16.70	21.99	18.47	18.72
1949	29.10	32.57	30.06	31.57
1950	24.12	25.17	24.37	24.68
1951	18.50	22.91	19.67	20.41
1952	18.25	24.60	20.73	21.72
1953	21.03	30.75	24.33	25.32
1954	15.97	16.19	16.24	16.45
1955	22.90	28.08	24.76	25.11
1956	12.35	17.70	13.99	14.44
1957	36.65	46.15	39.88	40.40
1958	25.00	32.22	27.28	27.87
1959	28.09	34.09	30.72	31.66
1960	26.25	33.81	28.88	30.18
1961	30.54	36.08	32.47	33.53
1962	26.35	27.11	26.77	27.13
1963	20.78	20.33	20.65	20.79
1964	22.31	31.91	25.16	25.74
1965	25.75	35.32	29.48	30.45
1966	24.29	28.76	26.31	26.73
1967	22.83	28.10	24.75	24.97
1968	29.41	39.97	32.93	34.24
1969	31.49	29.49	31.30	31.56
1970	19.14	28.66	21.98	22.89
1971	27.61	31.27	29.04	29.28
1972	25.70	24.86	25.88	26.38
1973	28.72	33.78	31.56	32.19
1974	28.47	34.18	30.68	31.09
1975	24.49	28.67	26.18	26.59
1976	26.09	33.43	28.90	28.61
1977	20.51	22.80	21.86	22.15
1978	23.16	25.89	24.29	24.77
1979	26.68	35.06	29.83	30.87
1980	23.40	27.50	24.42	24.84
1981	27.98	30.56	29.81	30.61
1982	27.63	28.61	28.26	28.64
1983	22.52	23.81	23.93	24.51
1984	24.52	27.21	26.11	26.45
1900-1984 mean	25.89	29.64	27.58	28.37
1940-1984 mean	24.96	30.06	26.89	27.55

Table 5.12
PRECIPITATION GAGES

Precipitation Gage	County	Watershed Above Stream Gage	Record Began
Friona	Parmer	Waco	1928
Muleshoe 1	Bailey	Waco	1922
Dimmit	Castro	Waco	1923
Plainview	Hale	Waco	1909
Lubbock WSFOAP	Lubbock	Waco	1912
Tahoka	Lynn	Waco	1929
Crosbyton	Crosby	Waco	1917
Munday	Knox	Waco	1916
Post 3 ENE	Garza	Waco	1913
Aspermont 1E	Stonewall	Waco	1909
Seymour	Baylor	Waco	1907
Stamford	Jones	Waco	1912
Rotan	Fisher	Waco	1926
Hamlin	Jones	Waco	1912
Roscoe	Nolan	Waco	1936
Abilene WSOAP	Taylor	Waco	1899
Throckmorton	Throckmorton	Waco	1924
Albany	Shackleford	Waco	1902
Graham	Young	Waco	1905
Breckenridge	Stephens	Waco	1924
Weatherford	Parker	Waco	1899
Dublin	Erath	Waco	1899
Hico	Hamilton	Waco	1911
Hillsboro	Hill	Waco	1904
Waco WSOAP	McLennan	Waco	1899
Cleburne	Johnson	Waco	1914
Rainbow	Somerville	Waco	1935
Hewitt 1 SE	McLennan	Waco	1899
Putnam	Callahan	Cameron	1912
Eastland	Eastland	Cameron	1912
Comanche	Comanche	Cameron	1925
Hamilton 1NW	Hamilton	Cameron	1916
Gatesville	Coryell	Cameron	1903
Cameron	Milam	Cameron	1909
Taylor	Williamson	Cameron	1902
Lampasas	Lampasas	Cameron	1899
Mexia	Limestone	Bryan	1905
Temple	Bell	Bryan	1899
Marlin 3NE	Falls	Bryan	1933
Brenham	Washington	Richmond	1899
Sealy	Austin	Richmond	1911

Table 5.13
NATURALIZED ANNUAL STREAMFLOW DATA
TWC Naturalized Streamflow (1940-1976)

Reservoir (R) or Gage (G)	Gage Number	Mean Annual Flow		Annual Extremes (ac-ft)		Year	
		inches	acre-feet	Low	High	Low	High
Hubbard R	367	1.69	98,310	698	385,340	1952	1941
South Bend G	369	0.59	711,940	55,080	3,267,090	1952	1941
Possum Kingdom R	376	0.68	861,520	69,200	3,686,376	1952	1957
Granbury R	381	0.85	1,166,340	134,000	4,783,570	1952	1957
Whitney R	387	1.21	1,755,920	370,320	6,475,600	1952	1957
Aquilla R	389	5.27	86,620	4,140	213,110	1963	1968
Clifton G	394	2.87	148,200	11,540	503,240	1954	1941
Waco R	400	3.89	343,140	29,620	1,130,140	1963	1941
Waco G	401	1.23	1,933,700	434,410	6,726,270	1952	1957
Proctor R	412	1.71	114,800	22,540	400,140	1948	1941
Belton R	418	2.74	518,150	21,810	1,531,590	1954	1941
Stillhouse R	424	3.57	251,240	17,710	672,770	1951	1968
Georgetown R	426	4.95	65,470	-0-	134,310	1956	1941
Granger R	431	4.44	174,980	2,000	446,820	1956	1957
Cameron G	434	3.53	1,328,640	98,450	3,384,820	1954	1957
Bryan G	439	1.90	4,006,580	787,590	11,779,920	1956	1957
Somerville R	443	4.15	223,060	10,010	549,420	1951	1968
Limestone R	448	6.19	319,440	8,790	677,230	1963	1976
Hempstead G	452	2.28	5,343,580	929,800	13,942,180	1956	1957
Richmond G	456	2.67	6,400,580	898,580	14,984,780	1956	1957

Table 5.14
MEAN MONTHLY STREAMFLOW AS A PERCENT OF ANNUAL MEAN
TWC Naturalized Streamflow (1940-1976)

Average Monthly Streamflow as a Percentage of Mean Annual Streamflow											
Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Brazos River at Waco (gage 401)											
4.5	5.8	6.2	12.3	24.5	11.8	6.6	3.7	6.8	9.1	4.9	3.9
Little River at Cameron (gage 434)											
8.2	9.3	9.0	12.5	20.0	9.4	5.2	2.1	4.2	7.4	5.9	6.7
Brazos River at Richmond (gage 456)											
7.6	8.2	8.2	10.9	20.3	10.8	5.8	2.8	4.8	6.8	6.3	7.5

CHAPTER 6
HYDROLOGIC FIRM YIELD

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 precise textbook definition of firm yield can be formulated for a simple river basin with one reservoir and one diversion location. However, for a complex multiple reservoir, multiple user system, firm yield must be defined in terms of the basic assumptions and approaches used in handling various complicating factors in the simulation. Firm yields are presented in this chapter for alternative conditions of sedimentation and alternative approaches for considering multiple reservoir interactions. The firm yields are based on physical reservoir characteristics and historical period-of-record hydrology, without consideration of water rights, return flows, and water quality constraints. Firm yields were computed for 13 reservoirs. The impacts of the numerous other smaller reservoirs in the basin on the firm yield supplied by the 13 reservoirs were neglected.

The term "hydrologic" firm yield is used here to imply that water rights are not considered in the computations. Firm yields are recomputed in Chapter 8 subject to constraints imposed by senior water rights. The impacts on the 13 reservoirs of both storage capacity and diversions throughout the basin are reflected in the firm yields presented in Chapter 8.

Firm yield computations consist of iteratively simulating a single reservoir or multireservoir system assuming alternative diversion or release rates. The firm yield is the diversion or release rate which will just empty the reservoir(s). Both HEC-3 and HEC-5 were used in the present study to compute firm yields. HEC-3 and HEC-5 contain optimization routines which automatically perform the iterative search for the firm yield. HEC-3 allows releases from multiple reservoirs, as required to supply flows at a downstream control point, to develop a system firm yield. Unlike HEC-3, the HEC-5 optimization capabilities do not include computation of system firm yields. The firm yield optimization routine in HEC-5 is limited to individual reservoirs. Upstream reservoirs can be modeled with specified diversions. In addition to the single-run optimization options, firm yield can be computed with either HEC-3 or HEC-5 by multiple-run trial-and-error simulations with alternative yield levels.

Reservoir yield versus reliability relationships are also presented in this chapter. Period reliability is represented here by the percentage of the months during the 85-year simulation period for which a specified yield level can be met without a shortage. Volume reliability is the percentage of the total target diversion volume over the 85-year simulation period which is actually supplied. Firm yield and lesser yields, by definition, have period and volume reliabilities of 100%. Yields greater than firm yield have reliabilities of less than 100%. For a given yield, the reliability is computed by a HEC-3 simulation.

Several of the key terms used in this chapter to express reservoir yield are defined in Table 6.1. The terms are also explained in the text of the

Table 6.1
GLOSSARY OF FIRM YIELD TERMS USED IN CHAPTER 6

Firm yield is the estimated maximum release or withdrawal rate which can be maintained continuously during a repetition of the 85-year hydrologic record, based on specified assumptions regarding various factors.

Hydrologic firm yield is computed ignoring the impacts of water rights and return flows. Chapter 6 is limited strictly to hydrologic firm yields.

Single reservoir firm yield is computed ignoring the impacts of all other reservoirs and water users.

Individual reservoir firm yield is 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 consist of spills from the next upstream reservoir plus incremental flows from the watershed between the reservoirs. The individual reservoir firm yield of the upstream reservoirs are diverted at the upstream reservoirs. No upstream reservoir other than the 13 reservoirs are included in the modeling.

System firm yield is the maximum diversion rate which can be maintained continuously during the 85-year hydrologic record with two or more reservoirs making releases as required to satisfy a diversion at a common downstream control point.

Condition of sedimentation is represented by the elevation versus storage and area tables provided as model input data. Reservoir storage characteristics for initial, ultimate, 1984, and 2010 conditions of sedimentation are included in the study. Initial condition refers to reservoir topography at the time of construction or resurvey after construction if a resurvey has been performed. Ultimate condition refers to the predicted reservoir topography when the sediment reserve has been depleted.

Unregulated local flows which are alternatively excluded and included in the system firm yield computations, refers to the difference between naturalized streamflows at the diversion location and the sum of the naturalized streamflows at the most downstream dam sites on the main stream and each tributary. Unregulated local flows represent water entering the river below the dams.

Standard operating plan refers to a hypothetical set of pool elevations and release criteria developed for purposes of the study to facilitate organization of the modeling effort and communication of results. System firm yields are computed for the standard operating plan and deviations thereof.

Period reliability is the percentage of months during the 85-year simulation period for which a specified yield level can be met without shortage. Firm yield, and lesser yields, have a period (or volume) reliability of 100%. Yields greater than firm yield have a reliability of less than 100%.

Volume reliability is the total actual diversion volume during the 85-year simulation period divided by the target diversion volume for a specified yield (diversion rate). The actual diversion is the target diversion minus shortages.

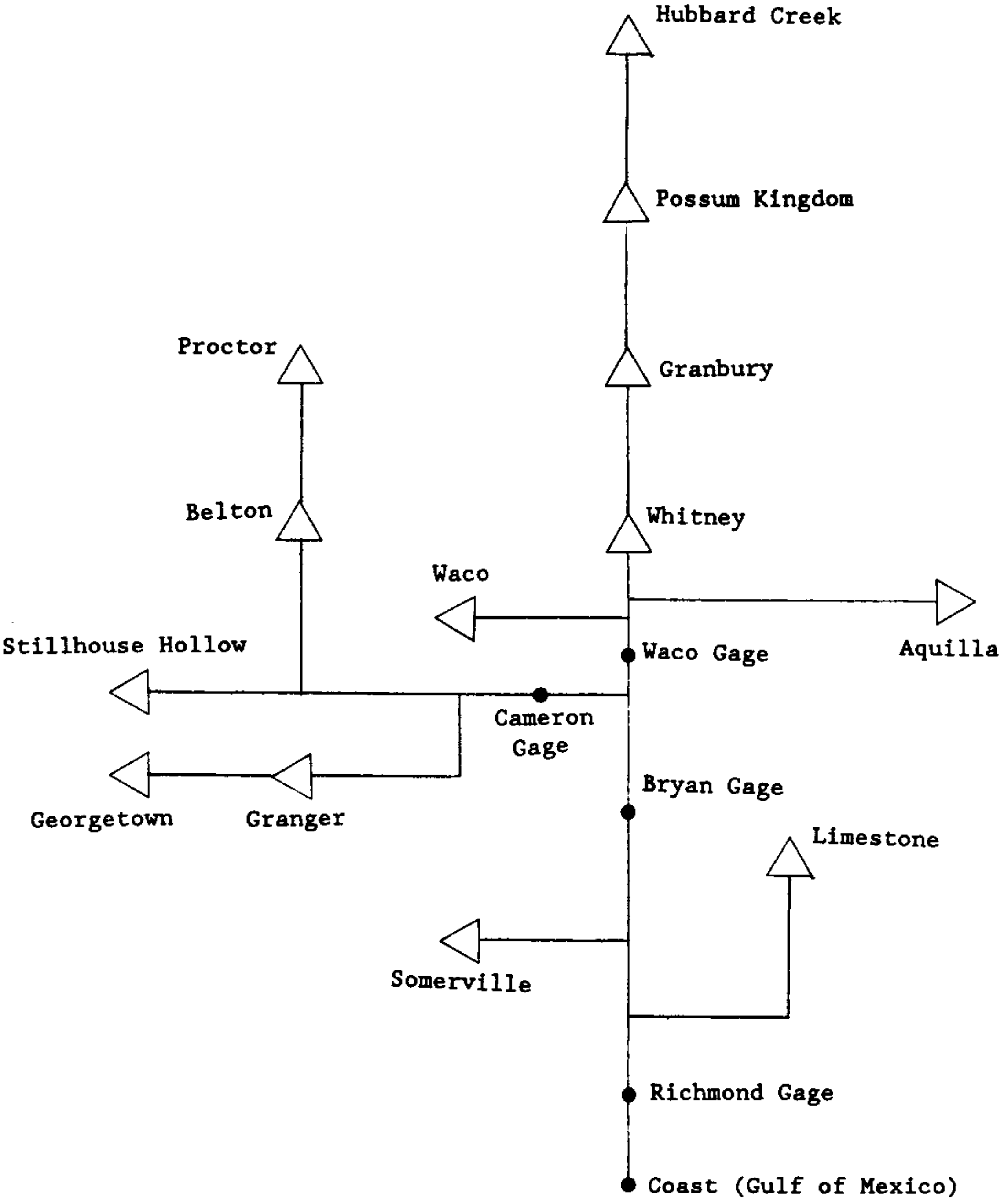


Figure 6.1 System Schematic

chapter. Figure 7.1 is a schematic showing the relative locations of the 13 reservoirs.

The estimated firm yields are presented to the nearest cfs or ac-ft/yr (and thus several significant figures in some cases) simply for convenience in documenting the computations and to facilitate comparison of small differences between the results of alternative simulation runs, not to imply accuracy. Firm yield estimates are necessarily approximate and normally should not be quoted with more than two or three significant figures.

Alternative Firm Yield Conditions

Firm yield estimates are presented for alternative conditions of sedimentation and for alternative approaches for considering the relationship between multiple reservoirs. Firm yields are repeated for pertinent alternative pool levels or operating plans for several of the reservoirs.

Reservoir Sedimentation

Four conditions of reservoir sedimentation are included in the analysis: base, 1984, 2010, and ultimate. The base condition represents the latest field survey of reservoir topography. The base condition is the date of initial impoundment unless the reservoir has since been resurveyed. Initial impoundment and latest survey dates are included in Table 3.10. The ultimate condition is the date at which the sediment reserve is predicted to be depleted, in the case of the Corps of Engineers reservoirs which have specified sediment reserves. For the reservoirs without formally designated sediment reserve capacities, the ultimate condition is an arbitrary future date for which area and capacity data have been developed. As discussed in Chapter 5, water surface elevation versus area and capacity relationships were obtained from prior studies for both base and ultimate sediment conditions. Linear interpolation was applied in the present study to develop data representing 1984 and 2010 sediment conditions.

Multiple Reservoirs

Firm yields are presented based on three alternative approaches for modeling the interactions between the 13 reservoirs. As indicated in Table 6.1, the resulting firm yields are termed single reservoir, individual reservoir, and system. Single reservoir firm yield is based on ignoring all reservoirs except the one under consideration. Individual reservoir firm yields were computed with upstream reservoirs included in the 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. System firm yield involves multiple reservoirs releasing for a diversion at a common downstream control point.

Federal and state agencies traditionally use the individual reservoir firm yield approach. However, system firm yields are particularly pertinent in quantifying the amount of water which can be provided by the Brazos River Authority system. A large portion of the actual water use is diverted at locations below all twelve reservoirs. Other diversions are made below subsystems of several of the reservoirs. System operation is an integral part of the actual operation of the BRA reservoirs. Water demands at downstream locations are met by releases from any of several reservoirs.

Reservoir Pool Elevations and Operating Policies

The top of inactive and conservation pool elevations for the 13 reservoirs are tabulated in Table 3.10. Possum Kingdom Reservoir has a top of inactive pool elevation of 970 feet msl, which was set in the past to facilitate hydroelectric power operations. The lowest outlet invert at Possum Kingdom is at elevation 875 feet msl. Likewise, Granbury Reservoir has a top of inactive pool elevation of 675 feet msl set by operation of a steam-electric plant near the reservoir, but the lowest outlet invert is at elevation 640 feet. Whitney Reservoir has top of inactive pool elevations of 520 feet and 449 feet, set by hydroelectric power operations and the lowest outlet elevation, respectively. Alternative firm yields for Possum Kingdom, Granbury, and Whitney Reservoirs were computed for both top of inactive pool elevations. Waco Reservoir has a top of conservation pool elevation of 455 feet. A planned storage reallocation will raise the top of conservation pool to an elevation of 462 feet. Firm yields for Waco Reservoir were computed for the two alternative top of conservation pool levels.

The conservation pool in Whitney Reservoir is used for both water supply and hydroelectric power. The USACE/BRA water supply contract designates 22.017 percent of the conservation pool between elevations 520 feet and 533 feet for water supply. The single and individual reservoir firm yields for the entire pool were computed. The water supply firm yield is assumed to be 22.017 percent of the computed value.

Hydroelectric power operations are not otherwise reflected in the single and individual reservoir water supply firm yield computations. As discussed later in this chapter, hydroelectric power operations at Whitney were included in the system firm yield computations. Hydroelectric power generation at Possum Kingdom Reservoir was assumed to be limited to passing water supply releases through the turbines. Thus, hydroelectric power operations at Possum Kingdom are not included in the modeling.

Flood control operations are not reflected in the firm yield simulations. When the water surface is at the top of conservation pool, releases from the flood control pool equal inflows. A sensitivity analysis indicated that flood control operations have essentially no effect on firm yields.

Reservoir storage levels are set at the top of conservation pool at the beginning of the simulation period.

Model Input Data

Input data are described in Chapter 5. The 1900-1984 monthly streamflow data consists of TWC naturalized streamflow for 1940-1976 and TAMU unregulated streamflow for 1900-1939 and 1977-1984. MOSS-IV was used to fill in missing monthly streamflows. TWDB Report 64 net monthly reservoir evaporation rates cover the period 1940-1984. Monthly average evaporation rates are used for 1900-1939.

Firm yield is expressed in terms of a constant average annual discharge rate. Seasonal variations in water use are represented in the model by a set of monthly use factors, which are fractions of the total annual yield used in each month. The two sets of monthly water use factors adopted for the firm yield analyses are tabulated in Table 6.2. One set was used for Waco and Hubbard Creek Reservoirs. The other set was applied to the other eleven reservoirs and the multireservoir system yields. The Waco and Hubbard Creek water use factors were developed from water use records obtained from the City of Waco (Wurbs, Cabezas, Tibbets 1985). Hubbard Creek Reservoir is also used primarily for municipal water supply purposes and should have similar seasonal water use patterns as Waco. The monthly water use factors for the other reservoirs were developed by the BRA based on historical reservoir release data. These are averages for the entire system.

Single Reservoir Firm Yields

The single reservoir firm yields presented in Tables 6.3, 6.4, 6.5 and 6.6 were computed for each reservoir alone, ignoring the effects of upstream reservoirs on inflows. Firm yields are tabulated in sets of four separate tables, representing the four conditions of sedimentation. The conservation capacity of the reservoirs are shown to vary with sediment condition. Firm yields are expressed alternatively in units of cubic feet per second (cfs) and acre-feet per year, and as a percentage of the average inflow to the reservoir. The critical drawdown period starts with the first month after a full reservoir and ends when the reservoir just empties. The mean inflow and spill are also shown. Spills are reservoir releases in excess of firm yield, as necessitated by inflows to a full conservation pool. The last column of the tables shows mean inflow minus spills and firm yield. The inflow minus releases consists almost entirely of evaporation, with a small amount representing difference in reservoir storage between the beginning and end of the 85-year simulation period. The firm yields for Possum Kingdom and Whitney Reservoirs are based on using the entire active conservation pool for water supply, without consideration of hydroelectric power.

Individual Reservoir Firm Yields

The firm yields tabulated in Tables 6.7, 6.8, 6.9, and 6.10 reflect the effects of upstream reservoirs on inflows. However, the 13 reservoirs incorporated in the model are the only upstream reservoirs considered. Hubbard Creek, Aquilla, Waco, Proctor, Stillhouse Hollow, Georgetown, Limestone, and Somerville Reservoirs have no reservoirs located upstream. Thus, single and individual reservoir firm yields are identical. The other reservoirs do have reservoirs located upstream. Individual reservoir firm yields are computed with upstream reservoirs included in the model with diversions equal to their previously computed firm yield. For example, in Table 6.7, the Whitney Reservoir (520 feet top of inactive pool elevation) firm yield of 191 cfs was computed assuming diversions of 84 cfs, 291 cfs, and 57 cfs at Granbury, Possum Kingdom, and Hubbard Creek Reservoirs, respectively. The Whitney (449 feet top of inactive pool elevation) firm yield of 408 cfs was computed assuming diversions of 121 cfs, 409 cfs, and 57 cfs at Granbury, Possum Kingdom, and Hubbard Creek, respectively. For the base condition of sedimentation, Belton Reservoir has a firm yield of 180 cfs computed with a diversion of 34 cfs occurring at Proctor Reservoir.

Table 6.2
MONTHLY WATER USE FACTORS

Month	Water Use Factors Waco and Hubbard	 All Other Reservoirs
January	0.066	0.02
February	0.062	0.02
March	0.064	0.03
April	0.070	0.07
May	0.079	0.10
June	0.096	0.17
July	0.115	0.27
August	0.117	0.16
September	0.103	0.07
October	0.085	0.04
November	0.073	0.03
December	0.070	0.02
Annual	1.000	1.00

Table 6.3

SINGLE RESERVOIR FIRM YIELD
BASE SEDIMENT CONDITION

Reservoir	Conservation Capacity (ac-ft)	Firm Yield			Critical Drawdown Period	Average Inflow (cfs)	Average Spill (cfs)	Inflow Minus Releases
		cfs	ac-ft/yr	% Mean Inflow				
Hubbard Creek	314,280	57	41,266	35.8	Nov 42-May 53	159	38	64
P.K. (Inactive 970 ft)	349,190	305	220,811	24.5	Jul 51-May 53	1,244	847	92
P.K. (Inactive 875 ft)	570,240	449	325,063	36.1	Jul 08-Sep 13	1,244	710	85
Granbury (Inactive 675 ft)	100,980	202	146,242	12.4	Jun 52-Nov 52	1,623	1,382	39
Granbury (Inactive 640 ft)	150,980	277	200,540	17.1	Jul 51-Nov 52	1,623	1,309	37
Whitney (Inactive 520 ft)	248,000	394	285,244	17.1	Jun 52-Nov 52	2,309	1,811	104
Whitney (Inactive 449 ft)	622,850	823	595,827	35.6	Jul 51-Nov 52	2,309	1,397	89
Aquilla	52,400	25	18,099	24.5	Jun 53-Oct 56	102	66	11
Waco (Conservation 455 ft)	151,920	121	87,600	26.6	Oct 50-Apr 55	455	307	27
Waco (Conservation 462 ft)	206,530	134	97,012	29.5	Oct 50-May 55	455	290	31
Proctor	59,330	34	24,615	21.3	Jun 77-Oct 81	160	105	21
Belton	447,480	216	156,378	33.2	Jun 08-Oct 12	651	392	43
Stillhouse Hollow	234,920	110	79,637	35.8	Jun 47-Nov 54	307	178	19
Georgetown	36,840	23	16,651	25.6	Mar 54-Mar 57	90	63	4
Granger	65,290	44	31,855	17.7	Feb 54-Nov 56	249	191	14
Limestone	218,970	105	76,017	34.3	Jun 62-Jan 65	306	164	37
Somerville	159,890	62	44,886	19.0	Jul 50-Mar 57	326	236	28

Table 6.4

SINGLE RESERVOIR FIRM YIELD

1984 SEDIMENT CONDITION

Reservoir	Conservation Capacity (ac-ft)	Firm Yield			Critical Drawdown Period	Average Inflow (cfs)	Average Spill (cfs)	Inflow Minus Releases
		cfs	ac-ft/yr	% Mean Inflow				
Hubbard Creek	308,070	57	41,266	35.8	Nov 42-May 53	159	39	63
P.K. (Inactive 970 ft)	341,870	300	217,191	24.1	Jul 51-May 53	1,244	853	91
P.K. (Inactive 875 ft)	544,510	443	320,719	35.6	Jul 08-Sep 13	1,244	717	84
Granbury (Inactive 675 ft)	95,250	193	139,726	12.0	Jun 52-Oct 52	1,623	1,392	38
Granbury (Inactive 640 ft)	137,400	267	193,299	16.5	Jul 51-Nov 52	1,623	1,318	36
Whitney (Inactive 520 ft)	238,170	376	272,213	16.3	Jun 52-Nov 52	2,309	1,830	103
Whitney (Inactive 449 ft)	599,160	803	581,348	34.8	Jul 51-Nov 52	2,309	1,417	89
Aquilla	52,210	25	18,099	24.5	Jun 53-Oct 56	102	66	11
Waco (Conservation 455 ft)	133,750	116	83,981	25.5	Jun 52-Apr 55	455	314	25
Waco (Conservation 462 ft)	186,330	129	93,392	28.4	Oct 50-May 55	455	295	31
Proctor	46,850	30	21,719	18.8	Jun 77-Jan 79	160	111	19
Belton	428,250	210	152,034	32.3	Jun 08-Mar 10	651	398	43
Stillhouse Hollow	225,310	108	78,189	35.2	Jun 47-Nov 54	307	179	20
Georgetown	36,540	23	16,651	25.6	Mar 54-Mar 57	90	64	3
Granger	64,190	44	31,855	17.7	Feb 54-Nov 56	249	191	14
Limestone	218,050	100	72,397	32.7	Jun 62-Jan 65	306	168	38
Somerville	154,450	61	44,162	18.8	Jul 50-Mar 57	326	237	28

Table 6.5

SINGLE RESERVOIR FIRM YIELD

2010 SEDIMENT CONDITION

Reservoir	Conservation Capacity (ac-ft)	Firm Yield			Critical Drawdown Period	Average Inflow (cfs)	Average Spill (cfs)	Inflow Minus Releases
		cfs	ac-ft/yr	% Mean Inflow				
Hubbard Creek	300,730	57	40,542	35.2	Nov 42-May 53	159	40	63
P.K. (Inactive 970 ft)	322,830	290	209,951	23.3	Jul 51-May 53	1,244	866	88
P.K. (Inactive 875 ft)	477,600	427	309,135	34.3	Jul 08-Sep 13	1,244	736	81
Granbury (Inactive 675 ft)	85,320	178	128,866	11.0	Jun 52-Oct 52	1,623	1,410	35
Granbury (Inactive 640 ft)	113,850	252	182,440	15.5	Jul 51-Oct 52	1,623	1,325	36
Whitney (Inactive 520 ft)	227,950	357	258,457	15.5	Jun 52-Nov 52	2,309	1,849	103
Whitney (Inactive 449 ft)	574,520	782	566,144	33.9	Jul 51-Nov 52	2,309	1,438	89
Aquilla	47,340	24	17,375	23.5	Jun 53-Oct 56	102	68	10
Waco (Conservation 455 ft)	108,880	106	76,741	23.3	Jun 52-Apr 55	455	326	23
Waco (Conservation 462 ft)	157,800	122	88,324	26.8	Oct 50-Apr 55	455	304	29
Proctor	31,400	20	14,479	12.5	Jun 77-Jan 79	160	124	16
Belton	372,700	192	139,002	29.5	Jun 08-Oct 12	651	414	45
Stillhouse Hollow	209,700	105	76,017	34.2	Jun 47-Dec 52	307	182	20
Georgetown	34,540	22	15,927	24.4	Mar 54-Mar 57	90	64	4
Granger	57,070	41	29,683	16.5	Feb 54-Nov 56	249	195	13
Limestone	214,060	98	70,949	32.0	Jun 62-Jan 65	306	170	38
Somerville	146,140	60	43,438	18.4	Jun 53-Mar 57	326	239	27

Table 6.6

SINGLE RESERVOIR FIRM YIELD

ULTIMATE SEDIMENT CONDITION

Reservoir	Conservation Capacity (ac-ft)	Firm Yield			Critical Drawdown Period	Average Inflow (cfs)	Average Spill (cfs)	Inflow Minus Releases
		cfs	ac-ft/yr	% Mean Inflow				
Hubbard Creek	297,910	57	41,266	35.8	Nov 42-May 53	159	40	62
P.K. (Inactive 970 ft)	315,510	286	207,055	23.0	Jul 51-May 53	1,244	871	87
P.K. (Inactive 875 ft)	451,860	415	300,448	33.4	Jul 51-May 53	1,244	749	80
Granbury (Inactive 675 ft)	81,490	172	124,522	10.6	Jun 52-Oct 52	1,623	1,417	34
Granbury (Inactive 640 ft)	104,790	246	178,096	39.5	Jun 52-Oct 52	1,623	1,330	35
Whitney (Inactive 520 ft)	227,950	357	258,457	15.5	Jun 52-Nov 52	2,309	1,849	103
Whitney (Inactive 449 ft)	574,520	782	566,145	33.9	Jul 51-Nov 52	2,309	1,438	89
Aquilla	33,650	20	14,480	19.6	Jul 82-Sep 84	102	73	9
Waco (Conservation 455 ft)	104,100	104	75,293	22.9	Jun 52-Apr 55	455	329	22
Waco (Conservation 462 ft)	151,630	121	87,600	26.6	Oct 50-Apr 55	455	306	28
Proctor	31,400	20	14,479	12.5	Jun 77-Jan 79	160	124	16
Belton	372,700	192	139,002	29.5	Jun 08-Oct 12	651	414	45
Stillhouse Hollow	204,900	104	75,293	33.9	Jun 47-Dec 52	307	184	19
Georgetown	29,180	19	13,755	21.1	Mar 54-Dec 56	90	67	4
Granger	37,900	29	20,995	11.6	Jul 55-Nov 56	249	208	12
Limestone	210,980	98	70,949	32.0	Jun 62-Jan 65	306	171	37
Somerville	143,900	59	42,714	18.1	Jul 53-Mar 57	326	240	27

Table 6.7

INDIVIDUAL RESERVOIR FIRM YIELD
BASE SEDIMENT CONDITION

Reservoir	Conservation Capacity (ac-ft)	Firm Yield			Critical Drawdown Period	Average Inflow (cfs)	Average Spill (cfs)	Inflow Minus Releases
		cfs	ac-ft/yr	% Mean Inflow				
Hubbard Creek	314,280	57	41,266	35.8	Nov 42-May 53	159	38	64
P.K. (Inactive 970 ft)	349,190	291	210,675	25.9	Jul 51-Jul 53	1,123	741	91
P.K. (Inactive 875 ft)	570,240	409	296,104	36.4	Jul 08-Sep 13	1,123	631	83
Granbury (Inactive 675 ft)	100,980	84	60,813	7.5	Jun 77-Sep 78	1,120	999	37
Granbury (Inactive 640 ft)	150,980	121	87,600	12.0	Jul 51-Oct 53	1,010	855	34
Whitney (Inactive 520 ft)	248,000	191	138,278	11.3	Jun 77-Sep 78	1,685	1,394	100
Whitney (Inactive 449 ft)	622,850	408	295,380	26.5	Jul 08-Oct 13	1,541	1,052	81
Aquilla	52,400	25	18,099	24.5	Jun 53-Oct 56	102	66	11
Waco (Conservation 455 ft)	151,920	121	87,600	26.6	Oct 50-Apr 55	455	307	27
Waco (Conservation 462 ft)	206,530	134	97,012	29.5	Oct 50-May 55	455	290	31
Proctor	59,330	34	24,615	21.3	Jun 77-Oct 81	160	105	21
Belton	447,480	180	130,315	30.2	Jun 08-Oct 12	596	374	42
Stillhouse Hollow	234,920	110	79,637	35.8	Jun 47-Nov 54	307	178	19
Georgetown	36,840	23	16,651	25.6	Mar 54-Mar 57	90	63	4
Granger	65,290	35	25,339	15.7	Feb 54-Dec 56	223	174	14
Limestone	218,970	105	76,017	34.3	Jun 62-Jan 65	306	164	37
Somerville	159,890	62	44,886	19.0	Jul 50-Mar 57	326	236	28

Table 6.8

INDIVIDUAL RESERVOIR FIRM YIELD
1984 SEDIMENT CONDITION

Reservoir	Conservation Capacity (ac-ft)	Firm Yield			Critical Drawdown Period	Average Inflow (cfs)	Average Spill (cfs)	Inflow Minus Releases
		cfs	ac-ft/yr	% Mean Inflow				
Hubbard Creek	308,070	57	41,266	35.8	Nov 42-May 53	159	39	63
P.K. (Inactive 970 ft)	341,870	288	208,503	25.6	Jul 51-Jul 53	1,124	746	90
P.K. (Inactive 875 ft)	544,510	403	291,760	35.9	Jul 08-Sep 13	1,124	638	83
Granbury (Inactive 675 ft)	95,250	83	60,090	7.4	Jun 77-Aug 78	1,126	1,004	38
Granbury (Inactive 640 ft)	137,400	120	86,880	11.8	Jul 51-Oct 53	1,018	862	35
Whitney (Inactive 520 ft)	238,170	183	132,487	10.8	Jun 77-Aug 78	1,690	1,408	99
Whitney (Inactive 449 ft)	599,160	403	291,760	26.0	Jul 08-Oct 13	1,549	1,066	80
Aquilla	52,210	25	18,099	24.5	Jun 53-Oct 56	102	66	11
Waco (Conservation 455 ft)	133,750	116	83,981	25.5	Jun 52-Apr 55	455	314	25
Waco (Conservation 462 ft)	186,330	129	93,392	28.4	Oct 50-May 55	455	295	31
Proctor	46,850	30	21,719	18.8	Jun 77-Jan 79	160	111	19
Belton	428,250	177	128,143	29.4	Jun 08-Oct 12	602	383	42
Stillhouse Hollow	225,310	108	78,189	35.2	Jun 47-Nov 54	307	179	20
Georgetown	36,540	23	16,651	25.6	Mar 54-Mar 57	90	64	3
Granger	64,190	34	24,615	15.2	Feb 54-Dec 56	223	175	14
Limestone	218,050	100	72,397	32.7	Jun 62-Jan 65	306	168	38
Somerville	154,450	61	44,162	18.7	Jul 50-Mar 57	326	237	28

Table 6.9

INDIVIDUAL RESERVOIR FIRM YIELD

2010 SEDIMENT CONDITION

Reservoir	Conservation Capacity (ac-ft)	Firm Yield			Critical Drawdown Period	Average Inflow (cfs)	Average Spill (cfs)	Inflow Minus Releases
		cfs	ac-ft/yr	% Mean Inflow				
Hubbard Creek	300,730	57	40,542	35.2	Nov 42-May 53	159	40	63
P.K. (Inactive 970 ft)	322,830	279	201,988	24.8	Jul 51-Jul 53	1,125	759	87
P.K. (Inactive 875 ft)	477,600	384	278,004	34.1	Jul 08-Aug 12	1,125	661	80
Granbury (Inactive 675 ft)	85,320	67	48,500	5.9	Jan 77-Aug 78	1,138	1,037	34
Granbury (Inactive 640 ft)	113,850	104	75,290	10.0	Jul 51-Oct 53	1,040	906	34
Whitney (Inactive 520 ft)	227,950	182	131,763	10.7	Jul 77-Aug 78	1,703	1,422	99
Whitney (Inactive 449 ft)	574,520	397	287,416	25.3	Jul 08-Oct 13	1,571	1,094	80
Aquilla	47,340	24	17,375	23.5	Jun 53-Oct 56	102	68	10
Waco (Conservation 455 ft)	108,880	106	76,741	23.3	Jun 52-Apr 55	455	326	23
Waco (Conservation 462 ft)	157,800	122	88,324	26.8	Oct 50-Apr 55	455	304	29
Proctor	31,400	20	14,479	12.5	Jun 77-Jan 79	160	124	16
Belton	372,700	165	119,455	26.8	Jul 08-Oct 12	615	406	44
Stillhouse Hollow	209,700	105	76,017	34.2	Jun 47-Dec 52	307	182	20
Georgetown	34,540	22	15,927	24.4	Mar 54-Mar 57	90	64	4
Granger	57,070	31	22,443	13.8	Feb 54-Dec 56	224	179	14
Limestone	214,060	98	70,949	32.0	Jun 62-Jun 65	306	170	38
Somerville	146,140	60	43,438	18.4	Jun 53-Mar 57	326	239	27

Table 6.10

INDIVIDUAL RESERVOIR FIRM YIELD

ULTIMATE SEDIMENT CONDITION

Reservoir	Conservation Capacity (ac-ft)	Firm Yield			Critical Drawdown Period	Average Inflow (cfs)	Average Spill (cfs)	Inflow Minus Releases
		cfs	ac-ft/yr	% Mean Inflow				
Hubbard Creek	297,910	57	41,266	35.8	Nov 42-May 53	159	40	62
P.K. (Inactive 970 ft)	315,510	276	199,816	24.5	Jul 51-Jul 53	1,126	764	86
P.K. (Inactive 875 ft)	451,860	376	272,213	33.4	Jul 08-Aug 12	1,126	670	80
Granbury (Inactive 675 ft)	81,490	67	48,500	5.9	Jul 77-Aug 78	1,143	1,021	38
Granbury (Inactive 640 ft)	104,790	104	75,290	9.9	Jul 51-Oct 53	1,050	894	35
Whitney (Inactive 520 ft)	227,950	182	133,934	10.8	Jul 77-Aug 78	1,708	1,423	100
Whitney (Inactive 449 ft)	574,520	397	287,416	25.1	Jul 08-Oct 13	1,580	1,103	80
Aquilla	33,650	20	14,480	19.6	Jul 82-Sep 84	102	73	9
Waco (Conservation 455 ft)	104,100	104	75,293	22.9	Jun 52-Apr 55	455	329	22
Waco (Conservation 462 ft)	151,630	121	87,600	26.6	Oct 50-Apr 55	455	306	28
Proctor	31,400	20	14,479	12.5	Jun 77-Jan 79	160	124	16
Belton	372,700	165	119,455	26.8	Jul 08-Oct 12	615	406	44
Stillhouse Hollow	204,900	104	75,293	33.9	Jun 47-Dec 52	307	184	19
Georgetown	29,180	19	13,755	21.1	Mar 54-Dec 56	90	67	4
Granger	37,900	22	15,927	9.7	Feb 54-Nov 56	226	192	12
Limestone	210,982	98	70,949	32.0	Jun 62-Jan 65	306	171	37
Somerville	143,900	59	42,714	18.1	Jul 53-Mar 57	326	240	27

Table 6.11
INDIVIDUAL RESERVOIR FIRM YIELDS FOR ALTERNATIVE SEDIMENT CONDITIONS

	Condition of Sedimentation				Year	
Reservoir	Base	1984	2010	Ultimate	Base	Ultimate
Hubbard Creek	57	57	57	57	1962	2020
P.K. (inactive 970 ft)	291	288	279	276	1974	2020
P.K. (inactive 875 ft)	409	403	384	376	1974	2020
Granbury (inactive 675 ft)	84	83	67	65	1969	2020
Granbury (inactive 640 ft)	121	121	104	103	1969	2020
Whitney (inactive 520 ft)	191	183	182	182	1959	2010
Whitney (inactive 449 ft)	408	403	397	397	1959	2010
Aquilla	25	25	24	20	1983	2083
Waco (conservation 455 ft)	121	116	106	104	1965	2015
Waco (conservation 462 ft)	134	129	122	121	1965	2015
Proctor	34	30	20	20	1963	2010
Belton	180	177	165	165	1975	2010
Stillhouse Hollow	110	108	105	104	1968	2018
Georgetown	23	23	22	19	1980	2080
Granger	35	34	31	22	1980	2080
Limestone	105	100	98	98	1978	2030
Somerville	62	61	60	59	1967	2017

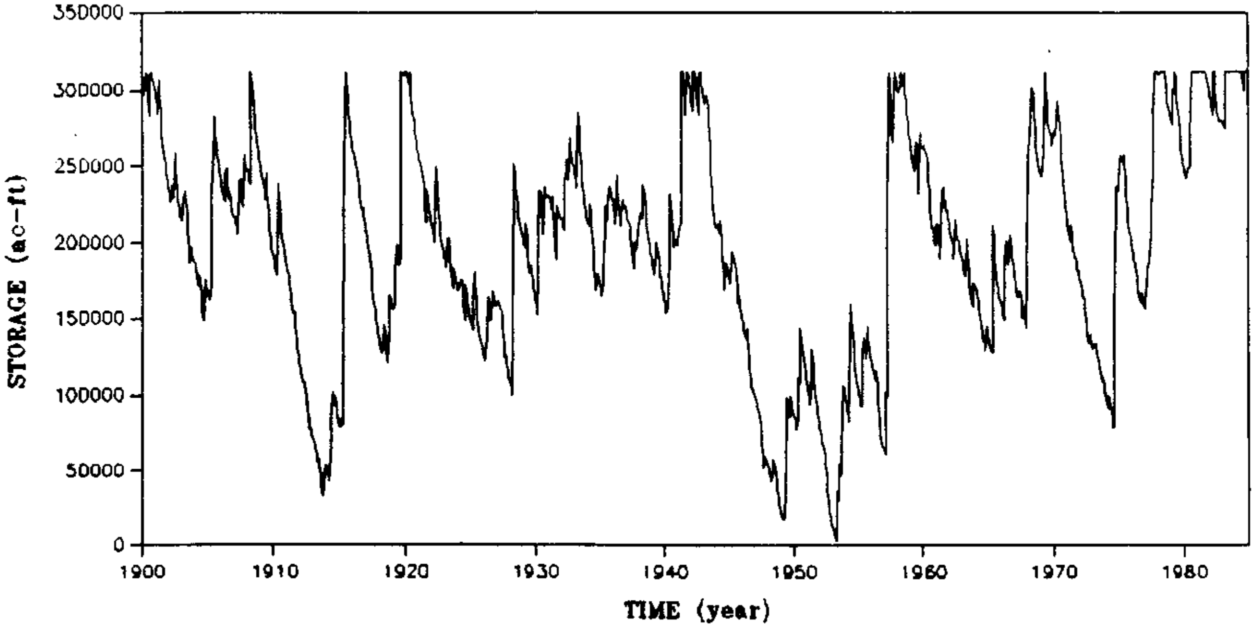


Figure 6.2 Hubbard Creek Reservoir Storage Hydrograph, Individual Reservoir Firm Yield, 1984 Sedimentation

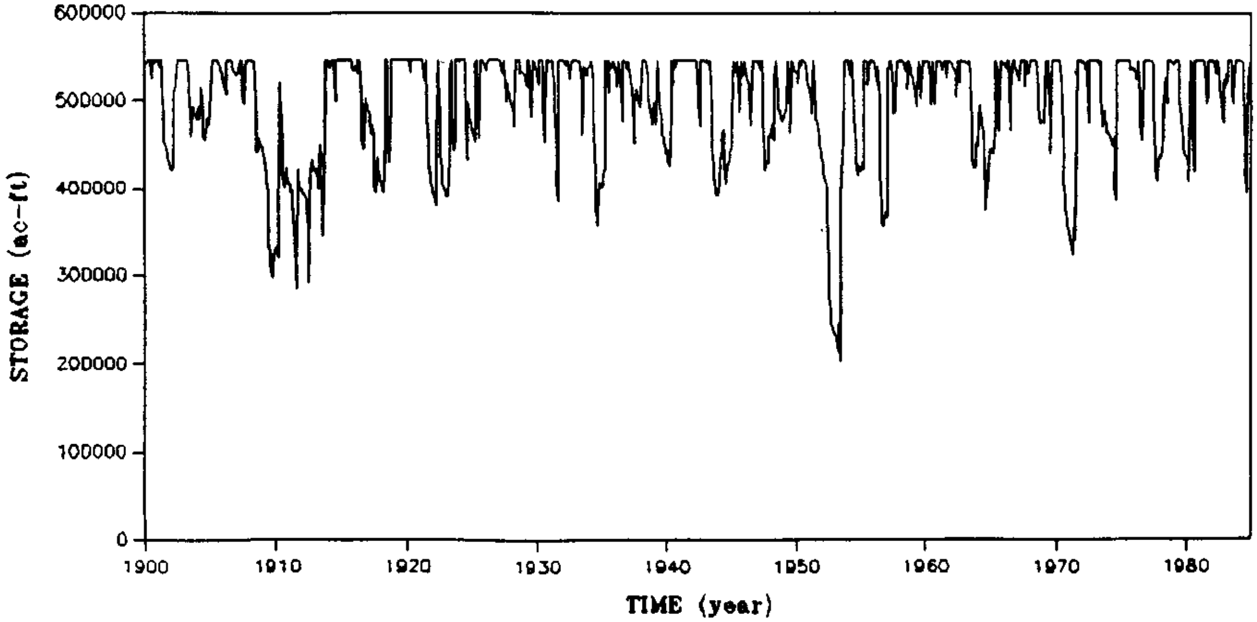


Figure 6.3 Possum Kingdom Reservoir Storage Hydrograph, Individual Reservoir Firm Yield, 1984 Sedimentation

