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Evaluation of Storage Reallocation and Related Strategies for Optimizing Reservoir System Operations

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INTRODUCTION

Statement of the Problem

Rapid population and economic growth combined with depleting groundwater reserves are resulting in ever increasing demands on surface water resources in Texas, as well as elsewhere. The climate of the state is characterized by extremes of floods and droughts. Reservoirs are necessary to control and utilize the highly variable streamflow. Due to a number of economic, environmental, institutional, and political considerations, construction of new reservoir projects is much more difficult now than in the past. Consequently, optimizing the beneficial use of existing reservoirs is becoming increasingly more important.

Reservoir operation is based on the conflicting objectives of maximizing the amount of water available for conservation purposes and maximizing the amount of empty space available for storing future flood waters to reduce downstream damages. Common practice is to operate a reservoir for either flood control only, conservation only, or a combination of flood control and conservation with separate pools designated for each. The conservation and flood control pools, or vertical zones, in a multipurpose project are fixed by a designated top of conservation (bottom of flood control) pool elevation. Conservation pools may be shared by various purposes, such as water supply, hydroelectric power, and recreation, which involve both complementary and conflicting interactions.

Public needs and objectives and numerous factors affecting reservoir operation change over time. An increasing necessity to use limited storage capacity as effectively as possible warrants periodic re-evaluations of operating policies. Reallocation of storage capacity between purposes represents a general strategy for optimizing the beneficial use of limited storage capacity in response to changing needs and conditions. A storage reallocation between flood control and conservation purposes typically involves a permanent or seasonal change in the designated top of conservation pool elevation. Reallocations between conservation purposes can be achieved by various modifications of operating policies. Although given relatively little consideration in the past, storage reallocations will likely be proposed more frequently as demands on limited resources increase.

Scope of Study

This report documents an investigation of: (1) the potential of storage capacity reallocation and other related modifications in operating policies as management strategies for optimizing the beneficial use of existing reservoirs in Texas and (2) modeling capabilities for formulating and evaluating such changes to operating policies. In general, storage reallocations can involve a variety of types of reservoir use. The present study focused primarily on flood control and water supply. Multiple purpose reservoir operations involving hydroelectric power were also investigated. Both permanent conversion of storage capacity between purposes and seasonal rule curve operations were addressed. Buffer pool operations were also considered. Multiple reservoir system operation was a major emphasis of the study.

The literature was reviewed and several reservoir management agencies contacted to (1) identify experiences in studying and/or implementing storage reallocations and (2) evaluate the state-of-the-art of associated modeling and analysis capabilities.

The feasibility of seasonal rule curve operation depends upon the seasonal characteristics of the various factors affecting reservoir operation. Precipitation, streamflow, reservoir evaporation, water demands, and reservoir storage content data for Texas were analyzed to identify seasonal characteristics.

A 12-reservoir system operated by the U.S. Army Corps of Engineers and Brazos River Authority provided a case study for evaluating the potential for storage reallocations and related operating strategies. This system, located in the Brazos River Basin, is considered representative of major reservoirs in Texas. The existing operating policies and possible modifications were investigated.

The case study includes (1) flood control storage frequency and conservation drawdown frequency analyses based on the results of monthly hydrologic period-of-record simulations of reservoir system operations and (2) firm yield and reliability analyses. The generalized computer programs HEC-3, HEC-5, STATS, and MOSS-IV, and several utility software packages were used in the modeling study. Simulation of reservoir system operations was based on an 85-year sequence of monthly hydrologic data.

The case study provides a preliminary assessment of the viability of permanent storage conversions and/or adoption of seasonal rule curve operations as potential reservoir management strategies. The objective is to evaluate storage reallocation potentialities in general, not develop detailed reallocation plans. The case study is basically a reconnaissance-level hydrologic analysis of reservoir operations. The monthly period-of-record simulations provide a reasonably precise analysis of water supply considerations. However, the daily hydrologic data required for detailed analysis of flood control operations were not included in the study.

Reallocation of reservoir storage capacity involves complex institutional, financial, economic, legal, political, and technical considerations not addressed in the case study. However, the hydrologic analyses provide a good starting point for determining what types of reallocation strategies and modeling approaches might be potentially effective and whether more detailed studies are worthwhile.

Organization of the Report

Chapter 2 is a general discussion of reservoir operation and institutional and technical aspects of storage reallocation and a review of reallocations which have been implemented or proposed throughout the nation. Chapter 3 addresses the seasonality of the hydrologic factors pertinent to seasonal rule curve operation in Texas. Chapter 4 reviews state-of-the-art modeling capabilities and describes the computer models adopted for use in the case study. The Brazos River Basin case study is presented in chapters 5 through 8. Study results are summarized, and conclusions are presented in chapter 9.

CHAPTER 2
RESERVOIR STORAGE REALLOCATION

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 ten acres. However, the 187 major reservoirs represent over 95 percent of the total storage capacity in all the reservoirs.

Three major reservoirs 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.

As indicated in 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. The Brazos River Basin also contains the largest flood control storage capacity.

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 reservoirs range in size from 5,000 acre-feet to over 5,000,000 acre-feet.

The 187 major reservoirs in Texas are owned, maintained, and operated by 4 federal agencies, 53 water districts and river authorities, 39 cities, 2 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. 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.

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

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)

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)

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 reimburseable 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 for steam electric power plants.

Reservoir Operation Practices and Procedures

Reservoir development and management are based on project purposes. Conservation purposes, such as municipal and industrial water supply, irrigation, hydroelectric power, and instream flow maintenance, involve storing water during periods of high streamflow and/or low demand for later beneficial use as needed. Conservation storage also provides opportunities for recreation. The purpose of flood control storage is to reduce the damages caused by extreme high flow events. Institutional arrangements, planning and design methods, and operating procedures traditionally have been based on separating and treating each project purpose as independently as possible.

Institutional Framework

The Flood Control Act of 1936 and subsequent legislative acts instituted a large-scale federal flood control program. The Corps of Engineers has constructed numerous dams and other flood control projects throughout the nation under this program. The Corps of Engineers is responsible for flood control operations at its own reservoirs and those constructed by the Bureau of Reclamation. The federal government has borne both the construction and the

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)

operation and maintenance costs associated with the flood control storage. Nonfederal water resources development entities typically do not include flood control storage in their reservoir projects due to the difficulties involved in financing flood control.

The Corps of Engineers owns and operates about 600 reservoirs including navigation locks and dams. These projects are operated and maintained through 10 division and 36 district offices located throughout the continental United States. The 32 Corps of Engineers reservoirs in Texas are operated by the Fort Worth District (26 reservoirs), Galveston District (3 reservoirs), and Tulsa District (3 reservoirs). With the one exception of Olmos Reservoir owned by the City of San Antonio, all the major reservoirs in Texas containing controlled (gated) flood control storage were constructed and are operated by the federal agencies. Olmos Reservoir is the oldest and smallest as well as only nonfederal project of the major reservoirs containing flood control storage. 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 two reservoirs on the Rio Grande River.

Municipal and industrial water supply has traditionally been a nonfederal responsibility. However, the concept of multipurpose water resources development is an integral part of the federal water program. 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 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 ten 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 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.

About three-fourths of the conservation storage capacity in the major reservoirs in Texas is designated for municipal and industrial water supply. Most of the water supply reservoirs are owned and operated by river authorities, water districts, and cities. However, municipal and industrial storage is also included in all but two of the federal reservoirs. 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.

Whereas flood control operations are highly centralized in a single agency, water supply is the responsibility of a multitude of entities. The river authorities, water districts, and cities own reservoirs, contract for storage in federal reservoirs, and, inturn, contract to supply water to municipalities, industries, water districts, and other users.

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.

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.

Reservoir Pools

Reservoir release policies or operating procedures are based on dividing the total storage capacity into designated pools. A typical reservoir consists of one or more of the vertical zones, or pools, illustrated by Figure 2.1.

Water releases or withdrawals are normally not made from the inactive pool, except through the natural processes of evaporation and seepage. The top of inactive pool elevation may be fixed by the invert of the lowest outlet or, in the case of hydroelectric power, by conditions of operating efficiency for the turbines. An inactive pool may also be contractual set to facilitate withdrawals from outlet structures which are significantly higher than the invert of the lowest outlet structure at the project. The inactive pool is sometimes called dead storage. It may provide sediment reserve, head for hydroelectric power, and water for recreation.

The conservation pool supplies water for various beneficial uses. The reservoir water surface is maintained at or as near the top of conservation pool elevation as streamflows and water demands allow. Drawdowns are made as required to meet water supply needs. Reservoir operation strategies may include designation of one or more buffer zones. Full demands are met as long as the reservoir water surface is above the top of buffer zone, with certain nonessential demands being curtailed whenever the water in storage falls below this level. Buffer zone operations have been used very little in Texas.

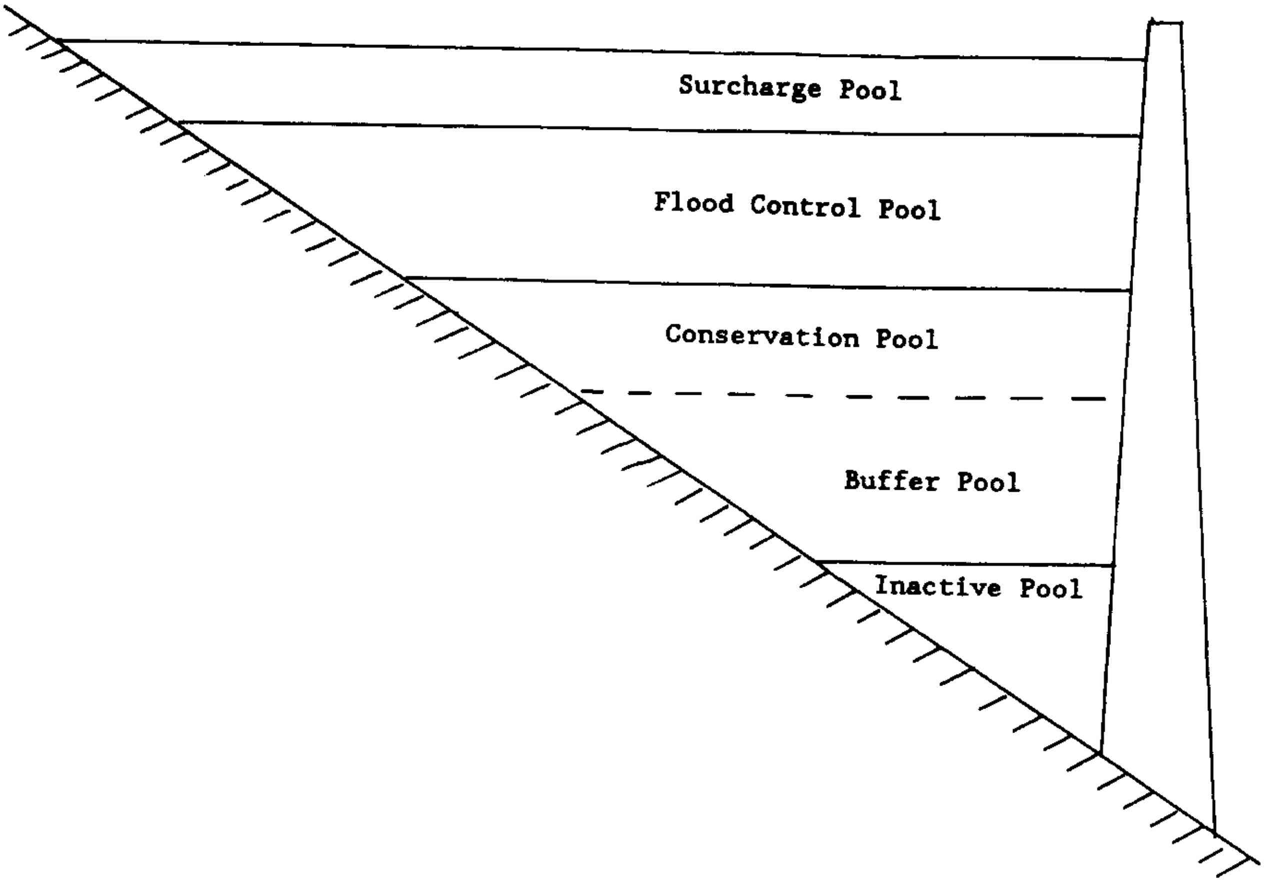


Figure 2.1 Reservoir Pools

The flood control pool remains empty except during and immediately following a flood event. The top of flood control elevation may be set by the crest of an uncontrolled spillway. Gated spillways allow the flood control pool to exceed the spillway crest elevation. For the common case of a reservoir with no designated flood control capacity, the top of conservation pool is often fixed by the elevation of an uncontrolled spillway crest. A number of flood control pools in Texas are divided into vertical zones, with the maximum allowable release rates depending upon the zone that the water surface falls within.

The surcharge pool is uncontrolled storage capacity above the conservation and/or flood control pools which occurs during a flood as inflow to a full reservoir exceeds outflow. The maximum design water surface is an elevation established during project design from the perspective of dam safety. The structural integrity of the dam could be threatened if the surcharge storage exceeds the maximum design water surface. Consequently, assuring that the reservoir water surface does not exceed the maximum design water surface is an important consideration in reservoir operation.

The top of conservation pool elevation can be varied seasonally. Likewise, top of buffer zone elevations and the elevations defining zones within a flood control pool could also be varied seasonally. However, seasonal rule curve operations have been used very little in Texas.

Flood Control Versus Conservation

Construction of a conservation reservoir can actually worsen downstream flooding conditions due to loss of valley storage, decrease in flood wave attenuation, and increase in travel time. However, conservation capacity provides some incidental flood protection whenever the flood event coincides with a partially drawn-down pool. Drought periods in Texas have sometimes been ended by major floods such that empty conservation storage space was available to store the flood waters. Surcharge storage in conservation only reservoirs may also provide some incidental flood protection. Downstream flooding is also considered in regulating releases from conservation projects. For example, Toledo Bend Reservoir, which has the largest conservation capacity in the state and is located in a basin with no flood control storage capacity, is operated to minimize deviations from the designated constant pool level to the extent practical. However, the operation procedures include monitoring of downstream streamflows in regard to damage potential and forecasting of reservoir inflows. The reservoir will be drawn down in anticipation of a flood or the pool will be maintained a foot or so high temporarily to prevent releases from contributing to downstream flooding. Likewise, temporary storage of flood water in flood control pools may provide some incidental benefits for conservation purposes, particularly hydroelectric power generation. However, reservoir operation throughout the state is based on treating flood control and conservation capacities as distinctly separate pools serving different purposes.

Institutional arrangements for constructing and operating multipurpose reservoirs are based on having separate pools for flood control and conservation purposes. Planning, design, and operational problems associated with flood control are typically handled separately from those associated with conservation storage.

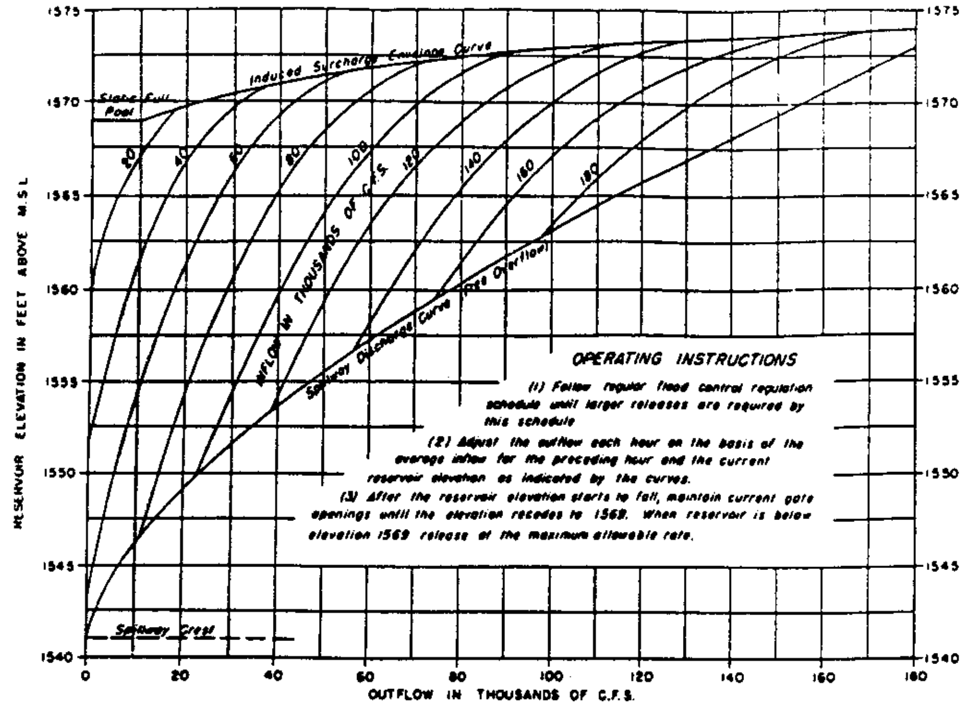
Flood Control Operating Procedures

Each of the Corps of Engineers flood control reservoirs has operating procedures which are documented in a reservoir regulation manual. A regulation schedule specifies the releases to be made under various conditions. Formulation or modification of a plan of operation requires extensive hydrologic, hydraulic, economic, and environmental studies. The plan of operation is established during project planning and design. Modifications in the operating procedures for operational projects are made as required to reflect experience gained in actual operation or changed conditions such as construction of additional projects in the basin. However, operation procedures tend to remain fairly constant over time.

Flood control regulation schedules are developed to address the particular conditions associated with each individual reservoir and river basin. Peculiarities and exceptions to standard operating procedures occur at various projects. However, the regulation schedules for all the projects were developed following essentially the same guidelines, as outlined in the Corps of Engineers manual on reservoir regulation, EM 1110-2-3600 dated May 1959, and have the same general strategy. An overview of flood control operating procedures is provided below.

The overall strategy for operating the gates of a flood control reservoir consists of two sets of procedures. The set of procedures requiring the largest release rate control for given flooding and storage conditions. The regular procedure, which usually controls, is based on the assumption that ample storage capacity is available to handle the flood without special precautions being necessary to prevent the water surface from rising above the top of flood control pool. Operation is switched over to an alternative schedule during extreme flooding conditions when the anticipated runoff from a storm is predicted to exceed the controlled capacity remaining in the reservoir. If the water surface level significantly exceeds the top of flood control pool, downstream damages will necessarily occur. The objective is to assure that reservoir releases do not contribute to downstream damages as long as the storage capacity is not exceeded. However, for extreme flood events which would exceed the reservoir storage capacity, moderately high damaging discharge rates beginning before the flood control pool is full are considered preferable to waiting until a full reservoir necessitates much higher release rates.

An example regulation schedule is presented in Figure 2.2 (USACE 1959). This type of schedule controls releases during an extreme flood which exceeds the capacity of the flood control pool. The reservoir release rate is read directly from the graphs. The schedule is repeated in two formats, labeled schedule A and schedule B. Using schedule A, release decisions are based on a current water surface elevation and inflow rate. With schedule B, release rates are dependent upon the current water surface elevation and rate of rise of water surface. The two forms of the schedule are intended to result in the same release rate. Schedule A is used if measured inflow rates are known. In the absence of measured inflow rates, schedule B is used based on rate of rise of water surface elevation. Release rates are typically determined at a reservoir control center which has access to real-time streamflow measurements. If communications between the control center and operator at the project are



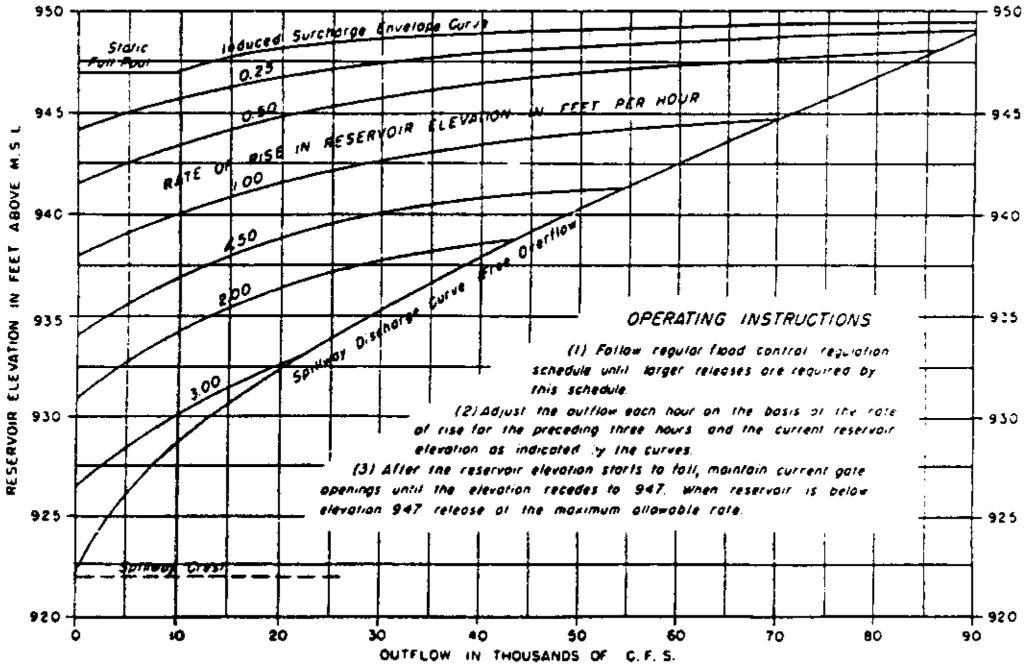
OPERATING INSTRUCTIONS

(1) Follow regular flood control regulation schedule until larger releases are required by this schedule

(2) Adjust the outflow each hour on the basis of the average inflow for the preceding hour and the current reservoir elevation as indicated by the curves.

(3) After the reservoir elevation starts to fall, maintain current gate openings until the elevation recedes to 1569. When reservoir is below elevation 1569 release at the maximum allowable rate.

SPILLWAY GATE REGULATION, SCHEDULE A



OPERATING INSTRUCTIONS

(1) Follow regular flood control regulation schedule until larger releases are required by this schedule.

(2) Adjust the outflow each hour on the basis of the rate of rise for the preceding three hours and the current reservoir elevation as indicated by the curves.

(3) After the reservoir elevation starts to fall, maintain current gate openings until the elevation recedes to 947. When reservoir is below elevation 947 release at the maximum allowable rate.

SPILLWAY GATE REGULATION, SCHEDULE B

Source: USACE EM 1110-2-3600 dated 25 May 1959

Figure 2.2 Flood Control Regulation Schedule interrupted during a flood emergency, the operator can determine gate releases based on schedule B without needing measurements of inflow rates.

Downstream flooding conditions are not reflected in the family of curves illustrated in Figure 2.2. These curves are intended to guide operations only if the regular operating procedure would result in overtopping the flood control pool. The regular procedure is based on not making releases which would contribute to downstream flooding. Releases are not made unless downstream flows are below damaging levels. The regular procedure could be followed until the flood control pool fills. However, after the flood control pool is full, tremendously high discharge rates may be required to prevent the surcharge storage from exceeding the design water surface. The much higher peak release rate necessitated by this hypothetical operation policy can be expected to be much more damaging than a lower release rate with a longer duration beginning before the flood control pool is full. On the other hand, an operator would not want to make damaging releases early in a storm if the flood control pool remained empty during the storm. Although streamflows that will occur several hours or days in the future are sometimes forecast during real-time operations, future flows are still highly uncertain.

The regulation schedule curves are developed based on estimating the minimum volume of inflow that can be expected in a flood, given the current inflow rate and reservoir elevation. Having estimated the minimum inflow volume to be expected during the remainder of the flood, the outflow required to limit storage to the available capacity is determined by mass balance computations. For a given current inflow rate, the minimum inflow volume for the remainder of the storm is obtained by assuming the inflow hydrograph has just crested and computing the volume under the recession side of the hydrograph. For conservatively low inflow volume estimates, the assumed recessive curve is made somewhat steeper than the average observed recession. The complete regulation schedule which allows the outflow to be adjusted on the basis of the current inflow and empty storage space remaining in the reservoir is developed by making a series of computations with various assumed values of inflows and amounts of remaining storage available.

As previously indicated, the flood control regulation strategy for a reservoir actually consists of two procedures. The regular procedure is followed as long as the indicated releases are greater than the outflow values read from the curves discussed above. The regular schedule is based on downstream flooding conditions. Nondamaging flow rates and stages are specified at selected index locations, called control points, which are representative of the damage potential in the associated reach of channel and flood plain. Nondamaging flow rates are equal to or closely related to bankful stream capacities. Stream gaging stations are located at the control points. Releases are made to empty the flood control pool as quickly as possible without exceeding the allowable flow rates at each downstream control point. The regulation schedule consists of specified flow rates to be maintained at the designated control points.

When a flood occurs, the spillway and outlet works gates are closed. The gates remain closed until a determination is made that the flood has crested and flows are below the nondamaging levels specified for each of the control points. The gates are then operated to empty the flood control pool as quickly as possible without exceeding the allowable flows at the control points.

Normally, no flood control releases are made if the reservoir level is at or below the top of conservation pool. However, if flood forecasts indicate that the inflow volume will exceed the available conservation storage, flood control releases from the conservation storage may be made if downstream conditions permit. The idea is to release some water before the stream rises downstream, if practical, for a forecasted flood.

For many reservoirs, the allowable flow rate associated with a given control point is constant regardless of the reservoir surface elevation, assuming the outflow still exceeds the value specified by the previously discussed graph illustrated by Figure 2.2. At other projects, the flood control pool is subdivided into two or more zones with the allowable flow rates at one or more of the control points varying depending upon the level of the reservoir surface with respect to the discrete alternative zones. This allows stringently low flow levels to be maintained at certain locations as long as only a relatively small portion of the flood control pool is occupied, with the flows increased to a higher level, at which minor damages could occur, as the reservoir fills. The variation in allowable flow rates at a control point may also be related to whether the reservoir level is rising or falling.

A reservoir is operated based on maintaining flow rates at several control points located various distances below the dam. The most downstream control points may be several hundred miles below the dam. Lateral inflows from uncontrolled watershed areas below the dam increase with distance downstream. Thus, the impact of the reservoir on flood flows decreases with distance downstream. Operating to downstream control points requires streamflow forecasts. Flood attenuation and travel time from the dam to the control point and inflows from watershed areas below the dam must be estimated as an integral part of the reservoir operating procedure.

Most flood control reservoirs are components of basinwide multi-reservoir systems. Two or more reservoirs located in the same river basin will have common control points. A reservoir may have one or more control points which are influenced only by that reservoir and several other control points which are influenced by other reservoirs as well. Reservoirs in a system are typically operated, to the extent practical, to maintain approximately the same percentage of flood-control storage utilized in each reservoir. Releases from all reservoirs, as well as runoff from uncontrolled watershed areas, must be considered in forecasting flows at control points.

Maximum allowable rate of change of reservoir release rates are also specified. Abrupt gate openings causing a flood wave with rapid changes in stage are dangerous and may contribute to streambank erosion.

Conservation Operations

Reservoir operation procedures for water supply purposes are based essentially on meeting water demands subject to institutional constraints related to project ownership, contractual agreements, and water rights. The complex organizational framework for water supply operations involves numerous 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.

Water supply withdrawals are made at many projects 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 major reservoir systems in Texas.

A majority of the water supply reservoirs are operated as individual units to supply specific customers. Even in those cases where a water district or city owns several reservoirs, each reservoir will typically be assigned to specific users with a minimum of interaction between reservoirs. However, a number of reservoirs are operated as systems with some degree of interaction between the component reservoirs. System operation typically means maintaining a balance between storage depletions and water surface fluctuations in the component reservoirs. Hydroelectric power generation is also a concern in system operation. Releases are coordinated to meet water supply demands while minimizing the amount of water bypassing the turbines.

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.

Changing Conditions Affecting Reservoir Operation

Reservoir storage capacities and operating policies are generally established prior to construction and tend to remain constant thereafter. However, public needs and objectives and numerous factors affecting reservoir effectiveness change over time. The increasing necessity to use limited storage capacity as effectively as possible warrants periodic reevaluations of operating policies. Operating policies should be responsive to changing needs and conditions. Reallocation of storage capacity represents one general strategy for modifying operating policies in response to changing needs and conditions.

The period from 1936 through the 1970's was the construction era of water resources development. In recent years, the dominant water policy emphasis has been on shifting to a greater reliance on managing flood plain land use, water demand management, and optimizing the operation of existing facilities. The best reservoir sites have already been developed. Due to a number of economic, environmental, institutional, and political factors, construction of additional new reservoir projects is much more difficult now than in the past. Consequently, optimizing the beneficial use of existing reservoirs is becoming increasingly more important.

Rapid population and economic growth in Texas is accompanied by increased needs for water supply and flood control. Depleting groundwater reserves are resulting in an increased reliance on surface water. During the 1970's, the rising cost of fossil fuel focused attention on increasing hydroelectric power generation. Instream flow needs for fish and wildlife habitat and maintenance of fresh water inflows to bays and estuaries have received increased attention in recent years.

In addition to increasing water related needs, other factors affecting reservoir operation change over time as well. Watershed and flood plain conditions are dynamic. Construction of numerous small flood retarding dams by the Soil Conservation Service and other entities in the watersheds of major reservoirs have reduced flood inflows to the reservoirs. Construction of numerous small ponds for recreation or watering livestock have also decreased reservoir inflows and yields. Increased runoff caused by watershed urbanization is significantly contributing to flooding problems in certain locations. The existing flood control reservoirs were planned and designed based on the expectation of ever increasing intensification of flood plain land use. However, the National Flood Insurance Program has resulted in regulation of 100-year flood plains. With stringent flood plain management, susceptibility to flooding could actually decrease over time as existing activities choose to leave the flood plain and regulation prevents other activities from moving into the flood plain. Reservoir sedimentation reduces available storage capacity. Construction of additional reservoirs, as well as other related types of projects such as conveyance facilities, flood control levees and channel improvements, and electric power plants, affect the operation of existing reservoirs. Technological advancements in hydrologic data collection, streamflow forecasting, system modeling and analysis, and computer technology provide opportunities for refining operating policies.

Types of Storage Reallocations

For purposes of the present discussion, reallocation of reservoir storage capacity between purposes is categorized as follows: (1) reallocation between flood control and conservation purposes, (2) reallocation between different conservation purposes, and (3) temporary use of sediment reserve. Other reservoir operation strategies are not actually reallocations of storage capacity but are closely related or may be implemented in conjunction with storage reallocations. The scope of the present study is limited to modifications to operating policies of existing reservoirs which involve no significant structural changes to the dam and appurtenant outlet structures. Constructing a new dam or raising an existing dam involves development of additional storage capacity rather than reallocating existing capacity.

Reallocation Between Flood Control and Conservation Purposes

Reallocation of storage capacity between flood control and conservation purposes could be physically implemented simply by lowering or raising the designated top of conservation pool elevation. Raising the top of conservation pool could necessitate modifications to various facilities such as relocation of roads and recreation facilities around the lake. Storage reallocations could be between pools in a single reservoir or between reservoirs in a multiple reservoir system. Reallocations could be either long-term, temporary, or continuously changing.

Storage reallocations can be either permanent or seasonal. A seasonal rule curve consists of varying the top of conservation pool elevation as a function of time of the year. For example, many parts of the world have distinct flood seasons. The top of conservation pool is raised during the season of the year having a low threat of floods.

Reallocations between flood control and conservation storage capacity can be categorized as follows: (1) permanent or seasonal conversion of conservation capacity to flood control, (2) permanent or seasonal conversion of flood control capacity to conservation, and (3) seasonal rule curve operations or multireservoir system reallocations that simultaneously enhance both flood control and conservation operations.

Flood control in Texas, as well as elsewhere in the nation, has generally been viewed as a federal responsibility. Practically all the flood control storage capacity in the state is owned and operated by federal agencies. Difficulties in financing flood control have been a major reason that reservoirs constructed by state and local entities have not included storage capacity designated for flood control. However, national water policy currently emphasizes shifting responsibilities from the federal government to the states. Consequently, the state could assume a greater role in flood control in the future which could stimulate interest in operating nonfederal reservoirs for flood control. Although new institutional arrangements might be necessary, the numerous conservation-only projects in the state could conceivably also be operated for flood control. Corps of Engineers reservoirs are usually designed to contain at least 50 to 100-year recurrence interval floods without overtopping the flood control pool. Providing this degree of protection by reallocating a portion of the storage capacity in a conservation reservoir to flood control would normally not be practical due to the large storage volume required. However, lesser degrees of protection could possibly be provided while still maintaining significant conservation storage capacity.

As indicated in Table 2.1, the Sabine River Basin has the second largest conservation capacity of the various river basins but no flood control capacity. Three federal projects (Carl L. Estes, Big Sandy, and Lake Fork Reservoirs) in the Sabine River Basin containing flood control capacity were previously authorized but never constructed. Nonfederal reservoirs have since been constructed, without flood control capacity, at two of the sites. The Trinity, Colorado, and Neches River Basins also contain a large amount of conservation storage capacity relative to flood control capacity. Reallocation of conservation capacity to flood control could be potentially worthwhile in these basins under appropriate conditions.

As discussed in the next section of this chapter, the majority of previous proposals for storage reallocation in Texas have involved conversion of flood control capacity to municipal and industrial water supply. Increasing needs for water supply could justify reallocation of flood control capacity under suitable conditions. Flood control capacity can be used to enhance hydroelectric power and recreation as well as water supply.

The case study, presented later in this report, focused on evaluating the potential for reallocating flood control capacity to water supply while minimizing adverse impacts on flood control, and also on simultaneously increasing the effectiveness of both flood control and water supply operations. Adoption of seasonal rule curve operations could potentially benefit both flood control and water supply purposes. Under certain circumstances, improvements in both flood control and conservation operations could conceivably be achieved by reallocations between reservoirs in a multireservoir system.

Reallocation Between Conservation Purposes

Reservoir operations to generate hydroelectric power and to supply water for municipal, industrial, and agricultural uses are typically closely related. Storage reallocations may involve various strategies for converting capacity between hydroelectric power and water supply. Operating policies may also be modified to enhance recreation.

Although not addressed by the present investigation, reallocation of water between municipal, industrial, and agricultural users can be expected to become increasingly more important as demands on limited resources intensify. Instream flow needs for fish and wildlife habitat and freshwater inflows to estuaries also may compete with other uses. Water rights and allocation of water between users is a major issue in Texas. However, municipal, industrial, and agricultural water supply was viewed essentially as a single purpose in the present reallocation study without analyzing allocation between users.

Temporary Use of Sediment Reserve

In planning and design of reservoir projects, additional storage capacity is typically included for 50 to 100 years of sedimentation. Sediment reserve is included in inactive, conservation, and flood control pools. Storage capacities and firm yields cited by the Corps of Engineers are typically exclusive of the extra capacity reserved for sediment deposition. Prior to depletion of the sediment reserve, this storage capacity can be used for various beneficial purposes. Water suppliers will sometimes execute several-year temporary contracts with water users based on yield provided by the sediment reserve.

Other Operating Strategies

Other potential approaches to modifying reservoir operating procedures are not actually reallocations of storage capacity but are closely related or may be implemented in conjunction with storage reallocations. Such operating strategies include (1) changes in flood control pool release rates, (2) buffer zone operation of conservation storage capacity, and (3) multireservoir system operation.

As previously discussed, flood control operations are based on maximum allowable discharges at downstream control points. Flood control pools are often zoned such that maximum allowable discharges vary with reservoir storage levels. The actual target discharges at the control points may be varied, up to the maximum allowable discharges, depending on considerations such as season of the year or floodplain activities. In many cases, some floodplain occupants will incur damages or inconvenience at practically any flood release rate. Consequently, reservoir operators frequently are pressured by floodplain occupants to limit releases to levels significantly below those dictated by the authorized maximum allowable discharges.

Weeks or even months may be required to completely evacuate a flood control pool after a major flood. Reductions in the release rates at which

Spring flood waters are evacuated can contribute to reductions in Summer drawdowns from conservation storage. Thus, reductions in flood control release rates could have effects similar to seasonal rule curve operations. In many cases, control points are located several days travel time below a dam. Unexpected additional precipitation occurring after a release is made can result in the release contributing to flooding several days later at a downstream location. Thus, maintaining actual target discharges at levels below the maximum allowable nondamaging discharges could simultaneously enhance conservation purposes and reduce the risk of contributing to flood damages.

Buffer zone operations provide a mechanism for triggering reductions in releases from conservation storage as reservoir storage is depleted. Firm and secondary yields can be differentiated. In the case study presented later in this report, buffer zone operation and reallocation are combined such that the original firm yield is maintained while the reallocation provides increases in secondary yield.

Multiple reservoir system operation has traditionally been an integral part of flood control operations. Water supply yields can also be significantly increased by system operation. Multireservoir system operation for water supply is a major focus of the case study.

System operations have been found to be beneficial in a number of river basins throughout the nation. For example, coordinated operation of several reservoirs in the Potomac River Basin to supply water for the Washington, D.C., metropolitan area has received considerable attention. Multiple reservoir system operation, rather than operating the several reservoirs individually, was found to increase yield by over 25%. System operation was achieved by cooperation, including contractual agreements, between the several agencies that own and manage the reservoirs. The increased yield achieved by improved operation of existing facilities was about equivalent to the combined yield of two new reservoir projects being considered. System operation saved about $250 million in construction costs and avoided many heated environmental fights over additional reservoir construction (Viessman and Welty 1985).

Actual and Proposed Storage Reallocations

A literature review revealed essentially no publications related to storage reallocation. For many years, the Corps of Engineers district offices and other water management agencies have studied and, in some cases, implemented storage reallocations. The studies have been documented by agency reports but not reported in the published literature. In some cases, reallocation studies have been included in comprehensive planning reports in which the consideration of storage reallocation was a relatively minor part of the overall study. Some reallocation studies have been documented by agency reports directed specifically to the reallocation study. In other cases, reallocation studies have been conducted without any documentation.

The following discussion focuses initially on reallocations which have been studied and/or implemented at reservoirs in Texas. Then reservoir storage reallocations throughout the nation are addressed.

Seasonal Rule Curve Operation in Texas

Although seasonal rule curves are fairly common in many parts of the United States, this type of operating policy has not been widely adopted in Texas. The top of conservation pool has been varied seasonally at four reservoirs in the state.

Two Corps of Engineers projects, Lake O' the Pines and Wright Patman Reservoir in the northeast corner of the state, are operated in accordance with seasonal rule curves. Lake O' the Pines and Wright Patman Reservoir are located on the Cypress Creek and Sulfur River, respectively, which are tributaries of the Red River. The operating rule curve for Lake O' the Pines provides for raising the top of conservation pool 1.5 feet from mid-May through mid-September for recreation purposes (USACE, New Orleans District 1974a). The rule curve for Wright Patman varies significantly during the year in response to an interim operating agreement with the conservation storage sponsor to provide additional municipal and industrial water supply (USACE, New Orleans District 1974b). The top of conservation pool is constant from November through March and varies with date from April through October. The top of conservation pool peaks on June 1 at a level 6.9 feet above the winter pool level. A permanent reallocation of flood control to conservation is planned for Wright Patman Reservoir upon completion of construction of Cooper Reservoir upstream. The seasonal rule curve is being followed until that time.

The top of conservation pool elevations for the International Falcon and Amistad Reservoirs on the Rio Grande River have been temporarily raised for seasonal rule curve operation in the past. However, the optional encroachment into the flood control pool does not necessarily occur routinely each year and the magnitude of encroachment can be varied within a fixed maximum limit. In most years, the International Boundary and Water Commission does not use a seasonal rule curve.

Permanent Reallocations in Texas

Storage capacity has actually been reallocated at several reservoirs and proposed or studied at several other reservoirs in Texas. In all cases, the actual or proposed permanent storage reallocation involved an increase in municipal and industrial water supply capacity. One case involved reallocation from hydroelectric power to water supply. The other reallocations involved flood control. In some cases, relatively small amounts of flood control capacity were lost to water supply. In other cases, the reallocation was accomplished or proposed to be accomplished in conjunction with construction of other reservoirs upstream. Thus, the total system flood control capacity was not reduced by the reallocation of storage in the existing reservoir combined with construction of a new reservoir.

Permanent reallocation of storage capacity has occurred at Texoma, Lewisville, Belton, and Sam Rayburn Reservoirs. Additional reallocations are proposed for Texoma and Sam Rayburn Reservoirs. Reallocations are also planned for Wright Patman and Waco Reservoirs. A reallocation in Grapevine Reservoir was previously proposed. Reallocations at Bardwell, Granger, and Lake O' the Pines have been recently considered.

Lake Texoma

Lake Texoma and Denison Dam, on the Red River in Texas and Oklahoma, has the largest storage capacity of any reservoir in Texas. With completion of construction in 1944, it is the oldest Corps of Engineers reservoir project in Texas. Lake Texoma contains 2,669,000 acre-feet of flood control capacity and 1,612,000 acre-feet conservation capacity. The project was constructed primarily for flood control and hydroelectric power, realizing that other purposes could become important in the future. For many years, the conservation capacity was used solely for hydroelectric power and recreation.

A number of reallocation plans have been studied and certain reallocations have been actually implemented at Lake Texoma (USACE, Tulsa District 1987). A total of 150,000 acre-feet, or 9.3%, of the conservation storage has been reallocated for municipal and industrial water supply. In August 1983, 72,600 acre-feet was reserved for water supply in an integrated hydropower and water supply conservation pool between specified pool elevations. This amount included 50,000 acre-feet which had been contracted for water supply use under the Chief of Engineer's discretionary authority and 22,600 acre-feet reserved for the city of Sherman, Texas, by Public Law 85-146, approved in August 1957. A reallocation of 77,400 acre-feet of hydropower storage to water supply storage was approved by the Assistant Secretary of the Army (Civil Works) in December 1985. A contract for 75,000 acre-feet of this storage was negotiated with the North Texas Municipal Water District. Most, but not all, of the remainder of the 150,000 acre-feet of water supply capacity has been committed by existing or pending contracts with other nonfederal entities.

The Water Resources Development Act of 1986 (Public Law 99-662) authorized the Secretary of the Army to reallocate an additional 300,000 acre-feet of storage in Lake Texoma from hydroelectric power to water supply in increments as needed. This storage is to be shared equally between the states of Oklahoma and Texas. The Act specifies that no payment is required or interest charged to water users for the reallocated storage capacity until it is actually first used for water supply. Until then, the storage may be used for hydropower production.

Belton Reservoir

Belton Reservoir, completed in 1954, and Proctor Reservoir, completed in 1963, are Corps of Engineers flood control, water supply, and recreation projects located on the Leon River in the Brazos River Basin. The Brazos River Authority has contracted for the conservation capacity in both reservoirs. The top of conservation pool at Belton Reservoir was raised 25 feet in 1972, reallocating flood control capacity to water supply (USACE, SWD 1981). The reallocation was facilitated by the flood protection provided by construction of Proctor Reservoir upstream. Belton Reservoir presently contains 644,200 acre-feet of flood control capacity, 365,500 acre-feet conservation capacity, and 76,500 acre-feet sediment reserve. Proctor Reservoir has flood control, conservation, and sediment reserve capacities of 310,100 acre-feet, 31,400 acre-feet, and 32,700 acre-feet, respectively.

Lewisville Reservoir

Ray Roberts Reservoir is a somewhat unusual Corps of Engineers project because its construction, combined with the accompanying Lewisville Reservoir reallocation, provided only additional water supply and recreation. Flood control, the traditional federal purpose, remained essentially unchanged.

The Corps of Engineers completed construction of Lewisville Reservoir in 1954 and Ray Roberts Reservoir in 1987 (USACE, SWD 1988). Both are located on the Elm Fork of the Trinity River, with Ray Roberts Reservoir just downstream of Lewisville Reservoir. The cities of Denton and Dallas are nonfederal sponsors for both projects. The conservation capacities of the two reservoirs are used for municipal and industrial water supply and recreation. Ray Roberts Reservoir has flood control, conservation, and sediment reserve capacities of 260,800 acre-feet, 749,200 acre-feet, and 54,600 acre-feet, respectively. Lewisville Reservoir originally had flood control, conservation, and sediment reserve capacities of 525,200 acre-feet, 436,000 acre-feet, and 20,500 acre-feet, respectively. However, upon completion of Ray Roberts Reservoir, flood control capacity in Lewisville Reservoir, equivalent to the additional flood control capacity provided by Ray Roberts Reservoir, was reallocated to water supply. The reallocation was an integral part of the planning and authorization process leading up to the construction of Ray Roberts Reservoir.

Grapevine Reservoir

Grapevine Reservoir is a Corps of Engineers project completed in 1952 and located on Denton Creek which is a tributary of the Elm Fork of the Trinity River. Roanoke Reservoir is an authorized project to be constructed just upstream of Grapevine Reservoir. The proposed Roanoke Reservoir is in an inactive status. Grapevine Reservoir has flood control, water supply, and sediment reserve capacities of 238,250 acre-feet, 161,250 acre-feet. and 26,000 acre-feet, respectively. The cities of Dallas, Park Cities, and Grapevine have contracted for use of the conservation capacity. Upon construction of Roanoke Reservoir, a planned reallocation in Grapevine Reservoir would increase the conservation capacity from 161,250 acre-feet to 372,100 acre-feet (USACE, SWD 1988).

Wright Patman Reservoir

Likewise, a reallocation of flood control to water supply capacity is planned for Wright Patman Reservoir upon completion of construction of Cooper Reservoir upstream, which is scheduled for 1991. In the interim awaiting completion of Cooper Reservoir, a seasonal rule curve was implemented for Wright Patman in 1968 in which the designated top of conservation pool is raised during certain months of the year to provide additional water supply storage. Wright Patman Reservoir is located on the Sulphur River and has 2,509,000 acre-feet of flood control capacity and 145,300 acre-feet of conservation capacity. Reallocation of 120,000 acre-feet of flood control capacity to water supply upon completion of Cooper Reservoir has been proposed (USACE, SWD 1981).

Sam Rayburn Reservoir

Sam Rayburn Reservoir is located on the Angelina River in east Texas. With a total capacity of 3,977,600 acre-feet, it is the fourth largest reservoir in the state. The conservation pool has a capacity of 1,446,200 acre-feet used primarily for hydroelectric power, recreation, and sediment reserve. The Corps of Engineers completed construction and began impoundment in 1965. A reallocation of 43,000 acre-feet of flood control capacity to water supply for the city of Lufkin was made in 1968. In 1983, the Lower Neches Valley Authority requested the Fort Worth District of the Corps of Engineers to study the feasibility of increasing the conservation storage space in Sam Rayburn Reservoir to supply water for the city of Huntington. A reallocation was determined to be feasible (USACE, FWD 1985 and 1986). Studies indicated that the conservation pool would have to be raised less than 0.1 foot to provide the needed storage. However, the reallocation was rounded to a 0.1 foot raise in the top of conservation pool elevation which involves 11,470 acre-feet of storage capacity. A reallocation of this magnitude was considered to have an insignificant impact on flood control. The proposed reallocation has not yet been implemented.

Waco Reservoir

Waco Reservoir is located on the Bosque River which is a tributary of the Brazos River. The Corps of Engineers completed construction of the project in 1965. Waco Reservoir has flood control, conservation, and sediment reserve capacities of 553,300 acre-feet, 104,100 acre-feet, and 69,000 acre-feet, respectively. The conservation capacity supplies water for the city of Waco.

In March 1979, the Brazos River Authority, in cooperation with the City of Waco, requested that the Fort Worth District investigate the feasibility of increasing the conservation storage capacity in Waco Reservoir to provide a greater dependable water supply yield. A subsequent study by the Corps of Engineers resulted in a recommendation that 47,500 acre-feet, or 8.6 percent, of the flood control capacity be reallocated to water supply (USACE, FWD 1982). The reallocation will raise the top of conservation pool seven feet. The proposed reallocation was approved by the Office of the Chief of Engineers in April 1983. A contract between the Brazos River Authority (BRA) and the federal government for the Waco Reservoir reallocation was executed in September 1984. The contract provides for the BRA to reimburse the cost for relocating recreation facilities plus the allocated value of the water supply storage. The next step in the process is for BRA to provide funds in an escrow account. The Corps of Engineers will then relocate the recreation facilities as required and impound water in accordance with the raised top of conservation pool elevation.

Bardwell Reservoir

Bardwell Reservoir is located on Waxahachie Creek in the Trinity River Basin. The Corps of Engineers initiated impoundment in 1965. The project has flood control, conservation, and sediment reserve capacities of 79,600 acre-feet, 42,800 acre-feet, and 15,240 acre-feet, respectively. The conservation capacity supplies water for the cities of Ennis and Waxahachie. In 1984, the city of Ennis requested that the Fort Worth District study the feasibility of raising the conservation pool at Bardwell Reservoir. The Corps of Engineers investigated a reallocation of 18,072 acre-feet from flood control to water supply (USACE, FWD 1985). The study resulted in a recommendation that additional funds be requested for a more detailed study.

Granger Reservoir

The Corps of Engineers recently investigated a reallocation of flood control to water supply capacity at Granger Reservoir in the Brazos River Basin. This investigation was a part of a study to reevaluate the feasibility of constructing the authorized South Fork Reservoir (USACE, FWD 1986). In regard to a reallocation at the existing Granger Reservoir, it was concluded that further studies should be deferred until water supply needs develop in the study area or definite interest is expressed by a local sponsor.

Lake O' the Pines

A study to evaluate the water resources problems and needs of the Cypress Bayou Basin was recently completed (USACE, FWD 1987a). Reallocation of storage at Lake O' the Pines was investigated as an alternative water supply source. The study concluded that further studies regarding a reallocation should be deferred until water supply needs develop within the study area.

Memorandum of Understanding

A memorandum of understanding (MOU) between the federal government and State of Kansas to facilitate reallocation of storage capacity in Corps of Engineers reservoirs in Kansas is discussed later in this chapter. Development of a similar memorandum of understanding for reallocation of reservoir storage capacity in Texas has been proposed by the water management community in the state. The Fort Worth District of the Corps of Engineers is presently drafting such an agreement for consideration.

Storage Reallocations Nationwide

Holley and Kane (1974) reviewed cases of Congressional reauthorization of federal reservoir projects. Seven cases of changes in authorized storage allocations in existing projects were identified. Four of the cases, involving reallocation of flood control capacity to water supply in (1) Lake Texoma, (2) Wright Patman Reservoir in conjunction with Cooper Reservoir, (3) Grapevine Reservoir in conjunction with Roanoke Reservoir, and (4) Lewisville Reservoir in conjunction with Ray Roberts Reservoir, are discussed above. The other three cases are (1) Alamogorda Dam and Los Esteros Lake in New Mexico involving reduction in sedimentation and transfer of irrigation storage, (2) John Martin Lake in Colorado involving the use of flood control storage for recreation and fish and wildlife, and (3) Cape Fear River Basin in North Carolina involving a reallocation of flood control capacity to water supply.

The National Hydropower Study assessed the potential for increasing hydroelectric power production throughout the nation. Reallocation of storage capacity from flood control to hydropower was one of several potential means for increasing electric energy considered (Davis and Buckley 1984).

Hydrologic Engineering Center Study

The Hydrologic Engineering Center (HEC) recently conducted an investigation, sponsored by the Institute for Water Resources, to identify opportunities for reallocation of storage capacity at Corps of Engineers reservoirs (USACE, HEC 1987). Sixteen reallocation study reports were examined. In addition, discussions were held with Corps of Engineers personnel in district and division offices where reallocation has been or is being considered. Also, a two-day workshop was held in September 1987 which brought together sixty people from various Corps of Engineers offices to discuss a wide-range of topics related to reallocation of reservoir storage. The HEC report also discusses the Memorandum of Understanding between the State of Kansas and Corps of Engineers.

Reports documenting the sixteen reallocation studies listed in Table 2.4 were examined in the HEC study. The table cites the reservoir, location by river and state, Corps of Engineers district office responsible for the reservoir, date of the report documenting the reallocation study, total storage capacity for all purposes contained in the reservoir, and proposed reallocation capacity in both acre-feet and as a percent of the total capacity. All of the reallocations increased the water supply capacity. The last column of Table 2.4 shows the purposes from which capacity was reallocated in order to increase the water supply capacity. The reallocation studies addressed single reservoirs except for the last study listed which was a basinwide study involving a system of several reservoirs (USACE, Little Rock District 1983).

Six of the reallocation studies are for reservoirs in Texas and are discussed in the previous paragraphs. Of the ten reallocations at reservoirs located outside of Texas, six have actually been implemented, and the others have been proposed and studied but not yet implemented. Reallocations at Barren River, Cowanesque, Rathbun, Rough River, Saylorville, and Wister Reservoirs have been implemented.

A review of the sixteen studies and subsequent discussions with Corps of Engineers personnel on other projects resulted in the development of eight general cases to describe the various opportunities which exist for reallocation of storage for municipal and industrial water supply in Corps of Engineers reservoirs (USACE, HEC 1987):

(1) Use of water supply storage not under contract,
(2) Temporary use of storage allocated for future conservation purposes and sediment,
(3) Storage made available by change in conservation demand or purpose,
(4) Seasonal use of flood control space during dry season,
(5) Reallocation of flood control space,
(6) Modification of reservoir rule curves and method of operation,
(7) Raising existing dams and
(8) System operation of Corps and non-Corps reservoirs.