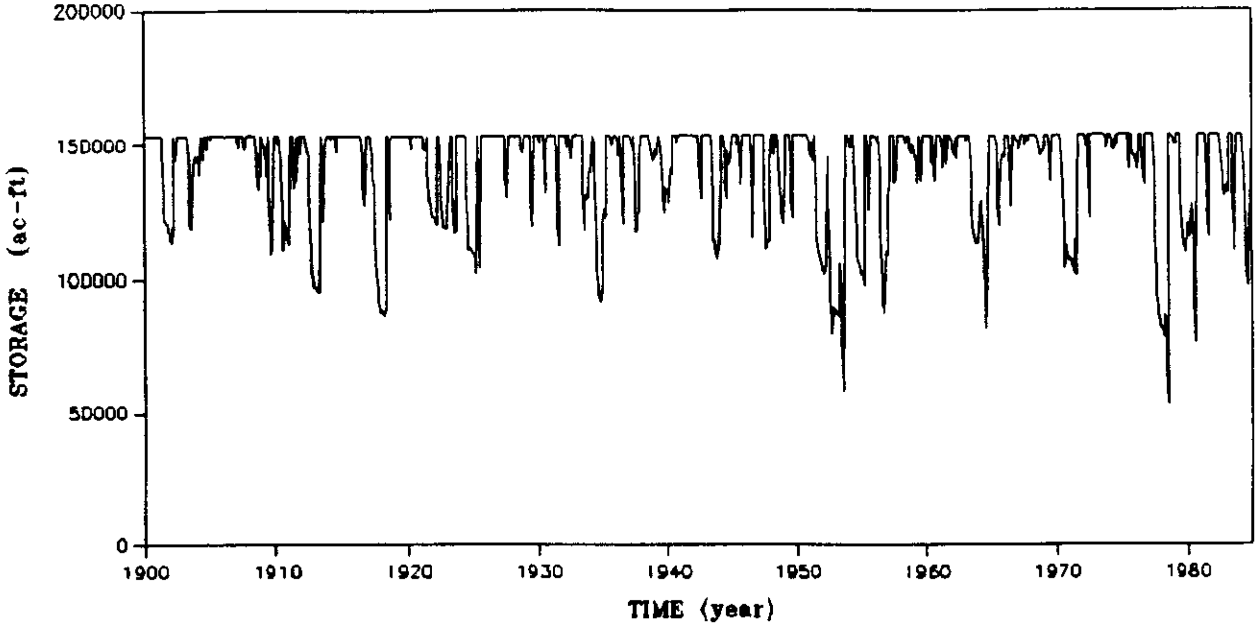


Figure 6.4 Granbury Reservoir Storage Hydrograph, Individual Reservoir Firm Yield, 1984 Sedimentation

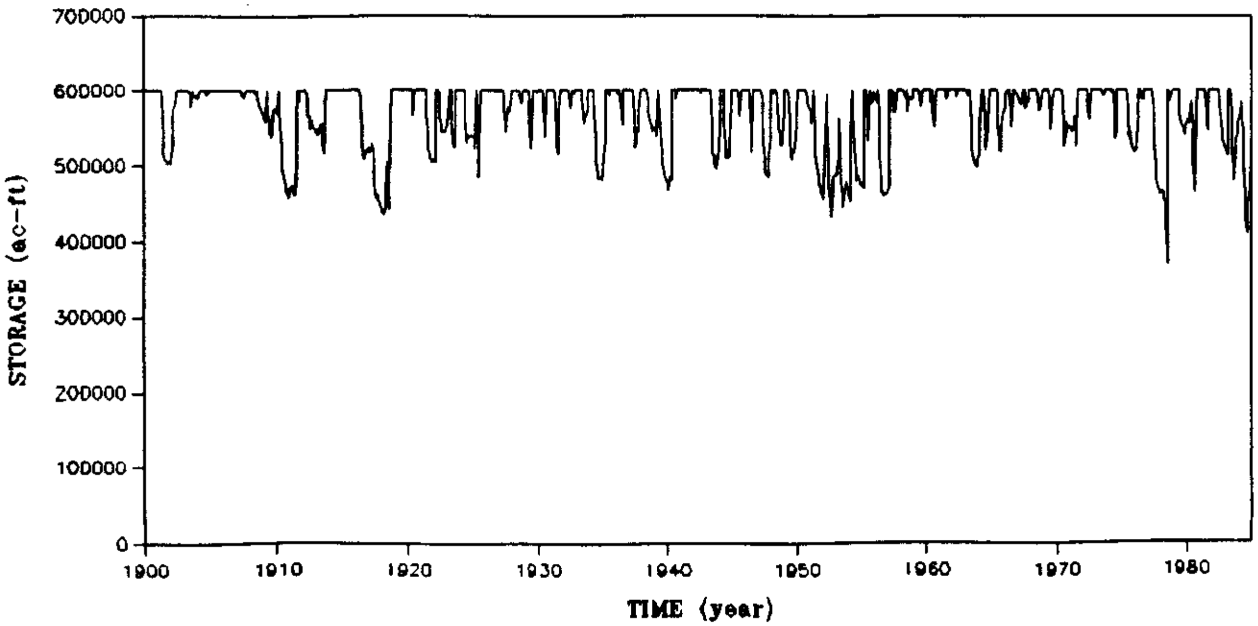


Figure 6.5 Whitney Reservoir Storage Hydrograph, Individual Reservoir Firm Yield, 1984 Sedimentation

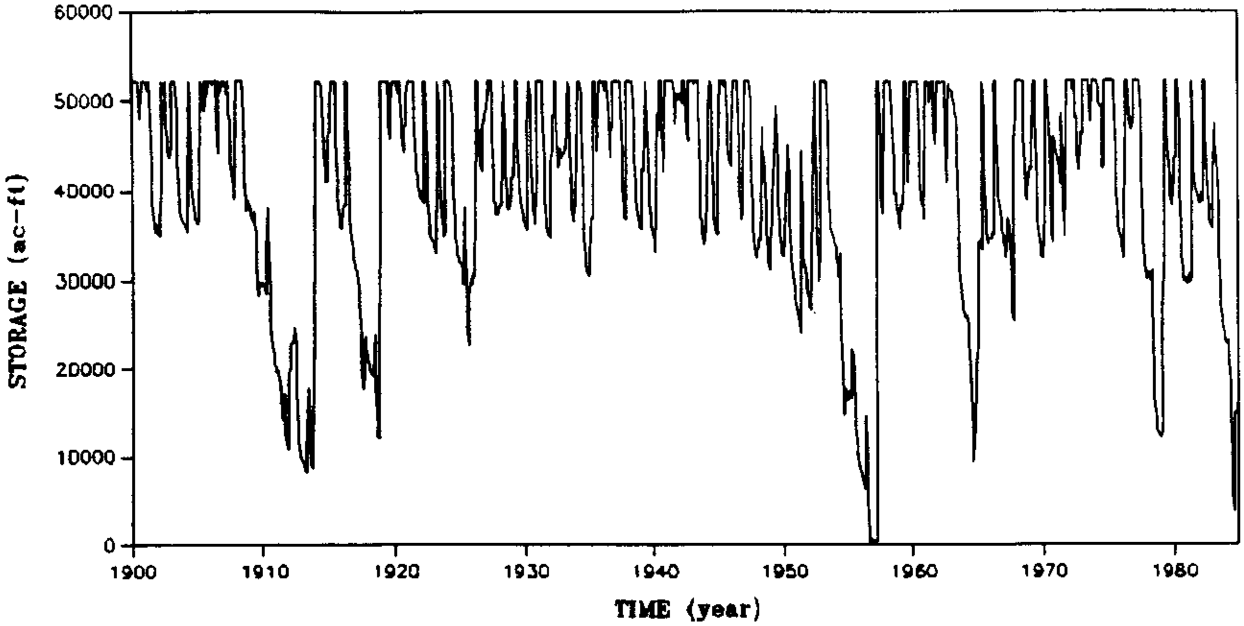


Figure 6.6 Aquilla Reservoir Storage Hydrograph, Individual Reservoir Firm Yield, 1984 Sedimentation

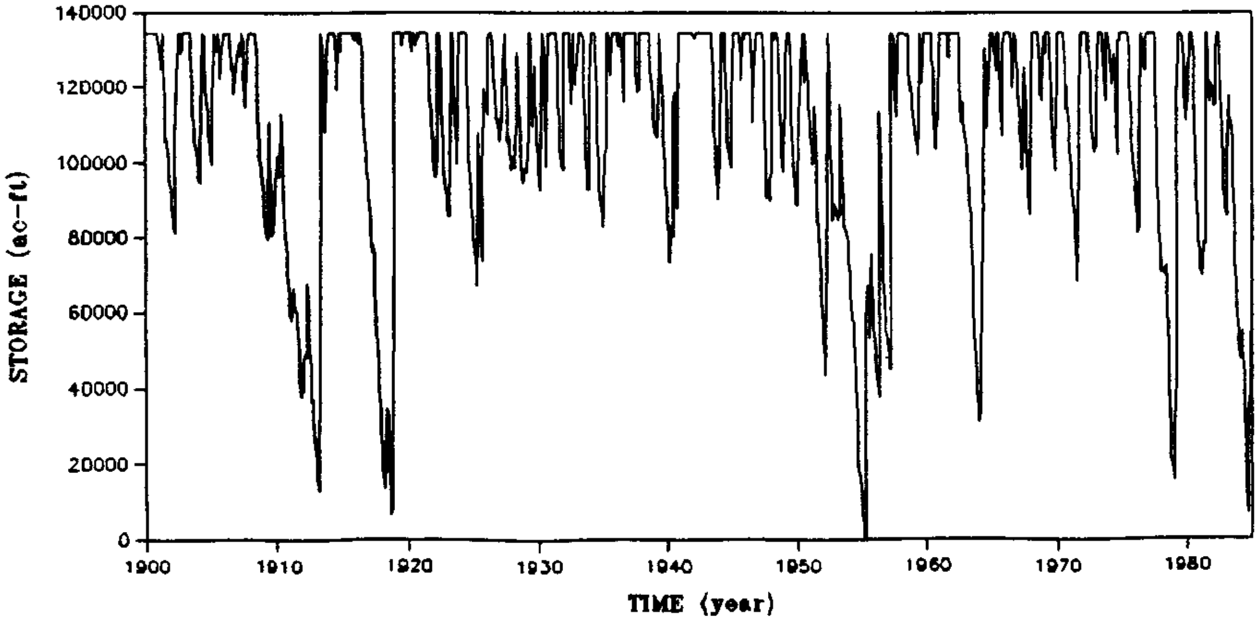


Figure 6.7 Waco Reservoir Storage Hydrograph, Individual Reservoir Firm Yield, 1984 Sedimentation

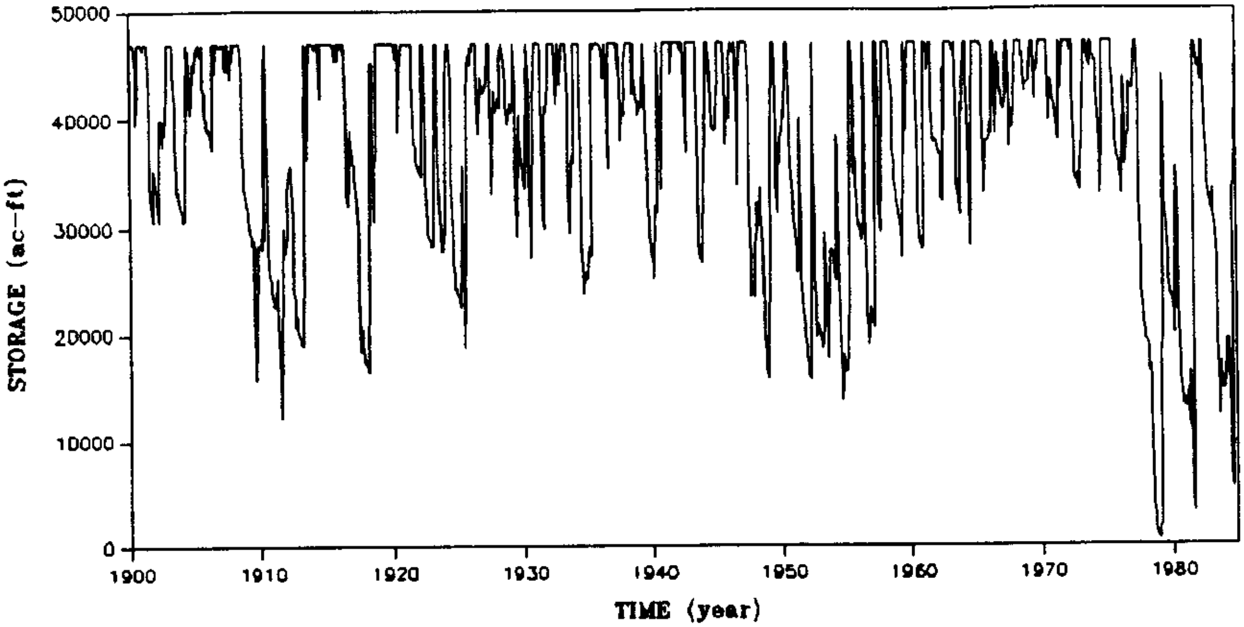


Figure 6.8 Proctor Reservoir Storage Hydrograph, Individual Reservoir Firm Yield, 1984 Sedimentation

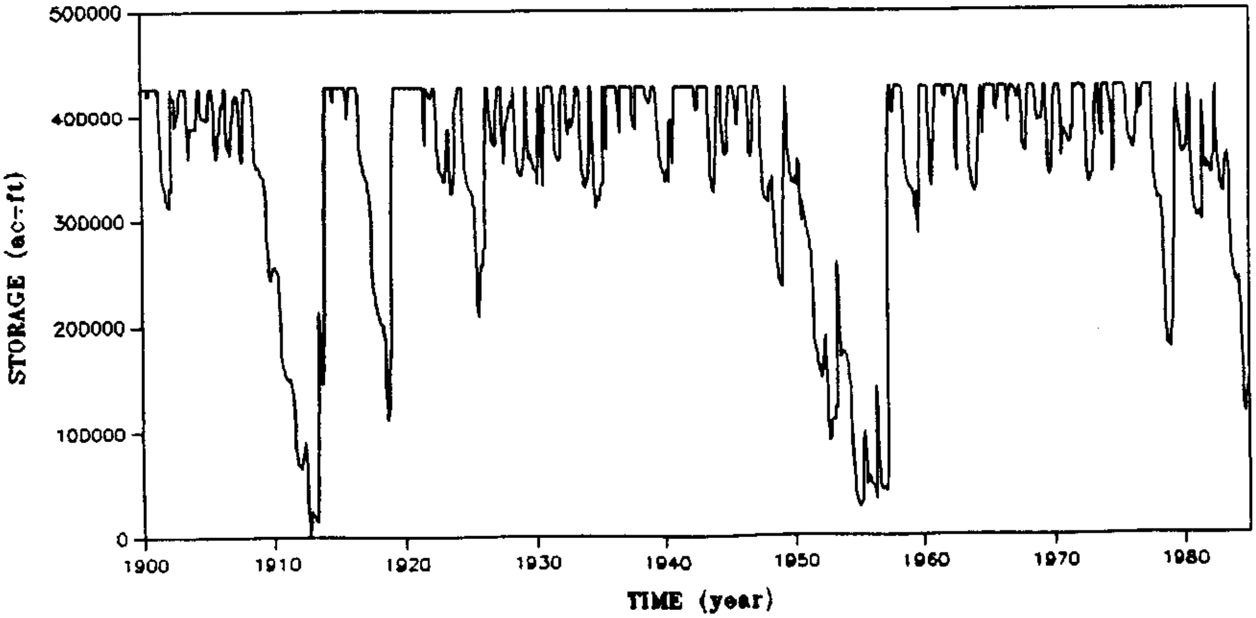


Figure 6.9 Belton Reservoir Storage Hydrograph, Individual Reservoir Firm Yield, 1984 Sedimentation

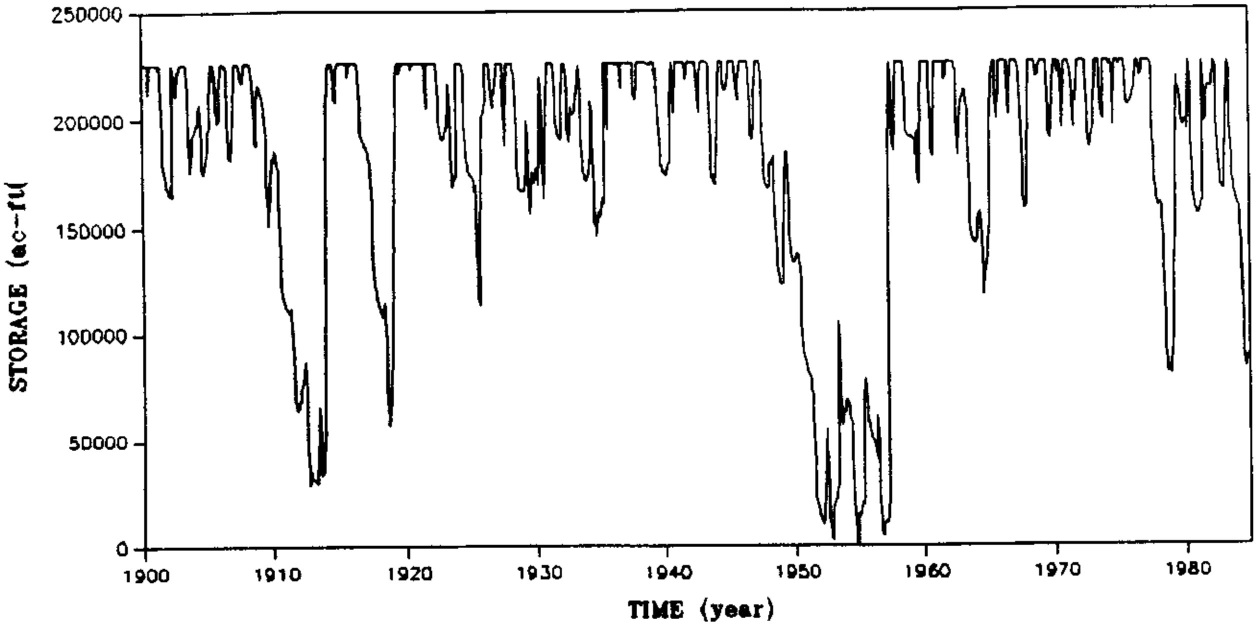


Figure 6.10 Stillhouse Hollow Reservoir Storage Hydrograph, Individual Reservoir Firm Yield, 1984 Sedimentation

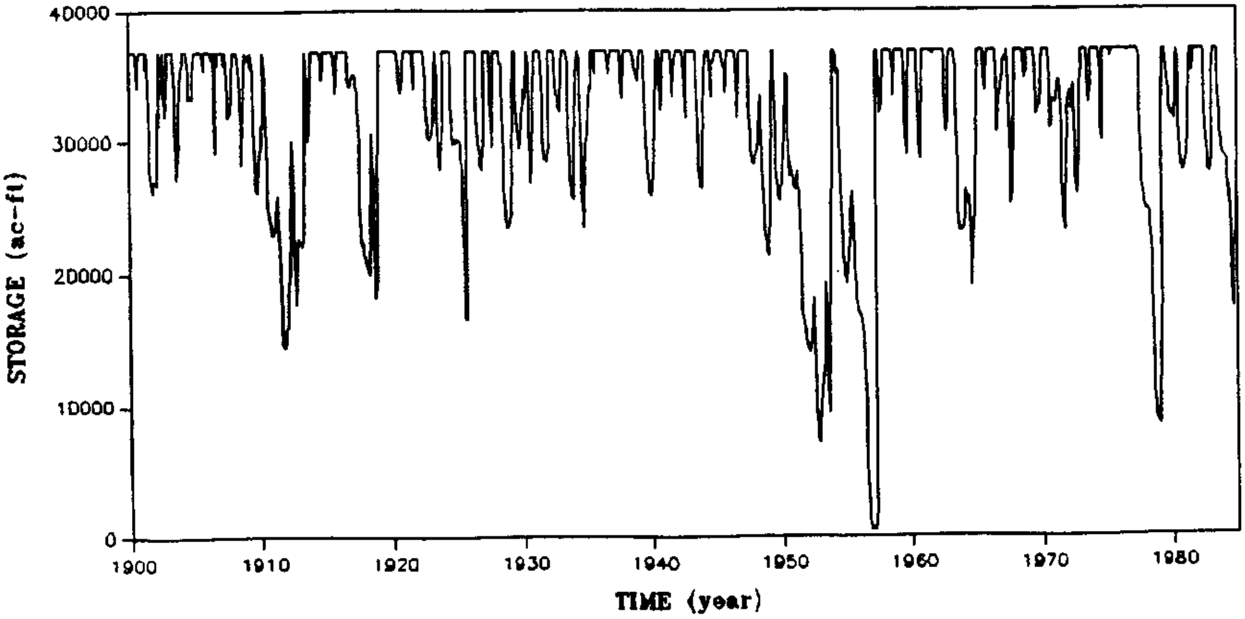


Figure 6.11 Georgetown Reservoir Storage Hydrograph, Individual Reservoir Firm Yield, 1984 Sedimentation

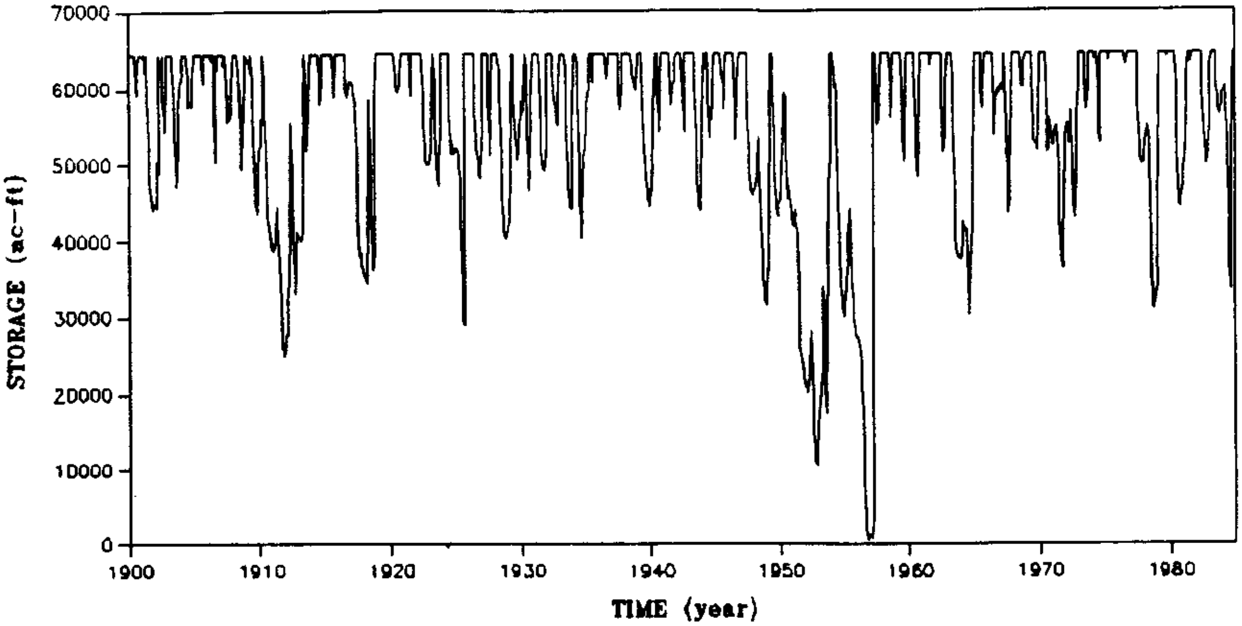


Figure 6.12 Granger Reservoir Storage Hydrograph, Individual Reservoir Firm Yield, 1984 Sedimentation

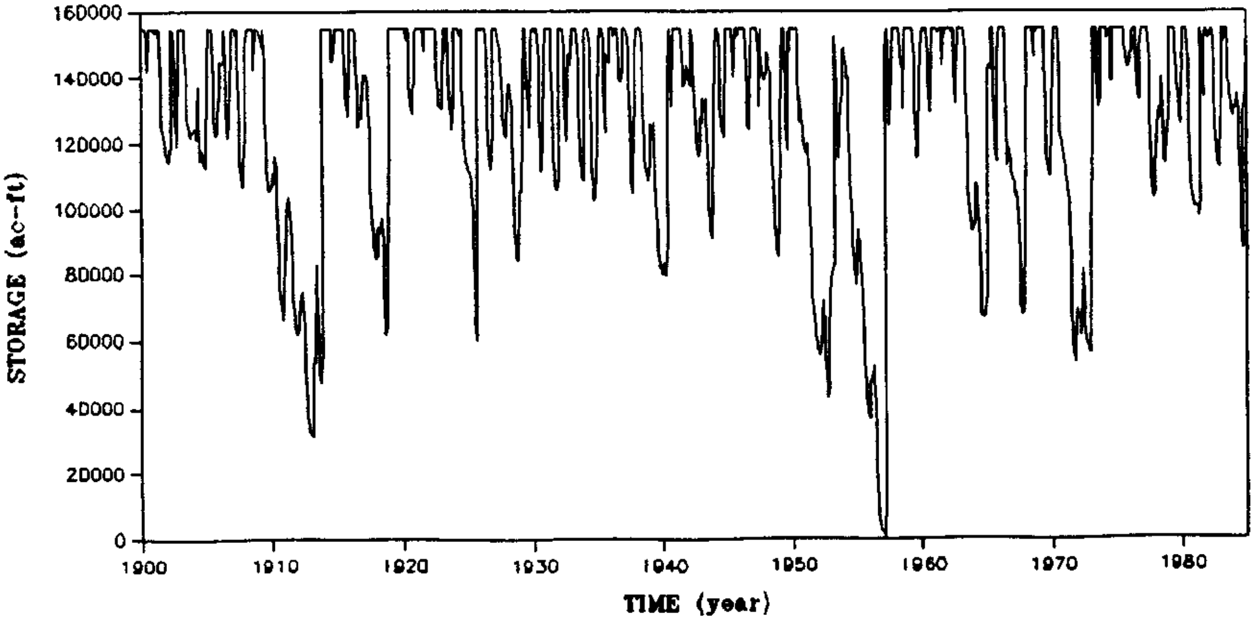


Figure 6.13 Somerville Reservoir Storage Hydrograph, Individual Reservoir Firm Yield, 1984 Sedimentation

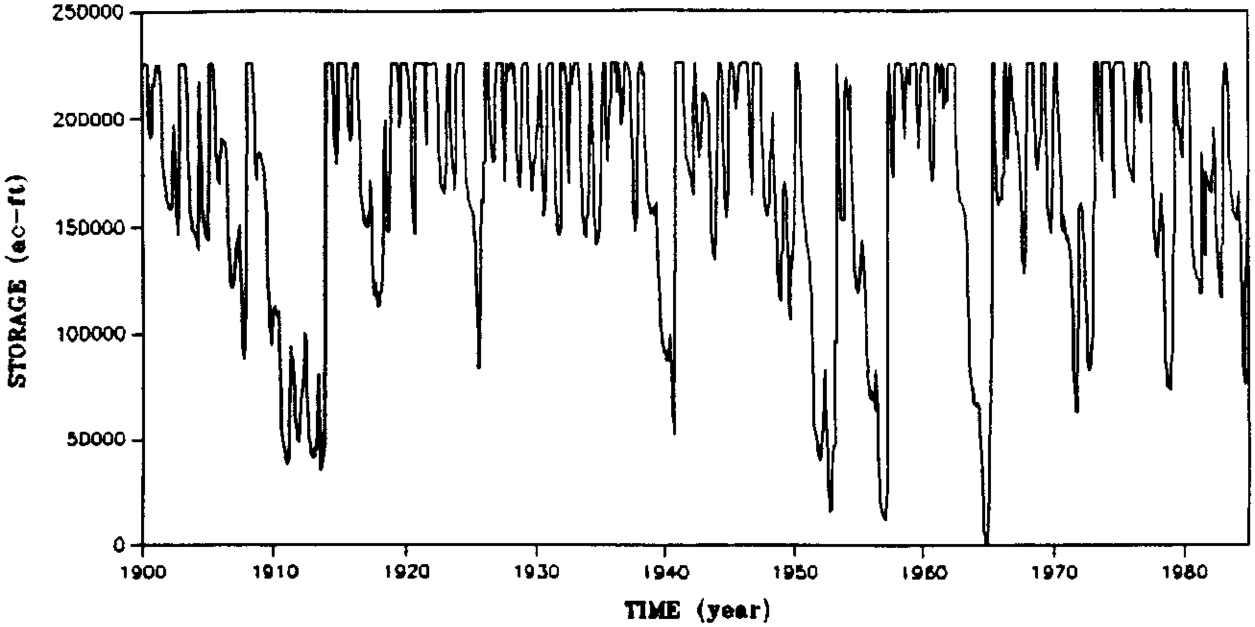


Figure 6.14 Limestone Reservoir Storage Hydrograph, Individual Reservoir Firm Yield, 1984 Sedimentation

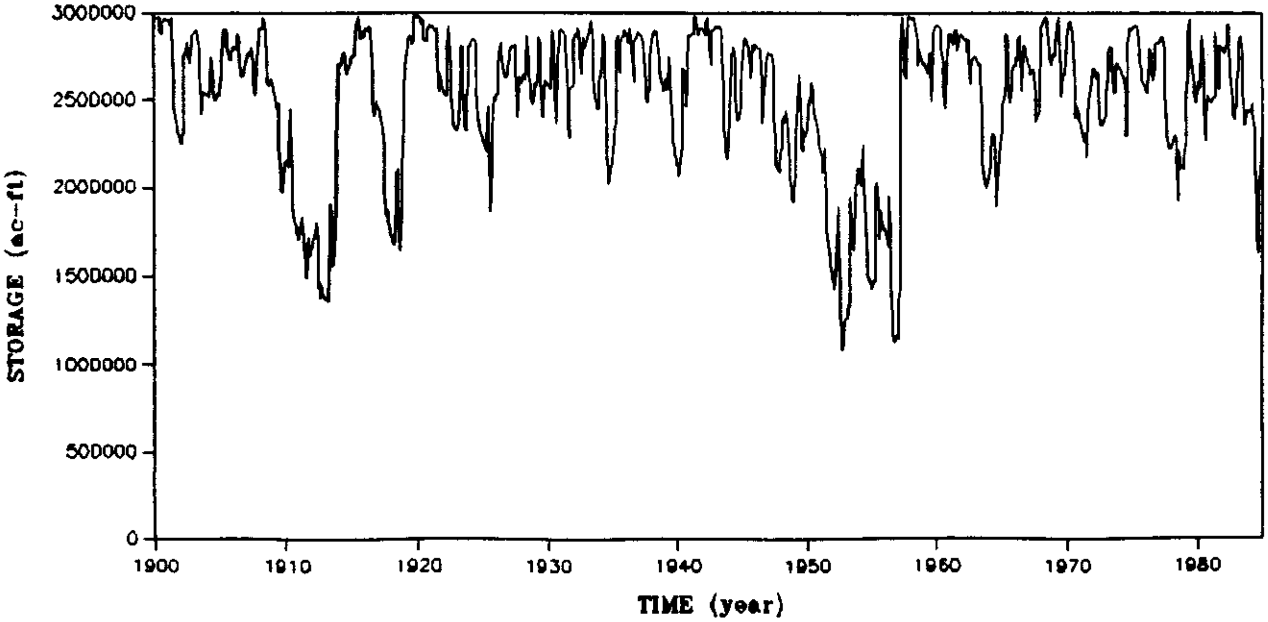


Figure 6.15 13-Reservoir Total Storage Hydrograph, Individual Reservoir Firm Yield, 1984 Sedimentation

Individual reservoir firm yields for Granbury and Whitney Reservoirs also were computed for the following combination of top of inactive pool elevations: Possum Kingdom (875 ft), Granbury (675 ft), and Whitney (520 ft). Assuming 1984 sediment conditions, Granbury and Whitney firm yields are 74 cfs and 177 cfs, respectively. Assuming 2010 sediment conditions, Granbury and Whitney firm yields are 67 cfs and 182 cfs, respectively. Thus, the 2010 sediment condition Granbury and Whitney individual reservoir firm yields are the same with the Possum Kingdom inactive pool at either 875 ft or 970 ft. The corresponding 1984 Granbury and Whitney firm yields are somewhat lower with the Possum Kingdom inactive pool at 875 ft.

The Whitney Reservoir active conservation pool is used for both water supply and hydroelectric power. The USACE/BRA water supply contract commits 22.017% of the active conservation pool to water supply. The Whitney water supply firm yield can be estimated as 22.017% of the values shown in the tables. Wurbs and Carriere (1988) present hydroelectric power firm yields for Whitney Reservoir.

Tables 6.7, 6.8, 6.9, and 6.10 show the individual reservoir firm yields along with critical drawdown periods, mean inflows and spills, and computed differences between inflows and releases, for alternative sediment conditions. The firm yields in these tables are summarized in Table 6.11.

Figures 6.2 through 6.14 are plots of end-of-month storage contents for simulations in which the individual reservoir firm yield is released from the reservoir. These simulations are based upon 1984 conditions of sedimentation and thus, correspond to Table 6.8. Possum Kingdom, Granbury, and Whitney top of inactive pool elevations are 970 feet, 675 feet, and 520 feet, respectively. Waco Reservoir has a top of conservation pool elevation of 455 feet in the simulations plotted.

Figure 6.15 is a plot of the summation of the end-of-month storages for the 13 reservoirs. With individual reservoir firm yields being withdrawn at each reservoir, the critical drawdown periods do not perfectly coincide. The reservoirs are not all empty simultaneously. Thus, at the maximum storage depletion, water is still available to provide additional firm yield from a system perspective.

With 1984 conditions of sedimentation, the 13 reservoirs have total inactive capacities of 620,000 acre-feet. The cumulative total system top of conservation pool capacity is 2,950,000 acre-feet. The minimum system storage level for the end-of-month total for the 13 reservoirs, as illustrated in Figure 6.15, is 1,080,000 acre-feet. Thus, 460,000 acre-feet or 19.7 percent of the 2,330,000 acre-feet of conservation capacity is still full of water at the time of maximum depletion.

System Firm Yields

System firm yield is the maximum diversion rate which can be supplied continuously throughout the 85-year hydrologic record by the 12-reservoir BRA system or subsystems thereof. A diversion, or instream flow requirement, is specified at a downstream location, with releases being made from upstream reservoirs as necessary to meet the downstream requirements. Multireservoir release decisions are made by the model based on balancing the percent depletion in each reservoir. The monthly water use factors tabulated in the first column of Table 6.2 were used for the system diversions. Streamflow and evaporation rate data are the same as the previously discussed simulations.

Standard Operating Plan

Firm yield represents a hypothetical potential rather than actual historical or projected future diversion. The system firm yield simulations are generally representative of actual operation of the reservoir system. However, actual detailed operating criteria and practices are not necessarily reflected in the simplified model. For purposes of the system firm yield analysis, a standard operating plan was defined. Firm yields were computed for the somewhat hypothetical standard operating plan and variations thereof. The term "standard operating plan" was simply adopted for purposes of the study to facilitate communication and organization of the modeling effort.

The standard operating plan is outlined in Table 6.12. The top of inactive and conservation pool elevations for each reservoir are shown. Active conservation capacities are included in Table 6.12 for both 1984 and 2010 conditions of sedimentation. Firm yield is computed for the 12-reservoir BRA system. Hubbard Creek Reservoir is also included in the HEC-3 and HEC-5 models. The Hubbard Creek individual reservoir firm yield is diverted at the reservoir. The Whitney and Waco individual reservoir firm yields are also diverted at these reservoirs. The remaining ten reservoirs are operated as a system to meet diversion, or instream flow, requirements at the Richmond gage control point. (For computational purposes, treating the downstream yield as either a diversion or an instream flow requirement provides identically the same result.) Multiple reservoir release decisions are made by the model based on maintaining approximately the same percent depletion of the conservation pools in each of the 10 reservoirs. In addition to releasing for the Richmond gage control point, Possum Kingdom and Granbury Reservoirs release to provide inflows required to meet Whitney Reservoir operating criteria if necessary.

Waco Reservoir is treated as a local use reservoir because the total conservation capacity is committed for supplying water for the City of Waco and its suburbs.

The Whitney Reservoir active conservation pool is used for both water supply and hydroelectric power. The USACE/BRA water supply contract commits 22.017 percent of the active conservation pool to water supply. The individual reservoir firm yield is estimated by multiplying the firm yield computed assuming the entire active conservation capacity is for water supply, by 22.017 percent. The resulting individual reservoir firm yield is treated as a diversion at Whitney Reservoir in the system firm yield simulation.

The standard operating plan includes hydroelectric power operation at Whitney Reservoir. The operation criteria incorporated in the model are based upon the hydroelectric power contract between the Southwestern Power Administration and the Brazos Electric Power Cooperative. Whitney provides 30,000 kilowatts of hydroelectric peaking power. The contract provides for annual energy of 1,200 kilowatt-hours per kilowatt of peaking power, with the energy not to exceed 200 kilowatt-hours per kilowatt in any one month or 600 kilowatt-hours per kilowatt during four consecutive months. The monthly energy distribution incorporated in the model, in terms of kilowatt-hours per kilowatt

Table 6.12
STANDARD OPERATING PLAN

Reservoir	Pool Elevation: Top of Inactive (feet)	Pool Elevation: Top of Conservation (feet)	2010 Conservation Capacity (acre-feet)	2010 Firm Yield Diversion (cfs)
Hubbard	1,136	1,183	300,370	57
Possum Kingdom	875	1,000	477,600	-
Granbury	675	693	85,320	-
Whitney	520	533	227,950	40
Aquilla	503	537.5	47,340	-
Waco	400	455	108,880	106
Proctor	1,128	1,162	31,400	-
Belton	483	594	372,700	-
Stillhouse	515	622	209,700	-
Georgetown	720	791	34,540	-
Granger	457	504	57,070	-
Limestone	326	363	214,060	-
Somerville	206	236	146,140	-

Notes

1. The individual reservoir firm yields for Hubbard Creek, Whitney, and Waco Reservoirs are diverted at these reservoirs. The other reservoirs make system releases for a common diversion at the Richmond gage control point. The firm yield for the 12-reservoir system consists of the sum of the Whitney, Waco, and Richmond gage diversions.

2. Whitney Reservoir provides 30,000 kilowatts of hydroelectric power. Annual energy of 1,200 kilowatt-hours per kilowatt of power is generated with a monthly distribution of 200 hours in July and August, 100 hours in June and Stepember, and 75 hours in each of the other eight months.

of the 30,000 kilowatts of peaking power, is 200 hours in July and August, 100 hours in June and September and 75 hours in each of the eight other months.

Possum Kingdom Reservoir was treated as a system water supply reservoir, without inclusion of the hydroelectric power operations in the model. Granbury Reservoir was constrained to a top of inactive pool elevation of 675, consistent with steam electric power cooling water operations, but otherwise treated as a system water supply reservoir.

The system firm yield was computed by HEC-3 with ten reservoirs releasing for a downstream control point. The Hubbard Creek, Whitney, and Waco Reservoir diversions were provided as input to HEC-3. The 12-reservoir system firm yield was then computed by manually adding the Whitney and Waco Reservoir firm yields to the 10-reservoir system firm yield computed with HEC-3.

As indicated in Tables 6.13 and 6.14, the system firm yield for the standard operating plan is 1,618 cfs, excluding local flows from the watershed below the dams, and 2,182 cfs including local flows. This includes diversions of 40 cfs and 106 cfs at Whitney and Waco Reservoirs and diversions of 1,472 cfs or 2,036 cfs (without and with local flows, respectively) at the Richmond gage control point.

System Firm Yield for Alternative Subsystems and Sediment Conditions

System firm yields are presented in Table 6.13 for the 12-reservoir system and three subsystems thereof. All model input data, except data specifying alternative subsystems and sediment conditions, are identical to the standard operating plan. The subsystems are delineated in terms of reservoirs located above specified control points or stream gaging stations. The 12-reservoir system is located above the Richmond gage. The 10-reservoir system above the Bryan gage excludes Limestone and Somerville Reservoirs. The 5-reservoir system above the Waco gage consists of Possum Kingdom, Granbury, Whitney, Aquilla, and Waco Reservoirs. The 5-reservoir system above the Cameron gage includes Proctor, Belton, Stillhouse Hollow, Georgetown, and Granger Reservoirs.

System firm yield simulations were repeated with and without inclusion of local uncontrolled flows originating from the watershed below the most downstream dams. The Richmond gage has a drainage area of about 45,000 square miles, of which 8,680 square miles or 19% of the total is not above one or more of the 13 reservoirs. The unregulated watershed areas above the Bryan, Cameron, and Waco gages but not above the reservoirs are 27%, 14%, and 1.6%, respectively, of the total watershed area above each gage. The large watershed below the dams provides a significant amount of runoff. System firm yield including and excluding unregulated local flows are presented in Table 6.13 for each control point except the Waco gage. The unregulated watershed above the Waco gage is too small to meaningfully quantify the impacts of including local flows in the firm yield computations.

System firm yields are presented in Table 6.13 for both 1984 and 2010 conditions of sedimentation. The sediment conditions are reflected in the elevation versus storage and area tables provided as model input data. All other factors, including top of conservation pool elevations, are the same for

Table 6.13
SYSTEM FIRM YIELD FOR ALTERNATIVE SUBSYSTEMS AND SEDIMENT CONDITIONS

Reservoirs above Control Point (Gage Station)	Conservation Storage Capacity (ac-ft)	Firm Yield (ac-ft/yr)		Firm Yield (cfs)	
		Excluding Local Flows	Including Local Flows	Excluding Local Flows	Including Local Flows
1984 Condition of Sedimentation					
Cameron Gage	801,140	292,500	354,700	404	490
Waco Gage	1,063,890	677,600	-	936	-
Bryan Gage	1,865,030	1,056,300	1,195,300	1,459	1,651
Richmond Gage	2,237,530	1,228,600	1,639,800	1,697	2,265
2010 Condition of Sedimentation					
Cameron Gage	705,410	277,300	347,500	383	480
Waco Gage	947,090	653,000	-	902	-
Bryan Gage	1,652,500	1,009,900	1,154,000	1,395	1,594
Richmond Gage	2,012,700	1,171,400	1,579,700	1,618	2,182

Table 6.14
COMPARISON OF INDIVIDUAL AND SYSTEM FIRM YIELDS

Reservoirs above Control Point (Gage Station)	Single Reservoir Firm Yield (cfs)	Individual Reservoir Firm Yield (cfs)	System Firm Yield			
			Excluding Local Flows (cfs)	Including Local Flows (cfs)	Excluding Local Flows (%)	Including Local Flows (%)
1984 Condition of Sedimentation						
Cameron Gage	415	372	404	490	109	132
Waco Gage	1,153	810	936	-	116	-
Bryan Gage	1,568	1,182	1,459	1,651	123	140
Richmond Gage	1,729	1,343	1,697	2,265	126	169
2010 Condition of Sedimentation						
Cameron Gage	380	343	383	480	112	140
Waco Gage	1,092	763	902	-	118	-
Bryan Gage	1,478	1,106	1,395	1,594	126	144
Richmond Gage	1,630	1,264	1,618	2,182	128	173

Note: The last two columns express system firm yield as a percentage of the sum of the individual reservoir firm yields.

the 1984 and 2010 sediment condition firm yields. The system firm yield for the 12-reservoir system, excluding the unregulated area below the dams, is 1,697 cfs based on 1984 sediment conditions and 1,618 cfs based on 2010 sediment conditions. Thus, 26 years of sediment deposition is indicated to reduce the firm yield by 4.7%.

For purposes of comparison, total individual and single reservoir firm yields are presented in Table 6.14. As previously discussed, single reservoir firm yields are computed ignoring all other reservoirs. Individual reservoir firm yields are computed based on including upstream reservoirs in the model with the previously computed firm yields being diverted at the upstream reservoirs. The individual and single reservoir firm yields for all the reservoirs located above the indicated control points are summed in the table. System firm yields are cited in Table 6.14 as a percentage of the sum of the corresponding individual reservoir firm yields.

Excluding local flows below the dams, the system firm yield for the standard operating plan (1,618 cfs) is 128% of the sum of the individual reservoir firm yields (1,264 cfs). The corresponding percentages for 2010 sediment condition firm yields, excluding local flows, at the Bryan, Waco, and Cameron gages are 126%, 118%, and 112%, respectively.

The single and individual reservoir firm yield for Whitney are computed based on assuming the active conservation pool is used entirely for water supply. Actual hydroelectric power operations are included in the system firm yield simulations. Thus, system firm yields are even larger percentages of the sum of the individual reservoir firm yields than indicated.

Each of the four gages have months of zero streamflow in the naturalized streamflow data for the 85-year simulation period. Thus, the unregulated, or zero reservoir storage, firm yields are zero. However, during most months of the simulation the control point flow requirements can be fully or partially met by unregulated local flows and thus, less reservoir drawdowns are required. For the standard operating plan, the system firm yield including local flows (2,182 cfs) is 135% higher than the system firm yield excluding local flows (1,618 cfs). The system firm yield including local flows (2,182 cfs) is 173% of the sum of the corresponding individual reservoir firm yields (1,264 cfs).

System Firm Yields for Alternative Operating Scenarios

System firm yields for variations from the standard operating plan are tabulated in Table 6.15. The firm yields are for the 12-reservoir system (Richmond gage) assuming 2010 conditions of sedimentation. The standard operating plan is listed first. The other scenarios represent a specific deviation from the standard operating plan. Firm yield is expressed both in cfs and as a percentage of the firm yield for the standard operating plan.

Simulation 2 involves raising the top of conservation pool elevation in Waco Reservoir from 455 feet to 462 feet, in accordance with the actual proposed reallocation plan. All other factors are the same as the standard operating plan. The reallocation of storage capacity from flood control to water supply increases the Waco Reservoir individual reservoir firm yield by 16 cfs, from 106 cfs to 122 cfs. The corresponding system firm yield increase from 1,264 cfs to 1,280 cfs is also 16 cfs.

Table 6.15

SYSTEM FIRM YIELDS FOR ALTERNATIVE OPERATING PLANS

2010 Sediment Condition, Richmond Gage

Simulation Scenario or Operating Plan	12-Reservoir System Firm Yield			
	Excluding Unregulated Flows		Including Unregulated Flows	
	cfs	%	cfs	%
1. standard operating plan	1,618	100.0	2,182	100.0
2. Waco conservation 462 ft	1,634	101.0	2,198	100.7
3. P.K. inactive 970 ft	1,558	96.3	2,020	92.6
4. P.K. 970 ft, Whitney no power	1,587	98.1	2,078	95.2
5. Whitney 520 ft, no power	1,670	103.2	2,311	105.9
6. Whitney 449 ft, no power	1,798	111.1	2,543	116.5
7. Granbury inactive 640 ft	1,669	103.2	2,233	102.3
8. eleven system reservoirs	1,650	102.0	2,221	101.8
9. seven system reservoirs	1,555	96.1	1,947	89.2
10. five system reservoirs	1,508	93.2	1,886	86.4
11. 30% inactive storage	1,392	86.0	1,812	83.0
12. maximum potential yield	1,846	114.1	2,543	116.5

Possum Kingdom Reservoir has a top of inactive pool elevation of 970 feet, set to facilitate hydroelectric power operations. The invert of the outlet works at 875 feet. The standard operating plan is based on operating for water supply, with the top of inactive set at elevation 875 feet. Simulation 4 in Table 6.15 shows the system firm yield corresponding to a top of inactive pool elevation of 970 feet. Raising the inactive pool level from 875 feet to 970 feet decreases the system firm yield to 1,558 cfs which is a decrease of 60 cfs from the standard operating plan. As indicated by Table 6.9, the Possum Kingdom individual reservoir firm yield is 384 cfs and 279 cfs, assuming top of inactive pool elevations of 875 feet and 970 feet, respectively, for a difference of 105 cfs. With the Possum Kingdom top of inactive pool at 970 ft, the 12-reservoir system firm yield (1,558 cfs) is 134% of the sum of the corresponding individual reservoir firm yields (1,159 cfs).

In simulations 4, 5, and 6 of Table 6.15, conservation releases from Whitney Reservoir are limited to water supply, with no releases solely for hydroelectric power. Releases from Whitney, along with the ten other system reservoirs, are made as required for the firm yield diversion at the Richmond gage. In simulations 5 and 6, the top of inactive pool elevation is 520 feet, which is the same for the standard operating plan. Simulation 7 is for a top of inactive pool elevation of 449 feet. With the pool elevations the same, operating Whitney strictly for water supply, rather than water supply and hydroelectric power, increases the firm yield to 1,670 cfs. Lowering the top of inactive pool to 449 feet increases the firm yield to 1,798 cfs. Thus, hydroelectric power operations at Whitney Reservoir reduce the firm yield otherwise available from the 12-reservoir system by 180 cfs (1,798 cfs minus 1,618 cfs).