Memorandum of Understanding between USACE and Kansas

The "Memorandum of Understanding between the State of Kansas and the U.S. Department of the Army Concerning the Purchase of Municipal and Industrial Water Supply Storage" was signed by the Assistant Secretary of the Army (Civil

Table 2.4
RESERVOIR REALLOCATION STUDIES

Reservoir	River	State	USACE District	Report Date	Total Storage Capacity (ac-ft)	Actual or Proposed Reallocation (ac-ft)	Actual or Proposed Reallocation (% Total Capacity)	Reallocation to Water Supply from Purpose Below
Bardwell	Trinity	Texas	Fort Worth	Dec 1985	122,392	19,329	15.8	flood control
Barren River	Barren	Kentucky	Louisville	Aug 1965	815,150	681	0.08	permanent pool
Bear Creek	South Platte	Colorado	Omaha	Nov 1984	58,400	18,400	31.5	flood control
Bloomington	Potomac	Maryland	Baltimore	Sep 1983	128,200	none to date		-
Chatfield	South Platte	Colorado	Omaha	Nov 1984	231,400	22,700	9.8	flood control
Cowanesque	Susquehanna	Pennsylvania	Baltimore	Jan 1985	86,700	24,335	28.1	flood control
Texoma	Red	Oklahoma & Texas	Tulsa	1985	4,281,000	77,400	1.8	hydropower
Granger	San Gabriel	Texas	Fort Worth	Oct 1986	200,100	65,950	33.0	flood control
Lake o' the Pines	Cypress	Texas	Fort Worth	Feb 1987	838,300	50,000	6.0	flood control
Rathbun	Chariton	Iowa	Kansas City	May 1985	528,000	3,340	0.6	recreation
Rough River	Rough	Kentucky	Louisville	1966 & 78	334,380	270	0.08	conservation
Sam Rayburn	Angelina	Texas	Fort Worth	Jun 1986	3,997,600	2,588	0.2	hydropower
Saylorville	Des Moines	Iowa	Rock Island	1981 & 82	676,000	14,900	2.2	flood control
Waco	Brazos	Texas	Fort Worth	Oct 1982	657,400	47,500	7.2	flood control
Wister	Poteau	Oklahoma	Tulsa	Feb 1987	410,640	4,400	1.1	conservation
*	White	Arkansas & Missouri	Little Rock	Oct 1983	-	none to date		-

*The White River Lakes Study, Arkansas and Missouri, includes Table Rock, Bull Shoals, Norfolk, Beaver, Greers Ferry, and Clearwater Reservoirs.

Source: USACE, HEC (1987)

Works) and Director the Kansas Water Office on December 11, 1985. The purpose of the Memorandum of Understanding (MOU) was to facilitate reallocation of storage capacity in Corps of Engineers reservoirs from low flow augmentation for water quality purposes to municipal and industrial water supply.

The Corps of Engineers has constructed 17 multipurpose reservoirs in Kansas. All the reservoirs contain flood control storage capacity. Several of the reservoirs contain conservation storage capacity for low flow augmentation to dilute pollution in the river at downstream locations. With the passage of the Federal Water Pollution Control Act Amendments of 1972, the emphasis in wastewater management shifted from dilution to point-source treatment and prevention. This lessened the need for water quality storage in reservoirs and created the opportunity to reallocate some of the existing water quality storage to other purposes. The withdrawal by irrigators and other users of water released for augmenting low flows for water quality was also a major issue in Kansas. The water quality releases from Corps of Engineers reservoirs did not fulfill the intended purpose due to being depleted by diversions by irrigators and other users.

Studies by a state task force on water resources, the Corps of Engineers, and others resulted in development and execution of the Kansas Memorandum of Understanding (MOU). The MOU provides for the Corps of Engineers to conduct studies on nine reservoirs to determine the feasibility of reallocating storage from water quality or other conservation purposes to water supply. The State of Kansas has a right of first refusal of all storage that may be reallocated to water supply. Under provisions of the MOU, the state established a water assurance program and an escrow account to be used for purchases of storage. The state also participates in the cost of each reallocation study.

A key provision of the MOU is that the purchase price for storage reallocated to water supply is to be computed as if it was authorized originally as municipal and industrial water supply. This approach is different from the Corps of Engineers policy of using the updated cost of storage for determining the charges to the local sponsor for a reallocation. The Secretary of the Army emphasized that the special cost provision in the MOU is due strictly to the unique circumstances of the Kansas water management situation which resulted in the MOU being developed.

Authority for Reallocating Storage Capacity

The Kansas Memorandum of Understanding is a unique agreement pertaining to a particular set of circumstances. In general, such an agreement is not necessary to study and implement storage reallocations. The Office of the Chief of Engineers of the Corps of Engineers has the discretionary authority to approve reallocations of up to the lesser of 50,000 acre-feet or 15% of the total storage capacity associated with federal purposes in a project. Congressional authorization would normally be required for larger reallocations in federal reservoirs. Obtaining Congressional authorization can be a lengthy process. Several examples of Congressionally authorized storage reallocations are cited above. Reallocations can be studied as a part of basinwide or other feasibility studies, or Congressional authorization could be obtained specifically for a reallocation study. Section 216 of Public Law 91-611, passed in December 1970, authorized a program for reviewing completed projects. Storage reallocation could be considered in conjunction with project review conducted under Section 216 authority. Corps of Engineers studies of the feasibility of storage reallocation are normally initiated in response to a specific request by a nonfederal water management entity.

Cost reimbursement is a major consideration in implementing storage reallocations. The Water Supply Act of 1958 authorized inclusion of municipal and industrial water supply storage in federal reservoir projects subject to reimbursement by nonfederal sponsors of all costs allocated to water supply. Likewise, reallocation of flood control capacity to water supply requires payment to the federal government by a nonfederal sponsor of associated costs. The costs include both the costs associated with implementation of the reallocation, such as relocation of recreation facilities and roads to be inundated by the pool raise, and a portion of the cost of the original project. All of the cost of implementing the reallocation are charged to the nonfederal sponsor. The Corps of Engineers has formulated three alternative approaches for assigning a portion of the cost of the original project to the reallocated storage capacity. The alternative approaches are based on (1) flood control and/or other benefits foregone, (2) replacement costs, or (3) a ratio of the storage capacity. The third approach has generally been adopted for storage reallocations in Texas. The ratio of the reallocated storage capacity to the total usable storage capacity is applied to the total project cost updated to present price levels by an appropriate price level index.

Appropriation and use of surface water in Texas requires a permit from the Texas Water Commission. Water rights diversions and storage capacities are typically based on initial reservoir site topography prior to sedimentation. If a storage reallocation can be shown to replace firm yield and storage capacity loss due to sedimentation, the water right previously granted for the original project might still cover the reallocation. Otherwise, the nonfederal water supply sponsor can obtain additional water rights through the normal permit application process.

CHAPTER 3
SEASONALLY VARYING FACTORS AFFECTING RESERVOIR OPERATION IN TEXAS

The feasibility of seasonal rule curve operation depends upon the seasonal characteristics of the various factors affecting reservoir operation. This chapter presents a compilation of pertinent data and accompanying discussion regarding the seasonality of factors affecting reservoir operation in Texas.

Risk of flooding, flood damage susceptibility, water supply demands, and water availability vary seasonally. Unlike many parts of the world in which almost all floods occur in a distinct season of the year, floods can occur at any time in Texas. However, the likelihood of flooding is higher during certain months than in others. Seasonal variations in flood damage susceptibility are related primarily to agricultural activities. The extent of damage depends upon whether the flood occurs during the growing season. The majority of the flood control benefits attributed to major reservoirs in Texas are related to agriculture. Municipal as well as agricultural water demands are highly seasonal. The seasonality of municipal demands is due largely to summer lawn watering. Hydroelectric power demands are also higher during the summer. Most reservoir recreation occurs during the summer. The availability of streamflow for water supply purposes is relatively low during the summer when the demands are highest.

Precipitation

Texas Weather

Seasonally varying factors affecting reservoir operation are generally related to weather. The climate of Texas is characterized by variations in the weather, both geographically and temporally. Variations in precipitation and temperature are determined primarily by the confluence of warm, moist Gulf air and relatively cool, dry air from the continental United States. The western half of the state has a semi-arid, continental-type climate, characterized by rapid and drastic fluctuations in temperature. The remainder of the state is influenced by a humid, subtropical climate, having moderate temperatures.

Data on Texas climate and weather is available from the Office of the State Climatologist, located at Texas A&M University. This includes a summary of 100 years of Texas weather by Griffiths and Ainsworth (1981) which was the primary source for the precipitation data cited below. The Texas Almanac and Industrial Guide (A.H. Belo Corp., 1987) also includes a summary of weather data prepared by the State Climatologist. Bomar (1983) provides a detailed description of Texas weather. The Texas Department of Water Resources (1983) also provides climatic data.

Practically all the precipitation in the state originates as moisture-laden clouds from the Gulf of Mexico. Although some snow does occur, most precipitation is in the form of rain. Mean annual precipitation statewide is about 28 inches. The wettest year of this century was 1941 with an average rainfall of 42.6 inches. The driest year was 1917 with only 14.3 inches. Statewide average, minimum, and maximum monthly precipitation during the period 1931 through 1979 are tabulated Table 3.1. From a statewide perspective, May is the wettest month. Winter is the driest time of the year.

Table 3.1
MONTHLY STATEWIDE PRECIPITATION
(Period 1931-1979)

Month	Statewide Precipitation (inches)		
	Average	Minimum	Maximum
Jan	1.7	0.2	3.9
Feb	1.7	0.3	2.9
Mar	1.6	0.3	3.2
Apr	2.5	0.8	6.7
May	3.4	1.2	7.1
Jun	2.8	0.7	5.6
Jul	2.4	0.9	5.1
Aug	2.4	0.6	5.7
Sep	3.2	0.6	6.9
Oct	2.4	0.0	5.9
Nov	1.7	0.1	5.3
Dec	1.8	0.2	4.0

Source: Griffiths and Ainsworth (1981)

Mean annual precipitation ranges from more than 56 inches at the eastern border to less than eight inches in the most western part of the state. Generally, mean annual precipitation increases from west to east across the state on the average of about one inch every 15 miles, with little variation from north to south. For purposes of identifying climatic types, the state is divided into the ten climatological divisions shown in Figure 3.1. Table 3.2 shows the mean annual precipitation and the average precipitation for the wettest and driest month for each climatological division. The mean precipitation for each month is tabulated in Table 3.3.

Patterns of seasonal precipitation vary considerably for different areas of the state (Orton 1969). Rains generally occur most frequently in late spring as a result of squall-line thunderstorms. Most areas, including most of the High and Low Rolling Plains, Edwards Plateau, North Central, and South Central Texas, show a peak in May. Rainfall in the Pecos Valley, most of southern Texas, the lower Rio Grande Valley, and the coastal region, peaks in September with a secondary peak in May. On the High Plains, particularly the northern portion, a significant percentage of the total annual precipitation occurs during the summer months, following the May peak. Throughout the central part of the state, July and August are relatively dry months. In the mountainous Trans-Pecos area of West Texas, afternoon thundershowers during July, August, and September account for most of the annual rainfall. Throughout most of East Texas, rainfall is fairly evenly distributed throughout the year.

Tropical cyclones, particularly tropical storms and hurricanes, are a perennial threat to the Texas Gulf coastal region during the summer and autumn. Essentially all the tropical cyclones that affect the Texas coast originate in the Gulf of Mexico, Caribbean Sea or in other parts of the North Atlantic Ocean. Hurricanes contribute large quantities of precipitation in addition to producing high winds and storm tides. The hurricane season extends from June to October. The 31 hurricanes that hit the Texas coast in the twentieth century were distributed among months as follows: June, 5 hurricanes; July, 4; August, 11; September, 9; and October, 2 hurricanes.

Although most precipitation in Texas is in the form of rain, snowfall also occurs. Mean annual snowfall varies from essentially zero in south Texas to 15 inches or more in the northern panhandle. Snow melts relatively quickly. Consequently, reservoir operation in the intrastate basins of Texas is not dependent upon snow pack conditions like in other parts of the country. Snow is significant in the Red and Rio Grande Basins which have large watershed areas outside the state.

Precipitation Probabilities

Dugas (1983) performed a statistical analysis of daily precipitation data from 36 stations located throughout the state. The probabilities of various amounts of precipitation being equalled or exceeded during each week of the year are shown in Table 3.4 for a precipitation station at the city of Temple. This station is located in the central portion of the Brazos River Basin in central Texas. The week of April 26 through May 2 is indicated to be the wettest week of the year at this station. There is a 63 percent probability of receiving at least 0.5 inch during this week at this station. The probabilities of receiving at least 1.0 inch and 5.0 inches and 47 percent and

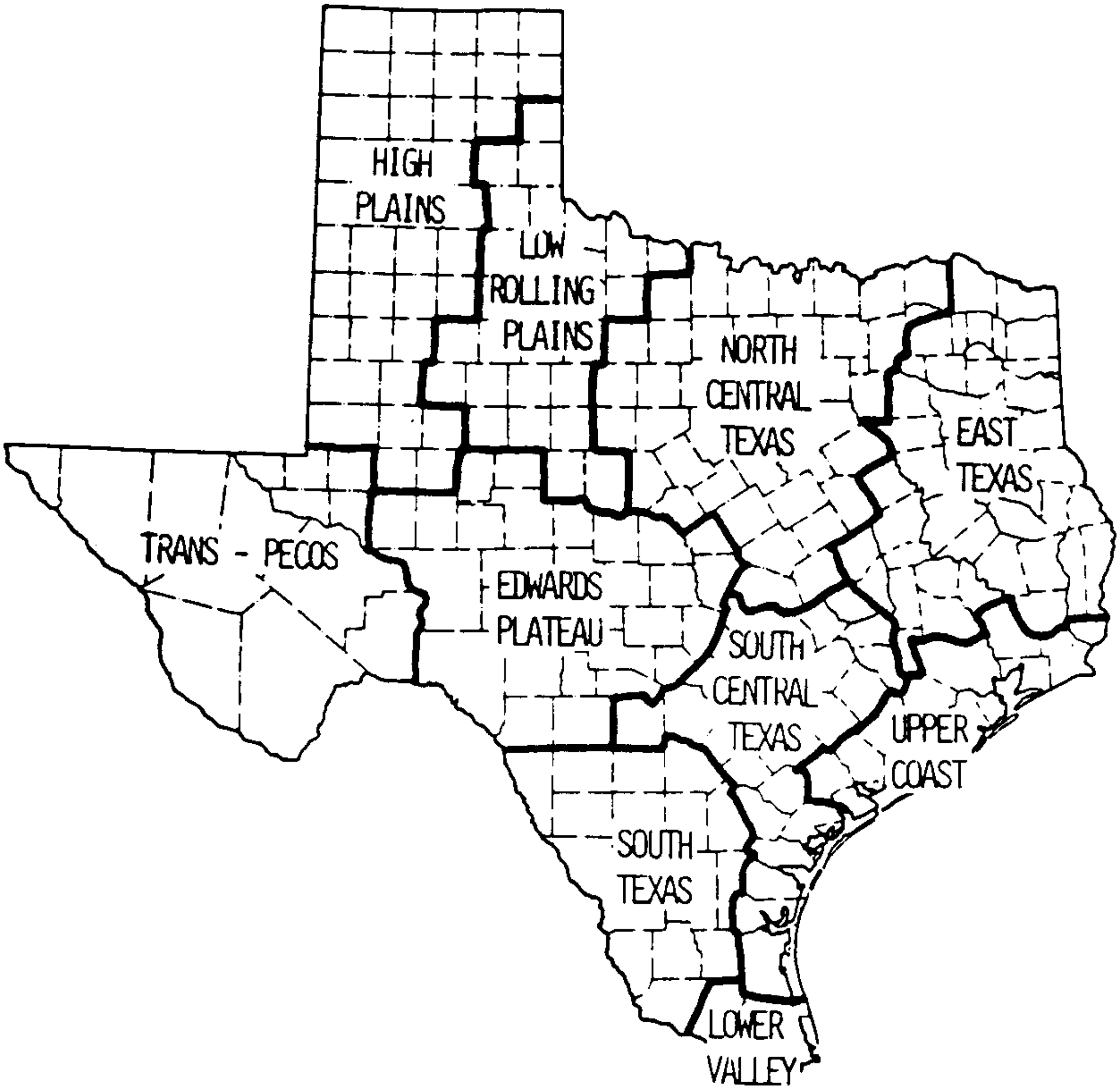


Figure 3.1 **Climatological Divisions**

Table 3.2
MEAN PRECIPITATION BY CLIMATOLOGICAL DIVISION
(Period 1951-1980)

Climatological Division	Mean Annual Precipitation (inches)	Wettest Month		Driest Month	
		Month	Mean Monthly Precipitation (inches)	Month	Mean Monthly Precipitation (inches)
High Plains	17.73	May	2.65	Jan	0.44
Rolling Plains	22.80	May	3.60	Jan	0.75
North Central	32.14	May	4.43	Jan	1.74
East	44.70	May	4.79	Aug	2.73
Trans-Pecos	11.65	Sep	2.05	Dec	0.38
Edwards Plateau	23.52	Sep	3.36	Jan	0.94
South Central	34.03	Sep	5.07	Mar	1.55
Upper Coast	45.93	Sep	6.19	Mar	2.27
Southern	22.91	Sep	4.06	Mar	0.71
Lower Valley	24.73	Sep	4.96	Mar	0.64

Table 3.3
MEAN PRECIPITATION BY CLIMATOLOGICAL DIVISION
(Period 1951-1980)

Location	Jan	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Annual
High Plains	.44	.60	.81	1.16	2.65	2.61	2.51	2.33	2.00	1.50	.67	.45	17.73
Rolling Plains	.75	.88	1.16	2.01	3.60	2.72	2.11	2.28	3.07	2.31	1.09	.82	22.80
North Central	1.74	2.00	2.12	3.75	4.43	2.83	2.13	2.12	3.67	3.19	2.26	1.90	32.14
East	3.47	3.43	3.37	4.83	4.79	3.69	3.03	2.73	4.25	3.38	3.79	3.94	44.70
Trans Pecos	.40	.42	.45	.42	1.01	1.26	1.81	1.84	2.05	1.11	.50	.38	11.65
Edwards Plateau	.94	1.33	1.16	2.21	3.10	2.34	1.74	2.36	3.36	2.63	1.33	1.02	23.52
South Central	2.01	2.32	1.55	2.98	4.05	3.43	1.93	2.82	5.07	3.39	2.41	2.07	34.03
Upper Coast	3.26	3.10	2.27	3.35	4.37	4.56	3.86	4.22	6.19	3.73	3.49	3.53	45.93
Southern	1.02	1.23	.71	1.75	3.04	2.55	1.43	2.46	4.06	2.47	1.24	.95	22.91
Lower Valley	1.32	1.26	.64	1.54	2.40	2.88	1.59	2.57	4.96	3.05	1.44	1.08	24.73

Source: **Bomar** (1985)

Table 3.4
PRECIPITATION AMOUNT PROBABILITIES FOR 1-WEEK PERIODS AT TEMPLE

PERIOD BEGINS	PRECIPITATION MEANS, MAXIMUMS, AND PROBABILITIES FOR A 1-WEEK PERIOD													
	MEAN		MAXIMUM		PROBABILITY (%) OF RECEIVING AT LEAST THE FOLLOWING AMOUNTS OF PRECIPITATION									
	MM	IN	MM	IN	MM	0.25	6.4	12.7	25.4	38.1	50.8	76.2	101.6	127.0
					IN	0.01	0.3	0.5	1.0	1.5	2.0	3.0	4.0	5.0
MAR 1	13	0.54	87	3.4		72	53	39	20	10	5	2	1	1
MAR 8	12	0.48	91	3.6		78	51	35	16	8	4	2	1	1
MAR 15	12	0.51	83	3.3		74	50	36	18	9	5	2	1	1
MAR 22	14	0.57	113	4.4		74	53	38	21	11	6	3	1	1
MAR 29	12	0.50	148	5.9		66	46	33	18	10	5	2	1	1
APR 5	19	0.75	93	3.7		77	58	45	27	17	11	4	2	1
APR 12	20	0.82	117	4.6		75	56	45	30	19	13	5	3	2
APR 19	28	1.13	168	6.6		85	69	58	40	28	19	10	5	3
APR 26	35	1.41	177	7.0		83	72	63	47	35	26	15	8	4
MAY 3	23	0.94	126	5.0		85	67	54	35	22	14	6	3	2
MAY 10	29	1.15	164	6.5		83	70	59	42	29	20	10	5	3
MAY 17	29	1.16	202	8.0		77	65	55	40	28	21	11	6	4
MAY 24	25	1.02	279	11.0		75	60	50	35	24	18	9	5	3
MAY 31	18	0.73	84	3.3		67	54	43	27	17	11	4	2	1
JUN 7	13	0.52	115	4.6		56	41	31	19	11	7	3	2	1
JUN 14	18	0.73	144	5.7		56	45	37	26	18	12	6	3	2
JUN 21	20	0.81	208	8.2		63	49	39	28	19	14	7	4	3
JUN 28	13	0.52	132	5.2		60	40	30	18	11	7	3	2	1
JUL 5	10	0.42	101	4.0		51	35	26	15	9	5	2	1	1
JUL 12	12	0.48	107	4.2		50	37	28	17	10	7	3	2	1
JUL 19	11	0.46	243	9.6		55	37	27	16	10	6	3	2	1
JUL 26	12	0.50	201	7.9		49	33	26	17	11	8	4	2	2
AUG 2	10	0.43	117	4.6		42	31	24	16	10	6	3	2	1
AUG 9	10	0.42	104	4.1		51	37	27	15	9	5	2	1	1
AUG 16	11	0.46	128	5.1		55	36	27	16	10	6	3	2	1
AUG 23	14	0.57	75	3.0		62	49	37	22	12	7	3	1	1
AUG 30	15	0.59	109	4.3		63	45	34	21	13	9	4	2	1
SEP 6	24	0.96	303	11.9		69	53	43	31	23	17	9	5	4
SEP 13	19	0.76	178	7.0		66	48	39	26	18	12	6	4	3
SEP 20	17	0.69	123	4.9		70	53	41	25	15	10	4	2	1
SEP 27	14	0.58	221	8.7		53	37	29	20	13	9	5	3	2
OCT 4	16	0.64	185	7.3		60	42	34	22	15	10	5	3	2
OCT 11	20	0.81	202	8.0		55	44	36	26	20	14	8	5	3
OCT 18	17	0.69	128	5.1		60	50	41	26	17	11	4	2	1
OCT 25	18	0.71	112	4.4		65	54	43	27	16	10	3	2	1
NOV 1	17	0.69	85	3.4		62	47	38	25	17	11	5	3	2
NOV 8	15	0.61	126	5.0		61	48	37	23	14	9	3	2	1
NOV 15	17	0.70	192	7.6		70	49	39	25	16	11	5	3	2
NOV 22	20	0.79	165	6.5		65	55	45	30	20	13	5	3	2
NOV 29	19	0.78	283	11.2		68	48	38	26	17	13	7	4	3
DEC 5	17	0.69	121	4.8		71	52	40	25	15	10	4	3	1
DEC 12	17	0.70	102	4.1		67	50	40	26	16	11	4	3	1
DEC 19	10	0.41	63	2.5		61	40	28	14	7	4	2	1	1
DEC 26	12	0.48	68	2.7		66	49	35	16	8	4	1	1	1
JAN 3	10	0.43	73	2.9		67	46	32	14	6	3	1	1	1
JAN 10	13	0.52	94	3.7		70	50	37	19	10	5	2	1	1
JAN 17	14	0.56	128	5.0		68	48	35	20	12	7	3	2	1
JAN 24	8	0.32	53	2.1		69	38	23	9	4	2	1	1	1
JAN 31	14	0.56	95	3.8		75	56	40	20	10	5	2	1	1
FEB 7	15	0.62	85	3.4		70	54	41	23	13	7	3	1	1
FEB 14	15	0.60	75	3.0		79	58	43	21	11	5	2	1	1
FEB 21	16	0.65	145	5.7		69	54	41	24	14	9	3	2	1

Source: Dugas (1983)

4 percent, respectively. The week of January 24 through January 30 is the driest week, with only a 23 percent probability of receiving at least 0.5 inch. The overall magnitude and seasonality of the precipitation probabilities vary significantly between stations located in different regions of the state.

Extreme Rainfall Events

Information provided by Griffiths and Ainsworth (1981) for each year from 1890 through 1980 includes the maximum 24-year precipitation occurring in the state. The Texas Almanac provides 24-hour maximum precipitation amounts for recent years. The frequencies tabulated in Table 3.5 were developed from the maximum 24-hour precipitation measurements at any station for each year from 1890 through 1984. The annual maximum statewide 24-hour precipitation happened to occur at various stations widely dispersed throughout the eastern half of the state during the different years. The frequencies in Table 3.5 were computed by dividing the number of years in which the maximum 24-hour precipitation occurred in a given month by the total number of years covered by the data. In 22.6 percent of the years, the maximum 24-hour precipitation occurred in June. The maximum 24-hour precipitation did not occur in February, March, or December in any of the years. The frequencies can be interpreted as estimates of the likelihood or probability of the maximum 24-hour rainfall in any future year occurring in a certain month.

Table 3.6 is a tabulation of recorded precipitation events in which a station received 15 inches or more during a 24-hour period (Griffiths and Ainsworth 1981). Forty-four percent of these extreme rainfall measurements occurred in the month of September. Most of the other events occurred during the summer months. The data in Table 3.7 are based on official precipitation gage readings. Unofficial measurements of 45 inches of rainfall was reported northwest of Alvin during Tropical Storm Claudette in July 1979 along with several other reports of more than 25 inches near the cities of Freeport and Clear Lake. During a storm in September 1921, more than 38 inches of rain was unofficially reported to have fallen in 24 hours at a point north of Thrall, in Central Texas.

Table 3.8 is a list of rainfall measurements for which a station received 25 inches or more during a month. The extreme rainfall measurements are distributed as follows: January, February, and March-none; April-6%; May-3%; June-12%; July-9%; August-9%; September-47%; October-9%; November-6%; and December-none.

Streamflow

Streamflow data for nine gaging stations are presented in Tables 3.9, 3.10, and 3.11. The selected gaging stations are representative of the major river basins of the state and have relatively long periods of record. The station on the Red River is located just upstream of Lake Texoma. The station on the Rio Grande River is a few miles upstream of its mouth on the Gulf of Mexico. The gaging stations on the other rivers are located about 50 to 100 miles upstream of their mouths on the Gulf. The data in the tables were compiled from Texas Department of Water Resources Report 244 (TDWR 1980). A check of the U.S. Geological Survey published water resources data verified that the record extreme maximum and minimum discharges shown are still valid through 1985.

Table 3.5
FREQUENCY OF THE MAXIMUM ANNUAL 24-HOUR PRECIPITATION STATEWIDE OCCURRING IN EACH MONTH

Month	Frequency (percent)
Jan	2.1
Feb	-0-
Mar	-0-
Apr	5.4
May	14.0
Jun	22.6
Jul	10.7
Aug	8.6
Sep	19.4
Oct	12.9
Nov	4.3
Dec	-0-
Total	100.0

Source: Frequency computed based on maximum 24-hour precipitation amounts for each year from 1890-1984 from Griffiths and Ainsworth (1981) and the Texas Almanac (A. H. Belo, Inc., 1987).

Table 3.6
GAGED RAINFALL EVENTS OF 15 INCHES OR MORE DURING 24 HOURS

Rainfall (inches)	Station	County	Date
29.05	Albany	Shackelford	4 Aug 1978
25.75	Alvin	Brazoria	26 Jul 1979
25.27	Orange	Orange	Sep 1963
25.24	Point Comfort	Calhoun	Jun 1960
25.06	Galveston Airport	Galveston	Sep 1958
25.06	Harleton	Harrison	Apr 1966
25.01	Armstrong	Kenedy	Sep 1967
23.11	Taylor	Williamson	9-10 Sep 1921
21.02	Kaffie Ranch	Jim Hogg	12 Sep 1971
20.70	Hye	Blanco	11 Sep 1952
20.60	Montell	Uvalde	27 Jun 1913
19.29	Danevang	Wharton	27-28 Aug 1945
19.20	Benavides No. 2	Duval	11 Sep 1971
19.03	Austin	Travis	9-10 Sep 1921
18.00	Fort Clark	Kinney	14-15 Jun 1899
17.76	Port Arthur	Jefferson	27-28 Jul 1943
17.47	Blanco	Blanco	11 Sep 1952
16.72	Freeport 2NW	Brazoria	26 Jul 1979
16.05	Smithville	Bastrop	30 Jun 1940
16.02	Hills Ranch	Travis	10 Sep 1921
16.02	Pandale	Val Verde	27 Jun 1954
16.00	Hempstead	Waller	24 Nov 1940
15.87	Anahuac	Chambers	27-28 Aug 1945
15.80	Orange	Orange	18 Sep 1963
15.71	Matagorda	Matagorda	1 May 1911
15.69	Whitsett 2SW	Live Oak	22 Sep 1967
15.65	Houston Airport	Harris	27-28 Aug 1945
15.60	Eagle Pass	Maverick	29 Jun 1936
15.49	Deweyville 5S	Orange	28 Oct 1970
15.20	World's End Ranch	Kerr	2 Aug 1978
15.00	Mercedes	Hidalgo	5 Sep 1933

Source: Griffiths and Ainsworth (1981)

Table 3.7
RECORD EXTREME 24-HOUR RAINFALL FOR SELECTED STATIONS

Location	Record 24-Hour Rainfall Amount (inches)	Date
Abilene	6.78	May 1908
Amarillo	6.75	May 1975
Austin	19.03	Sep 1921
Brownsville	12.19	Sep 1967
Corpus Christi	8.92	Aug 1980
Dallas-Fort Worth	9.57	Sep 1932
Del Rio	8.88	Jun 1935
El Paso	6.50	Jul 1881
Galveston	14.35	Jul 1900
Houston	15.65	Aug 1945
Lubbock	5.82	Oct 1983
Midland-Odessa	5.99	Jul 1961
Port Arthur-Beaumont	17.76	Jul 1943
San Angelo	11.75	Sep 1936
San Antonio	7.28	Sep 1973
Victoria	9.30	Jun 1977
Waco	7.18	May 1953
Wichita Falls	6.22	Sep 1980
Shreveport, Louisiana	7.17	Apr 1953

Source: Texas Almanac (A. H. Belo, Inc. 1987)

Table 3.8
PRECIPITATION STATIONS WHICH HAVE RECEIVED 25 INCHES OR MORE DURING A MONTH

Precipitation (inches)	Station	County	Date
35.70	Alvin	Brazoria	Jul 1979
32.78	Falfurrias	Brooks	Sep 1967
31.61	Freeport 2NW	Brazoria	Sep 1979
31.19	Albany	Shackelford	Aug 1978
30.95	Freeport 2NW	Brazoria	Jul 1979
30.57	Brownsville	Cameron	Sep 1886
29.76	Port Lavaca No. 2	Calhoun	Jun 1960
29.22	Aransas Pass No. 2	San Patricio	Sep 1967
29.19	Whitsett 2SW	Live Oak	Sep 1967
28.96	Deweyville 5S	Orange	Oct 1970
27.94	Weatherford	Parker	May 1884
27.89	Kaffie Ranch	Jim Hogg	Sep 1971
27.65	San Angelo	Tom Green	Sep 1936
26.86	Port Arthur (City)	Jefferson	Jul 1979
26.79	San Augustine	San Augustine	Aug 1915
26.68	Gladewater	Gregg	Apr 1966
26.31	Beaumont Filter Plant	Jefferson	Oct 1970
26.30	Refugio	Refugio	Sep 1971
26.06	Rio Grande City 3W	Starr	Sep 1967
26.01	Galveston	Galveston	Sep 1885
26.00	Cibolo Creek	Karnes	Sep 1967
25.87	Taylor	Williamson	Sep 1921
25.67	Pandale	Val Verde	Jun 1954
25.59	Sinton	San Patricio	Sep 1967
25.57	Hempstead	Waller	Nov 1940
25.54	New Gulf	Wharton	Jun 1960
25.34	Splendora	Montgomery	Oct 1949
25.30	Rockland	Tyler	Aug 1915
25.30	Goose Creek (Baytown)	Harris	Nov 1946
25.27	Orange (Gulf States Utilities)	Orange	Sep 1963
25.24	Point Comfort	Calhoun	Jun 1960
25.06	Galveston Airport	Galveston	Sep 1958
25.06	Harleton	Harrison	Apr 1966
25.01	Armstrong	Kenedy	Sep 1967

Oct 1949 - 8 other stations reported 20 inches or more
Sep 1967 - 17 other stations reported 20 inches or more

Source: Griffiths and Ainsworth (1981)

Table 3.9
SELECTED STREAM GAGE STATIONS

River	Nearest City	Gage Number	Rept 244 Period of Record	Drainage Area (sq mi)	Mean Discharge (cfs)	Minimum Monthly Discharge	
						Date	Discharge (cfs)
Rio Grande	Brownsville	08457500	1934-1975	176,333	2,200	Jun/Jul 53	-0-
Nueces	Three Rivers	08210000	1916-1975	15,600	855	several	-0-
Guadalupe	Victoria	08176500	1935-1975	5,198	1,740	Aug 56	38
Colorado	Columbus	08161000	1917-1975	41,070	3,250	Aug 17	130
Brazos	Richmond	08114000	1903-1905 1923-1975	45,007	7,320	Aug 34	144
Trinity	Romayor	0866500	1925-1975	17,186	7,260	Aug 56	130
Neches	Evandale	08041000	1905-1906 1922-1975	7,951	6,100	Nov 56	108
Sabine	Ruliff	08030500	1925-1975	9,329	8,230	Oct 56	290
Red	Gainesville	07316000	1937-1975	30,782	2,800	Jan 40	84

Source: TDWR Report 244

Table 3.10
MAXIMUM STREAMFLOW AT SELECTED GAGE STATIONS

River								
Rio Grande	Nueces	Guadalupe	Colorado	Brazos	Trinity	Neches	Sabine	Red
Peak Instantaneous Discharge (date/cfs/percent of mean discharge)								
8 Oct 45 31,700 1,444	23 Sep 67 141,000 16,486	3 Jul 36 179,000 10,301	18 Jun 35 190,000 5,847	6 Jun 29 123,000 1,680	9 May 42 111,000 1,528	11 May 44 92,700 1,509	22 May 53 121,000 1,469	9 Jun 41 168,000 6,009
Six Largest Mean Monthly Discharges (date/percent of mean discharge)								
Oct 41 1,077	Jun 35 2,909	Jul 36 1,081	May 22 1,275	May 57 1,075	Apr 45 892	May 44 832	May 53 817	May 57 1,742
Sep 42 1,009	Sep 67 2,727	May 41 762	Jun 35 912	Jun 57 786	May 57 870	May 53 781	Apr 45 677	Jun 41 1,535
Sep 44 932	Oct 71 1,646	May 72 717	May 57 868	May 05 775	May 42 852	Dec 40 743	Dec 40 586	Oct 41 1,135
Jun 35 877	Aug 71 1,257	Oct 73 619	Jul 38 806	May 35 749	May 66 729	May 22 668	May 44 575	May 41 1,074
Sep 38 789	Oct 19 1,161	Oct 60 541	May 35 744	Dec 40 736	May 35 689	May 23 654	May 57 499	Apr 42 932
Oct 71 670	Oct 46 978	Sep 67 530	May 41 738	May 44 635	May 44 687	May 35 648	Apr 69 398	Jun 57 738

Source: TDWR Report 244

Table 3.11
MEAN MONTHLY STREAMFLOW AS A PERCENTAGE OF MEAN ANNUAL STREAMFLOW

River :	Rio Grande :	Nueces :	Guadalupe :	Colorado :	Brazos :	Trinity :	Neches :	Sabine :	Red
Month :	Mean Monthly Discharge As A Percent of Mean Annual Discharge								
Jan	5.1	3.1	7.4	6.2	8.2	10.2	12.7	14.2	2.6
Feb	4.2	3.5	7.9	6.1	8.7	9.7	12.7	13.4	3.7
Mar	3.8	3.1	7.3	6.1	9.6	11.9	14.3	14.0	5.2
Apr	3.3	5.7	8.6	9.3	10.4	11.6	14.1	12.7	9.4
May	7.6	14.4	14.2	16.0	18.8	18.6	15.6	12.7	23.0
Jun	9.2	15.9	11.1	12.8	11.9	12.0	8.9	8.8	19.2
Jul	8.9	10.3	8.7	9.0	5.8	4.7	4.0	4.4	6.1
Aug	8.0	5.7	4.0	5.2	2.8	1.8	2.1	3.2	4.2
Sep	18.8	17.7	8.0	8.3	4.2	2.3	1.7	2.4	7.2
Oct	18.4	14.4	8.9	8.9	6.3	3.8	2.1	2.1	10.6
Nov	7.3	4.0	7.4	6.6	5.9	5.4	3.9	3.8	5.5
Dec	5.5	2.1	6.6	5.5	7.5	8.0	7.8	8.2	3.2

Source: TDWR Report 244

The selected gaging stations are identified in Table 3.9. The last two columns show the minimum mean monthly discharges which have occurred during the period-of-record at each gage. The Rio Grande River had no flow during June and July 1953. The Nueces River recorded zero flow during several months. The mean monthly discharges for the extreme low flow months at the other stations are very small compared to the mean discharges shown in the sixth column. The extreme low flow months occurred in August for the Guadalupe, Colorado, Brazos, and Trinity Rivers. Record low flows occurred in November, October, and January for the Neches, Sabine, and Red Rivers, respectively.

The maximum instantaneous discharge recorded at each of the selected gage stations are tabulated in Table 3.10. The peaks on the nine rivers were all caused by different flood events in different years. The record instantaneous peak discharges on the Rio Grande, Nueces, and Guadalupe Rivers occurred in the months of October, September, and July, respectively. The peak discharges on the other rivers occurred in May and June. The largest peak discharge to occur at the nine stations was 190,000 cfs on the Colorado River on June 18, 1935. The 190,000 cfs was 5,847 percent of the mean discharge at this gage.

Table 3.10 also contains a tabulation of the six largest mean monthly discharges recorded at each gage. Mean monthly discharges are expressed as a percent of the mean discharge over the period-of-record, as shown in the sixth column of Table 3.9. The high flow months on the Rio Grande and Nueces Rivers occur primarily in the Fall. For the Colorado, Brazos, Trinity, Neches, and Sabine Rivers, high flows tend to occur most often in May.

The mean monthly streamflow averaged over the period-of-record for each month is shown in Table 3.11 as a percentage of the mean annual streamflow. On the Rio Grande and Nueces Rivers, the highest streamflow means are in October. May is the highest mean streamflow month on the other rivers. August has the lowest mean flow on the Guadalupe, Colorado, Brazos, Trinity, and Neches Rivers. October has low mean flows on the Neches and Sabine Rivers. December has the lowest mean flow on the Nueces and Red Rivers. The low mean flow on the rio Grande is in April.

The seasonal characteristics of streamflow at the Brazos River gage at the City of Richmond are further illustrated in Table 3.12. The minimum, maximum, and mean streamflow for each month over the period-of-record are shown. The last two columns of Table 3.12 show the frequency for which the annual maximum and minimum monthly flow occurs in each month. During the 65 year period-of-record, May had the highest streamflow of the year during 36.9 percent of the years. There were no years in which July or August had the highest streamflow. The lowest monthly streamflow was in August for 20 percent of the years.

Reservoir Evaporation

Evaporation losses are an important consideration in the operation of reservoirs for conservation purposes. Reservoir evaporation in Texas ranges from 50 inches per year in East Texas to 80 inches per year in the Trans-pecos region. In East Texas, rainfall rates are high enough such that the net evaporation minus rainfall is near zero. In the western part of the state where evaporation rates are extremely high and rainfall rates low, evaporation is a serious detriment to reservoir development.

Table 3.12
MONTHLY STREAMFLOW DATA FOR BRAZOS RIVER AT RICHMOND
(Period 1903-1905 and 1928-1984)

Month	Minimum Flow (ac-ft)	Maximum Flow (ac-ft)	Mean Flow		Annual Frequency	
			(ac-ft)	(% annual)	Maximum (%)	Minimum (%)
Jan	33,380	2,237,000	412,425	8.0	10.8	7.7
Feb	34,400	1,932,000	449,735	8.7	4.6	3.1
Mar	27,390	2,194,000	27,390	9.4	7.7	4.6
Apr	27,000	2,493,000	545,074	10.5	9.2	6.2
May	67,660	4,747,000	963,504	18.6	36.9	1.5
Jun	35,900	3,472,000	638,954	12.3	10.8	-0-
Jul	13,600	1,307,000	310,156	6.0	-0-	1.5
Aug	8,670	718,200	147,532	2.9	-0-	20.0
Sep	24,650	1,181,000	209,436	4.0	1.5	18.5
Oct	12,470	1,769,000	322,165	6.2	6.2	12.3
Nov	24,780	1,926,000	304,880	5.9	6.2	16.9
Dec	29,510	3,251,000	382,414	7.4	6.2	7.7

Source: USGS streamflow data file

The Texas Water Development Board has developed monthly gross and net reservoir evaporation rates for the period January 1940 through December 1984, which cover the state on a one-degree quadrangle basis. These data files are described by TWDB Report 64 (Kane 1967). Additional information regarding reservoir evaporation data is provided by Doughtery (1975). The TWDB estimated evaporation rates from pan evaporation measurements, along with appropriate pan coefficients. The TWDB reservoir evaporation rates incorporate the limited available data regarding monthly pan coefficients.

Table 3.13 shows the seasonal variation in TWDB gross evaporation rates for four quadrangle locations. Monthly evaporation for each month is expressed as a percent of the average evaporation rate for the 1940-1984 period-of-record. Quadrangle F-10 is located in Central Texas and the Brazos River Basin, extends from Whitney Reservoir to Stillhouse Hollow Reservoir, and encompasses Waco and Belton Reservoirs. Quadrangle F-13 is located in South Texas, just north of the City of Corpus Christi, and encompasses Lake Corpus Christi. Quadrangle D-6 is located in the High Plains of Northwest Texas and includes the City of Lubbock. Quadrangle I-10 is in East Texas and includes Sam Rayburn Reservoir. As indicated in Table 3.13, evaporation rates during the summer months are three times greater than rates during the winter months.

Demands for Reservoir Capacity

Municipal, industrial, and agricultural water demands are highest during the hot summer months of June, July, and August. Seasonal variations are illustrated by the water use distribution factors developed by the Texas Water Commission for the Brazos River Basin, which are discussed in Chapter 6 and tabulated in Table 6.2.

The majority of the flood control benefits achieved by the major reservoirs in Texas are related to agriculture. The extent of damage depends upon whether the flood occurs during the growing season of the crops. A flood of a given magnitude may cause several times more dollar damages if it occurs in the summer than in the winter.

Hydroelectric power plays a relatively minor role in the overall production of electrical energy in Texas. However, hydroelectric power generation is major purpose of a number of reservoirs in the state. Hydroelectric power is used primarily for peak loads. Hydroelectric power generation is significantly higher during the summer months than the remainder of the year.

Reservoir recreation is very popular in the state. Recreationists demand a relatively high constant pool level, particularly during the summer recreation season.

Floods

Due to the variety in climate and physiography, flood characteristics vary between different areas of the state. In the east, where the annual rainfall is highest, broad flat valleys are densely covered with timber and brush. Streams have gentle slopes, limited capacity, and follow meandering courses. Intense general rainfalls in this area produce slow-moving floods which inundate floodplains for prolonged periods of time. In central and western

Table 3.13
MONTHLY VARIATION OF RESERVOIR EVAPORATION RATES

Month	Quadrangle F-10	 F-13	 D-6	 I-10
	Mean Monthly Evaporation As A Percent of Mean for All Months			
Jan	46	50	41	54
Feb	48	52	48	54
Mar	69	71	79	72
Apr	79	82	100	83
May	95	104	116	103
Jun	128	127	146	126
Jul	166	152	157	152
Aug	175	160	154	158
Sep	139	133	128	129
Oct	111	116	101	111
Nov	79	80	70	83
Dec	56	61	53	65

regions of the state, steep slopes, sparse vegetation, and relatively impervious ground result in flash floods. The high-peak, short-duration floods can be devastating in terms of property damage and loss of life. Floods in the flat coastal areas are caused by hurricanes, inland rains, and insufficient natural drainage. Rapid urbanization in the watersheds of many streams throughout the state is significantly increasing runoff rates.

The Texas Almanac and Industrial Guide (A.H. Belo Corp. 1987) contains a list of exceptionally destructive storms in Texas since 1766 which was compiled from data available for the Environmental Data and Information Service of the National Oceanic and Atmospheric Administration. The list includes floods, hurricanes, tornadoes, blizzards, and icestorms. Griffiths and Ainsworth (1981) also provide descriptions of past severe storm events in the state. Information from the Texas Almanac is summarized in the abbreviated descriptions of major floods occurring this century presented below. Dollar damages are as estimated at the time of the storm, without price level adjustments for inflation.

The 44 extreme flood events cited below are distributed among months of the year as follows: January, 1 flood; February, none; March, 2; April, 6; May, 6; June, 7; July, 3; August, 2; September, 10; October, 3; November, 2; and December, 2 floods. Thus, 23 percent of the floods occurred in September and 43 percent occurred in April, May, and June.

June 27-July 1, 1899 - A storm centered over the Brazos River Watershed resulted in an average of 17 inches of rain over an area of 7,000 square miles. At Turnersville, 33 inches of rain was recorded in three days. Between 30 and 35 lives were lost. Property damage was estimated at $9,000,000.

April 5-8, 1900 - A storm began in two centers, over Val Verde County on the Rio Grande River and over Swisher County in the High Plains, and converged in the vicinity of Travis County, causing disastrous floods on the Colorado, Brazos, and Guadalupe Rivers. McDonald Dam on the Colorado River at Austin was destroyed. A wall of water swept through Austin killing at least 23 people. Property damage was estimated at $1,250,000.

May 22-25, 1908 - This rainstorm was unique because it originated on the Pacific coast. It moved first into North Texas and thence to Central Texas, precipitating as much as ten inches. Heaviest floods were in the upper Trinity Basin, but flooding was general as far south as the Nueces Basin. Property damage exceeded $5,000,000 and 11 lives were lost in the Dallas vicinity.

December 1-5, 1913 - A rainstorm formed over Central Texas and spread both southwest and northeast with precipitation of 15 inches at San Marcos and 11 inches at Kaufman. Floods caused loss of 177 lives and $8,541,000 damage.

April 20-26, 1915 - A rainstorm originated over Central Texas and spread into North and East Texas with precipitation up to 17 inches, causing flooding on the Trinity, Brazos, Colorado, and Guadalupe Rivers. More than 40 lives were lost and property damage was $2,330,000.

September 8-10, 1921 - Probably the most severe rainstorm in Texas history entered Mexico as a hurricane from the Gulf and moved northeasterly across Texas. Torrential rains caused record floods in Bexar, Travis, Williamson, Bell, and Milam Counties, killing 215 persons and causing property losses of over $19,000,000. Five to nine feet of water stood in downtown San Antonio. A total of 24 inches of rain was measured in Taylor in 35 hours. The greatest 18-hour rainfall recorded in United States history, 36.4 inches, fell in Thrall in Williamson County.

April 23-28, 1922 - A rainstorm entered Texas from the west and moved from the Panhandle to North Central and East Texas. Rains up to 12.6 inches over Parker, Tarrant, and Dallas Counties caused severe floods on the upper Trinity River at Fort Worth. Eleven lives were lost. Damage was estimated at $11,000,000.

May 24-31, 1929 - A rainstorm began over Caldwell County and spread over much of central and coastal Texas with a maximum rainfall of 12.9 inches, causing floods in the Colorado, Guadalupe, Brazos, Trinity, Neches, Sabine Rivers. Much damage occurred in Houston from overflow of bayous. Damage was estimated at $6,000,000.

June 30-July 2, 1932 - Torrential rains fell over the upper watersheds of the Nueces and Guadalupe River, causing destructive floods. Seven persons drowned. Property losses exceeded $500,000.

July 22-25, 1933 - A tropical storm moved very slowly from Freeport across eastern Texas and into Louisiana. Rainfall averaged 12.50 inches over an area of about 25,000 square miles. Twenty inches or more fell in a small area of eastern Texas and western Louisiana surrounding Logansport. Property damage was estimated at $1,147,790.

September 15-18, 1936 - Excessive rains over the North Concho and Middle Concho Rivers caused a sharp rise in the Concho River which overflowed San Angelo. Much of the business district and 500 homes were flooded. Four people drowned and property losses were estimated at $5,000,000. Four-day storm rainfall at San Angelo measured 25.2 inches of which 11.8 inches fell in one day.

September 8-10, 1952 - Heavy rains over the Colorado and Guadalupe River watersheds caused loss of 5 lives and several million dollars of property damages including 17 homes destroyed and 454 damaged.

June 26-28, 1954 - Hurricane Alice moved in from the Gulf south of Brownsville up the Rio Grande River. Heaviest rains were in the Langtry-Sheffield-Ozona area, where as much as 27.1 inches of rain fell in 48 hours near Pandale. This resulted in the greatest flood on the middle Rio Grande since June 1865. Rises of 50 to 60 feet, or 30 to 40 feet above flood stage, within 48 hours, occurred at Eagle Pass and at Laredo. An 86-foot wall of water in the Pecos River canyon washed out the highway bridge constructed 50 feet above the river. The international bridge at Laredo was washed out. Most of the deaths and severe property damage were in Mexico.

April-May 1957 - Torrential rains caused flooding throughout the area east of the Pecos River to the Sabine River during the last 10 days of April causing 17 deaths and destroying several hundred homes. During May more than 4,000 people were evacuated from unprotected lowlands on the West Fork of the Trinity River above Fort Worth and along creeks in Fort Worth. Twenty-nine houses at

Christoval and 83 houses at San Angelo were damaged. Five persons were drowned in floods in South Central Texas.

October 28, 1960 - Rains of 7-10 inches fell in South Central Texas. Eleven people drowned in flash floods. About 300 families in Austin were driven from their homes. Damage in Austin was estimated at $2,500,000.

September 7, 1962 - Rainfall of up to 11 inches in three hours fell over the Big Fossil and Denton Creek watersheds in the vicinity of Fort Worth. Extensive damage from flash flooding occurred in Richland Hills and Haltom City.

September 16-20, 1963 - Hurricane Cindy caused rains of 15 to 23.5 inches to fall in portions of Jefferson, Newton, and Orange Counties resulting in $11,600,000 of property damage.

September 21-23, 1964 - Flash flooding on the Trinity River and its tributaries in Collin, Dallas, and Tarrant Counties resulted in two drownings and an estimated $3,000,000 property damage.

June 11, 1965 - Torrential rains of up to 8 inches in two hours near Sanderson caused a major flash flood that swept through the town. Twenty-six people drowned and property losses were estimated at $2,715,000.

April 22-29, 1966 - Twenty to 26 inches of rain fell in portions of Wood, Smith, Morris, Upshur, Gregg, Marion, and Harrison Counties. Nineteen people drowned in the rampaging rivers and creeks that swept away bridges, roads, and dams, and caused an estimated $12,000,000 damage.

September 18-23, 1967 - Hurricane Beulah moved inland near the mouth of the Rio Grande River. Rains of 10 to 20 inches over much of the area south of San Antonio resulted in record-breaking floods. An unofficial gaging station at Falfurrias registered 36 inches of rainfall. Also 1.4 million acres were inundated.

September 9-13, 1971 - Hurricane Fern caused 10 to 26 inches of rain in the Coastal Bend region. The resulting flooding killed two people and caused $30,231,000 of damages.

May 11-12, 1972 - A rainstorm in South Central Texas resulted in 17 drownings at New Braunfels and one drowning at McQueeney. Property damage was $17,500,000.

June 12-13, 1973 - From 10 to 15 inches of rain fell in southeastern Texas. Ten people drowned. Over $50,000,000 in property and crop damage occurred.

November 23-24, 1974 - Flash flooding in Central Texas killed 13 people and caused $1,000,000 in property damage.

January 31-February 1, 1975 - Flash flooding in Nacogdoches County resulted in 3 deaths and over $5,000,000 in property damage and 40 people injured. Four deaths were caused by drowning.

June 15, 1976 - Rains in excess of 13 inches in Harris County caused damage estimated at near $25,000,000. Eight deaths were storm-related including three drownings.

March 27, 1977 - Heavy rains were responsible for five drownings and over $1,000,000 damage in Tarrant, Somervell, and Dallas Counties.

March 26, 1978 - Four people drowned and 15 others were injured as 10 inches of rain fell in less than two hours west of Canyon, sending a wall of water through Palo Duro Canyon.

August 1-4, 1978 - Remnants of tropical storm Amelia caused some of the worst flooding of this century. As much as 30 inches of rain fell near Albany in Shackelford County, where six drownings were also reported. Bandera, Kerr, Kendall, and Gillespie Counties were also affected with 27 people drowned and damages of at least $50,000,000.

July 24-25, 1979 - Tropical storm Claudette caused over $750,000,000 in property and crop damages but few injuries. Near Alvin, 43 inches of rain fell setting a new state record for a 24-hour period.

September 18-20, 1979 - Coastal flooding occurred as 18 inches of rain fell in 24 hours at Aransas Pass and also as 13 inches fell at Rockport.

August 9-11, 1980 - Hurricane Allen hit south Texas. Over 20 inches of rain fell in extreme south Texas.

September 5-8, 1980 - Hurricane Danielle brought rain and flooding to Southeast and Central Texas. Seventeen inches fell at Port Arthur and 25 inches near Junction.

May 24-25, 1981 - Severe flooding in Austin claimed 13 lives, injured about 100 and caused $40,000,000 in damages. Up to 5.5 inches of rain fell in one hour just west of Austin.

May 10-13, 1982 - Heavy rains from a slow-moving cool front caused flash floods throughout North Central and northern East Texas. Rainfall of 5-8 inches within a 10-hour period resulted in raging floodwater entering more than 2,100 homes in and near Wichita Falls, forcing more than 5,000 residents to flee and property damage of about $25,000,000. General rains of 10 to 12 inches caused widespread urban flooding north and northeast of the Dallas-Fort Worth area.

December 24, 1982 - Rains of up to 15 inches occurred in Southeast Texas.

April 27-28, 1985 - Intense thunderstorms covered much of North Texas. About 10 inches of rain fell in two hours near Rockwall. Eight people drowned.

June 5-6, 1985 - Heavy rains in the Hill Country resulted in serious flash flooding.

November 11, 1985 - Serious flooding resulted from heavy rains over a broad area of Southeast Texas. Twenty-one inches fell near Garwood.

October 2-5, 1986 - Widespread, heavy rainfall occurred over most of Southwestern Texas. Serious flooding occurred in Val Verde County.

Droughts

Development and management of conservation storage reservoirs in Texas is based primarily on providing dependable quantities of acceptable quality water during extended drought periods. Severe droughts are characterized by several dry years rather than the dry season of a single year. During droughts, reservoir inflows are decreased simultaneously with increased demands on the water in storage. Droughts in Texas apparently occur at random with no predictable cycle. From the early days of Texas history recorded by Spaniards exploring the Southwest, drought has been a reoccurring problem. A drought in Central Texas dried up the San Gabriel River in 1756, forcing the abandonment of a settlement of missionaries and Indians (Orton 1969). By agricultural, economic, hydrologic, or meteorological standards, the worst drought on record began in 1950 in the western part of the state and spread until 244 of the 254 counties in the state were classified as disaster areas by the end of 1956. Other severe droughts occurred in 1909-1910, 1916-1917, and 1933-1934. In most years, some sections of the state receive less than normal rainfall, while other sections receive a greater than normal supply. Severe drought or excessively wet conditions rarely exist over the entire state at the same time. While the Great Plains drought of the early 1930's received considerable publicity as the "dust bowl days", its presence in Texas was confined largely to the western one-third of the state and to the years 1933-1934 (Orton 1969).

Reservoir Storage Contents

Whereas rainfall, streamflow, evaporation, and water demands experience significant variations throughout the year, reservoir storage levels remain relatively constant. The average end-of-month storage contents for several multipurpose flood control and conservation reservoirs are tabulated by month in Table 3.14. The average for each month is expressed as a percent of the average of all the months in the record. The average storage levels are highest in May and lowest in August. The reservoirs included in the table are all located in the Brazos River Basin. Some reservoirs in the state experience storage level fluctuations significantly greater than the reservoirs included in the table. However, pool levels tend to remain fairly constant seasonally throughout the state. Filling of a significant portion of a flood control pool occurs infrequently. Severe drawdowns are infrequent and typically are of several months duration.

The maximum storage levels which have occurred at the Corps of Engineers flood control reservoirs in the state are shown in Table 3.15. The reservoirs are listed by river basin along with their flood control capacity and date of initial impoundment. The last three columns describe the largest flood event, in terms of storage levels, that has occurred at each project since initial impoundment. The timing of the flood event is presented in terms of the date flood waters begin to rise into the flood control pool and the date the storage peaked. The maximum flood control storage is expressed as a percentage of the flood control pool capacity. The table represents 15 flood events which caused peak storage levels in the 29 reservoirs. The floods of April-May 1957 and April-May 1968 resulted in maximum storage levels in several reservoirs. For 8 of the 15 floods, initial flood storage occurred in April or early May. Another flood began on March 30, and another on May 25. Thus, April and May have been the key months historically from the perspective of filling flood control pools.

Table 3.14
MONTHLY VARIATION IN RESERVOIR STORAGE CONTENT

Month	Reservoir (Brazos River Basin)					
	Proctor	Somerville	Stillhouse	Waco	Belton	Whitney
	Average End-of-Month Storage As A Percent of Average for All Months					
Jan	98.2	102.9	95.9	99.6	97.3	95.4
Feb	92.9	101.6	97.8	96.8	101.3	95.5
Mar	103.3	104.2	101.6	100.0	97.6	96.8
Apr	103.1	105.8	104.4	104.3	103.2	102.5
May	120.6	111.6	105.4	105.0	114.2	115.3
Jun	116.0	108.9	104.1	103.1	106.3	103.6
Jul	98.2	95.4	101.3	100.0	98.5	98.7
Aug	89.4	90.4	101.0	96.4	95.4	96.0
Sep	91.6	94.2	95.4	95.5	96.3	96.6
Oct	95.8	94.3	97.5	102.4	98.0	101.9
Nov	96.5	94.8	97.9	98.7	96.1	100.9
Dec	94.5	95.7	97.7	98.2	95.7	96.8

Table 3.15
MAXIMUM FLOOD CONTROL STORAGE CONTENT

River Basin and Reservoir	Flood Control Capacity (ac-ft)	Date of Initial Impound.	Maximum Flood Event		
			Date of Initial Flood Storage	Date of Maximum Flood Storage	Maximum Flood Storage (% Capacity)
Guadalupe River Basin					
Canyon	354,700	Jun 64	3 Aug 78	4 Aug 78	58
Colorado River Basin					
Hords Creek	16,620	Apr 48	30 Apr 56	1 May 56	28
O. C. Fisher	277,000	Feb 52	2 Oct 57	14 Oct 57	21
Twin Buttes	454,400	Dec 62	8 May 75	12 May 75	4
Travis	778,000	Sep 40	24 Apr 57	18 May 57	77
Brazos River Basin					
Aquilla	93,600	Apr 83	none	10 Apr 84	0
Georgetown	93,720	Mar 80	26 May 81	22 Jun 81	56
Granger	335,800	Jan 80	25 May 81	19 Jun 81	55
Proctor	314,800	Sep 63	20 Jan 68	26 Jan 68	44
Somerville	347,400	Jan 67	10 May 79	9 Jun 79	90
Stillhouse	394,700	Feb 68	14 Apr 77	2-3 May 77	88
Waco	573,300	Feb 65	4 May 68	15 May 68	25
Belton	644,000	Mar 54	23 Apr 57	6 Jun 57	67
Whitney	1,372,400	Dec 51	26 Apr 57	29 May 57	144
San Jacinto River Basin					
Barker	199,000	Feb 46	10 May 68	15 May 68	20
Addicks	212,500	Dec 48	10 May 68	15 May 68	18
Trinity River Basin					
Benbrook	76,550	Sep 52	12 May 57	6 Jun 57	126
Bardwell	85,300	Nov 65	6 May 69	19 May 69	60
Navarro Mills	149,240	Mar 63	27 Apr 68	18 May 68	85
Lavon	291,700	Sep 53	30 Mar 82	26 May 82	95
Lewisville	524,200	Nov 54	1 May 57	3 Jun 57	131
Neches River Basin					
Sam Rayburn	1,145,000	Mar 65	1 Dec 73	7 Feb 74	90
Red River Basin					
Pat Mayse	67,000	Sep 67	19 Oct 71	11 Dec 71	128
Kemp	234,900	Oct 22	-	30 Jun 41	65
Lake o' the Pines	387,200	Aug 57	21 Apr 66	5 May 66	75
Wright Patman	2,509,000	Jun 56	4 May 66	9 May 66	70
Texoma	2,669,000	Oct 43	28 Apr 57	5 Jun 57	125
Canadian River Basin					
Meredith	543,300	Oct 64	none	28 Apr 73	0

Source: USGS Water Resources Data and Water Supply Papers

Record reservoir drawdowns occurred throughout the state in 1984. Table 3.16 shows the date that drawdowns began and the date of maximum storage depletion in 1984. The date the drawdown began is the day after the conservation pool was last full prior to the maximum depletion. For most of the reservoirs, the drawdown began during the period from June through September. The maximum drawdown to have occurred prior to 1984 is also cited in Table 3.16.

Summary

Extreme rainfall events can occur at any time in Texas but usually occur during the period from April through October. Mean monthly precipitation peaks in May in the central and eastern parts of the state and in September in the west. In the central and eastern parts of the state, May is the dominant month for high streamflows both in terms of extreme events and mean monthly flows. Streamflow peaks in September and October in west Texas. Historically, maximum reservoir storages have occurred most often from floods filling the reservoirs in April and May. July through August and November through February are dry periods. Demands on conservation storage are most pronounced in July and August when streamflows are lowest and evaporation is highest. Consequently, reservoir drawdowns occur during the summer.

Mean monthly data for Waco Reservoir, located in the Brazos River Basin in Central Texas, are presented in Table 3.17. Mean monthly rainfall, reservoir inflows, evaporation, water demands, and storage content are presented in terms of percent of the mean over the year. Although seasonal characteristics of these factors vary geographically over the state, the data for Waco Reservoir are generally illustrative of seasonal variations. Table 3.17 shows that mean monthly rainfall peaks in April and May with a secondary peak in September. Mean monthly streamflow has a distinct peak in May and varies more than rainfall. Rainfall varies from 62% in August to 179% in May. Streamflow varies from 26% in August to 252% in May. Water demands and evaporation are highest in August when streamflow is a minimum. Water demands for Waco Reservoir are for municipal use. Mean monthly reservoir storage levels exhibit much less variation than the other factors.

From the perspective of operating reservoirs for conservation purposes, a seasonal rule curve would logically consist of raising the pool in April or early May to capture additional May streamflow for use during July and August when streamflows are low and demands high. However, a high risk of extreme rainfall events exists from April through October. May is a particularly significant month for high streamflows and reservoir storage levels associated with major flood events. Consequently, development of strategies for beneficially utilizing May streamflows while minimizing the risk of contributing to flooding during May and June is a key aspect of designing seasonal rule curves. Lowering the pool in time for September and October floods is also an important consideration.

The lack of a distinctive flood season complicates the implementation of seasonal rule curves in Texas. However, the seasonality of water availability, water demands, and flood risks in combination could result in seasonal rule curve reservoir operation being worthwhile in appropriate circumstances.

Table 3.16
EXTREME RESERVOIR DRAWDOWNS

River Basin and Reservoir	Prior Drawdown		1984 Drawdown		
	Date of Minimum Storage	Minimum Storage (% capacity)	Date Drawdown Began	Date of Minimum Storage	Minimum Storage (% capacity)
Guadalupe River Basin					
Canyon	Sep 80	88	8 Aug 81	24 Nov 84	82
Colorado River Basin					
Hords Creek	May 80	28	*	2 Sep 84	19
O.C. Fisher	Jul 70- Apr 71	0	*	28 Sep 84	7
Twin Buttes	Apr 71	1	5 Jun 77	28 Sep 84	8
Travis	Aug 51	28	15 Jul 81	6 Oct 84	46
Brazos River Basin					
Georgetown	Mar 80	1	2 Sep 83	6 Oct 84	87
Granger	Jan 80	1	27 Apr 84	6 Oct 84	69
Proctor	Jan 79	38	21 Aug 82	4 Oct 84	32
Somerville	Sep 78	61	17 Apr 84	5 Oct 84	56
Stillhouse	Nov 78	77	18 Jul 83	5 Oct 84	76
Waco	Oct 78	62	16 Jun 83	8 Oct 84	58
Belton	Dec 56	26	2 Sep 82	6 Oct 84	74
Whitney	Nov 56	40	3 Aug 82	4 Oct 84	63
Trinity River Basin					
Benbrook	Sep 84	70	14 Aug 82	10 Oct 84	70
Bardwell	Nov 78	76	9 May 84	6 Oct 84	81
Navarro Mills	Dec 78	57	26 Jun 84	6 Oct 84	79
Lavon	Apr 76	18	19 Aug 82	18 Oct 84	76
Lewisville	Sep 80	40	29 Sep 82	20 Oct 84	65
Neches River Basin					
Sam Rayburn	Nov 77	63	11 Jun 84	18 Oct 84	74
Red River Basin					
Pat Mayse	Apr 68	83	18 Jul 84	4 Oct 84	94
Kemp	Jun 53	10	21 Apr 84	10-13 Oct 84	65
Lake o' the Pines	Sep 84	83	25 May 84	6 Oct 84	82
Wright Patman	Sep 58	95	**	-	-
Texoma	Sep 64	59	20 Dec 83	2-3 Oct 84	81
Canadian River Basin					
Meredith	May 81	20	*	10-11 Sep 84	32

* The conservation pools in Hords Creek, O.C. Fisher, and Meredith Reservoirs had not been full for several years prior to 1984.

** Wright Patman Reservoir was not drawn down below the top of conservation pool in 1984.

Table 3.17
MEAN MONTHLY DATA FOR WACO RESERVOIR
AS A PERCENT OF MEAN ANNUAL

Month	Average Rainfall	Average Inflows	Average Evaporation	Average Water Demand	Average Storage Content
	(percent of mean for all months)				
Jan	84	91	46	79	100
Feb	89	110	48	74	97
Mar	77	95	69	77	100
Apr	142	156	79	84	104
May	179	252	95	95	105
Jun	107	115	128	115	103
Jul	79	97	166	138	100
Aug	62	26	175	140	96
Sep	112	49	139	124	96
Oct	96	78	111	102	102
Nov	82	64	79	88	99
Dec	92	67	56	84	98

CHAPTER 4
ANALYSIS METHODS

This chapter consists of (1) an overview discussion of available reservoir systems analysis methods, from the perspective of evaluating storage reallocations, and (2) a description of the models adopted for the Brazos River Basin case study.

State-of-the-Art Reservoir System Analysis Models

Wurbs, Tibbets, Cabezas, and Roy (1985) present a state-of-the-art review and annotated bibliography of systems analysis techniques applied to reservoir operation. Over 700 references are cited in the bibliography. A literature review was also conducted in conjunction with the present study.

Numerous mathematical models have been developed for sizing reservoir storage capacities and establishing operating policies during project planning and for supporting release decisions during real-time operations. Each particular model was developed specifically for either planning or real-time applications or may be applicable in either situation. However, the present investigation addressed the somewhat different situation of evaluating plans for reallocating storage capacity in existing reservoir systems. Little attention has been directed in the literature toward reevaluating existing operating policies in response to changing needs and conditions. A comprehensive literature review revealed essentially no models developed specifically for evaluating reallocations between flood control and conservation or otherwise considering tradeoffs and interactions between flood control and conservation purposes. However, generalized models and modeling concepts are applied meaningfully to the analysis of storage reallocation plans even if they were not developed specifically for that particular application. The present discussion addresses modeling of reservoir operations in general but from the perspective of identifying those modeling concepts and techniques which are pertinent to the storage reallocation problem.

Flood Control Versus Water Supply Analyses

Flood control and conservation operations are typically analyzed separately using different approaches, or one purpose is treated as a constraint in modeling studies to optimize the other purpose. Fundamental differences exist between flood control and conservation analyses.

Hydrologic analysis of floods is probabilistic event oriented. Major flood events have durations of several hours to several weeks, with discharges changing greatly over periods of hours or days. Flood analyses are typically performed using daily or hourly streamflow data. Modeling flood wave attenuation effects is important. Hydrologic analysis of droughts is stochastic time series oriented. Reservoirs are planned and managed to supply water during extreme droughts with durations of several years. Conservation analyses are typically based on monthly streamflow and evaporation data.

Institutionally, flood control has been primarily a federal responsibility and water supply a nonfederal responsibility. Detailed economic evaluation procedures have been developed for flood control because the Flood Control Act of 1936 and subsequent statements of policy have required a benefit-cost justification for federal projects. Flood control benefits as well as costs are evaluated in terms of dollars. Legislative or other policy statements have never required a benefit-cost justification for municipal and industrial water supply, at least not in the same sense as flood control. Municipal and industrial water supply projects have been developed based on the concept of meeting demands at least cost. In federal planning of multipurpose reservoir projects, municipal and industrial water supply benefits are estimated as the cost of the least costly alternative means of providing the same quantity and quality of water assuming the proposed project is not implemented. The major policy emphasis in recent years on demand management and achieving more efficient water use has resulted in reservoir planning studies now including projections of water needs alternatively assuming reasonable demand management strategies are, and are not, adopted. Likewise, economic evaluations of flood control reservoirs are now based on the assumption of management of downstream flood plain land use.

Simulation of reservoir operations involves computation of storage levels and release rates for each time period during an assumed repetition of the hydrologic period-of-record for specified flood control and conservation operating policies. Major historical flood events may be selected for more detailed simulation of flood control operations. Conservation operations may also be simulated using synthetically generated streamflow sequences. Traditional hydrologic and economic evaluation of the flood control capabilities of reservoir projects has focused on (1) the estimated recurrence interval of the design flood which just fills the flood control pool and (2) reduction in expected annual economic damages. Water supply capabilities traditionally have been quantified in terms of firm yield and, to a lesser extent, reliability. These types of analyses are discussed later in this chapter.

Simulation Versus Optimization Models

Systems analysis models can be categorized as simulation or optimization. A broad range of types of analyses routinely applied in the planning, design, and operation of reservoir projects are included in the category of simulation modeling. The role of optimization, or mathematical programming, models is to provide the capability to search through a large number of possible combinations of values for a set of decision variables to find the decision policy which maximizes or minimizes a defined objective function.

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 a system under varying conditions. Although simulation only serves to analyze system performance under a given set of conditions, trial-and-error runs of a simulation model can be used to search for an optimal decision policy. However, numerous simulations may be required to achieve acceptable results, and the optimum decision policy may never be found. Consequently, application of mathematical programming or optimization techniques, which automatically find the optimum decision policy, to reservoir operation has received much attention.

Simulation models have been proven through practical application to be a valuable aid in sizing reservoirs and establishing operating policies. During the past twenty years, a major thrust of research and the resulting literature related to reservoir operation has been to supplement simulation models with optimization techniques such as linear programming, dynamic programming, search algorithms, and various other nonlinear programming algorithms. Linear programming and dynamic programming are the optimization techniques most frequently associated with analyzing reservoir systems. The academic research community in particular, and many practitioners as well, have been very enthusiastic about applying optimization techniques to reservoir operation problems. Research in this area has dominated the water resources planning and management literature. Research results, case studies, and experience in application of optimization models in actual planning and real-time operation decisions indicate a high potential for improving reservoir operations through their use. However, optimization techniques have not yet been widely accepted by the reservoir planning and management community for routine use. Optimization models have played a relatively minor role compared to simulation models in regard to influencing decisions made in the planning and operation of actual projects. Simulation is the "work-horse" of reservoir system analysis. Optimization techniques provide valuable supplemental analysis capabilities for a select number of specific types of problems.

Optimum sizing of storage capacities, establishing release policies, and real-time operations are complex tasks involving numerous hydrologic, economic, environmental, institutional, and political considerations. Defining system objectives, developing criteria for quantitatively measuring system performance in fulfilling the objectives, and handling interactions and conflicts between objectives are major areas of complexity. Mathematical optimization techniques require that the real system be represented in the proper mathematical format. Representing complex project objectives and performance criteria in the required format, without unrealistic simplifications, is a particularly difficult aspect of the modeling process which limits the application of optimization techniques.

Since simulation models are limited to predicting the system performance for a given decision policy, optimization models have a distinct advantage in this regard. However, simulation models have certain advantages over optimization models from a practical applications perspective. Simulation models generally permit more detailed and realistic representation of the complex hydrologic and economic characteristics of a reservoir system. Stochastic analysis methods can be combined with simulation models easier than with optimization models. The concepts inherent in simulation tend to be easier to understand and communicate than optimization modeling concepts.

Combined use of simulation and optimization models is an effective analysis strategy for certain reservoir operation problems. Preliminary screening with an optimization model may be used to develop a manageable range of alternative decision policies for further detailed analysis with a simulation model. Another approach is for an optimization model to be embedded as a component of a complex simulation model. Likewise, an optimization model may search for an optimum decision policy while activating a simulation model to compute the objective function value for any given set of decision variable values.

Although the potential for applying optimization techniques in analyzing storage reallocation plans was investigated, the evaluation strategy developed in the present case study is based strictly on simulation. The reallocation decision problem is basically to determine whether conversion of storage capacity between flood control and conservation purposes is warranted and, if so, the optimal storage capacity allocation. Capabilities are needed to assess system performance as precisely and meaningfully as possible for a few alternative reallocation plans rather than search through a large number of possible capacity allocations. Consequently, optimization models are not particularly advantageous for this particular application.

Reservoir System Simulation Models

Simulation modeling of major reservoir systems 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 objective was to maximize power generation subject to constraints imposed by specified requirements for navigation, flood control, and irrigation. The Streamflow Synthesis and Reservoir Regulation (SSARR) Model was developed by the North Pacific Division of the Corps of Engineers primarily for streamflow and flood forecasting and reservoir design and operation studies. Various versions of the SSARR model date back to 1956. More recently developed reservoir system simulation models include the Trent River System Model (Sigvaldason 1976), Massachusetts Institute of Technology Simulation Model (Strzepek and Lenton 1978), and Potomac River Interactive Simulation Model (Palmer, Wright, Smith, Cohon, and Revelle 1980).

The Texas Water Development Board 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). The present Reservoir Operating and Quality Routing Program (RESOP-II), Simulation Model (SIMYLD-II), Surface Water Resources Allocation Model (AL-V), and Multireservoir Simulation and Optimization Model (SIM-V) evolved from earlier versions. The TWDB generalized models provide a broad range of capabilities for analyzing conservation operations but include essentially no capabilities for simulating flood control operations.

A generalized reservoir regulation model developed by the Southwestern Division (SWD) of the U.S. Army Corps of Engineers is described by Hula (1981). 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 HEC-5 and the SWD model. The division and district offices in the five-state Southwestern Division have applied the model in a number of studies. The Reservoir Modeling Center in the Tulsa District office is using the SWD model to simulate the various major Corps of Engineers reservoir systems located in the division, including the Brazos River Basin system.

The Hydrologic Engineering Center (HEC) models HEC-3 Reservoir System Analysis for Conservation and HEC-5 Simulation of Flood Control and Conservation Systems were used in the present study to simulate the reservoir system in the Brazos River Basin. These generalized computer programs are described later in this chapter.

Firm Yield and Reliability

The relationship between storage capacity, yield, and reliability is a fundamental and extremely important aspect of the planning, design, and operation of a reservoir for conservation purposes. Yield is the amount of water which can be supplied from an unregulated stream, reservoir, or multireservoir system during a specified period of time. Methods for quantifying yield must consider the stochastic nature of streamflow and other pertinent variables. McMahon and Mein (1986) describe various approaches for quantifying yield. Traditional analyses have been based on the concepts of firm (or dependable or safe) yield and 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, based on specified assumptions regarding various factors such as interactions between multiple users and multiple reservoirs. Firm yield computation consists of iteratively simulating a stream/reservoir system assuming alternative diversion or release rates. The firm yield is the diversion or release rate which just empties the reservoir(s). Various simulation models, including HEC-3 and HEC-5, contain routines which automatically perform the iterative search for the firm yield. Loucks and Stedinger (1981) describe the use of linear programming models to compute firm yield.

Reservoir reliability is an expression of the likelihood or probability of meeting given yield levels. Reservoir reliability can be operationally defined in various ways. For example, in the Brazos River Basin case study, reliability was computed as the percentage of months during a simulation period that a specified yield level was met without shortages occurring. Thus, the computed reliability represents the probability that a specified demand will be met in any month. Another approach involves synthetic generation of numerous equally likely multiyear streamflow sequences using a model such as MOSS-IV which is discussed later in this chapter. Simulations of the stream/reservoir system are repeated with each alternative streamflow sequence. The reliability is computed as the percentage of the streamflow sequences for which a specified yield level was met. Thus, the computed reliability represents the probability of meeting a specified demand during a multiyear period of specified duration. Reliability is the complement of risk of failure or probability that the demand will not be met.

Flood Control Storage Frequency Analysis

Reservoir flood control capacity is often measured in terms of the recurrence interval, exceedence probability, or exceedence frequency of the flood which will deplete the flood control storage capacity. This represents the probability of filling the flood control pool to capacity. Frequency analyses, using a plotting position formula or probability distribution function, are typically performed based on the storage levels computed by a reservoir system simulation model. The peak annual storage level for each year of the simulation may serve as the data set for the frequency analysis. Alternatively, the peak storage data set may be limited to selected extreme flood events.

The simulation approach discussed above for developing reservoir storage data for a frequency analysis, requires a long sequence of naturalized streamflow data. An alternative approach involves use of hypothetical rainfall events developed for specified exceedence probabilities. Watershed (rainfall-runoff) modeling techniques are applied to compute streamflows for the statistical rain storms. Storms for alternative exceedence probabilities are routed through the reservoir/stream system to find the storm which fills the flood control pool.

Reservoir storage frequency analyses are complex, and necessarily approximate, because storage levels depend upon: the volume, duration, and timing of streamflow hydrographs as well as peak discharge; streamflow hydrographs for multiple locations at reservoirs and downstream control points throughout the stream/reservoir system; reservoir storage levels at the beginning of the flood; and flood control operating policies which are necessarily based on the judgement of the operator as well as specified operating criteria. Flood control operations are concerned with extreme flood events. Frequency analysis for extreme events requires longer data series and are more approximate than analysis of more frequent events.

Economic Evaluation

Economic evaluation consists of estimating and comparing the benefits and costs, expressed in dollars, which would result from alternative plans of action. Economic evaluation of flood control plans have traditionally been based on the concept of average annual damages. The inundation reduction benefit is defined as the difference in average annual damages without and with a proposed plan. Computing average annual damages using the damage-frequency method has been an integral part of the economic evaluation procedures followed by the Corps of Engineers and other federal agencies in planning flood control improvements for many years. The method is incorporated in the HEC-5 and SWD reservoir system simulation models.

Average annual damage computations are based on the statistical concept of expected value. Expected or average annual damage is computed as the integral of the damage versus exceedence probability function. Exceedence frequency versus peak discharge, discharge versus stage, and stage versus damage relationships are combined to develop the damage versus exceedence frequency function. Expected or average annual damage is a frequency weighted sum of damage for the full range of damaging flood events and can be viewed as what might be expected to occur, on the average, in any present or future year. Additional meaningful information, including discharges, stages, and damages associated with a range of storm magnitudes, are generated in the process of computing average annual damages.

Wurbs and Cabezas (1987) present an economic evaluation procedure for analyzing proposed reallocations of reservoir storage capacity between flood control and municipal and industrial water supply. The central thrust of the procedure is the estimation of average annual economic losses associated with alternative allocations of storage capacity between purposes. Average annual flood losses are computed using the damage-frequency method described above. Unlike traditional practices based on firm yield, water supply is treated analogously with flood control with economic consequences of water shortages being quantified. Average annual water supply losses, in dollars, are estimated by developing a water shortage versus economic loss function which is then applied to water shortages computed by a hydrologic simulation. The water shortage versus loss function reflects emergency demand management and supply augmentation measures. Average annual water supply losses are estimated for a given demand level. Long-term demand management strategies are reflected in the water demand projections. The economic evaluation procedure allows the impacts of a storage reallocation on flood control versus water supply to be compared in commensurate units of dollars, thus providing a better understanding of the tradeoffs.

Wurbs and Cabezas (1987) applied the economic evaluation procedure to the proposed storage capacity reallocation in Waco Reservoir. The results of the economic evaluation for this particular case study support the concept of reallocating storage capacity to maintain a firm yield somewhat in excess of water demand. If water demand levels exceed firm yield, the average annual economic losses associated with water shortages exceed the increased average annual flood losses which would result from reallocating flood control capacity to water supply to prevent shortages. The investigators concluded that water supply losses could be estimated as meaningfully as flood losses if a comparable level of effort were to be devoted to development and application of economic evaluation methods for water supply. Realizing of course, both water supply and flood control analyses involve significant estimations and engineering judgments and are necessarily approximate.

The Brazos River Basin reservoir system simulation study presented in later chapters of the present report included only a hydrologic analysis using monthly data. An economic evaluation for the multiple reservoir system far exceeded the scope of the study. The water supply portion of the previous economic evaluation of the Waco Reservoir reallocation was much simpler than a system-wide study because all the water supplied by Waco Reservoir is used for municipal and industrial purposes in the City of Waco and its suburbs. Expected annual flood damage computations must be based on daily, rather than monthly, streamflow data, which greatly increases the required effort. The previous economic evaluation of the Waco Reservoir reallocation was based on damage versus discharge data developed by the Corps of Engineers during preconstruction planning of the original project, updated by indices for inflation. A new damage survey for the entire basin would be required for a detailed reallocation study and would involve a prohibitively large amount of time and effort.

Flood control economic evaluation procedures have been used primarily in preconstruction planning and design. Expected annual damage estimates with and without a proposed new reservoir project are much more accurate and meaningful than the incremental changes in expected annual damages associated with a storage reallocation in an existing reservoir. Frequency versus discharge relationships can be most accurately estimated for the more frequent flood events. However, storage reallocations affect the releases only for the extreme, less frequent events, for which data is most uncertain. Storage reallocations also affect flow duration as much as peak discharge. The traditional expected annual damage estimation procedures treat damages as a function of peak discharge only.

The above discussion addresses flood control and water supply. Economic benefits for hydroelectric power can be estimated by a reservoir system simulation model based on inputed primary and secondary energy values in dollars and the purchase cost for obtaining energy from an alternative source in case of a shortage in primary energy. Firm energy demands and the associated benefits are provided as input data. Secondary energy is energy in excess of firm energy which is produced by routing releases for other purposes through the turbines. Shortages are computed whenever the firm energy demands cannot be met. Cost data is provided as input for assigning dollar losses to shortages. HEC-5, as well as other reservoir system simulation models, have routines for this type of hydroelectric power economic analysis.

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 performing the computations for 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.

Additional computational procedures were developed in conjunction with the study for analysis of the storage and discharge data computed with HEC-3 and HEC-5. These procedures are outlined in Chapters 5 and 6.

MOSS-IV runs on a mainframe computer. STATS runs on an IBM PC compatible microcomputer. HEC-3 and HEC-5 were originally developed for mainframe computers but have recently been converted to run on IBM PC compatible microcomputers. In the present study, mainframe versions of the programs were run on the VAX 8650 computer system operated by the Engineering Computer Services Center at Texas A&M University. Both the VAX 8650 and microcomputers were used, typically in combination with files being transferred between the two systems. However, most of the work was accomplished on the mainframe VAX system. Most of the graphics in the report were prepared with the PICSURE graphics package on the VAX 8650.

Feldman (1981) discusses the various generalized computer simulation programs available from the Hydrologic Engineering Center. The programs used in the present study are briefly described and pertinent references cited below.

HEC-3 Reservoir System Analysis for Conservation

HEC-3 is documented by a users manual (USACE, HEC 1981) and programmers 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, 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.

CHAPTER 5
BRAZOS RIVER BASIN CASE STUDY

The case study evaluation of the feasibility of reallocating storage capacity was accomplished as a part of a broader simulation modeling study of a system of twelve reservoirs in the Brazos River Basin operated by the Corps of Engineers and Brazos River Authority. Wurbs, Bergman, Carriere, and Walls (1988) document an evaluation of the yield supplied by the reservoir system. The present chapter summarizes a more detailed description presented in the other report of the river basin, reservoir system, and basic data incorporated in the models.

Description of Reservoir System

The Brazos River Basin extends from eastern New Mexico southeasterly across the state of Texas to the Gulf of Mexico. The basin drainage area is 45,600 square miles, with about 43,000 square miles in Texas and the remainder in New Mexico. Figures 5.1 and 5.2 are a map of the basin. The U.S. Army Corps of Engineers (1973 and 1987b) and Texas Department of Water Resources (1984) provide detailed descriptions of the basin.

The 13 reservoirs listed in Tables 5.1 and 5.2 were included in the simulation models developed by the study. These reservoirs include a system of nine multipurpose flood control and conservation reservoirs 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 in the federal projects. The BRA constructed and owns three other conservation reservoirs. The remaining reservoir, Hubbard Creek, is owned and operated by the West Central Texas Municipal Water District. The 12-reservoir USACE/BRA system was the primary focus of the case study. Hubbard Creek Reservoir has a relatively large storage capacity and was included in the models to reflect its impacts on inflows to the USACE/BRA system. Assumed potential reallocations of storage capacity in various reservoirs were analyzed. However, all 13 reservoirs were included in the models to reflect system interactions and the impacts of upstream reservoirs on inflows to the reservoirs for which storage was reallocated.

A total of 1,178 reservoirs located in the Brazos River Basin are included in the dam inventory maintained by the Texas Water Commission. Forty of these reservoirs have storage capacities of 5,000 acre-feet or greater. The 13 reservoirs included in the present study contain all of the controlled flood control storage capacity and about 78 percent of the conservation storage capacity 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.

Pertinent basic data describing the physical characteristics of the reservoirs are tabulated in Table 5.2. Reservoir operations are based on the top of conservation and flood control pool elevations cited. As discussed in Chapter 2, a proposed but not yet implemented reallocation of storage capacity in Waco Reservoir involves raising the top of conservation pool to elevation 462 feet.

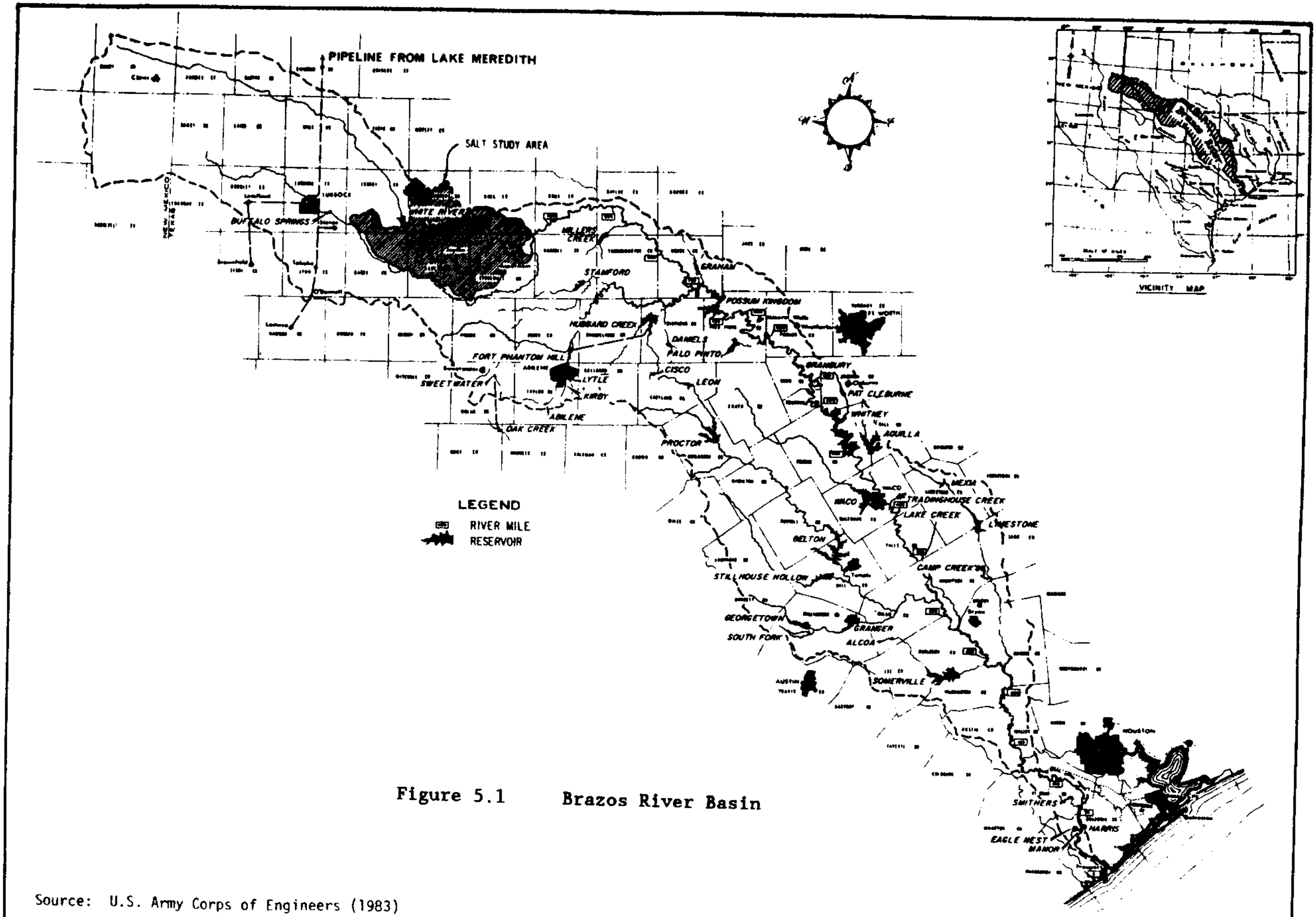


Figure 5.1 Brazos River Basin

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

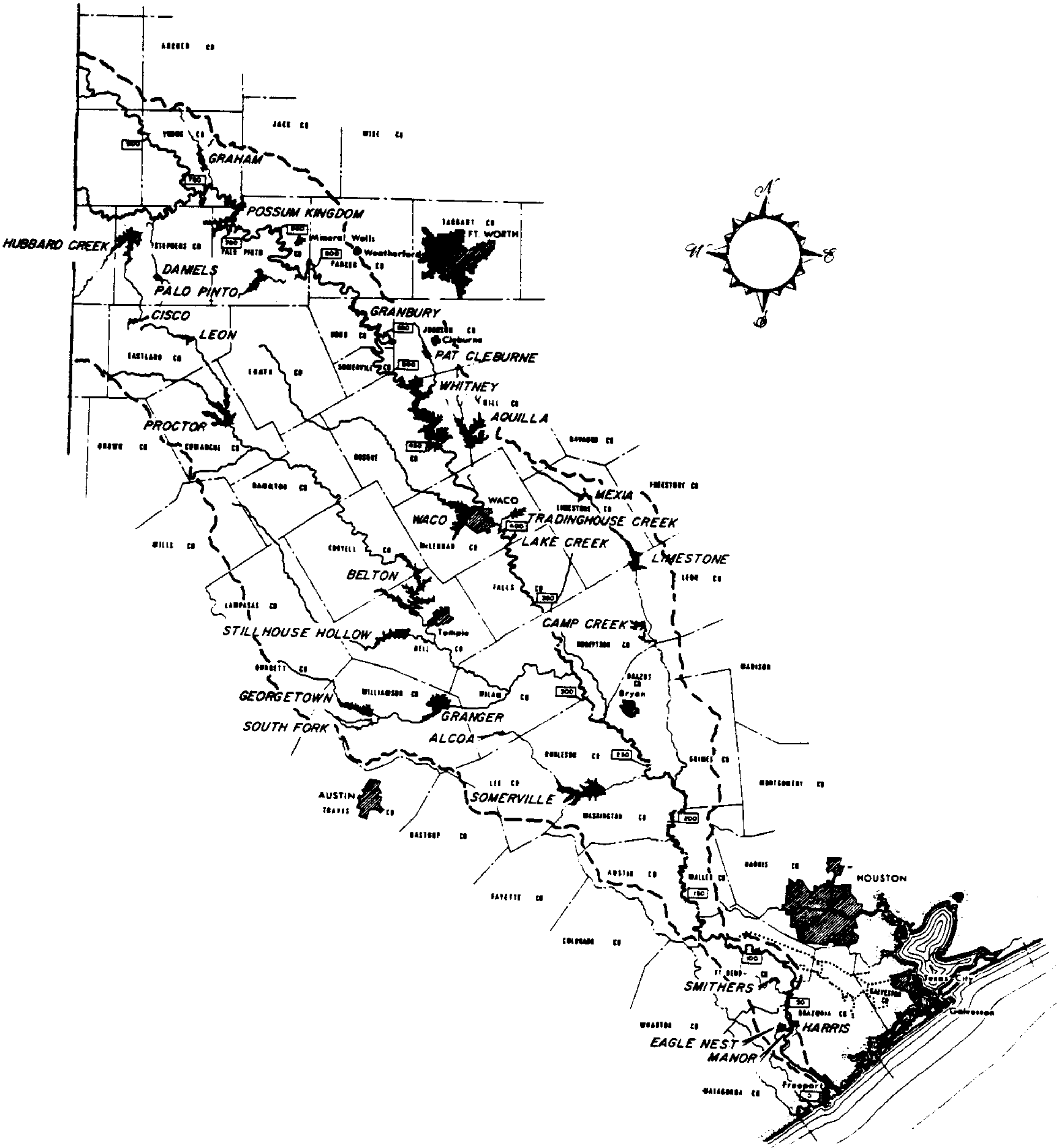


Figure 5.2 Middle and Lower Brazos River Basin

Table 5.1
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.

Table 5.2
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

The conservation storage in Whitney and Possum Kingdom Reservoirs provide both water supply and hydroelectric power generation. Twenty-two percent of the active conservation pool of Whitney Reservoir is designated for water supply and the remainder for hydroelectric power. The Whitney inactive pool is sediment reserve and dead storage for hydroelectric power. In the past, Possum Kingdom Reservoir was operated primarily for hydroelectric power but also provided water supply. In the future, hydroelectric power will likely be generated incidental to water supply operations. 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 accumulated storage capacities cited Table 5.2 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 5.2 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 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.

The stream gage stations used to represent reservoir inflows in the present simulation studies are also indicated. 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.

Overview of Basin Water Use

Water from the Brazos River and its tributaries is used in the Brazos River Basin and the adjoining San Jacinto-Brazos Coastal Basin. The amended Texas Water Plan includes a description of past and projected future water use. Tables 5.3, 5.4 and 5.5 were developed from Texas Water Development Board data. The year 2010 water use data is from the final Texas Water Plan report (TDWR 1984). The 1974 data is from an earlier draft (TWDB 1977), and the 1984 data is from a computer file of water use by county.

Table 5.3 shows the total 1974, 1984, and 2010 water use by category of use for the entire basin. Table 5.4 is a tabulation of the same information, excluding water use in the counties located in the watershed above Possum Kingdom Reservoir. The Table 5.4 data represents inbasin water needs at locations adjacent to and below the twelve USACE/BRA reservoirs. Total water use in the San Jacinto - Brazos Coastal Basin is tabulated in Table 5.5. All data are for water withdrawals, except steam electric reflects consumptive use only.

Table 5.3
WATER USE IN THE BRAZOS RIVER BASIN

Category	1974			1984			2010		
of Use	Ground Water	Surface Water	Total	Ground Water	Surface Water	Total	Ground Water	Surface Water	Total
				(acre-feet per year)					
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 5.4
WATER USE IN THE BRAZOS RIVER BASIN EXCLUDING THE SUBBASIN ABOVE POSSUM KINGBOM RESERVOIR

Category	1974			1984			2010		
of Use	Ground Water	Surface Water	Total	Ground Water	Surface Water	Total	Ground Water	Surface Water	Total
				(acre-feet per year)					
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 5.5
WATER USE IN THE SAN JACINTO-BRAZOS COASTAL BASIN

Category	1974			1984			2010		
of Use	Ground Water	Surface Water	Total	Ground Water	Surface Water	Total	Ground Water	Surface Water	Total
				(acre-feet per year)					
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

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 BRA reservoir system. 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 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 reservoir system simulation study.

As indicated by Table 5.4, 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 refinery 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 5.5. 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.

Little, if any, water from the Brazos River Basin is transported to basins other than the San Jacinto - Brazos Coastal Basin. Houston, in the San Jacinto Basin, and Fort Worth/Dallas, in the Trinity Basin, are located conveniently close to the Brazos River and could possible import water from the basin in the future. Water is imported via pipeline from Lake Meredith in the Canadian River Basin to Lubbock and other cities in the upper Brazos River Basin. The City of Sweetwater in the upper Brazos Basin obtains water from Oak Creek Reservoir in the Colorado River Basin.

Relative Water Supply and Use Quantities

Various water amounts for 1984 are tabulated in Table 5.6 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

Table 5.6
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

acre-feet. An additional 270,000 acre-feet was diverted from the Brazos River 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 percent) and in the adjoining coastal basin (34 percent). The total annual surface water use represents a volume equivalent of 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 withdrew 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.

Basic Data Used in the Simulation Models

Model formulation involved development of input data sets for the HEC-3 and HEC-5 computer programs. The models included operation of 13 reservoirs with monthly streamflow and evaporation data for the period 1900 through 1984. Fundamental hydrologic and reservoir data used throughout the simulation study are described below. Water use and other additional data used in specific analyses are discussed in Chapters 6 and 7.

Reservoir Storage Characteristics

The physical characteristics of a reservoir are represented in the model by water surface elevation versus storage capacity, water surface area, and outlet capacity relationships and top of inactive, conservation, and flood control pool elevations. Pool elevations and storage capacities for the 13 reservoirs operated in the simulation models are tabulated in Table 5.2 based on data provided by the BRA and USACE. Water surface elevation versus area and capacity tables and water surface elevation versus outlet capacity relationships were also provided by the BRA and USACE. Basic data for all of the reservoirs except Aquilla and Limestone are also published in Texas Water Development Report 126 (TWDB 1973).

Reservoir storage capacities change over time due to sedimentation. Water surface elevation versus area and 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. Belton, Whitney, and Possum Kingdom Reservoirs also have elevation versus area and capacity relationships updated by surveys made since initial impoundment. The sediment reserves tabulated in Table 5.2 correspond to the difference between initial and ultimate area and capacity tables. For purposes of the present study, linear interpolation was applied to the initial (or resurveyed) and ultimate elevation versus area and capacity tables to develop tables for 1984 and 2010 conditions.

Reservoir Evaporation Rates

Monthly net reservoir evaporation rates for the period January 1940 through December 1984 were obtained on magnetic tape from the Texas Natural Resources Information System. This data file is described by Texas Water Development Board (TWDB) Report 64 (Kane 1967). 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. HEC-3 and HEC-5 compute evaporation volumes by multiplying inputed evaporation rates by computed water surface areas.

Streamflow

The 23 gaging stations selected for inclusion in the simulation studies are listed in Table 5.7. Figure 5.3 shows the locations of the 23 stream gaging stations along with the 13 reservoirs operated in the simulation models.

Homogeneous time series of natural streamflow data is a fundamental requirement for a reservoir system simulation study. Gaged streamflow data are adjusted to remove nonhomogeneities caused by the activities of man. Gaps or data missing from the gage records are filled in or reconstituted. 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 (SCS) flood 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. MOSS-IV was used to fill in missing data for both data sets.

A complete set of monthly streamflows at the 23 gaging stations was developed for the period from January 1900 through December 1984. The TWC data was used for the time period 1940-1976. The TAMU unregulated streamflow was used for the periods 1900-1939 and 1977-1984, which are not covered by the TWC data.

The period-of-record for each gaging station is indicated in Table 5.7. The Brazos River gage at Waco (gage 10) has flow measurements dating back to October 1898. Ten gages date back to 1924 or before. All of the gages were reconstituted to cover the period January 1900 through December 1984, using the computer program MOSS-IV.

Table 5.7
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).

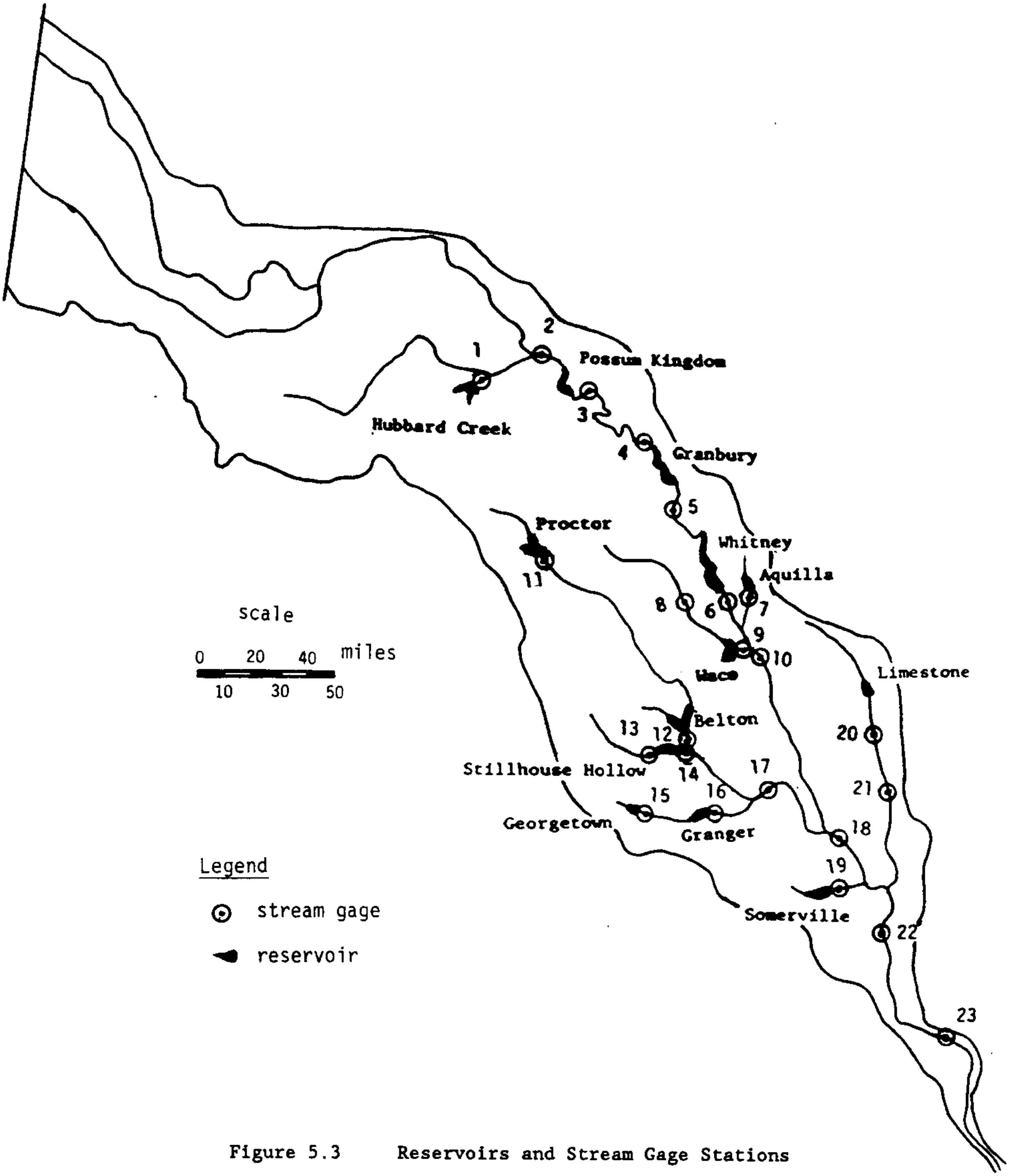


Figure 5.3 Reservoirs and Stream Gage Stations

Overview of the Simulation Study

The HEC-3 and HEC-5 simulation study was based on a 85-year historical sequence of monthly streamflow and evaporation data. Thirteen reservoirs were operated in the models for flood control and conservation purposes. Simulation runs alternatively incorporated 1984 and 2010 conditions of reservoir sedimentation. The study included two alternative approaches for representing withdrawals of water for beneficial use: (1) simulation of actual 1984 and projected 2010 water use and (2) computation of firm yields and reliabilities. The results of the 1984 and 2010 water use simulations are presented in Chapter 6. Firm yield and reliability analyses are covered in Chapter 7.

Chapter 6 presents a comparative evaluation of alternative storage capacity allocations based on system simulations representing 1984 or 2010 conditions of water use during an assumed repetition of the 1900-1984 historical hydrology. Simulation runs were made for several alternative storage reallocation plans. The analysis of simulation results included frequency analyses of filling of flood control storage capacities and frequency analyses of conservation storage drawdowns.

Chapter 7 presents an evaluation of firm yields and reliabilities associated with alternative storage reallocation plans.

CHAPTER 6
SYSTEM SIMULATION FOR SPECIFIED WATER USE SCENARIOS

Hydrologic period-of-record simulations were performed for years 1984 and 2010 conditions of water use and reservoir sedimentation. The reservoir system was simulated alternatively assuming existing top of conservation pool designations and permanent and seasonal reallocation plans. Flood control storage frequency and conservation drawdown frequency analyses were performed based on the results of the system simulations. The simulation results and accompanying frequency analyses provide a means for evaluating and comparing alternative storage allocations.