Simulation 7 is identical to the standard operating plan except the Granbury top of inactive pool is lowered to elevation 640 feet. Thus, the contractual constraint limiting the top of inactive pool to elevation 675 feet instead of 640 feet reduces the system firm yield by 51 cfs (1,669 cfs minus 1,618 cfs).

In the standard operating plan, ten reservoirs release to meet the diversion at the Richmond gage. Individual reservoir firm yield diversions occur at the two remaining reservoirs, Waco and Whitney. Whitney also makes hydropower releases. Simulations 8, 9, and 10 involve redesignating the number of reservoirs which release for the Richmond gage control point. In simulation 8, eleven reservoirs, including Waco in addition to the basic ten, release for the downstream control point. In simulation 9, seven reservoirs (Aquilla, Waco, Belton, Stillhouse Hollow, Granger, Limestone, and Somerville) release for the downstream control point. In simulation 10, five reservoirs (Aquilla, Stillhouse Hollow, Granger, Limestone, and Somerville) release for the downstream control point. In all cases, individual reservoir firm yields are diverted at the other reservoirs. The individual reservoir firm yield diversions are added to the system diversion at the Richmond gage control point to obtain the 12-reservoir system firm yields tabulated in Table 6.15.

Treating Waco as a system reservoir (simulation 8) increases the firm yield to 1,650 cfs which is a 2.0% increase over the standard operating plan. With the Whitney top of inactive pool at 449 feet (simulation 6), the total system firm yield (1,798 cfs) is essentially identical with Waco Reservoir treated as either a system or local use reservoir. With only 5 system reservoirs (simulation 10), the 12-reservoir system firm yield is reduced to 1,508 cfs.

Although Granbury and Whitney Reservoirs have large inactive pools, the other reservoirs are emptied in the standard operating plan firm yield simulation. In actuality, a water supply failure occurs prior to total depletion of storage capacity. Severe drawdowns will necessitate emergency actions due to the high risk of depleting supplies even if supplies are never actually depleted. In simulation 11, 30% of the active conservation in each of ten reservoirs was converted to inactive pools. Granbury and Whitney are not included since they already have inactive pools. Thirty percent of the conservation capacity of the ten reservoirs represents 25% of the total active conservation capacity of the 12-reservoir system. Simulation 11 represents the yield that can be provided continuously during the simulation period without drought contingency plans being implemented, where depletion to 30% capacity is arbitrarily considered to constitute an impending emergency which triggers the drought contingency action. The resulting 12-reservoir system firm yield is 1,846 cfs.

Simulation 12 represents the maximum firm yield which can be supplied by the existing physical system ignoring contractual constraints. The top of inactive pool elevations are set by the inverts of the lowest outlet works, which for Possum Kingdom, Granbury, and Whitney Reservoirs are 875 feet, 640 feet, and 449 feet, respectively. The top of conservation pools are set at the existing elevations which are reflected in the standard operating plan. All 12 reservoirs release for the Richmond gage control point. Hydropower operations are not included. The resulting firm yield of 1,846 cfs is 114% greater than the standard operating plan firm yield of 1,618 cfs.

Simulation Results for Standard Operating Plan

The previously discussed standard operating plan is outlined in Table 6.12. Assuming 2010 conditions of sedimentation, the 12-reservoir system firm yields for the standard operating plan are 1,618 cfs (1,171,400 acre-feet/year) and 2,182 cfs (1,579,700 acre-feet/year), respectively, excluding and including local flows from the watershed above the Richmond gage which is not controlled by the reservoir system. Firm yields for the standard operating plan are compared with firm yields for deviations from the standard operating plan in Tables 6.13, 6.14, and 6.15. The firm yield analysis for the standard operating plan is discussed in previous paragraphs. Additional results of the HEC-3 simulation of the standard operating plan are presented below.

The 12-reservoir system firm yields of 1,618 cfs and 2,182 cfs are diverted in the HEC-3 simulation at the following locations, 1,472 cfs or 2,036 at the Richmond gage, 40 cfs at Whitney Reservoir, and 106 cfs at Waco Reservoir. The ten reservoirs, excluding Whitney and Waco, make releases as necessary to satisfy the 1,618 cfs or 2,036 cfs diversion at the Richmond gage. The Hubbard Creek individual reservoir firm yield of 57 cfs is diverted at Hubbard Creek Reservoir. Whitney Reservoir is operated for hydroelectric power as previously discussed.

The results of the simulation are summarized in Tables 6.16, 6.17, and 6.18. Table 6.16 is a water balance of the stream/reservoir system. In the model, the total streamflow input leaves the system as water use diversions,

Table 6.16
SYSTEM WATER BALANCE FOR STANDARD OPERATING PLAN
2010 Sediment Condition

Flows from Unregulated Watershed below Dams	Exclude	Include
12-Reservoir System Firm Yield (cfs)	1,618	2,182
Average Flow (cfs) over 85-Year Simulation Period		
System Inflow	4,763	7,887
Diversions	1,675	2,239
Richmond Gage	(1,472)	(2,036)
Waco Reservoir	(106)	(106)
Whitney Reservoir	(40)	(40)
Hubbard Creek Reservoir	(57)	(57)
Evaporation from 13 Reservoirs	462	457
Flow to the Gulf of Mexico	2,641	5,203

Table 6.17
RESERVOIR WATER BALANCE FOR STANDARD OPERATING PLAN
2010 Sediment Condition

Reservoir	Averages in cfs over 85-year Simulation				
			Conservation Releases		
	Inflow	Evaporation	Downstream	Diversion	Spills
12-Reservoir Firm Yield of 1,618 cfs Excluding Unregulated Flows					
Hubbard Creek	157	62	-	57	39
Possum Kingdom	1,118	73	450	-	598
Granbury	1,471	32	585	-	855
Whitney	2,160	99	880	40	1,143
Aquilla	101	11	27	-	63
Waco	451	23	-	106	323
Proctor	159	16	25	-	118
Belton	636	46	191	-	402
Stillhouse	305	21	99	-	187
Georgetown	90	4	18	-	68
Granger	244	13	66	-	165
Limestone	305	40	90	-	178
Somerville	324	25	88	-	211
12-Reservoir Firm Yield of 2,182 cfs Including Unregulated Flows					
Hubbard Creek	157	62	-	57	39
Possum Kingbom	1,118	72	441	-	608
Granbury	1,472	31	569	-	872
Whitney	2,161	99	818	40	1,206
Aquilla	101	11	21	-	69
Waco	451	23	-	106	323
Proctor	159	16	23	-	120
Belton	636	45	160	-	435
Stillhouse	305	20	82	-	205
Georgetown	90	4	15	-	71
Granger	244	12	45	-	186
Limestone	305	37	70	-	199
Somerville	324	25	57	-	242

Table 6.18
RESERVOIR STORAGE FREQUENCY FOR STANDARD OPERATING PLAN
System Firm Yield of 2,182 cfs Including Local Flows

	Conservation Storage in Percent of Capacity									
Reservoir	99-100	95-99	90-95	80-90	70-80	60-70	40-60	20-40	1-20	0-1
	Storage Frequency in Percent of Capacity									
Hubbard	7.7	4.0	3.7	9.8	15.1	16.8	24.7	12.7	5.2	0.2
Possum Kingdom	34.5	7.4	5.5	10.2	10.1	6.4	12.2	5.6	6.0	2.3
Granbury	39.0	10.5	5.7	10.4	7.5	5.4	10.2	5.0	3.8	2.5
Whitney	48.6	13.6	10.5	16.3	4.5	6.3	0.2	0.0	0.0	0.0
Aquilla	32.8	7.0	5.3	10.6	10.9	11.8	9.3	5.4	5.6	1.4
Waco	38.5	5.6	7.5	12.6	12.5	8.3	8.6	3.7	2.4	0.2
Proctor	43.3	10.5	7.4	9.9	7.5	6.4	6.6	4.2	3.6	0.7
Belton	42.0	5.1	3.9	11.7	10.6	7.5	5.6	5.9	6.6	1.2
Stillhouse	43.3	4.9	6.1	8.6	10.2	8.2	4.6	6.7	6.5	0.9
Georgetown	49.4	5.2	4.8	11.8	8.5	5.4	5.1	3.7	5.2	0.9
Granger	48.8	5.3	4.2	11.1	9.2	5.7	5.0	4.7	5.1	0.9
Limestone	40.7	5.3	6.1	10.5	8.1	7.5	7.7	6.9	5.2	2.1
Somerville	33.6	5.8	6.9	8.5	11.3	12.4	7.1	7.1	5.8	1.7

Note: Frequency is computed by dividing the number of months for which the end-of-month storage fell within the indicated range by 1,020 months in the 85-year simulation period.

reservoir evaporation losses, or flow into the Gulf of Mexico. In table 6.16, diversions, evaporation losses, and flows into the Gulf are expressed in cfs as averages over the 1,020-month simulation period. System inflow, which is equal to the naturalized streamflow at the Richmond gage, averages 7,887 cfs. This includes average inflows of 4,763 cfs regulated by one or more of the 13 reservoirs and additional unregulated flows of 3,124 cfs. The 4,763 cfs average inflow to the reservoirs is the sum of the naturalized flows at the most downstream dam on the Brazos River and each of the tributaries, which includes Whitney, Aquilla, Waco, Belton, Stillhouse Hollow, Granger, Limestone, and Somerville Reservoirs. Thus, 3,124 cfs, or 40% of the total inflow occurs downstream of the dams. For the firm yield simulation including unregulated flows, the outflow from the system, expressed as average flow rates, are the firm yield diversions of 2,239 cfs, reservoir evaporation of 457 cfs, and an average flow into the Gulf of Mexico of 5,203 cfs.

Water balances for each of the individual reservoirs are presented in Table 6.17. The water balance consists of reservoir inflows, conservation releases, spills, and reservoir evaporation averaged over the 85-year simulation period. Average inflows essentially equal the sum of average evaporation, conservation releases, and spills. However, since the simulation begins with full conservation pools in January 1900 and does not necessarily end with full conservation pools in December 1984, the sum of the three outflow terms slightly exceeds the inflow at several of the reservoirs.

Reservoir storage versus frequency relationships are tabulated in Table 6.18. The number of months for which the end-of-month storage was within various ranges of the total conservation storage capacity was counted by HEC-3. Storage frequencies were determined by dividing the number of months by 1020, which is the number of months in the simulation period. Conservation pool ranges are defined in terms of percentage of the total conservation storage capacity.

Firm yield is controlled by two drawdown periods, July 1908 to August 1912 and July 1950 to August 1956. Both critical drawdown periods result in essentially the same firm yield. The critical periods are essentially the same for the firm yield simulations for both excluding and including unregulated flows. The reservoirs are full in June 1908, essentially empty in August 1912, and full again in January 1914. Thus, the first critical drawdown extends over a period of four years and two months. The second critical drawdown period for the ten reservoirs, which released for the common control point at the Richmond gage, begin in June and July 1950. The reservoirs are full and spilling in May 1950 and several are also full in June. The reservoirs are essentially empty in August 1956. Thus, the critical drawdown extends over a period of six years and two months. The reservoirs are almost empty from August 1956 through March 1957 and refill during the flood of April and May 1957. The reservoirs are essentially refilled during the single month of April 1957. As indicated in Table 6.9, the critical drawdown periods for Hubbard Creek and Waco Reservoirs are November 1942 to May 1953 and June 1952 to April 1955.

Reservoir Reliability

Definitions

A number of definitions of reservoir reliability are cited in the technical literature. A common definition is that reliability is the proportion of time that the reservoir is able to meet the consumer demand (McMahon and Mein 1986). Period reliability (R) is estimated from the results of a simulation as

$$R = n/N$$

where n denotes the number of time periods during the simulation for which demands could be met and N is the total number of months in the simulation. For example, the present study used a 1,020-month simulation period, which covers the January 1900 through December 1984 hydrologic record. Reliability is computed by dividing the number of months a specified diversion or flow requirement is met by 1,020. Reliability represents the probability or likelihood that demands can be met for any randomly selected month.

The risk or probability of failure (F) is the complement of the reliability (R)

$$F = 1-R$$

and represents the percent of the time periods for which the demand is not met or the likelihood that the demand will not be met in any randomly selected time period. Alternatively, probability of failure can be defined as the ratio of the time the reservoir is empty to the total time. Since a water management agency will likely place restrictions on the use of water before the reservoir becomes completely empty, an alternative definition for probability of failure can be based on the number of time periods for which restrictions are required (McMahon and Mein 1986).

Volumetric reliability is the ratio of the total volume of water supplied to the volume demanded over the simulation period. The shortage volume occurring in each period of a simulation are totalled. The volume reliability is computed as volume demanded minus shortages divided by volume demanded.

The HEC-3 and HEC-5 models compute the number of periods (months) in which shortages occur and the total shortage volume and also compute a shortage index. The shortage index is defined as follows.

$$\text{SHORTAGE INDEX} = \frac{100}{N} \sum_{1}^{N} \left(\frac{\text{ANNUAL SHORTAGE}}{\text{ANNUAL REQUIREMENT}} \right)^2$$

The index is a somewhat arbitrary means of measuring the frequency and magnitude of shortages.

Reliability Analysis Results

Individual reservoir reliabilities for several of the reservoirs are presented in Table 6.19, based on 1984 sediment conditions. Diversions range from 100 percent to 200 percent of the previously computed firm yields. The model computes the number of months in which the specified diversion is not met

Table 6.19
INDIVIDUAL RESERVOIR RELIABILITY

Diversion		Shortage Periods	Average Shortage	Shortage Index	Period Reliability	Volume Reliability
% Firm Yield	cfs	(months)	(cfs)	-	(%)	(%)
		Possum Kingdom Reservoir				
100%	288	0	0.00	0.00	100 %	100 %
105%	302	2	0.28	0.01	99.8%	99.9%
110%	317	4	0.59	0.03	99.6%	99.8%
125%	360	11	3.08	0.17	98.9%	99.1%
150%	432	23	8.86	0.71	97.7%	97.9%
175%	504	47	19.37	1.37	95.4%	96.2%
200%	576	73	37.68	2.53	92.8%	93.5%
		Aquilla Reservoir				
100%	25	1	0.00	0.00	99.9%	99.9%
105%	26	2	0.03	0.01	99.8%	99.9%
110%	28	2	0.07	0.05	99.8%	99.8%
125%	31	24	0.37	0.35	97.6%	99.8%
150%	38	49	1.41	1.52	95.2%	96.3%
175%	44	86	2.87	3.25	91.6%	93.5%
200%	50	113	4.53	4.78	88.9%	91.0%
		Waco Reservoir				
100%	116	0	0.00	0.00	100 %	100 %
105%	122	6	0.23	0.02	99.4%	99.8%
110%	128	15	0.88	0.08	98.5%	99.3%
125%	145	35	3.23	0.60	96.6%	97.8%
150%	174	83	8.92	1.85	91.9%	94.9%
175%	203	126	16.76	3.34	87.6%	91.7%
200%	232	170	26.71	5.41	83.3%	88.5%
		Belton Reservoir				
100%	177	0	0.00	0.00	100 %	100 %
105%	186	2	0.32	0.03	99.9%	99.8%
110%	195	9	1.19	0.16	99.1%	99.4%
125%	221	30	4.59	0.92	97.1%	97.9%
150%	266	63	14.05	3.14	93.8%	94.7%
175%	310	100	25.27	5.60	90.2%	91.8%
200%	354	145	40.18	7.37	85.8%	88.6%
		Stillhouse Hollow Reservoir				
100%	108	0	0.00	0.00	100.0%	100.0%
105%	113	12	0.40	0.04	98.8%	99.6%
110%	119	21	0.96	0.14	97.9%	99.2%
125%	135	28	3.50	1.14	97.3%	97.4%
150%	162	61	9.80	3.46	94.0%	94.0%
175%	189	111	17.59	5.82	89.1%	90.7%
200%	216	162	28.58	8.03	84.1%	86.8%
		Limestone Reservoir				
100%	105	0	0.00	0.00	100.0%	100.0%
105%	110	4	0.17	0.01	99.6%	99.9%
110%	116	9	0.37	0.05	99.1%	99.7%
125%	131	29	2.38	0.60	97.2%	98.2%
150%	158	62	7.41	2.32	93.9%	95.3%
175%	184	105	15.92	4.62	89.7%	91.3%
200%	210	142	26.27	7.18	86.1%	87.5%
		Somerville Reservoir				
100%	61	0	0.00	0.00	100.0%	100.0%
105%	64	6	0.09	0.01	99.4%	99.9%
110%	67	7	0.20	0.06	99.3%	99.7%
125%	76	10	0.58	0.39	99.0%	99.2%
150%	92	23	1.86	1.10	97.7%	98.0%
175%	107	46	3.95	1.89	95.5%	96.3%
200%	122	68	6.71	2.81	93.3%	94.5%

and also sums the magnitudes of the shortages. The average shortage is the summation of the shortage volumes divided by 1020 months. The volume reliability is the total shortage volume divided by the 1020-month total diversion requirement. The period reliability is the number of shortage periods divided by 1020. The shortage index was computed as described above. The firm yield is, by definition, met 100 percent of the time during the historical period-of-record simulation. At most of the reservoirs, a diversion of 110 percent of the firm yield can be maintained more than 99 percent of the time. Diversions of twice the firm yield have period reliabilities ranging from 83.3 percent at Waco Reservoir to 93.3 percent at Somerville reservoir. The volume reliability for a diversion of twice the firm yield ranges from 86.8 percent at Stillhouse Hollow Reservoir to 94.5 percent at Somerville Reservoir.

System reliabilities for the standard operating plan are presented in Table 6.20. The reliabilities are based on 2010 sediment conditions and are repeated with and without inclusion of unregulated flows. The relationship between diversions expressed as a percentage of firm yield and both period and volume reliability is similar for the system and the individual reservoirs.

Table 6.20
SYSTEM RELIABILITY FOR STANDARD OPERATING PLAN

Diversion % Firm Yield	 cfs	Shortage Periods (months)	Shortage Volume (cfs mon)	Shortage Index -	Period Reliability (%)	Volume Reliability (%)
Standard Operating Plan Excluding Unregulated Flows						
100	1,618	0	0	0.00	100.0	100.0
105	1,699	2	3	0.02	99.8	99.8
110	1,780	21	6	0.07	97.9	99.6
125	2,023	37	40	0.57	96.4	97.9
150	2,427	79	124	2.06	92.3	94.6
175	2,832	105	241	3.99	89.7	91.0
200	3,236	161	404	6.26	84.2	86.9
Standard Operating Plan Including Unregulated Flows						
100	2,182	0	0	0.00	100.0	100.0
105	2,291	6	8	0.04	99.4	99.6
110	2,400	9	19	0.12	99.1	99.2
125	2,728	29	61	0.65	97.2	97.6
150	3,273	68	180	1.90	93.3	94.2
175	3,819	109	334	3.72	89.3	90.9
200	4,364	158	543	5.85	84.5	87.1

CHAPTER 7
WATER RIGHTS SIMULATION

Water law in Texas is described in Chapter 2. Water rights in the Brazos River Basin are discussed in Chapter 3. The Texas Water Commission (TWC) Water Availability Model and the Texas A&M University (TAMU) Water Rights Analysis Program (WRAP) are described in Chapter 4. The present chapter documents the results of a basin simulation study, using TAMUWRAP, based on the assumption that all water users divert the full amount of water to which they are legally entitled. Data generated by the TAMUWRAP simulation are used as input data in the HEC-3 firm yield computations documented in the next chapter.

The TAMUWRAP simulation analysis summarized in this chapter provides an evaluation of water availability in the Brazos River Basin from the perspective of water rights. Permitted storage capacities and diversions associated with the over 1,000 water rights in the basin are combined with historical hydrology in the model. During each month of the hydrologic period-of-record simulation, diversions, diversion shortages, streamflow depletions, and reservoir storage levels are computed. Unappropriated streamflows are also determined. Thus, the simulation study includes analyses of both the capability of the river basin to satisfy existing water rights and the amount of unappropriated water remaining for potential additional water rights applicants. The simulation is based on the assumptions of (1) a repetition of historical hydrology and (2) the full amounts of all permitted diversions are withdrawn as long as water is available. In the next chapter, firm yields associated with 13 reservoirs are presented which reflect the impacts of senior water rights. The TAMUWRAP simulation also includes development of data required for the HEC-3 firm yield computations outlined in the next chapter.

Comparison with TWC Water Availability Model

The Texas Water Commission (TWC) has applied their Water Availability Model to the Brazos River Basin as well as the other major river basins in the state. The primary purpose of the TWC water availability modeling effort is to develop unappropriated flow data for use in considering applications for water use permits. The unappropriated flows computed with TAMUWRAP are compared with the TWC unappropriated flows later in this chapter.

The TWC Water Availability Model and TAMUWRAP perform essentially the same types of computations. A river basin is represented by a set of watersheds and subwatersheds in the TWC Water Availability Model. A river basin is represented by a set of control points in TAMUWRAP. If a control point is assigned to each subwatershed and the same input data are used, TAMUWRAP results should be essentially identical to the results obtained with the TWC Water Availability Model.

The naturalized streamflows, water rights, return flow factors, and monthly water use distribution factors incorporated in the TWC Water Availability Model were provided by the TWC for use in the TAMUWRAP simulation. Development of these data by the TWC represents the bulk of the overall modeling effort. TWDB Report 64 reservoir evaporation rates were used in both models. The storage versus area relationships for 35 reservoirs, which contain most of the storage capacity in the basin, are also essentially the same. The TWC Water Availability Model includes an individual storage versus elevation relationship for almost all of the reservoirs in the basin. The generalized storage versus area relationship used in the TAMUWRAP simulation for the numerous smaller reservoirs should not significantly affect the model results.

However, there are significant differences in the Brazos River Basin simulations performed by the TWC and the present study. The TWC must be able to evaluate applications for water diversions at essentially any location in the basin. Relatively small existing water rights throughout the basin, as well as the larger rights, must be precisely analyzed. Consequently, the basin is represented by numerous small subwatersheds in the TWC Water Availability Model. The present study focuses on a few large reservoirs with relatively large water rights. The numerous smaller water rights are important primarily from the perspective of their impacts on the major reservoir water rights and overall basin water balance. The TAMUWRAP simulation was simplified by representing the basin by 19 control points at selected key locations. Water rights are aggregated by control point. Due to the aggregation in the TAMUWRAP simulation, smaller water rights on tributaries may be supplied in the model with water for which there actually is not physical access. Thus, shortages associated with the smaller tributary water rights may be conservatively low. However, the results of the TAMUWRAP simulation, as used in the study, are not considered to be significantly affected by the aggregation to 19 control points.

A TAMUWRAP simulation could include control points at each of the TWC subwatersheds. However, streamflow data would have to be developed and provided as input for each control point. Since only a limited number of stream gages are available, streamflow data for most of the subwatersheds must be synthesized. The amount of effort involved would far exceed the scope of the TAMU study and is unnecessary in accomplishing the purposes of the study.

The Richmond gage is the most downstream streamflow gage included in the present study. Runoff entering the river below the Richmond gage is neglected. All water rights, including those located below the Richmond gage, are incorporated in TAMUWRAP. In the TWC model, runoff from the watershed below the Richmond gage is also available to supply lower basin water rights.

Two other significant differences between the TWC Water Availability Model and TAMUWRAP simulations of the Brazos River Basin are addressed by the sensitivity analyses included in the presentation of TAMUWRAP simulation results. In the TAMUWRAP simulation, water rights priority dates are associated with reservoir storage capacity as well as diversions. When each water right is considered in turn by priority in the model, the reservoir capacity is filled to the extent allowed by the availability of streamflow even if junior water rights experience a diversion shortage. In the TWC Water Availability Model, reservoirs associated with senior rights are not refilled if diversion shortages result for junior rights. The other difference is that the TWC excluded unappropriated flows originating from the watershed above Possum Kingdom Reservoir in computing unappropriated flows at downstream locations. Due to channel losses in the upper basin above Possum Kingdom Reservoir, unappropriated flow estimates are considered highly uncertain, and the unappropriated flows would probably be loss before reaching downstream locations.

There are other differences between the TWC Water Availability Model and TAMUWRAP simulations. However, for purposes of the present study, the differences cited above are probably the most important.

Input Data

Simulations were performed with the Texas A&M University Water Rights Analysis Program (TAMUWRAP). Input data include: monthly naturalized streamflows and reservoir evaporation rates; water rights diversions, storage capacities, priorities, and use types; reservoir storage versus area relationships; monthly water use factors; and return flow factors.

The configuration of a stream/reservoir/rights system is represented in TAMUWRAP by a set of control points. The Brazos River Basin was modeled using the 19 control points shown in Figure 7.1. Thirteen control points are located at dams, and the other six control points are at stream gage stations. As indicated in previous chapters, the dams also have associated stream gage stations. Naturalized monthly streamflows and reservoir evaporation rates are provided for each control point. Water rights are aggregated by control point. The Texas Water Commission (TWC) has located each individual water right. Locations are specified on the TWC water rights list by watersheds and subwatersheds, with the Brazos River Basin being divided into 44 watersheds which are each further divided into subwatersheds. For purposes of the TAMUWRAP simulation, the 1,328 water rights were each assigned to one of the 19 control points. The water rights associated with a control point includes all rights located between the control point and the next upstream control point. The most upstream control points on the Brazos River and each tributary include all water rights above the control point.

The water rights data presented in Chapter 3 and the present chapter are based on a list of water rights developed by the Texas Water Commission. The list is a printout of a computer file and is entitled "Brazos River Basin, List of Water Rights Including Permits, Certified Filings, Claims and Certificates of Adjudication As Existing on June 30, 1986." The water rights are summarized in Tables 3.14 through 3.21. The total water rights diversion at each control point in the model is also tabulated in Table 7.1.

As indicated by Tables 3.17 and 3.18, the water rights include storage capacities totalling 4,567,202 acre-feet in 598 reservoirs. As indicated by Tables 3.11 and 3.19, 3,221,891 acre-feet of this capacity is contained in the 13 reservoirs. The simulation model requires storage versus area relationships for each reservoir for use in the evaporation computations. For the 13 reservoirs, initial condition elevation versus area and capacity tables used in the hydrologic firm yield computations of Chapter 6 were also incorporated in the TAMUWRAP simulation. Area versus storage tables for 22 other major reservoirs were developed from curves included in TWDB Report 126 (1973). A single generalized storage versus area relationship was developed for all the other smaller reservoirs by averaging storage versus area curves for nine of the smallest reservoirs in the Brazos River Basin included in TWDB Report 126.

Monthly water use distribution factors have been developed by the Texas Water Commission (TDWR 1981) for the upper, middle, and lower Brazos River Basin for municipal, industrial, irrigation, and mining uses. In the present

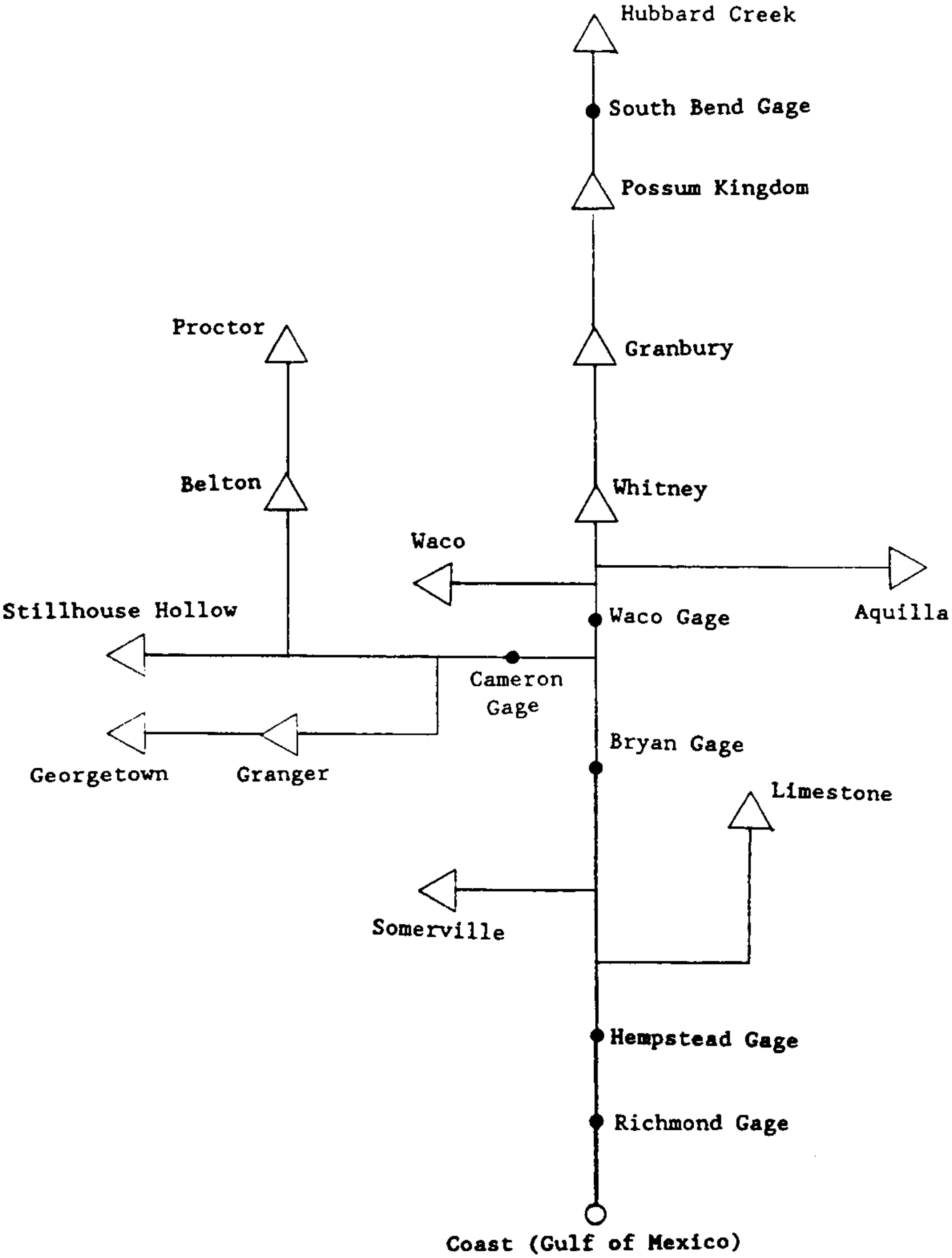


Figure 7.1 System Schematic

Table 7.1
DIVERSIONS AND RETURN FLOWS BY CONTROL POINT

Control Point	Diversion (ac-ft/yr)	Return Flow (ac-ft/yr)
1. Hubbard Creek Reservoir	60,442	15,254
2. South Bend Gage	198,527	31,869
3. Possum Kingdom Reservoir	251,371	10,530
4. Granbury Reservoir	96,642	13,337
5. Whitney Reservoir	67,127	7,371
6. Aquilla Reservoir	13,937	7,365
7. Waco Reservoir	68,231	31,645
8. Waco Gage	24,523	14,728
9. Proctor Reservoir	35,840	1,029
10. Belton Reservoir	144,801	100,801
11. Stillhouse Hollow Reservoir	75,529	28,659
12. Georgetown Reservoir	13,775	5,444
13. Granger Reservoir	21,163	8,605
14. Cameron Gage	101,756	50,072
15. Bryan Gage	80,418	11,559
16. Limestone Reservoir	71,200	25,440
17. Somerville Reservoir	48,119	2,501
18. Hempstead Gage	191,338	8,669
19. Richmond Gage	605,689	10,260
Total	2,170,428	385,138

Note:

Diversions assigned to a control point include all diversions located between that control point and the next upstream control point(s). Thus, diversions assigned to a reservoir control point include upstream diversions as well as diversions from the reservoir. Return flows are from the diversions assigned to the indicated control points.

study, the TWC factors for the upper, middle, and lower basin were averaged to obtain the basinwide factors tabulated in Table 7.2.

Return flow factors incorporated in the TWC Water Availability Model were also used in the TAMUWRAP simulation. A return flow factor is the fraction of a diversion which is returned to the stream. The TWC developed the return flow factors from reported measured return flows and diversions. Nonzero return flow factors are provided for 64 water rights, which include 58 rights with reservoir storage capacity and 6 streamflow rights without reservoirs. Included in the 58 reservoirs with nonzero return flow factors are Hubbard Creek (return flow factor of 0.26), Waco (0.53), Aquilla (0.53), Belton (0.76), Stillhouse Hollow (0.4), Georgetown (0.4), and Granger (0.4). The remainder of the BRA reservoirs have zero return flow in the model. The return flows associated with the diversions at each control point are tabulated in Table 7.1 With the exception of return flows from diversions at Waco Reservoir, the flows are returned at the next downstream control point. Waco Reservoir return flows are returned at the Bryan gage control point. Assuming no shortages, return flows total 385,138 acre-feet/year, of which 50% are from diversions from seven reservoirs: Hubbard Creek (14,560 ac-ft/yr), Granbury (5,500 ac-ft/yr), Waco (31,323 ac-ft/yr), Belton (100,515 ac-ft/yr), Stillhouse Hollow (27,107 ac-ft/yr), Georgetown (5,444 ac-ft/yr), and Granger (7,936 ac-ft/yr).

Monthly naturalized streamflow and reservoir evaporation rate data discussed in Chapters 5 and 6 were provided as input data for the 19 control points in the TAMUWRAP model. TWDB Report 64 net evaporation rates are provided on a quadrangle basis. The net evaporation rates adopted for the 13 reservoir control points are identical to the data used in the Chapter 6 firm yield simulations. An evaporation data quadrangle most representative of the locations of the associated reservoirs was selected for each of the six other control points.

The Richmond gage is the most downstream control point included in the model. Runoff from the watershed below the Richmond gage is neglected. All water rights, including those located below the Richmond gage, are incorporated in the model. The total system inflow is equal to the naturalized flow at the Richmond gage.

Explanation of Terms

The concepts of water rights, shortages, unappropriated streamflows, streamflow depletions, and naturalized streamflows are fundamental to the TAMUWRAP simulation and are discussed below.

In the model, a water right consists of: (1) a control point location, (2) diversion amount in ac-ft/yr, (3) reservoir storage capacity in ac-ft, (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. Also, certain optional output data can be tabulated by type of use. The priority number typically represents dates. For example, a priority date of May 12, 1965 is inputed as 19650512. Multiple water rights can be associated with the same reservoir.

Table 7.2
MONTHLY WATER USE DISTRIBUTION FACTORS

Month	Type of Use			
	Municipal	Industrial	Irrigation	Mining
Jan	0.070	0.070	0.000	0.080
Feb	0.060	0.070	0.010	0.080
Mar	0.070	0.070	0.060	0.080
Apr	0.070	0.080	0.060	0.080
May	0.080	0.090	0.130	0.080
Jun	0.100	0.100	0.220	0.090
Jul	0.130	0.100	0.230	0.090
Aug	0.120	0.100	0.150	0.090
Sep	0.090	0.080	0.060	0.090
Oct	0.080	0.080	0.080	0.080
Nov	0.060	0.080	0.000	0.080
Dec	0.070	0.080	0.000	0.080
Total	1.000	1.000	1.000	1.000

A water right is represented in the model by a single value of each of the variables listed above. 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 have several water rights with different priority dates. Likewise, 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. However, the total number of rights in the model, or in the TWC water rights list, may be somewhat misleading since a single appropriator owning a single reservoir may have several rights listed representing different water uses or other variables with multiple values.

In each month of the simulation, TAMUWRAP considers each water right in turn by priority number. The water right diversion amount is diverted as long as unappropriated streamflow or reservoir storage is available. A shortage occurs if sufficient streamflow and/or storage are not available to supply the water right that month.

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 basin. Naturalized streamflow data are discussed in previous chapters. Streamflow depletions and unappropriated streamflows are computed by a TAMUWRAP simulation. The total computed streamflow depletions and unappropriated streamflow equals the total inputed naturalized streamflow plus return flows for the entire basin.

A streamflow depletion represents the streamflow taken by a water right in a given month to (1) meet the target water right diversion and (2) fill the previously drawndown 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 flows represent the streamflow still available after all streamflow depletions or the water which flows into the Gulf of Mexico. The unappropriated flows represent water not used by the water rights included in the simulation.

Simulation Runs

For each month of the simulation period, TAMUWRAP performs the water accounting computations for each water right in turn on a priority basis. The computations proceed by month and, within each month, by water right with the most senior water right in the basin being considered first. Priorities are specified in the input data by year, month, and day. Water rights are input in order of location from upstream to downstream. If more than one water right has identically the same date, the most upstream location is given priority. TAMUWRAP computes diversions and diversion shortages associated with the water right. Permitted reservoir capacity is filled to the extent allowed by available streamflow. Computed streamflow depletions include water used to replenish reservoir storage as well as meet diversion requirements. Reservoir evaporation is computed and incorporated in the water balance. Return flows are computed as a percentage of diversions and reenter the stream at the next downstream control point, except Waco Reservoir return flows reenter at the second downstream control point. An accounting is maintained of reservoir storage levels in each of the 598 reservoirs and streamflow still available at each of the 19 control points. The simulation begins with all reservoirs full.

The results of a base simulation run and four other alternative simulation runs are presented. The 1900-1984 hydrologic simulation period adopted in the hydrologic firm yield simulation study (Chapter 6) was also used in the water rights simulation study (Chapter 7). The TWC Water Availability Model uses a 1940-1976 simulation period. In order to compare results with TWC unappropriated flows, the TAMUWRAP simulation was repeated for a 1940-1976 period. Priorities associated with municipal use could possibly be changed in the future in conjunction with the Wagstaff Act. An alternative run reflects all municipal rights with priority dates after May 17, 1931 being changed to May 17, 1931. Return flow estimates are highly uncertain. An alternative run is based on the assumption of no return flows. In the above runs, water right priorities are assumed to apply to refilling depleted reservoir storage capacity as well as to diversions. Another run is presented in which storage capacities in the major reservoirs were given priorities junior to all diversions.

The five alternative simulation runs are listed below.

Run 1: Run 1 reflects a 1900-1984 hydrologic simulation period, priorities based on dates specified by the water rights, and TWC return flow factors.

Run 2: Run 2 reflects a 1940-1976 hydrologic simulation period, priorities based on dates specified by the water rights, and TWC return flow factors. Run 2 is identical to Run 1 except for the shorter simulation period.

Run 3: Run 3 reflects a 1900-1984 hydrologic simulation period, Wagstaff Act priorities, and return flow factors. Run 3 is identical to Run 1 except all municipal rights with priority dates after May 17, 1931 are changed to May 17, 1931.

Run 4: Run 4 reflects a 1900-1984 hydrologic simulation period, priorities based on dates specified by the water rights, and zero return flows for all rights. Run 4 is identical to Run 1 except for return flow factors.

Run 5: Run 5 reflects a 1900-1984 hydrologic simulation period, priorities associated with storage capacities in major reservoirs junior to all diversions, and TWC return flow factors. Run 5 is identical to run 1 except the priorities associated with refilling storage capacity in the major reservoirs (storage capacities equal to or greater than 5,000 acre-feet) are junior to all diversions.

The analysis of results in this chapter focuses on simulation run 1. The other four runs demonstrate the sensitivity of simulation results to specific factors. The alternative runs provide a comparative evaluation of these factors. The firm yield computations in the next chapter are based on simulation run 1.

Simulation Results

The TAMUWRAP output, like HEC-3 and HEC-5 output, can be extremely voluminous. Simulation results are briefly summarized here in terms of annual totals of shortages, streamflow depletions, unappropriated flows, and the components of a water balance. Selected monthly unappropriated streamflow data are also included in the summary.

System Water Balance

System water balances for the five runs are presented in Table 7.3 with all quantities expressed in terms of averages over the entire simulation period. Annual water balances for the basin are presented in Tables 7.4 through 7.8. The quantities in Table 7.3 are averages of the values in Tables 7.4 through 7.8. The columns of the tables are related by the water balance equation as follows:

naturalized streamflow + return flows = reservoir evaporation + diversions + unappropriated flows + storage change

where all terms are annual totals of monthly values from the model and are expressed in units of acre-feet. In addition to the terms in the above water balance equation, end-of-year storage and diversion shortages are also included in the tables. The total storage in all 598 reservoirs at the end of December is shown. Shortages occur whenever insufficient water is available to satisfy water rights.

The system inflow is the naturalized streamflow at the Richmond gage, which is provided as input to TAMUWRAP. The other terms in Tables 7.3 through 7.8 are computed by the model. The return flows from diversions at the Richmond gage control point are included in the unappropriated flows but do not reenter the stream since this is the most downstream control point. Return flows from diversions at the other control points reenter the stream at the next downstream control point except return flows from Waco Reservoir reenter at the second downstream control point. A dummy water right was inserted at the Waco gage with a diversion amount of 31,323 ac-ft/yr, which equals the return flow from Waco Reservoir diversions, and a return flow factor of 1.0 in order to make the Waco Reservoir diversion return flows reenter at the Bryan gage rather than the Waco gage control point. Thus, the diversion and return flow totals are both 31,323 ac-ft/yr too high in Tables 7.4 through 7.8. The diversion and return flow means have been adjusted in Table 7.3 to remove the artificial increase. Reservoir evaporation is computed each month at 598 reservoirs. The net change in the total storage in the reservoirs during the year is also included in Tables 7.3 through 7.8. The diversions are water rights target diversion amounts minus shortages. Unappropriated streamflow is flow into the Gulf of Mexico.

Table 7.3 consists of mean annual rates, in acre-feet/year, over the simulation period. In simulation run 1, inflows of 5,667,440 ac-ft/yr are available to the system. This is the naturalized streamflow at the Richmond gage averaged over the 1900-1984 simulation period. Return flows averaging 356,949 ac-ft/yr and a net storage depletion averaging 14,496 ac-ft/yr also provide water to the system. The 6,038,885 ac-ft/yr (5,667,440 + 356,949 + 14,496) input is accounted for as follows: reservoir evaporation (529,699 ac-

Table 7.3
SYSTEM WATER BALANCE FOR ALTERNATIVE RUNS

Run	Naturalized Streamflow	Return Flows	Reservoir Evaporation	Rights Diversions	Unappropriated Streamflow	Storage Change	End-of-Year Storage	Shortages
Means in acre-feet/year								
1	5,667,440	356,949	529,699	1,962,582	3,546,215	-14,496	3,558,050	207,847
2	5,805,580	359,060	518,692	1,966,604	3,690,471	-11,416	3,576,896	203,826
3	5,667,440	343,100	538,124	1,944,251	3,541,774	-14,466	3,619,086	226,178
4	5,667,440	-0-	509,893	1,938,888	3,235,218	-16,607	3,416,599	231,541
5	5,667,440	357,614	529,375	2,030,315	3,478,583	-16,699	3,435,152	140,116

Run 1 - 1900-1984 simulation period, permitted priorities, TWC return flow factors
Run 2 - 1940-1976 simulation period
Run 3 - Wagstaff Act priorities
Run 4 - zero return flows
Run 5 - zero priority for storage capacity in major reservoirs

Table 7.4
ANNUAL WATER BALANCE (RUN 1)

Year	Naturalized Streamflow	Return Flows	Reservoir Evaporation	Rights Diversions	Unapprop. Flows	Storage Change	End-of-Year Storage	Shortages
	(acre-feet)							
1900.	11682666.	412245.	653513.	2129707.	9378520.	-67245.	4381936.	72047.
1901.	1791948.	379149.	598395.	1937800.	541641.	-907095.	3474843.	263951.
1902.	4915118.	401914.	578162.	2080647.	2027786.	650095.	4124936.	141107.
1903.	6212631.	398018.	588487.	2093470.	4314728.	-386711.	3738225.	108284.
1904.	2461067.	402843.	535315.	1994883.	675019.	-341925.	3396299.	206869.
1905.	8098545.	402064.	580588.	2079439.	5367569.	472659.	3868959.	122314.
1906.	3628073.	404622.	550344.	2046924.	1549199.	-113812.	3755146.	154828.
1907.	4398889.	405502.	540777.	2102245.	1936581.	223820.	3978966.	99508.
1908.	10209155.	404304.	590464.	2082753.	8216381.	-276500.	3702467.	118999.
1909.	1153469.	383656.	478404.	1892971.	48920.	-884322.	2818146.	308780.
1910.	1244616.	349561.	384279.	1680331.	286025.	-757390.	2060756.	521420.
1911.	1962789.	348392.	324882.	1862819.	423051.	-300404.	1760353.	338932.
1912.	2469477.	286780.	282327.	1674565.	1067208.	-268181.	1492173.	527186.
1913.	6637021.	336707.	324042.	1829895.	2795222.	2024386.	3516558.	371857.
1914.	12022316.	403720.	560882.	2080646.	9323132.	461261.	3977819.	121108.
1915.	11292281.	408975.	629433.	2170669.	8698311.	202243.	4180062.	31086.
1916.	5487508.	392004.	595647.	2032414.	3823906.	-572967.	3607097.	169338.
1917.	997265.	370714.	464789.	1877525.	127826.	-1102732.	2504368.	324225.
1918.	4022818.	374938.	406455.	1890472.	1094698.	1005925.	3510292.	311280.
1919.	11614557.	415924.	607459.	2186304.	8409884.	826741.	4337030.	15450.
1920.	8040568.	415602.	633745.	2180789.	5708449.	-66907.	4270125.	20966.
1921.	5075127.	400437.	602874.	2088588.	3306500.	-522574.	3747551.	113166.
1922.	12151902.	386692.	580474.	2066435.	10142914.	-251435.	3496116.	135318.
1923.	6290273.	399596.	548313.	2021605.	3624625.	495262.	3991377.	180147.
1924.	5719830.	378568.	538880.	1956800.	4248963.	-646290.	3345088.	244951.
1925.	3274109	366942.	458064.	1738632.	1357487.	86609.	3431697.	463120.
1926.	7843222	400357.	568168.	2134944.	5028625.	511794.	3943489.	66809.
1927.	5038272	397497.	555433.	2066025.	3018164.	-203912.	3739579.	135727.
1928.	2864894	389160.	528697.	1965085.	943693.	-184037.	3555543.	236666.
1929.	6429473.	381841.	536013.	1992607.	4162554.	119791.	3675333.	209146.
1930.	6543061.	383924.	548191.	1989228.	4000654.	388579.	4063912.	212526.
1931.	4083469.	393542.	553334.	1985183.	2403563.	-465117.	3598795.	216568.
1932.	7947029.	405539.	593436.	2132324.	5253929.	372639.	3971432.	69431.
1933.	2416065.	386115.	560595.	1982962.	825789.	-567814.	3403619.	218788.
1934.	3699377.	370478.	498198.	1779814.	2073740.	-282217.	3121400.	421937.
1935.	8768609.	404004.	582324.	2127032.	5457568.	1005356.	4126754.	74722.
1936.	6923648.	407223.	591044.	2102858.	4695654.	-58780.	4067974.	98896.
1937.	3549565.	387079.	546553.	1944119.	1857282.	-411531.	3656445.	257632.
1938.	6334270.	400229.	583116.	2116236.	4076304.	-41259.	3615186.	85516.
1939.	2055990.	376634.	522049.	1950816.	365196.	-405595.	3209591.	250936.
1940.	7850608.	392694.	453108.	1998663.	4870225.	921006.	4130596.	203090.
1941.	13806996.	415706.	429754.	2196272.	11396148.	200458.	4331051.	5483.
1942.	8517753.	411920.	467543.	2137621.	6299472.	24960.	4356014.	64134.
1943.	1984786.	396419.	739565.	2051196.	591327.	-1001283.	3354731.	150556.
1944.	8901734.	401148.	527930.	2034893.	6443162.	296818.	3651550.	166857.
1945.	10074292.	409131.	538958.	2130514.	7543223.	270652.	3922201.	71240.
1946.	8406420.	395112.	543577.	2015833.	6155707.	85857.	4008059.	185919.
1947.	4876952.	377360.	636046.	1981582.	3224203.	-587692.	3420367.	220169.
1948.	1873208.	366751.	624012.	1834292.	388098.	-606525.	2813841.	367468.
1949.	4321941.	387357.	416526.	1968374.	1669027.	655057.	3468898.	233380.
1950.	3960386.	390855.	601588.	2023123.	1820359.	-93888.	3375009.	178630.
1951.	996849.	365855.	553671.	1761398.	10260.	-963043.	2411966.	440354.
1952.	1623246.	357426.	467543.	1709215.	214596.	-410894.	2001072.	492538.
1953.	4607306.	366264.	397349.	1834981.	2042553.	698392.	2699464.	366771.
1954.	1362340.	314433.	626601.	1644065.	108827.	-703154.	1996310.	557687.
1955.	2986948.	360227.	445525.	1837289.	230482.	833116.	2829426.	364455.
1956.	929191.	314980.	571448.	1535049.	23623.	-887237.	1942188.	666705.
1957.	14983308.	395489.	336338.	2064959.	10505152.	2471950.	4414140.	136794.
1958.	5932074.	395011.	539003.	2107822.	4101024.	-421107.	3993033.	93931.
1959.	5876065.	401293.	459692.	2095361.	3409815.	311845.	4304878.	106393.
1960.	7158198.	401011.	554094.	2098232.	5009803.	-103266.	4201613.	103522.
1961.	10018476.	412711.	498038.	2162114.	7785772.	-14832.	4186782.	39640.
1962.	3381713.	411325.	545261.	2119263.	1308980.	-180845.	4005936.	82490.
1963.	1698274.	392733.	622662.	1957077.	412355.	-901123.	3104814.	244674.
1964.	2209915.	389875.	424101.	1871862.	242549.	60936.	3165750.	329890.
1965.	8631581.	403923.	419766.	2066312.	5826915.	722431.	3888180.	135441.
1966.	6411800.	406350.	528542.	2106515.	4153534.	29221.	3917400.	95237.
1967.	1963572.	395585.	561997.	1965844.	323508.	-492701.	3424699.	235908.
1968.	11074828.	409095.	498507.	2160957.	8385562.	438812.	3863510.	40797.
1969.	6405519.	407700.	503511.	2060934.	4054338.	194356.	4057866.	140819.
1970.	5020008.	399985.	528832.	2053776.	3360123.	-522766.	3535102.	147976.
1971.	3342968.	406844.	533511.	1996572.	927188.	292436.	3827537.	205180.
1972.	3001679.	390975.	522538.	1965267.	1144144.	-239374.	3588164.	236485.
1973.	9112670.	396114.	431208.	2072990.	6728100.	276441.	3864604.	128763.
1974.	7822334.	390434.	502267.	1948950.	5415640.	345857.	4210462.	252803.
1975.	7279962.	404034.	551161.	2142717.	5444212.	-454788.	3755672.	59038.
1976.	6400484.	403808.	460698.	2099583.	3973138.	270543.	4026217.	102169.
1977.	6396303.	383937.	674570.	2003666.	4768333.	-667330.	3358887.	198086.
1978.	2267881.	365638.	536218.	1852506.	569975.	-327623.	3031265.	349247.
1979.	8864448.	395081.	478705.	2075806.	6065448.	638771.	3670036.	125947.
1980.	3940466.	381954.	681946.	1903526.	1915599.	-179018.	3491018.	298227.
1981.	6337486.	393300.	502215.	2057715.	3534742.	634903.	4125920.	144038.
1982.	4359863.	382872.	547508.	2012444.	2617236.	-434470.	3691450.	189308.
1983.	4298145.	374134.	571574.	1953645.	2253715.	-109312.	3582139.	248108.
1984.	3110466.	374746.	564975.	1782592.	1502778.	-365142.	3216997.	419161.
TOTALS:	481732352.	33003086.	45024432.	169481952.	301428256.	-1232189.	302434272.	17667034.
MEANS:	5667440.	388272.	529699.	1993905.	3546215.	-14496.	3558050.	207847.