Input Data for the System Simulation Models

The simulations were performed with HEC-5. The model included operation of 13 reservoirs with monthly streamflow and evaporation data for the period 1900-1984. Simulations were performed with both 1984 and 2010 water use data. Figure 6.1 is a schematic of the system modeled. Model input data include reservoir storage characteristics, basin hydrology, diversions for beneficial uses, and reservoir operating criteria.

Reservoir Storage Characteristics and Basin Hydrology

Development of input data representing the reservoir storage characteristics and basin hydrology is described in the previous chapter. Each reservoir is characterized by tables relating water surface elevation to storage capacity, surface area, and outlet capacity and by top of inactive, conservation, and flood control pool elevations. Basin hydrology consists of monthly evaporation rates for each reservoir and monthly streamflow for each control point for the 1900-1984 simulation period.

Naturalized streamflows are provided as HEC-5 input data for all pertinent reservoir and nonreservoir control points. In most cases, model control points coincide with stream gaging stations. In some cases, streamflow at a control point is computed in the model by applying a drainage area ratio to streamflow data associated with another control point. The Richmond gage is the most downstream control point for which streamflow is input to the model. Runoff from the relatively small watershed below the Richmond gage is considered insignificant for purposes of the simulation. Computed inflows at the coast control point are streamflows at Richmond minus diversions at Richmond. The coast control point serves the modeling purpose of providing a point of diversion for water transported to the San Jacinto - Brazos Coastal Basin as well as inbasin diversions in Brazoria and Fort Bend County. Flows computed by HEC-5 at the Richmond control point have not yet accounted for diversions made in Fort Bend and Brazoria County. Flows computed at the coast represent streamflow into the Gulf after all diversions have been made.

1984 and 2010 Water Use

Texas Water Development Board county water use data were aggregated by control point. A water use diversion at a control point in the model represents the upstream water use between that control point and the next upstream control point. The upstream counties assigned to each control point are listed in Table 6.1. In the model, the control point labeled the coast serves as the

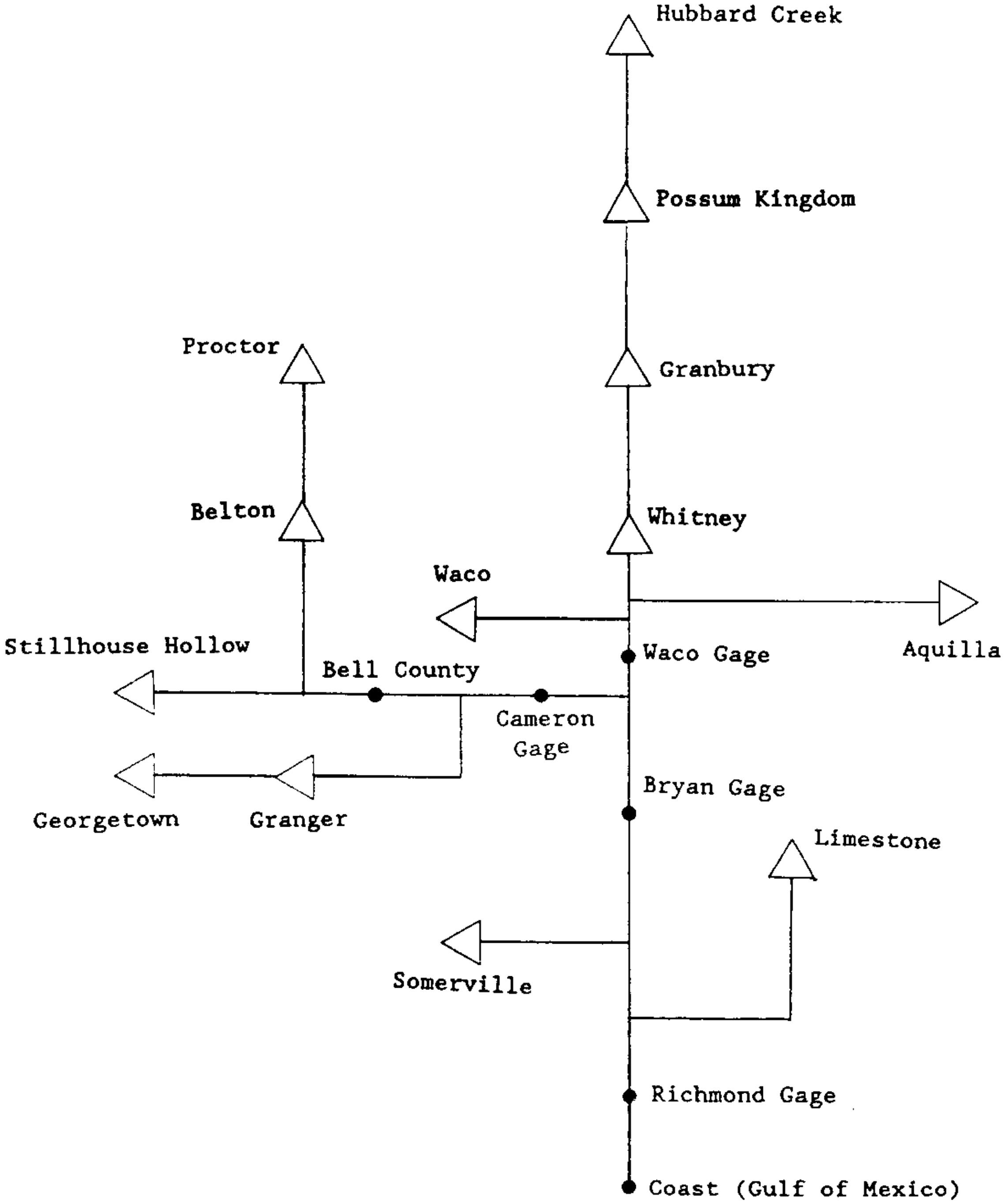


Figure 6.1 System Schematic

Table 6.1
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, Somervell, 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. Water use in these counties was not included in the simulation.

Water transported from the Brazos River Basin for use in the San Jacinto-Brazos Coastal Basin is diverted at the Coast control point along with diversions for in-basin water use in Brazoria and Fort Bend Counties. The San Jacinto-Brazos Coastal Basin encompasses portions of Brazoria, Fort Bend, Galveston, and Harris Counties.

point of diversion for water transported for use in the San Jacinto - Brazos Coastal Basin as well as inbasin water use in Fort Bend and Brazoria Counties. Water use in a group of counties in the extreme upper basin was considered to have insignificant impact on the reservoir system being studied and consequently was not included in the simulation. These upper basin counties are also listed in Table 6.1.

In many cases, the TWDB annual water use data was allocated among months by multiplying by the distribution factors developed by the Texas Water Commission (TDWR 1981) and reproduced as Table 6.2. Factors are provided for municipal, industrial (manufacturing and steam electric), irrigation, and mining uses for the upper, middle, and lower basin. Subbasins are delineated in Figure 6.2. Livestock use was assumed to be uniformly distributed throughout the year. In those situations in which the water use could be clearly identified with specific reservoir releases, the annual TWDB water use data was distributed in proportion to BRA and FWD monthly reservoir release data.

Return flows were estimated as a fraction of water use. Return flow factors were established based on a review of TWDB and TWC data. Return flow factors have been developed by the TWDB in conjunction with the Texas Water Plan and by the TWC in conjunction with the water availability modeling effort. Although consideration was given to developing a set of return flow factors for various locations in the basin, the approach finally adopted was to apply the same ratios for the entire basin. The return flow to water use ratios are as follows: municipal, 40%; manufacturing, 35%; and steam electric cooling from groundwater, 25%. Zero return flows were assumed for irrigation, livestock, and mining uses. The 40% and 35% return flow factors for municipal and manufacturing uses, respectively, were applied to both surface water and ground water. The 25% return flow for steam electric use is applicable only to the limited amount of groundwater used for this purpose. The TWDB water use data are for total withdrawals except for surface water used for steam electric purposes which is consumptive use only. Return flows were computed by multiplying the water use by the appropriate factor. In some cases, water diversions occurred at a reservoir control point with the associated return flows occurring downstream. Water transported to the San Jacinto -Brazos Basin had no return flows to the system modeled. Inbasin water use in Brazoria County was also modeled as having no return flow.

Annual water use for 1984 assigned to each control point is tabulated in Table 6.3. The ground water use was included in the return flow computations. The upper basin water use was not included in the simulation at all. These data were compiled from a paper printout of a TWDB computer data file in which water use is tabulated by county. Another data file provides municipal and manufacturing use data by city as well as county. These data files are a detailed breakdown of the water use data summarized in the Texas Water Plan (TDWR 1984).

Although surface water use in the San Jacinto-Brazos Coastal Basin was included in the data base used in the study, the proportion of the coastal basin water use supplied from the Brazos River is not readily available. However, TDWR (1984) data indicate that 86.75 percent of the surface water used in the San Jacinto-Brazos Coastal Basin in 1980 had been transported from the Brazos Basin. TWDB (1977) data indicate the percentage was higher in 1974.

Table 6.2
TWC MONTHLY WATER USE DISTRIBUTION FACTORS

Subbasin	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Municipal												
Upper	0.05	0.05	0.06	0.08	0.10	0.12	0.15	0.14	0.08	0.07	0.05	0.05
Middle	0.07	0.06	0.07	0.07	0.08	0.10	0.13	0.12	0.09	0.08	0.08	0.06
Lower	0.08	0.07	0.07	0.07	0.08	0.09	0.11	0.11	0.09	0.08	0.07	0.08
Industrial												
Upper	0.06	0.06	0.07	0.08	0.09	0.11	0.12	0.11	0.08	0.08	0.07	0.07
Middle	0.07	0.07	0.06	0.09	0.09	0.10	0.09	0.09	0.09	0.10	0.07	0.08
Lower	0.08	0.07	0.09	0.08	0.09	0.08	0.09	0.09	0.09	0.08	0.08	0.08
Irrigation												
Upper	0.03	0.02	0.12	0.02	0.11	0.22	0.27	0.15	0.03	0.03	0.00	0.00
Middle	0.00	0.00	0.03	0.06	0.16	0.21	0.21	0.20	0.09	0.04	0.00	0.00
Lower	0.00	0.00	0.04	0.12	0.19	0.22	0.22	0.15	0.05	0.01	0.00	0.00
Mining												
Upper	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.09	0.08	0.09	0.09	0.09
Middle	0.08	0.09	0.08	0.08	0.09	0.09	0.09	0.08	0.08	0.08	0.08	0.08
Lower	0.08	0.08	0.08	0.08	0.08	0.09	0.09	0.09	0.09	0.08	0.08	0.08

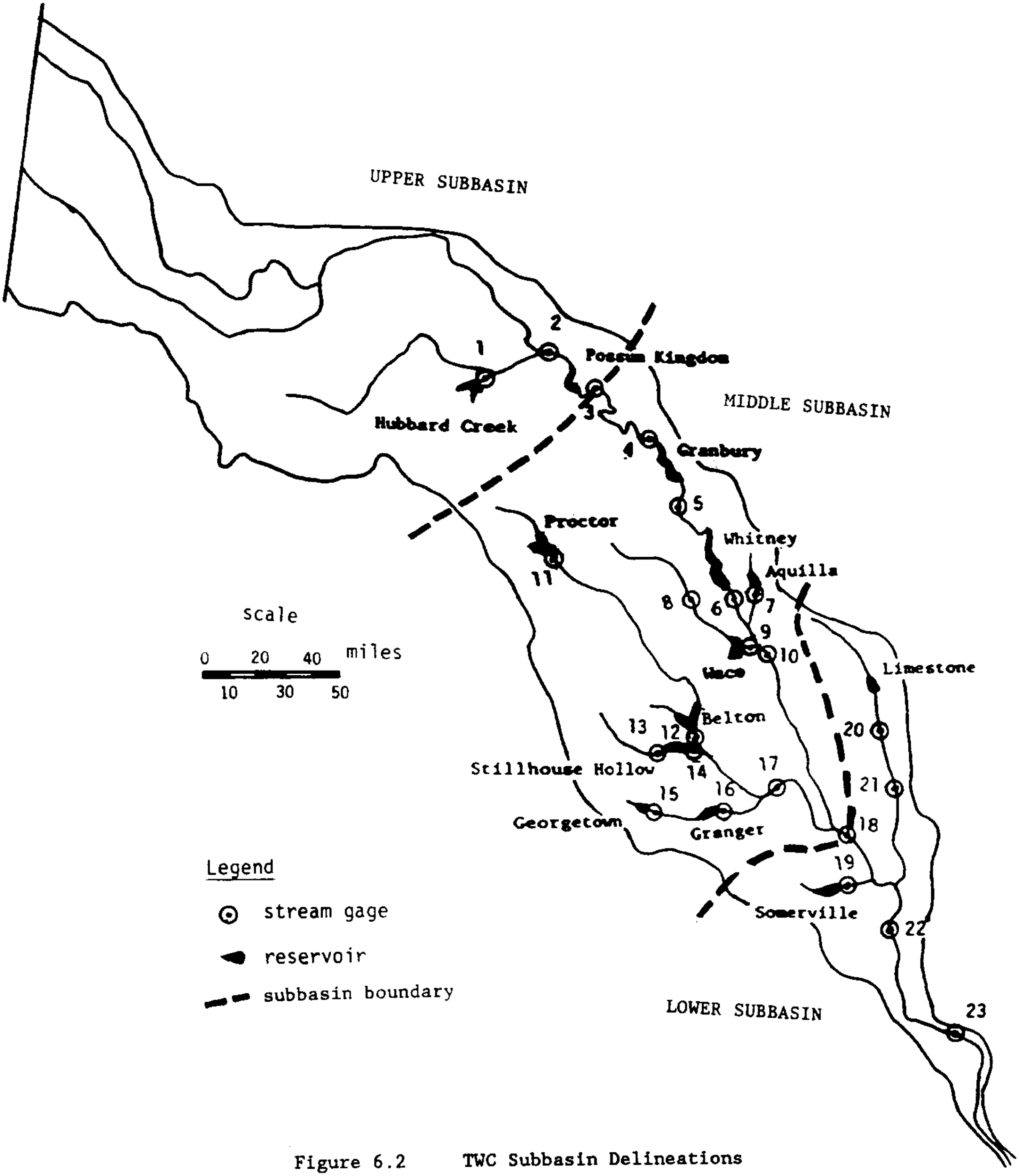


Figure 6.2 TWC Subbasin Delineations

Table 6.3
1984 WATER USE BY CONTROL POINT

Control Point	Surface Water Use							Ground Water Use			Total Use
	Municipal	Manufact.	Steam Elec.	Irrigation	Mining	Livestock	Total	Municipal	Manufact.	Steam Elec.	
					(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				

For purposes of the present study, the 86.75 percent was adopted for both 1984 and 2010. The surface water use in the San Jacinto-Brazos Coastal basin was multiplied by 86.75 percent to estimate the diversion from the Brazos River Basin.

Actual measured hydroelectric power releases during each month in 1984 at Whitney and Possum Kingdom Reservoirs are incorporated in the model input data. Essentially all of the actual releases through the hydroelectric power turbines in 1984 were from conservation storage rather than spills and flood control pool releases.

Table 6.4 presents an annual summary of the 1984 monthly water use and reservoir release data provided as input to HEC-5. Each control point is provided a net diversion which is water permanently removed from the reservoir-stream system. The net diversion represents withdrawals from the reservoir and stream system at locations from the control point upstream to the next control point, minus return flows. Most of the reservoir control points are provided a downstream release. This water is released from the reservoir and is available for downstream diversions. In most cases, the downstream release represents hydroelectric power releases and/or water supply releases to be diverted at downstream locations. The Waco Reservoir downstream release is return flow.

Water use projections for the year 2010, along with other years, are presented by the TDWR (1984). The Brazos River Basin is divided into six zones, with water use projections being developed by zone. In the present study, the projections had to be compiled by control point. The counties were grouped into the six zones. The 1984 county water use, by use category, was increased in proportion to the total zone water use, by use category, to obtain 2010 water use data for each county. The county data was then aggregated in accordance with Table 6.1 to obtain the control point water use data summarized in Table 6.5. The return flow factors used for the 1984 simulation were also used for the 2010 simulation. The monthly distribution factors tabulated in Table 6.2 were also used. The 1984 reservoir release data for the two hydroelectric power projects were used again in the 2010 simulation. An annual summary of the 2010 monthly diversions and downstream releases provided as input data for the model is presented in Table 6.6.

Conservation Operations

In the model, water supply diversions are made from unregulated streamflow as long as sufficient streamflow is available. If the streamflow is inadequate to meet diversion requirements, the model makes additional reservoir releases as required. Multireservoir release decisions are based on balancing the percent depletion in each reservoir. Aquilla, Belton, Stillhouse Hollow, Granger, Limestone, and Somerville Reservoirs were operated in the model to make releases as required to meet diversions at downstream control points. Thus, the simulation is based on the assumption that the 13 reservoirs are used, as needed, to meet demands for all users except those located in the upper basin above the reservoirs. All of the other major water supply reservoirs in the basin are located above the 13 modeled reservoirs. However, in actuality, the 13 reservoirs included in the model are not committed to all the water users assumed in the model.

Table 6.4
1984 DIVERSIONS AND DOWNSTREAM RELEASES

Control Point	Diversion	Return Flow	Net Diversion	Downstream Release
		(acre-feet)		
Hubbard Creek Reservoir	2,198	609	1,589	-
Possum Kingdom Reservoir	62,992	17,600	45,392	108,630
Granbury Reservoir	31,924	2,345	29,579	43,027
Whitney Reservoir	14,095	3,645	10,450	186,355
Aquilla Reservoir	1,256	1,064	192	-
Waco Reservoir	34,729	14,245	20,484	11,568
Waco Gage	18,404	5,978	12,426	-
Proctor Reservoir	32,625	2,748	29,877	-
Belton Reservoir	13,394	5,533	7,861	83,676
Stillhouse Hollow Reservoir	1,872	872	1,000	36,983
Bell County	45,182	17,564	27,618	-
Georgetown Reservoir	229	270	-41	1,329
Granger Reservoir	5,251	7,290	-2,039	-
Cameron Gage	28,089	18,433	9,656	-
Limestone Reservoir	2,818	1,144	1,674	64
Somerville Reservoir	956	496	460	49,133
Bryan Gage	9,574	2,016	7,558	-
Richmond Gage	19,366	17,260	2,106	-
Coast	476,418	-	476,418	-
Total	801,372	119,112	682,260	520,765

Table 6.5
2010 WATER USE BY CONTROL POINT

Control Point	Surface Water Use in Acre-Feet						Total
	Municipal	Manufact.	Steam Elec.	Irrigation	Mining	Livestock	
Hubbard Creek	1,641	-	-	8,699	162	825	11,327
Possum Kingdom	61,439	6,957	12,546	146,542	1,053	7,273	235,810
Granbury	12,820	718	15,490	22,959	1,453	2,430	55,870
Whitney	9,179	1,826	-	1,137	723	702	13,567
Aquilla	1,388	160	-	-	-	1,135	2,683
Waco Reservoir	77,642	13,410	-	13,198	-	3,121	107,371
Waco Gage	-	-	42,463	3,158	1,424	2,071	49,116
Proctor	15,356	44	-	87,686	-	2,761	105,847
Belton	31,767	57	-	5,360	-	1,486	38,670
Stillhouse	3,838	80	-	150	-	475	4,543
Bell County	101,586	5,544	-	2,330	-	1,032	110,492
Georgetown	1	-	-	-	1,905	241	2,147
Granger	11,540	8	-	469	595	1,478	14,090
Cameron Gage	5,109	8,466	25,600	5,203	-	1,344	45,722
Limestone	11,172	-	-	-	630	2,464	14,266
Somerville	-	-	-	728	630	1,800	3,158
Bryan Gage	20,955	1,121	-	10,729	630	3,821	37,256
Richmond Gage	31,378	1,079	44,500	5,024	2,205	8,891	93,085
Coast	19,595	576,500	34,300	18,914	-	1,148	650,455
In-basin Sub-total	416,406	615,970	174,899	332,286	11,410	44,498	1,595,475
Upper Basin	80,288	8,429	13,200	24,209	81	3,141	129,348
In-basin Total	496,694	624,399	188,099	356,495	11,491	47,639	1,724,823
Coast (San Jacinto-Brazos Coastal Basin)	134,100	249,100	-	-	177,900	800	561,890
Coast Total	153,695	825,600	34,300	18,914	177,900	1,948	1,212,345

Table 6.6
2010 DIVERSIONS AND DOWNSTREAM RELEASES

Control Point	Diversion	Return Flow	Net Diversion	Downstream Release
		(acre-feet)		
Hubbard Creek Reservoir	11,327	914	10,413	-
Possum Kingdom Reservoir	236,267	27,845	208,422	108,630
Granbury Reservoir	55,870	4,453	51,417	-
Whitney Reservoir	13,567	7,061	6,506	186,355
Aquilla Reservoir	2,683	2,110	573	-
Waco Reservoir	107,371	37,555	69,816	35,266
Waco Gage	49,116	2,084	47,031	-
Proctor Reservoir	105,847	5,991	99,856	-
Belton Reservoir	38,670	12,855	25,815	-
Stillhouse Hollow Reservoir	4,543	2,170	2,373	-
Bell County	110,492	33,996	76,496	-
Georgetown Reservoir	2,147	765	1,382	-
Granger Reservoir	14,090	16,660	-2,570	-
Cameron Gage	45,722	7,081	38,641	-
Limestone Reservoir	14,266	2,387	11,879	-
Somerville Reservoir	3,158	1,634	1,524	-
Bryan Gage	37,256	4,235	33,021	-
Richmond Gage	93,085	46,991	46,094	-
Coast	1,212,345	-	1,212,345	-
	2,157,822	216,787	1,941,034	330,251

Hydroelectric power operations are approximated in the simulation by repeating the actual releases through the turbines from conservation storage made during 1984.

Flood Control Operations

Flood control operations occur whenever water encroaches into a flood control pool. As long as the capacity of the flood control pool is not exceeded, releases are based on emptying the pool as quickly as possible without contributing to flooding downstream. The maximum allowable discharges tabulated in Table 6.7 are based on information provided in the reservoir regulation manuals (USACE 1971, 1973, 1974) supplemented by additional information provided by FWD personnel. Waco, Belton, Stillhouse Hollow, Georgetown, and Somerville Reservoirs have zoned flood control pools. Maximum allowable discharges vary depending upon which zone the reservoir water surface level falls within. Reservoir releases are also limited by maximum rate of change in release rates and other criteria and by outlet capacities. Multiple reservoir release decisions are based on approximately balancing the percentage of the flood control pool occupied in each reservoir. When the water surface is forecasted to rise above the top of flood control pool elevation, releases are made in accordance with procedures outlined by the USACE (1959). The objective is to minimize downstream flooding while assuring that the maximum design water surface is not exceeded.

Since floods are short time period events, flood control operations are typically simulated using a computational interval of a day or less. The monthly interval used in the present study is somewhat approximate for flood control.

HEC-5 computes flood control releases based on input values of maximum allowable discharges at reservoir and downstream control points. The values used in the model are tabulated in the last column of Table 6.7. The actual maximum allowable discharges are simplified to a single value at each control point. When the flood control pool rises above the top of flood control pool elevation, releases are set equal to inflows. Multiple reservoir release decisions are made by HEC-5 based on approximately balancing the percent of the flood control pools occupied at each reservoir.

Overview of Simulation Study

The objective of the HEC-5 simulation study is to evaluate the hydrologic impacts of reallocating storage capacity between flood control and conservation purposes. A model, or data set, representing surface water use and supply in the basin was developed and coded for input to HEC-5. HEC-5 was run for alternative storage allocation plans. The HEC-5 output provided basic data for evaluating the storage allocation plans. Several types of analyses of the simulation output were performed, including analyses of the frequency of filling flood control storage capacity and the frequency of conservation storage drawdowns.

A simplifying assumption in the simulation modeling was the inclusion of only 13 reservoirs. All water users adjacent to and downstream of the 13 reservoirs were supplied by unregulated flows and the 13 reservoirs. Flood control operations are also approximated since the model uses a monthly, rather

Table 6.7
MAXIMUM ALLOWABLE DISCHARGES FOR FLOOD CONTROL OPERATIONS

Control Point (Reservoir)	Flood Pool Elevations (feet msl)	Actual Allowable Discharge (cfs)	Model Allowable Discharge (cfs)
Gage 387-Brazos River below Whitney Dam	-	25,000	25,000
Gage 389-Aquilla Creek below Aquilla Dam	-	3,000	3,000
Gage 400-Bosque River below Waco Dam (Waco Reservoir)	455 -457.4	3,000	30,000
	457.4-460	5,000	30,000
	460 -470	10,000	30,000
	470 -500	30,000	30,000
Gage 412-Leon River below Proctor Dam	-	2,000	2,000
Gage 425-Little River near Little River (Belton Reservoir)	594 -596.5	3,000	3,000
	596.5-610	6,000	3,000
	610 -631	10,000	3,000
Gage 425-Little River near Little River (Stillhouse Hollow Reservoir)	622 -625	3,000	3,000
	625 -666	10,000	3,000
Gage 426-San Gabriel below Georgetown Dam (Georgetown Reservoir)	791 -795	3,000	3,000
	795 -834	6,000	3,000
Gage 431-San Gabriel below Granger Dam	-	6,000	6,000
Gage 434-Little River at Cameron	-	10,000	10,000
Gages 443 & 444-Yequa & Davidson Creeks (Somerville Reservoir)	238 -243	1,000	-
	243 -258	2,500	-
Gage 401-Brazos River at Waco	-	60,000	60,000
Gage 439-Brazos River at Bryan	-	60,000	60,000
Gage 456-Brazos River at Richmond	-	60,000	60,000

than daily, time period. However, the simulation study stills provides a valid and meaningful comparative evaluation of the impacts of storage reallocations.

Simulation Runs and Results

Simulation Runs

Results are summarized here for seven HEC-5 simulation runs involving two alternative water use scenarios and six storage allocation plans. Years 1984 and 2010 conditions of water use and reservoir sedimentation were simulated assuming the present allocation of storage capacity in each reservoir (runs 1 and 2). The top of conservation pool elevations are cited in Table 5.2. Water surface elevation versus area and capacity tables for 1984 and 2010 conditions of sedimentation were incorporated in the model, along with 1984 and 2010 water use diversions.

Simulation of 2010 conditions of water use and sedimentation was repeated for five alternative plans for reallocating storage capacity. As discussed in Chapter 2, the USACE is authorized to reallocate storage capacity in its reservoirs without obtaining congressional approval as long as the reallocation does not exceed either 50,000 acre-feet or 15 percent of the flood control capacity. Storage capacity was reallocated, both permanently (run 4) and seasonally (runs 5 and 6), in seven reservoirs to meet this criteria. The seven reservoirs are Whitney, Aquilla, Waco, Belton, Stillhouse Hollow, Granger, and Somerville. Two alternative seasonal rule curve plans involved raising the top of conservation pool alternatively during the periods April through October (run 5) and May through October (run 6). Another reallocation plan (run 3) involved a permanent conversion of 50,000 acre-feet of flood control capacity in Waco Reservoir to water supply, without changing the other reservoirs.

Flood control and conservation capacities for each of the reservoirs are reproduced in Table 6.8 for 1984 and 2010 conditions of sedimentation. The amounts of storage reallocation and resulting conservation storage, for runs 4 through 6, are shown in Table 6.9. Storage capacity was reallocated only in the seven reservoirs included in Table 6.9. For the seasonal rule curve plans, the top of conservation pool was raised at the beginning of either April or May and lowered at the end of October. The winter and summer storage capacities are those shown in Tables 6.8 and 6.9, respectively. The general form of the rule curve is illustrated by Figure 6.3.

The reallocation plans described above involved permanent or seasonal conversions of flood control capacity to water supply. The final reallocation plan (run 7) is a seasonal rule curve in which conservation capacity is reallocated to flood control in April, and then flood control capacity is reallocated to conservation during May through October. Thus, the top of conservation pool is lowered during April and raised during May through December as illustrated by Figure 6.4. The seasonal reallocations consist of 15% of the conservation capacity in seven reservoirs (Whitney, Aquilla, Waco, Belton, Stillhouse Hollow, Granger, and Somerville). As discussed in Chapter 7, this reallocation plan (run 7) simultaneously increases water supply firm yield and flood control recurrence intervals.

Table 6.8
RESERVOIR STORAGE CAPACITY

	Condition of Sedimentation			
	1984		2010	
	Storage Capacity (acre-feet)			
Reservoir	Conservation	Flood Control	Conservation	Flood Control
Hubbard Creek	308,070	-	300,730	-
P.K. (inactive 875 ft)	544,510	-	477,600	-
P.K. (inactive 970 ft)	341,870	-	322,830	-
Granbury (inactive 640 ft)	137,400	-	113,850	-
Granbury (inactive 675 ft)	95,250	-	85,320	-
Whitney (inactive 449 ft)	599,160	1,368,400	574,520	1,364,250
Whitney (inactive 520 ft)	238,170	1,368,400	227,950	1,364,250
Aquilla	52,210	93,530	47,340	91,720
Waco (conservation 455 ft)	133,750	566,030	108,880	555,320
Waco (conservation 462 ft)	186,330	513,460	157,790	506,410
Proctor	46,850	312,700	31,400	310,100
Belton	428,250	642,900	372,700	640,200
Stillhouse Hollow	225,310	393,380	209,700	391,220
Georgetown	36,540	93,480	34,540	91,900
Granger	64,190	178,000	57,070	173,720
Limestone	218,050	-	214,060	-
Somerville	154,450	344,110	146,140	339,070

Table 6.9
STORAGE CAPACITY REALLOCATIONS BASED ON 2010 SEDIMENTATION

Reservoir	2010 Capacity Before Reallocation: Active Conservation (acre-feet)	2010 Capacity Before Reallocation: Flood Control (acre-feet)	Capacity Reallocated (acre-feet)	Capacity Reallocated (% F.C.)	Capacity Reallocated % Cons
P.K. (inactive 875 ft)	322,830	-0-	-0-	-0-	-0-
Granbury (inactive 675 ft)	85,320	-0-	-0-	-0-	-0-
Whitney (inactive 520 ft)	227,950	1,364,250	50,000	3.7	21.9
Aquilla	47,340	91,720	13,760	15.0	29.1
Waco (conservation 455 ft)	108,880	555,320	50,000	9.0	45.9
Proctor	31,400	310,100	-0-	-0-	-0-
Belton	372,700	640,200	50,000	7.8	13.4
Stillhouse Hollow	209,700	391,220	50,000	12.8	23.8
Georgetown	34,540	91,900	-0-	-0-	-0-
Granger	57,070	173,720	26,060	15.0	45.7
Limestone	214,060	-0-	-0-	-0-	-0-
Somerville	146,140	339,070	50,000	14.7	34.2
Total	1,857,930	3,957,500	289,820	7.3	15.6

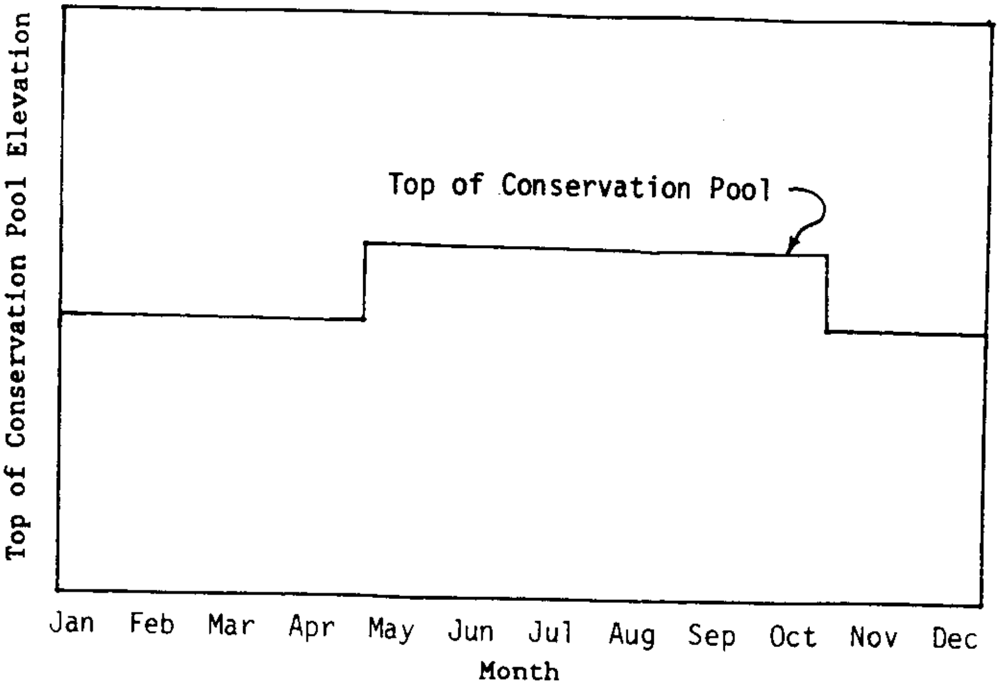


Figure 6.3 **Seasonal Rule Curve**

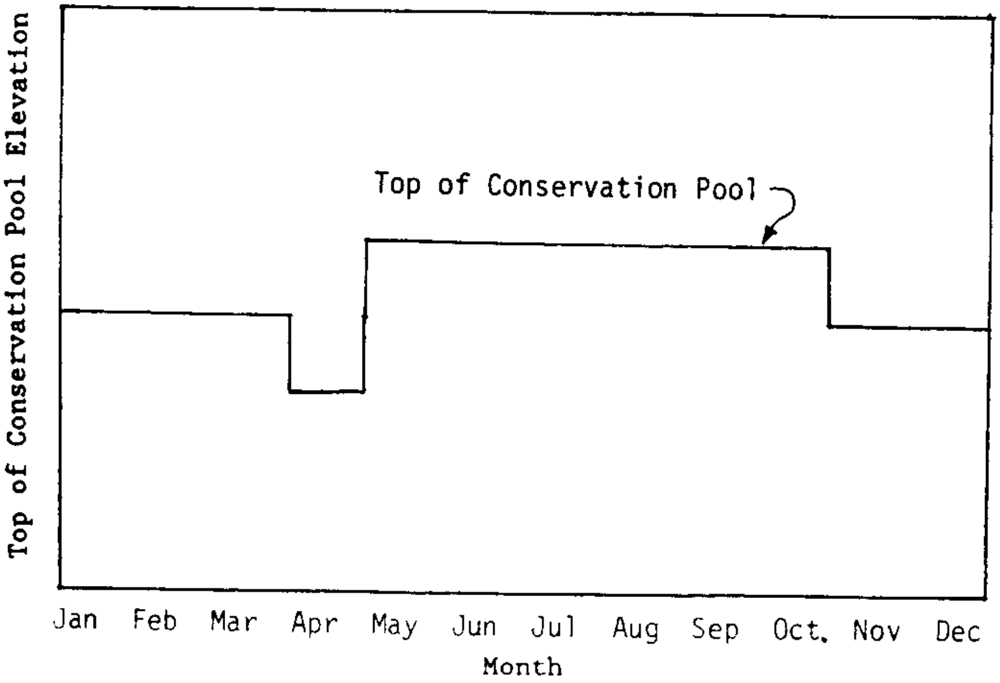


Figure 6.4 **Seasonal Rule Curve**

The seven alternative simulation runs are described below.

Run 1: The first simulation reflects 1984 conditions of water use and reservoir sedimentation and no storage reallocations.

Run 2: The second simulation reflects 2010 conditions of water use and reservoir sedimentation and no storage reallocations.

Runs 3 through 7 reflect 2010 conditions of water use and reservoir sedimentation and the following alternative reallocation plans.

Run 3: Run 3 is identical to Run 2 except 50,000 acre-feet of flood control capacity is permanently reallocated to conservation in Waco Reservoir.

Run 4: Run 4 reflects a permanent reallocation of storage capacity from flood control to conservation in seven reservoirs. In each reservoir, the reallocation is 50,000 acre-feet or 15 percent of the flood control capacity, whichever is less.

Run 5: Run 5 is identical to Run 4 except the reallocation is seasonal rather than permanent. The top of conservation pool is raised from April through October.

Run 6: Run 6 is identical to Run 5 except the top of conservation pool is raised from May through October.

Run 7: Run 7 reflects a seasonal reallocation of 15% conservation capacity in seven reservoirs. The top of conservation pool is lowered in the single month of April and raised in May through October.

System Water Balance

Table 6.10 is a water balance for the entire system. In the model, the total streamflow input leaves the system as water use diversions, reservoir evaporation losses, or flow into the Gulf of Mexico. Table 6.10 consists of flows expressed in cfs as averages over the 85-year simulation period.

The total inflow to the system, which is the naturalized flow at the Richmond gage, averages 7,887 cfs over the 85-year simulation period. In run 1, which reflects 1984 conditions of water use and sedimentation, 12.0% of the streamflow is diverted for beneficial use, 7.1% is loss through reservoir evaporation, and 80.9% flows into the Gulf of Mexico. With 2010 conditions reflected in run 2, 31.6% of the streamflow is diverted for beneficial use, 6.2% is loss through reservoir evaporation, and 62.2% becomes flow to the Gulf. The diversions are actually net diversions which equal water withdrawals minus return flows. The 1984 water demand of 948 cfs was met with shortages of only 5 cfs (run 1). The 2010 demand of 2,681 cfs compared to actual diversions averaging 2,496 cfs results in a shortage volume equivalent to an average flow of 185 cfs over the simulation period (run 2). Thus, the volume of the shortage is 6.9% of the diversion target.

Water balances for the alternative storage reallocation plans are also presented in Table 6.10. Reallocation of 50,000 acre-feet from flood control to water supply in Waco Reservoir (run 3) has negligible impact on the overall

Table 6.10
SYSTEM WATER BALANCE FOR ALTERNATIVE SIMULATIONS

Simulation Run	System Inflow (cfs)	Flow to Gulf (cfs)	Reservoir Evaporation (cfs)	Actual Diversions (cfs)	Diversion Shortages (cfs)
1	7,887	6,383	561	943	5
2	7,887	4,904	487	2,496	185
3	7,887	4,898	494	2,495	186
4	7,887	4,872	522	2,493	188
5	7,887	4,876	517	2,494	187
6	7,887	4,879	514	2,494	187
7	7,887	4,896	496	2,495	186

Notes:

Run 1 - 1984 simulation with existing storage allocation
Run 2 - 2010 simulation with existing storage allocation
Run 3 - 2010 simulation with Waco Reservoir permanent reallocation
Run 4 - 2010 simulation with seven reservoir reallocation
Run 5 - 2010 simulation with Apr-Oct seasonal reallocation
Run 6 - 2010 simulation with May-Oct seasonal reallocation
Run 7 - 2010 simulation with May-Oct seasonal reallocation and April lowered

Water use diversion targets are 948 cfs for the 1984 simulation (Run 1) and 2,681 cfs for the 2010 simulation (Runs 2-7).

system water balance. The permanent and seasonal reallocations at the seven reservoirs (runs 4,5, and 6) result in a 5.5% to 7.2% increase in reservoir evaporation and corresponding decrease in flow to the Gulf. Actual diversions and diversion shortages are essentially unaffected by the storage reallocations. The seasonal reallocation from water supply to flood control has no impact on diversions and diversion shortages. Likewise, the system water balance for run 7 is similar to the other reallocations.

Streamflow

Flow duration curves at the Cameron, Waco, and Richmond gages and the coast for the naturalized streamflows and streamflows computed for 1984 conditions (run 1) and 2010 conditions (run 2) are plotted in Figures 6.5 through 6.8. Streamflow hydrographs at the four locations for 2010 conditions (run 2) are plotted in Figures 6.9 through 6.12.

End-of-month Storage

Storages for each of the 13 reservoirs for simulation run 2 are plotted in Figures 6.13 through 6.25. The total system storages for simulation runs 1 through 7 are plotted in Figures 6.26 through 6.32. The total system storage consists of the summation of the storage contents in each of the 13 reservoirs at the end of each month of the simulation.

The summation of accumulative storage capacities at top of inactive pool, top of conservation pool, and top of flood control pool are indicated in Table 6.11. Total system storages of 579,000 acre-feet and 510,000 acre-feet represent all 13 active conservation pools being empty simultaneously, for 1984 and 2010 sediment conditions, respectively.

Table 6.12 shows the mean and standard deviation of the end-of-month system storage totals for each of the seven simulation runs. The minimum and maximum end-of-month total system storage to occur during the 85-year simulation period are also shown.

System storage versus duration relationships are presented in Table 6.13 and Figure 6.33. Total system end-of-month storage values are related to the percentage of the 1,020 months in the simulation period for which the storage values are equalled or exceeded.

Flood Control Storage Frequency Analysis

A procedure was developed for estimating the exceedence probability or recurrence interval associated with filling a flood control pool to various levels. The end-of-month storages computed with HEC-5 provided the input data for the frequency analysis procedure. The procedure was used to compute the recurrence interval for filling a flood control pool to full capacity, associated with alternative storage allocation plans. The full flood control pool recurrence interval served as an index for comparing the level of flood protection provided by alternative storage capacity allocations.

Flood control operating policies are based on making no releases which contribute to downstream flooding conditions, as long as the flood control storage capacity is not exceeded. When the flood control pool is overtopped

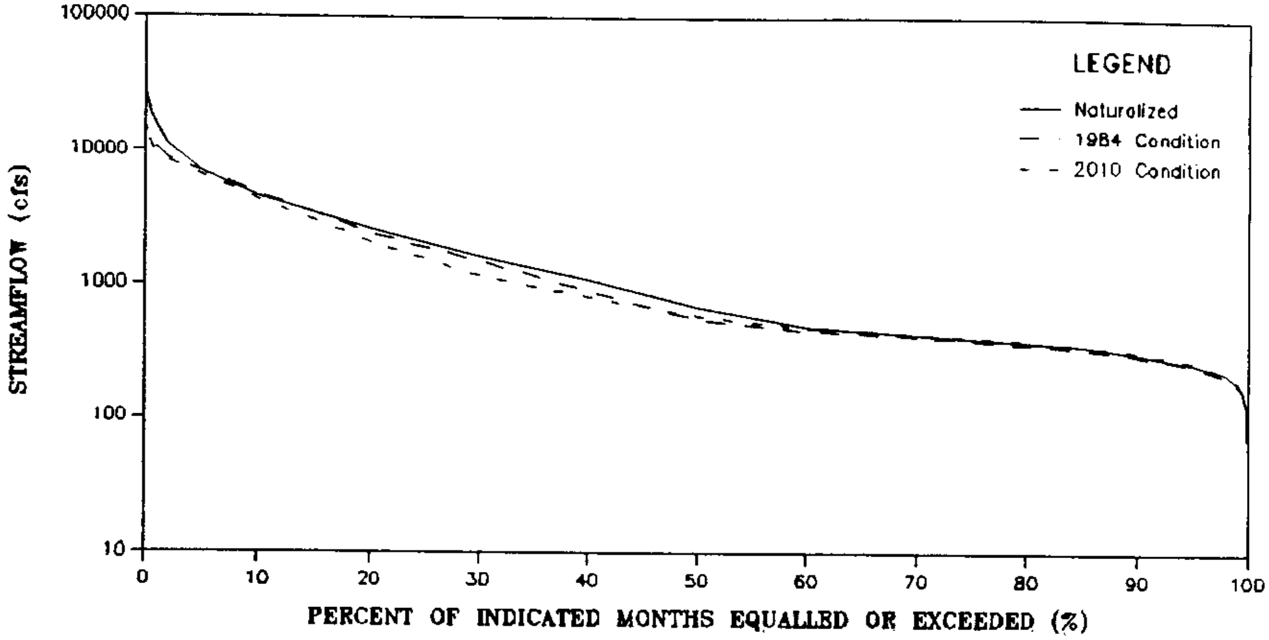


Figure 6.5 Flow Duration Curves at Cameron Gage

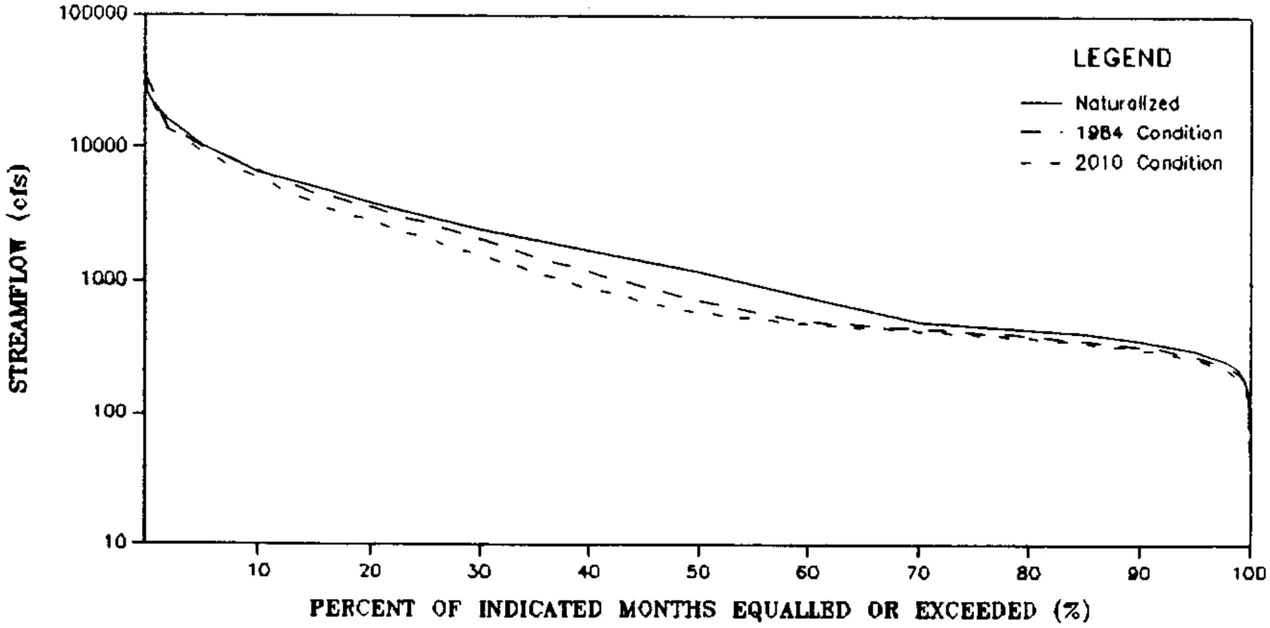


Figure 6.6 Flow Duration Curves at Waco Gage

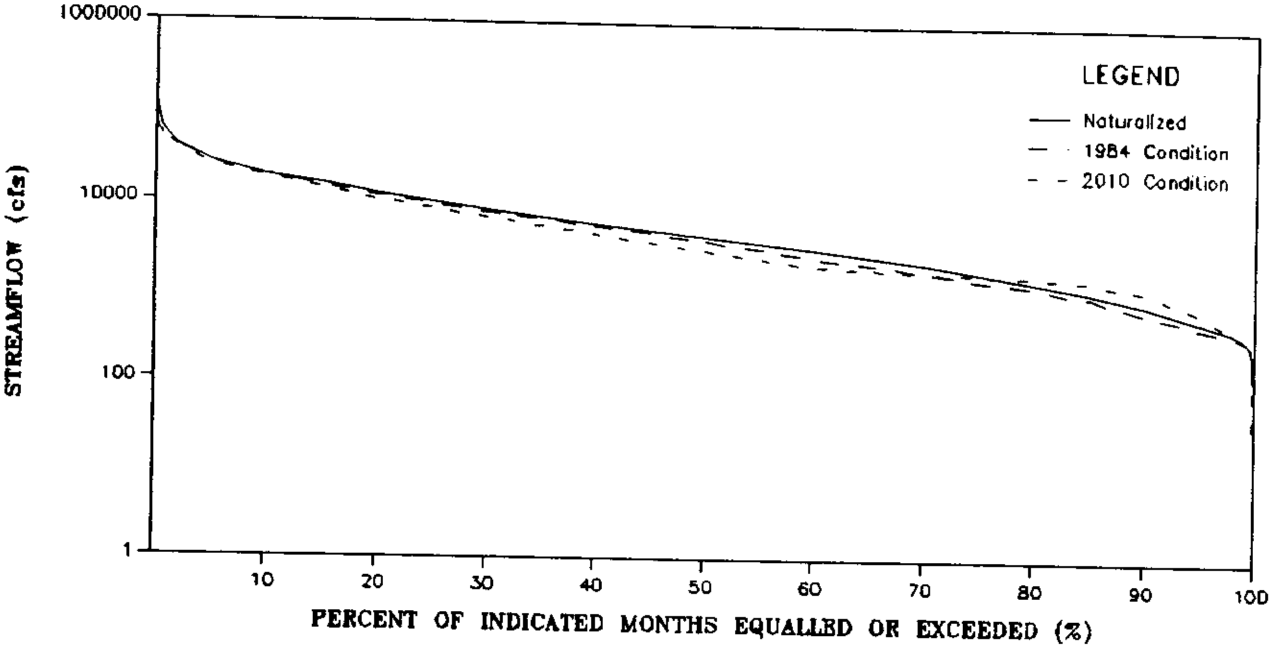


Figure 6.7 Flow Duration Curves at Richmond Gage

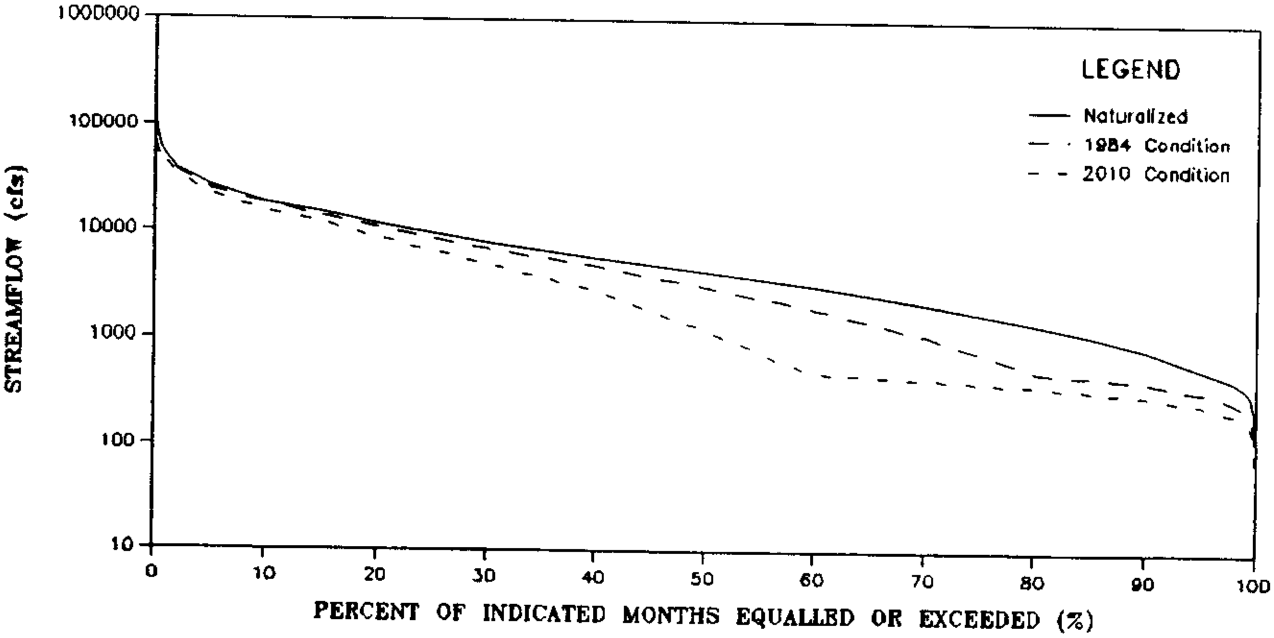


Figure 6.8 Flow Duration Curves at Coast

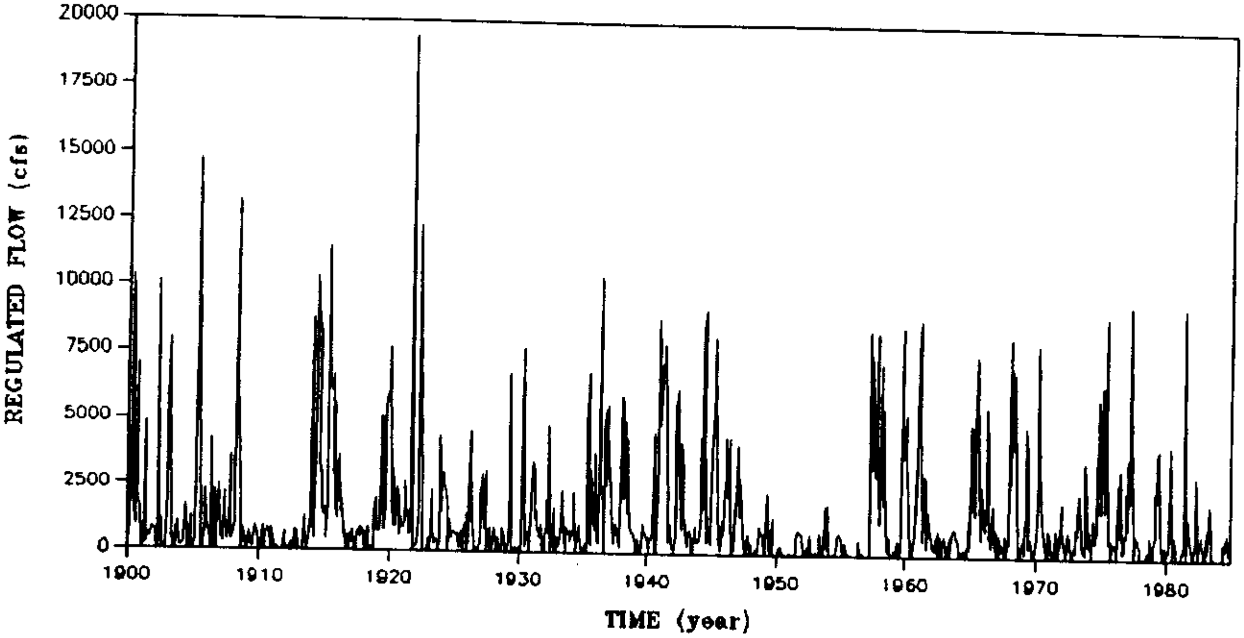


Figure 6.9 **Regulated Flow Hydrograph at Cameron Gage, 2010 Water Use Simulation (Run 2)**

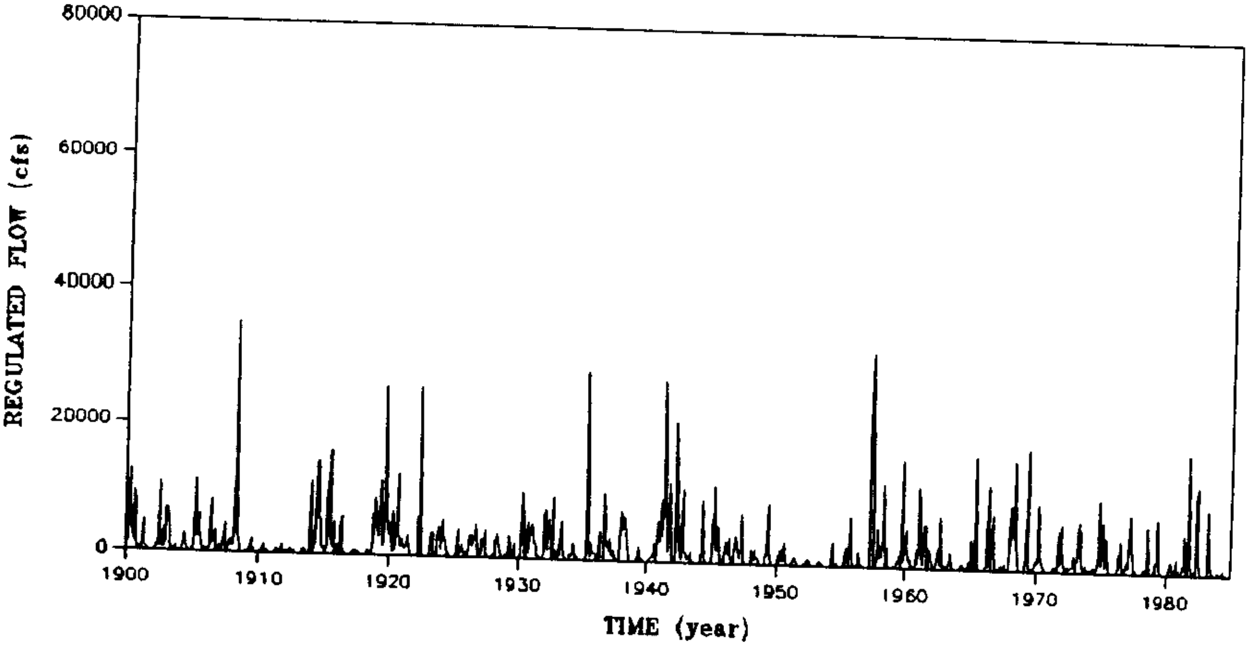


Figure 6.10 Regulated Flow Hydrograph at Waco Gage, 2010 Water Use Simulation (Run 2)

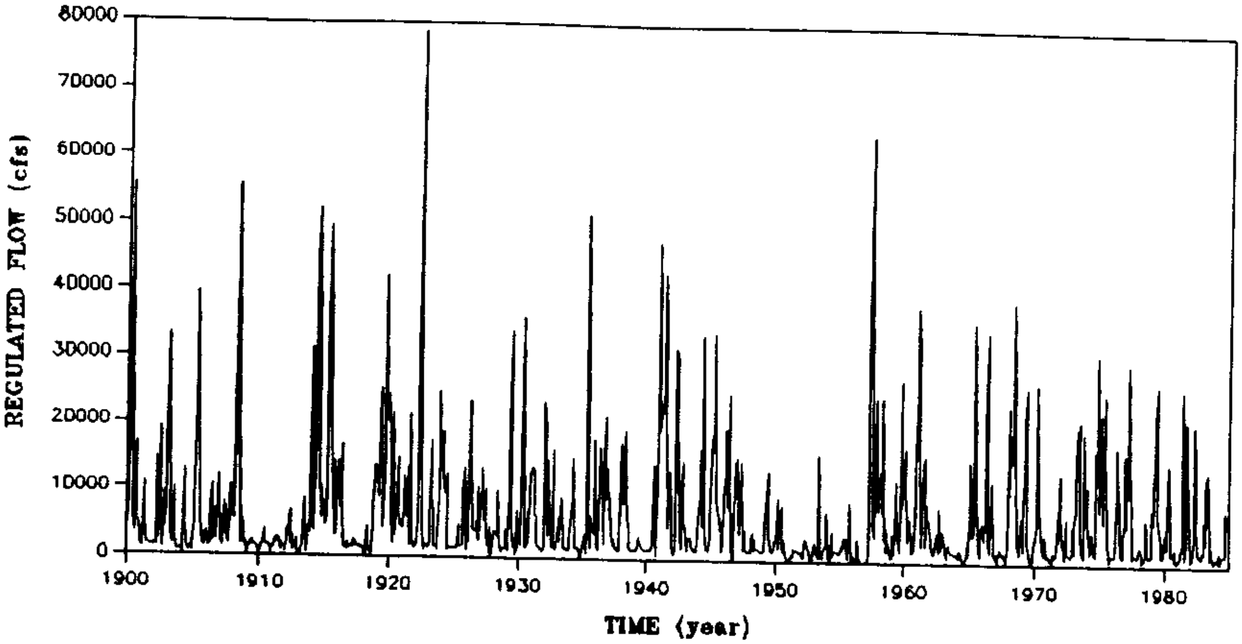


Figure 6.11 Regulated Flow Hydrograph at Richmond Gage, 2010 Water Use Simulation (Run 2)

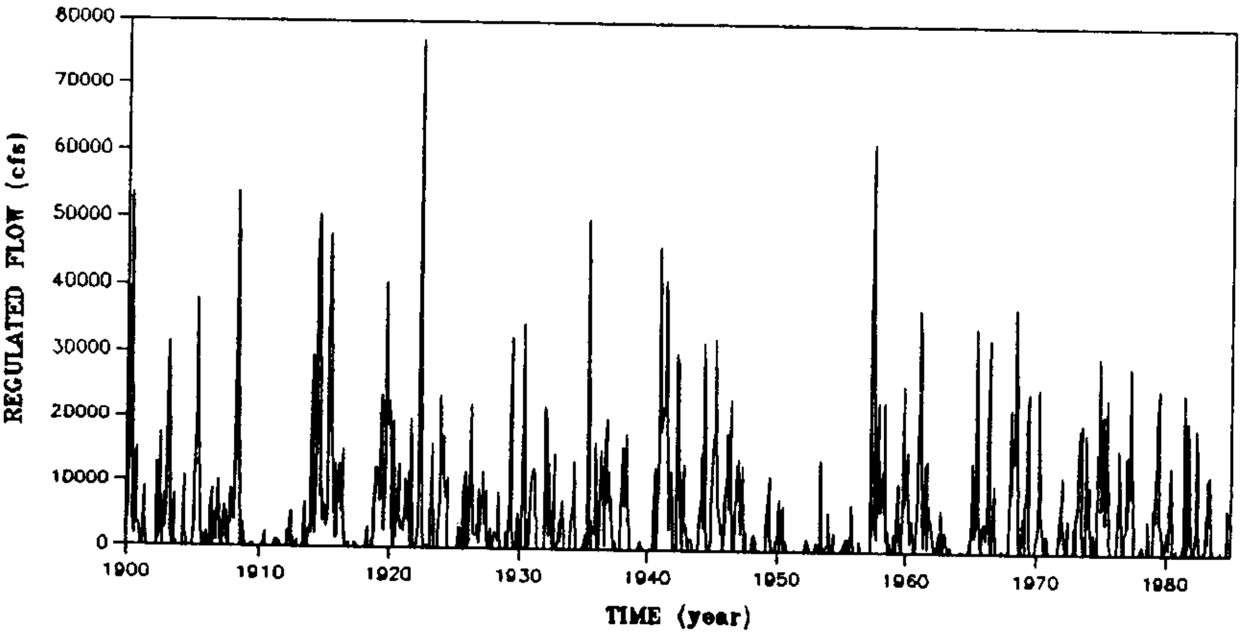


Figure 6.12 Regulated Flow Hydrograph at Coast, 2010 Water Use Simulation (Run 2)

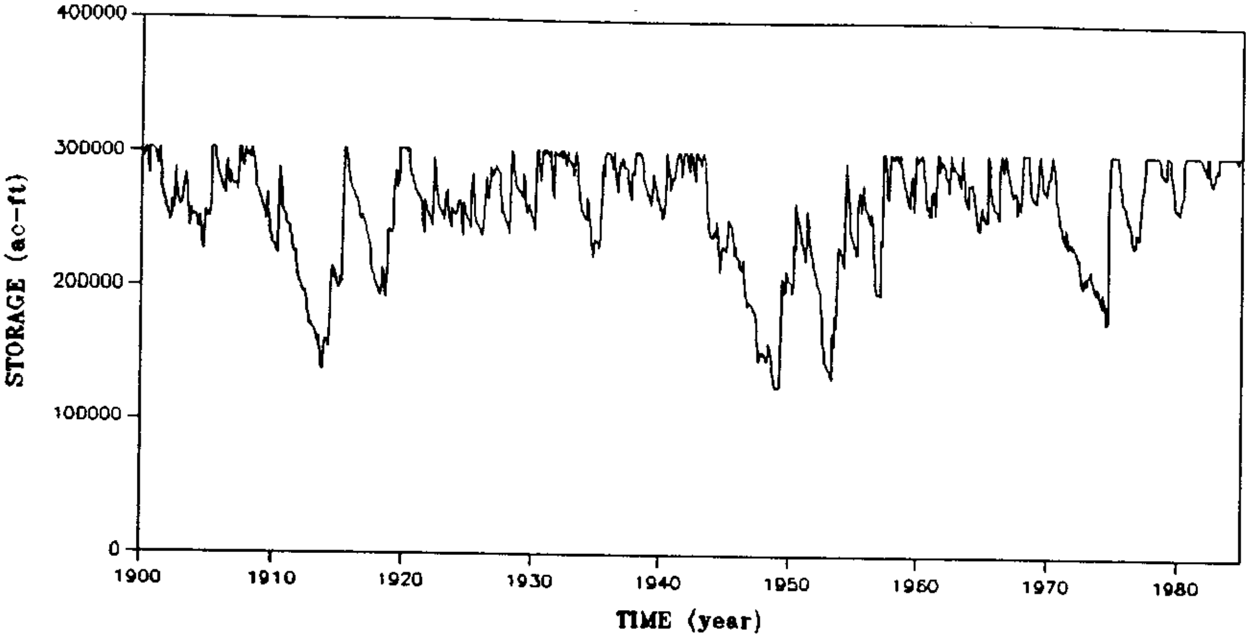


Figure 6.13 **Hubbard Creek Reservoir Storage Hydrograph, 2010 Water Use Simulation (Run 2)**

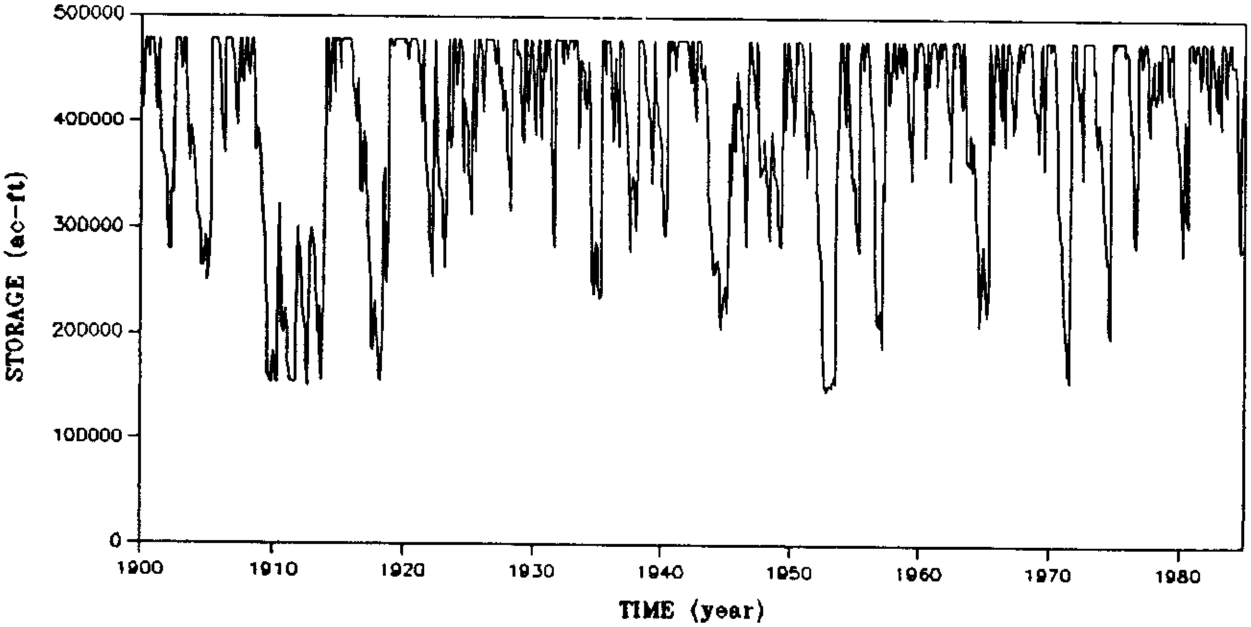


Figure 6.14 Possum Kingdom Reservoir Storage Hydrograph, 2010 Water Use Simulation (Run 2)

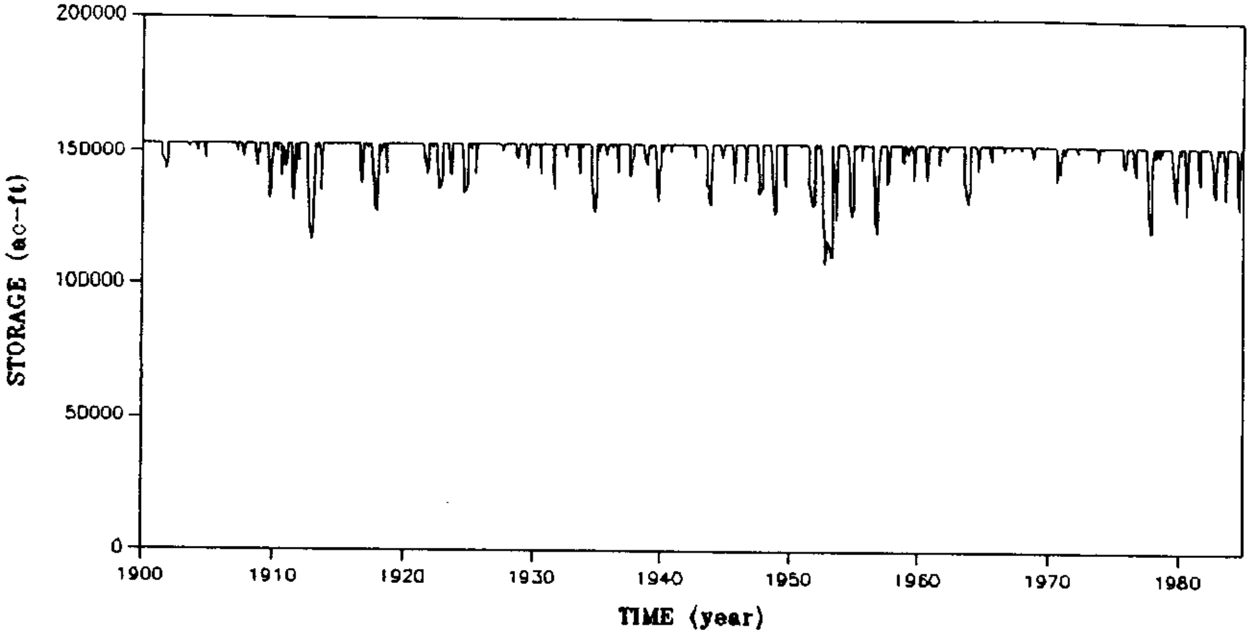


Figure 6.15 Granbury Reservoir Storage Hydrograph, 2010 Water Use Simulation (Run 2)

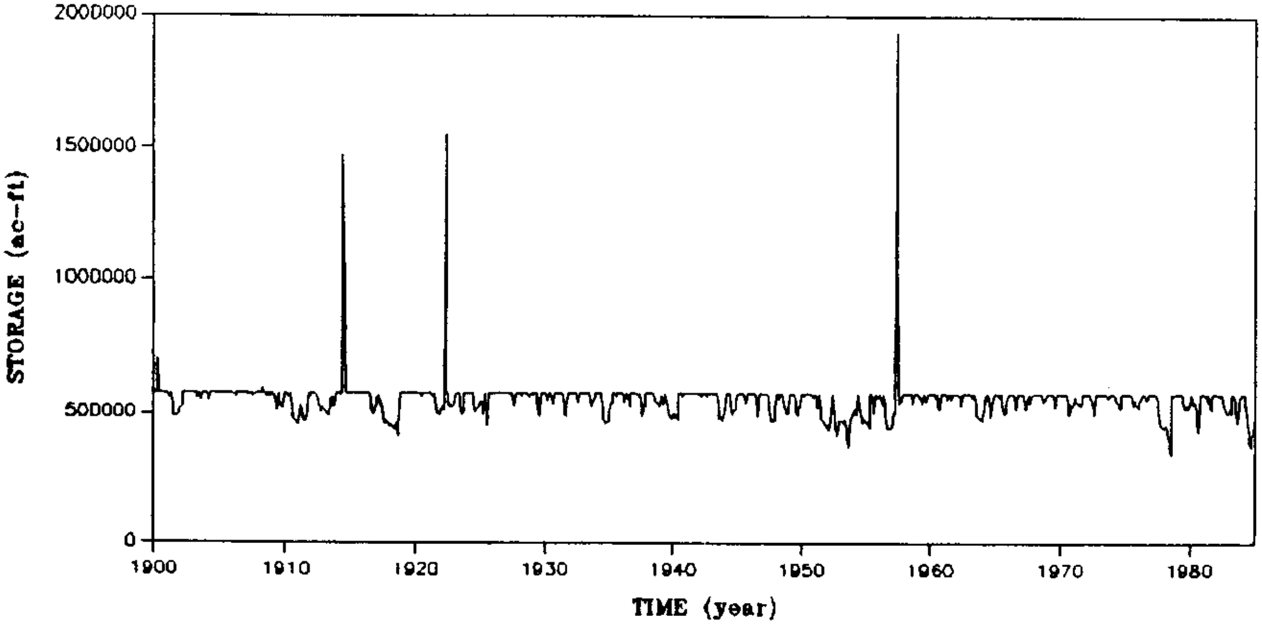


Figure 6.16 Whitney Reservoir Storage Hydrograph, 2010 Water Use Simulation (Run 2)

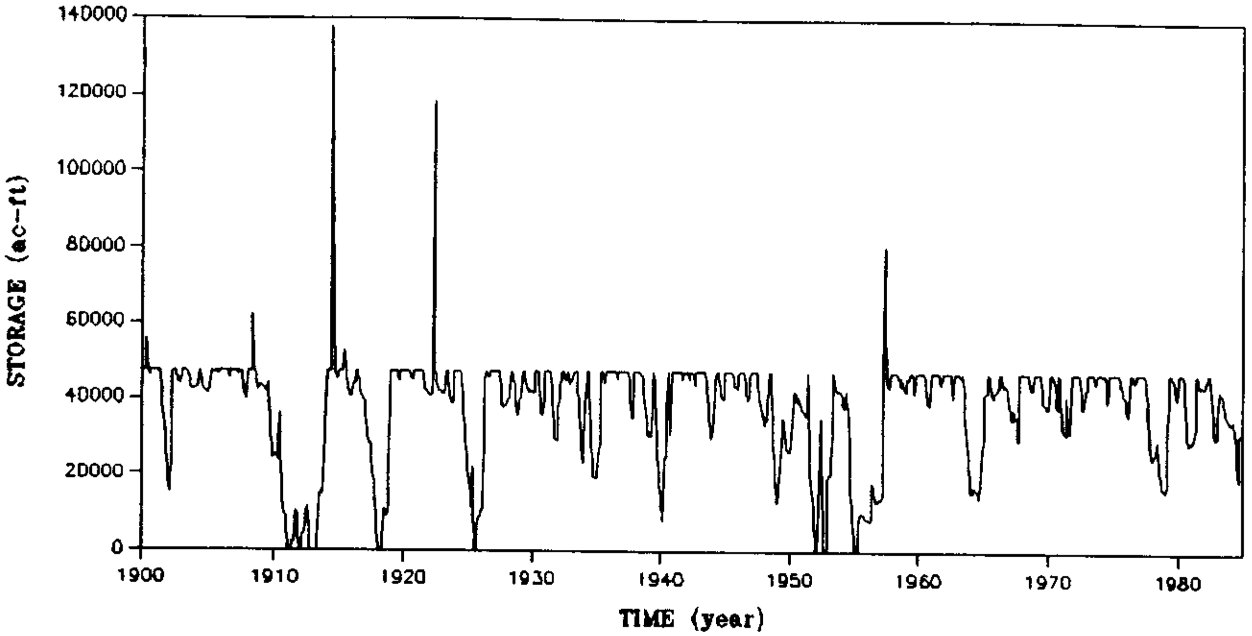


Figure 6.17 Aquilla Reservoir Storage Hydrograph, 2010 Water Use Simulation (Run 2)

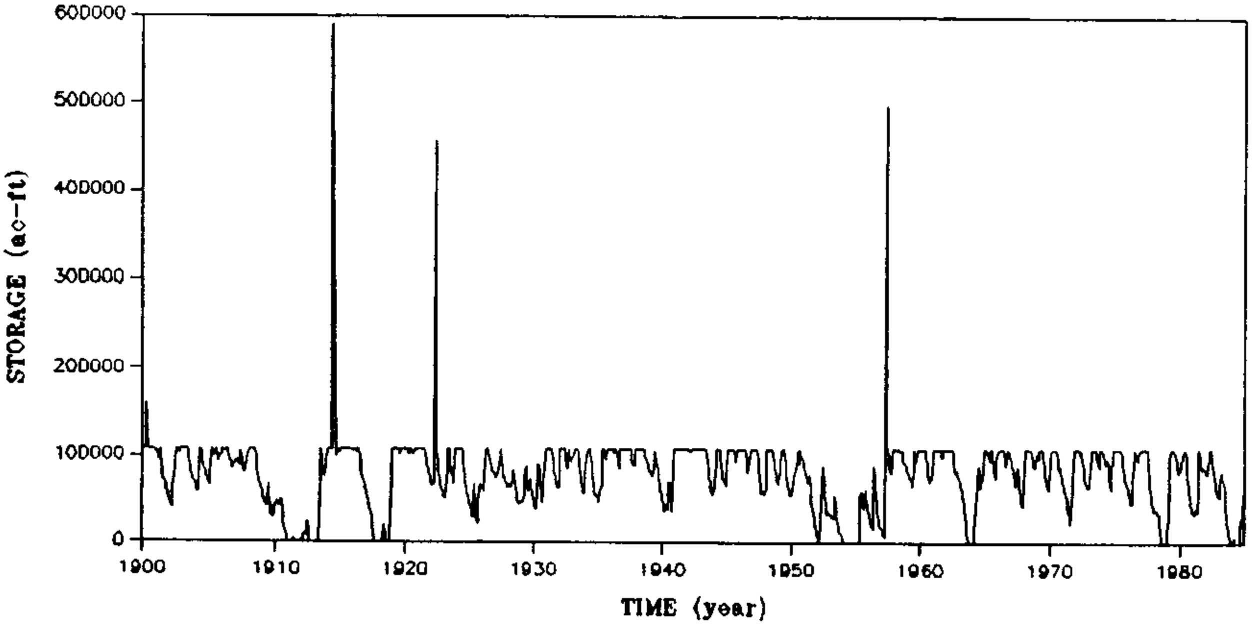


Figure 6.18 Waco Reservoir Storage Hydrograph, 2010 Water Use Simulation (Run 2)

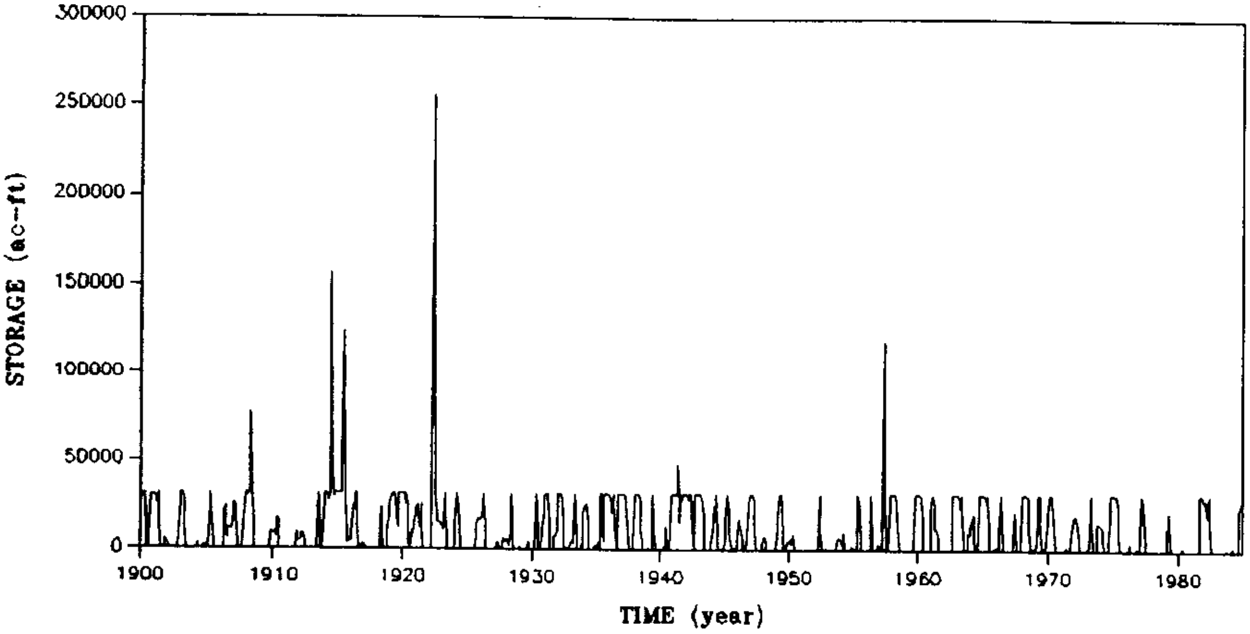


Figure 6.19 Proctor Reservoir Storage Hydrograph, 2010 Water Use Simulation (Run 2)

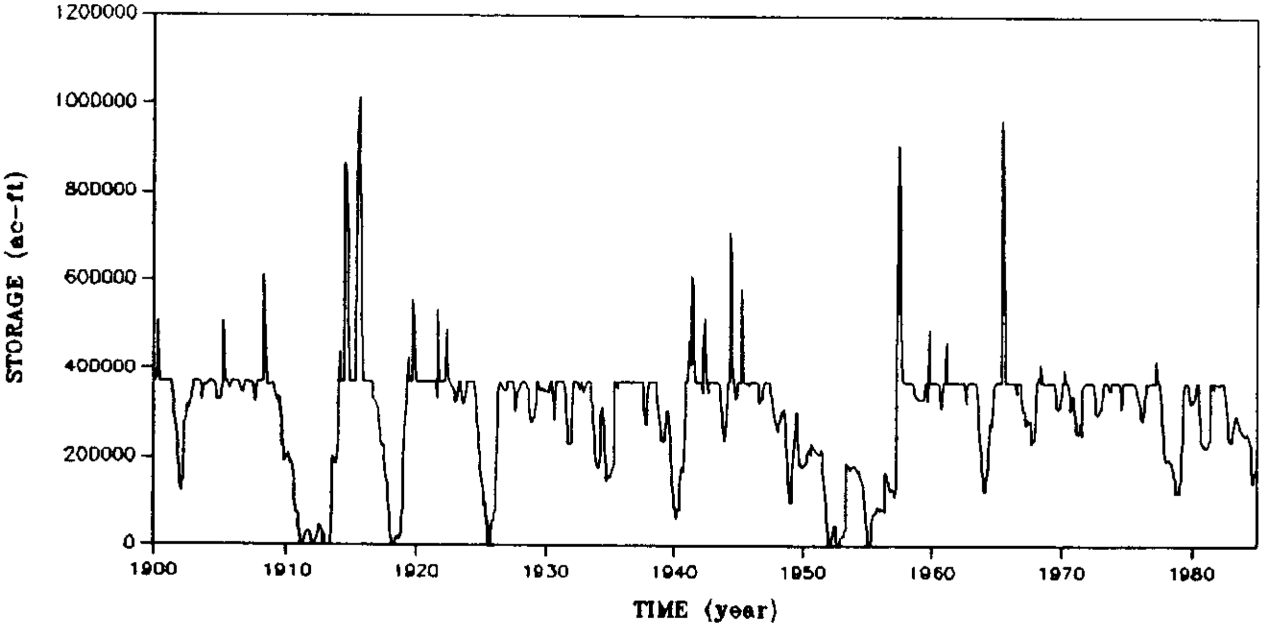


Figure 6.20 Belton Reservoir Storage Hydrograph, 2010 Water Use Simulation (Run 2)

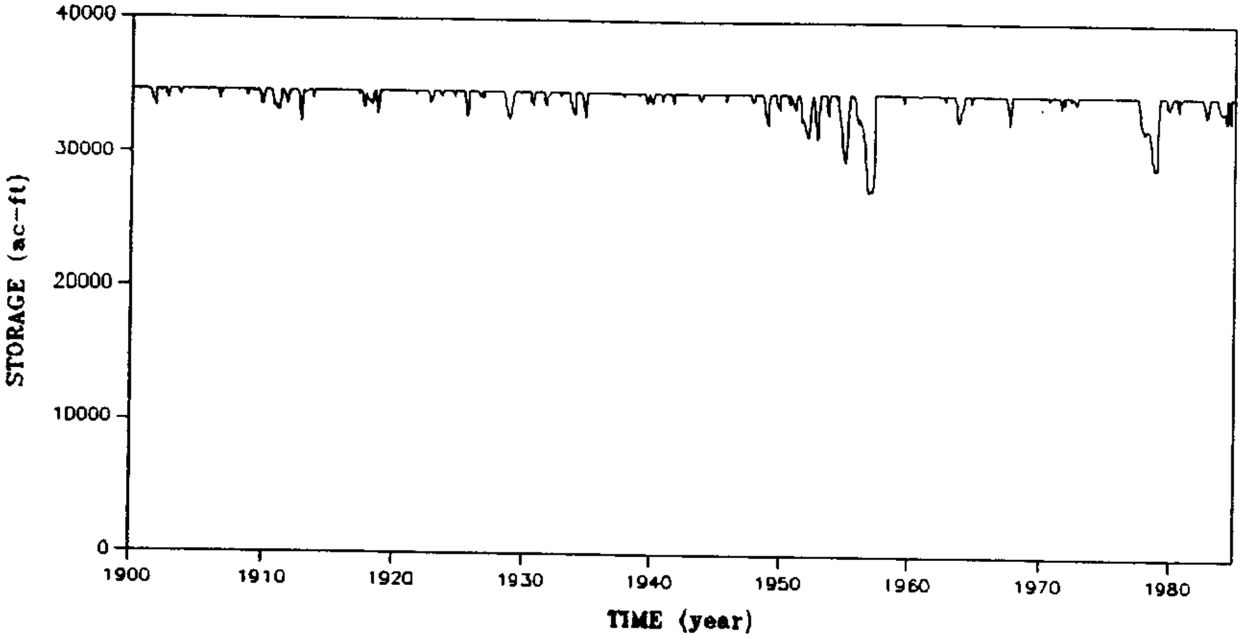


Figure 6.22 **Georgetown Reservoir Storage Hydrograph, 2010 Water Use Simulation (Run 2)**

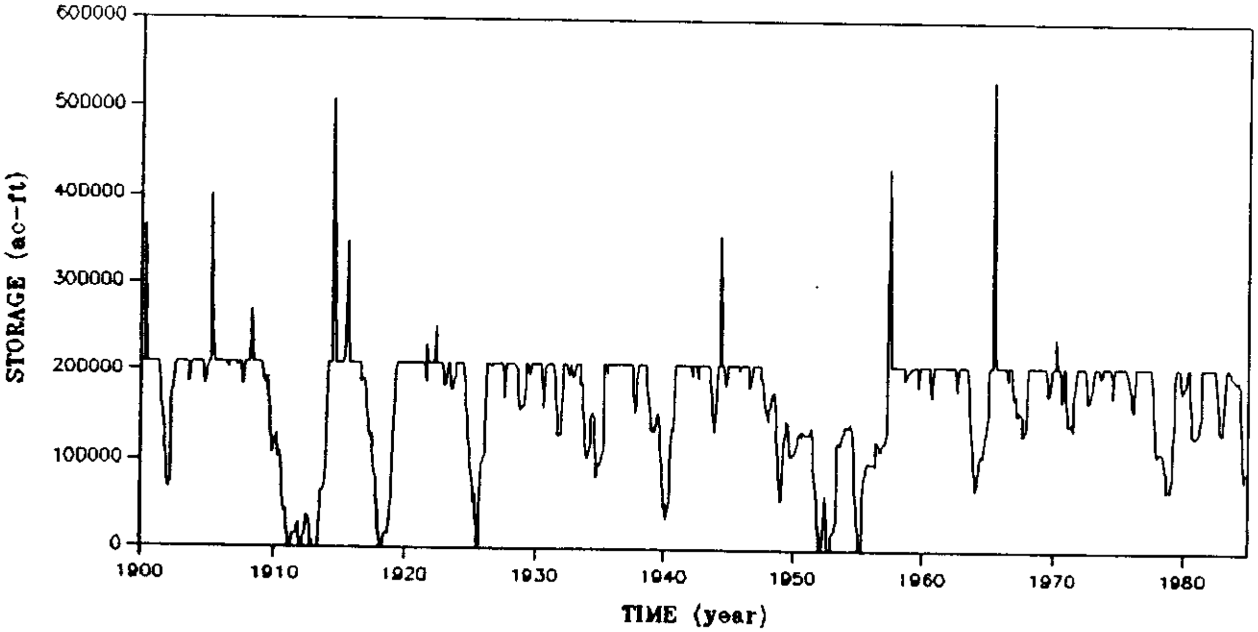


Figure 6.21 Stillhouse Hollow Reservoir Storage Hydrograph, 2010 Water Use Simulation (Run 2)

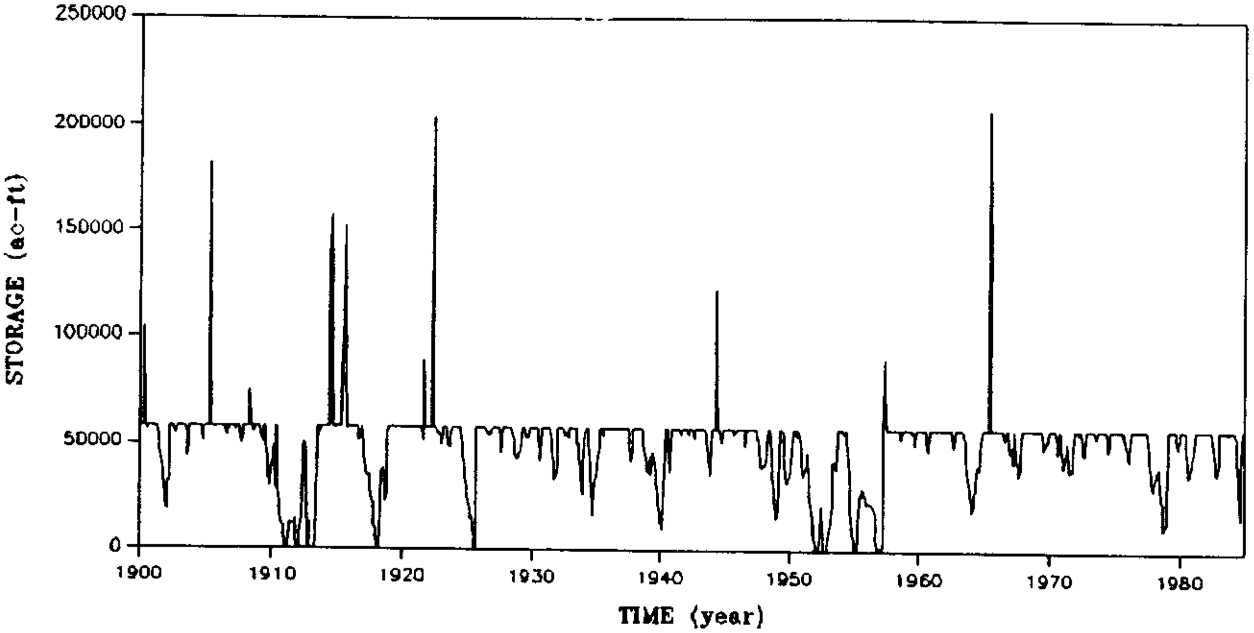


Figure 6.23 **Granger Reservoir Storage Hydrograph, 2010 Water Use Simulation (Run 2)**

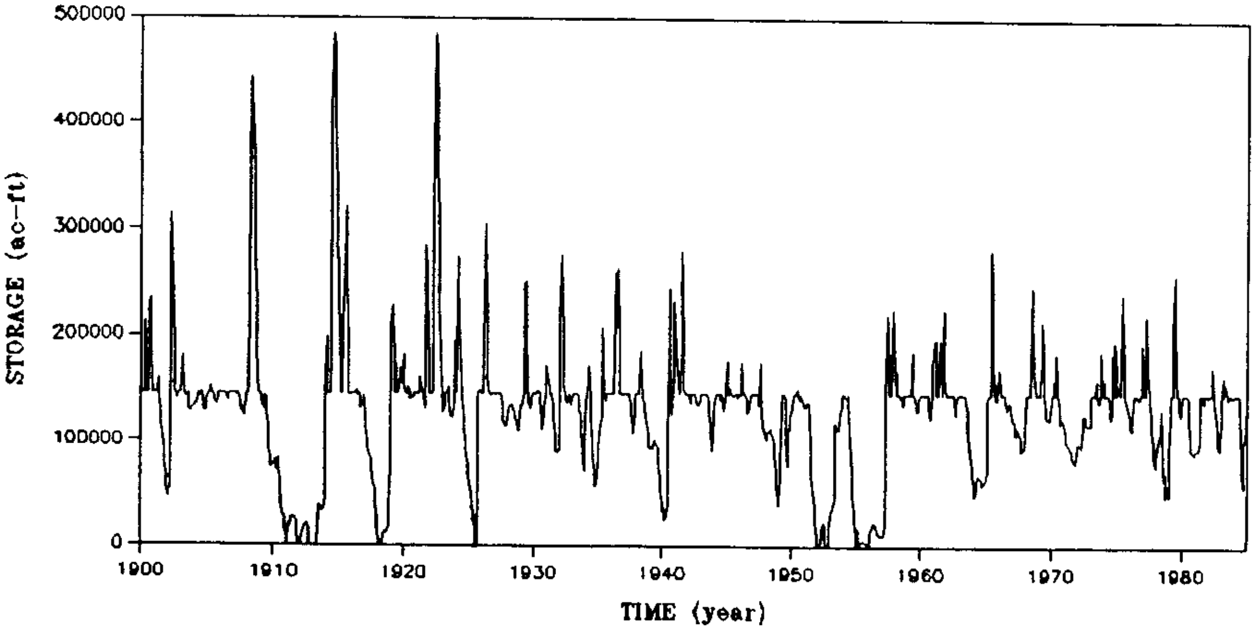


Figure 6.24 Somerville Reservoir Storage Hydrograph, 2010 Water Use Simulation (Run 2)

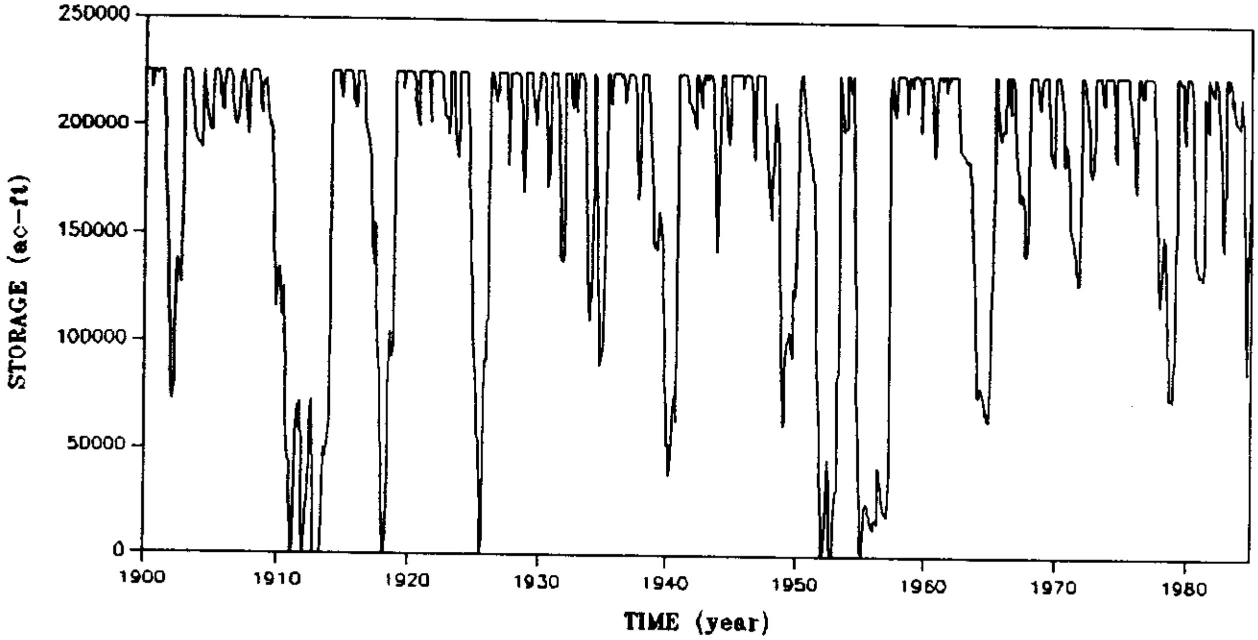


Figure 6.25 Limestone Reservoir Storage Hydrograph, 2010 Water Use Simulation (Run 2)

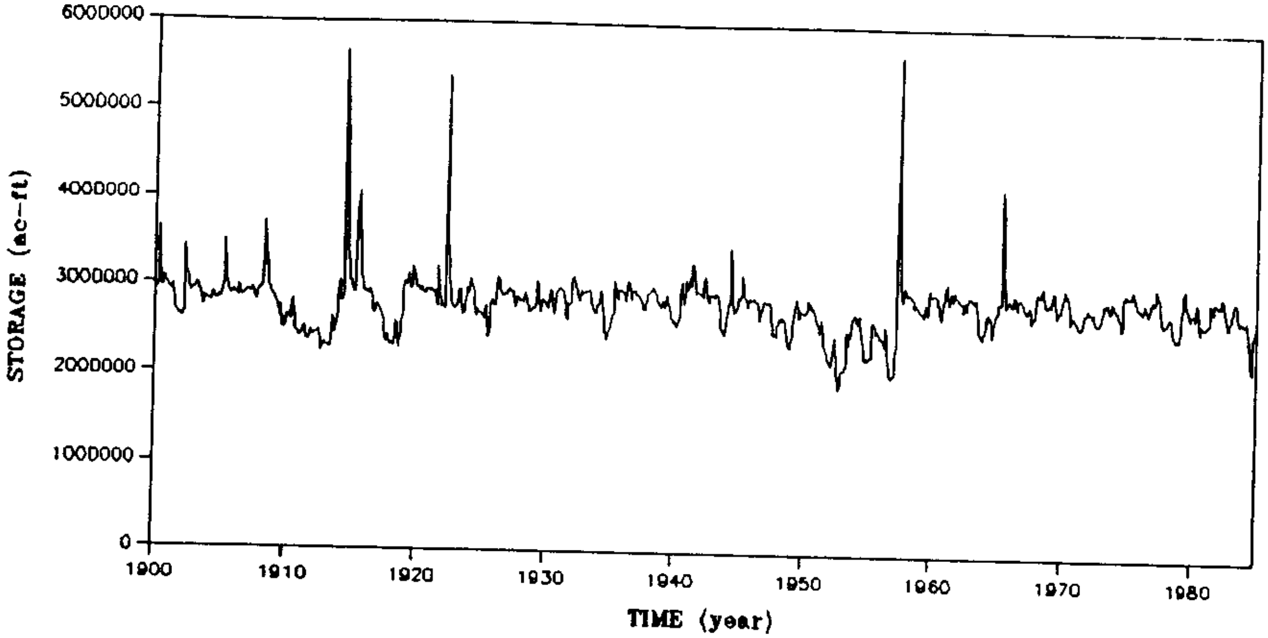


Figure 6.26 12-Reservoir Total Storage Hydrograph (Run 1)

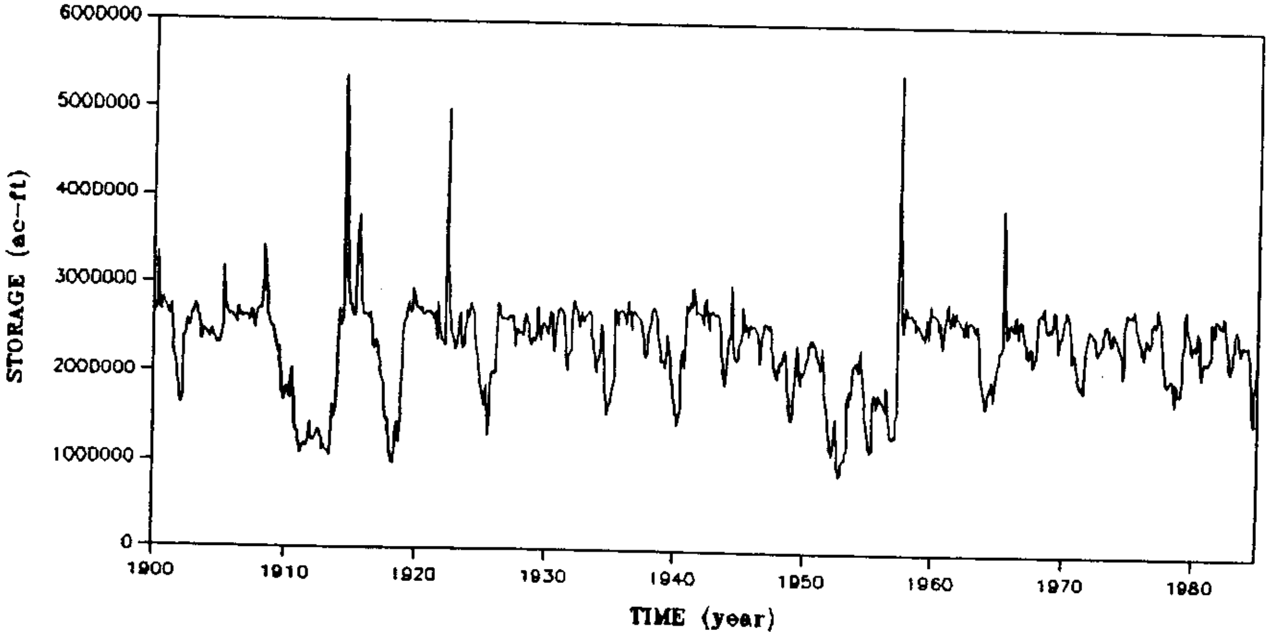


Figure 6.27 12-Reservoir Total Storage Hydrograph (Run 2)

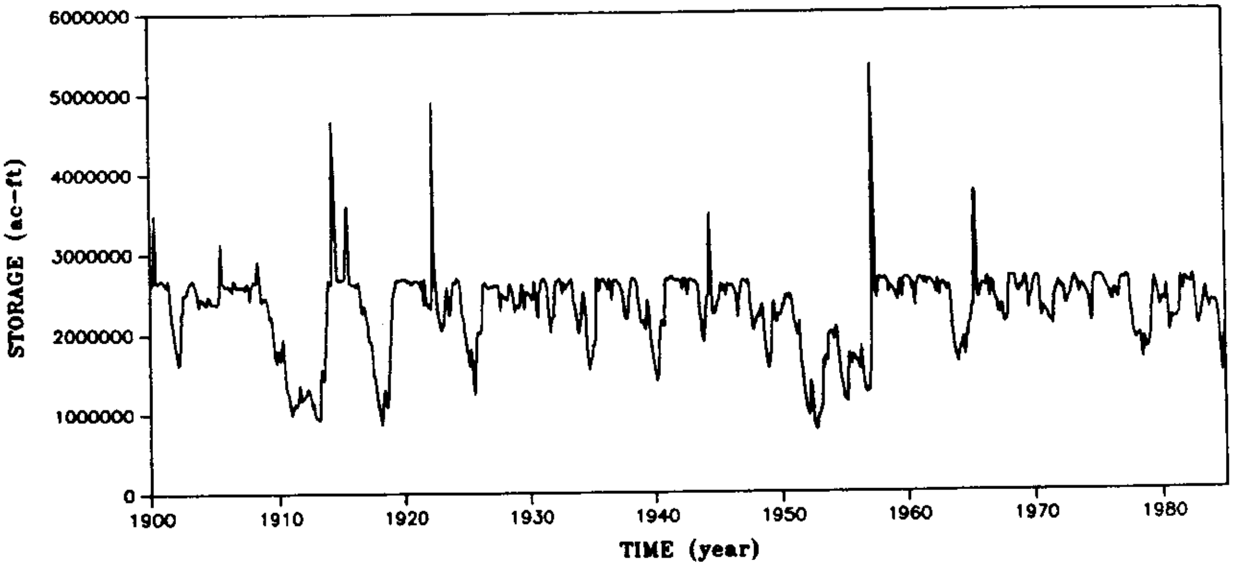


Figure 6.28 12-Reservoir Total Storage Hydrograph (Run 3)

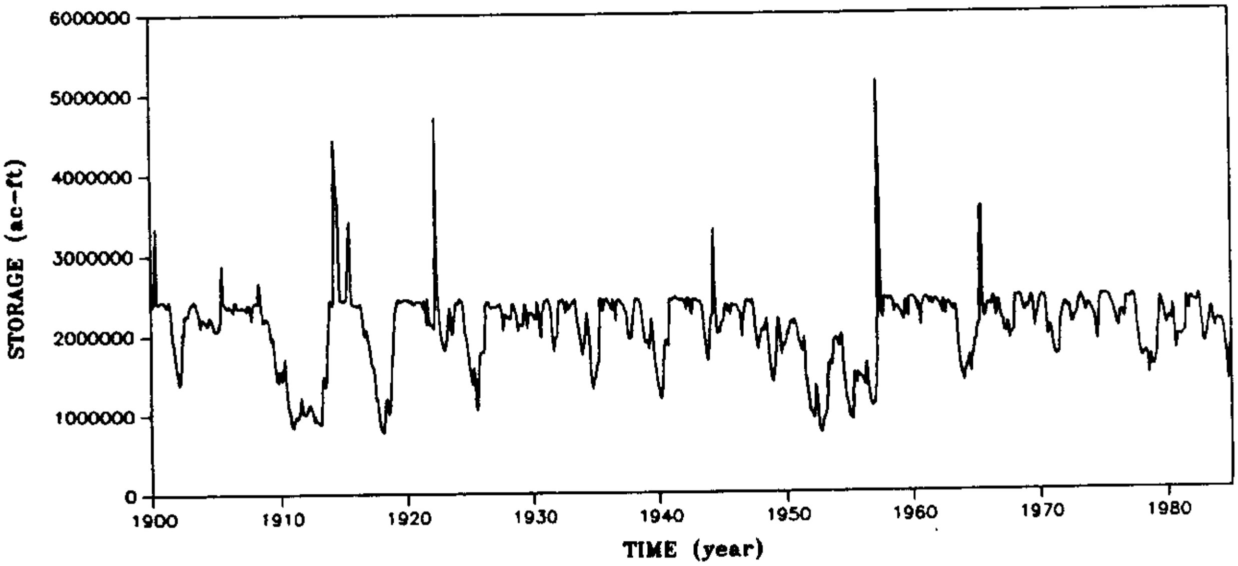


Figure 6.29 12-Reservoir Total Storage Hydrograph (Run 4)