Table 7.5
ANNUAL WATER BALANCE (RUN 2)

(acre-feet)

Year	:Naturalized : Streamflow	: Return: Flows	Reservoir : Evaporation	: Rights :Diversions	:Unapprop.: Flows	: Storage : Change	:End-of-Year: Storage	: Shortages
1940.	7850608.	399005.	575375.	2107042.	5623647.	-56773.	4392409.	94710.
1941.	13806996.	415706.	436732.	2196315.	11638770.	-49185.	4343222.	5440.
1942.	8517753.	411920.	467977.	2137626.	6310353.	13640.	4356864.	64129.
1943.	1984786.	396419.	739564.	2051385.	591327.	-1001471.	3355393.	150367.
1944.	8901734.	401148.	527930.	2035026.	6443162.	296686.	3652080.	166725.
1945.	10074292.	409131.	538932.	2130554.	7543223.	270637.	3922716.	71199.
1946.	8406420.	395112.	543573.	2015694.	6155707.	86000.	4008718.	186059.
1947.	4876952.	377360.	636046.	1981732.	3223982.	-587622.	3421096.	220018.
1948.	1873208.	366683.	624012.	1834316.	388098.	-606618.	2814478.	367434.
1949.	4321941.	387357.	416523.	1968508.	1668784.	655169.	3469647.	233246.
1950.	3960386.	390855.	601569.	2023210.	1820245.	-93842.	3375803.	178543.
1951.	996849.	365855.	553600.	1761699.	10260.	-963274.	2412530.	440052.
1952.	1623246.	357426.	467530.	1709542.	214596.	-411209.	2001322.	492210.
1953.	4607306.	366264.	397340.	1835231.	2042553.	698151.	2699471.	366520.
1954.	1362340.	314433.	626486.	1644268.	108827.	-703243.	1996229.	557484.
1955.	2986948.	360227.	445470.	1837330.	230482.	833140.	2829369.	364424.
1956.	929191.	314980.	571304.	1535300.	23623.	-887345.	1942023.	666454.
1957.	14983308.	395489.	336336.	2065023.	10504077.	2472965.	4414990.	136731.
1958.	5932074.	395011.	539003.	2107855.	4101020.	-421136.	3993854.	93898.
1959.	5876065.	401293.	459669.	2095484.	3409685.	311874.	4305728.	106269.
1960.	7158198.	401011.	554094.	2098298.	5009737.	-103266.	4202463.	103456.
1961.	10018476.	412711.	498038.	2162127.	7785762.	-14835.	4187628.	39627.
1962.	3381713.	411325.	545261.	2119277.	1308964.	-180842.	4006786.	82477.
1963.	1698274.	392733.	622662.	1957171.	412354.	-901216.	3105570.	244580.
1964.	2209915.	389875.	424101.	1872003.	242549.	60795.	3166365.	329749.
1965.	8631581.	403923.	419765.	2066375.	5826648.	722635.	3889000.	135378.
1966.	6411800.	406350.	528542.	2106577.	4153442.	29251.	3918250.	95176.
1967.	1963572.	395577.	561996.	1965868.	323508.	-492724.	3425526.	235884.
1968.	11074828.	409095.	498507.	2160988.	8385539.	438804.	3864329.	40766.
1969.	6405519.	407700.	503511.	2060954.	4054288.	194387.	4058716.	140800.
1970.	5020008.	399985.	528832.	2053881.	3360123.	-522871.	3535846.	147871.
1971.	3342968.	406844.	533508.	1996732.	927188.	292280.	3828126.	205021.
1972.	3001679.	390975.	522537.	1965322.	1143829.	-239113.	3589014.	236430.
1973.	9112670.	396114.	431208.	2073062.	6728100.	276369.	3865381.	128690.
1974.	7822334.	390434.	502262.	1949099.	5415640.	345714.	4211095.	252654.
1975.	7279962.	404034.	551128.	2142747.	5444212.	-454785.	3756308.	59008.
1976.	6400484.	403808.	460663.	2099666.	3973138.	270494.	4026804.	102086.
TOTALS:	214806448.	14444168.	19191586.	73923280.	136547440.	-422380.	132345152.	7541565.
MEANS:	5805580.	390383.	518692.	1997927.	3690471.	-11416.	3576896.	203826.

Table 7.6
ANNUAL WATER BALANCE (RUN 3)

Year	Naturalized Streamflow	Return Flows	Reservoir Evaporation	Rights Diversions	Unapprop. Flows	Storage Change	End-of-Year Storage	Shortages
				(acre-feet)				
1900.	11682666.	408656.	652016.	2121994.	9382728.	-65874.	4383073.	79760.
1901.	1791948.	368932.	592859.	1923660.	544882.	-901403.	3481672.	278091.
1902.	4915118	371084.	575842.	2009969.	2108047.	591804.	4073474.	191783.
1903.	6212631	385354.	591561.	2090958.	4224176.	-309031.	3764443.	110794.
1904.	2461067	379298.	537091.	1960736.	621281.	-279070.	3485372.	241014.
1905.	8098545.	383914.	596106.	2032119.	5365506.	488086.	3973459.	169633.
1906.	3628073.	370828.	578925.	1967778.	1555843.	-103901.	3869558.	233973.
1907.	4398889.	372467.	571639.	2074298.	1907569.	217569.	4087127.	127453.
1908.	10209155.	381637.	602033.	2056451.	8215422.	-283382.	3803746.	145301.
1909.	1153469.	357240.	490930.	1818844.	38706.	-839093.	2964652.	382907.
1910.	1244616.	348071.	414839.	1728336.	191110.	-743662.	2220991.	473414.
1911.	1962789.	357710.	351097.	1770842.	359395.	-163823.	2057167.	430908.
1912.	2469477.	320451.	301325.	1582450.	1069900.	-168004.	1889165.	619301.
1913.	6637021.	333930.	366581.	1748364.	2902037.	1950765.	3839929.	453387.
1914.	12022316.	389099.	593098.	2066594.	9471765.	279281.	4119209.	135160.
1915.	11292281.	407627.	632768.	2177064.	8810795.	78781.	4197992.	24690.
1916.	5487508.	388263.	593066.	2034245.	3821386.	-573141.	3624851.	167507.
1917.	997265.	357066.	463793.	1853914.	111147.	-1075662.	2549191.	347836.
1918.	4022818.	362986.	417062.	1896803.	1033792.	1038005.	3587195.	304948.
1919.	11614557.	405094.	619149.	2177966.	8430225.	791839.	4379031.	23788.
1920.	8040568.	405469.	639651.	2163155.	5708738.	-66032.	4313000.	38599.
1921.	5075127.	390466.	609105.	2069801.	3302316.	-516291.	3796710.	131952.
1922.	12151902.	377321.	586201.	2052591.	10148295.	-258178.	3538531.	149161.
1923.	6290273.	366220.	559972.	1973706.	3599631.	522898.	4061428.	228044.
1924.	5719830	379111.	559913.	1990960.	4223835.	-676039.	3385391.	210790.
1925.	3274109.	356686.	462054.	1704237.	1218656.	243844.	3629234.	497515.
1926.	7843222.	386686.	573266.	2120236.	5200473.	335504.	3964738.	81516.
1927.	5038272.	377816.	561679.	2052734.	2985208.	-183753.	3780986.	149018.
1928.	2864894.	363841.	562049.	1903263.	852920.	-90430.	3690556.	298488.
1929.	6429473	367825.	565502.	2018065.	4158869.	54766.	3745322.	183687.
1930.	6543061.	368863.	564012.	2005058.	4002609.	339788.	4085110.	196694.
1931.	4083469.	383188.	564045.	1977944.	2382903.	-458651.	3626461.	223808.
1932.	7947029.	392041.	605573.	2114753.	5204594.	413753.	4040213.	87001.
1933.	2416065.	373122.	572761.	1954052.	826277.	-564470.	3475745.	247700.
1934.	3699377.	359599.	510889.	1815010.	2008407.	-276944.	3198799.	386741.
1935.	8768609.	395398.	587316.	2134244.	5509012.	933043.	4131838.	67510.
1936.	6923648.	394797.	591590.	2081811.	4671600.	-26973.	4104864.	119942.
1937.	3549565.	386815.	551984.	1983246.	1837769.	-437325.	3667542.	218505.
1938.	6334270.	399244.	586831.	2130922.	4053298.	-38052.	3629490.	70832.
1939.	2055990.	369354.	528533.	1967072.	334045.	-404812.	3224679.	234679.
1940.	7850608.	373449.	464329.	1935519.	4878180.	945422.	4170100.	266234.
1941.	13806996.	413445.	431665.	2193699.	11419655.	174984.	4345081.	8055.
1942.	8517753.	396921.	466931.	2103615.	6333926.	9577.	4354662.	98140.
1943.	1984786.	381465.	734904.	2021036.	572472.	-962595.	3392066.	180716.
1944.	8901734.	389453.	523740.	2019982.	6465009.	282019.	3674086.	181769.
1945.	10074292.	400701.	532461.	2123537.	7566914.	251683.	3925768.	78215.
1946.	8406420.	389594.	542660.	2019160.	6092951.	140310.	4066079.	182592.
1947.	4876952.	374207.	643032.	2002523.	3234911.	-629516.	3436564.	199227.
1948.	1873208.	350920.	624082.	1832290.	373938.	-607042.	2829522.	369460.
1949.	4321941.	363284.	425966.	1965380.	1607764.	685054.	3514577.	236371.
1950.	3960386.	372238.	619189.	2023608.	1793555.	-103837.	3410741.	178144.
1951.	996849.	352998.	563082.	1732061.	10260.	-957573.	2453167.	469689.
1952.	1623246.	338687.	476291.	1708430.	177657.	-403922.	2049245.	493321.
1953.	4607306.	355910.	410257.	1862030.	1978369.	711983.	2761228.	339720.
1954.	1362340.	299588.	608670.	1623668.	108046.	-681279.	2079949.	578084.
1955.	2986948.	330596.	465861.	1774246.	225009.	851217.	2931165.	427506.
1956.	929191.	301268.	591406.	1532719.	6430.	-904885.	2026281.	669034.
1957.	14983308.	376438.	332760.	2043149.	10595640.	2386788.	4413075.	158603.
1958.	5932074.	389171.	538685.	2090899.	4084293.	-393229.	4019846.	110854.
1959.	5876065.	381848.	458440.	2058576.	3451018.	289656.	4309503.	143176.
1960.	7158198.	389435.	553922.	2083811.	5007192.	-97461.	4212042.	117943.
1961.	10018476.	405355.	497691.	2156798.	7786920.	-18021.	4194022.	44956.
1962.	3381713.	377486.	547487.	2085030.	1269637.	-143319.	4050702.	116722.
1963.	1698274.	368264.	637356.	1934203.	395016.	-900574.	3150128.	267549.
1964.	2209915.	368197.	440057.	1838401.	150372.	147715.	3297843.	363350.
1965.	8631581.	398106.	419730.	2057990.	5961994.	589694.	3887538.	143763.
1966.	6411800.	397873.	529334.	2098357.	4131506.	49854.	3937392.	103387.
1967.	1963572.	369712.	564688.	1916747.	243196.	-391977.	3545415.	285004.
1968.	11074828.	396974.	498162.	2145534.	8491702.	336015.	3881429.	56221.
1969.	6405519.	379692.	507090.	2018259.	4032094.	227471.	4108901.	183493.
1970.	5020008.	384355.	533320.	2027339.	3373262.	-529893.	3579009.	174414.
1971.	3342968.	377216.	542187.	1904926.	931530.	340989.	3919998.	296828.
1972.	3001679.	371957.	535469.	1930667.	1185790.	-279066.	3640933.	271085.
1973.	9112670.	373720.	439801.	2056523.	6714701.	275087.	3916019.	145228.
1974.	7822334.	369745.	515035.	1906553.	5414087.	355726.	4271746.	295200.
1975.	7279962.	394843.	557762.	2133307.	5464549.	-481149.	3790596.	68448.
1976.	6400484.	381739.	462627.	2085791.	3957130.	276453.	4067051.	115960.
1977.	6396303.	383013.	684263.	2000502.	4778572.	-685486.	3381565.	201250.
1978.	2267881.	358241.	556258.	1793198.	474677.	-199929.	3181636.	408554.
1979.	8864448.	375090.	489172.	2065099.	6097673.	587236.	3768870.	136652.
1980.	3940466.	363417.	685845.	1890097.	1924823.	-198015.	3570856.	311652.
1981.	6337486.	372648.	513107.	2029537.	3588834.	578534.	4149389.	172216.
1982.	4359863.	367550.	556782.	2024292.	2583565.	-437562.	3711828.	177459.
1983.	4298145.	364913.	573402.	1974395.	2241877.	-128381.	3583447.	227357.
1984.	3110466.	360672.	561165.	1794056.	1478898.	-364086.	3219362.	407697.
TOTALS:	481732352.	31825962.	45740524.	167923824.	301050752.	-1229597.	307622304.	19225144.
MEANS:	5667440.	374423.	538124.	1975574.	3541774.	-14466.	3619086.	226178.

Table 7.7
ANNUAL WATER BALANCE (RUN 4)

(acre-feet)

Year	:Naturalized : Streamflow	: Return: Flows	Reservoir : Evaporation	: Rights : Diversions	:Unapprop.: Flows	: Storage : Change	:End-of-Year: : Storage	: Shortages
1900.	11682666.	0.	650560.	2097979.	9019698.	-85669.	4363512.	72452.
1901.	1791948.	0.	583884.	1873805.	411165	-1076919.	3286595.	296623.
1902.	4915118.	0.	555695.	1996109.	1652876.	710367.	3996961.	174321.
1903.	6212631.	0.	581239.	2063412.	3908518.	-340597.	3656365.	107017.
1904.	2461067.	0.	506418.	1961885.	516402.	-523705.	3132658.	208542.
1905.	8098545.	0.	570768.	2032941.	4830659.	664136.	3796796.	137488.
1906.	3628073.	0.	533919.	2000736.	1268184.	-174806.	3621989.	169691.
1907.	4398889.	0.	528898.	2041803.	1535476.	292638.	3914627.	128626.
1908.	10209155.	0.	580259.	2057653.	7875180.	-304012.	3610616.	112776.
1909.	1153469.	0.	445612.	1832647.	0.	-1124809.	2485808.	337780.
1910.	1244616.	0.	335670.	1596885.	128382.	-816329.	1669481.	573543.
1911.	1962789.	0.	280465.	1777935.	220745.	-316374.	1353107.	392492.
1912.	2469477.	0.	216039.	1466986.	916746.	-130319.	1222788.	703444.
1913.	6637021.	0.	300786.	1711903.	2406926.	2217363.	3440151.	458525.
1914.	12022316.	0.	564692.	2013075.	8928992.	515465.	3955614.	157355.
1915.	11292281.	0.	628427.	2127720.	8322018.	214025.	4169639.	42711.
1916.	5487508.	0.	584234.	2007666.	3580366.	-684808.	3484833.	162762.
1917.	997265.	0.	432778.	1825850.	31663.	-1293051.	2191783.	344577.
1918.	4022818.	0.	359453.	1777845.	741981.	1143507.	3335290.	392584.
1919.	11614557.	0.	606639.	2153522.	7858040.	996262.	4331550.	16909.
1920.	8040568.	0.	631332.	2121515.	5363301.	-75674.	4255878.	48916.
1921.	5075127.	0.	597789.	2067258.	2980527.	-570517.	3685362.	103172.
1922.	12151902.	0.	572701.	2022128.	9878445.	-321391.	3363970.	148301.
1923.	6290273.	0.	530815.	1949869.	3200771.	608766.	3972736.	220558.
1924.	5719830.	0.	527913.	1902198.	4066915.	-777232.	3195505.	268229.
1925.	3274109.	0.	415630.	1661571.	1147940.	48946.	3244450.	508857.
1926.	7843222.	0.	562798.	2081353.	4509679.	689344.	3933793.	89077.
1927.	5038272.	0.	548955.	2032381.	2715338.	-258462.	3675333.	138048.
1928.	2864894.	0.	518729.	1913068.	672336.	-239282.	3436051.	257360.
1929.	6429473.	0.	529050.	1954976.	3850601.	94811.	3530862.	215453.
1930.	6543061.	0.	538185.	1963065.	3540243.	501544.	4032407.	207365.
1931.	4083469.	0.	541983.	1905787.	2242182.	-606515.	3425893.	264641.
1932.	7947029.	0.	590056.	2099218.	4769816.	487863.	3913756.	71213.
1933.	2416065.	0.	550630.	1938471.	603128.	-676190.	3237565.	231957.
1934.	3699377.	0.	474126.	1724722.	1787683.	-287178.	2950387.	445705.
1935.	8768609.	0.	578172.	2087015.	4941706.	1161643.	4112027.	83416.
1936.	6923648.	0.	580327.	2068758.	4327011.	-52525.	4059502.	101672.
1937.	3549565.	0.	530142.	1900215.	1671722.	-552575.	3506931.	270212.
1938.	6334270.	0.	579459.	2078371.	3678679.	-2324.	3504605.	92059.
1939.	2055990.	0.	506863.	1897001.	172522.	-520439.	2984167.	273427.
1940.	7850608.	0.	428646.	1953961.	4419007.	1048975.	4033141.	216467.
1941.	13806996.	0.	429073.	2165107.	10921338.	291409.	4324548.	5326.
1942.	8517753.	0.	465722.	2101844.	5922834.	27278.	4351828.	68586.
1943.	1984786.	0.	728010.	1998406.	396839.	-1138520.	3213309.	172022.
1944.	8901734.	0.	514429.	2014355.	6064516.	308350.	3521657.	156072.
1945.	10074292.	0.	524723.	2107417.	7197340.	244729.	3766385.	63011.
1946.	8406420.	0.	527205.	1943754.	5769686.	165705.	3932091.	226674.
1947.	4876952.	0.	631276.	1956668.	2861862.	-572883.	3359208.	213760.
1948.	1873208.	0.	594215.	1794996.	253806.	-769858.	2589349.	375431.
1949.	4321941.	0.	405136.	1917758.	1276750.	722261.	3311611.	252670.
1950.	3960386.	0.	581124.	1953228.	1542585.	-116580.	3195031.	217204.
1951.	996849.	0.	489812.	1676073.	0.	-1169042.	2025989.	494355.
1952.	1623246.	0.	397687.	1629577.	55530.	-459567.	1566422.	540852.
1953.	4607306.	0.	341689.	1730080.	1770050.	765467.	2331889.	440348.
1954.	1362340.	0.	527827.	1533381.	71654.	-770527.	1561364.	637048.
1955.	2986948.	0.	368302.	1732810.	145121.	740673.	2302036.	437618.
1956.	929191.	0.	430958.	1402484.	0.	-904256.	1397781.	767947.
1957.	14983308.	0.	336639.	2001069.	9633101.	3012441.	4410225.	169362.
1958.	5932074.	0.	536423.	2087475.	3776687.	-468550.	3941675.	82956.
1959.	5876065.	0.	448584.	2026378.	3061780.	339280.	4280955.	144052.
1960.	7158198.	0.	546678.	2064753.	4648473.	-101731.	4179225.	105678.
1961.	10018476.	0.	494547.	2138238.	7416843.	-31249.	4147977.	32192.
1962.	3381713.	0.	539526.	2088739.	918412.	-165064.	3982912.	81691.
1963.	1698274.	0.	606305.	1873989.	276611.	-1058666.	2924247.	296438.
1964.	2209915.	0.	388018.	1800435.	26717.	-5293.	2918954.	369993.
1965.	8631581.	0.	410702.	2021119.	5358266.	841410.	3760364.	149310.
1966.	6411800.	0.	525255.	2069878.	3717295.	99311.	3859674.	100553.
1967.	1963572.	0.	539871.	1905353.	130112.	-611821.	3247854.	265075.
1968.	11074828.	0.	496863.	2120797.	7887523.	569587.	3817440.	49635.
1969.	6405519.	0.	496491.	2030741.	3727839.	150367.	3967807.	139688.
1970.	5020008.	0.	521535.	2011439.	3023735.	-536729.	3431078.	158990.
1971.	3342968.	0.	498392.	1917633.	631433.	295436.	3726514.	252796.
1972.	3001679.	0.	506185.	1889812.	928851.	-323211.	3403304.	280616.
1973.	9112670.	0.	428709.	2045341.	6218951.	419623.	3822927.	125089.
1974.	7822334.	0.	490897.	1918489.	5083470.	329436.	4152362.	251941.
1975.	7279962.	0.	540021.	2102441.	5123726.	-486276.	3666085.	67989.
1976.	6400484.	0.	443833.	2050997.	3635200.	270398.	3936485.	119431.
1977.	6396303.	0.	655339.	1945329.	4557749.	-762151.	3174332.	225100.
1978.	2267881.	0.	506573.	1771878.	355880.	-366453.	2807880.	398550.
1979.	8864448.	0.	470704.	2056291.	5621203.	716213.	3524093.	114139.
1980.	3940466.	0.	651295.	1836875.	1766830.	-314577.	3209517.	333551.
1981.	6337486.	0.	482450.	1999231.	2954103.	901671.	4111187.	171200.
1982.	4359863.	0.	541964.	1982092.	2313136.	-477345.	3633843.	188336.
1983.	4298145.	0.	564110.	1919336.	1939165.	-124480.	3509363.	251094.
1984.	3110466.	0.	535069.	1730148.	1316992.	-471754.	3037609.	440282.
TOTALS:	481732352.	0.	43340904.	164805488.	274993536.	-1411585.	290410880.	19680972.
MEANS:	5667440.	0.	509893.	1938888.	3235218.	-16607.	3416599.	231541.

Table 7.8
ANNUAL WATER BALANCE (RUN 5)

(acre-feet)

Year	Naturalized Streamflow	Return Flows	Reservoir Evaporation	Rights Diversions	Unapprop. Flows	Storage Change	End-of-Year Storage	Shortages
1900.	11682666.	413185.	655719.	2187503.	9280647.	-70372.	4330408.	14253.
1901.	1791948.	384683.	598084.	1983178.	547463.	-929226.	3401184.	218574.
1902.	4915118	406678.	573141.	2164985.	2052762.	488984.	3890169.	36770.
1903.	6212631.	402242.	599343.	2147538.	4106346.	-197656.	3692514.	54217.
1904.	2461067.	409125.	540183.	2143026.	651904.	-467473.	3225041.	58728.
1905.	8098545.	405010.	588441.	2132530.	5158827.	593411.	3818453.	69225.
1906.	3628073.	405318.	567242.	2171185.	1478113.	-183287.	3635164.	30570.
1907.	4398889.	410416.	553742.	2170468.	1887691.	180762.	3815926.	31286.
1908.	10209155.	406613.	596796.	2151715.	8067523.	-156861.	3659066.	50038.
1909.	1153469.	386577.	482001.	1977499.	39209.	-971782.	2687285.	224254.
1910.	1244616.	367074	387317.	1802387.	236100.	-832579.	1854706.	399366.
1911.	1962789.	356975.	298579.	1925313.	405678.	-314698.	1540008.	276439.
1912.	2469477.	282576.	255850.	1651523.	1083613.	-239765.	1300242.	550229.
1913.	6637021	343838.	324455.	1874067.	2632873.	2096178.	3396420.	327687.
1914.	12022316.	409324.	568717.	2139569.	9238271.	487737.	3884157.	62185.
1915.	11292281.	411886.	632373.	2190907.	8633778.	251655.	4135811.	10847.
1916.	5487508.	396120.	593960.	2108982.	3812701.	-597139.	3538675.	92771.
1917	997265.	374677.	466168.	1918885.	128425.	-1141803.	2396871.	282866.
1918.	4022818.	388386.	404959.	2048616.	1010761.	900030.	3296901.	153137.
1919.	11614557.	416025.	617289.	2200691.	8205887.	1006614.	4303515.	1064.
1920.	8040568	415671.	641524.	2198201.	5681059.	-62726.	4240789.	3554.
1921.	5075127.	402308.	612076.	2121045.	3295219.	-509310.	3731479.	80708.
1922.	12151902.	387552.	584591.	2106679.	10125577.	-278423.	3453057.	95073.
1923.	6290273.	402841.	561598.	2096064.	3522442.	466667.	3919725.	105690.
1924.	5719830.	388068.	559479.	2065172.	4197925.	-670264.	3249461.	136581.
1925.	3274109.	366741.	454264.	1803802.	1267902.	64844.	3314305.	397952.
1926.	7843222.	400902.	573420.	2161890.	4955859.	539444.	3853749.	39865.
1927.	5038272.	400904.	563198.	2141191.	2974302.	-194724.	3659024.	60563.
1928.	2864894.	395055.	544441.	2118011.	899267.	-304311.	3354715.	83742.
1929.	6429473.	391810.	539543.	2095485.	4132354.	38262.	3392975.	106269.
1930.	6543061.	389926.	561459.	2091193.	3765399.	483189.	3876166.	110561.
1931.	4083469.	400363.	565430.	2056243.	2296807.	-436325.	3439841.	145509.
1932.	7947029.	408341.	607000.	2178509.	5073934.	495838.	3935676.	23246.
1933.	2416065.	390139.	574868.	2063800.	813211.	-600844.	3334835.	137953.
1934.	3699377.	381360.	504790.	1848738.	2047325.	-350140.	2984693.	353014.
1935.	8768609.	408042.	586064.	2162436.	5306342.	1116666.	4101358.	39319.
1936.	6923648	408723.	594440.	2160558.	4603797.	-54474.	4046885.	41197.
1937.	3549565.	401522.	556384.	2064194.	1801982.	-440335.	3606550.	137560.
1938.	6334270.	404465.	586168.	2153682.	4022327.	-24815.	3581736.	48071.
1939.	2055990.	382786.	530288.	2019995.	349928.	-462926.	3118809.	181759.
1940.	7850608.	395984.	458987.	2130742.	4655354.	952664.	4071473.	71013.
1941.	13806996.	415853.	433463.	2199683.	11377090.	212543.	4284014.	2072.
1942.	8517753.	412642.	471110.	2164645.	6281219.	19442.	4303459.	37110.
1943.	1984786.	398093.	740934.	2114063.	564778.	-998524.	3304935.	87689.
1944.	8901734.	407153.	526880.	2095840.	6448344.	236742.	3541677.	105914.
1945.	10074292.	412201.	523817.	2183216.	7552681.	190483.	3732160.	18538.
1946.	8406420.	407506.	530334.	2119479.	6047147.	106124.	3838282.	82276.
1947.	4876952.	382446.	639784.	2044323.	3109311.	-498719.	3339564.	157429.
1948.	1873208	377793.	607445.	1970303.	390459.	-713624.	2625940.	231449.
1949.	4321941.	390377.	419338.	2071520.	1636869.	577207.	3203146.	130235.
1950.	3960386	393001.	588084.	2140326.	1734894.	-115300.	3087846.	61430.
1951.	996849.	348599.	516286.	1860911.	10260.	-1037168.	2050680.	340840.
1952.	1623246.	286837.	421962.	1653405.	154422.	-323157.	1727523.	548347.
1953.	4607306.	377733.	373182.	1983222.	1992825.	602423.	2329946.	218533.
1954.	1362340.	300046.	545954.	1707965.	108682.	-676189.	1653757.	493786.
1955.	2986948.	313166.	402686.	1937506.	206626.	736939.	2390696.	264247.
1956	929191.	202940.	495808.	1403741.	6430.	-760600.	1630096.	798013.
1957.	14983308.	381152.	332004.	2092841.	10172231.	2724388.	4354487.	108914.
1958.	5932074.	397087.	540107.	2159262.	4083268.	-425457.	3929033.	42492.
1959.	5876065.	403473.	456848.	2152674.	3321092.	323059.	4252091.	49080.
1960.	7158198.	402480.	557945.	2145452.	4958301.	-99428.	4152663.	56302.
1961.	10018476	414023.	500450.	2192082.	7770845.	-35969.	4116694.	9673.
1962.	3381713.	411864.	552613.	2167976.	1255722.	-187169.	3929528.	33779.
1963.	1698274.	393983.	644068.	2022948.	407910.	-947039.	2982487.	178805.
1964.	2209915	401093.	437568.	2032746.	155594.	-17931.	2964557.	169009.
1965.	8631581.	409293.	416771.	2154158.	5669324.	767170.	3731729.	47597.
1966.	6411800.	409343.	532486.	2143598.	4005860.	148730.	3880459.	58158.
1967.	1963572.	401399.	566088.	2134885.	289167.	-601592.	3278866.	66870.
1968.	11074828.	409447.	502795.	2179836.	8248005.	553556.	3832421.	21918.
1969.	6405519.	409576.	508490.	2145238.	3947917.	167739.	4000160.	56517.
1970.	5020008.	400808.	539980.	2077659.	3339946.	-493324.	3506837.	124094.
1971.	3342968.	409550.	545659.	2129316.	757640.	272235.	3779072.	72438.
1972.	3001679.	398733.	524246.	2101316.	1092013.	-312733.	3466339.	100438.
1973.	9112670.	399071.	439924.	2130583.	6657667.	314623.	3780959.	71170.
1974.	7822334.	396718.	511762.	2020867.	5258820.	382530.	4163492.	180887.
1975.	7279962.	404838.	556276.	2176718.	5438875.	-450218.	3713273.	25038.
1976.	6400484.	406768.	463545.	2140117.	3960950.	202585.	3915859.	61637.
1977.	6396303.	387418.	678442.	2050675.	4717931.	-624270.	3291589.	151078.
1978.	2267881.	371517.	535732.	1945113.	511113.	-354362.	2937228.	256639.
1979.	8864448.	396770.	484859.	2135283.	5953144.	686446.	3623674.	66472.
1980.	3940466.	384517.	678889.	1973432.	1910737.	-290659.	3333016.	228321.
1981.	6337486.	398793.	501857.	2116117.	3425927.	700017.	4033033.	85637.
1982.	4359863.	384408.	562529.	2097025.	2601468.	-498068.	3534963.	104728.
1983.	4298145.	379699.	573069.	2019607.	2225794.	-126483.	3408481.	182146.
1984.	3110466.	369239.	550449.	1823349.	1473403.	-427123.	2981359.	378406.
TOTALS:	481732352.	33059682.	44996884.	175239184.	295679584.	-1419429.	291987872.	11909852.
MEANS:	5667440.	388937.	529375.	2061638.	3478583.	-16699.	3435152.	140116.

ft/yr), diversions for beneficial use (1,962,582 ac-ft/yr), and unappropriated flows to the Gulf of Mexico (3,546,215 ac-ft/yr) for a total of 6,038,496 ac-ft/yr. Total water rights diversions of 2,170,428 ac-ft/yr resulted in actual diversions of 1,962,582 ac-ft/yr and shortages of 207,847 ac-ft/yr.

Shortages

Mean total annual shortages associated with all the water rights in the basin are tabulated in the last column of Table 5.3 for each of the five TAMUWRAP runs. Total system shortages, averaged over the simulation period, are 9.6%, 9.4%, 10.4%, 10.7%, and 6.5% of the target water rights diversions for runs 1,2,3,4,and 5, respectively. Thus, shortages are a maximum for run 4 which included no return flows. Assigning zero priority to the storage capacity of the major reservoirs (run 5) decreased the mean shortages by 32.6%, from 207,847 ac-ft/yr to 140,116 ac-ft/yr. Runs 1 and 5 are compared in Table 7.9. The 32.6% decrease in shortages, and corresponding 1.9% increase in water right diversions, came primarily from a 1.9% decrease in unappropriated flow between the two runs.

Tables 7.10 and 7.11 summarize annual shortages by control point for runs 1 and 5. The tables include the mean annual shortage averaged over the 85-year simulation period, minimum and maximum annual shortage to occur in any year, and number of years for which shortages occurred. The shortages are totals for all the water rights assigned to each control point location. The shortages associated with water rights diversions from each of the 13 reservoirs are also summarized in the lower half of the tables. The reservoir shortages are components of the total shortages at the reservoir control points. Annual shortages associated with the 13 reservoirs are tabulated by year in Tables 7.12 and 7.13 for runs 1 and 5, respectively.

A comparison of Tables 7.10, 7.11, 7.12, and 7.13 shows how shortages are shifted between reservoirs by assigning zero priority to the storage capacity of the 44 reservoirs with capacities of 5,000 acre-feet or greater. Mean shortages associated with the BRA water rights diversions from 11 reservoirs increase 5,877 ac-ft/yr, from 9,428 ac-ft/yr (run 1) to 15,305 ac-ft/yr (run 5). Waco Reservoir shortages increase from zero (run 1) to 776 ac-ft/yr (run 5). Mean shortages associated with diversions from Hubbard Creek Reservoir decrease from 14,005 ac-ft/yr (run 1) to 7,368 ac-ft/yr (run 5). Mean shortages associated with the 12 USACE/BRA reservoirs increase 6,653 ac-ft/yr (run 5). Mean shortages not associated with the 12 USACE/BRA reservoirs decrease 74,384 ac-ft/yr or 37%, from 198,419 ac-ft/yr (run 1) to 124,035 ac-ft/yr (run 5).

Minimum end-of-month storages during the 85-year simulation period are tabulated in Table 7.14 for run 1. Possum Kingdom, Whitney, Waco, Stillhouse Hollow, Georgetown, and Granger Reservoirs have no shortages and do not empty during the simulation. The storage level in Waco Reservoir does not fall below 37% of the conservation capacity. Hubbard Creek, Granbury, Aquilla, Proctor, Belton, Limestone, and Somerville Reservoirs are empty several months during the simulation.

Table 7.9
COMPARISON OF RUNS 1 AND 5

1900-1984 Means	Difference Between Runs 1 and 5	
	ac-ft/yr	%
Naturalized Streamflow	-0-	-0-
Return Flows	+665	+0.19%
Reservoir Evaporation	-324	-0.06%
Water Rights Diversions	+67,733	+1.9%
Unappropriated Flows	-67,632	-1.9%
Storage Change	+2,203	+15.2%
Shortages	-67,731	-32.6%

Table 7.10
SHORTAGES BY CONTROL POINT AND BY RESERVOIR (RUN 1)

Control Point or Reservoir	Mean Shortage (ac-ft/yr)	Minimum Shortage (ac-ft/yr)	Maximum Shortage (ac-ft/yr)	Number of Years With Shortages
Control Point Shortages				
1. Hubbard Reservoir	14,711	93	58,265	85
2. South Bend Gage	52,269	4,151	113,397	85
3. P.K. Reservoir	988	19	14,155	85
4. Granbury Reservoir	2,319	0	19,757	83
5. Whitney Reservoir	1,095	0	3,687	83
6. Aquilla Reservoir	371	0	11,069	68
7. Waco Reservoir	3,340	0	8,801	84
8. Waco Gage	598	0	2,584	81
9. Proctor Reservoir	12,911	485	31,193	85
10. Belton Reservoir	31,926	13	128,304	85
11. Stillhouse Reservoir	1,565	0	5,291	84
12. Georgetown Reservoir	18	0	108	55
13. Granger Reservoir	270	0	980	83
14. Cameron Gage	4,412	0	17,945	76
15. Bryan Gage	14,873	0	40,609	76
16. Limestone Reservoir	1,006	0	32,311	81
17. Somerville Reservoir	2,394	0	21,545	83
18. Hempstead Gage	4,653	0	13,136	76
19. Richmond Gage	57,129	0	285,837	75
Reservoir Shortages				
Hubbard Creek	14,005	0	56,000	40
Possum Kingdom	0	0	0	0
Granbury	196	0	16,677	1
Whitney	0	0	0	0
Aquilla	361	0	11,040	5
Waco	0	0	0	0
Proctor	5,331	0	19,658	30
Belton	2,358	0	72,657	7
Stillhouse	0	0	0	0
Georgetown	0	0	0	0
Granger	0	0	0	0
Limestone	211	0	9,010	2
Somerville	971	0	32,266	5

Table 7.11
SHORTAGES BY CONTROL POINT AND BY RESERVOIR (RUN 5)

Control Point or Reservoir	Mean Shortage (ac-ft/yr)	Minimum Shortage (ac-ft/yr)	Maximum Shortage (ac-ft/yr)	Number of Years With Shortages
Control Point Shortages				
1. Hubbard Reservoir	7,754	0	57,095	84
2. South Bend Gage	27,752	975	76,626	85
3. P.K. Reservoir	5,385	0	134,804	81
4. Granbury Reservoir	871	0	4,130	72
5. Whitney Reservoir	392	0	3,722	66
6. Aquilla Reservoir	268	0	12,308	58
7. Waco Reservoir	2,679	0	28,974	81
8. Waco Gage	480	0	9,598	64
9. Proctor Reservoir	5,059	11	29,734	85
10. Belton Reservoir	31,439	0	173,584	84
11. Stillhouse Reservoir	1,820	0	52,105	82
12. Georgetown Reservoir	16	0	666	40
13. Granger Reservoir	171	0	1,038	77
14. Cameron Gage	3,202	0	17,992	64
15. Bryan Gage	8,496	0	38,727	63
16. Limestone Reservoir	1,139	0	36,725	68
17. Somerville Reservoir	1,515	0	14,129	73
18. Hempstead Gage	2,179	0	11,812	61
19. Richmond Gage	39,499	0	305,819	60
Reservoir Shortages				
Hubbard Creek	7,368	0	56,000	26
Possum Kingdom	4,961	0	122,087	6
Granbury	0	0	0	0
Whitney	0	0	0	0
Aquilla	261	0	12,273	7
Waco	776	0	25,377	6
Proctor	1,880	0	19,658	22
Belton	6,281	0	100,257	11
Stillhouse	672	0	49,598	2
Georgetown	0	0	0	0
Granger	0	0	0	0
Limestone	119	0	7,362	2
Somerville	1,131	0	36,703	7

Table 7.12
SHORTAGES ASSOCIATED WITH THE 13 RESERVOIRS (RUN 1)

Annual Diversion Shortages (acre-feet/year)					
Year	Shortage	Year	Shortage	Year	Shortage
Hubbard Creek Reservoir (water rights 56,000 ac-ft/yr)					
1907	13,917	1930	15,164	1952	56,000
1910	46,913	1932	7,345	1953	56,000
1911	55,962	1934	30,464	1954	15,164
1912	56,000	1935	15,126	1955	15,112
1913	56,000	1937	46,774	1956	50,717
1914	22,384	1938	20,803	1957	11,192
1915	9,238	1939	42,577	1964	23,260
1918	9,448	1940	19,756	1965	15,164
1924	31,382	1946	35,522	1967	14,938
1925	40,716	1947	56,000	1972	46,861
1926	11,192	1948	56,000	1973	43,697
1927	17,805	1949	15,164	1974	39,316
1928	26,721	1951	7,236	1978	5,872
1929	31,502				
Possum Kingdom Reservoir (water rights 230,760 ac-ft/yr)					
no shortages					
Granbury Reservoir (water rights 64,712 ac-ft/yr)					
1913	16,677				
Whitney Reservoir (water rights 18,336 ac-ft/yr)					
no shortages					
Aquilla Reservoir (water rights 13,896 ac-ft/yr)					
1911	9,669	1956	11,040		
1912	4,132	1957	2,332		
1913	3,521				
Waco Reservoir (water rights 59,100 ac-ft/yr)					
no shortages					

Table 7.12 (continued)
SHORTAGES ASSOCIATED WITH THE 13 RESERVOIRS (RUN 1)

Annual Diversion Shortages (acre-feet/year)					
Year	Shortage	Year	Shortage	Year	Shortage
Proctor Reservoir (water rights 19,658 ac-ft/yr)					
1910	10,660	1930	19,658	1957	3,610
1911	19,631	1948	448	1963	6,140
1912	19,658	1949	19,658	1964	15,707
1913	19,130	1950	19,658	1974	11,746
1918	12,060	1951	19,658	1979	14,866
1919	3,610	1952	19,658	1980	9,173
1925	17,334	1953	19,658	1981	19,658
1926	2,336	1954	19,658	1982	18,649
1928	12,832	1955	19,658	1983	19,658
1929	19,658	1956	19,658	1984	19,658
Belton Reservoir (water rights 100,257 ac-ft/yr)					
1911	17,731	1954	59,607		
1912	72,657	1955	25,524		
1913	12,695	1956	11,850		
		1957	367		
Stillhouse Hollow Reservoir (water rights 67,768 ac-ft/yr)					
no shortages					
Georgetown Reservoir (water rights 13,610 ac-ft/yr)					
no shortages					
Granger Reservoir (water rights 19,840 ac-ft/yr)					
no shortages					
Somerville Reservoir (water rights 48,000 ac-ft/yr)					
1912	21,360	1955	18,894		
1913	3,360	1956	32,266		
		1957	6,662		
Limestone Reservoir (water rights 65,074 ac-ft/yr)					
1956	8,923	1957	9,010		

Table 7.13
SHORTAGES ASSOCIATED WITH THE 13 RESERVOIRS (RUN 5)

Annual Diversion Shortages (acre-feet/year)					
Year	Shortage	Year	Shortage	Year	Shortage
Hubbard Creek Reservoir (water rights 56,000 ac-ft/yr)					
1911	45,320	1935	10,000	1952	55,681
1912	56,000	1937	7,230	1953	20,720
1913	42,903	1938	7,460	1956	23,260
1914	11,192	1939	31,536	1957	3,850
1924	3,736	1940	15,164	1965	7,871
1925	46,471	1947	43,042	1967	2,510
1926	11,192	1948	41,947	1972	20,689
1927	12,203	1949	15,164	1973	40,621
1928	15,164			1974	35,344
Possum Kingdom Reservoir (water rights 230,760 ac-ft/yr)					
1911	49,250	1913	104,333	1953	68,159
1912	122,087	1914	34,942	1954	42,876
Granbury Reservoir (water rights 64,712 ac-ft/yr)					
no shortages					
Whitney Reservoir (water rights 18,336 ac-ft/yr)					
no shortages					
Aquilla Reservoir (water rights 13,896 ac-ft/yr)					
1911	745	1952	1,716	1956	12,273
1912	547	1953	738	1957	1,753
1913	4,445				
Waco Reservoir (water rights 59,100 ac-ft/yr)					
1912	3,966	1954	6,593	1956	25,377
1913	8,642	1955	16,623	1957	4,723
1956	25,377				
1957	4,723				

Table 7.13 (continued)
SHORTAGES ASSOCIATED WITH THE 13 RESERVOIRS (RUN 5)

Annual Diversion Shortages (acre-feet/year)					
Year	Shortage	Year	Shortage	Year	Shortage
		Proctor Reservoir (water rights 19,658 ac-ft/yr)			
1910	6,849	1948	3,410	1979	3,841
1911	18,252	1949	1,084	1980	16,658
1912	13,274	1951	1,048	1981	13,347
1913	3,588	1952	6,358	1984	13,446
1918	2,763	1953	14,452		
1927	2,115	1954	19,658		
1928	1,745	1955	2,336		
1929	8,272	1956	1,379		
1930	3,610	1957	2,336		
		Belton Reservoir (water rights 100,257 ac-ft/yr)			
1911	27,527	1951	27,766	1955	79,560
1912	79,356	1952	93,392	1956	100,257
1913	33,821	1953	20,048	1957	17,316
		1954	85,551	1984	15,192
		Stillhouse Hollow Reservoir (water rights 67,768 ac-ft/yr)			
1956	49,598			1957	7,531
		Georgetown Reservoir (water rights 13,610 ac-ft/yr)			
		no shortages			
		Granger Reservoir (water rights 19,840 ac-ft/yr)			
		no shortages			
		Somerville Reservoir (water rights 48,000 ac-ft/yr)			
1911	1,976	1952	110	1956	36,703
1912	25,328	1955	22,199	1957	6,426
1913	3,360				
		Limestone Reservoir (water rights 65,074 ac-ft/yr)			
1956	2,774			1957	7,362

Table 7.14
MINIMUM RESERVOIR STORAGES (RUN 1)

Reservoir	Minimum Storage	
	ac-ft	% capacity
Hubbard Creek	-0-	-0-
Possum Kingdom	78,416	14%
Granbury	-0-	-0-
Whitney	264,146	42%
Aquilla	-0-	-0-
Waco	56,288	37%
Proctor	-0-	-0-
Belton	-0-	-0-
Stillhouse	26,666	11%
Georgetown	2,864	8%
Granger	17,187	26%
Limestone	-0-	-0-
Somerville	-0-	-0-

Unappropriated Streamflow

Unappropriated streamflow is the water remaining after all water rights diversions. A shortage and nonzero unappropriated flow can not both occur in the same month at the same control point. However, shortages can occur at upstream control points simultaneously with unappropriated flows at downstream control points. Unappropriated streamflows are presented as cumulative or total flows rather than incremental or local flows. For example, the unappropriated streamflow at the Bryan gage control point includes the unappropriated streamflow at the Waco gage and Cameron gage control points plus additional flows originating in the reaches between the Bryan gage and the two upstream gages. In a given month, the unappropriated streamflow at a control point must equal or exceed the unappropriated streamflow at the next upstream control point.

Mean annual unappropriated streamflows, streamflow depletions, and naturalized steamflows for run 1 are tabulated by control point in Table 7.15. The basin total streamflow depletions plus unappropriated streamflows equal naturalized streamflows plus return flows. The basin total unappropriated streamflow equals the unappropriated streamflow at the Richmond gage plus return flows from diversions at the Richmond gage. The basin total unappropriated streamflow is 63% of the naturalized streamflow.

During the 85-year simulation period, months of zero unappropriated flow occur during each of the twelve months of the year at all of the 19 control points. The average unappropriated flow for each month of the year at four different control points are tabulated in Table 7.16. The means are computed from the results of simulation run 1. Mean unappropriated flows at the Richmond gage control point range from 37,907 acre-feet/month in August to 901,908 acre-feet/month in May, with an average over the year of 294,673 acre-feet/month. Unappropriated streamflow at the Richmond gage control point includes all unappropriated flow in the basin except for return flows from diversions at the Richmond gage.

Flow duration relationships computed with STATS from the TAMUWRAP run 1 results are presented in Table 7.17. At the Richmond gage, an unappropriated flow level of 388 acre-feet/month is equalled or exceeded during 99.0% of the 1,020 months simulated. Unappropriated flows of 666 acre-feet/month and 69,700 acre-feet/month are equalled or exceeded during 90.0% and 50.0% of the months, respectively.

Mean annual unappropriated streamflows resulting from five alternative simulation runs are included in Table 7.3. Unappropriated flows averaged over the 1940-1976 simulation period (run 2) are about 4% higher than those for the 1900-1984 period (run 1). Changing the municipal priorities (run 3) decreases the unappropriated flows by about 0.1%. Removing the return flows (run 4) decreases unappropriated flows by about 1%. Changing the priorities of reservoir storage capacity (run 5) decreases the unappropriated flows by about 2%.

Unappropriated streamflows computed in TAMUWRAP runs 1 and 2 are compared with unappropriated streamflows computed by the Texas Water Commission (TWC) in Tables 7.18 through 7.23. The streamflows included in the tables cover the period 1940-1976. For run 1, the basin total unappropriated streamflows computed by the TWC and the present study are 65.8% and 63.1%, respectively, of the naturalized streamflow. The TAMUWRAP run 1 mean unappropriated flow is 95.9% of the corresponding TWC mean unappropriated flow. The TAMUWRAP run 1 mean unappropriated flow is 98.3%, 109.6%, 130.2%, 113.2%, and 101.3% of the TWC mean unappropriated flow at the Richmond gage, Bryan gage, Waco gage, South Bend gage, and Cameron gage control points, respectively. Thus, the TWC and TAMU unappropriated flows compare most closely at the Cameron gage. The TWC and TAMU unappropriated flows are 72.4% and 73.4%, respectively, of naturalized flows. The greatest differences occur at the Waco gage where the TWC and TAMU unappropriated flows average 37.8% and 49.2% of the naturalized flows.

Unappropriated streamflows computed in TAMUWRAP run 5 are compared with unappropriated streamflows computed by the Texas Water Commission in Tables 7.24 through 7.29. These tables also include data for an adjusted run 5. The adjustment consists of subtracting the unappropriated flows at the South Bend gage control point from the unappropriated flows at the downstream control points. Thus, unappropriated flows originating upstream of Possum Kingdom Reservoir are excluded from the unappropriated flows at downstream locations. Of the several TAMUWRAP simulation runs, the adjusted run 5 (run 5A) should most closely represent the assumptions and input data incorporated in the TWC Water Availability Model. For run 5, the TAMUWRAP mean unappropriated flows are 94.2%, 96.5%, 107.0%, 125.7%, 100.9%, and 98.0% of the TWC mean unappropriated flows at the coast, Richmond gage, Bryan gage, Waco gage, South Bend gage, and Cameron gage, respectively. For run 5A, the TAMUWRAP mean unappropriated flows are 89.1%, 91.3%, 98.5%, 99.2%, 100.9%, and 98.0% at the coast and Richmond, Bryan, Waco, South Bend, and Cameron gages. The lower values at the coast (basin total) and Richmond gage are due largely to neglecting the naturalized streamflows entering the river below the Richmond gage in the TAMUWRAP simulation.

Table 7.15
COMPARISON OF NATURALIZED FLOWS, STREAMFLOW DEPLETIONS, AND UNAPPROPRIATED FLOWS BY CONTROL POINT (RUN 1)

Control Point	Run 1 1900-1984 Means (acre-ft/year)			
	Naturalized Streamflow	Streamflow Depletions		Unappropriated Streamflow
		Incremental	Accumulative	
1. Hubbard Reservoir	113,976	77,947	77,947	5,886
2. South Bend Gage	738,065	142,198	220,145	203,200
3. P.K. Reservoir	893,664	324,630	544,775	239,588
4. Granbury Reservoir	1,164,598	133,969	678,744	399,043
5. Whitney Reservoir	1,659,474	173,527	852,271	680,849
6. Aquilla Reservoir	73,124	21,754	21,754	44,392
7. Waco Reservoir	326,718	91,144	91,144	210,513
8. Waco Gage	1,878,340	37,205	1,002,374	866,142
9. Proctor Reservoir	115,170	41,890	41,890	35,686
10. Belton Reservoir	467,710	218,078	259,968	203,116
11. Stillhouse Reservoir	220,493	88,985	88,985	125,974
12. Georgetown Reservoir	64,839	16,899	16,899	45,478
13. Granger Reservoir	179,035	31,678	48,577	129,083
14. Cameron Gage	1,286,294	28,875	426,405	911,415
15. Bryan Gage	3,893,436	88,947	1,517,726	2,365,622
16. Limestone Reservoir	234,211	89,819	89,819	140,734
17. Somerville Reservoir	220,932	115,726	115,726	102,239
18. Hempstead Gage	5,222,676	59,606	1,782,877	3,290,487
19. Richmond Gage	5,667,440	726,621	2,509,498	3,536,071
Basin Total	5,667,440	2,509,498	2,509,498	3,546,215

Table 7.16
UNAPPROPRIATED STREAMFLOW MONTHLY MEANS (RUN 1)

Month	Mean Unappropriated Streamflow (acre-feet/month)			
	Richmond Gage	Waco Gage	South Bend Gage	Cameron Gage
Jan	277,964	44,622	1,398	70,171
Feb	309,323	53,643	1,429	81,308
Mar	312,952	56,844	1,951	80,066
Apr	463,981	137,630	19,026	132,001
May	901,908	256,932	67,384	224,732
Jun	391,084	104,181	39,069	87,104
Jul	116,217	27,624	12,251	34,439
Aug	37,907	7,136	2,352	8,649
Sep	91,568	37,522	21,198	29,764
Oct	165,626	58,331	30,292	53,842
Nov	188,098	36,359	5,483	45,244
Dec	279,442	45,317	1,367	64,095
Annual	294,673	72,178	16,933	75,951

Table 7.17
UNAPPROPRIATED STREAMFLOW VERSUS DURATION RELATIONSHIPS (RUN 1)

Percent of Months Equalled or Exceeded	Unappropriated Flow (ac-ft/yr)			
	Richmond Gage	Waco Gage	South Bend Gage	Cameron Gage
0.01	6,900,000	3,180,000	1,200,000	1,630,000
0.05	6,900,000	3,180,000	1,200,000	1,630,000
0.10	6,900,000	2,000,000	1,200,000	1,500,000
0.20	6,450,000	1,240,000	742,000	1,190,000
0.50	4,790,000	1,040,000	496,000	907,000
1.00	3,200,000	873,000	383,000	687,000
2.00	1,980,000	698,000	274,000	534,000
5.00	1,280,000	426,000	82,500	347,000
10.00	846,000	225,000	27,600	212,000
15.00	627,000	128,000	1,360	145,000
20.00	478,000	78,600	937	108,000
30.00	253,000	30,000	838	58,700
40.00	136,000	6,390	761	35,400
50.00	69,700	969	694	21,500
60.00	27,600	872	632	12,900
70.00	958	778	571	952
80.00	825	678	506	820
90.00	666	558	425	663
95.00	556	472	366	553
98.00	449	388	307	447
99.00	388	338	271	386
99.50	337	296	240	336
99.80	281	250	204	280
99.90	245	219	180	245
99.95	213	191	158	213
99.99	150	135	112	149
100.00	0	0	0	0

TABLE 7.18
BASIN TOTAL UNAPPROPRIATED STREAMFLOW
TWC AND TAMU RUNS 1 AND 2 COMPARISON

Year	Naturalized Streamflow (ac-ft)	Unappropriated Streamflow TWC (ac-ft)	TWC (% Nat)	Run 1 (ac-ft)	Run 1 (% Nat)	Run 1 (% TWC)	Run 2 (ac-ft)	Run 2 (% Nat)	Run 2 (% TWC)
1940	7,850,608	5,914,085	75.3	4,870,225	62.0	82.3	5,623,647	71.6	95.1
1941	13,806,996	10,019,062	72.6	11,396,148	82.5	113.7	11,638,770	84.3	116.2
1942	8,517,753	5,813,924	68.3	6,299,472	74.0	108.4	6,310,353	74.1	108.5
1943	1,984,786	864,205	43.5	591,327	29.8	68.4	591,327	29.8	68.4
1944	8,901,734	6,865,228	77.1	6,443,162	72.4	93.9	6,443,162	72.4	93.9
1945	10,074,292	7,913,017	78.5	7,543,223	74.9	95.3	7,543,223	74.9	95.3
1946	8,406,420	6,542,371	77.8	6,155,707	73.2	94.1	6,155,707	73.2	94.1
1947	4,876,952	3,167,869	65.0	3,224,203	66.1	101.8	3,223,982	66.1	101.8
1948	1,873,208	534,236	28.5	388,098	20.7	72.6	388,098	20.7	72.6
1949	4,321,941	1,911,840	44.2	1,669,027	38.6	87.3	1,668,784	38.6	87.3
1950	3,960,386	2,060,782	52.0	1,820,359	46.0	88.3	1,820,245	46.0	88.3
1951	996,849	50,394	5.1	10,260	1.0	20.4	10,260	1.0	20.4
1952	1,623,246	514,531	31.7	214,596	13.2	41.7	214,596	13.2	41.7
1953	4,607,306	2,239,852	48.6	2,042,553	44.3	91.2	2,042,553	44.3	91.2
1954	1,362,340	162,127	11.9	108,827	8.0	67.1	108,827	8.0	67.1
1955	2,986,948	472,374	15.8	230,482	7.7	48.8	230,482	7.7	48.8
1956	929,191	41,206	4.4	23,623	2.5	57.3	23,623	2.5	57.3
1957	14,983,308	9,141,182	61.0	10,505,152	70.1	114.9	10,504,077	70.1	114.9
1958	5,932,074	4,232,360	71.3	4,101,024	69.1	96.9	4,101,020	69.1	96.9
1959	5,876,065	3,762,557	64.0	3,409,815	58.0	90.6	3,409,685	58.0	90.6
1960	7,158,198	5,518,867	77.1	5,009,803	70.0	90.8	5,009,737	70.0	90.8
1961	10,018,476	8,295,053	82.8	7,785,772	77.7	93.9	7,785,762	77.7	93.9
1962	3,381,713	1,151,548	34.1	1,308,980	38.7	113.7	1,308,964	38.7	113.7
1963	1,698,274	493,984	29.1	412,355	24.3	83.5	412,354	24.3	83.5
1964	2,209,915	525,547	23.8	242,549	11.0	46.2	242,549	11.0	46.2
1965	8,631,581	6,264,911	72.6	5,826,915	67.5	93.0	5,826,648	67.5	93.0
1966	6,411,800	4,066,322	63.4	4,153,534	64.8	102.1	4,153,442	64.8	102.1
1967	1,963,572	416,196	21.2	323,508	16.5	77.7	323,508	16.5	77.7
1968	11,074,828	8,519,382	76.9	8,385,562	75.7	98.4	8,385,539	75.7	98.4
1969	6,405,519	4,046,492	63.2	4,054,338	63.3	100.2	4,054,288	63.3	100.2
1970	5,020,008	3,594,914	71.6	3,360,123	66.9	93.5	3,360,123	66.9	93.5
1971	3,342,968	1,152,547	34.5	927,188	27.7	80.4	927,188	27.7	80.4
1972	3,001,679	1,451,922	48.4	1,144,144	38.1	78.8	1,143,829	38.1	78.8
1973	9,112,670	7,348,891	80.6	6,728,100	73.8	91.6	6,728,100	73.8	91.6
1974	7,822,334	5,877,303	75.1	5,415,640	69.2	92.1	5,415,640	69.2	92.1
1975	7,279,962	5,858,243	80.5	5,444,212	74.8	92.9	5,444,212	74.8	92.9
1976	6,400,484	4,513,836	70.5	3,973,138	62.1	88.0	3,973,138	62.1	88.0
Mean	5,805,578	3,819,437	65.8	3,663,328	63.1	95.9	3,690,471	63.6	96.6

TABLE 7.19
UNAPPROPRIATED STREAMFLOW AT THE RICHMOND GAGE
TWC AND TAMU RUNS 1 AND 2 COMPARISON

Year	Naturalized Streamflow (ac-ft)	Unappropriated Streamflow							
		TWC (ac-ft)	TWC (% Nat)	Run 1 (ac-ft)	Run 1 (% Nat)	Run 1 (% TWC)	Run 2 (ac-ft)	Run 2 (% Nat)	Run 2 (% TWC)
1940	7,850,608	5,589,806	71.2	4,859,965	61.9	86.9	5,613,387	71.5	100.4
1941	13,806,996	9,564,030	69.3	11,385,889	82.5	119.0	11,130,937	80.6	116.4
1942	8,517,753	5,750,306	67.5	6,289,212	73.8	109.4	6,300,093	74.0	109.6
1943	1,984,786	846,224	42.6	581,067	29.3	68.7	581,067	29.3	68.7
1944	8,901,734	6,777,958	76.1	6,432,902	72.3	94.9	6,432,902	72.3	94.9
1945	10,074,292	7,834,801	77.8	7,532,963	74.8	96.1	7,532,963	74.8	96.1
1946	8,406,420	6,469,510	77.0	6,145,447	73.1	95.0	6,145,447	73.1	95.0
1947	4,876,952	3,146,672	64.5	3,213,943	65.9	102.1	3,213,722	65.9	102.1
1948	1,873,208	511,571	27.3	379,350	20.3	74.2	379,350	20.3	74.2
1949	4,321,941	1,896,301	43.9	1,658,767	38.4	87.5	1,658,524	38.4	87.5
1950	3,960,386	2,016,789	50.9	1,810,099	45.7	89.8	1,809,985	45.7	89.7
1951	996,849	48,059	4.8	0	0.0	0.0	0	0.0	0.0
1952	1,623,246	499,355	30.8	205,848	12.7	41.2	205,848	12.7	41.2
1953	4,607,306	2,211,583	48.0	2,032,293	44.1	91.9	2,032,293	44.1	91.9
1954	1,362,340	160,254	11.8	98,567	7.2	61.5	98,567	7.2	61.5
1955	2,986,948	469,106	15.7	220,222	7.4	46.9	220,222	7.4	46.9
1956	929,191	40,809	4.4	17,193	1.9	42.1	17,193	1.9	42.1
1957	14,983,308	8,660,428	57.8	10,494,892	70.0	121.2	10,493,816	70.0	121.2
1958	5,932,074	4,144,734	69.9	4,090,764	69.0	98.7	4,090,760	69.0	98.7
1959	5,876,065	3,667,556	62.4	3,399,555	57.9	92.7	3,399,425	57.9	92.7
1960	7,158,198	5,360,902	74.9	4,999,543	69.8	93.3	4,999,477	69.8	93.3
1961	10,018,476	7,949,869	79.4	7,775,512	77.6	97.8	7,775,502	77.6	97.8
1962	3,381,713	1,139,981	33.7	1,298,720	38.4	113.9	1,298,704	38.4	113.9
1963	1,698,274	480,296	28.3	402,095	23.7	83.7	402,094	23.7	83.7
1964	2,209,915	513,798	23.2	232,289	10.5	45.2	232,289	10.5	45.2
1965	8,631,581	6,162,297	71.4	5,816,655	67.4	94.4	5,816,388	67.4	94.4
1966	6,411,800	3,920,207	61.1	4,143,274	64.6	105.7	4,143,182	64.6	105.7
1967	1,963,572	412,079	21.0	313,248	16.0	76.0	313,248	16.0	76.0
1968	11,074,828	8,349,786	75.4	8,375,302	75.6	100.3	8,375,279	75.6	100.3
1969	6,405,519	3,967,951	61.9	4,044,078	63.1	101.9	4,044,028	63.1	101.9
1970	5,020,008	3,517,176	70.1	3,349,863	66.7	95.2	3,349,863	66.7	95.2
1971	3,342,968	1,131,017	33.8	916,928	27.4	81.1	916,928	27.4	81.1
1972	3,001,679	1,360,250	45.3	1,133,884	37.8	83.4	1,133,569	37.8	83.3
1973	9,112,670	7,080,819	77.7	6,717,840	73.7	94.9	6,717,840	73.7	94.9
1974	7,822,334	5,632,210	72.0	5,405,380	69.1	96.0	5,405,380	69.1	96.0
1975	7,279,962	5,730,616	78.7	5,433,952	74.6	94.8	5,433,952	74.6	94.8
1976	6,400,484	4,460,123	69.7	3,962,878	61.9	88.9	3,962,878	61.9	88.9
Mean	5,805,578	3,715,547	64.0	3,653,253	62.9	98.3	3,666,949	63.2	98.7

TABLE 7.20
UNAPPROPRIATED STREAMFLOW AT THE BRYAN GAGE
TWC AND TAMU RUNS 1 AND 2 COMPARISON

Year	Naturalized Streamflow (ac-ft)	Unappropriated Streamflow							
		TWC (ac-ft)	TWC (% Nat)	Run 1 (ac-ft)	Run 1 (% Nat)	Run 1 (% TWC)	Run 2 (ac-ft)	Run 2 (% Nat)	Run 2 (% TWC)
1940	4,964,432	2,825,504	56.9	2,600,762	52.4	92.0	3,204,012	64.5	113.4
1941	10,297,301	6,201,199	60.2	8,528,483	82.8	137.5	8,771,105	85.2	141.4
1942	6,898,760	4,669,741	67.7	5,417,483	78.5	116.0	5,428,365	78.7	116.2
1943	1,316,920	548,833	41.7	425,890	32.3	77.6	425,890	32.3	77.6
1944	6,017,878	4,479,951	74.4	4,562,641	75.8	101.8	4,562,641	75.8	101.8
1945	7,030,153	5,310,507	75.5	5,421,434	77.1	102.1	5,421,434	77.1	102.1
1946	5,064,349	3,635,380	71.8	3,658,887	72.2	100.6	3,658,887	72.2	100.6
1947	2,956,511	1,727,633	58.4	2,133,632	72.2	123.5	2,133,411	72.2	123.5
1948	1,269,120	254,692	20.1	216,413	17.1	85.0	216,413	17.1	85.0
1949	2,699,115	916,376	34.0	967,738	35.9	105.6	967,496	35.8	105.6
1950	2,151,513	683,108	31.8	691,496	32.1	101.2	691,382	32.1	101.2
1951	815,011	28,449	3.5	0	0.0	0.0	0	0.0	0.0
1952	965,988	256,463	26.5	148,241	15.3	57.8	148,241	15.3	57.8
1953	2,917,570	1,228,522	42.1	1,191,127	40.8	97.0	1,191,127	40.8	97.0
1954	1,031,429	62,372	6.0	43,772	4.2	70.2	43,772	4.2	70.2
1955	2,625,378	261,908	10.0	187,515	7.1	71.6	187,515	7.1	71.6
1956	804,488	23,974	3.0	17,193	2.1	71.7	17,193	2.1	71.7
1957	11,779,138	5,290,728	44.9	7,602,095	64.5	143.7	7,601,020	64.5	143.7
1958	4,420,957	2,964,698	67.1	3,328,157	75.3	112.3	3,328,153	75.3	112.3
1959	4,025,388	2,132,613	53.0	2,182,318	54.2	102.3	2,182,188	54.2	102.3
1960	4,583,661	3,183,408	69.5	3,177,954	69.3	99.8	3,177,888	69.3	99.8
1961	6,310,567	4,655,477	73.8	4,981,512	78.9	107.0	4,981,502	78.9	107.0
1962	2,682,399	607,024	22.6	1,000,107	37.3	164.8	1,000,091	37.3	164.8
1963	1,178,243	203,341	17.3	204,590	17.4	100.6	204,590	17.4	100.6
1964	1,699,216	264,268	15.6	141,181	8.3	53.4	141,181	8.3	53.4
1965	6,502,837	4,536,162	69.8	4,723,622	72.6	104.1	4,723,354	72.6	104.1
1966	4,836,314	2,373,533	49.1	3,008,428	62.2	126.7	3,008,336	62.2	126.7
1967	1,733,784	373,714	21.6	313,248	18.1	83.8	313,248	18.1	83.8
1968	7,287,639	5,127,396	70.4	5,644,167	77.4	110.1	5,644,144	77.4	110.1
1969	4,306,718	2,329,386	54.1	2,589,558	60.1	111.2	2,589,508	60.1	111.2
1970	3,537,772	2,489,899	70.4	2,598,370	73.4	104.4	2,598,370	73.4	104.4
1971	2,931,861	960,340	32.8	816,743	27.9	85.0	816,743	27.9	85.0
1972	2,001,175	696,760	34.8	642,269	32.1	92.2	641,955	32.1	92.1
1973	4,936,095	3,659,996	74.1	3,777,862	76.5	103.2	3,777,862	76.5	103.2
1974	4,719,176	2,848,651	60.4	3,018,621	64.0	106.0	3,018,621	64.0	106.0
1975	4,791,048	3,763,324	78.5	3,787,674	79.1	100.6	3,787,674	79.1	100.6
1976	4,173,335	2,756,979	66.1	2,665,852	63.9	96.7	2,665,853	63.9	96.7
Mean	4,007,115	2,279,252	56.9	2,497,758	62.3	109.6	2,520,842	62.9	110.6

TABLE 7.21
UNAPPROPRIATED STREAMFLOW AT THE WACO GAGE
TWC AND TAMU RUNS 1 AND 2 COMPARISON

Year	Naturalized Streamflow (ac-ft)	Unappropriated Streamflow							
		TWC (ac-ft)	TWC (% Nat)	Run 1 (ac-ft)	Run 1 (% Nat)	Run 1 (% TWC)	Run 2 (ac-ft)	Run 2 (% Nat)	Run 2 (% TWC)
1940	2,039,016	716,884	35.2	579,960	28.4	80.9	979,235	48.0	136.6
1941	5,700,387	2,036,923	35.7	4,401,563	77.2	216.1	4,630,251	81.2	227.3
1942	3,973,192	2,235,315	56.3	3,040,719	76.5	136.0	3,051,600	76.8	136.5
1943	512,271	122,287	23.9	70,225	13.7	57.4	70,225	13.7	57.4
1944	1,681,214	837,959	49.8	815,781	48.5	97.4	815,781	48.5	97.4
1945	3,103,724	1,971,671	63.5	1,989,931	64.1	100.9	1,989,931	64.1	100.9
1946	1,909,200	855,868	44.8	866,799	45.4	101.3	866,799	45.4	101.3
1947	1,344,035	446,773	33.2	753,776	56.1	168.7	753,555	56.1	168.7
1948	795,052	94,356	11.9	27,823	3.5	29.5	27,823	3.5	29.5
1949	1,707,370	429,730	25.2	505,616	29.6	117.7	505,374	29.6	117.6
1950	1,363,620	130,718	9.6	140,348	10.3	107.4	140,234	10.3	107.3
1951	593,258	5,603	0.9	0	0.0	0.0	0	0.0	0.0
1952	440,643	63,858	14.5	4,835	1.1	7.6	4,835	1.1	7.6
1953	1,244,367	216,031	17.4	164,455	13.2	76.1	164,455	13.2	76.1
1954	836,391	3,734	0.4	0	0.0	0.0	0	0.0	0.0
1955	1,864,647	69,221	3.7	2,600	0.1	3.8	2,600	0.1	3.8
1956	481,593	345	0.1	0	0.0	0.0	0	0.0	0.0
1957	6,726,090	2,179,347	32.4	4,557,902	67.8	209.1	4,556,826	67.7	209.1
1958	1,926,829	957,491	49.7	1,175,809	61.0	122.8	1,175,805	61.0	122.8
1959	1,871,692	686,639	36.7	837,441	44.7	122.0	837,311	44.7	121.9
1960	1,631,659	704,827	43.2	747,318	45.8	106.0	747,252	45.8	106.0
1961	2,830,364	1,591,940	56.2	1,925,743	68.0	121.0	1,925,733	68.0	121.0
1962	1,889,009	279,706	14.8	735,705	38.9	263.0	735,688	38.9	263.0
1963	750,997	31,530	4.2	53,198	7.1	168.7	53,197	7.1	168.7
1964	879,136	71,898	8.2	0	0.0	0.0	0	0.0	0.0
1965	2,227,849	1,131,528	50.8	1,098,409	49.3	97.1	1,097,142	49.2	97.0
1966	2,529,951	861,188	34.0	1,513,383	59.8	175.7	1,513,291	59.8	175.7
1967	921,780	77,154	8.4	53,302	5.8	69.1	53,302	5.8	69.1
1968	3,372,397	1,925,780	57.1	2,297,117	68.1	119.3	2,297,094	68.1	119.3
1969	2,524,635	1,029,235	40.8	1,332,781	52.8	129.5	1,332,731	52.8	129.5
1970	1,399,530	814,473	58.2	945,545	67.6	116.1	945,545	67.6	116.1
1971	1,864,511	520,482	27.9	433,883	23.3	83.4	433,883	23.3	83.4
1972	1,157,314	219,799	19.0	179,793	15.5	81.8	179,478	15.5	81.7
1973	2,076,842	1,318,812	63.5	1,388,260	66.8	105.3	1,388,260	66.8	105.3
1974	2,043,269	747,097	36.6	849,131	41.6	113.7	849,131	41.6	113.7
1975	1,898,362	1,036,418	54.6	1,243,563	65.5	120.0	1,243,563	65.5	120.0
1976	1,464,693	614,003	41.9	478,435	32.7	77.9	478,535	32.7	77.9
Mean	1,934,511	730,720	37.8	951,653	49.2	130.2	968,823	50.1	132.6

TABLE 7.22
UNAPPROPRIATED STREAMFLOW AT THE SOUTH BEND GAGE
TWC AND TAMU RUNS 1 AND 2 COMPARISON

Year	Naturalized Streamflow (ac-ft)	Unappropriated Streamflow							
		TWC (ac-ft)	TWC (% Nat)	Run 1 (ac-ft)	Run 1 (% Nat)	Run 1 (% TWC)	Run 2 (ac-ft)	Run 2 (% Nat)	Run 2 (% TWC)
1940	705,873	104,295	14.8	23,018	3.3	22.1	146,896	20.8	140.8
1941	3,263,806	2,397,456	73.5	2,423,920	74.3	101.1	2,652,608	81.3	110.6
1942	1,033,443	567,579	54.9	601,876	58.2	106.0	612,746	59.3	108.0
1943	191,097	0	0.0	4	0.0	---	4	0.0	---
1944	264,473	0	0.0	0	0.0	---	0	0.0	---
1945	458,106	0	0.0	0	0.0	---	0	0.0	---
1946	523,693	56,786	10.8	0	0.0	0.0	0	0.0	0.0
1947	646,795	221,355	34.2	294,224	45.5	132.9	294,003	45.5	132.8
1948	360,640	0	0.0	0	0.0	---	0	0.0	---
1949	600,962	40,863	6.8	39,782	6.6	97.4	39,540	6.6	96.8
1950	696,159	32,284	4.6	97,482	14.0	302.0	97,368	14.0	301.6
1951	294,620	0	0.0	0	0.0	---	0	0.0	---
1952	56,732	0	0.0	0	0.0	---	0	0.0	---
1953	720,092	0	0.0	0	0.0	---	0	0.0	---
1954	597,990	0	0.0	0	0.0	---	0	0.0	---
1955	1,338,219	164,464	12.3	0	0.0	0.0	0	0.0	0.0
1956	107,052	0	0.0	0	0.0	---	0	0.0	---
1957	2,783,249	1,434,637	51.5	1,815,785	65.2	126.6	1,815,442	65.2	126.5
1958	458,618	129,221	28.2	143,073	31.2	110.7	143,070	31.2	110.7
1959	587,596	64,413	11.0	66,292	11.3	102.9	66,261	11.3	102.9
1960	652,584	38,956	6.0	48,605	7.4	124.8	48,539	7.4	124.6
1961	900,964	220,268	24.4	345,953	38.4	157.1	345,944	38.4	157.1
1962	887,010	293,611	33.1	439,459	49.5	149.7	439,443	49.5	149.7
1963	497,349	17,818	3.6	48,761	9.8	273.7	48,761	9.8	273.7
1964	228,432	0	0.0	0	0.0	---	0	0.0	---
1965	607,792	0	0.0	30,868	5.1	---	30,601	5.0	---
1966	971,358	294,889	30.4	497,286	51.2	168.6	497,194	51.2	168.6
1967	469,220	0	0.0	0	0.0	---	0	0.0	---
1968	718,540	230,294	32.1	284,906	39.7	123.7	284,899	39.6	123.7
1969	911,732	266,896	29.3	330,564	36.3	123.9	330,529	36.3	123.8
1970	245,021	91,304	37.3	93,248	38.1	102.1	93,248	38.1	102.1
1971	876,010	50,609	5.8	0	0.0	0.0	0	0.0	0.0
1972	673,502	67,833	10.1	7,152	1.1	10.5	6,837	1.0	10.1
1973	374,543	105,534	28.2	132,616	35.4	125.7	132,616	35.4	125.7
1974	804,524	109,130	13.6	164,645	20.5	150.9	164,644	20.5	150.9
1975	467,541	98,461	21.1	109,773	23.5	111.5	109,773	23.5	111.5
1976	351,146	0	0.0	0	0.0	---	0	0.0	---
Mean	711,527	191,864	27.0	217,278	30.5	113.2	227,053	31.9	118.3

TABLE 7.23
UNAPPROPRIATED STREAMFLOW AT THE CAMERON GAGE
TWC AND TAMU RUNS 1 AND 2 COMPARISON

Year	Naturalized Streamflow (ac-ft)	Unappropriated Streamflow							
		TWC (ac-ft)	TWC (% Nat)	Run 1 (ac-ft)	Run 1 (% Nat)	Run 1 (% TWC)	Run 2 (ac-ft)	Run 2 (% Nat)	Run 2 (% TWC)
1940	2,054,824	1,446,334	70.4	1,329,627	64.7	91.9	1,622,755	79.0	112.2
1941	3,282,196	3,003,918	91.5	2,993,363	91.2	99.6	3,007,297	91.6	100.1
1942	2,155,038	1,806,820	83.8	1,839,224	85.3	101.8	1,839,224	85.3	101.8
1943	391,839	228,931	58.4	234,080	59.7	102.2	234,080	59.7	102.2
1944	2,590,127	2,083,373	80.4	2,098,789	81.0	100.7	2,098,789	81.0	100.7
1945	2,448,643	2,079,381	84.9	2,094,638	85.5	100.7	2,094,639	85.5	100.7
1946	1,694,076	1,397,906	82.5	1,398,878	82.6	100.1	1,398,878	82.6	100.1
1947	1,002,748	817,706	81.5	839,761	83.7	102.7	839,761	83.7	102.7
1948	266,781	68,778	25.8	103,813	38.9	150.9	103,813	38.9	150.9
1949	721,202	291,474	40.4	327,319	45.4	112.3	327,319	45.4	112.3
1950	367,974	162,196	44.1	199,984	54.3	123.3	199,984	54.3	123.3
1951	138,339	18,569	13.4	0	0.0	0.0	0	0.0	0.0
1952	333,454	93,174	27.9	98,426	29.5	105.6	98,426	29.5	105.6
1953	861,207	338,062	39.3	336,331	39.1	99.5	336,331	39.1	99.5
1954	98,452	24,294	24.7	24,710	25.1	101.7	24,710	25.1	101.7
1955	489,005	57,579	11.8	45,913	9.4	79.7	45,913	9.4	79.7
1956	232,190	7,845	3.4	12,369	5.3	157.7	12,369	5.3	157.7
1957	3,384,809	1,961,352	57.9	2,230,371	65.9	113.7	2,229,330	65.9	113.7
1958	1,645,758	1,439,330	87.5	1,501,700	91.2	104.3	1,501,700	91.2	104.3
1959	1,501,138	979,977	65.3	1,006,817	67.1	102.7	1,006,817	67.1	102.7
1960	1,778,333	1,435,065	80.7	1,450,576	81.6	101.1	1,450,545	81.6	101.1
1961	2,423,299	2,127,775	87.8	2,102,562	86.8	98.8	2,102,562	86.8	98.8
1962	605,634	238,941	39.5	360,691	59.6	151.0	360,691	59.6	151.0
1963	299,715	108,565	36.2	120,342	40.2	110.8	120,342	40.2	110.8
1964	757,588	168,346	22.2	133,915	17.7	79.5	133,945	17.7	79.6
1965	2,973,530	2,507,390	84.3	2,477,250	83.3	98.8	2,477,250	83.3	98.8
1966	1,409,392	927,562	65.8	1,083,313	76.9	116.8	1,083,316	76.9	116.8
1967	463,112	172,406	37.2	222,324	48.0	129.0	222,324	48.0	129.0
1968	2,673,830	2,199,678	82.3	2,224,961	83.2	101.1	2,224,961	83.2	101.1
1969	1,156,106	783,674	67.8	767,777	66.4	98.0	767,777	66.4	98.0
1970	1,513,336	1,203,195	79.5	1,154,576	76.3	96.0	1,154,576	76.3	96.0
1971	733,566	234,536	32.0	174,959	23.9	74.6	174,959	23.9	74.6
1972	502,649	242,928	48.3	236,258	47.0	97.3	236,258	47.0	97.3
1973	1,388,676	1,007,391	72.5	1,002,792	72.2	99.5	1,002,792	72.2	99.5
1974	1,534,885	1,103,354	71.9	1,107,052	72.1	100.3	1,107,052	72.1	100.3
1975	1,962,659	1,816,754	92.6	1,744,200	88.9	96.0	1,744,200	88.9	96.0
1976	1,324,058	1,001,309	75.6	983,317	74.3	98.2	983,317	74.3	98.2
Mean	1,328,653	961,780	72.4	974,675	73.4	101.3	982,946	74.0	102.2

TABLE 7.24
BASIN TOTAL UNAPPROPRIATED STREAMFLOW
TWC AND TAMU RUNS 5 AND 5A COMPARISON

Year	Naturalized Streamflow (ac-ft)	Unappropriated Streamflow							
		TWC (ac-ft)	TWC (% Nat)	Run 5 (ac-ft)	Run 5 (% Nat)	Run 5 (% TWC)	Run 5A (ac-ft)	Run 5A (% Nat)	Run 5A (% TWC)
1940	7,850,608	5,914,085	75.3	4,655,354	59.3	78.7	4,655,354	59.3	78.7
1941	13,806,996	10,019,062	72.6	11,377,090	82.4	113.6	8,961,850	64.9	89.4
1942	8,517,753	5,813,924	68.3	6,281,219	73.7	108.0	5,701,190	66.9	98.1
1943	1,984,786	864,205	43.5	564,778	28.5	65.4	564,778	28.5	65.4
1944	8,901,734	6,865,228	77.1	6,448,344	72.4	93.9	6,448,344	72.4	93.9
1945	10,074,292	7,913,017	78.5	7,552,681	75.0	95.4	7,552,681	75.0	95.4
1946	8,406,420	6,542,371	77.8	6,047,147	71.9	92.4	6,047,147	71.9	92.4
1947	4,876,952	3,167,869	65.0	3,109,311	63.8	98.2	2,908,193	59.6	91.8
1948	1,873,208	534,236	28.5	390,459	20.8	73.1	390,459	20.8	73.1
1949	4,321,941	1,911,840	44.2	1,636,869	37.9	85.6	1,636,869	37.9	85.6
1950	3,960,386	2,060,782	52.0	1,734,894	43.8	84.2	1,734,894	43.8	84.2
1951	996,849	50,394	5.1	10,260	1.0	20.4	10,260	1.0	20.4
1952	1,623,246	514,531	31.7	154,422	9.5	30.0	154,422	9.5	30.0
1953	4,607,306	2,239,852	48.6	1,992,825	43.3	89.0	1,992,825	43.3	89.0
1954	1,362,340	162,127	11.9	108,682	8.0	67.0	108,682	8.0	67.0
1955	2,986,948	472,374	15.8	206,626	6.9	43.7	206,626	6.9	43.7
1956	929,191	41,206	4.4	6,430	0.7	15.6	6,430	0.7	15.6
1957	14,983,308	9,141,182	61.0	10,172,231	67.9	111.3	8,523,898	56.9	93.2
1958	5,932,074	4,232,360	71.3	4,083,268	68.8	96.5	3,938,951	66.4	93.1
1959	5,876,065	3,762,557	64.0	3,321,092	56.5	88.3	3,312,586	56.4	88.0
1960	7,158,198	5,518,867	77.1	4,958,301	69.3	89.8	4,949,426	69.1	89.7
1961	10,018,476	8,295,053	82.8	7,770,845	77.6	93.7	7,442,737	74.3	89.7
1962	3,381,713	1,151,548	34.1	1,255,722	37.1	109.0	868,071	25.7	75.4
1963	1,698,274	493,984	29.1	407,910	24.0	82.6	366,340	21.6	74.2
1964	2,209,915	525,547	23.8	155,594	7.0	29.6	155,594	7.0	29.6
1965	8,631,581	6,264,911	72.6	5,669,324	65.7	90.5	5,669,324	65.7	90.5
1966	6,411,800	4,066,322	63.4	4,005,860	62.5	98.5	3,548,543	55.3	87.3
1967	1,963,572	416,196	21.2	289,167	14.7	69.5	289,167	14.7	69.5
1968	11,074,828	8,519,382	76.9	8,248,005	74.5	96.8	8,044,379	72.6	94.4
1969	6,405,519	4,046,492	63.2	3,947,917	61.6	97.6	3,658,364	57.1	90.4
1970	5,020,008	3,594,914	71.6	3,339,946	66.5	92.9	3,246,871	64.7	90.3
1971	3,342,968	1,152,547	34.5	757,640	22.7	65.7	757,640	22.7	65.7
1972	3,001,679	1,451,922	48.4	1,092,013	36.4	75.2	1,092,013	36.4	75.2
1973	9,112,670	7,348,891	80.6	6,657,667	73.1	90.6	6,525,353	71.6	88.8
1974	7,822,334	5,877,303	75.1	5,258,820	67.2	89.5	5,143,561	65.8	87.5
1975	7,279,962	5,858,243	80.5	5,438,875	74.7	92.8	5,333,675	73.3	91.0
1976	6,400,484	4,513,836	70.5	3,960,950	61.9	87.8	3,960,950	61.9	87.8
Mean	5,805,578	3,819,437	65.8	3,596,447	61.9	94.2	3,402,931	58.6	89.1

TABLE 7.25
UNAPPROPRIATED STREAMFLOW AT THE RICHMOND GAGE
TWC AND TAMU RUNS 5 AND 5A COMPARISON

Year	Naturalized Streamflow (ac-ft)	Unappropriated Streamflow							
		TWC (ac-ft)	TWC (% Nat)	Run 5 (ac-ft)	Run 5 (% Nat)	Run 5 (% TWC)	Run 5A (ac-ft)	Run 5A (% Nat)	Run 5A (% TWC)
1940	7,850,608	5,589,806	71.2	4,645,094	59.2	83.1	4,645,094	59.2	83.1
1941	13,806,996	9,564,030	69.3	11,366,829	82.3	118.8	8,951,589	64.8	93.6
1942	8,517,753	5,750,306	67.5	6,270,959	73.6	109.1	5,690,930	66.8	99.0
1943	1,984,786	846,224	42.6	554,518	27.9	65.5	554,518	27.9	65.5
1944	8,901,734	6,777,958	76.1	6,438,084	72.3	95.0	6,438,084	72.3	95.0
1945	10,074,292	7,834,801	77.8	7,542,421	74.9	96.3	7,542,421	74.9	96.3
1946	8,406,420	6,469,510	77.0	6,036,887	71.8	93.3	6,036,887	71.8	93.3
1947	4,876,952	3,146,672	64.5	3,099,051	63.5	98.5	2,897,933	59.4	92.1
1948	1,873,208	511,571	27.3	381,711	20.4	74.6	381,711	20.4	74.6
1949	4,321,941	1,896,301	43.9	1,626,609	37.6	85.8	1,626,609	37.6	85.8
1950	3,960,386	2,016,789	50.9	1,724,634	43.5	85.5	1,724,634	43.5	85.5
1951	996,849	48,059	4.8	0	0.0	0.0	0	0.0	0.0
1952	1,623,246	499,355	30.8	145,674	9.0	29.2	145,674	9.0	29.2
1953	4,607,306	2,211,583	48.0	1,982,565	43.0	89.6	1,982,565	43.0	89.6
1954	1,362,340	160,254	11.8	98,422	7.2	61.4	98,422	7.2	61.4
1955	2,986,948	469,106	15.7	196,366	6.6	41.9	196,366	6.6	41.9
1956	929,191	40,809	4.4	0	0.0	0.0	0	0.0	0.0
1957	14,983,308	8,660,428	57.8	10,161,971	67.8	117.3	8,513,638	56.8	98.3
1958	5,932,074	4,144,734	69.9	4,073,008	68.7	98.3	3,928,691	66.2	94.8
1959	5,876,065	3,667,556	62.4	3,310,832	56.3	90.3	3,302,326	56.2	90.0
1960	7,158,198	5,360,902	74.9	4,948,041	69.1	92.3	4,939,166	69.0	92.1
1961	10,018,476	7,949,869	79.4	7,760,585	77.5	97.6	7,432,477	74.2	93.5
1962	3,381,713	1,139,981	33.7	1,245,462	36.8	109.3	857,811	25.4	75.2
1963	1,698,274	480,296	28.3	397,650	23.4	82.8	356,080	21.0	74.1
1964	2,209,915	513,798	23.2	145,334	6.6	28.3	145,334	6.6	28.3
1965	8,631,581	6,162,297	71.4	5,659,064	65.6	91.8	5,659,064	65.6	91.8
1966	6,411,800	3,920,207	61.1	3,995,600	62.3	101.9	3,538,283	55.2	90.3
1967	1,963,572	412,079	21.0	278,907	14.2	67.7	278,907	14.2	67.7
1968	11,074,828	8,349,786	75.4	8,237,745	74.4	98.7	8,034,119	72.5	96.2
1969	6,405,519	3,967,951	61.9	3,937,657	61.5	99.2	3,648,104	57.0	91.9
1970	5,020,008	3,517,176	70.1	3,329,686	66.3	94.7	3,236,611	64.5	92.0
1971	3,342,968	1,131,017	33.8	747,380	22.4	66.1	747,380	22.4	66.1
1972	3,001,679	1,360,250	45.3	1,081,753	36.0	79.5	1,081,753	36.0	79.5
1973	9,112,670	7,080,819	77.7	6,647,407	72.9	93.9	6,515,093	71.5	92.0
1974	7,822,334	5,632,210	72.0	5,248,560	67.1	93.2	5,133,301	65.6	91.1
1975	7,279,962	5,730,616	78.7	5,428,615	74.6	94.7	5,323,415	73.1	92.9
1976	6,400,484	4,460,123	69.7	3,950,690	61.7	88.6	3,950,690	61.7	88.6
Mean	5,805,578	3,715,547	64.0	3,586,372	61.8	96.5	3,392,856	58.4	91.3

TABLE 7.26
UNAPPROPRIATED STREAMFLOW AT THE BRYAN GAGE
TWC AND TAMU RUNS 5 AND 5A COMPARISON

Year	Naturalized Streamflow[a] (ac-ft)	Unappropriated Streamflow							
		TWC (ac-ft)	TWC (% Nat)	Run 5 (ac-ft)	Run 5 (% Nat)	Run 5 (% TWC)	Run 5A (ac-ft)	Run 5A (% Nat)	Run 5A (% TWC)
1940	4,964,432	2,825,504	56.9	2,437,063	49.1	86.3	2,437,063	49.1	86.3
1941	10,297,301	6,201,199	60.2	8,515,501	82.7	137.3	6,100,261	59.2	98.4
1942	6,898,760	4,669,741	67.7	5,400,198	78.3	115.6	4,820,169	69.9	103.2
1943	1,316,920	548,833	41.7	418,266	31.8	76.2	418,266	31.8	76.2
1944	6,017,878	4,479,951	74.4	4,564,056	75.8	101.9	4,564,056	75.8	101.9
1945	7,030,153	5,310,507	75.5	5,432,348	77.3	102.3	5,432,348	77.3	102.3
1946	5,064,349	3,635,380	71.8	3,551,786	70.1	97.7	3,551,786	70.1	97.7
1947	2,956,511	1,727,633	58.4	2,013,282	68.1	116.5	1,812,164	61.3	104.9
1948	1,269,120	254,692	20.1	219,114	17.3	86.0	219,114	17.3	86.0
1949	2,699,115	916,376	34.0	947,090	35.1	103.4	947,090	35.1	103.4
1950	2,151,513	683,108	31.8	606,806	28.2	88.8	606,806	28.2	88.8
1951	815,011	28,449	3.5	0	0.0	0.0	0	0.0	0.0
1952	965,988	256,463	26.5	106,786	11.1	41.6	106,786	11.1	41.6
1953	2,917,570	1,228,522	42.1	1,174,709	40.3	95.6	1,174,709	40.3	95.6
1954	1,031,429	62,372	6.0	43,649	4.2	70.0	43,649	4.2	70.0
1955	2,625,378	261,908	10.0	164,215	6.3	62.7	164,215	6.3	62.7
1956	804,488	23,974	3.0	0	0.0	0.0	0	0.0	0.0
1957	11,779,138	5,290,728	44.9	7,280,018	61.8	137.6	5,631,685	47.8	106.4
1958	4,420,957	2,964,698	67.1	3,310,789	74.9	111.7	3,166,472	71.6	106.8
1959	4,025,388	2,132,613	53.0	2,087,076	51.8	97.9	2,078,570	51.6	97.5
1960	4,583,661	3,183,408	69.5	3,127,420	68.2	98.2	3,118,545	68.0	98.0
1961	6,310,567	4,655,477	73.8	4,967,882	78.7	106.7	4,639,774	73.5	99.7
1962	2,682,399	607,024	22.6	947,168	35.3	156.0	559,517	20.9	92.2
1963	1,178,243	203,341	17.3	200,369	17.0	98.5	158,799	13.5	78.1
1964	1,699,216	264,268	15.6	78,457	4.6	29.7	78,457	4.6	29.7
1965	6,502,837	4,536,162	69.8	4,568,010	70.2	100.7	4,568,010	70.2	100.7
1966	4,836,314	2,373,533	49.1	2,861,320	59.2	120.6	2,404,003	49.7	101.3
1967	1,733,784	373,714	21.6	278,907	16.1	74.6	278,907	16.1	74.6
1968	7,287,639	5,127,396	70.4	5,510,319	75.6	107.5	5,306,693	72.8	103.5
1969	4,306,718	2,329,386	54.1	2,483,567	57.7	106.6	2,194,014	50.9	94.2
1970	3,537,772	2,489,899	70.4	2,578,087	72.9	103.5	2,485,012	70.2	99.8
1971	2,931,861	960,340	32.8	672,347	22.9	70.0	672,347	22.9	70.0
1972	2,001,175	696,760	34.8	619,003	30.9	88.8	619,003	30.9	88.8
1973	4,936,095	3,659,996	74.1	3,732,084	75.6	102.0	3,599,770	72.9	98.4
1974	4,719,176	2,848,651	60.4	2,896,792	61.4	101.7	2,781,533	58.9	97.6
1975	4,791,048	3,763,324	78.5	3,783,154	79.0	100.5	3,677,954	76.8	97.7
1976	4,173,335	2,756,979	66.1	2,654,532	63.6	96.3	2,654,532	63.6	96.3
Mean	4,007,115	2,279,252	56.9	2,438,707	60.9	107.0	2,245,191	56.0	98.5