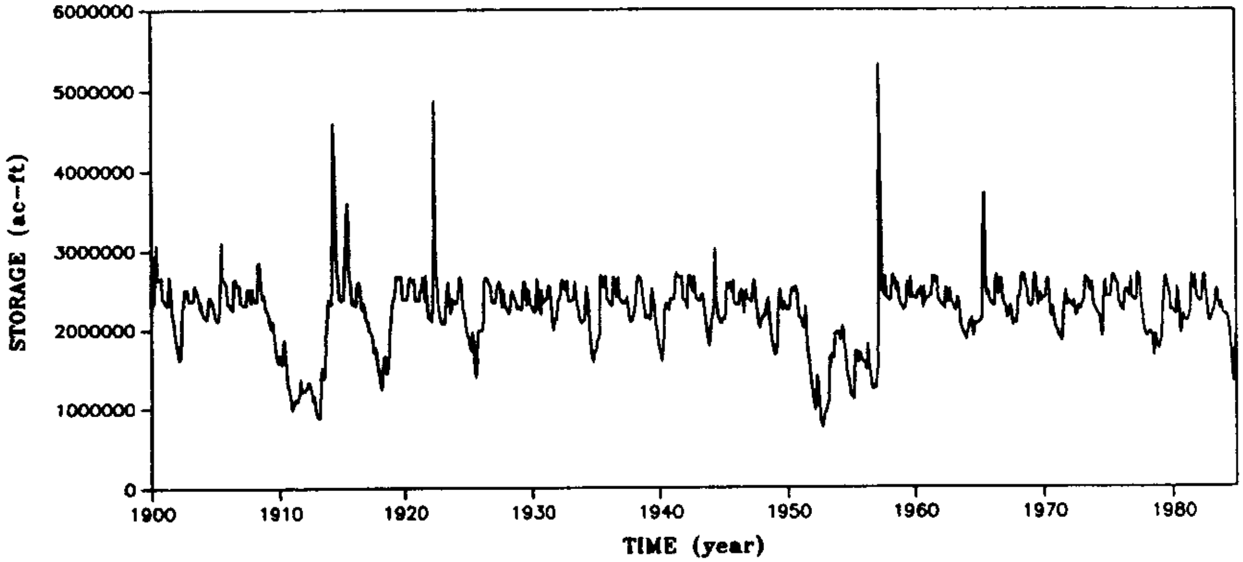


Figure 6.30 12-Reservoir Total Storage Hydrograph (Run 5)

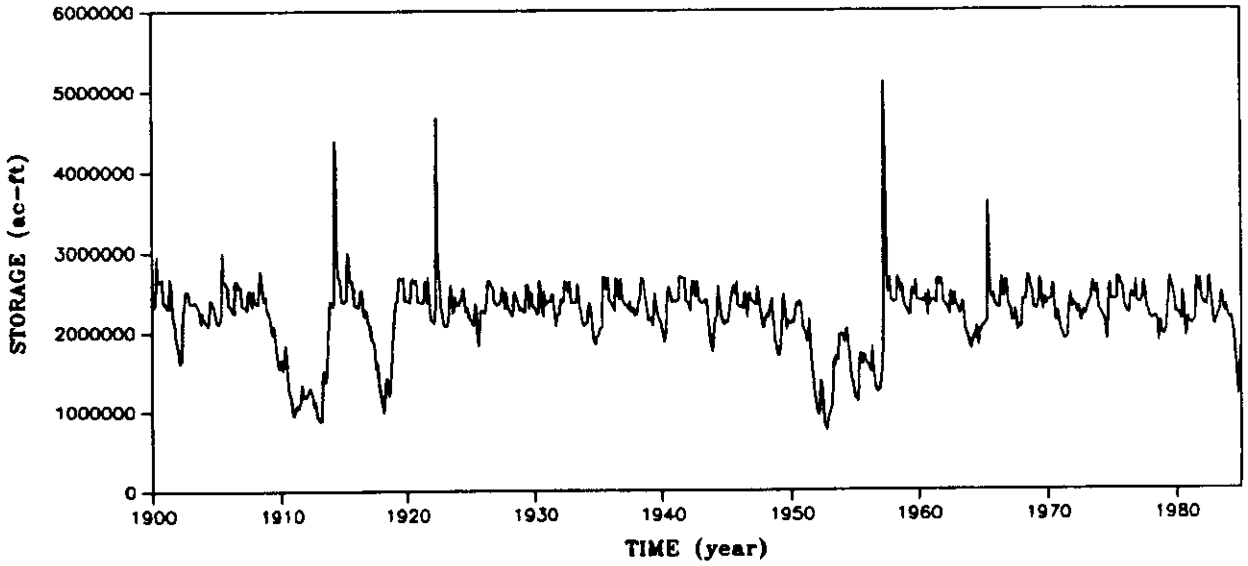


Figure 6.31 12-Reservoir Total Storage Hydrograph (Run 6)

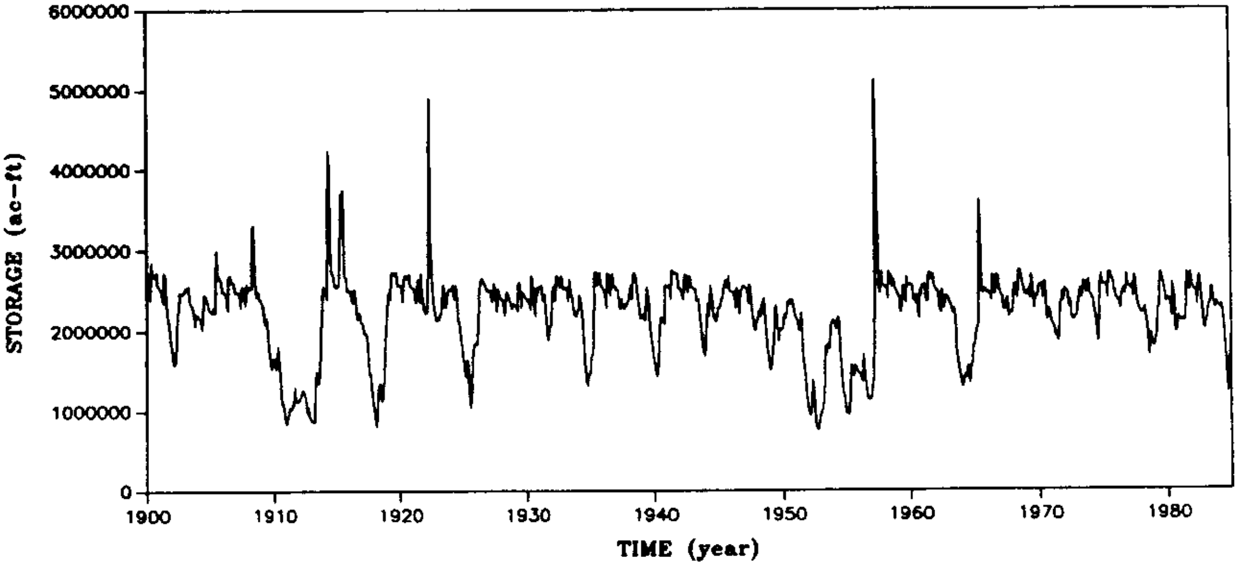


Figure 6.32 12-Reservoir Total Storage Hydrograph (Run 7)

Table 6.11
SYSTEM STORAGE CAPACITY

Below Top of Pool	Storage Capacity (thousand acre-feet) 1984 Sedimentation	2010 Sedimentation
12-Reservoir BRA System		
Inactive	575	506
Conservation	2,652	2,393
Flood Control	5,737	5,541
13 Reservoirs Including Hubbard Creek		
Inactive	579	510
Conservation	2,964	2,697
Flood Control	5,737	5,541

Table 6.12
SYSTEM STORAGE STATISTICS FOR ALTERNATIVE SIMULATIONS

	Storage (thousand acre-feet)			
Simulation Run	1900-1984 Mean	Standard Deviation	Minimum Storage	Maximum Storage
1	2,578	125	2,053	5,395
2	1,998	469	700	5,112
3	2,044	469	740	5,162
4	2,284	452	780	5,334
5	2,209	397	760	5,330
6	2,189	400	760	5,112
7	2,219	422	744	5,112

Table 6.13
SYSTEM STORAGE VERSUS DURATION

Percent of Months Equalled or Exceeded	Simulation Run					
	2	3	4	5	6	7
	No	Permanent Reallocation		Seasonal Reallocation		
	Reallocation	Waco	7 Reservoirs	Apr-Oct	May-Oct	Apr,May-Oct
	End-of-Month Storage (thousand acre-feet)					
0.10	5,000	5,000	5,000	5,000	5,000	5,000
0.20	4,480	4,490	4,670	4,670	4,490	4,490
0.50	3,740	3,850	3,980	3,980	3,980	3,990
1.00	3,430	3,430	3,480	3,430	3,430	3,220
2.00	2,640	2,640	2,820	2,790	2,680	2,790
5.00	2,370	2,460	2,670	2,650	2,640	2,710
10.00	2,350	2,440	2,650	2,630	2,610	2,630
15.00	2,340	2,420	2,640	2,590	2,540	2,590
20.00	2,330	2,410	2,630	2,530	2,460	2,560
30.00	2,310	2,360	2,600	2,400	2,380	2,510
40.00	2,250	2,300	2,540	2,350	2,340	2,430
50.00	2,160	2,210	2,450	2,310	2,300	2,350
60.00	2,060	2,110	2,340	2,230	2,230	2,260
70.00	1,900	1,950	2,180	2,130	2,130	2,140
80.00	1,630	1,680	1,950	1,940	1,940	1,920
85.00	1,450	1,500	1,780	1,780	1,780	1,720
90.00	1,240	1,280	1,550	1,550	1,550	1,460
95.00	1,030	1,040	1,250	1,250	1,250	1,130
98.00	950	962	1,030	1,030	1,030	979
99.00	912	926	978	978	972	940
99.50	880	897	946	943	937	909
99.80	847	867	912	905	900	877
99.90	826	848	891	882	877	857
99.95	808	832	874	862	858	840
99.99	774	801	843	826	823	808
100.00	702	738	781	755	755	744

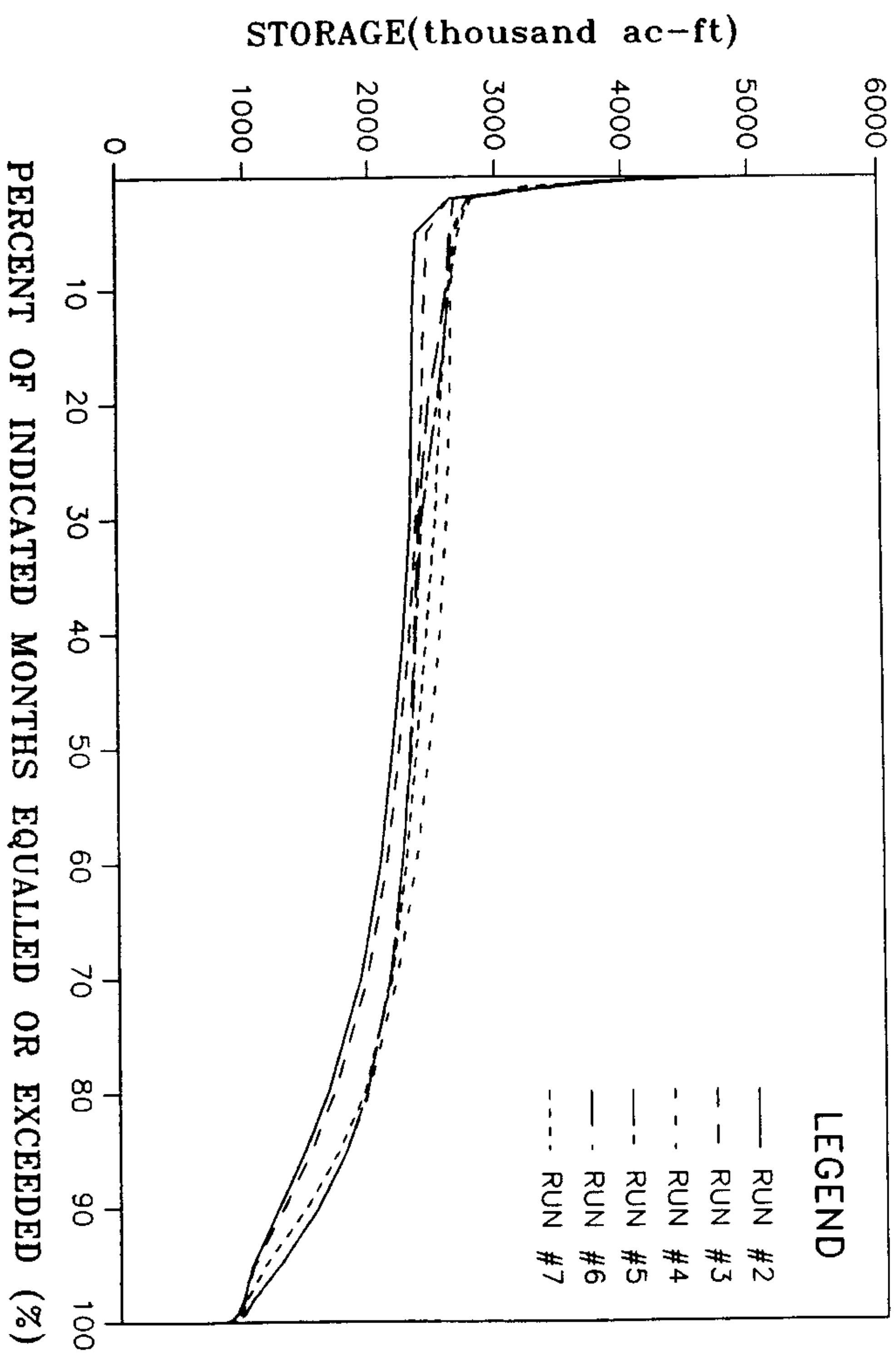


Figure 6.33 System Storage Versus Duration

during extreme flood events, spills and/or controlled releases are made even though additional downstream damages result. Reallocation of flood control capacity to conservation should not adversely affect downstream flooding conditions except during those flood events for which the flood control pool capacity is exceeded.

Computational Procedure

The recurrence interval (T_f) and exceedence probability (P_f) associated with a flood control pool being filled to 100% capacity are computed as follows.

$$T_f = 1/P_f$$

$$P_f = (n/N)\ P_{f/25\%}$$

where

T_f is the average interval in years between successive occurrences of the flood control pool filling to 100% capacity or overtopping

P_f is the probability that the flood control pool will fill to 100% capacity or overtop in any year

n is the number of years in the data series for which the peak annual storage equals or exceeds 25% of the flood control pool capacity

N is the total number of years in the data series (85 years in the present study)

n/N is the probability that the peak annual storage will equal or exceed 25% of the flood control pool capacity

$P_{f/25\%}$ is the conditional probability that the flood control pool will fill to 100% capacity or overtop in any year given that the peak annual storage equals or exceeds 25% of the flood control pool capacity

$$P_{f/25\%} = 1 - \exp(-\exp(-\ 0.7797s\ \ (\ 1.0 - \bar{x} + .45s))$$

where $\bar{x}$ and s are the mean and standard deviation of the peak annual storages for the n years that the peak annual storage equals or exceeds 25% of the flood control pool capacity. The random variable peak annual storage is expressed in units of percent of flood control pool capacity.

The variables n, N, $\bar{x}$, and s in the above equations are determined from an annual series of peak storage data, which is developed from the output of the HEC-5 simulation model. In the present study, N is 85 since a 85-year simulation period was used. The end-of-month storages computed by HEC-5 are adjusted to account for the peak annual storage occurring during a month rather than at the end of a month. The adjustment consists of adding the volume of the releases during the month to the end-of-month storage. The reservoir outlet works and spillways gates are assumed to be closed prior to the peak storage occurring, with all spills and controlled releases during the month occurring after the peak storage. This adjustment also allows the reservoir to be treated as having an infinite capacity for those peak annual storages exceeding 100% of the actual capacity. Thus, the random variable peak annual storage can assume values greater than 100%.

The data set used in the above computation consists of the peak annual flood storages, expressed as a percent of capacity, for each year of the HEC-5 simulation. The end-of-month storages computed by HEC-5 are adjusted as described above. The number of years (n) in which the peak storage is less than 25% capacity is counted and used in the computations. However, only the storage values equalling or exceeding 25% capacity are actually used in the computations (to compute $\bar{x}$ and s).

The above equations were also used to estimate the probability that the flood control pool will be filled or overtopped in any year in at least one reservoir of a system of several reservoirs. The recurrence interval or exceedence probability is computed for filling or overtopping of the flood control pool of at least one reservoir located above a given location. The peak annual storage data set for each reservoir is developed as described above. Then, for each year, the peak storages (expressed as a percent of capacity) in each of the several reservoirs are compared and the largest selected. Thus, an annual peak storage data series is compiled with one value for each year. The peak storage occurs in different reservoirs in different years. The computational procedure described above is applied to this data set. Thus, the random variable is the peak storage (as a percent of capacity) in any one of a set of several reservoirs. This approach was applied to compute the probability of the flood control pool being filled or overtopped in any year in at least one reservoir located above the Waco, Cameron, Bryan, and Richmond stream gages.

The computational procedure is described above assuming the probability of the storage equalling or exceeding 100% of capacity is to be computed. However, the exceedence probabilities for storage levels other than 100% capacity can be computed as well, using the equations. Likewise, a major flood was somewhat arbitrarily considered to be characterized by a peak storage equalling or exceeding 25% of capacity. Other percentage could be used as well.

Discussion of the Computational Procedure

From fundamental probability and statistics, exceedence frequency or probability (P) is defined as the probability that a given magnitude will be equalled or exceeded in any year. The recurrence interval (T) is the average interval in years between successive occurrences of events equalling or exceeding a given magnitude. Exceedence probability and recurrence interval are reciprocals, $T = 1/P$.

Peak annual flood control pool storage, expressed as a percentage of the flood control pool storage capacity, is the random variable analyzed. The recurrence interval associated with the peak annual storage taking a value of 100% of the flood control capacity is computed. The analysis is based on an annual data series consisting of the peak storage occurring each year during the 85-year simulation period. For years in which the peak storage exceeds 100% of the flood control capacity, the storage is adjusted to reflect the storage which would have occurred assuming infinite flood control capacity.

Thus, the random variable (peak annual storage) may have values much greater than 100% of the flood control storage capacity. The probability distribution function is the same for values of the random variable less than and greater than 100% capacity.

The data series for the frequency analysis is developed by adjusting storages computed by a HEC-5 simulation. The monthly HEC-5 simulations result in end-of-month storages. In actuality, the instantaneous peak storage during a year will likely be greater than the largest end-of-month storage. In the analysis procedure, the HEC-5 computed end-of-month storages are adjusted by adding the volume of the total release during the month to the end-of-month storage. During a major flood event, the outlet works gates will likely be closed for some period of time leading up to the peak storage occurring. After downstream flows recede below nondamaging levels, the gates are opened and reservoir storage recedes below the peak storage. The analysis procedure is based on the assumption that in the month during which the peak storage occurs, all releases are made after the peak storage. Thus, releases are added to the end-of-month storage to obtain the peak storage during the month.

A major flood event was somewhat arbitrarily considered to be a flood resulting in a peak storage of 25% or more of the flood control pool capacity. Peak annual storages less than 25% capacity are considered to likely have a different probability distribution function than peak storages greater than 25% capacity. Only peak annual storages, computed as described above, with values of 25% or more of the flood control pool capacity are actually used in the computational procedure.

The frequency analysis procedure is based on the total probability theorem, which can be expressed as

$$P(A) = P(A/E_1)\ P(E_2) + P(A/E_2)\ P(E_2)$$

where E_1 and E_2 are mutually exclusive events, and A is a third event. The probability of event A, P(A), is dependent upon the occurrence of events E_1 and E_2. $P(A/E_1)$ and $P(A/E_2)$ are the conditional probabilities of A occurring given that E_1 and E_2 occur. The total probability theorem is discussed by most statistics textbooks including Hann (1978).

For the present study, the variables in the total probability theorem are defined as follows.

A - the peak storage is greater than or equal to 100% of the flood control pool capacity

E_1- the peak storage is greater than or equal to 25% of the flood control pool capacity

E_2- the peak storage is less than 25% of the flood control pool capacity

Therefore, $P(A/E_2) = 0$ and the total probability theorem simplifies to

$$P(A) = P(A/E_1)\ P(E_1).$$

The peak annual storages for each year of the 85-year simulation are divided into two categories: (1) storages of 25% or more of the capacity and (2) storages of less than 25% of the capacity. The probability of the peak storage capacity in any year being greater than or equal to 25% of the capacity, $P(E_1)$, is computed as

$$P(E_1) = n/N$$

where N is the number of years of data (85 years in the HEC-5 simulation) and n is the number of years in the data for which the peak storage was greater than or equal to 25% of the capacity.

The extreme value type I probability distribution was used to estimate the probability of the peak storage equalling or exceeding 100% capacity given that it exceeded 25% capacity, $P(A/E_1)$. The Gumbel distribution can be expressed as follows:

$$P = 1 - \exp(-\exp-(.7797s\ (x - \bar{x} + 0.45s)$$

where P denotes exceedence probability, x is the random variable, $\bar{x}$ and s denote mean and standard deviation, and exp refers to raising e, the base of the napierian logarithms, to a power. The extreme value type I probability distribution, which is also called the Gumbel distribution, is discussed by most hydrology textbooks including Hann (1978). In the present problem, $P = P(A/E_1)$, $x = 100\%$, and $\bar{x}$ and s are computed using peak annual storages for the n years of data for which the peak annual storage equalled or exceeded 25% capacity.

The procedure would provide better exceedence probability estimates if daily data were used in the HEC-5 simulation. However, the monthly data, adjusted as described above, are considered to provide reasonably good probability estimates for purposes of the present study. Development of daily HEC-5 input data for a 85-year simulation period would be extremely difficult. A 85-year annual series developed from monthly data probably provides better probability estimates than a much shorter annual series developed from daily data.

Flood Control Recurrence Intervals for Alternative Storage Allocations

The alternative HEC-5 simulation runs are defined in Table 6.10. Flood control recurrence intervals for runs 1 and 2 are tabulated in Table 6.14. Recurrence intervals for runs 2, 3, 4, 5, 6,and 7 are shown in Table 6.15. The recurrence intervals for the control points located at the downstream stream gages are estimates of the average interval in years between successive occurrences of a flood control pool capacity being filled to 100% capacity or overtopped in at least one reservoir located above the stream gage. Recurrence intervals are shown to the nearest tenth of a year to facilitate comparison of small differences between alternative runs, not to imply precision. The recurrence interval estimates are approximate and serve primarily as an index to quantify changes resulting from storage reallocations.

Table 6.14 shows the recurrence intervals computed for the existing allocation of storage capacities in the reservoirs. Run 1 represents 1984

Table 6.14
RECURRENCE INTERVALS FOR FILLING FLOOD CONTROL POOLS FOR ALTERNATIVE SIMULATION SCENARIOS
(Existing Storage Allocations)

Simulation Run	Run 1		Run 2
Sedimentation Condition	1984	1984	2010
Water Use Scenario	1984	2010	2010
Reservoir	**Recurrence Interval (years)**		
Whitney	37.4	38.9	38.8
Aquilla	73.7	75.3	71.6
Waco	138.4	144.1	131.7
Belton	39.8	87.6	45.5
Stillhouse	116.4	131.2	115.3
Granger	114.4	143.8	111.8
Somerville	49.0	53.3	51.1
Gage			
Waco	29.5	30.0	29.6
Cameron	35.2	66.4	40.3
Bryan	16.3	18.0	17.4
Richmond	13.7	16.3	14.7

Table 6.15
RECURRENCE INTERVALS FOR FILLING FLOOD CONTROL POOLS FOR ALTERNATE SYSTEM REALLOCATION PLANS BASED ON 2010 SIMULATION

Reservoir or Gage	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7
	Reallocation Plan					
	No Reallocation	Permanent Reallocation		Seasonal Reallocation		
		Waco	7 Reservoirs	Apr-Oct	May-Oct	Apr, May-Oct
Reservoir	Recurrence Interval (Years)					
Whitney	38.8	38.8	37.3	37.3	38.4	39.8
Aquilla	71.6	71.6	56.0	56.0	69.2	80.8
Waco	131.7	87.7	87.7	88.9	130.9	149.5
Belton	45.5	45.5	35.3	35.9	45.5	71.5
Stillhouse	115.3	115.3	62.5	80.8	115.3	174.1
Granger	111.8	111.8	49.5	53.2	111.8	144.8
Somerville	51.1	51.1	29.5	42.9	43.9	53.1
Gage						
Waco	29.6	28.7	26.9	27.0	29.4	31.2
Cameron	40.3	40.3	27.4	28.0	40.3	58.7
Bryan	17.4	17.2	14.9	15.3	17.4	18.9
Richmond	14.7	14.6	11.5	11.7	13.9	15.6

conditions of water use and reservoir sedimentation. Run 2 represents 2010 conditions of water use and reservoir sedimentation. Runs 1 and 2 have approximately the same recurrence intervals. An additional simulation run was analyzed and included in Table 6.14 in which 2010 conditions of water use were combined with 1984 conditions of reservoir sedimentation. Sedimentation decreases the storage capacity and thus decrease the recurrence intervals. Increases in water use have an incidental benefit of increasing the flood control recurrence intervals.

Table 6.15 is a comparison of alternative storage allocations. For 2010 conditions of water use and reservoir sedimentation and the existing storage allocation (run 2), the flood control pool in Whitney Reservoir has an estimated probability of 2.58% of being filled or exceeded in any year. The corresponding recurrence interval (T = 1/P) is 38.8 years. The alternative reallocation plans have little impact on the recurrence interval for Whitney Reservoir. The computed recurrence interval for Whitney Reservoir is relatively small compared to the other reservoirs due to the impact on the computations of the 1957 flood. Inflows to Whitney Reservoir, relative to flood control storage capacity, for the 1957 flood were much larger than the inflows at the other reservoirs for the 1957 flood or any other flood.

Waco Reservoir with the existing storage allocation (run 2) has a recurrence interval of 131.7 years. Reallocation of 50,000 acre-feet of flood control capacity to water supply (run 3) reduces the recurrence interval to 87.7 years. The reallocation of storage in Waco Reservoir had minor effects on the computed releases and storages in the other reservoirs but no effect on the recurrence intervals.

Run 4 involved a permanent reallocation of the lesser of 50,000 acre-feet or 15% of the flood control storage in each of the seven reservoirs. Runs 5 and 6 represent seasonal rule curves involving the same capacities as run 4. In run 5, the top of conservation pool is raised from April through October. In run 6, the pool is raised from May through October. The permanent reallocations (run 4) resulted in significant reductions in the recurrence intervals. Run 5 recurrence intervals are slightly larger but close to the same as run 4. Run 6 recurrence intervals are essentially the same as no reallocation (run 2). Thus, a seasonal pool raise has little impact on the recurrence intervals as long as the top of conservation pool is not raised before May. As long as the pool is not lowered before August, the October date for lowering the pool can be varied without significantly affecting the recurrence intervals.

Run 7 includes lowering the top of conservation pool during April and raising it during May through October. As indicated in Table 6.15, providing extra flood control capacity during April increases the recurrence intervals.

Tables 6.16 and 6.17 provides information about the floods that determine the recurrence intervals. The data presented in Tables 6.16 and 6.17 are for simulation run 1 but are representative of the other runs as well. Table 6.16 lists the floods that exceeded the flood control pool capacities. Waco, Stillhouse, and Granger Reservoirs did not have their flood control pool capacities exceeded during the 85-year simulation. The flood control capacities of Whitney and Aquilla Reservoirs were exceeded in May 1957 and May 1914, respectively. The Belton Reservoir flood control pool capacity was

Table 6.16
FLOODS EQUALLING OR EXCEEDING FLOOD CONTROL CAPACITY BASED ON 1984 SIMULATION (RUN 1)

Reservoir	Floods Equalling or Exceeding Flood Control Capacity	
	Number	Dates
Whitney	1	May 1957
Aquilla	1	May 1914
Waco	none	
Belton	3	Jun/Jul 1914, Jun 1957, Jun/Jul 1965
Stillhouse	none	
Granger	none	
Somerville	1	May 1922

Table 6.17
NUMBER OF MONTHS OF FLOOD CONTROL STORAGE BASED ON 1984 SIMULATION (RUN 1)

Month	Reservoir						
	Whitney	Aquilla	Waco	Belton	Stillhouse	Granger	Somerville
	Total Number of Months of Flood Control Storage (First Month of One-Month or Several-Month-Long Flood Control Storage)						
Jan							2 (2)
Feb							
Mar							1 (1)
Apr				1 (1)			3 (3)
May	5 (5)	4 (4)	5 (5)	10 (10)	8 (8)	9 (9)	10 (8)
Jun	1 (0)	2 (0)		5 (0)	5 (0)	5 (0)	5 (1)
Jul				5 (0)	3 (0)	3 (0)	4 (2)
Aug				2 (0)	1 (0)	1 (0)	1 (0)
Sep				2 (1)	1 (1)	1 (1)	1 (1)
Oct							1 (1)
Nov							
Dec							
Total	6 (5)	6 (4)	5 (5)	25 (12)	18 (9)	19 (10)	28 (19)

exceeded in the simulation in June-July 1914, June 1957, and June-July 1965. The Somerville Reservoir flood control pool was overtopped in May 1922.

The number of months in the run 1 simulation for which end-of-month storages were in the flood control pool are listed in Table 6.17. The total number of months is cited first. Some floods resulted in storage in the flood control pool for two or more consecutive months. The number of months for which flood control storage initiated in the month is tabulated in parenthesis. Table 6.17 indicates that most of the floods started in May.

Tables 6.18, 6.19, and 6.20 show recurrence intervals for storage capacity reallocations in a individual reservoir. In most cases, reallocation of capacity in a single reservoir had essentially no impact on the recurrence intervals for the other reservoirs. Tables 6.18, 6.19, and 6.20 were developed from a series of HEC-5 simulations based on 1984 conditions of water use and reservoir sedimentation.

Table 6.18 presents recurrence intervals associated with permanent reallocations of flood control capacity to conservation. For example the flood control recurrence interval for Waco Reservoir decreases from 138.4 years with the existing storage allocation to 45.9 years if 25% of the flood control capacity is reallocated to conservation.

Figures 6.19 and 6.20 show recurrence intervals for alternative seasonal rule curves for Waco and Stillhouse Hollow Reservoirs, respectively. Raising the top of conservation pool in May has little effect on the recurrence intervals. A seasonal rule curve involving raising the top of conservation pool in April reduces the recurrence intervals almost as much as a corresponding permanent reallocation. Thus, the timing of the pool raise is the determinate factor in the impacts of a seasonal rule curve of the computed recurrence intervals. As long as the pool is not lowered before August, the date for lowering the rule curve does not affect the computed results.

Conservation Storage Drawdown Frequency Analysis

System storage versus duration relationships for the seven simulation runs were previously presented in Table 6.13 and Figure 6.36. Drawdown frequency data are presented in Tables 6.21 through 6.24 in terms of number of drawdowns of various magnitudes of storage depletion which occurred during the 85-year simulation period. A drawdown extends from the time the reservoir storage level drops below the top of conservation pool to the time the conservation pool is full again. The length of time of the drawdowns range from a month to several years.

The number of drawdowns which resulted in completely empty conservation pools are indicated in Tables 6.21 and 6.22. For 1984 conditions of water use and sedimentation and existing storage allocations, none of the reservoirs emptied during the 85-year simulation. For 2010 conditions of water use and sedimentation and existing storage allocations, Aquilla, Belton, Stillhouse, Somerville, and Limestone each emptied 8 times. Waco Reservoir had 13 drawdowns which emptied the conservation pool. Table 6.21 also includes the number of drawdowns for a simulation combining 2010 water use with 1984 reservoir sedimentation.

Table 6.18
RECURRENCE INTERVAL FOR FILLING FLOOD CONTROL POOL FOR INDIVIDUAL RESERVOIR REALLOCATIONS BASED ON 1984 SIMULATION

Reservoir	Storage Reallocation (Percent of Flood Control Capacity)					
	0%	5%	10%	15%	20%	25%
	Recurrence Interval (years)					
Whitney	37.4	27.9	26.1	24.7	23.4	22.2
Aquilla	73.7	68.2	63.2	58.7	54.7	51.3
Waco	138.4	109.6	87.3	69.8	56.3	45.9
Belton	39.8	34.6	30.3	27.1	24.1	20.5
Stillhouse	116.4	84.5	69.7	55.9	48.0	42.2
Granger	114.4	84.5	57.4	45.3	35.8	21.4
Somerville	49.0	34.5	29.3	25.0	22.1	17.7

Table 6.19
RECURRENCE INTERVAL FOR FILLING FLOOD CONTROL POOL FOR ALTERNATIVE REALLOCATION PLANS FOR WACO RESERVOIR BASED ON 1984 SIMULATION

Rule Curve	Storage Reallocation (Percent of Flood Control Capacity)					
	0%	5%	10%	15%	20%	25%
	Recurrence Interval (years)					
constant	138.4	109.6	87.2	69.8	56.3	45.9
May-Aug	138.4	137.8	137.2	136.6	135.7	135.1
Apr-Aug	138.4	109.6	87.9	72.5	63.1	56.1
May-Oct	138.4	137.8	137.2	136.6	135.7	135.1
Apr-Oct	138.4	109.6	87.9	72.5	63.1	56.1

Table 6.20
RECURRENCE INTERVAL FOR FILLING FLOOD CONTROL POOL FOR ALTERNATIVE REALLOCATION PLANS FOR STILLHOUSE HOLLOW RESERVOIR BASED ON 1984 SIMULATION

Rule Curve	Storage Reallocation (Percent of Flood Control Capacity)					
	0%	5%	10%	15%	20%	25%
	Recurrence Interval (years)					
constant	116.4	84.5	69.7	55.9	48.0	42.2
May-Aug	116.4	116.4	116.4	116.4	116.4	116.4
Apr-Aug	116.4	84.5	78.0	71.4	61.4	59.6
May-Oct	116.4	116.4	116.4	116.4	116.4	116.4
Apr-Oct	116.4	84.5	78.0	71.4	61.4	59.6

Table 6.21
NUMBER OF DRAWDOWNS
RESULTING IN A COMPLETELY EMPTY CONSERVATION POOL FOR ALTERNATIVE SIMULATION SCENARIOS

Run	1	-	2
Sedimentation Condition	1984	1984	2010
Water Use Scenario	1984	2010	2010
Reservoir	**Times Emptied in 85 Years**		
Hubbard Creek	-0-	-0-	-0-
Possum Kingdom	-0-	7	7
Granbury	-0-	-0-	-0-
Whitney	-0-	1	1
Aquilla	-0-	7	8
Waco	-0-	7	13
Belton	-0-	7	8
Stillhouse	-0-	7	8
Granger	-0-	7	10
Somerville	-0-	7	8
Limestone	-0-	7	8

Table 6.22
NUMBER OF DRAWDOWNS
RESULTING IN A COMPLETELY EMPTY CONSERVATION POOL FOR ALTERNATIVE REALLOCATION PLANS BASED ON 2010 SIMULATION

Run	2	3	4	5	6	7
	Reallocation Plan					
	No	Permanent Reallocation		Seasonal Reallocation		
Reservoir	Reallocation	Waco	7 Reservoirs	Apr-Oct	May-Oct	Apr,May-Oct
	Number of Times Reservoir Emptied in 85 Years					
Hubbard	-0-	-0-	-0-	-0-	-0-	-0-
Possum Kingdom	7	7	7	7	7	7
Granbury	-0-	-0-	-0-	-0-	-0-	-0-
Whitney	1	1	-0-	-0-	-0-	-0-
Aquilla	8	8	3	3	3	5
Waco	13	7	7	8	8	9
Belton	8	8	3	3	3	5
Stillhouse	8	8	3	3	3	5
Granger	10	10	3	3	3	5
Somerville	8	8	3	3	3	5
Limestone	8	8	3	3	3	5

Table 6.23
NUMBER OF DRAWDOWNS TO BELOW 50% CONSERVATION CAPACITY FOR ALTERNATIVE REALLOCATION PLANS BASED ON 2010 SIMULATION

Run	2	3	4	5	6
	Reallocation Plan				
	No	Permanent Reallocation		Seasonal Reallocation	
Reservoir	Reallocation	Waco	7 Reservoirs	Apr-Oct	May-Oct
Hubbard	2	2	2	2	2
Possum Kingdom	23	23	23	23	23
Granbury	-0-	-0-	-0-	-0-	-0-
Whitney	10	10	3	5	5
Aquilla	12	12	6	5	6
Waco	18	7	7	9	10
Belton	9	9	7	7	7
Stillhouse	10	10	4	5	5
Granger	14	14	8	6	6
Somerville	13	13	6	6	6
Limestone	13	13	6	6	6

Table 6.24
NUMBER OF DRAWDOWNS TO BELOW 75% CONSERVATION CAPACITY FOR ALTERNATIVE REALLOCATION PLANS BASED ON 2010 SIMULATION

Run	2	3	4	5	6
	Reallocation Plan				
	No	Permanent Reallocation		Seasonal Reallocation	
Reservoir	Reallocation	Waco	7 Reservoirs	Apr-Oct	May-Oct
Hubbard	6	6	6	6	6
Possum Kingdom	44	44	44	44	44
Granbury	15	15	15	15	15
Whitney	36	36	11	13	13
Aquilla	22	22	10	11	11
Waco	34	11	11	18	18
Belton	16	16	12	14	14
Stillhouse	16	16	10	10	10
Granger	23	23	10	10	11
Somerville	22	22	11	12	13
Limestone	21	21	10	11	12

Table 6.22 is a tabulation of the number of drawdowns resulting in a completely empty conservation pool for the alternative storage allocation plans. The storage reallocation plans significantly reduced the number of times the reservoirs emptied. With the exception of Waco Reservoir, the permanent and seasonal (runs 5 and 6) reallocation plans resulted in the reservoirs emptying the same number of times. Waco Reservoir emptied 7 and 8 times with the permanent (runs 3 and 4) and seasonal (runs 5 and 6) reallocations, respectively, as compared to 13 times with no reallocation. Aquilla, Belton, Stillhouse, Somerville, and Granger Reservoirs emptied eight times with the existing storage allocation. Each of the storage reallocation plans resulted in these reservoirs emptying three times. The seasonal rule curve which included lowering the pool in April (run 7) resulted in Possum Kingdom and Waco emptying 7 and 9 times, respectively, and five other reservoirs emptying 5 times.

Table 6.23 shows the number of drawdowns which depleted at least 50 percent of the conservation capacity, based on simulations with alternative storage capacity allocations. The capacity reallocations significantly reduce the number of times the reservoir storage levels drop below half full. Table 6.24 shows the number of drawdowns resulting in storage levels falling below 75% full. The relationship between the alternative storage capacity allocation, for the greater than 25% storage depletions, indicated in Table 6.24, is similar to the 50% and 100% drawdowns shown in Tables 6.23 and 6.22.

Drawdowns are not an annual series of statistically independent events. The likelihood of a reservoir emptying in a given year is highly dependent upon storage levels in the previous year. However, the drawdown frequencies can still be viewed, in an approximate manner, in terms of recurrence intervals. The recurrence interval is computed by dividing the 85-year simulation period by the number of drawdowns. Thus, if a reservoir empties once in 85 years, the estimated recurrence interval for the reservoir emptying is 85 years. If the reservoir does not empty during the 85 year simulation, the recurrence interval is concluded to be greater than 85 years. For several of the reservoirs, storage reallocation resulted in the reservoir emptying 3 times rather than 8 times during the 85-year simulation. Thus, the recurrence intervals for emptying the reservoirs are 10.6 years with no reallocation and 28.3 years if the reallocation plan is implemented.

Seasonal Characteristics of Drawdowns

The effectiveness of seasonal rule curve operation is largely dependent upon drawdowns initiating at a set time of the year. The top of conservation pool must be raised and additional water stored prior to initiation of the drawdown. Tables 6.25 and 6.27 show that most of the drawdowns during the simulation begin in June, July, or August. Thus, raising the top of conservation pool to capture additional spring flows can reduce the storage depletions occurring during these drawdown periods.

Drawdowns resulting in depletion of at least 50% of the active conservation capacity at each of seven reservoirs are listed in Table 6.25. These drawdowns occurred during the 85-year simulation of 2010 conditions of water use and reservoir sedimentation and existing top of conservation pool elevations. The first and last month and critical month of maximum storage depletion are shown for each drawdown. The maximum storage depletions are also

Table 6.25
DRAWDOWNS TO BELOW 50% OF CONSERVATION CAPACITY
2010 SIMULATION

First Month	Critical Month	Last Month	Storage Depletion (ac-ft)	Prior Spills (acre-feet)		
				April	May	After May
		Whitney Reservoir (227,750 acre-feet active conservation)				
Jun 10	Dec 10	Sep 11	117,215	-0-	41,271	-0-
Jul 16	Aug 18	Nov 18	163,745	188,628	161,590	34,274
Jun 25	Aug 25	Sep 25	118,091	-0-	213,854	-0-
Jul 51	Mar 52	May 52	134,155	-0-	-0-	57,957
Jun 52	Sep 53	May 54	201,719	-0-	24,288	-0-
Jun 54	Apr 55	May 55	132,306	-0-	177,577	-0-
Jun 56	Sep 56	Apr 57	130,851	-0-	94,322	-0-
Jun 77	Jul 78	Nov 78	227,750	231,054	51,527	-0-
Jul 79	Aug 80	Oct 80	142,478	54,744	312,850	73,547
Mar 84	Sep 84	-	200,028	-0-	-0-	-0-
Average			156,834	47,443	107,728	16,578
		Aquilla Reservoir (47,337 acre-feet conservation capacity)				
Jul 01	Feb 02	Jun 02	32,485	2,678	95,736	1,250
Jul 08	Jan 11	Dec 13	47,337	7,557	30,313	-0-
Jun 16	Jan 18	Jan 19	47,337	13,507	43,164	-0-
Jun 24	Aug 25	Jun 26	47,337	19,814	1,045	-0-
Jun 34	Dec 34	May 35	29,095	5,295	491	-0-
Jul 39	Mar 40	Jul 40	39,754	3,213	-0-	14,162
Aug 48	Dec 48	Jun 51	31,850	-0-	5,041	3,927
Jul 51	Dec 51	May 53	47,337	-0-	5,472	2,915
Jun 53	Jan 55	Apr 57	47,337	-0-	4,120	-0-
Jun 63	Aug 64	May 65	33,507	-0-	492	-0-
Jun 77	Dec 78	Jun 79	31,365	53,613	19,307	-0-
Jul 82	Sep 84	-	28,428	-0-	13,773	8,687
Average			38,597	8,806	18,246	2,578

Table 6.25 (continued)
DRAWDOWNS TO BELOW 50% OF CONSERVATION CAPACITY
2010 SIMULATION

First Month	Critical Month	Last Month	Storage Depletion (ac-ft)	Prior Spills (acre-feet)		
				April	May	After May
Waco Reservoir (108,882 acre-feet active conservation)						
Jun 01	Apr 02	Jul 02	68,816	-0-	73,416	-0-
Jul 08	Dec 10	Jun 13	108,882	131,384	593,541	9,877
Jun 16	Sep 17	Jan 19	108,882	17,791	110,432	-0-
Jul 22	Feb 23	May 23	58,159	2,737	-0-	347,741
Jul 24	Sep 25	Apr 26	86,233	42,247	10,206	4,760
Jul 27	Mar 30	Dec 30	71,792	-0-	-0-	50,518
Jun 34	Jan 35	May 35	63,481	24,872	3,812	-0-
Sep 38	Oct 40	Nov 40	74,771	56,290	78,581	101,811
Jun 43	Dec 43	Mar 44	55,421	4,641	111,661	-0-
Jun 47	Nov 47	Feb 48	55,668	20,707	7,808	-0-
Jun 49	Jan 50	Sep 50	55,661	33,738	101,393	-0-
Oct 50	Mar 52	Apr 57	108,882	-0-	-0-	8,806
Jul 62	Oct 63	Nov 64	108,882	1,666	-0-	7,854
Dec 66	Nov 67	Jan 68	67,819	17,315	182,188	33,322
Jul 70	Jul 71	Oct 71	87,322	40,938	5,533	22,492
Jul 75	Mar 76	Jul 76	63,579	65,632	51,957	23,980
Jul 77	Aug 78	Apr 79	108,882	204,376	126,418	774
Jul 82	Jan 84	-	108,882	-0-	33,203	9,996
Average			81,224	36,908	82,786	34,551
Belton Reservoir (372,700 acre-feet active conservation)						
Jun 01	Feb 02	Feb 03	255,769	1,071	156,547	-0-
Jul 08	Jan 11	Dec 13	372,700	106,928	368,926	95,265
Aug 16	Feb 18	May 19	372,700	37,606	15,003	18,029
Jul 24	Aug 25	Jul 26	372,700	38,320	43,471	20,588
Jul 33	Oct 34	May 35	226,508	22,909	106,558	51,589
Sep 38	Mar 40	Dec 40	309,974	108,713	88,665	232,541
Jul 47	Jan 52	Apr 57	372,700	36,178	50,174	21,004
Jun 63	Jan 64	Nov 64	248,057	357	38,614	-0-
Jul 82	Sep 84	-	228,763	13,447	46,300	35,345
Average			306,652	40,614	101,584	52,706

Table 6.25 (continued)
DRAWDOWNS TO BELOW 50% OF CONSERVATION CAPACITY
2010 SIMULATION

First Month	Critical Month	Last Month	Storage Depletion (ac-ft)	Prior Spills (acre-feet)		
				April	May	After May
Stillhouse Hollow Reservoir (209,703 acre-feet active conservation)						
Jul 01	Feb 02	Sep 02	143,786	3,867	93,153	7,795
Jan 09	Jan 11	Dec 13	209,703	-0-	-0-	-0-
Aug 16	Jan 18	May 19	209,703	9,937	18,138	26,181
Aug 24	Aug 25	May 26	209,703	31,894	25,640	8,033
Jul 33	Oct 34	May 35	131,711	1,130	21,705	3,153
Sep 38	Mar 40	Nov 40	175,983	27,847	37,876	187,616
Jul 47	Dec 51	Apr 57	209,703	26,300	21,828	6,842
Jun 63	Jan 64	Mar 65	140,643	1,309	3,504	-0-
Jul 77	Dec 78	Jun 79	141,510	141,202	52,141	9,818
Jul 83	Sep 84	-	129,603	-0-	5,902	7,735
Average			170,204	24,348	27,989	25,717
Granger Reservoir (57,070 acre-feet active conservtion)						
Jul 01	Feb 02	May 02	39,010	-0-	52,203	3,153
Jul 09	Nov 09	Apr 10	29,643	1,368	7,317	1,963
May 10	Jan 11	May 13	57,070	5,712	-0-	-0-
Aug 16	Jan 18	Dec 18	57,070	30,704	16,540	24,932
Jul 24	Aug 25	Oct 25	57,070	38,380	35,332	43,735
Jul 33	Dec 33	Mar 24	32,618	6,902	15,371	4,284
Jun 34	Oct 34	May 35	41,905	23,504	2,152	-0-
Sep 38	Mar 40	May 40	47,773	36,416	11,682	87,649
Aug 48	Jan 49	Apr 49	40,842	-0-	3,197	4,344
Jul 50	Oct 52	Oct 53	57,070	4,819	4,919	5,890
Feb 54	Jan 55	Apr 57	57,070	-0-	-0-	-0-
May 63	Jan 64	Nov 64	38,155	3,986	-0-	-0-
Average			45,923	16,964	12,576	13,082

Table 6.25 (continued)
DRAWDOWNS TO BELOW 50% OF CONSERVATION CAPACITY
2010 SIMULATION

First Month	Critical Month	Last Month	Storage Depletion (ac-ft)	Prior Spills (acre-feet)		
				April	May	After May
Somerville Reservoir (146,138 acre-feet active conservation)						
Jul 01	Feb 02	May 02	99,218	5,058	75,568	38,142
Mar 09	Jan 13	Nov 13	146,138	3,748	-0-	-0-
Aug 16	Feb 18	Jan 19	146,138	61,884	3,258	2,023
Jul 24	Aug 25	Oct 25	146,138	67,596	2,090	16,720
Jun 33	Dec 33	Feb 34	74,398	3,213	4,427	-0-
May 34	Oct 34	May 35	88,119	72,594	-0-	-0-
Jul 38	Mar 40	Aug 40	121,515	100,621	49,497	1,844
Sep 47	Jan 49	Apr 49	110,684	9,461	26,993	94,908
Oct 50	Oct 52	Dec 53	146,138	54,208	22,135	65,156
Jun 54	Mar 55	Apr 57	146,138	-0-	122	-0-
May 63	Jan 64	Apr 65	97,234	15,173	-0-	-0-
Jun 77	Dec 78	Mar 79	98,009	134,240	8,731	-0-
Jun 84	Sep 84	-	88,989	714	983	-0-
Average			116,065	40,654	14,908	16,831

cited. Reservoir spills occurring in the months just prior to the drawdowns are also shown. The prior spills are relatively large compared to the maximum storage depletions. Thus, sufficient water is typically available in April and May, for capture by a seasonal rule curve, to significantly raise storage levels during the drawdowns which begin in the summer.

Table 6.26 shows the number of drawdowns which occurred during the 85-year simulation. The drawdowns are categorized by the maximum storage depletion during the drawdown. For example, Somerville reservoir had 28, 8, and 5 drawdowns which resulted in storage depletions of 10%-49%, 50%-99%, and 100%, respectively, of the conservation capacity. A storage depletion of 100% means the conservation pool was emptied. A total of 295 drawdowns occurred at the seven reservoirs which resulted in depletions of at least 10% of the conservation capacity.

Table 6.27 shows the number of drawdowns occurring at any of the seven reservoirs in each month of the year. The month in which the drawdowns begin is counted. 19.3%, 41.7%, and 19.0% of the drawdowns began in June, July, and August, respectively. Thus 80% of the drawdowns began in the three summer months. This definite seasonal pattern indicates that seasonal rule curve operations could potentially be effective in reducing storage depletions. Spring flows can be captured to reduce summer drawdowns.

Table 6.26
NUMBER OF DRAWDOWNS
2010 SIMULATION

Reservoir	Maximum Storage Depletion (Percent of Conservation Capacity) 10%-49%	 50-99%	 100% (empty)
	Number of Drawdowns		
Whitney	57	9	1
Aquilla	27	7	5
Waco	26	12	6
Belton	25	5	4
Stillhouse	21	6	4
Granger	25	9	5
Somerville	28	8	5
Total	209	56	30

Table 6.27
FREQUENCY OF DRAWDOWNS BEGINNING IN EACH MONTH
2010 SIMULATION

Month	Maximum Storage Depletion (Percent of Conservation Capacity) 10-49%	 50-99%	 100% empty	 10-100%	 10-100%
	Number of Drawdowns				Frequency
Jan	1	0	1	2	0.7%
Feb	0	0	1	1	0.3%
Mar	10	0	2	12	4.1%
Apr	5	1	0	6	2.0%
May	3	3	1	7	2.4%
Jun	31	20	6	57	19.3%
Jul	87	23	13	123	41.7%
Aug	49	2	5	56	19.0%
Sep	11	4	0	15	5.1%
Oct	4	2	1	7	2.4%
Nov	7	0	0	7	2.4%
Dec	1	1	0	2	0.7%
Total	209	56	30	295	100.0%

CHAPTER 7
FIRM YIELD AND RELIABILITY

Potential storage reallocations are evaluated in this chapter from the perspective of increases in reservoir yield. Firm yields and reliabilities are presented for alternative allocations of storage capacity.

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 conditions. Firm yields are presented in this chapter for alternative conditions of sedimentation and alternative approaches for considering interactions between reservoirs. Reservoir yield versus reliability relationships are also developed. 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, have period and volume reliabilities of 100%. Yields greater than firm yield have reliabilities of less than 100%.

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. Reliability, for a given yield, is computed by a HEC-3 simulation.