TABLE 7.27
UNAPPROPRIATED STREAMFLOW AT THE WACO GAGE
TWC AND TAMU RUNS 5 AND 5A COMPARISON

Year	Naturalized Streamflow (ac-ft)	Unappropriated Streamflow							
		TWC (ac-ft)	TWC (% Nat)	Run 5 (ac-ft)	Run 5 (% Nat)	Run 5 (% TWC)	Run 5A (ac-ft)	Run 5A (% Nat)	Run 5A (% TWC)
1940	2,039,016	716,884	35.2	541,316	26.5	75.5	541,316	26.5	75.5
1941	5,700,387	2,036,923	35.7	4,376,313	76.8	214.8	1,961,073	34.4	96.3
1942	3,973,192	2,235,315	56.3	3,022,285	76.1	135.2	2,442,256	61.5	109.3
1943	512,271	122,287	23.9	74,409	14.5	60.8	74,409	14.5	60.8
1944	1,681,214	837,959	49.8	838,718	49.9	100.1	838,718	49.9	100.1
1945	3,103,724	1,971,671	63.5	2,008,927	64.7	101.9	2,008,927	64.7	101.9
1946	1,909,200	855,868	44.8	787,628	41.3	92.0	787,628	41.3	92.0
1947	1,344,035	446,773	33.2	660,213	49.1	147.8	459,095	34.2	102.8
1948	795,052	94,356	11.9	30,660	3.9	32.5	30,660	3.9	32.5
1949	1,707,370	429,730	25.2	479,592	28.1	111.6	479,592	28.1	111.6
1950	1,363,620	130,718	9.6	57,930	4.2	44.3	57,930	4.2	44.3
1951	593,258	5,603	0.9	0	0.0	0.0	0	0.0	0.0
1952	440,643	63,858	14.5	0	0.0	0.0	0	0.0	0.0
1953	1,244,367	216,031	17.4	144,752	11.6	67.0	144,752	11.6	67.0
1954	836,391	3,734	0.4	0	0.0	0.0	0	0.0	0.0
1955	1,864,647	69,221	3.7	1,431	0.1	2.1	1,431	0.1	2.1
1956	481,593	345	0.1	0	0.0	0.0	0	0.0	0.0
1957	6,726,090	2,179,347	32.4	4,265,595	63.4	195.7	2,617,262	38.9	120.1
1958	1,926,829	957,491	49.7	1,157,586	60.1	120.9	1,013,269	52.6	105.8
1959	1,871,692	686,639	36.7	763,358	40.8	111.2	754,852	40.3	109.9
1960	1,631,659	704,827	43.2	702,130	43.0	99.6	693,255	42.5	98.4
1961	2,830,364	1,591,940	56.2	1,917,701	67.8	120.5	1,589,593	56.2	99.9
1962	1,889,009	279,706	14.8	683,401	36.2	244.3	295,750	15.7	105.7
1963	750,997	31,530	4.2	49,116	6.5	155.8	7,546	1.0	23.9
1964	879,136	71,898	8.2	568	0.1	0.8	568	0.1	0.8
1965	2,227,849	1,131,528	50.8	1,141,997	51.3	100.9	1,141,997	51.3	100.9
1966	2,529,951	861,188	34.0	1,376,787	54.4	159.9	919,470	36.3	106.8
1967	921,780	77,154	8.4	51,744	5.6	67.1	51,744	5.6	67.1
1968	3,372,397	1,925,780	57.1	2,207,673	65.5	114.6	2,004,047	59.4	104.1
1969	2,524,635	1,029,235	40.8	1,264,638	50.1	122.9	975,085	38.6	94.7
1970	1,399,530	814,473	58.2	931,289	66.5	114.3	838,214	59.9	102.9
1971	1,864,511	520,482	27.9	365,243	19.6	70.2	365,243	19.6	70.2
1972	1,157,314	219,799	19.0	172,283	14.9	78.4	172,283	14.9	78.4
1973	2,076,842	1,318,812	63.5	1,364,720	65.7	103.5	1,232,406	59.3	93.4
1974	2,043,269	747,097	36.6	797,172	39.0	106.7	681,913	33.4	91.3
1975	1,898,362	1,036,418	54.6	1,238,956	65.3	119.5	1,133,756	59.7	109.4
1976	1,464,693	614,003	41.9	497,531	34.0	81.0	497,531	34.0	81.0
Mean	1,934,511	730,720	37.8	918,207	47.5	125.7	724,691	37.5	99.2

TABLE 7.28
UNAPPROPRIATED STREAMFLOW AT THE SOUTH BEND GAGE
TWC AND TAMU RUNS 5 AND 5A COMPARISON

Year	Naturalized Streamflow (ac-ft)	Unappropriated Streamflow							
		TWC (ac-ft)	TWC (% Nat)	Run 5 (ac-ft)	Run 5 (% Nat)	Run 5 (% TWC)	Run 5A (ac-ft)	Run 5A (% Nat)	Run 5A (% TWC)
1940	705,873	104,295	14.8	0	0.0	0.0	0	0.0	0.0
1941	3,263,806	2,397,456	73.5	2,415,240	74.0	100.7	2,415,240	74.0	100.7
1942	1,033,443	567,579	54.9	580,029	56.1	102.2	580,029	56.1	102.2
1943	191,097	0	0.0	0	0.0	---	0	0.0	---
1944	264,473	0	0.0	0	0.0	---	0	0.0	---
1945	458,106	0	0.0	0	0.0	---	0	0.0	---
1946	523,693	56,786	10.8	0	0.0	0.0	0	0.0	0.0
1947	646,795	221,355	34.2	201,118	31.1	90.9	201,118	31.1	90.9
1948	360,640	0	0.0	0	0.0	---	0	0.0	---
1949	600,962	40,863	6.8	0	0.0	0.0	0	0.0	---
1950	696,159	32,284	4.6	0	0.0	0.0	0	0.0	0.0
1951	294,620	0	0.0	0	0.0	---	0	0.0	0.0
1952	56,732	0	0.0	0	0.0	---	0	0.0	---
1953	720,092	0	0.0	0	0.0	---	0	0.0	---
1954	597,990	0	0.0	0	0.0	---	0	0.0	---
1955	1,338,219	164,464	12.3	0	0.0	0.0	0	0.0	0.0
1956	107,052	0	0.0	0	0.0	---	0	0.0	---
1957	2,783,249	1,434,637	51.5	1,648,333	59.2	114.9	1,648,333	59.2	114.9
1958	458,618	129,221	28.2	144,317	31.5	111.7	144,317	31.5	111.7
1959	587,596	64,413	11.0	8,506	1.4	13.2	8,506	1.4	13.2
1960	652,584	38,956	6.0	8,875	1.4	22.8	8,875	1.4	22.8
1961	900,964	220,268	24.4	328,108	36.4	149.0	328,108	36.4	149.0
1962	887,010	293,611	33.1	387,651	43.7	132.0	387,651	43.7	132.0
1963	497,349	17,818	3.6	41,570	8.4	233.3	41,570	8.4	233.3
1964	228,432	0	0.0	0	0.0	---	0	0.0	---
1965	607,792	0	0.0	0	0.0	---	0	0.0	---
1966	971,358	294,889	30.4	457,317	47.1	155.1	457,317	47.1	155.1
1967	469,220	0	0.0	0	0.0	---	0	0.0	---
1968	718,540	230,294	32.1	203,626	28.3	88.4	203,626	28.3	88.4
1969	911,732	266,896	29.3	289,553	31.8	108.5	289,553	31.8	108.5
1970	245,021	91,304	37.3	93,075	38.0	101.9	93,075	38.0	101.9
1971	876,010	50,609	5.8	0	0.0	0.0	0	0.0	0.0
1972	673,502	67,833	10.1	0	0.0	0.0	0	0.0	0.0
1973	374,543	105,534	28.2	132,314	35.3	125.4	132,314	35.3	125.4
1974	804,524	109,130	13.6	115,259	14.3	105.6	115,259	14.3	105.6
1975	467,541	98,461	21.1	105,200	22.5	106.8	105,200	22.5	106.8
1976	351,146	0	0.0	0	0.0	---	0	0.0	---
Mean	711,527	191,864	27.0	193,516	27.2	100.9	193,516	27.2	100.9

TABLE 7.29
UNAPPROPRIATED STREAMFLOW AT THE CAMERON GAGE
TWC AND TAMU RUNS 5 AND 5A COMPARISON

Year	Naturalized Streamflow (ac-ft)	Unappropriated Streamflow							
		TWC (ac-ft)	TWC (% Nat)	Run 5 (ac-ft)	Run 5 (% Nat)	Run 5 (% TWC)	Run 5A (ac-ft)	Run 5A (% Nat)	Run 5A (% TWC)
1940	2,054,824	1,446,334	70.4	1,216,555	59.2	84.1	1,216,555	59.2	84.1
1941	3,282,196	3,003,918	91.5	3,005,459	91.6	100.1	3,005,459	91.6	100.1
1942	2,155,038	1,806,820	83.8	1,832,038	85.0	101.4	1,832,038	85.0	101.4
1943	391,839	228,931	58.4	227,666	58.1	99.4	227,666	58.1	99.4
1944	2,590,127	2,083,373	80.4	2,082,076	80.4	99.9	2,082,076	80.4	99.9
1945	2,448,643	2,079,381	84.9	2,086,985	85.2	100.4	2,086,985	85.2	100.4
1946	1,694,076	1,397,906	82.5	1,375,925	81.2	98.4	1,375,925	81.2	98.4
1947	1,002,748	817,706	81.5	817,259	81.5	99.9	817,259	81.5	99.9
1948	266,781	68,778	25.8	103,889	38.9	151.0	103,889	38.9	151.0
1949	721,202	291,474	40.4	330,440	45.8	113.4	330,440	45.8	113.4
1950	367,974	162,196	44.1	164,215	44.6	101.2	164,215	44.6	101.2
1951	138,339	18,569	13.4	0	0.0	0.0	0	0.0	0.0
1952	333,454	93,174	27.9	91,425	27.4	98.1	91,425	27.4	98.1
1953	861,207	338,062	39.3	339,745	39.4	100.5	339,745	39.4	100.5
1954	98,452	24,294	24.7	24,586	25.0	101.2	24,586	25.0	101.2
1955	489,005	57,579	11.8	42,385	8.7	73.6	42,385	8.7	73.6
1956	232,190	7,845	3.4	0	0.0	0.0	0	0.0	0.0
1957	3,384,809	1,961,352	57.9	1,900,553	56.1	96.9	1,900,553	56.1	96.9
1958	1,645,758	1,439,330	87.5	1,503,655	91.4	104.5	1,503,655	91.4	104.5
1959	1,501,138	979,977	65.3	988,722	65.9	100.9	988,722	65.9	100.9
1960	1,778,333	1,435,065	80.7	1,402,482	78.9	97.7	1,402,482	78.9	97.7
1961	2,423,299	2,127,775	87.8	2,096,972	86.5	98.6	2,096,972	86.5	98.6
1962	605,634	238,941	39.5	358,171	59.1	149.9	358,171	59.1	149.9
1963	299,715	108,565	36.2	120,054	40.1	110.6	120,054	40.1	110.6
1964	757,588	168,346	22.2	70,818	9.3	42.1	70,818	9.3	42.1
1965	2,973,530	2,507,390	84.3	2,283,076	76.8	91.1	2,283,076	76.8	91.1
1966	1,409,392	927,562	65.8	1,078,798	76.5	116.3	1,078,798	76.5	116.3
1967	463,112	172,406	37.2	212,652	45.9	123.3	212,652	45.9	123.3
1968	2,673,830	2,199,678	82.3	2,179,979	81.5	99.1	2,179,979	81.5	99.1
1969	1,156,106	783,674	67.8	748,829	64.8	95.6	748,829	64.8	95.6
1970	1,513,336	1,203,195	79.5	1,148,787	75.9	95.5	1,148,787	75.9	95.5
1971	733,566	234,536	32.0	89,567	12.2	38.2	89,567	12.2	38.2
1972	502,649	242,928	48.3	222,100	44.2	91.4	222,100	44.2	91.4
1973	1,388,676	1,007,391	72.5	980,547	70.6	97.3	980,547	70.6	97.3
1974	1,534,885	1,103,354	71.9	1,036,489	67.5	93.9	1,036,489	67.5	93.9
1975	1,962,659	1,816,754	92.6	1,744,746	88.9	96.0	1,744,746	88.9	96.0
1976	1,324,058	1,001,309	75.6	953,234	72.0	95.2	953,234	72.0	95.2
Mean	1,328,653	961,780	72.4	942,186	70.9	98.0	942,186	70.9	98.0

CHAPTER 8
FIRM YIELD CONSTRAINED BY SENIOR WATER RIGHTS

Firm yields documented in this chapter for the 13 reservoirs reflect the impacts of all the water rights in the basin. Water rights senior to the rights associated with an individual reservoir or group of reservoirs reduce the individual reservoir or system firm yield. Firm yields, constrained by senior water rights, are presented for 13 individual reservoirs. System firm yields are presented for a system of ten reservoirs and subsystems thereof.

The firm yields were computed with HEC-3 with streamflow data developed with TAMUWRAP. Although several simulation runs are included in Chapter 7, the firm yield computations are based on data from TAMUWRAP run 1 only. All input data, other than monthly streamflows, are identical to the hydrologic firm yield simulations discussed in Chapter 6.

All firm yields presented in this chapter are for year 2010 conditions of sedimentation. Although base condition storage versus area relationships are incorporated in the TAMUWRAP simulation, the HEC-3 firm yield computations were performed with the 2010 sediment condition storage versus area relationships.

Several key terms used in this chapter are defined in Table 8.1. Figure 8.1 is a system schematic showing the relative locations of the 13 reservoirs and pertinent downstream control points.

Streamflow Data Sets

Firm yield is the estimated maximum release or withdrawal rate which can be maintained continuously for a specified set of streamflow data. Two alternative streamflow data sets were used to compute firm yields adjusted for water rights: (1) streamflow depletions only and (2) streamflow depletions plus unappropriated flows. In the TAMUWRAP simulation, water is provided to the stream/reservoir system as inputed naturalized streamflows. Return flows are also available for further diversions. This total available water becomes either streamflow depletions or unappropriated streamflows. As discussed in Chapter 7, streamflow depletions include water appropriated from the streamflow to supply diversions and refill reservoir storage capacity associated with the water rights. Unappropriated streamflow is the water remaining after the depletions. TAMUWRAP computes the streamflow depletions for each water right and the remaining unappropriated flows.

The streamflow depletion data set is the water beneficially used by the specified water rights during the TAMUWRAP simulation. This represents the water available to the reservoir owner or water manager under existing permits assuming a repetition of historical hydrologic conditions. The second streamflow data set includes unappropriated flows in addition to streamflow depletions. This represents the water which can be appropriated by the specified reservoir owner or water manager without adversely impacting any other water rights. The streamflow data includes the reservoir owner or water manager's already permitted appropriations plus water still available for appropriation.

Tables 8.2 through 8.14 are tabulations of annual naturalized streamflows, streamflow depletions, and unappropriated streamflows at each of the 13

Table 8.1
GLOSSARY OF FIRM YIELD TERMS USED IN CHAPTER 8

Firm yield is the estimated maximum release or withdrawal rate which can be maintained continuously during a repetition of the 85-year hydrologic record, based on specified assumptions regarding various factors.

Firm yield constrained by senior water rights is the maximum release or withdrawal rate which can be maintained continuously during a repetition of the 85-year hydrologic record, assuming other users in the basin with senior rights withdraw the full amounts to which they are legally entitled.

Individual reservoir firm yield is computed assuming a reservoir is operated alone rather than as a component of a multireservoir system.

System firm yield is the maximum diversion rate which can be maintained continuously during the 85-year hydrologic record with two or more reservoirs making releases as required to satisfy a diversion at a common downstream control point.

Streamflow depletions computed by TAMUWRAP represent the streamflow used to meet diversions and refill previously drawn-down reservoir storage capacity associated with specified water rights.

Unappropriated streamflows computed by TAMUWRAP represent water still remaining after all streamflow depletions.

Downstream local streamflows represent water entering the river below the most downstream dam on the Brazos River and the tributaries.

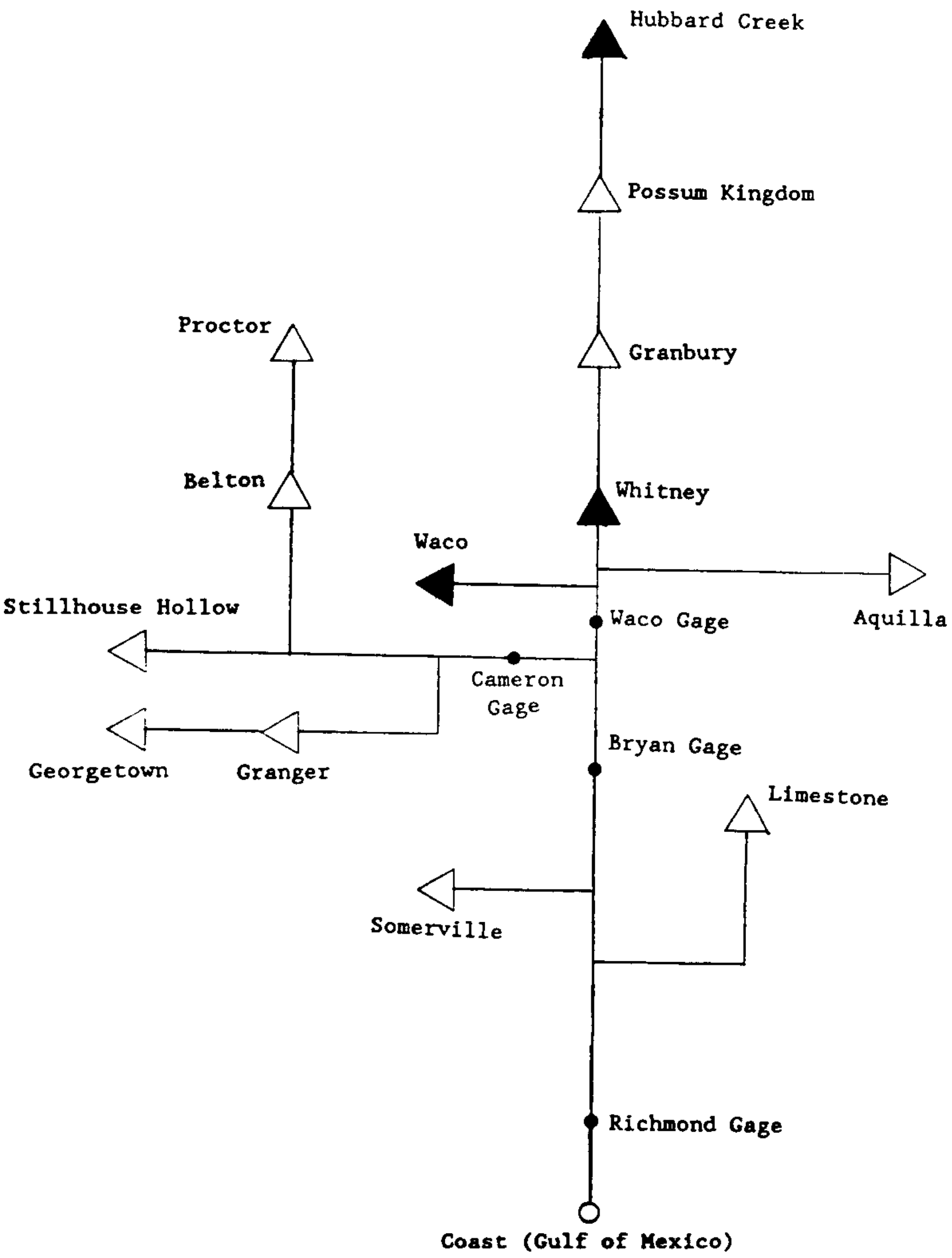


Figure 8.1 System Schematic

Table 8.2
NATURALIZED STREAMFLOW, STREAMFLOW DEPLETIONS, AND UNAPPROPRIATED STREAMFLOW AT HUBBARD CREEK RESERVOIR

Year	Naturalised Streamflow (ac-ft/yr)	Streamflow Depletion (ac-ft/yr)	Unappropriated Streamflow (ac-ft/yr)
1900	166884.	105884.	25854.
1901	35956.	28245.	0.
1902	69298.	37715.	0.
1903	60274.	29616.	0.
1904	62715.	5860.	0.
1905	171008.	91690.	0.
1906	63930.	28857.	0.
1907	120875.	99918.	0.
1908	144530.	121430.	0.
1909	31151.	1742.	0.
1910	79426.	120.	0.
1911	16995.	48.	0.
1912	19901.	0.	0.
1913	40955.	0.	0.
1914	94326.	42515.	0.
1915	323979.	302140.	0.
1916	39323.	8436.	0.
1917	12128.	1057.	0.
1918	100240.	28142.	0.
1919	297128.	274749.	0.
1920	84790.	67009.	4.
1921	49672.	4616.	0.
1922	66680.	55340.	0.
1923	67345.	20937.	0.
1924	62950.	18546.	0.
1925	55836.	16418.	0.
1926	108351.	83487.	0.
1927	36844.	15427.	0.
1928	175726.	34137.	0.
1929	50935.	28624.	0.
1930	144515.	124987.	0.
1931	75362.	8868.	4.
1932	131085.	109866.	0.
1933	63476.	53224.	0.
1934	42753.	971.	0.
1935	141731.	91646.	0.
1936	85739.	39132.	0.
1937	58000.	1696.	4.
1938	89122.	43536.	0.
1939	59071.	15609.	0.
1940	123573.	61871.	0.
1941	385323.	371975.	0.
1942	271130.	115228.	137798.
1943	25040.	8169.	0.
1944	57425.	2559.	0.
1945	62898.	9219.	0.
1946	32271.	1687.	0.
1947	23868.	3109.	0.
1948	32928.	0.	0.
1949	125566.	94172.	0.
1950	97803.	75963.	0.
1951	46687.	21394.	0.
1952	1312.	0.	0.
1953	138386.	162.	0.
1954	94170.	73316.	0.
1955	101699.	43332.	0.
1956	25337.	0.	0.
1957	518512.	385120.	70008.
1958	90812.	72396.	2652.
1959	79882.	56270.	0.
1960	28940.	6350.	0.
1961	101843.	85090.	0.
1962	53831.	39166.	0.
1963	64974.	32238.	0.
1964	51477.	2992.	0.
1965	98215.	78986.	0.
1966	105530.	84765.	0.
1967	42567.	13459.	0.
1968	189462.	175700.	0.
1969	139159.	94002.	0.
1970	44464.	40184.	0.
1971	43211.	10976.	0.
1972	26042.	6730.	0.
1973	39643.	13467.	0.
1974	200713.	149637.	0.
1975	59401.	49353.	0.
1976	33067.	8203.	0.
1977	295468.	68875.	0.
1978	517190.	287230.	0.
1979	78249.	40729.	0.
1980	212711.	55712.	0.
1981	468031.	263300.	86587.
1982	116886.	59595.	26063.
1983	496363.	115250.	151376.
1984	244907.	18804.	0.
mean	113976.	61635.	5886.

Table 8.3
NATURALIZED STREAMFLOW, STREAMFLOW DEPLETIONS, AND UNAPPROPRIATED STREAMFLOW AT POSSUM KINGDOM RESERVOIR

Year	Naturalized Streamflow (ac-ft/yr)	Streamflow Depletion (ac-ft/yr)	Unappropriated Streamflow (ac-ft/yr)
1900	1663370.	301105.	759244.
1901	368315.	155437.	4.
1902	834980.	429324.	94239.
1903	473727.	231211.	31205.
1904	329096.	268879.	0.
1905	1254258.	351591.	156110.
1906	1429630.	311214.	165080.
1907	1001587.	335577.	97469.
1908	1340055.	176338.	922900.
1909	163768.	106668.	0.
1910	418988.	276850.	0.
1911	263269.	165739.	0.
1912	291563.	133639.	0.
1913	620598.	558545.	0.
1914	1573309.	470642.	71727.
1915	2141863.	281242.	803154.
1916	330193.	268915.	4.
1917	191827.	117045.	0.
1918	987378.	516421.	91577.
1919	2829229.	303145.	1292918.
1920	1672203.	303029.	707494.
1921	281425.	144738.	43656.
1922	504766.	280669.	18892.
1923	948157.	456635.	97953.
1924	388031.	205750.	40101.
1925	959994.	362170.	0.
1926	1368346.	327741.	384944.
1927	443640.	223050.	88260.
1928	964647.	311489.	48335.
1929	740135.	333967.	5246.
1930	1697529.	328122.	820842.
1931	558640.	296021.	16872.
1932	1887193.	302774.	920385.
1933	617172.	244083.	46757.
1934	246253.	170296.	0.
1935	1519683.	457797.	632365.
1936	1041978.	298208.	103930.
1937	289324.	169145.	4.
1938	877204.	335053.	168459.
1939	502615.	265116.	8815.
1940	927696.	425661.	41139.
1941	3586069.	284973.	2556786.
1942	1427766.	279982.	866641.
1943	230408.	155738.	4.
1944	375209.	295581.	0.
1945	625650.	426302.	0.
1946	726330.	342700.	22919.
1947	699259.	205814.	294224.
1948	371718.	296650.	0.
1949	792512.	370398.	42683.
1950	782503.	285068.	97482.
1951	363624.	197311.	0.
1952	69196.	12621.	0.
1953	791983.	682937.	0.
1954	651442.	180102.	0.
1955	1544755.	445816.	0.
1956	159021.	99892.	0.
1957	3686030.	487733.	2310234.
1958	730433.	237233.	228435.
1959	707000.	332111.	66292.
1960	744026.	312160.	53526.
1961	930907.	285097.	348953.
1962	1109224.	293495.	511010.
1963	585257.	200630.	48761.
1964	311898.	255116.	0.
1965	755770.	386998.	30868.
1966	1221023.	275183.	629928.
1967	531174.	291154.	0.
1968	971610.	229071.	372770.
1969	1137029.	392447.	363721.
1970	354957.	105008.	149104.
1971	860851.	461314.	0.
1972	731477.	290607.	7152.
1973	443091.	193226.	132616.
1974	948321.	376424.	209005.
1975	650279.	245210.	175267.
1976	460206.	322485.	5542.
1977	606264.	292463.	54382.
1978	1145734.	270394.	0.
1979	381208.	221443.	0.
1980	991314.	425174.	0.
1981	1479694.	279644.	625341.
1982	1513243.	246889.	1069047.
1983	1336830.	342403.	415220.
1984	495500.	317379.	0.
mean	893664.	293429.	239588.

Table 8.4
NATURALIZED STREAMFLOW, STREAMFLOW DEPLETIONS, AND UNAPPROPRIATED STREAMFLOW AT GRANBURY RESERVOIR

Year	Naturalized Streamflow (ac-ft/yr)	Streamflow Depletion (ac-ft/yr)	Unappropriated Streamflow (ac-ft/yr)
1900	2079899.	89336.	1218508.
1901	366839.	36070.	4.
1902	1246781.	147230.	166892.
1903	906342.	54622.	284766.
1904	546843.	112855.	0.
1905	1647971.	108600.	391644.
1906	1330537.	94049.	172610.
1907	1026087.	93682.	101110.
1908	1844266.	59496.	1310702.
1909	290324.	83283.	0.
1910	415678.	20829.	0.
1911	519679.	59568.	0.
1912	287166.	29504.	0.
1913	1142169.	215352.	148282.
1914	1954356.	93979.	429629.
1915	2306479.	91931.	1008948.
1916	632303.	51602.	154746.
1917	204485.	22009.	0.
1918	1406614.	174588.	183940.
1919	3423194.	94128.	1939329.
1920	1948034.	94101.	992521.
1921	454119.	51718.	134970.
1922	1038152.	83781.	430677.
1923	1449694.	138906.	192878.
1924	637159.	54512.	213274.
1925	1119793.	123205.	0.
1926	1771971.	97593.	570085.
1927	653595.	90869.	159743.
1928	1130078.	96700.	85892.
1929	927478.	89678.	59830.
1930	1854825.	96729.	880600.
1931	767917.	76813.	88943.
1932	2177875.	108795.	1082816.
1933	735875.	60211.	100150.
1934	285290.	26906.	0.
1935	2011043.	180780.	880845.
1936	1419055.	92942.	249002.
1937	399082.	86552.	11925.
1938	1232796.	79685.	401982.
1939	569282.	90122.	8815.
1940	1285535.	111159.	230763.
1941	4120080.	81501.	3024129.
1942	2434966.	85300.	1757237.
1943	325706.	46790.	12876.
1944	651751.	114956.	110015.
1945	1179934.	105042.	391683.
1946	1107670.	96375.	253229.
1947	808757.	66779.	356292.
1948	510972.	74491.	11830.
1949	1285447.	127039.	353862.
1950	1076100.	94359.	131485.
1951	438949.	87131.	0.
1952	135790.	51551.	0.
1953	876603.	21147.	0.
1954	710555.	176126.	0.
1955	1680132.	131450.	0.
1956	273698.	53839.	0.
1957	4782966.	143226.	3372646.
1958	1167369.	72761.	533564.
1959	1067374.	103615.	368872.
1960	838241.	91980.	129726.
1961	1058425.	90592.	415259.
1962	1503237.	90723.	560863.
1963	698017.	58108.	48761.
1964	466971.	112233.	0.
1965	1035572.	53456.	223338.
1966	1715611.	119846.	948889.
1967	644013.	90347.	0.
1968	1513236.	80352.	798533.
1969	1611899.	110198.	693868.
1970	634397.	28142.	372801.
1971	1070470.	143250.	153155.
1972	836866.	92835.	14786.
1973	773830.	72197.	354181.
1974	1295783.	99464.	396616.
1975	994619.	71960.	441751.
1976	658320.	107981.	49920.
1977	794916.	28869.	244183.
1978	1135095.	130590.	0.
1979	701967.	62234.	182256.
1980	967696.	139993.	0.
1981	2034940.	90053.	882054.
1982	2132459.	59853.	1887419.
1983	1283684.	88822.	485756.
1984	509040.	35718.	0.
mean	1164598.	88673.	399043.

Table 8.5
NATURALIZED STREAMFLOW, STREAMFLOW DEPLETIONS, AND UNAPPROPRIATED STREAMFLOW AT WHITNEY RESERVOIR

Year	:Naturalized : Streamflow : (ac-ft/yr)	: Streamflow : Depletion : (ac-ft/yr)	:Unappropriated : Streamflow : (ac-ft/yr)
1900	2838486.	91812.	1727849.
1901	458204.	34389.	43330.
1902	1838529.	155938.	333142.
1903	1439097.	88167.	666506.
1904	847968.	10612.	0.
1905	2153687.	180859.	662625.
1906	1439382.	94989.	307260.
1907	1356507.	94890.	169476.
1908	3036708.	47713.	2020580.
1909	585636.	550.	0.
1910	492307.	808.	0.
1911	805650.	916.	0.
1912	484591.	1471.	0.
1913	1613207.	396133.	148282.
1914	2655163.	94966.	1036844.
1915	2667222.	95565.	1184441.
1916	1083441.	30702.	532143.
1917	323233.	1549.	0.
1918	1931409.	223731.	197551.
1919	4672713.	95567.	2892313.
1920	2570410.	95516.	1581202.
1921	821584.	30851.	397573.
1922	2056003.	110581.	1198936.
1923	1950485.	139463.	338583.
1924	1170057.	30587.	537577.
1925	1198512.	493.	0.
1926	1931966.	240695.	608773.
1927	1079129.	66622.	441511.
1928	1308450.	80907.	150612.
1929	1258736.	92411.	153007.
1930	2075121.	137094.	1019330.
1931	1239913.	30295.	445343.
1932	2835875.	145361.	1572934.
1933	1042015.	43928.	166139.
1934	588539.	81691.	76486.
1935	3472274.	167811.	1575412.
1936	2034462.	94879.	559388.
1937	969709.	30485.	255255.
1938	2008319.	119466.	918897.
1939	695007.	68206.	8815.
1940	1759525.	139285.	435022.
1941	5587550.	67866.	4125237.
1942	3626603.	72043.	2624295.
1943	546063.	32045.	69470.
1944	1204339.	97475.	421001.
1945	2474952.	137022.	1425693.
1946	1778202.	96269.	699279.
1947	1195767.	27688.	618693.
1948	876224.	102688.	27823.
1949	1638160.	99726.	430575.
1950	1385220.	133835.	136154.
1951	569101.	705.	0.
1952	370322.	11573.	0.
1953	1010689.	69330.	0.
1954	785344.	398.	0.
1955	1898330.	315219.	0.
1956	476429.	659.	0.
1957	6475701.	262481.	4488408.
1958	1786418.	42839.	1021155.
1959	1818786.	121915.	824838.
1960	1471629.	90790.	658601.
1961	2500763.	84527.	1656363.
1962	1709909.	96025.	677034.
1963	762458.	36939.	48761.
1964	828870.	31274.	0.
1965	1835711.	147850.	775258.
1966	2200687.	114908.	1293710.
1967	788748.	9621.	0.
1968	2957593.	146215.	1976847.
1969	2240538.	117598.	1122245.
1970	1284291.	37534.	860558.
1971	1767276.	144321.	422926.
1972	1111818.	97629.	170547.
1973	1632619.	75665.	1053508.
1974	1809390.	89092.	659353.
1975	1617519.	25150.	982016.
1976	1203272.	140377.	317024.
1977	1255673.	20263.	628535.
1978	1132863.	913.	0.
1979	1102707.	218244.	253224.
1980	1063393.	64544.	0.
1981	2185898.	176818.	919017.
1982	2292087.	41893.	1647882.
1983	1411904.	135541.	472997.
1984	594244.	832.	0.
mean	1659474.	88521.	680849.

Table 8.6
NATURALIZED STREAMFLOW, STREAMFLOW DEPLETIONS, AND UNAPPROPRIATED STREAMFLOW AT AQUILLA RESERVOIR

Year	:Naturalized : Streamflow : (ac-ft/yr)	: Streamflow : Depletion : (ac-ft/yr)	:Unappropriated : Streamflow : (ac-ft/yr)
1900	179855.	24629.	151605.
1901	103657.	9139.	9992.
1902	93564.	29263.	32217.
1903	46300.	20520.	25314.
1904	36963.	14231.	0.
1905	211896.	43994.	150524.
1906	74320.	24343.	25723.
1907	50645.	24120.	24359.
1908	58175.	12810.	45102.
1909	16520.	0.	0.
1910	15255.	0.	0.
1911	21297.	5875.	0.
1912	13093.	5850.	0.
1913	86817.	65340.	3637.
1914	171139.	16343.	150172.
1915	191022.	17296.	169314.
1916	64764.	20204.	43886.
1917	13396.	0.	0.
1918	40900.	38262.	0.
1919	155804.	41004.	114710.
1920	81555.	20355.	55916.
1921	81663.	15150.	44229.
1922	174977.	20751.	152854.
1923	72461.	38278.	27992.
1924	60359.	7299.	51658.
1925	21718.	3660.	901.
1926	57562.	54416.	2606.
1927	45817.	12869.	31948.
1928	58483.	12355.	0.
1929	34812.	31243.	1916.
1930	33716.	28231.	2685.
1931	81384.	17705.	61500.
1932	43586.	32590.	9888.
1933	29791.	16082.	8737.
1934	34302.	20470.	6635.
1935	105938.	41335.	63967.
1936	80059.	24222.	45495.
1937	60036.	23789.	31324.
1938	323369.	11145.	311917.
1939	44406.	21992.	10857.
1940	93665.	36315.	46459.
1941	139643.	18869.	120698.
1942	141566.	23056.	114642.
1943	35104.	8312.	22693.
1944	104790.	32904.	68956.
1945	168263.	18914.	149175.
1946	69854.	25727.	43634.
1947	43563.	16279.	25771.
1948	25823.	23577.	0.
1949	27037.	21344.	0.
1950	21619.	21430.	0.
1951	27922.	17281.	0.
1952	59509.	49824.	0.
1953	36156.	7190.	19818.
1954	10818.	4940.	0.
1955	13950.	3916.	0.
1956	13234.	0.	0.
1957	125374.	68352.	56293.
1958	89519.	9925.	78219.
1959	73786.	34358.	35003.
1960	65708.	23160.	42322.
1961	151108.	22870.	128150.
1962	48855.	22840.	25918.
1963	3385.	3057.	155.
1964	16743.	12327.	0.
1965	79208.	36012.	42794.
1966	82499.	22279.	60070.
1967	42624.	18185.	0.
1968	174320.	31597.	141801.
1969	80263.	15029.	65147.
1970	44727.	34326.	10084.
1971	79437.	28020.	47966.
1972	32448.	15562.	9601.
1973	172888.	30214.	140277.
1974	67800.	23607.	38341.
1975	113856.	8847.	104724.
1976	95309.	35730.	58413.
1977	104931.	7474.	96766.
1978	6697.	1825.	0.
1979	73491.	48118.	25246.
1980	48242.	18378.	28535.
1981	79257.	30081.	47334.
1982	29324.	20532.	8701.
1983	14429.	7653.	0.
1984	15387.	14591.	0.
mean	73124.	21670.	44392.

Table 8.7
NATURALIZED STREAMFLOW, STREAMFLOW DEPLETIONS, AND UNAPPROPRIATED STREAMFLOW AT WACO RESERVOIR

Year	Naturalized Streamflow (ac-ft/yr)	Streamflow Depletion (ac-ft/yr)	Unappropriated Streamflow (ac-ft/yr)
1900	724504.	82156.	541893.
1901	140789.	54704.	9215.
1902	253028.	108259.	96537.
1903	316591.	64589.	215478.
1904	207558.	81037.	0.
1905	606516.	99778.	330040.
1906	196987.	82097.	36657.
1907	135970.	81987.	35286.
1908	802662.	57125.	739072.
1909	99102.	96923.	0.
1910	70575.	47670.	0.
1911	72579.	68464.	0.
1912	84167.	84150.	0.
1913	355330.	128156.	121196.
1914	763476.	82002.	585189.
1915	637646.	82133.	525807.
1916	251420.	54993.	190933.
1917	32576.	32559.	0.
1918	141997.	140439.	0.
1919	1223209.	89928.	1106541.
1920	525032.	82150.	355152.
1921	332473.	64217.	140462.
1922	445885.	67687.	367220.
1923	318229.	112146.	72431.
1924	270481.	44691.	219324.
1925	128873.	113086.	0.
1926	177208.	73243.	92002.
1927	159555.	73200.	76469.
1928	100464.	83503.	6651.
1929	126430.	85261.	29436.
1930	215467.	95969.	102830.
1931	452591.	58399.	310518.
1932	475711.	100752.	341310.
1933	207512.	57679.	106362.
1934	198173.	69279.	65142.
1935	636398.	121101.	495209.
1936	487417.	81988.	222475.
1937	270622.	81982.	156086.
1938	710422.	67498.	549399.
1939	92110.	64714.	8815.
1940	275005.	108896.	152264.
1941	1130145.	75626.	1037423.
1942	930094.	74686.	767112.
1943	161793.	56776.	35829.
1944	275596.	94975.	154688.
1945	688005.	90913.	567027.
1946	364953.	81020.	270413.
1947	179402.	58550.	117754.
1948	220308.	83880.	27823.
1949	225694.	74993.	104886.
1950	169047.	103485.	21732.
1951	50347.	44871.	0.
1952	139726.	96111.	0.
1953	85073.	81991.	0.
1954	43225.	41580.	0.
1955	138954.	138937.	0.
1956	108013.	70635.	0.
1957	972114.	122584.	828672.
1958	416255.	74643.	331683.
1959	443354.	82365.	306676.
1960	328199.	77984.	240044.
1961	900449.	79466.	802632.
1962	109452.	69707.	33000.
1963	29620.	29603.	0.
1964	227075.	145526.	0.
1965	487670.	71659.	384022.
1966	356642.	72616.	249743.
1967	74775.	69581.	0.
1968	858592.	97611.	735578.
1969	317374.	80841.	215707.
1970	342563.	55276.	251303.
1971	270760.	106299.	153020.
1972	135362.	67690.	62693.
1973	370893.	92203.	258509.
1974	258356.	80872.	166346.
1975	332660.	52348.	274193.
1976	278514.	102658.	157630.
1977	509998.	39457.	463943.
1978	40716.	40699.	0.
1979	407990.	150099.	237021.
1980	124484.	54912.	62563.
1981	227396.	114471.	100117.
1982	134951.	50748.	70450.
1983	69286.	43838.	0.
1984	112383.	110936.	0.
mean	326718.	80380.	210513.

Table 8.8
NATURALIZED STREAMFLOW, STREAMFLOW DEPLETIONS, AND UNAPPROPRIATED STREAMFLOW AT PROCTOR RESERVOIR

Year	Naturalized Streamflow (ac-ft/yr)	Streamflow Depletion (ac-ft/yr)	Unappropriated Streamflow (ac-ft/yr)
1900	184809.	36076.	114014.
1901	50648.	11091.	8313.
1902	48379.	3819.	0.
1903	94323.	55994.	0.
1904	48406.	9911.	0.
1905	99788.	57051.	2291.
1906	108342.	14427.	0.
1907	90151.	32559.	0.
1908	222087.	44276.	139951.
1909	27766.	0.	0.
1910	38338.	0.	0.
1911	35523.	27.	0.
1912	24338.	0.	0.
1913	185362.	30204.	0.
1914	434241.	60261.	262523.
1915	419502.	32969.	344671.
1916	102776.	22204.	28630.
1917	13038.	0.	0.
1918	72464.	0.	0.
1919	306886.	90221.	122001.
1920	116826.	35284.	43061.
1921	71735.	18078.	24694.
1922	497043.	35607.	312260.
1923	62759.	0.	0.
1924	66080.	16683.	0.
1925	53250.	0.	0.
1926	71301.	45462.	0.
1927	47361.	15446.	0.
1928	96169.	0.	0.
1929	34991.	0.	0.
1930	172804.	0.	0.
1931	120656.	68423.	0.
1932	147305.	39506.	43965.
1933	180969.	30815.	0.
1934	46145.	0.	0.
1935	283040.	87355.	117130.
1936	120099.	36927.	22978.
1937	77668.	15720.	20770.
1938	195169.	48990.	113009.
1939	88247.	23322.	0.
1940	105061.	48265.	0.
1941	400125.	32917.	277791.
1942	344179.	31953.	277938.
1943	35793.	12666.	0.
1944	99897.	34920.	16278.
1945	149330.	47395.	63304.
1946	87946.	32598.	0.
1947	37565.	23569.	0.
1948	22543.	0.	0.
1949	186154.	0.	0.
1950	59876.	0.	0.
1951	22805.	0.	0.
1952	64649.	0.	0.
1953	38547.	0.	0.
1954	25274.	0.	0.
1955	88145.	0.	0.
1956	109594.	0.	0.
1957	330111.	86448.	156538.
1958	77023.	8562.	49036.
1959	132797.	52305.	24634.
1960	51415.	9154.	27189.
1961	98178.	44125.	15504.
1962	134218.	0.	0.
1963	94986.	0.	0.
1964	145420.	45767.	0.
1965	145301.	31107.	87929.
1966	102201.	43231.	26468.
1967	76408.	0.	0.
1968	327736.	58834.	229281.
1969	161107.	25479.	25811.
1970	114834.	37385.	31148.
1971	78837.	24409.	0.
1972	30490.	3257.	0.
1973	90860.	20254.	0.
1974	73637.	34614.	0.
1975	64371.	42906.	0.
1976	40638.	1931.	0.
1977	79756.	55052.	4179.
1978	7505.	0.	0.
1979	53274.	0.	0.
1980	22723.	11755.	0.
1981	58725.	0.	0.
1982	81912.	1009.	0.
1983	13308.	0.	0.
1984	67389.	0.	0.
mean	115170.	22595.	35686.