In the present study, firm yields were computed for the 13 reservoirs, neglecting the effects of other reservoirs and water users in the basin. Wurbs, Bergman, Carriere, and Walls (1988) present a water rights analysis which includes consideration of the impacts of other water users and reservoirs on the firm yields 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 Simulation 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 5.2. 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 7.1, 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 5.2. Possum Kingdom Reservoir has a top of inactive pool elevation of 970 feet msl, which was set in the past by a hydroelectric power contract. However, the hydropower contract will soon expire. 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

Table 7.1
GLOSSARY OF FIRM YIELD TERMS

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.

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.

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.

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. Individual reservoir hydropower firm yield was also computed for Whitney. 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 were not included in a majority of the simulation runs. If maximum allowable discharges are not specified, when the water is at the top of conservation pool, releases from the flood control pool equal inflows. Maximum allowable discharges were included in some of the analyses of storage reallocations. The discussions of firm yields and reliabilities indicate which simulations included flood control operations. However, specification of maximum allowable discharges representing flood control operations was found to have essentially no effect on firm yields and reliabilities.

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

Model Input Data

The hydrologic data and reservoir storage characteristics used in the yield studies are described in Chapter 5 and were also used in the simulation studies presented in Chapter 6. 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 yield analyses are tabulated in Table 7.2. 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

Table 7.2
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

developed by the BRA based on historical reservoir release data. These are averages for the entire system.

Firm Yields for Existing Storage Allocations

Single Reservoir Firm Yields

The single reservoir firm yields presented in Table 7.3 were computed for each reservoir alone, ignoring the effects of upstream reservoirs on inflows. The firm yields are presented for the four alternative conditions of sedimentation.

Individual Reservoir Firm Yields

The firm yields tabulated in Tables 7.4, 7.5, 7.6, 7.7, and 7.8 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 7.5, 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.

Tables 7.5, 7.6, 7.7, and 7.8 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 7.4. 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.

Figures 7.1 through 7.13 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 7.6. 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.

Table 7.3
SINGLE RESERVOIR FIRM YIELDS FOR ALTERNATIVE SEDIMENT CONDITIONS

Reservoir	Condition of Sedimentation				Year	
	Base	1984	2010	Ultimate	Base	Ultimate
Hubbard Creek	57	57	57	57	1962	2020
P.K. (inactive 970 ft)	305	300	290	286	1974	2020
P.K. (inactive 875 ft)	449	443	427	415	1974	2020
Granbury (inactive 675 ft)	202	193	178	172	1969	2020
Granbury (inactive 640 ft)	277	267	252	246	1969	2020
Whitney (inactive 520 ft)	394	376	357	357	1959	2010
Whitney (inactive 449 ft)	823	803	782	782	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	216	210	192	192	1975	2010
Stillhouse Hollow	110	108	105	104	1968	2018
Georgetown	23	23	22	19	1980	2080
Granger	44	44	41	29	1980	2080
Limestone	105	100	98	98	1978	2030
Somerville	62	61	60	59	1967	2017

Table 7.4
INDIVIDUAL RESERVOIR FIRM YIELDS FOR ALTERNATIVE SEDIMENT CONDITIONS

Reservoir	Condition of Sedimentation				Year	
	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

Table 7.5
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 7.6
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	60,813	7.5	Jun 77-Aug 78	1,126	1,004	38
Granbury (Inactive 640 ft)	137,400	120	87,600	11.9	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 7.7
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	60,812	5.9	Jan 77-Aug 78	1,138	1,037	34
Granbury (Inactive 640 ft)	113,850	104	87,600	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 7.8
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	60,813	5.9	Jul 77-Aug 78	1,143	1,021	38
Granbury (Inactive 640 ft)	104,790	104	87,600	10.0	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

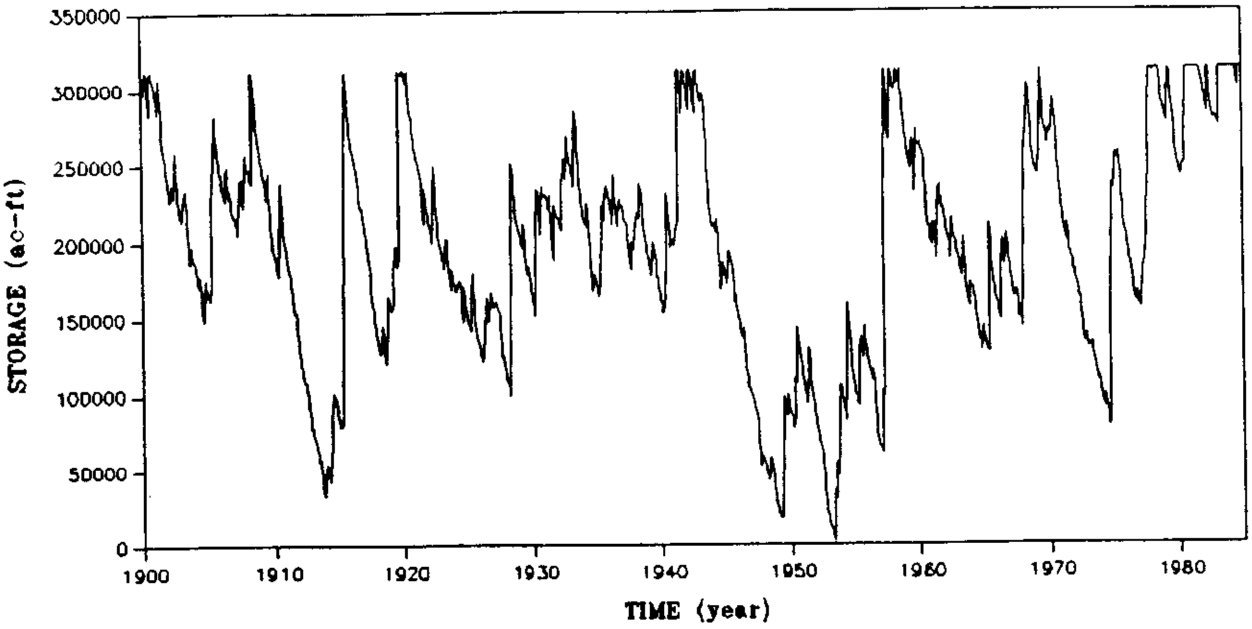


Figure 7.1 Hubbard Creek Reservoir Storage Hydrograph, Individual Reservoir Firm Yield, 1984 Sedimentation

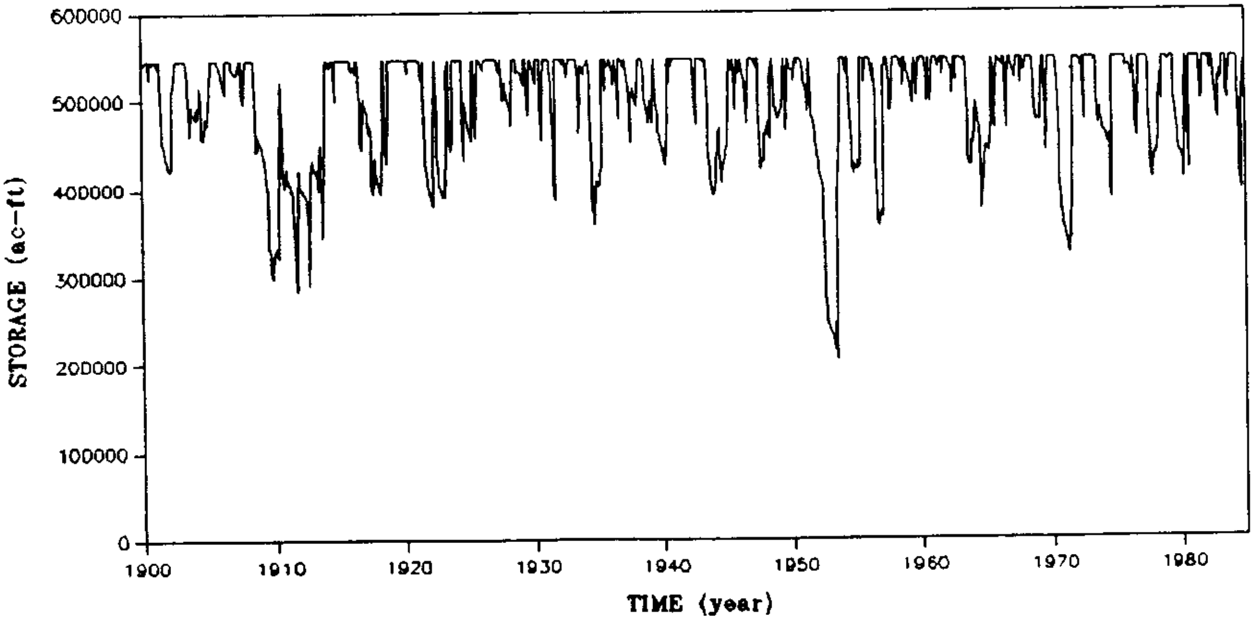


Figure 7.2 Possum Kingdom Reservoir Storage Hydrograph, Individual Reservoir Firm Yield, 1984 Sedimentation

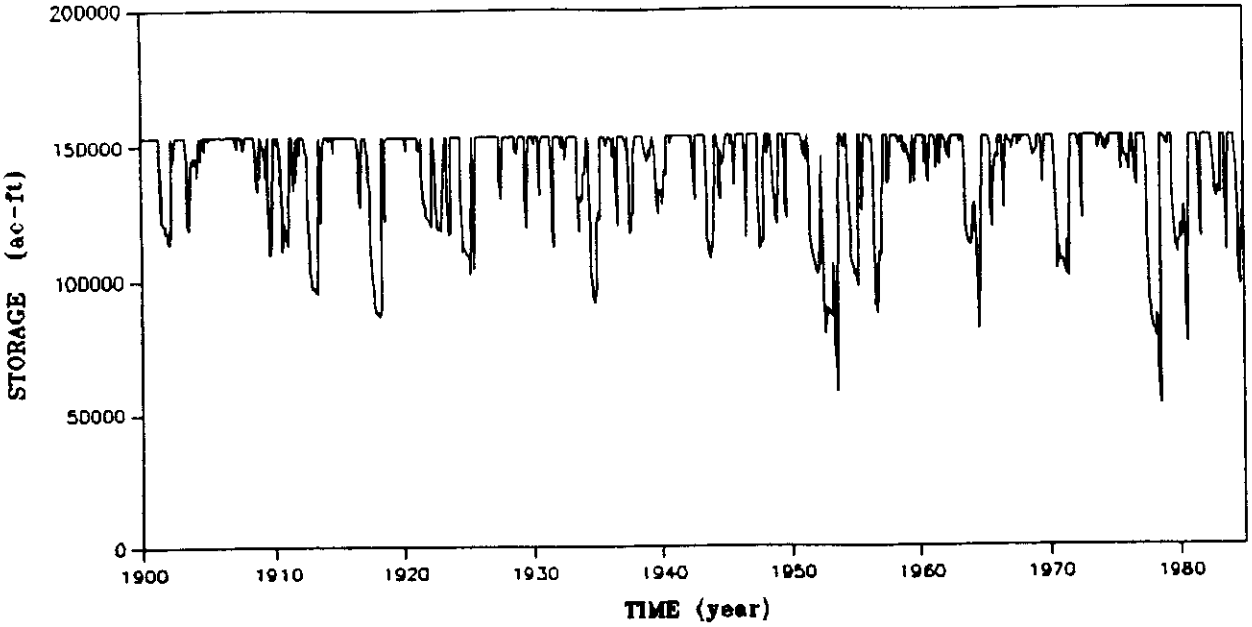


Figure 7.3 Granbury Reservoir Storage Hydrograph, Individual Reservoir Firm Yield, 1984 Sedimentation

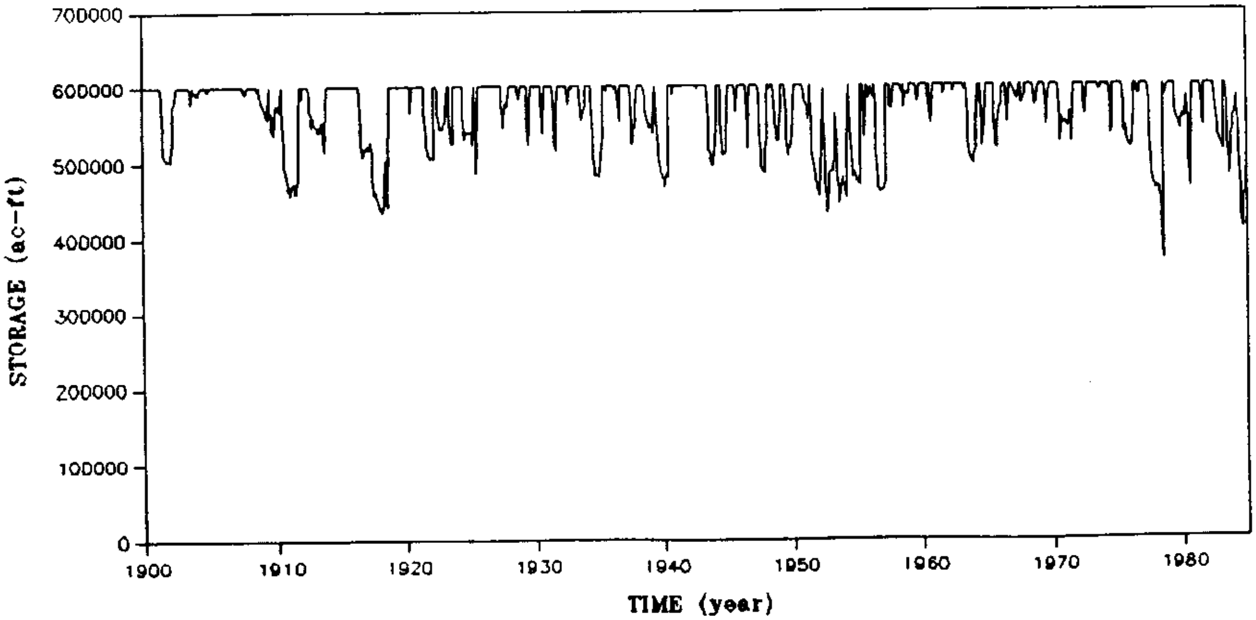


Figure 7.4 Whitney Reservoir Storage Hydrograph, Individual Reservoir Firm Yield, 1984 Sedimentation

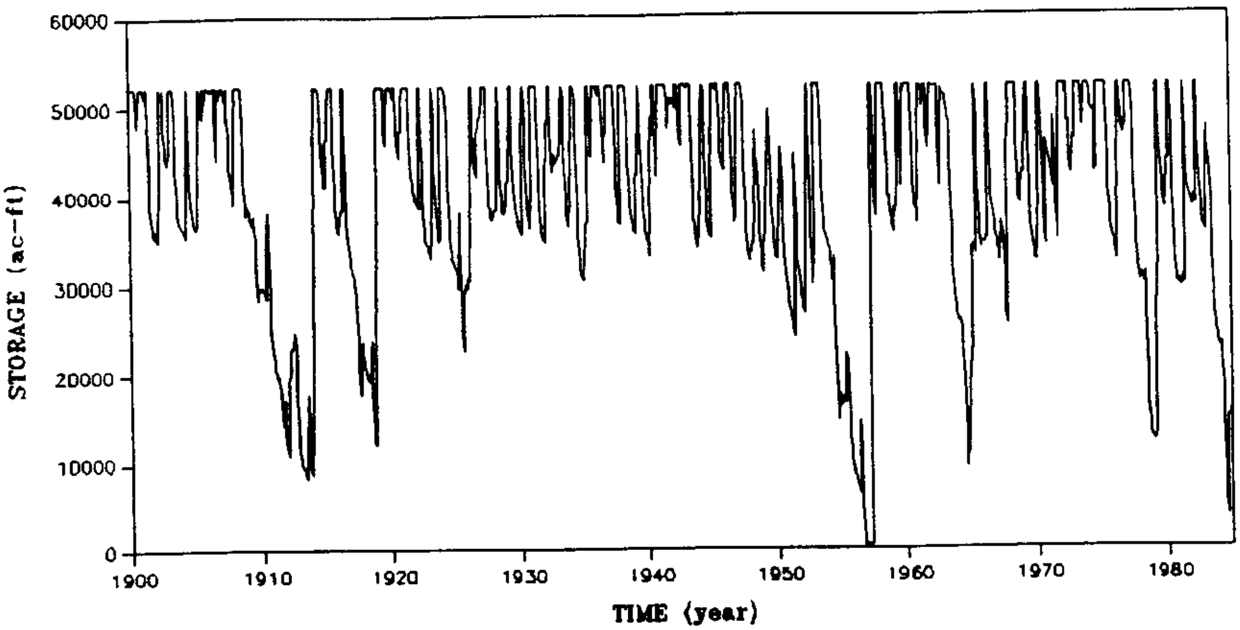


Figure 7.5 Aquilla Reservoir Storage Hydrograph, Individual Reservoir Firm Yield, 1984 Sedimentation

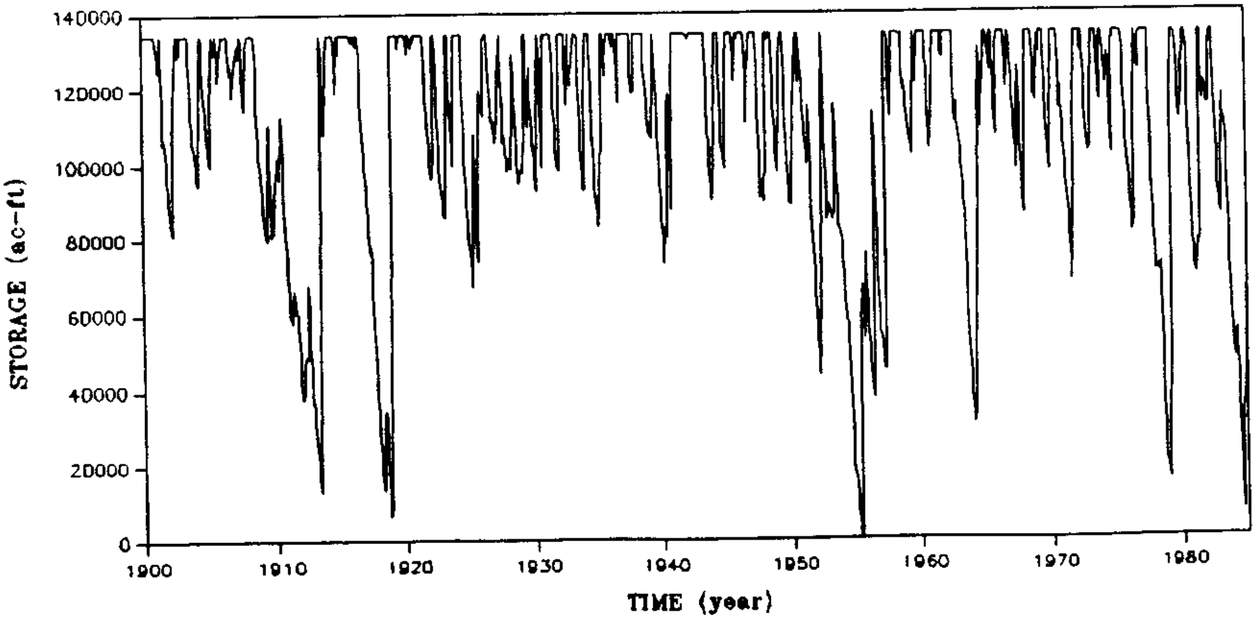


Figure 7.6 Waco Reservoir Storage Hydrograph, Individual Reservoir Firm Yield, 1984 Sedimentation

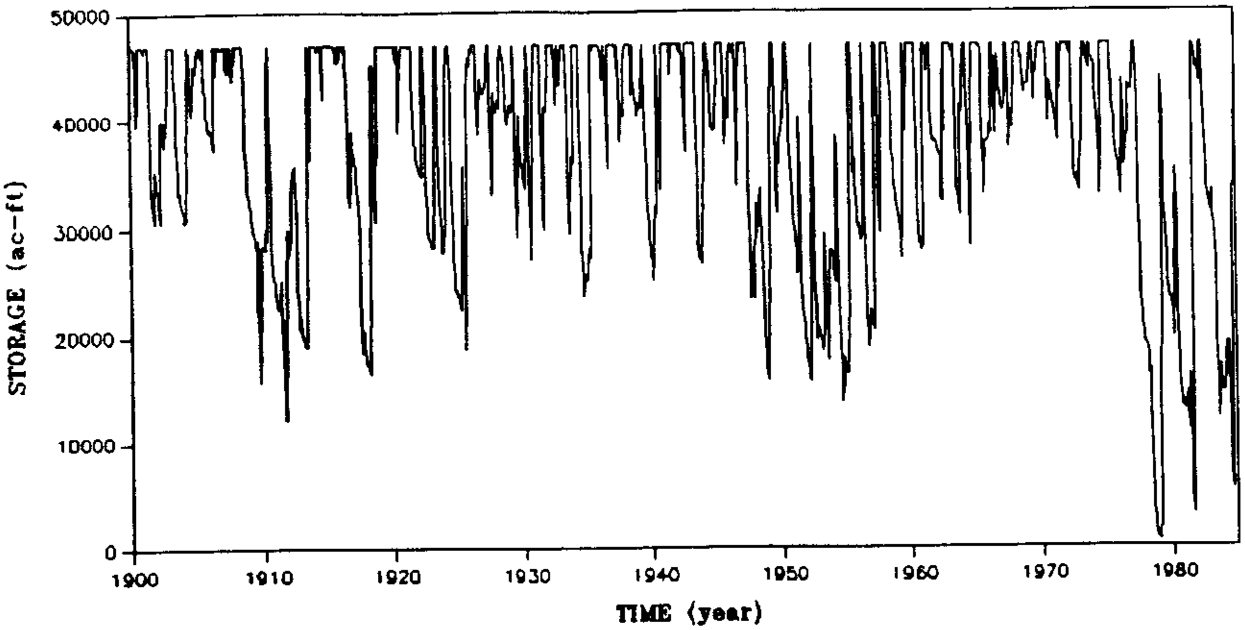


Figure 7.7 Proctor Reservoir Storage Hydrograph, Individual Reservoir Firm Yield, 1984 Sedimentation

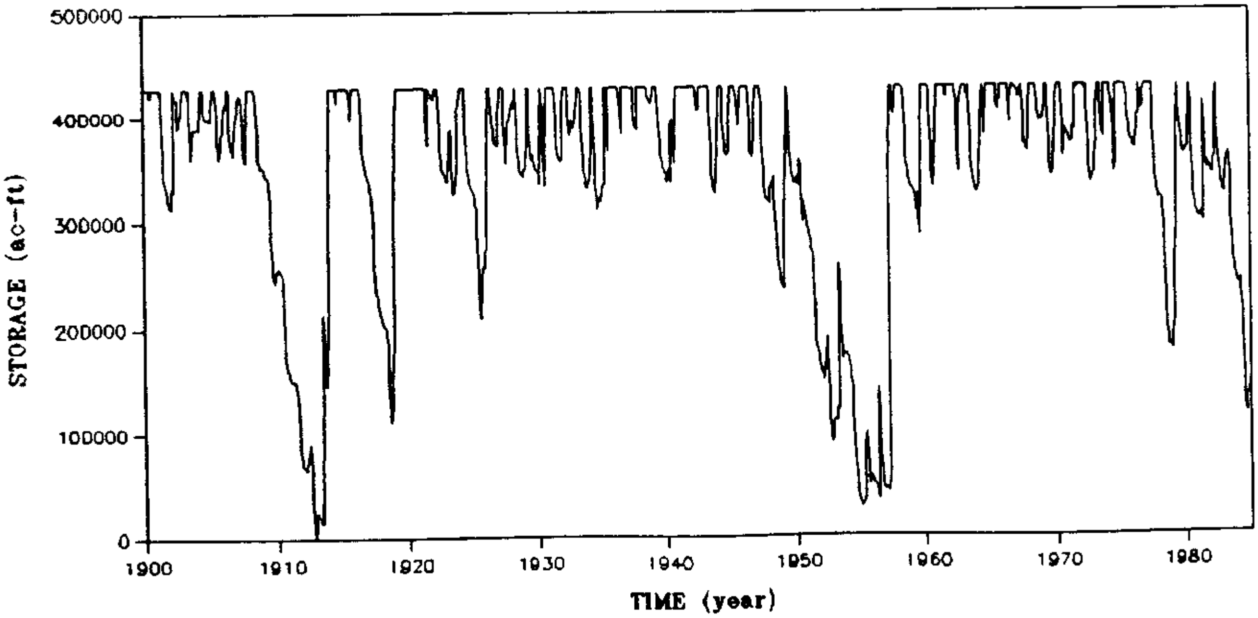


Figure 7.8 Belton Reservoir Storage Hydrograph, Individual Reservoir Firm Yield, 1984 Sedimentation

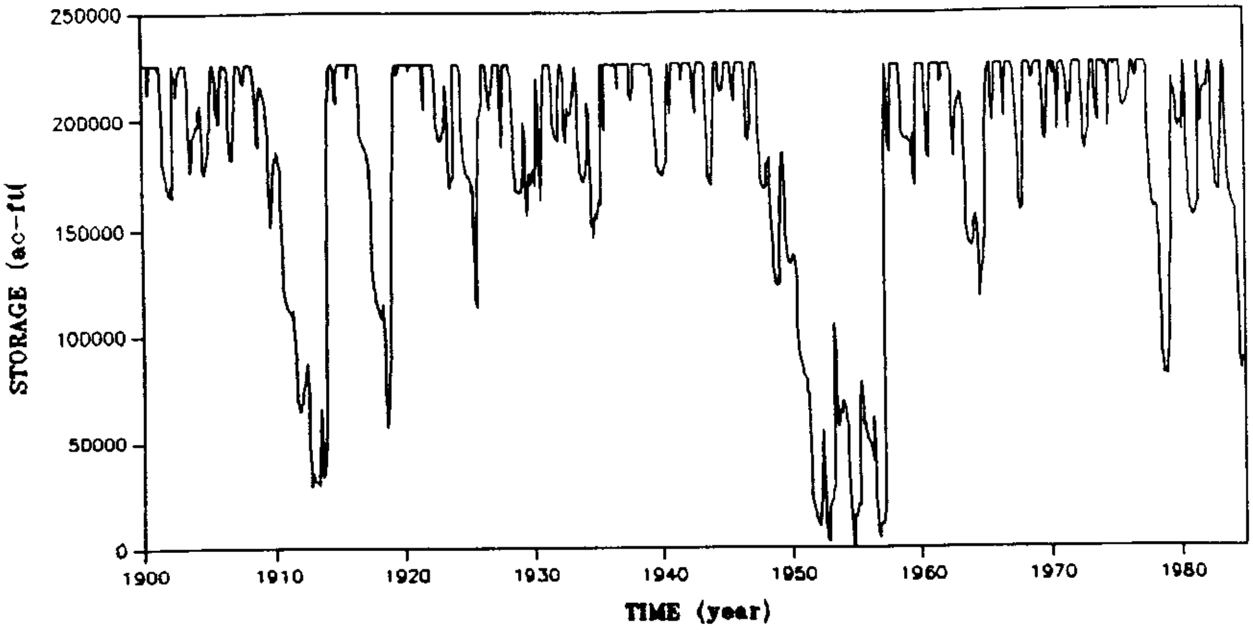


Figure 7.9 Stillhouse Hollow Reservoir Storage Hydrograph, Individual Reservoir Firm Yield, 1984 Sedimentation

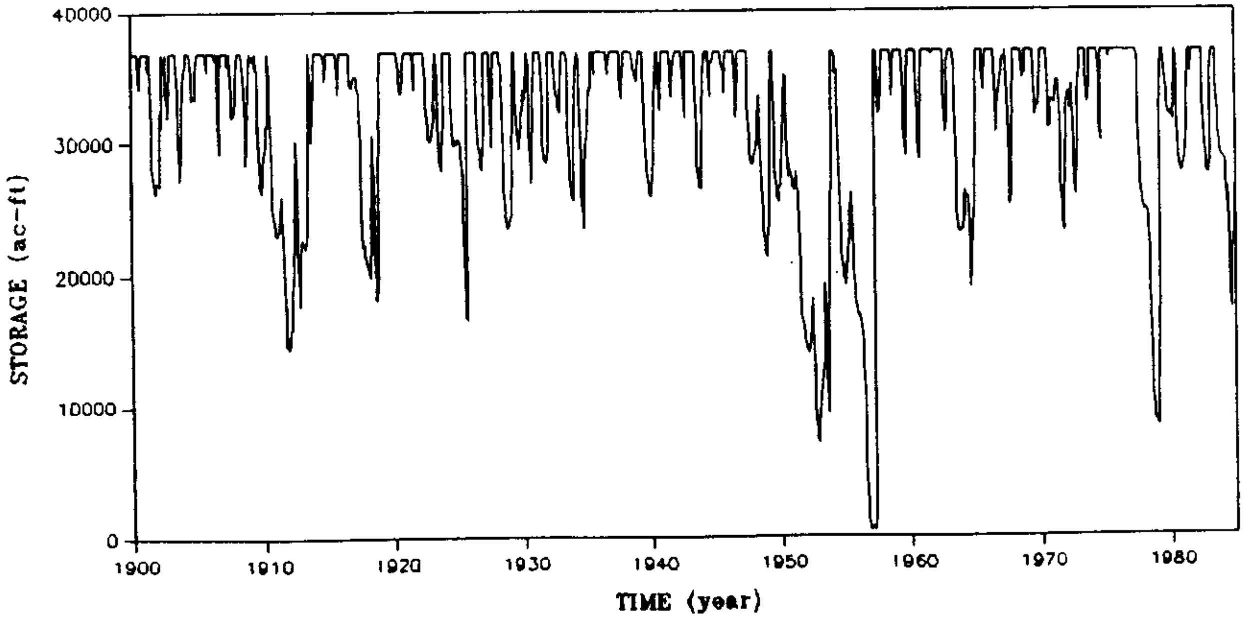


Figure 7.10 Georgetown Reservoir Storage Hydrograph, Individual Reservoir Firm Yield, 1984 Sedimentation

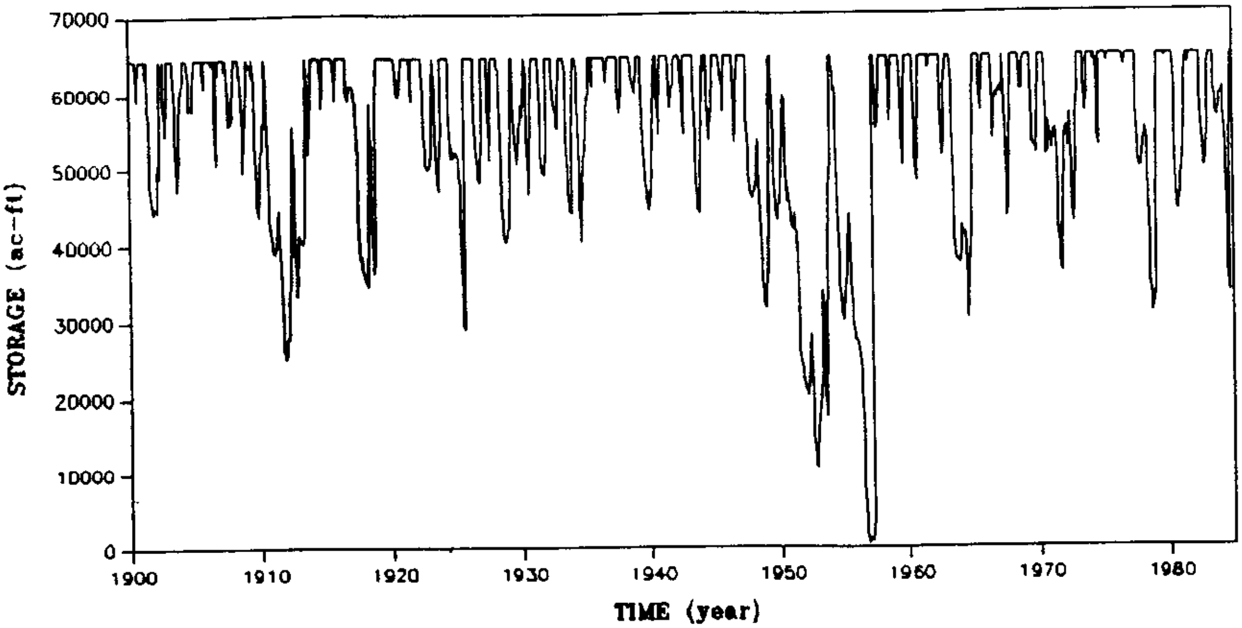


Figure 7.11 Granger Reservoir Storage Hydrograph, Individual Reservoir Firm Yield, 1984 Sedimentation

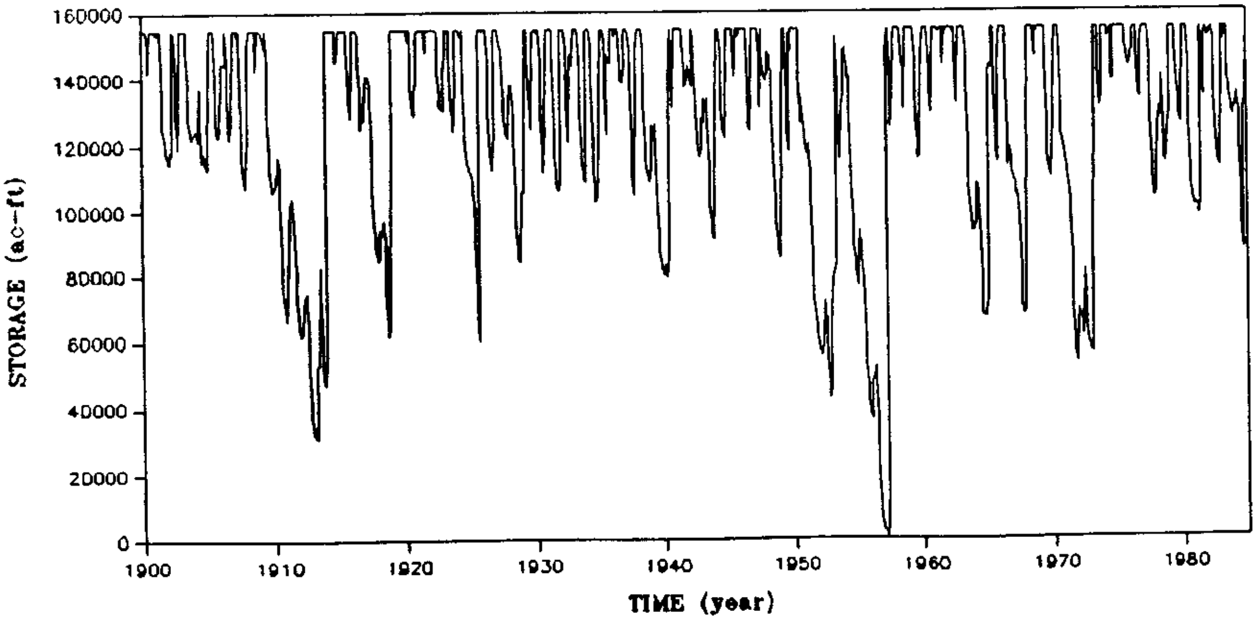


Figure 7.12 Somerville Reservoir Storage Hydrograph, Individual Reservoir Firm Yield, 1984 Sedimentation

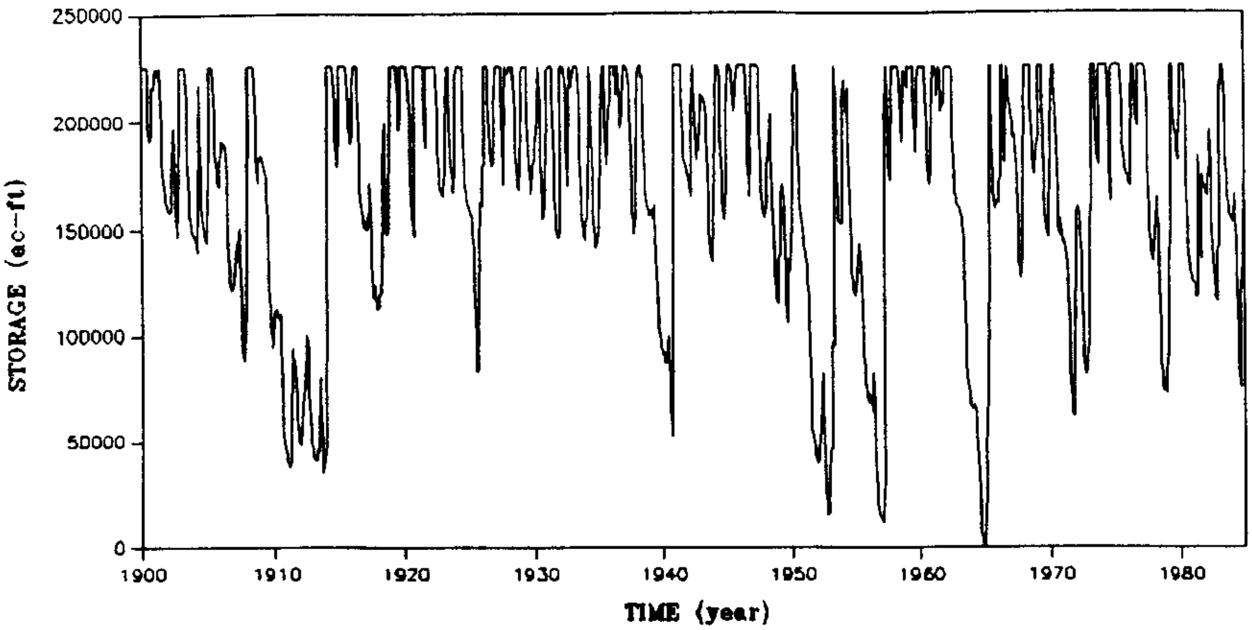


Figure 7.13 **Limestone Reservoir Storage Hydrograph, Individual Reservoir Firm Yield, 1984 Sedimentation**

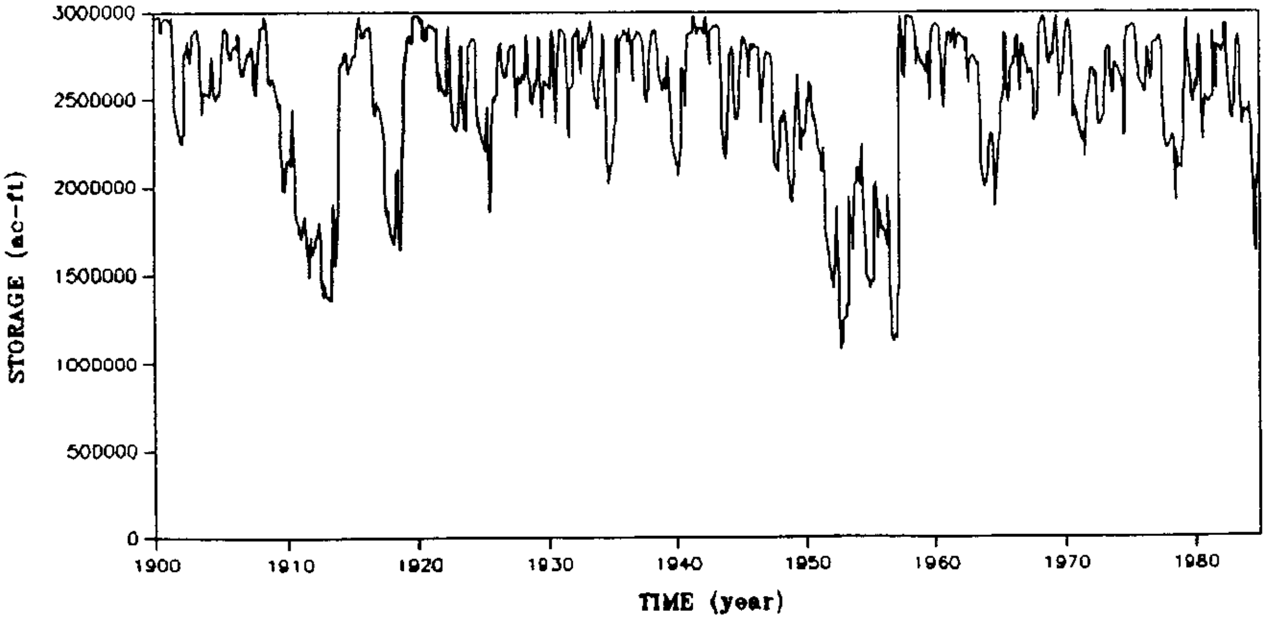


Figure 7.14 **Summation of Storage Hydrographs for Individual Reservoir Firm Yield Simulations**

Figure 7.14 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.

Whitney Reservoir Water Supply and Hydroelectric Power Firm Yields

Possum Kingdom and Whitney Reservoirs each have hydroelectric power plants. In the past, Possum Kingdom Reservoir was operated primarily for hydroelectric power generation. In the future, it probably will be operated primarily as a water supply reservoir with hydroelectric power generation being limited essentially to incidental use of water supply releases. In the present yield study, Possum Kingdom Reservoir was treated as a water supply reservoir, without considering hydropower. However, hydroelectric power generation at Whitney Reservoir was incorporated into the yield study.

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 (between elevations 520 ft and 533 ft) to water supply. The individual reservoir firm yield is estimated by multiplying the firm yield computed assuming the entire active conservation pool is used for water supply, by 22.017 percent. Thus, the Whitney individual reservoir firm yield is 22.017 percent of the values shown in Tables 7.4, 7.5, 7.6, 7.7, and 7.8, or 42 cfs for base sediment conditions and 40 cfs for 1984, 2010, and ultimate sediment conditions.

Hydroelectric power is generated at Whitney Reservoir in accordance with a 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. In computing system firm yields for water supply, as discussed below, the monthly energy distribution incorporated in the model, in terms of kilowatt-hours per kilowatt 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. In computing the individual reservoir hydropower firm yield, the same relative monthly distribution was used. Additional HEC-3 input data included an overload ratio of 1.15, powerplant efficiency of 0.86, and the tailwater rating curve taken from the reservoir regulation manual.

Hydroelectric power firm yields for Whitney Reservoir are presented in Table 7.9 for alternative assumptions regarding upstream reservoirs and water supply diversions. Scenario 1 consists of a single reservoir hydropower firm yield for Whitney with no other reservoirs or diversions included in the model. In all the other scenarios, Hubbard Creek Reservoir is included in the model with a diversion equal to its firm yield. Possum Kingdom and Granbury Reservoirs are also included in runs 2,3,4, and 5. In runs 2 and 3, Possum Kingdom and Granbury are included in the model, but with no releases or diversions. In runs 4 and 5, the Possum Kingdom and Granbury firm yields are

Table 7.9

WHITNEY HYDROELECTRIC POWER FIRM AND SECONDARY YIELD

Scenario	1984 Sediment Condition		2010 Sediment Condition	
	Firm Energy	Secondary Energy	Firm Energy	Secondary Energy
	megawatt -hours			
1	29,800	78,800	25,900	80,400
2	24,500	75,000	22,300	75,900
3	22,500	73,800	19,000	76,900
4	14,750	59,500	11,000	62,600
5	11,500	59,400	8,400	63,500

Scenario 1 - no upstream reservoirs, no diversions

Scenario 2 - firm yield diverted at Hubbard Creek Reservoir, Possum Kingdom and Granbury Reservoirs included with no diversions

Scenario 3 - firm yield diverted at Hubbard Creek Reservoir, Possum Kingdom and Granbury Reservoirs included with no diversions, water supply diversion of 40 cfs at Whitney Reservoir

Scenario 4 - same as Scenario 2 except firm yields are diverted at Possum Kingdom and Granbury Reservoirs

Scenario 5 - same as Scenario 3 except firm yields are diverted at Possum Kingdom and Granbury Reservoirs diverted at these reservoirs, and thus inflows to Whitney are reduced. In runs 3 and 5, the water supply yield of 40 cfs is also diverted at Whitney Reservoir. Simulation runs were repeated for 1984 and 2010 conditions of sedimentation.

The hydropower firm yield is termed firm energy in Table 7.9. Additional energy, termed secondary energy, is produced as spills from the Whitney flood control pool and conservation releases from Possum Kingdom and Granbury pass through the turbines at Whitney. The firm yield is provided continuously through the 85-year simulation period. Secondary energy is additional energy provided only when releases from other purposes are available to incidentally generate electricity.

Ignoring all other reservoirs and diversions and assuming 1984 sedimentation, Whitney has a hydroelectric power firm yield of 29,800 megawatt-hours. Hubbard Creek, Possum Kingdom, and Granbury Reservoirs, with their firm yields diverted at the reservoirs, and a 40 cfs water supply diversion at Whitney Reservoir reduce the hydropower firm yield to 11,500 megawatt-hours.

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 7.2 were used for the system diversions. Streamflow and evaporation rate data are the same as the previously discussed simulations.

System firm yields were repeated excluding and including unregulated flows originating from the watershed which is not upstream of, and thus not regulated by, any of the reservoirs. 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. About 40% of the naturalized flow at the Richmond gage enters the river below the dams.

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 7.10 for 1984 and 2010 sediment conditions, respectively. The top of inactive and conservation pool elevations for each reservoir are shown. Firm yield is computed for the 12-reservoir BRA system. Hubbard Creek Reservoir is also included in the HEC-3

Table 7.10
STANDARD OPERATING PLAN

Reservoir	Pool Elevation		1984	2010
	Top of Inactive (feet)	Top of Conservation (feet)	Conservation Capacity (acre-feet)	Conservation Capacity (acre-feet)
Hubbard	1,136	1,183	308,070	300,370
Possum Kingdom	875	1,000	544,510	477,600
Granbury	675	693	137,400	85,320
Whitney	520	533	238,180	227,950
Aquilla	503	537.5	52,213	47,340
Waco	400	455	133,750	108,880
Proctor	1,128	1,162	46,850	31,400
Belton	483	594	428,250	372,700
Stillhouse	515	622	225,320	209,700
Georgetown	720	791	36,540	34,540
Granger	457	504	64,190	57,070
Limestone	325.5	363	218,050	214,060
Somerville	206	238	154,450	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 September, and 75 hours in each of the other eight months.

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 ten 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.

As previously discussed, 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 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 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 ft, 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.

Assuming 1984 sediment conditions, the system firm yield for the standard operating plan is 1,697 cfs, excluding unregulated flows from the watershed below the dams, and 2,265 cfs including the unregulated flows. This includes diversions of 40 cfs and 116 cfs at Whitney and Waco Reservoirs and a diversion of 1,531 cfs or 2,109 cfs (excluding and including unregulated flows) at the Richmond gage control point.

Assuming 2010 sediment conditions, the system firm yield for the standard operating plan is 1,618 cfs and 2,182 cfs excluding and including unregulated flows, respectively. This includes diversions of 40 cfs and 106 cfs at Whitney and Waco Reservoirs and a diversion of 1,531 cfs or 2,109 cfs (excluding and including unregulated flows) at the Richmond gage control point.

Simulation Results for Standard Operating Plan

The results of simulating the standard operating plan with its firm yield diversions, assuming 1984 sediment conditions, are summarized in Tables 7.11, 7.12, and 7.13. The 12-reservoir system firm yield is 1,697 cfs or 2,265 cfs excluding and including unregulated flows, respectively, with 1,531 cfs or 2,109 cfs of the firm yield being diverted at the Richmond gage. Other diversions and storage capacities are shown in Table 7.10. Table 7.11 is a water balance for the stream/reservoir system. In the model, the total streamflow input leaves the system as water use diversions, reservoir evaporation losses, or flow into the Gulf of Mexico. In table 7.11, 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. Outflow from the system, expressed as average flow rates, are the firm yield diversions, reservoir evaporation, and flow into the Gulf of Mexico.

Water balances for each of the individual reservoirs are presented in Table 7.12. 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 7.13. 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.

For the four firm yield simulations, excluding and including unregulated flows and 1984 and 2010 sediment conditions, the firm yield provided by the ten reservoirs, which released for the common control point at the Richmond gage, is controlled by two critical drawdown periods, July 1908 to August 1912 and July 1950 to August 1956. Both critical drawdown periods result in essentially the same firm yield. All the reservoirs are full in June 1908, essentially empty in August 1912, and full again in January 1914. Thus, the critical drawdown extends over a period of four years and two months. The reservoirs gradually refill during late 1912 and throughout 1913, with particularly high inflows during late 1913. The second critical period begins in June and July 1950. All the reservoirs are full and spilling in May 1950 and several are

Table 7.11
SYSTEM WATER BALANCE FOR STANDARD OPERATING PLAN
1984 Sediment Condition

Flows from Unregulated Watershed below Dams	Exclude	Include
12-Reservoir System Firm Yield (cfs)	1,697	2,265
Average Flow (cfs) over 85-Year Simulation Period		
System Inflow	4,763	7,887
Diversions	1,754	2,322
Richmond Gage	(1,541)	(2,109)
Waco Reservoir	(116)	(116)
Whitney Reservoir	(40)	(40)
Hubbard Creek Reservoir	(57)	(57)
Evaporation from 13 Reservoirs	483	479
Flow to the Gulf of Mexico	2,548	5,127

Table 7.12
RESERVOIR WATER BALANCE FOR STANDARD OPERATING PLAN
1984 Sediment Condition

Reservoir	Averages in cfs over 85-year Simulation				
			Conservation Releases		
	Inflow	Evaporation	Downstream	Diversion	Spills
12-Reservoir Firm Yield of 1,697 cfs Excluding Unregulated Flows					
Hubbard Creek	157	63	-	57	31
Possum Kingdom	1,116	76	472	-	574
Granbury	1,469	34	608	-	828
Whitney	2,155	101	904	40	1,113
Aquilla	101	12	28	-	62
Waco	451	26	-	116	270
Proctor	159	20	24	-	115
Belton	632	46	205	-	386
Stillhouse	305	21	103	-	183
Georgetown	90	4	18	-	68
Granger	243	13	70	-	160
Limestone	305	39	91	-	177
Somerville	324	26	91	-	207
12-Reservoir Firm Yield of 2,265 cfs Including Unregulated Flows					
Hubbard Creek	157	63	-	57	39
Possum Kingbom	1,116	75	459	-	587
Granbury	1,469	34	588	-	848
Whitney	2,156	101	837	40	1,181
Aquilla	101	12	22	-	68
Waco	451	26	-	116	286
Proctor	159	20	22	-	118
Belton	632	45	173	-	419
Stillhouse	305	21	85	-	201
Georgetown	90	4	16	-	70
Granger	243	13	48	-	183
Limestone	305	38	70	-	198
Somerville	324	26	59	-	239

Table 7.13
RESERVOIR STORAGE FREQUENCY FOR STANDARD OPERATING PLAN
System Firm Yield of 2,265 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	3.9	3.6	8.7	14.2	17.5	25.5	13.1	5.4	0.2
Possum Kingdom	34.1	7.2	5.9	10.0	11.3	6.9	11.2	5.8	5.5	2.3
Granbury	39.2	10.0	5.9	8.6	5.7	9.3	5.6	3.7	3.8	2.3
Whitney	48.8	14.3	12.0	14.9	4.1	5.2	0.7	0.0	0.0	0.0
Aquilla	32.3	7.3	5.1	11.3	11.7	12.0	8.7	5.2	5.5	1.1
Waco	35.2	6.7	7.6	13.3	13.3	7.5	8.0	5.5	2.5	0.2
Proctor	42.4	10.6	10.6	12.1	7.3	4.5	6.2	2.9	2.9	0.6
Belton	39.9	6.2	3.9	12.5	12.2	6.6	5.3	5.5	7.4	0.7
Stillhouse	42.5	5.2	6.2	9.3	11.6	7.5	4.1	6.1	7.1	0.5
Georgetown	48.7	5.3	5.5	12.0	9.2	4.4	5.9	3.7	4.7	0.6
Granger	47.7	5.5	4.7	11.7	9.5	5.7	4.6	4.8	5.2	0.6
Limestone	40.1	5.6	6.0	11.2	8.2	7.5	7.8	6.5	5.7	1.4
Somerville	33.5	6.2	6.9	8.7	11.9	11.9	7.1	6.5	6.3	1.2

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.

also full in June. The reservoirs are 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 7.6, the critical drawdown periods for Hubbard Creek and Waco Reservoirs were November 1942 to May 1953 and June 1952 to April 1955.

System Firm Yield for Alternative Subsystems and Sediment Conditions

System firm yields are presented in Table 7.14 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 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 7.14 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 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 7.15. 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.

Table 7.14
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) Excluding Local Flows	Firm Yield (ac-ft/yr) Including Local Flows	Firm Yield (cfs) Excluding Local Flows	Firm Yield (cfs) 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 7.15
COMPARISON OF INDIVIDUAL AND SYSTEM FIRM YIELDS

Reservoirs above Control Point (Gage Station)	Sum of Single Reservoir Firm Yield (cfs)	Sum of 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	795	936	-	118	-
Bryan Gage	1,568	1,167	1,459	1,651	125	141
Richmond Gage	1,729	1,328	1,697	2,265	128	171
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 single and individual reservoir firm yields for Whitney included in the sums are based on the assumption that the entire active conservation pool is used for water supply.

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.