Table 8.9
NATURALIZED STREAMFLOW, STREAMFLOW DEPLETIONS, AND UNAPPROPRIATED STREAMFLOW AT BELTON RESERVOIR

Year	Naturalized Streamflow (ac-ft/yr)	Streamflow Depletion (ac-ft/yr)	Unappropriated Streamflow (ac-ft/yr)
1900	773235.	164145.	453658.
1901	233203.	64466.	9215.
1902	327532.	243485.	0.
1903	539381.	150024.	253292.
1904	276793.	165871.	0.
1905	530893.	165654.	209729.
1906	323727.	174792.	0.
1907	335449.	221375.	0.
1908	754603.	77147.	537528.
1909	82267.	21479.	0.
1910	79259.	40288.	0.
1911	87553.	22632.	0.
1912	112766.	60104.	0.
1913	792434.	567313.	125573.
1914	1139881.	171575.	789726.
1915	1664774.	171383.	1341821.
1916	330313.	74593.	149647.
1917	41998.	6592.	0.
1918	177439.	121097.	0.
1919	1531721.	450132.	844453.
1920	556675:	171621.	219149.
1921	489720.	137156.	237550.
1922	592153.	105013.	374050.
1923	265069.	196338.	0.
1924	257821.	139619.	42103.
1925	125882.	74004.	0.
1926	441070.	279476.	38099.
1927	348824.	200771.	54272.
1928	163893.	101799.	0.
1929	206086.	150761.	0.
1930	337246.	277488.	0.
1931	367519.	96850.	98036.
1932	645367.	204687.	297467.
1933	206357.	119359.	0.
1934	209858.	156797.	0.
1935	738435.	285317.	238309.
1936	941608.	171247.	510013.
1937	491900.	162203.	179911.
1938	913986.	129582.	545043.
1939	202667.	116256.	0.
1940	596691.	264333.	209587.
1941	1531572.	156178.	1211602.
1942	1236766.	162865.	929385.
1943	147930.	58153.	4831.
1944	1082886.	232682.	708649.
1945	1119190.	214096.	746329.
1946	629018.	132849.	373683.
1947	313588.	91638.	133629.
1948	111517.	55002.	0.
1949	317064.	253795.	0.
1950	154107.	101143.	0.
1951	52747.	21035.	0.
1952	136490.	87128.	0.
1953	251191.	180532.	0.
1954	24462.	300.	0.
1955	209432.	139539.	0.
1956	172831.	129816.	0.
1957	1392113.	581383.	603183.
1958	528534.	65443.	382752.
1959	622514.	259690.	217353.
1960	529127.	163227.	282039.
1961	1013360.	166860.	678967.
1962	202810.	122069.	0.
1963	143334.	76026.	0.
1964	460918.	305567.	18717.
1965	1112097.	160338.	815884.
1966	485557.	134010.	200516.
1967	156972.	84580.	0.
1968	1073500.	217029.	685726.
1969	385504.	186579.	79837.
1970	574065.	152128.	285613.
1971	442102.	234960.	76537.
1972	165491.	60295.	30036.
1973	375734.	251164.	15546.
1974	502361.	188512.	199647.
1975	575584.	91328.	355135.
1976	348943.	234972.	29267.
1977	609142.	72080.	416728.
1978	22062.	92.	0.
1979	451534.	345484.	24114.
1980	199964.	142753.	907.
1981	259283.	194688.	0.
1982	187445.	143249.	0.
1983	93583.	31789.	0.
1984	116865.	62567.	0.
mean	467710.	157888.	203116.

Table 8.10
NATURALIZED STREAMFLOW, STREAMFLOW DEPLETIONS, AND UNAPPROPRIATED STREAMFLOW AT STILLHOUSE HOLLOW RESERVOIR

Year	Naturalized Streamflow (ac-ft/yr)	Streamflow Depletion (ac-ft/yr)	Unappropriated Streamflow (ac-ft/yr)
1900	409594.	86508.	299142.
1901	124955.	39636.	10184.
1902	186301.	118738.	0.
1903	365181.	78484.	279617.
1904	86522.	79150.	0.
1905	327756.	96080.	215155.
1906	140788.	82329.	7134.
1907	293957.	105722.	178015.
1908	404613.	83318.	314018.
1909	60069.	44581.	0.
1910	21588.	17615.	0.
1911	43344.	34872.	0.
1912	49563.	45406.	0.
1913	256036.	250086.	0.
1914	498448.	92728.	396794.
1915	479607.	86471.	384689.
1916	205752.	53382.	145347.
1917	17454.	13009.	0.
1918	64542.	59257.	0.
1919	374353.	206664.	158713.
1920	338565.	86508.	240901.
1921	225561.	84385.	133152.
1922	147179.	59867.	80178.
1923	132255.	113169.	12444.
1924	155816.	45638.	103327.
1925	118989.	114746.	0.
1926	251836.	77429.	166005.
1927	212254.	97908.	106141.
1928	52442.	44453.	2122.
1929	97386.	91579.	0.
1930	146273.	124443.	14820.
1931	235826.	56448.	165091.
1932	224183.	103256.	113787.
1933	63510.	55393.	1344.
1934	79660.	67561.	0.
1935	378164.	145233.	225110.
1936	509365.	86451.	343435.
1937	220222.	85997.	100086.
1938	389978.	78461.	278862.
1939	51536.	46093.	0.
1940	334467.	128007.	198838.
1941	621629.	75734.	538559.
1942	351043.	82590.	260529.
1943	58322.	45517.	6294.
1944	642922.	125386.	506359.
1945	576163.	82102.	486249.
1946	232275.	72512.	152868.
1947	163545.	50049.	106462.
1948	50844.	45039.	0.
1949	102107.	96224.	0.
1950	39485.	33874.	0.
1951	17709.	13261.	0.
1952	87055.	82435.	0.
1953	134269.	128557.	0.
1954	32244.	12447.	0.
1955	121173.	115181.	0.
1956	47055.	40167.	0.
1957	553525.	277670.	268188.
1958	314875.	54698.	253157.
1959	290424.	108094.	175410.
1960	382623.	81664.	293675.
1961	441896.	82729.	351215.
1962	93082.	80705.	5454.
1963	34025.	28250.	0.
1964	86825.	81282.	0.
1965	548620.	151385.	388964.
1966	242606.	82114.	152480.
1967	35820.	29878.	0.
1968	672802.	136900.	527710.
1969	231998.	88911.	135049.
1970	372522.	85112.	275477.
1971	129856.	90440.	17956.
1972	109165.	69278.	33399.
1973	201116.	101609.	91143.
1974	406131.	86101.	257067.
1975	346420.	73225.	266427.
1976	239577.	94004.	137081.
1977	284986.	36533.	244539.
1978	11793.	8994.	0.
1979	207443.	184398.	16044.
1980	94245.	58680.	31446.
1981	177483.	130159.	40207.
1982	63652.	44170.	13968.
1983	94271.	67254.	0.
1984	20380.	17679.	0.
mean	220493.	82354.	125974.

Table 8.11
NATURALIZED STREAMFLOW, STREAMFLOW DEPLETIONS, AND UNAPPROPRIATED STREAMFLOW AT GEORGETOWN RESERVOIR

Year	Naturalized Streamflow (ac-ft/yr)	Streamflow Depletion (ac-ft/yr)	Unappropriated Streamflow (ac-ft/yr)
1900	106218.	17068.	82942.
1901	31953.	9719.	14265.
1902	70380.	22471.	0.
1903	80076.	18450.	61129.
1904	27470.	17065.	5626.
1905	115446.	17014.	90917.
1906	79215.	16975.	44517.
1907	64779.	17061.	47029.
1908	109981.	17021.	92438.
1909	14596.	11531.	1911.
1910	18106.	11316.	5815.
1911	11328.	6370.	0.
1912	25231.	24917.	0.
1913	116026.	26792.	88661.
1914	99570.	17028.	78232.
1915	135100.	17060.	117739.
1916	59101.	14741.	40705.
1917	4728.	4361.	0.
1918	34832.	30651.	3946.
1919	125019.	17085.	107630.
1920	89316.	17085.	71786.
1921	67416.	17066.	50047.
1922	154117.	12279.	141229.
1923	39433.	21677.	17408.
1924	93057.	9915.	80764.
1925	39331.	23195.	13599.
1926	68094.	10684.	57232.
1927	69889.	23257.	46239.
1928	12078.	6049.	4119.
1929	55888.	23898.	31018.
1930	53879.	20580.	32733.
1931	45583.	8846.	33443.
1932	51425.	22211.	28979.
1933	23146.	11100.	11626.
1934	37733.	16749.	14379.
1935	89523.	25645.	63553.
1936	140001.	17084.	120390.
1937	76222.	16876.	41940.
1938	92085.	14472.	77366.
1939	14458.	11633.	2080.
1940	126782.	23439.	91393.
1941	134610.	15235.	118431.
1942	68176.	15485.	52200.
1943	23886.	10618.	12816.
1944	107327.	22509.	82035.
1945	92962.	16050.	76407.
1946	101886.	15494.	81848.
1947	68946.	11477.	57286.
1948	12411.	12214.	0.
1949	34686.	20695.	13731.
1950	20281.	18257.	1767.
1951	7614.	3354.	0.
1952	12193.	11906.	0.
1953	50822.	40242.	10345.
1954	5151.	4708.	76.
1955	16774.	14296.	0.
1956	2196.	1152.	0.
1957	157659.	47492.	109757.
1958	94381.	15898.	76968.
1959	66493.	15910.	50190.
1960	103045.	15879.	86918.
1961	115721.	16040.	99418.
1962	38380.	17477.	20598.
1963	13936.	9211.	4529.
1964	22897.	14957.	0.
1965	152972.	27773.	123210.
1966	80176.	16953.	62890.
1967	29492.	17490.	11463.
1968	112200.	15575.	96390.
1969	66152.	16668.	49219.
1970	70819.	15440.	55212.
1971	17850.	17064.	0.
1972	24099.	20022.	2469.
1973	94323.	16501.	77543.
1974	72740.	16990.	52391.
1975	121277.	16877.	103641.
1976	89325.	16551.	72163.
1977	76469.	8523.	67754.
1978	2027.	1589.	0.
1979	78237.	34912.	43044.
1980	29536.	14076.	11999.
1981	150332.	24994.	125001.
1982	27152.	9629.	17355.
1983	56694.	17870.	23713.
1984	18004.	12866.	0.
mean	64839.	16651.	45478.

Table 8.12
NATURALIZED STREAMFLOW, STREAMFLOW DEPLETIONS, AND UNAPPROPRIATED STREAMFLOW AT GRANGER RESERVOIR

Year	Naturalized Streamflow (ac-ft/yr)	Streamflow Depletion (ac-ft/yr)	Unappropriated Streamflow (ac-ft/yr)
1900	295597.	31449.	234486.
1901	88794.	19171.	16502.
1902	196400.	42297.	0.
1903	216155.	31222.	169306.
1904	73427.	31448.	16400.
1905	320493.	31368.	256360.
1906	234323.	31240.	143434.
1907	172657.	31393.	126325.
1908	301870.	31342.	257422.
1909	41183.	21650.	6908.
1910	53075.	22938.	22414.
1911	31289.	21106.	0.
1912	70782.	47323.	3254.
1913	333204.	38150.	272147.
1914	264998.	31362.	209289.
1915	355994.	31441.	311340.
1916	167515.	28928.	120332.
1917	12978.	11697.	0.
1918	107206.	50735.	30204.
1919	357706.	31475.	312933.
1920	262789.	31475.	218046.
1921	172450.	31441.	127776.
1922	435280.	22791.	404211.
1923	108140.	39417.	50876.
1924	264138.	19856.	232081.
1925	108474.	39919.	45788.
1926	181445.	21599.	153336.
1927	198367.	40694.	138212.
1928	32438.	14816.	11975.
1929	150769.	42366.	87290.
1930	154663.	35221.	102838.
1931	124363.	21592.	89615.
1932	146843.	38232.	90474.
1933	65258.	20550.	37852.
1934	100330.	28914.	41162.
1935	248268.	45606.	180902.
1936	410620.	31475.	358769.
1937	208409.	30975.	125203.
1938	262405.	28241.	197688.
1939	37750.	21384.	6582.
1940	353222.	39113.	261930.
1941	357120.	25086.	321050.
1942	178963.	26322.	141008.
1943	59001.	20728.	31811.
1944	273828.	38719.	215249.
1945	239061.	28027.	198949.
1946	263420.	26091.	214945.
1947	168051.	20359.	140312.
1948	32741.	24954.	0.
1949	96552.	37687.	42344.
1950	54250.	32786.	7281.
1951	20537.	12467.	0.
1952	33604.	26276.	0.
1953	142724.	62380.	44397.
1954	13067.	12984.	76.
1955	47122.	32878.	0.
1956	6137.	8127.	0.
1957	446793.	71120.	332150.
1958	251888.	27552.	210411.
1959	181550.	27604.	142209.
1960	272123.	27452.	232733.
1961	305121.	27977.	264942.
1962	97607.	32753.	51274.
1963	35619.	17673.	11150.
1964	62138.	30806.	0.
1965	410652.	47501.	335929.
1966	212356.	29932.	169424.
1967	81707.	33985.	34260.
1968	293304.	26456.	255225.
1969	169691.	29904.	127089.
1970	182218.	25893.	144234.
1971	50712.	37413.	0.
1972	68842.	35121.	13027.
1973	255024.	29551.	212819.
1974	197084.	31294.	146495.
1975	339425.	30789.	295604.
1976	235324.	29691.	192928.
1977	204410.	25889.	174096.
1978	19731.	20813.	0.
1979	299190.	47721.	220428.
1980	78731.	23903.	41631.
1981	416093.	38423.	355573.
1982	98238.	24775.	67944.
1983	163431.	34040.	81636.
1984	80709.	35877.	29790.
mean	179035.	30602.	129083.

Table 8.13
NATURALIZED STREAMFLOW, STREAMFLOW DEPLETIONS, AND UNAPPROPRIATED STREAMFLOW AT LIMESTONE RESERVOIR

Year	Naturalized Streamflow (ac-ft/yr)	Streamflow Depletion (ac-ft/yr)	Unappropriated Streamflow (ac-ft/yr)
1900	465412.	92196.	355327.
1901	55341.	47048.	0.
1902	187162.	151434.	0.
1903	172059.	28937.	114869.
1904	99644.	87358.	0.
1905	300257.	127902.	125270.
1906	47144.	28820.	0.
1907	169110.	158548.	0.
1908	281087.	96144.	133430.
1909	27763.	5476.	0.
1910	20935.	17320.	0.
1911	102809.	79739.	0.
1912	84522.	76789.	0.
1913	298483.	268355.	0.
1914	494616.	98125.	346188.
1915	383521.	57854.	305516.
1916	148768.	72333.	55006.
1917	63846.	33071.	0.
1918	239652.	214386.	0.
1919	601646.	99000.	444670.
1920	300543.	96824.	177043.
1921	198885.	93900.	78130.
1922	636146.	48893.	570824.
1923	337685.	148376.	104286.
1924	313279.	42235.	246267.
1925	99125.	85349.	0.
1926	261300.	143932.	75133.
1927	265762.	103088.	127722.
1928	137961.	88626.	23692.
1929	391243.	74620.	289306.
1930	294407.	123116.	146265.
1931	146692.	44913.	75186.
1932	479171.	143800.	296998.
1933	86000.	51051.	20625.
1934	144464.	96575.	17538.
1935	487568.	164305.	275660.
1936	176846.	98322.	57712.
1937	156030.	41793.	94032.
1938	138729.	93972.	19030.
1939	37602.	28584.	0.
1940	270649.	193844.	28891.
1941	224819.	41690.	167513.
1942	167007.	121728.	19592.
1943	36809.	26918.	0.
1944	461376.	157933.	266511.
1945	458871.	90556.	334957.
1946	382779.	85945.	272667.
1947	238311.	35276.	188678.
1948	67997.	59775.	0.
1949	108352.	80279.	0.
1950	145638.	135151.	0.
1951	12094.	0.	0.
1952	79717.	57936.	0.
1953	281856.	273233.	0.
1954	33497.	27421.	0.
1955	48402.	29875.	0.
1956	37411.	0.	0.
1957	507494.	281062.	169317.
1958	145272.	75306.	36652.
1959	266114.	93358.	140647.
1960	265133.	78358.	164963.
1961	367853.	75369.	276736.
1962	65210.	43270.	379.
1963	6147.	913.	0.
1964	18007.	1956.	0.
1965	388519.	254166.	87823.
1966	310206.	129692.	147746.
1967	67417.	54620.	0.
1968	415427.	131433.	247084.
1969	318701.	105731.	187582.
1970	155828.	57427.	73471.
1971	90073.	77154.	0.
1972	71273.	54713.	0.
1973	590088.	220371.	311046.
1974	393956.	101030.	264606.
1975	268712.	51045.	199545.
1976	472036.	139396.	296958.
1977	220923.	34645.	174961.
1978	46738.	31275.	0.
1979	248223.	207497.	0.
1980	144999.	62086.	56264.
1981	144813.	127216.	0.
1982	81099.	69407.	0.
1983	184729.	121258.	0.
1984	135394.	123280.	0.
mean	220932.	92632.	102239.

Table 8.14
NATURALIZED STREAMFLOW, STREAMFLOW DEPLETIONS, AND UNAPPROPRIATED STREAMFLOW AT SOMERVILLE RESERVOIR

Year	Naturalized Streamflow (ac-ft/yr)	Streamflow Depletion (ac-ft/yr)	Unappropriated Streamflow (ac-ft/yr)
1900	469839.	96456.	349185.
1901	131326.	41243.	40032.
1902	406508.	144017.	230430.
1903	195207.	45523.	145560.
1904	51959.	48064.	0.
1905	209252.	134089.	69966.
1906	111415.	73475.	0.
1907	71932.	67933.	0.
1908	594739.	158082.	428626.
1909	20220.	16654.	0.
1910	36804.	26049.	0.
1911	41372.	38004.	0.
1912	27107.	24940.	0.
1913	297642.	224758.	66194.
1914	681768.	95962.	581436.
1915	422614.	69908.	348512.
1916	191532.	87564.	99719.
1917	7043.	4865.	0.
1918	95158.	86193.	0.
1919	781603.	188251.	588811.
1920	219218.	77394.	137630.
1921	489537.	113336.	371725.
1922	694707.	53101.	634969.
1923	301040.	136143.	107023.
1924	287233.	39987.	245483.
1925	258998.	129716.	123100.
1926	426227.	97959.	323974.
1927	137785.	45840.	88929.
1928	45837.	40772.	0.
1929	325540.	164482.	156790.
1930	172974.	105072.	63662.
1931	217657.	36604.	176815.
1932	405730.	125680.	275822.
1933	109668.	56607.	49565.
1934	284490.	110325.	168441.
1935	253232.	137388.	111607.
1936	327174.	64364.	258466.
1937	89427.	85404.	0.
1938	232843.	68521.	161801.
1939	35621.	31444.	0.
1940	502819.	196339.	300445.
1941	465538.	55180.	407413.
1942	72806.	61178.	8215.
1943	34343.	30434.	0.
1944	289772.	205402.	76368.
1945	294523.	93237.	196312.
1946	281188.	112839.	163258.
1947	238828.	72011.	161632.
1948	15216.	12848.	0.
1949	218666.	183713.	28785.
1950	216414.	67346.	145685.
1951	10014.	7120.	0.
1952	66854.	51149.	0.
1953	146224.	141780.	0.
1954	13519.	12379.	0.
1955	26650.	20935.	0.
1956	25342.	16784.	0.
1957	503930.	229473.	267142.
1958	285112.	82460.	199123.
1959	194386.	72147.	118604.
1960	335892.	114936.	216506.
1961	455107.	88108.	363334.
1962	159612.	86721.	69408.
1963	73199.	25493.	44637.
1964	37131.	31727.	0.
1965	415604.	200994.	210762.
1966	157353.	39761.	113759.
1967	26599.	22481.	0.
1968	549441.	195017.	350757.
1969	303623.	45054.	255548.
1970	266888.	72679.	190160.
1971	22385.	18603.	0.
1972	45891.	42168.	0.
1973	378521.	223850.	151026.
1974	417808.	92515.	308708.
1975	348240.	65249.	279197.
1976	359998.	111746.	244564.
1977	235947.	33806.	197714.
1978	95289.	79414.	0.
1979	418377.	113916.	300720.
1980	115413.	76467.	34255.
1981	142770.	139241.	0.
1982	128123.	52342.	72075.
1983	254121.	91661.	82020.
1984	102446.	98020.	0.
mean	234211.	85634.	140734.

reservoirs. The streamflow depletions are for the water rights associated with each reservoir. These data sets are the reservoir inflows in the firm yield computations. Annual totals of the monthly data computed by TAMUWRAP and provided as input to HEC-3 are shown. Unappropriated streamflows at the nonreservoir control points reflected in the system firm yield computations are included in several tables in Chapter 7. The firm yields presented in Chapter 6 are based on the naturalized streamflow data. The firm yields presented in the present chapter are based alternatively of the streamflow depletions and summation of streamflow depletions and unappropriated flows.

The 1900-1984 mean naturalized streamflow, streamflow depletions, and unappropriated streamflow at each reservoir are presented in Table 8.15. The incremental streamflow depletions are for water rights associated with an individual reservoir. System firm yields are computed for a 10-reservoir system consisting of Possum Kingdom, Granbury, Aquilla, Proctor, Belton, Stillhouse Hollow, Georgetown, Granger, Limestone, and Somerville Reservoirs. The accumulative streamflow depletions in Table 8.15 refer to this 10-reservoir system. The accumulative streamflow depletion is the sum of the streamflow depletions for the indicated reservoir and upstream reservoirs.

Individual Reservoir Firm Yields

The firm yields presented in Tables 8.16 and 8.17 are provided by each individual reservoir without adversely impacting senior water rights. The firm yields in Table 8.16 are limited to utilization of water available under the existing water rights permits associated with the reservoir, without impacting unappropriated flows. The firm yields in Table 8.17 protect senior water rights but allow use of unappropriated flows.

Individual reservoir firm yields for streamflow depletions only are presented in Table 8.16. The TAMUWRAP computed streamflow depletions for the water rights associated with each reservoir provide reservoir inflows for the HEC-3 firm yield computations. Likewise, individual reservoir firm yields for streamflow depletions plus unappropriated flows are presented in Table 8.17. A water balance is presented in the tables for each firm yield. The summation of the firm yield, mean spills, and mean reservoir evaporation equals or slightly exceeds mean inflow. The summation of the outflows can slightly exceed inflows due to storage depletions. The reservoirs are full in January 1900 but not necessarily full in December 1984, which are the beginning and ending months of the simulation period.

Individual reservoir firm yields for the three sets of inflow data are compared in Table 8.18. The firm yields computed with naturalized streamflows are reproduced from Table 6.5. These are single reservoir firm yields computed ignoring the effects of all other water users and reservoirs in the basin. The firm yields adjusted for senior water rights are reproduced from Tables 8.16 and 8.17. Firm yields are expressed in ac-ft/yr and as a percent of mean reservoir inflow. The permitted water rights diversions are also included in Table 8.18. Senior water rights throughout the basin greatly reduce the firm yield supplied by each individual reservoir. Firm yields computed for reservoir inflows provided by alternatively streamflow depletions and streamflow depletions plus unappropriated flows result in essentially the same firm yields. The unappropriated flows greatly increase reservoir inflows but do not increase firm yields. The unappropriated flows are spills in the

Table 8.15
MEAN FLOWS

Control Point (Reservoir)	Naturalized Streamflow	Streamflow Depletion		Unappropriated Streamflow	Depletion + Unappropriated	
		Incremental	Accumulative		Incremental	Accumulative
Hubbard Creek	157	85.1	85.1	8.1	93.2	93.2
Possum Kingdom	1,234	405	405	331	736	736
Granbury	1,609	122	527	551	673	1,078
Whitney	2,292	122	649	940	1,063	1,589
Aquilla	101	29.9	29.9	61.3	91.2	91.2
Waco	451	111	111	291	402	402
Proctor	159	31.2	31.2	49.3	80.5	80.5
Belton	646	218	249	281	499	530
Stillhouse	305	114	114	174	288	288
Georgetown	89.6	23.0	23.0	62.8	85.8	85.8
Granger	247	42.3	65.3	178	221	243
Limestone	305	128	128	141	269	269
Somerville	324	118	118	194	313	312

Table 8.16
INDIVIDUAL RESERVOIR FIRM YIELDS FOR STREAMFLOW DEPLETIONS ONLY

Reservoir	Firm Yield			Mean Inflow (cfs)	Mean Spills (cfs)	Mean Evap (cfs)
	(cfs)	(ac-ft/yr)	% Mean Inflow			
Hubbard Creek	19	13,800	22	85	12	56
P.K. (inactive 970 ft)	195	141,200	48	405	123	88
P.K. (inactive 875 ft)	286	207,100	71	405	39	81
Granbury (inactive 675 ft)	46	33,300	38	122	44	33
Granbury (inactive 640 ft)	68	49,200	56	122	24	32
Whitney	9	6,500	7	123	18	98
Aquilla	11	8,000	37	30	8	12
Waco (conservation 455 ft)	90	65,200	81	111	0	22
Waco (conservation 462 ft)	90	65,200	81	111	0	23
Proctor	0	0	0	31	19	13
Belton	120	86,900	55	218	54	48
Stillhouse Hollow	98	70,900	86	114	0	19
Georgetown	20	14,500	87	23	0	3
Granger	36	26,000	86	42	0	7
Limestone	81	58,600	63	128	10	38
Somerville	53	38,400	45	118	39	26

Table 8.17
INDIVIDUAL RESERVOIR FIRM YIELDS FOR STREAMFLOW DEPLETIONS PLUS UNAPPROPRIATED FLOWS

Reservoir	Firm Yield (cfs)	Firm Yield (ac-ft/yr)	Firm Yield % Mean Inflow	Mean Inflow (cfs)	Mean Spills (cfs)	Mean Evap (cfs)
Hubbard Creek	19	13,800	20.4	93	20	56
P.K. (inactive 970 ft)	195	141,200	26.5	736	454	88
P.K. (inactive 875 ft)	286	207,100	38.9	736	369	82
Granbury (inactive 675 ft)	46	33,300	6.8	674	595	33
Granbury (inactive 640 ft)	68	49,230	10.1	674	575	32
Whitney	9	6,500	0.8	1,046	941	98
Aquilla	11	8,000	12.1	91	69	12
Waco (conservation 455 ft)	93	67,300	23.1	402	286	23
Waco (conservation 462 ft)	108	78,200	26.9	402	268	27
Proctor	0	0	0	81	68	13
Belton	121	87,600	24.2	499	333	48
Stillhouse Hollow	98	70,900	34.0	288	172	20
Georgetown	20	14,500	23.3	86	62	4
Granger	37	26,800	16.7	221	171	13
Limestone	85	61,500	31.6	269	147	38
Somerville	53	38,400	16.9	313	233	26

Table 8.18
INDIVIDUAL RESERVOIR FIRM YIELD COMPARISON FOR ALTERNATIVE RESERVOIR INFLOW DATA

Reservoir	Water Rights	Firm Yield (ac-ft/yr and % Inflow) for Alternative Reservoir Inflow					
		Naturalized Streamflow		Streamflow Depletions		Depletion + Unappropriated	
	(ac-ft/yr)	(ac-ft/yr)	(%)	(ac-ft/yr)	(%)	(ac-ft/yr)	(%)
Hubbard Creek	56,000	40,500	35.2	13,800	22.4	13,800	20.4
P.K. (inactive 970 ft)	230,750	210,000	23.2	141,200	48.1	141,200	26.5
P.K. (inactive 875 ft)	230,750	309,100	34.3	207,100	70.6	207,100	38.9
Granbury (inactive 675 ft)	64,712	128,900	11.0	33,300	37.7	33,300	6.8
Granbury (inactive 640 ft)	64,712	182,400	15.5	49,200	55.7	49,200	10.1
Whitney	18,336	258,500	15.5	6,500	7.3	6,500	0.9
Aquilla	13,896	17,400	23.5	8,000	36.7	8,000	12.1
Waco (conservation 455 ft)	59,100	76,700	23.3	65,200	81.1	67,300	23.1
Waco (conservation 462 ft)	—	88,300	26.8	65,200	81.1	78,200	26.9
Proctor	19,658	14,500	12.5	0	0	0	0
Belton	100,257	139,000	29.5	86,900	55.0	87,600	24.2
Stillhouse Hollow	67,768	76,000	34.2	70,900	86.0	70,900	34.0
Georgetown	13,610	15,900	24.4	14,500	87.0	14,500	23.3
Granger	19,840	29,700	16.5	26,000	85.7	26,800	16.7
Limestone	65,074	70,900	32.0	58,600	63.3	61,500	31.6
Somerville	48,000	43,400	18.4	38,400	44.9	38,400	16.9

TAMUWRAP simulation and continue to be spills in the HEC-3 firm yield simulations.

Firm yields are presented for Waco Reservoir for the proposed storage reallocation as well as for the existing 455 top of conservation pool elevation of 455 feet. Firm yield based on storage depletions only does not increase with an increase in conservation storage capacity. If unappropriated flows are included in the reservoir inflows, the increased conservation capacity does significantly increase the firm yield.

Proctor Reservoir has zero firm yield. As indicated in Table 8.8, the streamflow depletions, which serve as reservoir inflows, are zero during the nine-year period from 1948 through 1956. Evaporation empties the reservoir during this period in the firm yield simulation. Proctor has a firm yield of 14,500 ac-ft/yr based on naturalized streamflows. However, senior water rights diversions of 4,800 ac-ft/yr upstream of Proctor Reservoir reduces inflows. In the TAMUWRAP simulation, Proctor Reservoir also passes inflows, along with the other reservoirs, as required by senior water rights of 794,705 ac-ft/yr located downstream. In actual operation, the BRA can conserve the storage in Proctor Reservoir by meeting senior water rights requirements in the lower basin by releases from other reservoirs rather than passing inflows through Proctor.

As indicated by Table 8.18, individual reservoir firm yields for Waco, Stillhouse Hollow, Georgetown, and Granger Reservoirs are greater than the diversions permitted by the water rights associated with the reservoirs. The individual reservoir firm yields for the other reservoirs are less than the corresponding water rights.

System Firm Yields

System firm yield is the maximum diversion rate which can be supplied continuously throughout the 85-year simulation period by a 10-reservoir system, or subsystems thereof. A diversion, or instream flow requirement, is specified at a downstream location, with releases being made from upstream reservoirs as necessary to meet the downstream requirements. Multireservoir release decisions are made by the model based on balancing the percent depletion in each reservoir. The ten reservoirs included in the system firm yield simulations are Possum Kingdom, Granbury, Aquilla, Proctor, Belton, Stillhouse Hollow, Georgetown, Granger, Limestone, and Somerville. Hubbard Creek Reservoir is not a component of the 12-reservoir USACE/BRA system. Waco Reservoir was also excluded, since it is used solely for the City of Waco and suburbs, and the City of Waco owns the water rights. Whitney Reservoir is unique in that the conservation pool is used for both hydroelectric power and water supply, with hydroelectric power being the dominant use.

For the system firm yield simulations, accumulative streamflow depletions were used for the streamflow data. Streamflow data at Granbury Reservoir includes streamflow depletions associated with both Granbury and Possum Kingdom Reservoirs. Likewise, streamflow data at Belton Reservoir includes streamflow depletions associated with both Belton and Proctor Reservoir. Streamflow data at Granger includes Granger and Georgetown depletions. For the other reservoirs, accumulative and incremental depletions are identical. All the naturalized and unappropriated streamflow data included in the tables is accumulative. The means for the alternative data sets are tabulated in Table 8.15.

System firm yields were computed with streamflow data alternatively consisting of streamflow depletions only and streamflow depletions plus unappropriated flows. System firm yields were also computed excluding and including local flows entering the river below the dams at Granbury, Aquilla, Belton, Stillhouse Hollow, Granger, Limestone, and Somerville Reservoirs. Whitney Reservoir was included in the simulations which included the downstream local flows. Whitney Reservoir was operated for hydroelectric power in accordance with the previously discussed standard operating plan. A water rights diversion of 25.3 cfs was also made from Whitney Reservoir. Thus, although Whitney Reservoir was not included in the 10-reservoir system operation, its impacts on downstream local flows and Granbury spills are reflected in one alternative set of system firm yields.

System firm yields were computed for the 10-reservoir system and subsystems thereof. Subsystems are labeled by a control point above which all the reservoirs are located. The Richmond gage system includes all ten reservoirs. The Bryan gage subsystem excludes Limestone and Somerville reservoirs. The Waco gage subsystem includes Possum Kingdom, Granbury, and Aquilla Reservoirs. The Cameron gage subsystem includes Proctor, Belton, Stillhouse Hollow, Georgetown, and Granger Reservoirs. Firm yields for the Richmond gage are repeated with Possum Kingdom top of inactive pool elevations of 875 feet and 970 feet.

System firm yields are presented in Table 8.19. A water balance is also provided for each firm yield simulation. The summation of the firm yield, mean excess flows pass the control point, and mean evaporation in ten reservoirs equals or slightly exceeds the mean inflow.

Water rights, individual reservoir firm yields, and system firm yields are compared in Table 8.20. The sum of the water rights associated with those reservoirs of the 10-reservoir system which are located upstream of the indicated streamflow gages (control points) are tabulated. The sum of the individual reservoir firm yields (from Tables 8.16 and 8.17) for the pertinent reservoirs for the two alternative inflow data sets are tabulated next. System firm yields are presented for two streamflow data sets. Firm yields for one streamflow data set are repeated excluding and including downstream local flows. The firm yields are in units of cfs. The system firm yields are also shown as a percent of the sum of the individual reservoir firm yields.

For the 10-reservoir system and the 8-reservoir, 3-reservoir, and 4-reservoir subsystems, the sums of the individual reservoir firm yields are less than the sums of the water rights. System firm yields for streamflow depletions only are also less than the water rights if the downstream local flows are excluded. Including downstream local flows, system firm yields exceed the water rights.

System firm yields are much larger than the sum of the corresponding individual reservoir firm yields. For the 10-reservoir system, with the Possum Kingdom top of inactive pool at elevation 875 feet, for streamflow depletions only, the system firm yield is 115% of the sum of the individual reservoir firm yields. For depletions plus unappropriated flows, the system firm yield

Table 8.19
SYSTEM FIRM YIELDS

System Inflows System Configuration	System Firm Yield (cfs)	System Firm Yield (ac-ft/yr)	System Firm Yield % Mean Inflow	Mean Inflow (cfs)	Excess Flows (cfs)	Mean Evap (cfs)
Streamflow Depletions Only						
Richmond Gage (P.K. 970 ft)	807	584,200	66	1,232	149	285
Richmond Gage (P.K. 875 ft)	866	627,000	70	1,232	98	279
Bryan Gage (P.K. 875 ft)	691	500,200	70	986	86	218
Waco Gage (P.K. 875 ft)	378	273,700	68	558	58	123
Cameron Gage (P.K. 875 ft)	300	217,200	70	428	42	93
Streamflow Depletions and Unappropriated Flows Excluding Downstream Local Flows						
Richmond Gage (P.K. 970 ft)	826	598,000	29	2,813	1,704	291
Richmond Gage (P.K. 875 ft)	896	648,700	32	2,813	1,641	286
Bryan Gage (P.K. 875 ft)	704	509,700	32	2,231	1,312	223
Waco Gage (P.K. 875 ft)	379	274,400	32	1,170	667	126
Cameron Gage (P.K. 875 ft)	311	225,200	29	1,061	662	95
Including Downstream Local Flows (Note: Diversion of 25.4 cfs at Whitney Reservoir is not included in the system firm yield.)						
Richmond Gage (P.K. 970 ft)	1,087	787,000	18	6,141	4,662	378
Richmond Gage (P.K. 875 ft)	1,167	844,900	19	6,141	4,590	372
Bryan Gage (P.K. 875 ft)	845	611,800	20	4,256	3,077	319
Waco Gage (P.K. 875 ft)	491	355,500	14	3,505	2,769	224
Cameron Gage (P.K. 875 ft)	370	267,900	22	1,677	1,217	96

Table 8.20
COMPARISON OF 10-RESERVOIR SYSTEM AND INDIVIDUAL RESERVOIR FIRM YIELDS

Reservoirs Located Above Control Point	Richmond Gage	Richmond Gage	Bryan Gage	Waco Gage	Cameron Gage
Possum Kingdom Inactive Pool	970 ft	875 ft	875 ft	875 ft	875 ft
	Water Rights and Firm Yields in cfs				
Sum of Water Rights	889	889	733	427	305
Sum of Individual Reservoir Firm Yields					
Streamflow Depletions Only	660	751	617	343	274
Depletions and Unappropriated Flows	666	757	619	343	276
System Firm Yield for Depletions Only	807	866	691	378	300
System Firm Yield for Depletions and Unappropriated Flows					
Excluding Downstream Local Flows	826	896	704	379	311
Including Downstream Local Flows	1,087	1,167	845	491	370
	System Firm Yield as a Percent of Sum of Individual Reservoir Firm Yields				
System Firm Yield for Depletions Only	122	115	112	110	109
System Firm Yield for Depletions and Unappropriated Flows					
Excluding Downstream Local Flows	124	118	114	110	113
Including Downstream Local Flows	163	154	137	143	134

Note: The water rights and firm yields are for the following 10 reservoirs: Possum Kingdom, Granbury, Aquilla, Proctor, Belton, Stillhouse Hollow, Georgetown, Granger, Limestone, and Somerville.

excluding and including downstream local flows is 118% and 154%, respectively, of the sum of the individual reservoir firm yields.

Water balances and storage frequencies for the ten reservoirs for each of the three Richmond gage (Possum Kingdom 875 ft) firm yield simulations are tabulated in Tables 8.21 through 8.25. Storage frequencies for the individual reservoir firm yield simulations are presented in Table 8.24.

System Reliability

Reliabilities for yield levels ranging from 100% to 200% of firm yield are presented in Table 8.26 for the 10-reservoir system for the three inflow data sets. As discussed in Chapter 6, period reliability is computed by dividing the number of months the specified yield level is met by the 1,020 months in the simulation. Volumetric reliability is the ratio of the total volume of water supplied to the volume demanded over the simulation period. The shortage index is defined as follows.

$$\text{SHORTAGE INDEX} = \frac{100}{N} \sum_{1}^{N} \left(\frac{\text{ANNUAL SHORTAGE}}{\text{ANNUAL REQUIREMENT}} \right)^2$$

where N is the number of years in the simulation.

The reliabilities indicate that demands larger than firm yield can be maintained almost continuously during the simulation period, with shortages occurring relatively infrequently. A demand of 110% of the firm yield can be met more than 98% of the time under the three alternative conditions simulated, with the shortage volume during the 85-year simulation period being 0.4% of the demand. In the simulations based on streamflow depletions plus unappropriated flows, a demand of 200% of the firm yield is met almost 90% of the time, and the shortage volume is less than 10% of the demand. In the simulations based on streamflow depletions only, the reliabilities associated with the higher demand levels are significantly less than the simulation including unappropriated streamflows.

Table 8.21
RESERVOIR WATER BALANCE FOR SYSTEM FIRM YIELD SIMULATION
BRA STREAMFLOW DEPLETIONS ONLY
RICHMOND GAGE

Reservoir	1900-1984 Averages (cfs)			
	Inflow	Evaporation	Conservation Releases	Spills
Possum Kingdom	405	81	281	45
Granbury	448	33	366	50
Aquilla	30	10	19	1
Proctor	31	10	11	10
Belton	239	45	177	21
Stillhouse	114	20	92	3
Georgetown	23	4	17	2
Granger	62	13	47	2
Somerville	118	25	80	14
Limestone	128	37	85	7

Table 8.22
RESERVOIR WATER BALANCE FOR SYSTEM FIRM YIELD SIMULATION
BRA STREAMFLOW DEPLETIONS AND UNAPPROPRIATED FLOWS
EXCLUDING DOWNSTREAM LOCAL FLOWS
RICHMOND GAGE

Reservoir	1900-1984 Averages (cfs)			
	Inflow	Evaporation	Conservation Releases	Spills
Possum Kingdom	736	82	239	416
Granbury	998	33	361	604
Aquilla	91	11	24	57
Proctor	81	11	5	65
Belton	519	46	160	317
Stillhouse	288	21	98	171
Georgetown	86	4	17	65
Granger	240	13	76	150
Somerville	313	26	93	194
Limestone	269	38	83	149

Table 8.23
RESERVOIR WATER BALANCE FOR SYSTEM FIRM YIELD SIMULATION
BRA STREAMFLOW DEPLETIONS AND UNAPPROPRIATED FLOWS
INCLUDING DOWNSTREAM LOCAL FLOWS
RICHMOND GAGE

Reservoir	1900-1984 Averages (cfs)			
	Inflow	Evaporation	Conservation Releases	Spills
Possum Kingdom	736	82	218	437
Granbury	998	34	290	675
Whitney	1,472	84	570	797
Aquilla	91	11	13	67
Proctor	81	11	4	66
Belton	519	46	105	371
Stillhouse	288	21	62	206
Georgetown	86	4	12	70
Granger	240	13	36	190
Somerville	313	26	44	243
Limestone	269	38	52	179

Note: Whitney Reservoir has a diversion of 25 cfs not shown above.

TABLE 8.24
STORAGE FREQUENCIES FOR INDIVIDUAL RESERVOIR FIRM YIELD SIMULATIONS

RESERVOIR	Conservation Storage in Percent of Capacity									
	99-100	95-99	90-95	80-90	70-80	60-70	40-60	20-40	1-20	0-1
					Streamflow Depletions					
Hubbard	4.4	4.3	4.2	10.0	9.4	11.0	26.1	18.8	11.1	0.7
Possum Kingdom (Top of Inactive 875 ft)	20.9	15.9	15.5	18.5	13.6	7.3	4.2	1.7	2.4	0.1
Possum Kingdom (Top of Inactive 970 ft)	44.2	13.6	7.0	13.1	7.8	7.3	4.9	1.0	0.9	0.2
Granbury (Top of Inactive 675 ft)	47.0	6.7	6.9	10.7	8.0	7.8	8.3	3.5	1.0	0.1
Granbury (Top of Inactive 640 ft)	38.1	12.4	6.6	11.6	9.6	8.1	9.3	2.5	1.8	0.1
Whitney	42.0	14.5	17.7	12.9	5.7	3.1	4.0	0.0	0.0	0.0
Aquilla	30.3	5.4	10.0	17.8	17.8	5.2	5.9	3.7	3.3	0.5
Waco (Top of Conservation 455 ft)	19.9	3.4	5.2	12.2	12.7	9.6	11.5	9.5	7.5	8.4
Waco (Top of Conservation 462 ft)	0.8	0.7	1.7	5.2	6.1	36.5	36.7	9.0	3.2	0.2
Proctor	21.5	3.5	5.1	9.1	12.9	9.8	11.1	10.0	7.8	9.1
Belton	30.5	8.5	10.9	18.3	12.8	2.7	8.3	5.2	2.5	0.2
Stillhouse	0.9	5.1	15.5	32.1	14.5	11.4	7.2	6.7	5.1	1.7
Georgetown	0.5	1.5	3.9	16.5	32.4	15.0	20.4	5.6	3.2	1.1
Granger	0.4	0.1	0.4	1.2	3.4	6.8	48.8	29.5	7.3	2.2
Somerville	33.9	6.0	8.4	15.7	13.6	7.2	9.0	5.2	0.6	0.4
Limestone	19.9	9.1	7.4	14.2	17.0	11.1	10.4	8.1	2.5	0.3
					Streamflow Depletions and Unappropriated Flow					
Hubbard	4.4	4.3	4.2	10.0	9.3	11.0	25.8	19.1	11.1	0.8
Possum Kingdom (Top of Inactive 875 ft)	32.9	11.6	11.8	16.1	12.5	6.8	4.4	1.7	2.2	0.1
Possum Kingdom (Top of Inactive 970 ft)	45.4	12.7	7.1	13.0	7.4	7.5	4.9	1.0	0.9	0.2
Granbury (Top of Inactive 675 ft)	47.1	6.6	7.0	10.7	7.9	7.8	8.3	3.5	1.0	0.1
Granbury (Top of Inactive 640 ft)	42.2	9.5	6.6	11.1	8.6	8.3	9.1	2.7	1.8	0.1
Whitney	42.0	14.5	17.7	12.9	5.7	3.1	4.0	0.0	0.0	0.0
Aquilla	30.4	5.4	10.0	17.5	18.0	5.2	5.8	3.7	3.3	0.6
Waco (Top of Conservation 455 ft)	36.2	8.3	9.7	14.3	11.4	7.0	8.1	3.4	1.5	0.1
Waco (Top of Conservation 462 ft)	30.4	7.9	10.8	16.6	12.7	6.5	7.1	6.1	1.7	0.3
Proctor	21.5	3.5	5.1	9.1	12.9	9.8	11.1	10.0	7.7	9.2
Belton	31.6	8.3	10.2	17.9	13.0	2.7	8.1	5.3	2.5	0.3
Stillhouse	33.3	7.3	10.1	13.9	12.7	4.8	5.6	6.2	5.1	1.0
Georgetown	44.0	6.3	7.7	12.7	12.8	6.8	5.3	3.4	0.6	0.3
Granger	43.8	4.8	5.9	14.2	11.0	8.0	7.8	3.2	0.6	0.6
Somerville	35.3	5.6	7.5	15.7	13.4	7.2	9.1	5.1	0.6	0.5
Limestone	25.6	5.0	6.6	13.5	14.3	12.2	10.7	7.0	4.3	0.9

Table 8.25
STORAGE FREQUENCY FOR SYSTEM FIRM YIELD SIMULATIONS

	Conservation Storage in Percent of Capacity									
Reservoir	99-100	95-99	90-95	80-90	70-80	60-70	40-60	20-40	1-20	0-1
	Storage Frequency (%)									
	BRA Streamflow Depletions Only (Firm Yield = 866 cfs)									
P.K.	22.5	16.3	14.3	20.2	12.5	5.1	4.3	2.1	2.2	0.5
Granbury	30.3	17.5	11.3	10.3	11.9	7.3	5.4	4.4	0.9	0.8
Aquilla	13.4	11.9	7.4	12.9	15.6	16.1	9.1	6.3	6.6	0.8
Proctor	14.3	6.8	2.8	5.2	5.4	8.3	17.7	10.3	14.5	14.6
Belton	16.5	11.4	8.5	16.6	17.2	11.0	5.0	8.3	4.9	0.7
Stillhouse	14.2	13.7	15.7	19.5	13.9	6.2	6.9	6.5	2.8	0.6
Georgetown	22.0	17.3	11.9	17.6	13.5	3.9	8.0	3.1	2.3	0.4
Granger	19.1	18.4	12.5	19.9	12.8	4.2	7.9	2.3	2.5	0.3
Somerville	24.6	10.2	6.6	14.0	13.9	11.0	8.9	5.9	4.2	0.7
Limestone	14.5	11.6	7.3	11.5	17.0	14.5	10.8	7.2	5.0	0.8
	BRA Depletions and Unappropriated Flows Excluding Downstream Local Flows (Firm Yield = 896cfs)									
P.K.	37.2	10.7	11.8	17.1	9.8	5.0	3.9	2.2	1.7	0.8
Granbury	42.5	11.0	8.9	10.0	10.9	5.8	5.7	3.6	0.8	0.8
Aquilla	28.4	7.1	4.5	12.5	14.0	12.3	9.1	5.8	5.5	0.9
Proctor	20.0	2.9	2.9	5.1	7.2	7.6	17.3	8.3	14.3	14.3
Belton	31.9	7.3	6.6	12.6	15.5	8.3	4.9	7.8	4.4	0.7
Stillhouse	36.3	7.9	8.4	13.8	11.8	6.0	6.4	6.3	2.4	0.8
Georgetown	42.5	9.6	7.5	13.8	11.1	3.4	7.0	2.5	2.0	0.5
Granger	44.0	9.6	7.6	13.3	10.4	4.4	6.9	1.5	1.8	0.5
Somerville	35.0	6.0	7.9	11.8	12.1	9.3	7.7	5.5	4.0	0.7
Limestone	27.9	7.1	5.2	13.2	13.1	12.1	9.1	6.9	4.6	0.8
	BRA Depletions and Unappropriated Flows Including Downstream Local Flows (Firm Yield = 1,167 cfs)									
P.K.	44.4	13.5	9.9	11.6	7.1	2.5	4.7	3.0	2.3	1.1
Granbury	48.7	11.2	6.6	10.0	6.7	6.0	4.5	3.4	1.7	1.3
Whitney	27.5	4.8	4.4	9.1	9.2	18.3	23.6	2.9	0.0	0.0
Aquilla	31.6	7.1	6.1	15.6	12.5	9.2	4.5	6.1	5.7	1.7
Proctor	20.1	3.1	4.0	5.9	8.5	9.9	13.9	6.7	14.2	13.6
Belton	36.5	8.2	8.1	13.9	13.2	3.3	3.7	5.8	6.0	1.2
Stillhouse	44.9	6.8	7.4	14.4	8.5	2.5	4.4	6.9	3.2	1.0
Georgetown	49.7	8.2	7.8	12.3	7.2	2.3	5.3	3.6	2.6	1.0
Granger	51.2	8.4	6.8	13.3	5.5	3.1	5.2	3.7	2.0	0.8
Somerville	40.6	7.4	6.8	13.2	8.9	5.2	7.0	5.3	4.5	1.2
Limestone	32.6	6.2	7.0	13.3	13.9	8.1	5.6	6.6	5.4	1.3

Table 8.26
10-RESERVOIR SYSTEM RELIABILITY

Diversion % Firm Yield	cfs	Shortage Periods (months)	Shortage Volume (cfs mon)	Shortage Index -	Period Reliability (%)	Volume Reliability (%)
Streamflow Depletions Only						
100	866	0	0	0.00	100.0	100.0
105	909	6	2	0.03	99.4	99.8
110	953	11	4	0.13	98.9	99.6
125	1,083	40	30	1.09	96.0	97.2
150	1,299	177	159	5.04	82.6	87.8
175	1,516	287	346	9.91	71.9	77.2
200	1,732	371	548	14.63	63.6	68.4
Streamflow Depletions and Unappropriated Flows Excluding Downstream Local Flows						
100	896	0	0	0.00	100.0	100.0
105	941	6	3	0.04	99.4	99.7
110	986	8	4	0.13	99.2	99.6
125	1,120	23	17	0.49	97.7	98.5
150	1,344	51	47	1.81	95.0	96.5
175	1,568	75	92	3.02	92.6	94.1
200	1,792	107	147	4.49	89.5	91.8
Streamflow Depletions and Unappropriated Flows Including Downstream Local Flows						
100	1,167	0	0	0	100.0	100.0
105	1,225	10	6	0.10	99.0	99.5
110	1,284	13	10	0.26	98.7	99.2
125	1,459	30	28	0.74	97.1	98.1
150	1,751	54	67	1.63	94.7	96.2
175	2,042	78	120	2.80	92.4	94.1
200	2,334	101	193	4.15	90.1	91.7

CHAPTER 9
EVALUATION OF KEY FACTORS AFFECTING RESERVOIR YIELD

Key aspects of reservoir yield studies are identified and discussed in this chapter. Yield is viewed primarily from the perspective of firm yield. The sensitivity of firm yield estimates to various factors is addressed. Modeling procedures, assumptions, and input data are categorized as (1) basin hydrology, (2) simulating the reservoir system, and (3) modeling the impacts of other reservoirs and water users in the basin.

Sizing reservoir storage capacity, developing water supply contracts, water rights applications, and other water supply planning and management decisions are typically based on the concept of firm yield, somewhat arbitrarily. Other related decision criteria could be adopted as well. For example, the maximum yield that can be provided without the reservoir storage falling below a specified level, rather than completely emptying, during a hydrologic period-of-record simulation, represents a more stringent criterion. Firm yield, by definiton, has a reliability of 100% assuming a repetition of historical hydrology. Management decisions could also be based on specifying yields with lesser reliabilities. However, the discussion below follows the traditional practice of focusing on firm yield.

Basin Hydrology

Streamflow and reservoir evaporation rates are required to represent the basin hydrology in a model. Development of the basic hydrologic input data is clearly a key factor in reservoir yield studies.

Complete homogeneous series of monthly streamflows covering the 1900-1984 simulation period at selected locations were compiled for the Brazos River Basin study. TWC naturalized streamflow data were used for the period 1940-1976. Additional streamflow data covering the remainder of the 1900-1984 simulation period were developed as a part of the study. Monthly streamflow series at all of the selected locations were compiled using a consistent methodology. However, it should be noted that detailed hydrologic studies focusing on a specific location could result in significantly different streamflow estimates. For example, more refined Corps of Engineers studies resulted in inflows at Waco Reservoir which are different from those used in the present study. However, to maintain a consistent methodology for all the locations in the basin, more refined data for a single location was not adopted even if available.

Representation of Future Hydrology Using Historical Data

Future, not past, conditions are of concern in water resources management. However, because future streamflows are unknown, reservoir yield studies are based on historical period-of-record hydrology. In actuality, the sequence of historical streamflows will not be repeated in the future. A drought more severe than the critical historical period-of-record drought will occur at some future time, but the timing is unknown.

A comparison of hydrologic firm yields computed using two alternative simulation periods was developed by simply dividing the 85-year simulation period into two periods, 1900-1939 and 1940-1984. Firm yields computed using the two alternative simulation periods are also compared with the firm yields for the entire 1900-1984 period. The 1900-1939 and 1940-1984 simulation periods are not perfectly consistent. The early period contains a large amount of missing streamflow data filled in with the MOSS-IV computer program. Also, average monthly evaporation rates are used for the earlier period. However, the comparison is still considered to be reasonably valid. These are hydrologic firm yields, computed without considering water rights.

A comparison of single reservoir firm yields, assuming base sediment conditions, is presented in Table 9.1 for the 1900-1939 and 1940-1984 simulation periods. Belton Reservoir has firm yields of 216 cfs and 260 cfs based on the 1900-1939 and 1940-1984 simulation periods, respectively. All the other reservoirs have larger firm yields based on the earlier simulation period. The 1900-1939 firm yields range from 83% to 150% of 1940-1984 firm yields. The sum of the 1900-1939 single reservoir firm yields is 115% of the corresponding sum of 1940-1984 firm yields. A comparison with Table 6.3 indicates that the 1900-1984 firm yields are identical to the 1940-1984 firm yields except for Belton which has identical 1900-1984 and 1900-1939 firm yields. The critical periods do not include January 1940, and thus the 1900-1984 firm yields are identical to either the corresponding 1900-1939 or 1940-1984 firm yields in all cases.

Single and individual reservoir firm yields based on the three alternative simulation periods and 1984 sediment conditions are presented in Tables 9.2 and 9.3. The firm yields vary significantly between simulation periods for several of the reservoirs. However, the sum of the firm yields for all the reservoirs are about the same with either simulation period. The sum of the individual reservoir firm yields for the 12 BRA reservoirs is 5% greater for the 1900-1939 than for the 1940-1984 simulation period.

As indicated by Table 9.4, the 12-reservoir system firm yields are essentially the same based on either simulation period. The 1900-1939 system firm yield is controlled by a critical drawdown period extending from essentially full reservoirs in June 1908 to essentially empty reservoirs in August 1912. The reservoirs are full again in January 1914. The 1940-1984 firm yield is controlled by a critical period with the reservoirs going from full in May 1950 to empty in August 1956 and full again in May 1957. Either critical period results in about the same system firm yield, with the 1940-1984 firm yield being slightly higher.

Based on a 1900-1984 simulation period, the 12-reservoir system firm yields, excluding and including unregulated flows, are 128% and 171%, respectively of the sum of the individual reservoir firm yields. With a 1900-1939 simulation period, system firm yields, excluding and including unregulated flows, are 117% and 157% of the sum of the individual reservoir firm yields. With a 1940-1984 simulation period, system firm yields are 125% and 166% of individual reservoir firm yields. Thus, the benefits of multiple reservoir system operations are significant with either of the simulation periods.

Although not addressed in the present study, the reliability or likelihood that the firm yield for a specified future period will equal or exceed various levels can be estimated based on synthetically generated streamflow sequences. A large number (say 100) of monthly streamflow sequences of a specified length (say 50 years) can be synthesized using a model such as MOSS-IV. Firm yields

Table 9.1
COMPARISON OF SINGLE RESERVOIR FIRM YIELDS COMPUTED WITH ALTERNATIVE SIMULATION PERIODS
Base Sediment Condition

Reservoir	Firm Yield		Critical Drawdown Period	
	Simulation Period		Simulation Period	
	1900-1939	1940-1984	1900-1939	1940-1984
Hubbard Creek	69	57	Nov 00-Oct 13	Nov 42-May 53
Possum Kingdom (970 ft)	370	305	Jul 08-Aug 12	Jul 51-May 53
Granbury (675 ft)	206	202	May 34-Nov 34	Jun 52-Nov 52
Whitney (520 ft)	487	394	Jun 34-Nov 34	Jun 52-Nov 52
Aquilla	30	25	Jul 08-Oct 13	Jun 53-Oct 56
Waco	125	121	Jul 08-Apr 13	Oct 50-Apr 55
Proctor	46	34	Jul 08-May 13	Jun 77-Oct 81
Belton	216	260	Jun 08-Oct 12	Jun 47-Feb 55
Stillhouse	121	110	Jun 08-Sep 13	Jun 47-Nov 54
Georgetown	32	23	Jun 08-Oct 12	Mar 54-Mar 57
Granger	66	44	May 10-Nov 11	Feb 54-Nov 56
Limestone	119	105	Jul 08-Sep 13	Jun 62-Jan 65
Somerville	77	62	Jun 09-Feb 13	Jul 50-Mar 57

Table 9.2
COMPARISON OF SINGLE RESERVOIR FIRM YIELDS
COMPUTED WITH ALTERNATIVE SIMULATION PERIODS
1984 Sediment Conditions

Reservoir	Single Reservoir Firm Yield				
	1900-1984 (cfs)	1900-1939 (cfs)	1940-1984 (cfs)	1900-1939 (% of 1900-1984)	1940-1984 (% of 1900-1984)
Hubbard Creek	57	69	57	121.1%	100.0%
Possum Kingdom (875 ft)	443	443	484	100.0%	109.2%
Granbury (675 ft)	193	198	193	102.6%	100.0%
Whitney (520 ft)	376	391	376	104.0%	100.0%
Aquilla	25	30	25	120.0%	100.0%
Waco	116	119	116	102.6%	100.0%
Proctor	30	42	30	140.0%	100.0%
Belton	210	210	226	100.0%	107.6%
Stillhouse Hollow	108	118	108	109.3%	100.0%
Georgetown	23	32	23	139.0%	100.0%
Granger	44	57	44	129.5%	100.0%
Limestone	100	101	100	101.0%	100.0%
Somerville	61	76	61	124.6%	100.0%
Total	1,786	1,886	1,843	105.6%	103.2%
12-Reservoir Subtotal	1,729	1,817	1,786	105.1%	103.3%

Table 9.3
COMPARISON OF INDIVIDUAL RESERVOIR FIRM YIELDS
COMPUTED WITH ALTERNATIVE SIMULATION PERIODS
1984 Sediment Conditions

Reservoir	Individual Reservoir Firm Yield				
	1900-1984 (cfs)	1900-1939 (cfs)	1940-1984 (cfs)	1900-1939 (% of 1900-1984)	1940-1984 (% of 1900-1984)
Hubbard Creek	57	69	57	121.1%	100.0%
Possum Kingdom (875 ft)	403	403	440	100.0%	109.2%
Granbury (675 ft)	74	94	74	127.0%	100.0%
Whitney (520 ft)	177	200	177	113.0%	100.0%
Aquilla	25	30	25	120.0%	100.0%
Waco	116	119	116	102.6%	100.0%
Proctor	30	42	30	140.0%	100.0%
Belton	177	177	189	100.0%	106.8%
Stillhouse Hollow	108	118	108	109.3%	100.0%
Georgetown	23	32	23	139.1%	100.0%
Granger	34	54	34	129.5%	100.0%
Limestone	100	101	100	101.0%	100.0%
Somerville	61	76	61	124.6%	100.0%
Total	1,385	1,515	1,434	109.4%	103.5%
12-Reservoir Subtotal	1,328	1,446	1,377	108.9%	103.7%

Table 9.4
COMPARISON OF SYSTEM FIRM YIELDS COMPUTED WITH ALTERNATIVE SIMULATION PERIODS
Standard Operating Plan, 1984 Sediment Conditions

Excluding or Including Unregulated Flows	12-Reservoir System Firm Yield				
	1900-1984	1900-1939	1940-1984	1900-1939	1940-1984
	(cfs)	(cfs)	(cfs)	(% of 1900-1984)	
Excluding Unregulated Flows	1,697	1,696	1,720	100.0%	101.4%
Including Unregulated Flows	2,265	2,265	2,291	100.0%	101.1%

Table 9.5
COMPARISON OF FIRM YIELDS COMPUTED WITH TAMU UNREGULATED VERSUS TWC NATURALIZED STREAMFLOW

Reservoir	Single Reservoir Firm Yield (cfs)		Percent Difference
	TWC Naturalized Streamflow	TAMU Unregulated Streamflow	
Possum Kingdom	305	297	2.6
Granbury	202	195	3.5
Whitney	394	322	18.3
Aquilla	25	25	0
Proctor	34	28	17.6
Belton	216	228	5.6
Limestone	105	103	1.9
Somerville	62	63	1.6

could then be computed for each of the 100 streamflow sequences and the number of times the computed firm yield equalled or exceeded various levels counted. The reliability associated with a given firm yield value would be the number of streamflow sequences for which the firm yield value was equalled or exceeded divided by 100.

As discussed in Chapter 4, synthetic streamflow generation models accept period-of-record monthly streamflow as input. Monthly streamflow sequences of any specified length are synthesized based on preserving the statistics of the input data. Markov models, such as MOSS-IV preserve the mean, standard deviation, and lag-1 autocorrelation coefficient. Estimation of reservoir reliability using synthetically generated streamflow sequences is based on the concept that preservation of the statistical parameters results in a set of streamflow sequences which are equally likely to occur. The historical streamflow represents one sequence which could possibly occur in the future. The synthetically generated streamflow sequences represent alternative sequences which have the same likelihood of occurring in the future. The validity of synthetic streamflow generation models in representing the likelihood of extreme low flow conditions is an aspect of this approach to estimating reservoir reliability which is generally considered to be particularly questionable.

A reservoir reliability study using synthetically generated streamflow sequences would be a logical extension of the present study. However, a comprehensive reliability analysis would require a great amount of effort relative to the scope of the yield study documented by this report.

Streamflow Data Adjustments

Complete, homogeneous time series of streamflow data for pertinent locations in the system are a fundamental requirement for a yield simulation. Streamflow data is then naturalized to remove nonhomogeneities caused by the activities of man in the basin. Missing data in the streamflow records at one location are filled in by a regression analysis with available streamflow at other locations.

As previously discussed, missing data were reconstituted using MOSS-IV, which is an improved version of HEC-4. Early in the study, a streamflow data set was also reconstituted using HEC-4. A cursory analysis of streamflow data sets and associated firm yields developed alternatively using HEC-4 and MOSS-IV indicated significant differences. Since MOSS-IV was considered to incorporate definite improvements over HEC-4, MOSS-IV was selected for the study, without a detailed evaluation of the differences in results obtained with the two models.

Two alternative sets of naturalized streamflow data, termed the TAMU unregulated and TWC naturalized streamflow are described in Chapter 5. Although not documented by the present report, a detailed statistical comparison of the two streamflow data sets was performed. The two sets of streamflows were found to be similar. A comparison of hydrologic firm yields computed with TAMU unregulated versus TWC naturalized streamflow is presented in Table 9.5. The reservoirs with streamflow gage records dating back to at least 1940 are included in the tabulation. The single reservoir firm yields are based on base sediment conditions and a 1940-1984 simulation period. The computed drawdown periods were identical for both data sets and are tabulated in the last column of Table 9.1. Firm yields for Whitney and Proctor Reservoirs are 18.3 percent and 17.6 percent lower based on the TAMU unregulated flows. For the other reservoirs, the firm yields are about the same with either streamflow data set. Although the two streamflow data sets are almost identical from certain perspectives, the corresponding firm yields in Table 6.5 are significantly different. This probably is due to the streamflow data differences being most pronounced during the low flow periods which most affect firm yield.

Reservoir Evaporation

In the simulation model, conservation storage depletions are the result of (1) releases or diversions for various beneficial purposes and (2) evaporation. Evaporation is an important component of a reservoir water balance. In the individual reservoir firm yield simulations, evaporation is in the range of roughly 20 to 60 percent of the firm yield for most of the reservoirs. In computing system firm yield at the Richmond gage, which includes unregulated runoff below the dams, the reservoir evaporation is about 21 percent of the firm yield.

Evaporation is computed in the model by multiplying the average water surface area during the time period by the inputed net evaporation rate. The net evaporation rate consists of the gross rate corrected for the portion of the precipitation falling directly on the reservoir surface which provides inflow not already reflected in the naturalized streamflow data. Evaporation rate data come from pan evaporation measurements corrected by a pan coefficient which reflects the differences in reservoir and pan evaporation. Average annual pan coefficients tend to be fairly constant, but monthly coefficients can fluctuate greatly within the year and between years.

The TWDB Report 64 (Kane 1967) net monthly reservoir evaporation rates were used in the present study. The data are provided on a one-degree quadrangle basis and cover the period January 1940 through December 1984. Average values (1940 through 1984) for each month were used in the simulation models for the period prior to January 1940. The TWDB evaporation rates are based on a compilation of available pan evaporation data in Texas and adjacent states and published and unpublished information on pan coefficients. The TWDB used monthly pan coefficients rather than the common, but more approximate, approach of using an average annual value. Average values of runoff as a percentage of precipitation were incorporated in the development of the net evaporation rates. The rainfall that is effective in offsetting a part of the evaporation loss was defined as the rainfall over the reservoir site less the amount that has run off and is already reflected in the streamflow records (Kane 1967).

Table 9.6 is a comparison of gross and net monthly reservoir evaporation rates from three sources. The regulation manual for Waco Reservoir (USACE, FWD 1971) presents average monthly evaporation data developed from pan measurements at Waco Dam during the period 1965-1969. Evaporation data for Waco Reservoir from the water master reports for 1985 are also shown. These data sets are based on a constant pan coefficient of 0.69, and net evaporation is simply reservoir evaporation minus precipitation. The TWDB data for 1940-1984 were averaged to provide the other data set in Table 9.6.

Table 9.6
COMPARISON OF AVERAGE MONTHLY EVAPORATION FOR WACO RESERVOIR

Month	Average Monthly and Annual Reservoir Evaporation in Inches					
	Regulation Manual		TWDB		1985 Daily Records	
	Net	Gross	Net	Gross	Net	Gross
Jan	0.28	1.90	0.84	2.52	1.28	2.38
Feb	0.08	2.51	0.72	2.66	0.68	3.17
Mar	1.60	4.20	1.92	3.79	1.67	4.95
Apr	-0.11	5.04	1.20	4.36	3.57	6.74
May	-1.78	5.23	1.68	5.24	7.48	9.44
Jun	5.25	7.08	4.44	7.05	5.03	10.62
Jul	7.94	8.69	7.44	9.10	11.40	12.12
Aug	6.11	7.93	7.80	9.60	12.74	13.99
Sep	0.66	5.41	5.16	7.63	2.03	8.77
Oct	1.61	4.63	3.60	6.11	1.30	5.04
Nov	-0.08	2.94	2.16	4.32	-0.79	3.48
Dec	-0.15	2.13	1.20	3.07	0.17	2.56
Annual	21.41	57.69	38.16	65.45	46.56	83.26

Table 9.7
WACO RESERVOIR FIRM YIELD
FOR ALTERNATIVE EVAPORTATION DATA

Run	Evaporation Data	Firm Yield	
		cfs	% of base run
1	TWDB net evaporation (base run)	121	100
2	TWDB gross evaporation	107	88
3	TWDB average net evaporation	125	103
4	TWDB average gross evaporation	111	92
5	regulation manual net evaporation	115	95
6	regulation manual gross evaporation	105	87

Table 9.8
STORAGE CAPACITY VERSUS FIRM YIELD BASED ON ALTERNATIVE SEDIMENT CONDITONS

Reservoir	1984 Condition		2010 Condition		Percent Change	
	Capacity (ac-ft)	Yield (ac-ft/yr)	Capacity (ac-ft)	Yield (ac-ft/yr)	Capacity (%)	Yield (%)
Hubbard Creek	308,070	41,270	300,730	40,540	2.4	1.8
Possum Kingdom	341,870	208,500	322,830	201,990	5.6	3.1
Granbury	137,400	87,600	113,850	75,300	17.1	14.0
Whitney	238,170	132,490	227,950	131,760	4.3	0.6
Aquilla	52,210	18,100	47,340	17,380	9.3	4.0
Waco	133,750	83,980	108,880	76,740	18.6	8.6
Proctor	46,850	21,720	31,400	14,480	33.0	33.3
Belton	428,250	128,140	372,700	119,460	13.0	6.8
Stillhouse	225,310	78,190	209,700	76,020	6.9	2.8
Georgetown	36,540	16,650	34,540	15,930	5.5	4.3
Granger	64,190	24,620	57,070	22,440	11.1	8.9
Limestone	218,050	72,400	214,060	70,950	1.8	2.0
Somerville	154,450	44,160	146,140	43,440	5.4	1.6

Firm yields for Waco Reservoir are presented in Table 9.7 based on alternative sets of evaporation data, with all other input data held constant. The base run firm yield of 121 cfs corresponds to Table 6.3 and reflects the 1940-1984 TWDB net evaporation rates. The firm yields are tabulated in Table 9.7 alternatively in units of cfs and percent of the base run firm yield. Run 2 reflects the 1940-1984 TWDB gross evaporation, instead of net, and results in a 11.6 percent decrease in the computed firm yield. Runs 3 and 4 incorporates the averages of the 1940-1984 TWDB data as shown in Table 9.6. Using average, instead of period-of-record, net evaporation increases the firm yield 3.3 percent. Runs 5 and 6 are based on using the data from the reservoir regulation manual, as shown in Table 9.6. The critical drawdown period for runs 1 and 2, is October 1950 to May 1955. The critical drawdown period for runs 3, 4, 5 and 6 is July 1908 through April 1913.

Channel Losses

Losses of reservoir releases in the downstream river channel result from seepage, evaporation, and unauthorized diversions. The simulation study is based on gaged streamflow data. The measured streamflow reflects historical channel losses upstream of the gage. However, the models do not reflect changes in channel losses due to alternative reservoir operating policies. Firm yields can be viewed as water available to cover channel losses as well as meet specified demands for beneficial use. Development of methods and data for quantifying channel losses is a major area of needed research.

Reservoir System Simulation

Modeling reservoir characteristics and operating policies is another major aspect of yield studies. Yield depends upon physical characteristics of a reservoir such as the elevation versus storage and area relationships. Sedimentation changes storage capacities over time. Yield also depends upon reservoir operating procedures. The actual yield can be increased by improvements in operating procedures. The accuracy of yield estimates is dependent on the manner in which actual operating procedures are representated in the computer model. Yield, either firm yield or yield associated with a specified reliability, is a hypothetical potential, rather than actual historical or projected future, water use. Yield computations necessarily involve simplified representations of actual reservoir operating procedures.

Reservoir Sedimentation

As discussed in previous chapters, sedimentation is reflected in the simulation models by the elevation versus storage and area relationships. The Corps of Engineers (USACE) provided initial and ultimate condition elevation versus storage and area tables from their files for each of the nine Corps of Engineers reservoirs. Ultimate conditions represent either 50-year or 100-year sedimentation after initial impoundment. Similar tables for Possum Kingdom, Granbury, and Limestone Reservoirs were provided by the Brazos River Authority (BRA). Tables were developed for Hubbard Creek Reservoir based on a sediment volume estimate included in a BRA report (URS/Forrest and Cotton 1975).

The sediment volume estimates developed by the USACE and BRA are based on data provided by Texas Board of Water Engineers (now the Texas Water Development Board) Bulletin 5912 (TWDB 1959). TWDB Bulletin 5912 contains empirically developed curves which provide average annual sediment rates as a function of watershed size and land use. Data is also provided to reflect land treatment measures. The distribution of sediment volume within the reservoir pool was computed using methods presented by Borland and Miller (1958).

The topography of Possum Kingdom, Whitney, and Belton Reservoirs were resurveyed since construction. Base condition elevation versus capacity and area relationships for the other reservoirs represent preconstruction topography. For purposes of the present study, linear interpolation was applied to base condition and ultimate condition elevation versus capacity and area tables to develop tables for years 1984 and 2010 conditions of sedimentation.

Prediction of reservoir sedimentation is extremely approximate. Since sediment transport fluctuates widely from very little during dry weather to large amounts during major flood events, predicting the sediment accumulation expected during a short period of a few years is even more difficult than predicting long-term averages.

Table 9.8 shows the decreases in estimated firm yield caused by decreases in conservation storage capacity due to estimated sedimentation. Individual reservoir hydrologic firm yields for 1984 and 2010 condition of sedimentation are reproduced from Table 6.8 and 6.9. The system firm yields are from Table 6.13. The decreases in storage capacity and firm yield between 1984 and 2010 sediment conditions are also shown in Table 7.8 as a percentage of the values for 1984 conditions. For example, for Belton Reservoir, the 24 years of sedimentation would cause an estimated 13.0 percent decrease in conservation storage capacity and corresponding 6.8 percent decrease in firm yield.

Multiple Reservoir System Operation and Use of Unregulated Flows in Combination with Reservoir Releases

Reservoir yield has traditionally been quantified in terms of individual reservoir firm yield. The total yield supplied by a river basin or reservoir system is typically viewed as the summation of individual firm yields for the reservoirs included in the basin or reservoir system. However, system firm yield is an important consideration in quantifying water availability in the Brazos River Basin. The concept of system firm yield should be equally pertinent to other river basins in Texas and elsewhere. System operations can greatly increase yields.

System operation is a major emphasis of the present study. The simulation results demonstrate the increases in yield achieved by system operation. The comparison of hydrologic firm yields in Table 6.14 and comparison of water rights adjusted firm yields in Table 8.20 show that system firm yields are much larger than the sum of the corresponding individual reservoir firm yields. Tables 9.3 and 9.4 indicate that the system versus individual reservoir firm yield comparison is valid for alternative simulation periods.

The study focuses on two aspects of system operations: (1) coordinated operation of multiple reservoirs and (2) coordinated operation of reservoir releases with unregulated flows entering the river downstream of the dams. If only reservoir inflows are considered, multireservoir system operation is advantageous. If the runoff entering the river below the dams is also considered, the yield can be increased significantly more. The entire river basin should be viewed as a system.

Multireservoir system operation involves coordinated releases from two or more reservoirs to supply common diversions at downstream locations. 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.

In the present case study, release decisions in the model were based on balancing the percentage of storage depletion in each of the reservoirs. This operational plan probably results in near-maximum system firm yields for the BRA system. However, a more selective release approach might be beneficial for the BRA system and other reservoir systems. The objective might be to release from the reservoir with the highest probability of spills and/or highest evaporation potential.

Utilization of unregulated flows entering the river below the 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 represents a hypothetical potential rather than actual historical or projected future diversion. The system firm yield simulations are generally representative of actual operation of the reservoir system. However, actual detailed operating criteria and practices are not reflected in the simplified model. System operation requires that a major portion of the water use diversions occur in the lower basin. The USACE/BRA system has both lakeside and downstream users. However, much of the water use is in the lower basin and can be supplied by releases from any of the reservoirs or by unregulated flows. Since the computations assume diversions occur at a single downstream location, system firm yield represents a potential maximum. However, a combination of many lakeside and downstream diversion locations should not greatly reduce the system firm yield as long as a significant portion of the water use is at downstream locations.

For the BRA system, the increases in estimated firm yield can be achieved primarily by properly crediting existing operating policies rather than by changing operating policies. System operation in the Brazos River Basin is facilitated by a single water management agency, the BRA, operating a large portion of the conservation storage capacity of the basin.

Seasonal Distribution of Water Use

Water demands, as well as water availability, are highly seasonal. Water use generally is highest in July and August, concurrently with low streamflows. The monthly distribution factors tabulated in Table 6.2 were used in the firm yield computations to reflect the seasonal water use characteristics. Water use rates during the summer months are indicated to be as much as several times higher than during the winter months. Maximum annual reservoir storage depletions occur at any time during the year. In dry years, the maximum storage depletion is often in late winter, just before Spring inflows refill the reservoir. Thus, assuming uniform demands over the year instead of using monthly distribution factors, can either decrease or increase the estimated firm yield.

Variations in monthly distribution factors were found to have relatively little impact on firm yield estimates. For example, the 12-reservoir system firm yield at the Richmond gage is increased by roughly 1.5% by assuming a constant diversion throughout the year rather than using the water use factors tabulated in Table 6.2.

Flood Control Operations

The firm yields and reliabilities presented in this report were computed without consideration of flood control operations. In the model, whenever the conservation pool was full, outflows from the flood control pool were set equal to inflows. Several simulation runs made to test the effects of flood control operations on firm yields and reliabilities showed essentially no effect.

If, in the first month of the critical drawdown period, water remained in a flood control pool from flooding during the previous month, the firm yield could be increased by flood control operations. However, this situation does not occur in the Brazos River Basin data set. Several severe drawdown periods are ended by major flood events, but drawdown periods do not follow flood events.

Allocation of Reservoir Storage Capacity

Storage capacity can be reallocated between purposes by raising or lowering top of conservation pool and inactive pool elevations. Firm yields for several alternative allocations of storage capacity are presented in Table 6.15. Wurbs and Carriere (1988) present a detailed analysis of storage reallocations.

Definition of Water Supply Storage Failure

Possum Kingdom, Granbury, and Whitney Reservoirs have inactive pools set by hydroelectric power or steam electric cooling water operation criteria. The bottom of the conservation pool is the lowest outlet invert, which essentially means an empty reservoir, at the other projects. In the simulation models, shortages occurred whenever diversions or releases could not be made due to completely depleted conservation storage capacity. Firm yield is the release rate which will just empty a conservation pool. In the model, releases continue uninterrupted until the conservation capacity is totally depleted.

In actuality, storage depletions can be expected to significantly affect water supply capabilities before the reservoir is completely empty. In an actual drought, as storage depletions increase the risk of future severe shortages, water managers will likely impose restrictions on water use. Such restrictions would represent a shortage or inability to meet full demands before the conservation storage capacity is totally depleted. Development of an unacceptably high risk of severe shortage in the unknown future is actually a water supply storage failure, which occurs prior to emptying the reservoir. Low reservoir storage levels can also cause water quality problems which severely restrict the use of the remaining water.

Drought contingency planning consists of predicting the consequences of shortages and development of plans of action to be implemented as reservoir storage depletions and other drought indicators reach various levels of severity. Although not addressed by the present study, drought contingency planning and reservoir yield studies could be closely interrelated.

If a water supply storage failure is defined more stringently than totally depleted conservation storage capacity, the simulated shortages, firm yields, and reliabilities computed in the present study could be significantly affected.

Natural Salt Pollution

As mentioned in Chapter 2, natural salt pollution is a serious problem in using mainstem Brazos River water. The natural salt deposits are located in the upper basin some distance above Possum Kingdom Reservoir. Inflows to Possum Kingdom Reservoir are contaminated by upstream salt springs and seeps and surface runoff from the areas of salt deposits. Waters in the three mainstem reservoirs, Possum Kingdom, Granbury, and Whitney, have high salt concentrations which severely restricts their suitability for water supply. The quality of the river improves significantly in the lower basin due to dilution by good quality water from tributaries below Whitney Reservoir.

The natural salt pollution problem was not addressed in the study documented by this report. Firm yields were computed without consideration of water quality constraints.

Impacts of Other Reservoirs and Water Users in the Basin

A river basin is a complex system. A reservoir subsystem is a part of the overall basin system. The reservoirs have hydrologic and institutional interactions with various activities in the basin. Yield is impacted by the numerous other reservoirs, water users, and other activities in the basin.

Basin Changes

Streamflow characteristics change with time as a result of man's activities in the basin. Land use changes, water use, river regulation by major reservoirs, and capture of runoff by numerous small reservoirs affect the inflow to downstream major reservoirs. Certain activities, such as brush clearing and phreatophyte removal, increase streamflow. However, most basin development activities tend to decrease streamflow. Riggs (1985) provides a general discussion of factors which change streamflow along with a list of references on the subject.

Naturalized streamflows are provided as input to the stream/reservoir system in the simulation models. As discussed in Chapter 5, the objective of streamflow naturalization is to develop a homogeneous set of streamflows representing conditions existing prior to man's activities changing the basin. The water rights simulation presented in Chapter 7 reflects certain assumptions regarding reservoir development and water use in the basin. However, land use changes, changes in base flow from groundwater due to pumping, and various other changes are not modeled.

Evaluation of the impacts of man's activities in a basin on reservoir inflows and streamflows at other locations is a major research area pertinent to surface water management in the Brazos River Basin as well as throughout the state and world.

Evaporation Losses from Upstream Reservoirs

Runoff is loss through evaporation, transpiration, and seepage of stored water. Reservoirs include both large reservoirs on the main stem and major tributary rivers and the numerous small reservoirs scattered throughout the watershed.

The Texas Society of Professional Engineers and Texas Section of the American Society of Civil Engineers (1974) point out that ponds and small reservoirs significantly impact streamflow and reservoir yield in Texas. A total of 272,550 ponds and small reservoirs with surface areas of 40 acres or less is indicated to have existed in Texas in 1967, concentrated primarily in Central Texas. These reservoirs result in an estimated average annual water loss of 1,858,000 acre-feet.

As discussed in Chapter 3, a total of 1,178 reservoirs in the Brazos River Basin are presently included in the dam inventory maintained by the Texas Water Commission. This includes all reservoirs meeting at least one of the following two conditions: (1) storage capacity of 15 acre-feet or greater and dam height of 25 feet or greater or (2) storage capacity of 50 acre-feet or greater and dam height of 6 feet or greater. For purposes of the present discussion, reservoirs are categorized as small or major, depending on whether total controlled storage capacity is less than 5,000 acre-feet. There are 40 major and 1,138 small reservoirs in the dam inventory.

The number of reservoirs located above each of the control points used in the simulation models is indicated in Table 9.9, along with total normal pool surface area. An estimate of reservoir evaporation in a typical year was developed by applying TWDB Report 64 evaporation rates to the water surface areas. Monthly evaporation volumes were computed by multiplying water surface areas by the monthly mean evaporation rates associated with the appropriate quadrangles. For the larger reservoirs, water surface areas were estimated as a function of gaged 1984 end-of-month storages. For the remaining reservoirs, the water surface area at normal pool level was used. The computations were repeated using gross and net evaporation rates. The estimated gross and net evaporation for the 1,178 reservoirs is 894,000 ac-ft/yr and 630,000 ac-ft/yr. This includes gross and net evaporation of 557,000 ac-ft/yr and 382,000 ac-ft/yr from the 12 USACE/BRA reservoirs and 337,000 ac-ft/yr and 248,000 ac-ft/yr from the 1,166 other reservoirs. Thus, the 12 USACE/BRA reservoirs account for about 62% of the evaporation. The annual gross evaporation from the 1,178 reservoirs is about 22% of the conservation storage capacity or 159% of the 1984 total basin use of surface water.

Table 9.9
UPSTREAM RESERVOIRS

Control Point	Small Reservoirs		Major Reservoirs		
	Number	Area (acres)	Number	Area (acres)	Capacity (ac-ft)
Reservoir					
Hubbard	28	664	1	440	8,800
Possum Kingdom	177	4,060	10	18,660	286,500
Granbury	83	1,030	2	3,310	48,960
Whitney	32	491	2	4,780	176,350
Aquilla	26	177	-0-	-0-	-0-
Waco	178	2,019	-0-	-0-	-0-
Proctor	76	1,270	1	1,590	26,420
Belton	78	1,050	-0-	-0-	-0-
Stillhouse	37	326	-0-	-0-	-0-
Georgetown	2	26	-0-	-0-	-0-
Granger	63	608	-0-	-0-	-0-
Limestone	15	525	1	1,200	10,000
Somerville	39	464	1	880	14,750
Subtotal	834	12,710	18	30,860	571,780
Gage					
Cameron	45	456	-0-	-0-	-0-
Bryan	87	1,250	4	4,850	89,070
Richmond	126	1,931	2	3,240	35,370
Subtotal	258	3,637	6	8,090	124,440
Gulf Coast	20	5,313	3	6,000	52,670
Upper Basin	26	991	-0-	-0-	-0-
Total	1,135	22,651	27	58,820	748,890

Basinwide Water Management and Use

A river basin or reservoir/stream system simulation model combines historical hydrology with some form of representation of water use. Historical sequences of streamflow and evaporation rates vary annually as well as monthly. Water use diversions are typically assumed to vary monthly within the year but remain constant from year to year. In actuality water use as well as streamflow varies annually. For example, municipal lawn watering and agricultural irrigation are highly dependent on precipitation which varies between years. Water demands are generally highest when streamflows are lowest.

The various approaches for modeling water use diversions are based on (1) historical or projected future use, (2) water rights, or (3) a hypothetical potential yield such as the firm yield.

Wurbs and Carriere (1988) simulated the Brazos River Basin based on historical and projected future water use. Year 1984 levels of water use were supplied continuously, during the 85-year hydrologic simulation period, with only small isolated shortages. Projected 2010 water use conditions resulted in significant shortages.

The TAMUWRAP simulation documented in Chapter 7 of the present report is based on the assumption that all water users withdraw the full amount to which they are legally entitled.

Firm yield or yields associated with alternative levels of reliability are hypothetical potential diversions used to quantify the amount of water a system can supply. Firm yields constrained by senior water rights are presented in Chapter 8. Thus, the impacts of other water users in the basin are reflected in the firm yield computations for the specified reservoirs. Water rights are a relatively severe representation of the effects of other water users on the yield of a specified reservoir or multireservoir system because the permitted water rights diversions are much greater than actual water use.

A TAMUWRAP simulation provided the adjusted streamflow data necessary to compute firm yields constrained by senior water rights. Several key factors in the TAMUWRAP simulation are discussed in Chapter 7 and noted below.

Return flows are difficult to accurately estimate. Assuming no shortages, return flows of 385,138 ac-ft/yr, or 17.7% of the water rights diversions, are incorporated in the TAMUWRAP simulation. An alternative estimate of return flows could be developed as follows. The Texas Water Development Board (TWDB) developed estimates of average return flow factors for the Brazos River Basin in conjunction with the Texas Water Plan (TDWR 1984). Return flow factors for municipal and manufacturing uses are 40% and 35%, respectively. Since steam-electric power cooling water has return flows of almost 100%, TWDB data include consumptive use only for steam-electric cooling water. Water rights aggregate steam electric cooling water with other industrial uses, which means the following return flow estimate will be conservatively low. The 40% and 35% return flow factors applied to 1984 groundwater use, excluding the watershed above Possum Kingdom Reservoir, results in return flows of 96,560 ac-ft/yr. The 40% and 35% factors applied to municipal and industrial water rights diversions result in return flows of 663,440 ac-ft/yr. Other uses are assumed to have zero return flows. The resulting return flow of 760,000 ac-ft/yr, or

35% of the water rights diversions, is conservatively low but significantly higher than the return flows included in the TAMUWRAP simulation.

Administration of a water rights system, like operation of a reservoir system, involves subjective judgements as well as quantitative criteria and, consequently, is difficult to precisely model. The water rights system implemented by the recent adjudication process has not yet been tested and refined under severe drought conditions.

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, or even an almost empty, reservoir is difficult.

CHAPTER 10
SUMMARY AND CONCLUSIONS

Summary

The hydrologic and institutional availability of water in the Brazos River Basin was investigated. However, the models adopted, study approach, and findings are pertinent to other river basins in Texas and elsewhere.

The study included a review of: reservoir operation practices and procedures; the legal system for allocating water between users in Texas; surface water management in the Brazos River Basin; and state-of-the-art computer modeling capabilities for evaluating reservoir yield and surface water availability. The simulation modeling analysis of reservoir yield and water rights in the Brazos River Basin was a central focus of the project. The simulation study included: compilation, synthesis, and analysis of the extensive input data required for the modeling effort; implementation of selected computer models; organization and execution of simulation runs; and analysis of model results.

The simulation models applied in the study are useful tools for analyzing surface water availability. HEC-3 and HEC-5 provide a broad range of capabilities for hydrologic simulation of a stream/reservoir system. TAMUWRAP combines water rights analysis capabilities with hydrologic simulation. The case study illustrates an approach for using the models together, with TAMUWRAP providing input data for HEC-3. TAMUWRAP determines the amount of streamflow available to specified water rights under a priority system. These streamflow depletions and unappropriated flows are inputed as streamflow data to HEC-3, which is then used to compute firm yields and reliabilities or otherwise simulate the stream/reservoir system. MOSS-IV and STATS provide capabilities for streamflow synthesis and statistical analysis of simulation input and output data.

A broad range of information regarding water availability in the Brazos River Basin is presented in this report. Selected quantities are tabulated in Table 10.1 to facilitate summarizing water availability and use from a general overview perspective.

The ultimate source of water is precipitation. Roughly 10% of the precipitation falling in the basin becomes streamflow. The naturalized streamflow at the Richmond gage averages 5,670,000 ac-ft/yr over the 1900-1984 simulation period. The Richmond gage is the most downstream control point in the simulation models for which streamflow was input. The naturalized flow at this location represents the total inflow to the modeled stream/reservoir system. The sum of the mean naturalized streamflows at the most downstream dam on the Brazos River and the tributaries is about 60% of the mean naturalized flow at the Richmond gage. Thus, about 40% of the flow enters the river below the USACE/BRA reservoirs.

The U.S. Army Corps of Engineers (USACE) owns and operates nine of the 12 reservoirs in the USACE/BRA system. The Brazos River Authority (BRA) owns and operates the other three reservoirs and has contracted for most of the conservation capacity in the USACE reservoirs, except the hydroelectric power storage in Whitney Reservoir.

Table 10.1
OVERVIEW COMPARISON OF PERTINENT WATER QUANTITIES

Quantity	1,000 ac-ft/yr	cfs
1900-84 mean naturalized streamflow at Richmond gage	5,670	7,830
water rights:		
10 BRA reservoirs	644	889
Whitney Reservoir	18	25
Waco Reservoir	59	82
other priority rights	1,449	2,002
total priority rights	2,170	2,998
BRA excess flow permit	650	899
1984 surface water use:		
Brazos River Basin	564	779
San Jacinto-Brazos Coastal Basin	311	429
2010 TWDB projected surface water use:		
Brazos River Basin	1,725	2,382
San Jacinto-Brazos Coastal Basin	648	895
BRA water supply commitments	568	785
1984 water supply and hydropower releases from 12 USACE/BRA reservoirs	594	820
individual reservoir hydrologic firm yields for 2010 sediment conditions:		
10 BRA reservoirs	707	976
Whitney Reservoir	29	40
Waco Reservoir	77	106
10-reservoir system hydrologic firm yields for 2010 sediment conditions:		
excluding downstream local flows	1,066	1,472
including downstream local flows	1,474	2,036
individual reservoir firm yields for 2010 sediment conditions constrained by senior water rights:		
10 BRA reservoirs	548	757
Whitney Reservoir	7	9
Waco Reservoir	67	93
10-reservoir system firm yields constrained by senior water rights:		
excluding downstream local flows	649	896
including downstream local flows	845	1,167
95% reliability 10-reservoir system yield constrained by senior water rights:		
excluding downstream local flows	973	1,344
including downstream local flows	1,242	1,715

Water rights associated with the 12 USACE/BRA reservoirs total 721,001 ac-ft/yr, which includes 18,336 ac-ft/yr from Whitney Reservoir, 59,100 ac-ft/yr from Waco Reservoir, and 643,565 ac-ft/yr from the other 10 reservoirs. The City of Waco holds the water rights for Waco Reservoir. The BRA has almost all of the water rights for the other eleven reservoirs. Whitney Reservoir is somewhat unique. The USACE owns and operates Whitney Reservoir. The BRA has contracted for 22.017% of the water available from the active conservation pool. The remainder of the conservation storage capacity is used for hydroelectric power, which is marketed by the Southwestern Power Administration to the Brazos Electric Power Cooperative. Other priority rights in the basin total 1,449,427 ac-ft/yr. Thus, 33% of the 2,170,428 ac-ft/yr total priority water rights diversions in the basin are for releases or withdrawals from the 12 USACE/BRA reservoirs. The BRA also has an excess flows permit for 650,000 ac-ft/yr which has no priority. The BRA diversions of excess flows from the lower Brazos River are permitted if priority water rights are not adversely affected. The BRA can also transfer up to 200,000 ac-ft/yr diverted under its other permits to the San Jacinto-Brazos Coastal Basin. Other water suppliers also divert water to the adjoining coastal basin.

Most, but not all, of the surface water used in both the Brazos River Basin and the San Jacinto-Brazos Coastal Basin is supplied from the Brazos River and its tributaries. Surface water use in the Brazos River Basin and San Jacinto-Brazos Coastal Basin in 1984 was 563,800 acre-feet and 310,820 acre-feet, respectively, which totals 874,620 acre-feet or 37% of the priority water rights in the Brazos River Basin. The Texas Water Development Board projected year 2010 water use cited in Table 10.1 is 271% of 1984 use. The projected future water use does not include potential interbasin transfers to other areas such as Houston in the adjoining San Jacinto Basin.

BRA water supply commitments associated with 10 reservoirs and the 1984 recorded water supply and hydroelectric power releases from 12 reservoirs are also included in Table 10.1.

Hydrologic firm yields, which were computed ignoring the impacts of all other water users and reservoirs except the 13 reservoirs included in the HEC-3/HEC-5 models, and firm yields constrained by senior water rights throughout the basin are included in the table. Firm yields are presented based alternatively on each reservoir operating individually and with multiple reservoir system operations. System firm yields are shown excluding and including local flows which enter the river below the dams. The firm yields are based on 2010 sediment conditions.

Individual reservoir hydrologic firm yields total 813,000 ac-ft/yr for the 12 reservoirs, which includes 29,000 ac-ft/yr, 77,000 ac-ft/yr, and 707,000 ac-ft/yr, respectively, for Whitney, Waco, and the other ten reservoirs. System firm yields are computed based on the ten reservoirs making coordinated releases for a diversion at the Richmond gage. Excluding flows entering the river below the dams, the 10-reservoir system firm yield is 1,066,000 ac-ft/yr or 151% of the sum of the individual reservoir firm yields. Including downstream local flows, the 10-reservoir system firm yield is 1,474,000 ac-ft/yr or 208% of the sum of the individual reservoir firm yields.

Individual reservoir firm yields constrained by senior water rights total 548,000 ac-ft/yr for the ten reservoirs. The corresponding 10-reservoir system firm yields are 649,000 ac-ft/yr and 845,000 ac-ft/yr, respectively, excluding and including downstream local flows, or 118% and 154% of the sum of the individual reservoir firm yields. Individual reservoir firm yields computed considering water rights are 77% of the hydrologic firm yields for the 12 reservoirs. System firm yields for the 10-reservoir system, considering water rights are 61% and 57% of the hydrologic system firm yields, excluding and including downstream local flows, respectively. Thus, senior water rights significantly decrease firm yields, and system operations significantly increase firm yields.

Firm yield, by definition, has a reliability of 100% based on a hydrologic period-of-record simulation. Larger yields have lesser reliabilities. However, yield levels significantly larger than firm yield result in shortages only a relatively small percent of the time. For example, a demand of 973,000 ac-ft/yr, which is 150% of the firm yield, has a reliability of 95%.

Conclusions

A package of generalized computer programs consisting of HEC-3, HEC-5, TAMUWRAP, MOSS-IV, and STATS provide a comprehensive range of simulation modeling capabilities for reservoir yield and related surface water availability studies. HEC-3 and TAMUWRAP can be used in combination to compute firm yields constrained by senior water rights.

A number of factors affecting reservoir yield are addressed in this report. The stochastic nature of streamflow, loss of capacity due to sedimentation, multiple reservoir interactions, and multiple users are particularly important fundamental aspects of a water supply and use system which must be considered in yield studies.

Consideration of senior water rights significantly decreases estimated reservoir yield. Coordinated system operation of multiple reservoirs significantly increases yield. The unregulated flows entering the river below the dams are a large portion of the total basin water resource. Reservoirs can develop dependable supplies from downstream unregulated flows as well as from reservoir inflows. The entire river basin should be viewed as an integrated system in analyzing reservoir yield and other aspects of surface water availability.

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