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 local flows and thus, less reservoir drawdowns are required. For the standard operating plan, the system firm yield including local flows (2,162 cfs) is 135% higher than the system firm yield excluding local flows (1,618 cfs). The system firm yield including local flows (2,162 cfs) is 171% of the sum of the corresponding individual reservoir firm yields (1,264 cfs).

Maximum Potential Firm Yield for Storage Reallocation

The records of measured mean monthly flow at the Richmond gage contains a minimum flow of 144 cfs. However, the naturalized streamflow data includes two months of zero flow at the Richmond gage. Thus, the basin firm yield with no reservoir storage would be zero. The 85-year sequence of naturalized monthly streamflow at the Richmond gage has a mean of 7,887 cfs. This represents the total runoff supplied by the basin. An imaginary reservoir at the Richmond gage with infinite storage capacity and no evaporation would have a firm yield of 7,887 cfs. Thus, the firm yield for any reservoir system configuration in the basin must be between zero and 7,887 cfs. Reservoir evaporation, spills, and unregulated flows result in system firm yield being much less than 7,887 cfs.

As a representation of the absolute upper limit of system firm yields to be achieved by storage reallocations, firm yields were computed assuming all the storage capacity in the twelve reservoirs is allocated to water supply. There is no flood control or hydroelectric power. The twelve reservoirs release to meet the firm yield diversion at the Richmond gage. The reservoir storage levels were set at the actual existing top of conservation pools at the beginning of the simulation, rather than at the raised levels included in the reallocation. The resulting firm yields, assuming 1984 sediment conditions, are 2,484 cfs and 3,147 cfs respectively, excluding and including unregulated flows. Assuming 2010 sediment conditions, system firm yields are 2,472 cfs and 3,130 cfs, respectively, excluding and including unregulated flows. A system water balance for the firm yield simulations is presented as Table 7.16. Water balances for each reservoir are shown in Table 7.17. Table 7.18 presents storage frequency relationships for the system firm yield including unregulated flows for 1984 sediment conditions.

Firm Yields for Conservation Reallocations

As previously discussed, Possum Kingdom and Whitney Reservoirs are operated for hydroelectric power generation and have significant inactive storage for this purpose. A large inactive pool is also maintained in Granbury

Table 7.16
SYSTEM WATER BALANCE FOR ABSOLUTE MAXIMUM REALLOCATION

Unregulated Flows	Excluding		Including	
Sediment Condition	1984	2010	1984	2010
System Firm Yield (cfs)	2,484	2,472	3,147	3,130

Average Flow (cfs) Over 85-Year Simulation Period

System Inflow	4,763	4,763	7,887	7,887
Richmond Gage Diversion	2,484	2,472	3,147	3,130
Hubbard Reservoir Diversion	57	57	57	57
Reservoir Evaporation	770	751	793	774
Flow to Gulf	1,458	1,479	3,899	3,932

Table 7.17
RESERVOIR WATER BALANCE FOR ABSOLUTE MAXIMUM REALLOCATION
1984 Sediment Condition

Reservoir	Averages in cfs over 85-year Simulation				
			Conservation Releases		
	Inflow	Evaporation	Downstream	Diversion	Spills
12-Reservoir Firm Yield of 2,484 cfs Excluding Unregulated Flows					
Hubbard Creek	157	64	-	57	27
Possum Kingdom	1,116	87	533	-	498
Granbury	1,454	35	716	-	703
Whitney	2,138	189	1,208	-	740
Aquilla	101	23	50	-	28
Waco	451	67	243	-	140
Proctor	159	51	76	-	32
Belton	600	77	372	-	156
Stillhouse	305	37	186	-	83
Georgetown	90	9	43	-	37
Granger	238	31	135	-	70
Somerville	305	39	150	-	126
Limestone	324	57	141	-	113
12-Reservoir Firm Yield of 3,147 cfs Including Unregulated Flows					
Hubbard Creek	157	64	-	57	29
Possum Kingbom	1,116	89	426	-	603
Granbury	1,452	36	541	-	875
Whitney	2,135	195	933	-	1,001
Aquilla	101	24	37	-	40
Waco	451	70	195	-	185
Proctor	159	54	69	-	36
Belton	597	81	303	-	215
Stillhouse	305	39	146	-	119
Georgetown	90	10	33	-	46
Granger	237	32	94	-	109
Somerville	305	41	67	-	188
Limestone	324	58	77	-	184

Table 7.18
RESERVOIR STORAGE FREQUENCY FOR ABSOLUTE MAXIMUM REALLOCATION
System Firm Yield of 3,147 cfs Including Local Flows

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
	Storage Frequency in Percent of Capacity									
Hubbard	7.7	3.9	3.6	8.7	14.2	17.5	25.5	13.1	5.4	0.2
Possum Kingdom	42.4	15.3	13.3	13.9	6.2	4.2	2.0	2.0	0.2	0.5
Granbury	50.0	14.2	10.3	11.0	5.7	4.2	2.5	1.5	0.2	0.4
Whitney	33.3	8.1	10.8	21.7	9.4	3.1	4.8	4.6	3.4	0.7
Aquilla	17.2	6.2	8.8	16.0	20.8	8.2	11.5	6.3	4.3	0.8
Waco	22.5	6.7	10.4	19.9	16.9	7.7	5.9	4.8	4.5	0.7
Proctor	9.3	5.6	4.6	11.6	13.4	10.7	26.9	10.7	6.7	0.6
Belton	17.3	6.3	7.6	18.8	17.4	10.8	10.0	4.8	6.4	0.7
Stillhouse	20.2	8.6	8.7	19.4	15.9	8.1	7.7	5.7	4.9	0.7
Georgetown	29.5	8.8	9.3	19.2	10.7	5.9	7.5	5.5	2.8	0.8
Granger	25.9	6.9	9.6	18.4	11.7	7.3	9.4	5.6	4.5	0.8
Limestone	30.7	11.7	16.4	17.2	7.4	4.9	5.2	2.8	2.9	0.9
Somerville	32.8	5.8	8.9	15.4	14.2	8.7	6.4	5.1	2.1	0.6

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 to facilitate withdrawals for cooling water for a steam electric power plant.

In the past, Possum Kingdom has been operated primarily for hydroelectric power. Although the invert of the lowest outlet is at elevation 875 feet, the top of inactive pool has been set at elevation 970 feet to facilitate power generation. In the hypothetical standard operating plan assumed for purposes of this chapter, Possum Kingdom Reservoir is operated as a system water supply reservoir with the top of inactive at 875 feet. Hydroelectric power is assumed to be generated only by water supply releases passed through the turbines to be withdrawn from the river at downstream diversion locations. Thus, hydroelectric power data are not included in the model for Possum Kingdom Reservoir. Hydroelectric power generation at Whitney Reservoir is included in the model for the standard operating plan.

The lowest outlet invert elevations at Granbury and Whitney Reservoirs are 640 feet and 449 feet, respectively. The top of inactive pool elevations are set at 675 feet and 520 feet, respectively, to facilitate cooling water withdrawals and hydropower releases. The top of inactive pool elevation of 675 feet at Granbury and 520 feet at Whitney are included in the standard operating plan.

An evaluation is presented below of the increases in firm yield which would result from converting the inactive pools at Possum Kingdom, Granbury, and Whitney Reservoirs to active water supply storage. The impacts of hydroelectric power releases at Whitney Reservoir on water supply firm yields are also evaluated.

Single and Individual Reservoir Firm Yields

As previously discussed, Tables 7.3 through 7.8 include single and individual reservoir firm yields for the alternative top of inactive pool elevations. For example, Table 7.3 indicates that based on 1984 sediment conditions, the single reservoir firm yields for Possum Kingdom Reservoir are 300 cfs and 443 cfs for top of inactive pool elevations of 970 feet and 875 feet, respectively. Single reservoir firm yields for Granbury are 193 cfs and 267 cfs for inactive pools levels of 675 feet and 640 feet respectively, based on 1984 sediment conditions. Whitney single reservoir firm yields are 376 cfs and 803 cfs for inactive pool levels of 520 feet and 449 feet respectively, assuming the entire active conservation pool is used for water supply.

System Firm Yields

Table 7.19 shows the sensitivity of system firm yield to reallocation of inactive storage capacity to active water supply capacity. The standard operating plan is listed first. The other operating plans represent specific deviations from the standard operating plan with all other factors remaining constant. Firm yield is expressed both in units of cfs and as a percentage of the firm yield for the standard operating plan. System firm yields are repeated for 1984 and 2010 conditions of sedimentation and both with and without unregulated local flows.

The second operating plan in Table 7.19 is identical to the standard operating plan except the top of inactive pool elevation for Possum Kingdom is

Table 7.19
12-RESERVOIR SYSTEM FIRM YIELDS FOR CONSERVATION REALLOCATIONS

Operation Plan or Storage Allocation	System Firm Yield (cfs and % of standard operating plan)							
	1984 Sediment Conditions				2010 Sediment Conditions			
	Excluding Local Flows		Including Local Flows		Excluding Local Flows		Including Local Flows	
	(cfs)	(%)	(cfs)	(%)	(cfs)	(%)	(cfs)	(%)
Standard Operating Plan	1,697	100.0	2,265	100.0	1,618	100.0	2,182	100.0
Possum Kingdom Reservoir								
top of inactive 970 ft	1,606	94.6	2,069	91.3	1,558	96.3	2,020	92.6
Granbury Reservoir								
top of inactive 640 ft	1,705	100.5	2,279	100.6	1,669	103.2	2,233	102.3
Whitney without hydropower								
top of inactive 520 ft	1,717	101.2	2,405	106.1	1,670	103.2	2,311	105.4
top of inactive 449 ft	1,867	110.0	2,596	114.6	1,798	111.1	2,543	116.5
Whitney Drought Storage	1,838	108.3	2,538	112.1	1,764	109.0	2,455	112.5
Maximum Potential Yield								
with hydropower	1,744	102.8	2,353	103.9	1,683	104.0	2,292	105.0
without hydropower	1,899	111.9	2,615	115.5	1,846	114.1	2,543	116.5

raised to 970 feet. The resulting 12-reservoir system firm yield (1984 sediment conditions and excluding unregulated flows) is 1,606 cfs, which is 94.6% of the corresponding standard operating plan firm yield of 1,697 cfs. Thus, maintaining the 970 feet inactive pool level for hydroelectric power generation at Possum Kingdom Reservoir reduces the system firm yield 5.4% for the specified conditions.

The third operating plan in Table 7.19 is identical to the standard operating plan except the Granbury top of inactive pool is lowered to 640 feet. The resulting 12-reservoir system firm yield is 1,705 cfs, assuming 1984 sediment conditions and excluding unregulated flows.

The fourth assumed operating plan is identical to the standard operating plan except Whitney Reservoir is included with the ten other reservoirs which release for the water supply diversion at the Richmond gage control point. The 40 cfs diversion does not occur at Whitney and no releases are made specifically for hydropower. The fourth and fifth operating plans are identical except the top of inactive pool elevation is 520 feet and 449 feet, respectively. The resulting system firm yields are 1,717 cfs and 1,867 cfs, respectively. Thus, hydroelectric power releases at Whitney Reservoir do decrease the system firm yield even if the top of inactive pool remains constant at 520 feet. However, the top of inactive pool elevation has a much greater impact on system firm yield. Converting the inactive storage capacity at Whitney to water supply increases the system firm yield to 110.0%, 114.6%, 111.1%, and 116.5%, respectively, of the standard operating plan firm yield for the four sets of conditions depicted in Table 7.19.

The operating plan labeled "Whitney drought storage" is based on using the inactive pool in Whitney Reservoir for water supply only when the other reservoirs in the system are empty. The Whitney inactive pool provides contingency storage capacity to be used only during a severe drought. In the model, eleven reservoirs release to meet the diversion at the Richmond gage control point. (The Waco Reservoir firm yield is diverted at Waco Reservoir.) However, releases from Whitney for the Richmond gage are made only if the other ten reservoirs are empty. The resulting system firm yield is 108.3%, 112.8%, 109.0%, and 112.5% of the standard operating plan firm yield for the four sets of conditions included in Table 7.19. Thus, the Whitney drought contingency storage plan increases the system firm yield almost as much as treating Whitney as a system water supply reservoir with the percent depletion being balanced in Whitney and the other ten reservoirs.

The last two operating plans included in Table 7.19 represent the maximum system firm yield that can be obtained with and without operating Whitney Reservoir for hydropower. In the last plan, the top of inactive pool elevations at Possum Kingdom, Granbury, and Whitney Reservoirs are 875 feet, 640 feet, and 449 feet respectively. All twelve reservoirs, including Waco and Whitney, release for a common diversion at the Richmond gage. The resulting system firm yield is 111.9%, 115.5%, 114.1%, and 116.5% of the standard operating plan for the four conditions.

The next-to-last operating plan is identical to the last plan except for Whitney Reservoir. Operation of Whitney is identical to the standard operating plan. Thus, the next-to-last plan is identical to the standard operating plan except Granbury has a lower inactive pool and Waco releases for the Richmond gage.

Table 7.20 is a comparison the Whitney drought contingency storage plan and standard operating plan. Simulation results are repeated for 1984 and 2010 sediment conditions, excluding and including unregulated flows. The data for the Whitney drought contingency storage plan is presented under the corresponding data for the standard operating plan. For 1984 sediment conditions and excluding unregulated flows, the Whitney drought plan provides a water supply firm yield of 1,838 cfs, which is 108.3 % of the standard operating plan firm yield of 1,697 cfs. However, hydroelectric power shortages are increased. Both plans include a target or required annual energy production of 36,000 megawatt-hours. The power shortages for the standard operating plan, averaged over the 1,020 month simulation period, are 9 megawatt-hours per year. The average annual shortage increases to 203 megawatt-hours for the Whitney drought plan, which is 0.56% of the 36,000 megawatt-hours required annual energy. The maximum shortage to occur in any month is 786 megawatt-hours and 2,041 megawatt-hours, respectively, for the two plans. The standard operating plan has 1 month with a power shortage compared to 15 months, which is 1.5% of the 1,020 months, for the Whitney drought plan. The secondary energy of 72,748 megawatt-hours per year for the Whitney drought plan is actually an increase over the standard operating plan.

A system water balance, reservoir water balance, and storage frequency table for the Whitney drought plan are presented as Tables 7.21, 7.22, and 7.23. The corresponding simulation results for the standard operating plan are previously presented as Tables 7.11, 7.12, and 7.13.

Firm Yields for Reallocations Between Flood Control and Conservation Purposes

Single reservoir and system firm yields are presented for permanent and seasonal reallocations of storage capacity between flood control and water supply.

Single Reservoir Storage Capacity Versus Firm Yield Relationships

Firm yield versus storage capacity relationships for the nine multipurpose flood control and conservation reservoirs are presented in Table 7.24 and Figures 7.15 through 7.23. These are single reservoir firm yields, meaning the effects of other reservoirs on inflows are ignored. 1984 conditions of sedimentation are assumed. For a given reservoir, the firm yield was computed for specified alternative storage capacities, representing changes in the top of conservation pool elevation, with all other factors held constant.

Incremental increases in firm yield decrease with increasing storage capacity. However, significant changes in firm yield would result at each of the reservoirs from raising or lowering the top of conservation pool. For example, referring to Table 7.24, increasing the conservation storage capacity of Waco Reservoir by 10 percent or 50 percent would increase the firm yield by 3 percent or 12 percent, respectively. Doubling the capacity and decreasing the capacity by half results in a 26 percent increase and 31 percent decrease, respectively, in firm yield at Waco Reservoir.

Table 7.20
COMPARISON OF WHITNEY DROUGHT PLAN WITH STANDARD OPERATING PLAN

Measure of Effectiveness	1984 Sediment Conditions		2010 Sediment Conditions	
	Excluding Unregulated Flows	Including Unregulated Flows	Excluding Unregulated Flows	Including Unregulated Flows
	Standard Operating Plan Whitney Drought Plan			
water supply firm yield (cfs)	1,697	2,265	2,618	2,182
	1,838	2,538	1,764	2,455
required power (megawatt hrs)	36,000	36,000	36,000	36,000
	36,000	36,000	36,000	36,000
average shortage (megawatt hrs)	9	100	14	113
	203	1,106	302	1,023
maximum shortage (megawatt hrs)	786	1,961	1,171	1,974
	2,041	3,000	3,000	5,259
months with shortage	1	9	1	20
	15	45	19	47
power shortage index	0.001	0.022	0.001	0.023
	0.075	0.957	0.192	0.991
secondary power (megawatt hrs)	71,082	71,559	70,674	71,330
	72,748	75,311	74,407	75,549

Table 7.21
SYSTEM WATER BALANCE FOR WHITNEY DROUGHT CONTINGENCY STORAGE PLAN
1984 Sediment Condition

Flows from Unregulated Watershed below Dams	Exclude	Include
12-Reservoir System Firm Yield (cfs)	1,838	2,578

Average Flow (cfs) over 85-Year Simulation Period

System Inflow	4,763	7,887
Diversions	1,895	2,635
Richmond Gage	(1,682)	(2,422)
Waco Reservoir	(116)	(116)
Whitney Reservoir	(40)	(40)
Hubbard Creek Reservoir	(57)	(57)
Evaporation from 13 Reservoirs	471	427
Flow to the Gulf of Mexico	2,423	4,877

Table 7.22
RESERVOIR WATER BALANCE FOR WHITNEY DROUGHT CONTINGENCY STORAGE PLAN
1984 Sediment Condition

Reservoir	Averages in cfs over 85-year Simulation				
			Conservation Releases		
	Inflow	Evaporation	Downstream	Diversion	Spills
12-Reservoir Firm Yield of 1,838 cfs Excluding Unregulated Flows					
Hubbard Creek	157	63	-	57	30
Possum Kingdom	1,116	73	505	-	599
Granbury	1,472	33	653	-	787
Whitney	2,160	101	959	40	1,063
Aquilla	101	11	32	-	58
Waco	451	26	-	116	264
Proctor	159	19	29	-	111
Belton	633	43	234	-	360
Stillhouse	305	20	116	-	171
Georgetown	90	4	22	-	64
Granger	244	13	80	-	151
Limestone	305	37	105	-	165
Somerville	324	25	104	-	196
12-Reservoir Firm Yield of 2,578 cfs Including Unregulated Flows					
Hubbard Creek	157	64	-	57	31
Possum Kingbom	1,116	72	509	-	541
Granbury	1,474	33	649	-	793
Whitney	2,161	94	966	40	1,105
Aquilla	101	11	26	-	65
Waco	451	26	-	116	280
Proctor	159	19	27	-	113
Belton	633	43	204	-	391
Stillhouse	305	20	97	-	191
Georgetown	90	4	19	-	67
Granger	244	13	57	-	174
Limestone	305	37	82	-	188
Somerville	324	25	69	-	231

Table 7.23
RESERVOIR STORAGE FREQUENCY FOR WHITNEY DROUGHT CONTINGENCY STORAGE PLAN
System Firm Yield of 2,578 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	3.9	3.6	8.7	14.2	17.5	25.5	13.1	5.4	0.2
Possum Kingdom	32.3	7.1	5.3	8.0	11.5	8.5	11.5	5.0	4.1	6.8
Granbury	36.1	9.4	6.3	10.2	8.1	5.5	9.6	4.9	2.9	7.0
Whitney	41.5	8.9	9.5	16.5	10.2	6.2	3.5	0.7	2.6	0.4
Aquilla	30.5	6.7	5.2	9.1	11.9	12.5	8.4	6.0	4.7	5.0
Waco	35.2	6.7	7.6	13.3	13.3	7.5	8.0	5.5	2.5	0.2
Proctor	40.2	9.9	10.4	11.8	7.9	5.1	5.0	1.9	4.8	3.0
Belton	36.5	6.3	4.4	9.4	13.6	9.0	5.1	5.2	6.5	4.0
Stillhouse	39.6	3.9	5.6	11.6	9.7	8.3	6.3	4.6	6.6	3.8
Georgetown	45.3	5.7	4.6	12.5	8.6	6.6	4.5	3.7	4.6	3.9
Granger	44.4	5.5	4.9	10.9	9.5	7.0	5.4	4.3	4.1	4.0
Limestone	37.9	5.8	5.7	9.9	9.8	7.6	6.9	7.1	4.9	4.4
Somerville	30.9	6.4	6.0	8.7	11.5	11.5	8.1	6.8	5.7	4.5

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.

Table 7.24
STORAGE CAPACITY VERSUS FIRM YIELD RELATIONSHIPS

Reservoir	Conservation Storage Capacity as a Percent of Actual Capacity								
	50	80	90	110	120	130	150	175	200
	Firm Yield as a Percent of Firm Yield for 100% Actual Capacity								
Whitney	42	77	88	112	123	130	140	152	165
Aquilla	60	88	96	104	108	116	124	128	132
Waco	69	91	95	103	106	109	112	121	126
Proctor	60	83	93	107	110	113	117	120	127
Belton	76	90	95	105	110	115	120	125	130
Stillhouse	77	94	97	103	105	106	111	116	120
Georgetown	65	87	91	104	104	109	113	117	122
Granger	66	91	95	105	109	114	123	134	139
Somerville	64	85	95	103	107	110	115	123	131

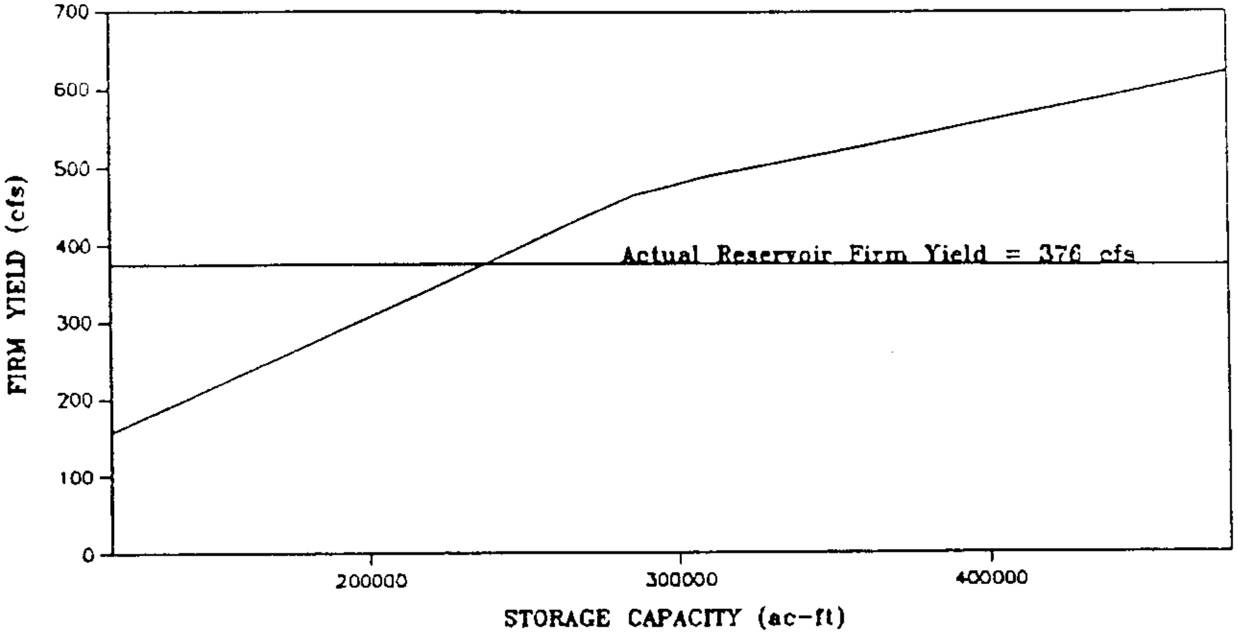


Figure 7.15 Single Reservoir Firm Yield Versus Storage Capacity, Whitney Reservoir, 1984 Sedimentation

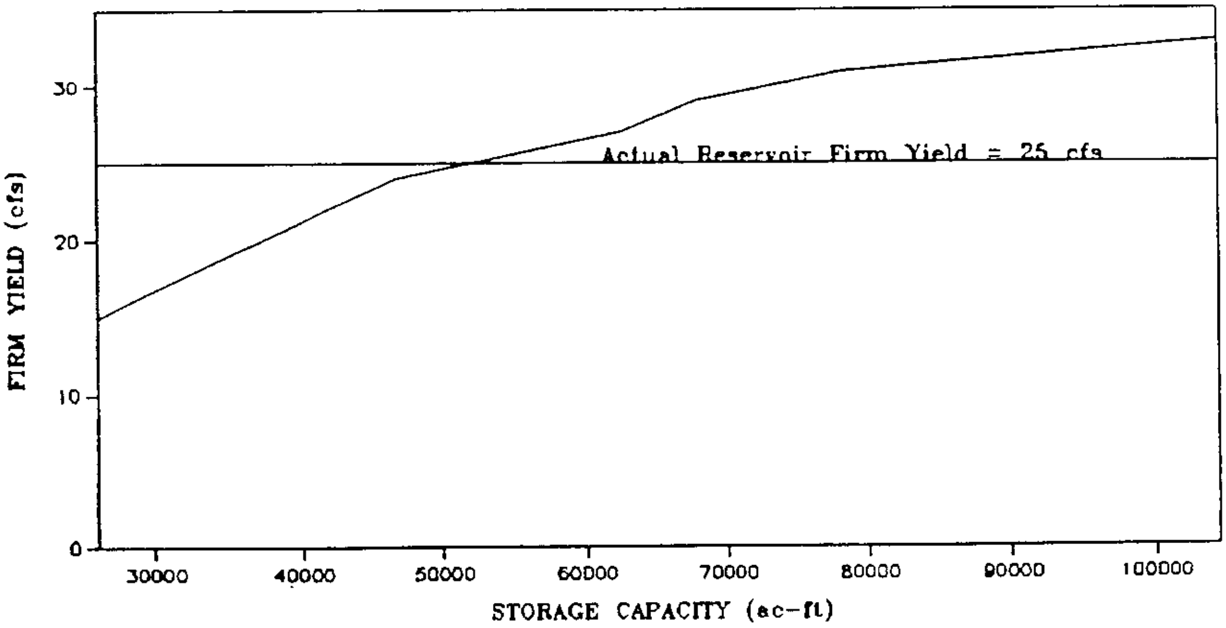


Figure 7.16 Single Reservoir Firm Yield Versus Storage Capacity, Aquilla Reservoir, 1984 Sedimentation

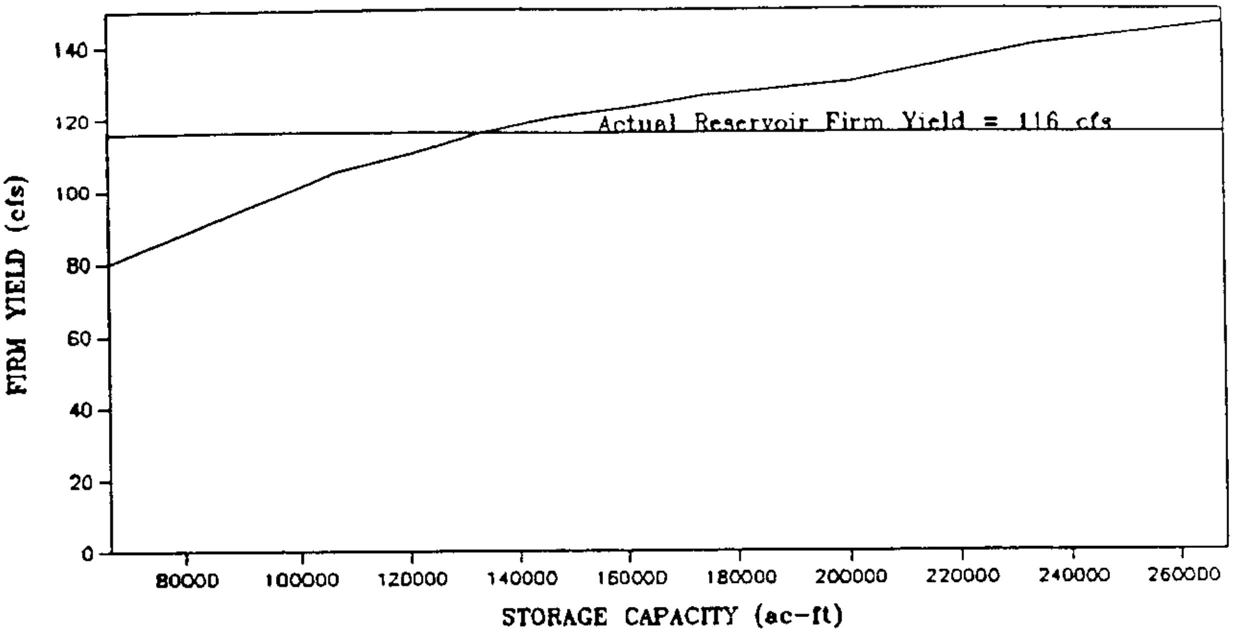


Figure 7.17 Single Reservoir Firm Yield Versus Storage Capacity, Waco Reservoir, 1984 Sedimetation

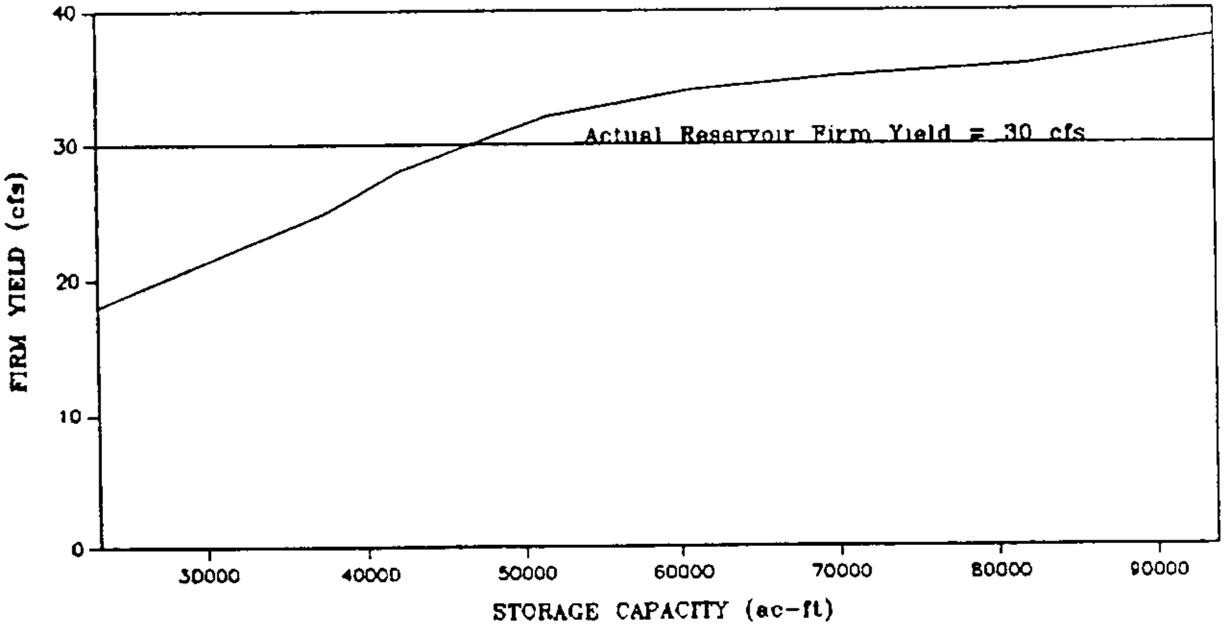


Figure 7.18 Single Reservoir Firm Yield Versus Storage Capacity, Proctor Reservoir, 1984 Sedimentation

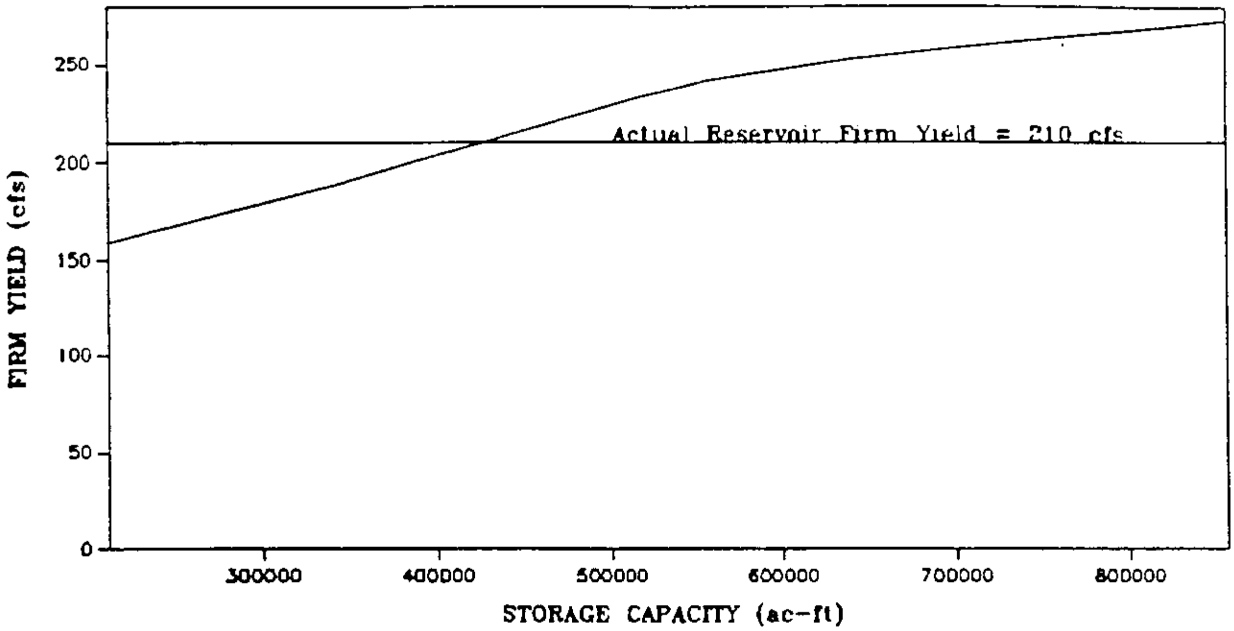


Figure 7.19 **Single Reservoir Firm Yield Versus Storage Capacity, Belton Reservoir, 1984 Sedimentation**

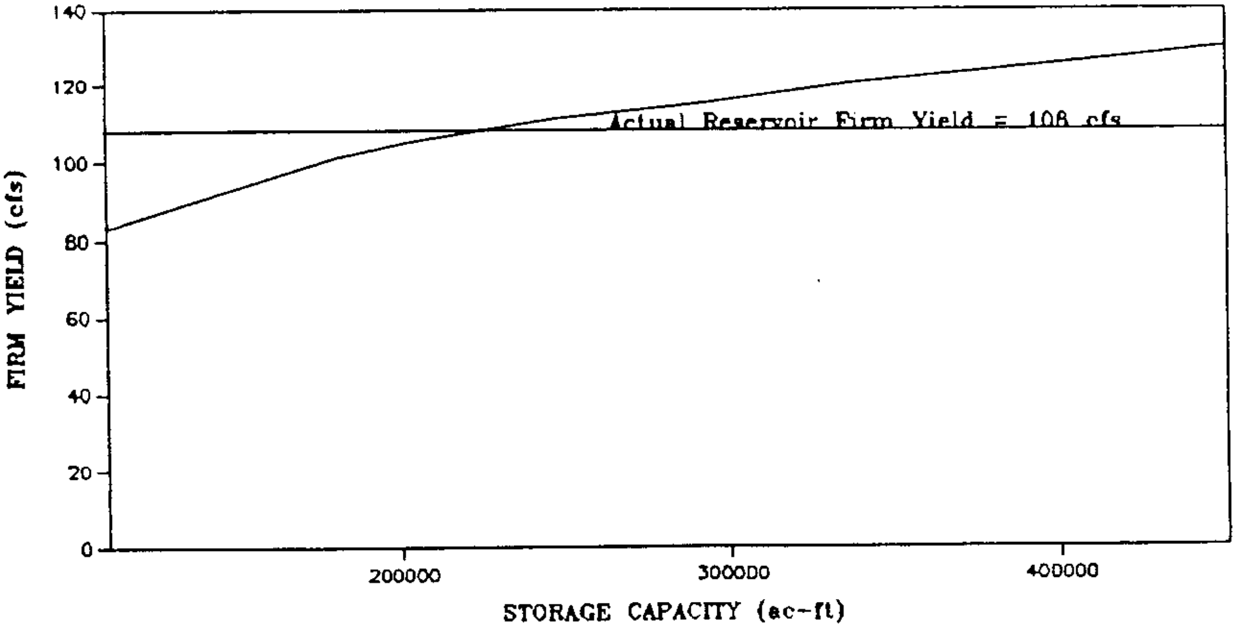


Figure 7.20 **Single Reservoir Firm Yield Versus Storage Capacity, Stillhouse Hollow Reservoir, 1984 Sedimentation**

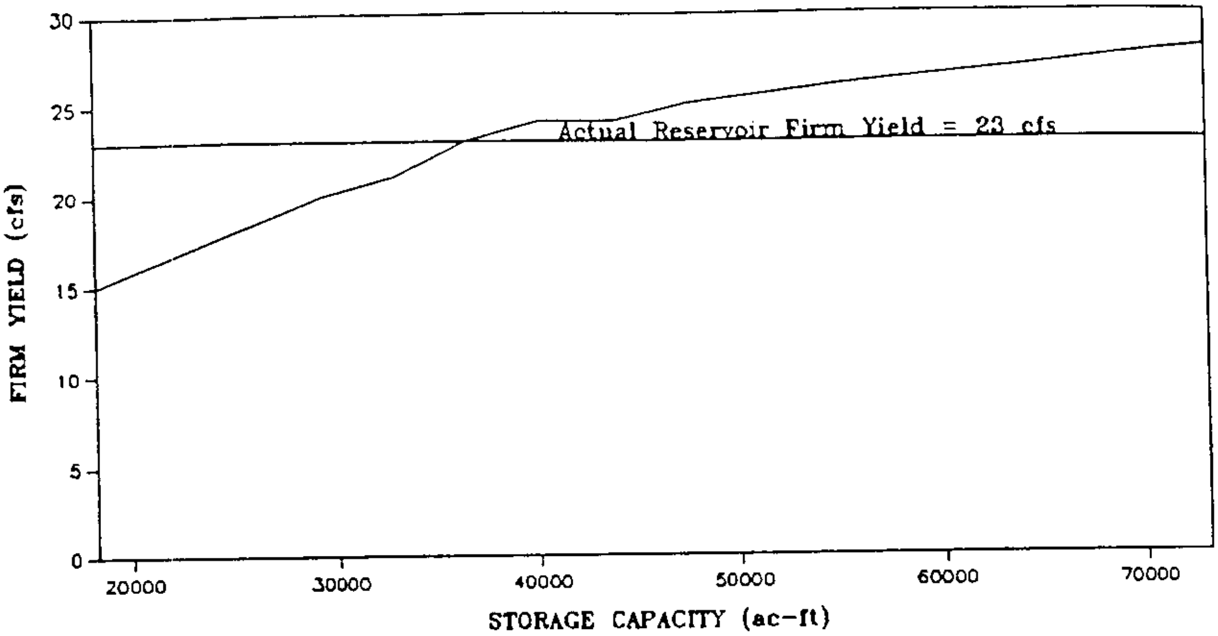


Figure 7.21 Single Reservoir Firm Yield Versus Storage Capacity, Georgetown Reservoir, 1984 Sedimentation

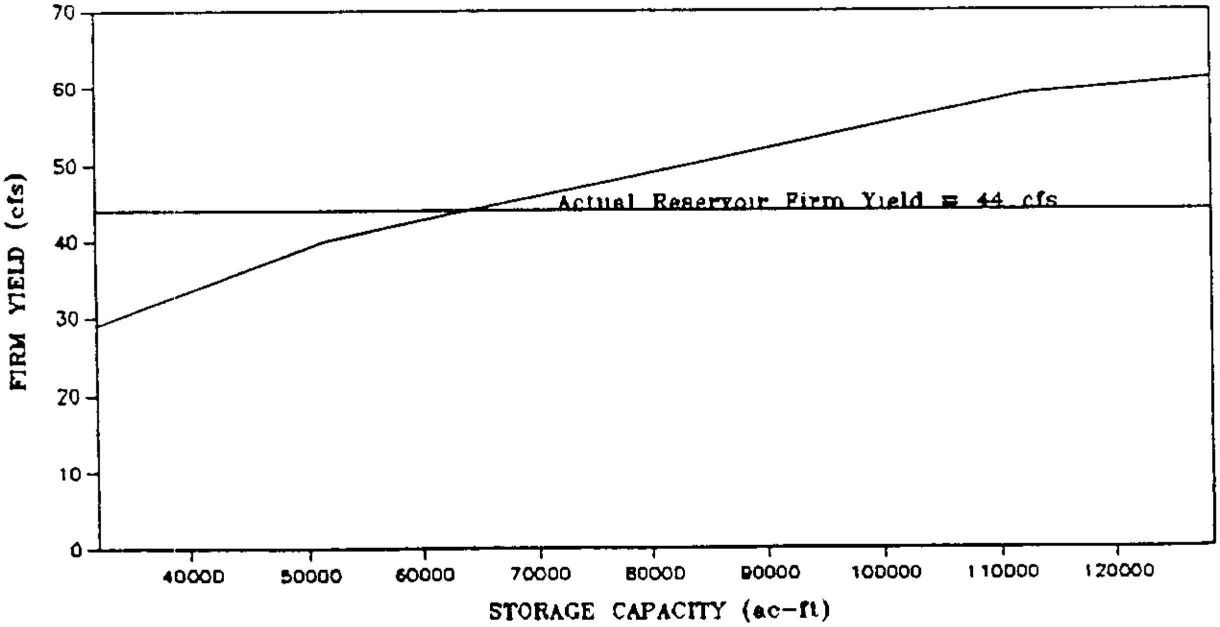


Figure 7.22 Single Reservoir Firm Yield Versus Storage Capacity, Granger Reservoir, 1984 Sedimentation

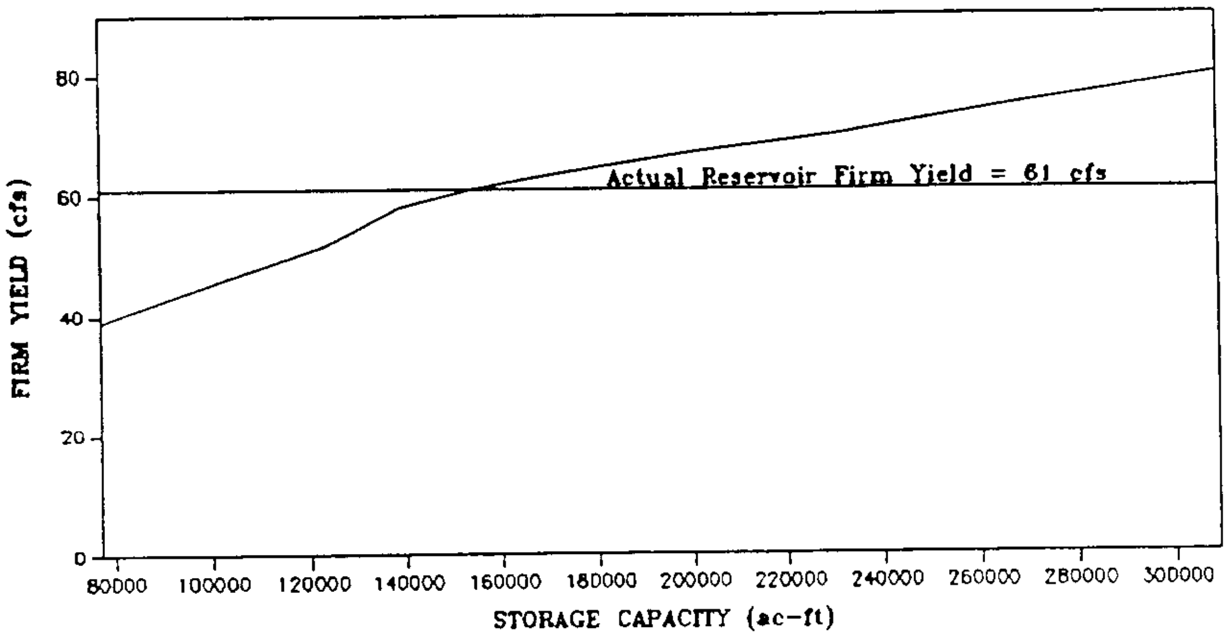


Figure 7.23 Single Reservoir Firm Yield Versus Storage Capacity, Somerville Reservoir, 1984 Sedimentation

Most of the reservoir sites have several months of zero flows in both the measured and naturalized historical streamflow sequences. The other sites have near zero monthly streamflows. Consequently, the unregulated firm yields are zero or essentially zero at all of the reservoir sites. Zero storage capacity results in zero firm yield.

Single reservoir firm yields are tabulated in Table 7.25 for permanent and seasonal storage reallocations. The storage reallocations are expressed in terms of the percent of the flood control capacity that has been converted to conservation. Firm yields are presented for a permanent reallocation, a seasonal rule curve in which the top of conservation pool is raised from April through October, and a seasonal rule curve with a May through October pool raise.

In most cases, the firm yields for seasonal rule curve operating plans were found to not be affected by the month in which the pool is lowered as long as it is not lowered before September. Likewise, the month in which the pool is raised does not significantly affect firm yields as long as it is not raised after the beginning of April. In most cases, a seasonal rule curve in which the pool is raised eleven months, which include the period April through September, will result in the same firm yield as an April through September pool raise.

In many cases, a seasonal rule curve will increase the firm yield as much as a permanent reallocation. For example, Belton Reservoir has a firm yield of 210 cfs with no reallocation. The firm yield is increased to 226 cfs by reallocating 10% of the flood control pool to water supply, regardless of whether the reallocation is permanent or only occurs from May through October of each year.

System Firm Yields for Permanent Reallocations

System firm yields for the 12-reservoir system are presented in Table 7.26 for a range of permanent storage reallocations in seven reservoirs, which include Whitney, Aquilla, Waco, Proctor, Belton, Stillhouse Hollow, Granger, and Somerville. The remaining five reservoirs not included in the storage reallocations include Possum Kingdom, Granbury, and Limestone which have no flood control capacity and Proctor and Georgetown which are upstream tandem reservoirs with relatively small conservation capacities. The firm yields at the Richmond gage include unregulated flows and are based on 1984 conditions of sedimentation. The system firm yield versus permanent storage reallocation relationship tabulated in Table 7.26 is also shown graphically in Figure 7.24. The reallocations consist of conversion of a portion of the flood control storage capacity in each of the seven reservoirs to conservation. Alternative plans consist of the following storage reallocation amounts: 5%, 10%, 15%, and 20% of the prereallocation active conservation capacity and 5%, 10%, 15%, 20%, and 25% of the flood control capacity. The standard operating plan is followed except for the reallocated storage capacity. Thus, Whitney Reservoir is operated for hydroelectric power and a 40 cfs water supply diversion for all reallocation plans.

The flood control and conservation capacities of the individual reservoirs are tabulated in Table 6.8. Assuming 1984 conditions of sedimentation, the 12 USACE/BRA reservoirs have total flood control and active conservation

Table 7.25
SINGLE RESERVOIR FIRM YIELDS FOR PERMANENT AND SEASONAL STORAGE REALLOCATIONS
1984 Sediment Conditions

	Storage Reallocation as a Percent of Flood Control Capacity					
Reservoir	0%	5%	10%	15%	20%	25%
	firm yield (cfs) for a permanent reallocation firm yield (cfs) for a seasonal reallocation, April-October firm yield (cfs) for a seasonal reallocation, May-October					
Whitney	376 376 376	484 484 484	539 508 484	594 508 484	649 508 484	705 508 484
Aquilla	26 26 26	27 27 27	28 28 28	30 30 30	31 30 30	31 30 30
Waco	116 116 116	124 120 120	130 120 120	137 120 120	142 120 120	147 120 120
Proctor	30 30 30	34 34 33	36 35 33	38 35 33	40 35 33	43 35 33
Belton	210 210 210	218 218 218	226 226 226	234 234 233	242 235 233	247 235 233
Stillhouse	108 108 108	111 111 110	113 112 110	115 112 110	116 112 110	118 112 110
Georgetown	23 23 23	24 23 23	25 23 23	25 23 23	26 23 23	26 23 23
Granger	44 44 44	47 44 44	50 44 44	53 44 44	56 44 44	58 44 44
Somerville	61 61 61	63 63 63	65 65 65	67 66 66	69 66 66	72 66 66

Table 7.26
12-RESERVOIR SYSTEM FIRM YIELDS FOR PERMANENT REALLOCATIONS IN SEVEN RESERVOIRS
1984 Sediment Conditions, Including Unregulated Flows

Storage Reallocations as Percent of Capacity				12-Reservoir		12-Reservoir System Firm Yield		
7 Reservoirs		12 Reservoirs						
Active Conservation (%)	Flood Control (%)	Active Conservation (%)	Flood Control (%)	Active Conservation Capacity (ac-ft)	Flood Control Capacity (ac-ft)	(cfs)	(ac-ft/yr)	(%)
0	0	0	0	2,237,530	3,992,530	2,265	1,628,000	100.0
5	1.8	2.9	1.6	2,302,350	3,927,710	2,309	1,659,000	101.9
10	3.6	5.8	3.2	2,367,170	3,862,900	2,326	1,671,000	102.7
13.8	5	8.0	4.5	2,416,850	3,813,210	2,339	1,681,000	103.3
15	5.4	8.7	4.9	2,431,980	3,798,080	2,342	1,683,000	103.4
20	7.2	11.6	6.5	2,496,800	3,733,270	2,359	1,695,000	104.2
27.7	10	16.0	9.1	2,596,170	3,633,900	2,370	1,703,000	104.6
41.5	15	24.0	13.5	2,775,480	3,454,580	2,370	1,703,000	104.6
55.3	20	32.1	18.1	2,954,800	3,275,260	2,370	1,703,000	104.6
69.1	25	40.0	22.5	3,133,910	3,096,160	2,385	1,714,000	105.3

Note: The 7 reservoirs (Whitney, Aquilla, Waco, Proctor, Belton, Stillhouse Hollow, Granger, and Somerville) have total active conservation and flood control capacities of 1,296,330 acre-feet and 3,586,350 acre-feet, respectively.

capacities of 3,992,530 acre-feet and 2,237,530 acre-feet, respectively. The conservation capacity does not include inactive storage capacity which is significant at Granbury and Whitney. The seven reservoirs, at which storage is reallocated in the present analysis, have total flood control and conservation capacities of 3,586,350 acre-feet and 1,296,330 acre-feet, respectively. Thus, 10% of the conservation capacity of the 7 reservoirs is a volume equal to 3.6% of the flood control capacity of the 7 reservoirs, or 5.8% of the conservation capacity of the 12 reservoirs, or 3.2% of the flood control capacity of the 12 reservoirs.

The third and ninth (last) columns of Table 7.26 show the percent increase in the active conservation capacity of the 12-reservoir system and the corresponding increase in firm yield. Increases of 2.9%, 5.8%, and 8.0% in conservation storage capacity result in corresponding increases of 1.9%, 2.7%, and 3.3% in firm yield. Conservation storage capacity increases of 16.0% to 32.1% result in the same firm yield which represents an increase of 4.6% of the standard operating plan firm yield. A 40.0% increase in storage capacity provides a 5.3% increase in system firm yield.

Thus, as further illustrated by Figure 7.24, the firm yield versus storage capacity relationship is highly nonlinear. Incremental increases in firm yield are significantly large relative to incremental increases in storage capacity for relatively small reallocations. However, reallocations of the magnitude of more than about 16% of the present conservation capacity are essentially ineffective in terms of incremental increases in firm yield.

System Firm Yield for Seasonal Rule Curves

System firm yields for the twelve reservoirs for permanent and seasonal storage reallocations in the seven reservoirs are presented in Table 7.27 and Figure 7.25. Alternative plans involve reallocation of storage capacity amounts equal to 5%, 10%, 15%, and 20% of the present conservation capacity of each of the seven reservoirs. The permanent reallocations included in Table 7.26 are also presented in Table 7.27 and discussed above. However, seasonal rule curve schemes are also considered.

The three alternative seasonal rule curves are: (1) a April through October pool raise, (2) a May through October raise, and (3) the May through October pool raise combined with lowering the top of conservation pool below the present normal pool level during April. The third seasonal rule curve is illustrated by Figure 6.4. The objective is to simultaneously enhance both flood control and water supply. Lowering the top of conservation pool in April increases flood control capacity while raising the pool from May through October increases firm yields.

As previously discussed, the standard operating plan has a firm yield of 1,697 cfs, excluding unregulated flows below the dam. As indicated by Table 7.27, reallocation of flood control capacity to water supply in the seven reservoirs in amounts equivalent to 5%, 10%, 15%, and 20% of their conservation capacity increases the 12-reservoir system firm yield to 1,728 cfs, 1,742 cfs, 1,772 cfs, and 1,786 cfs, respectively. Increasing the conservation capacity by 10% in the seven reservoirs increases the 12-reservoir system total conservation capacity by 5.8% and the corresponding firm yield from 1,697 cfs to 1,742 cfs which is a 2.65% increase.

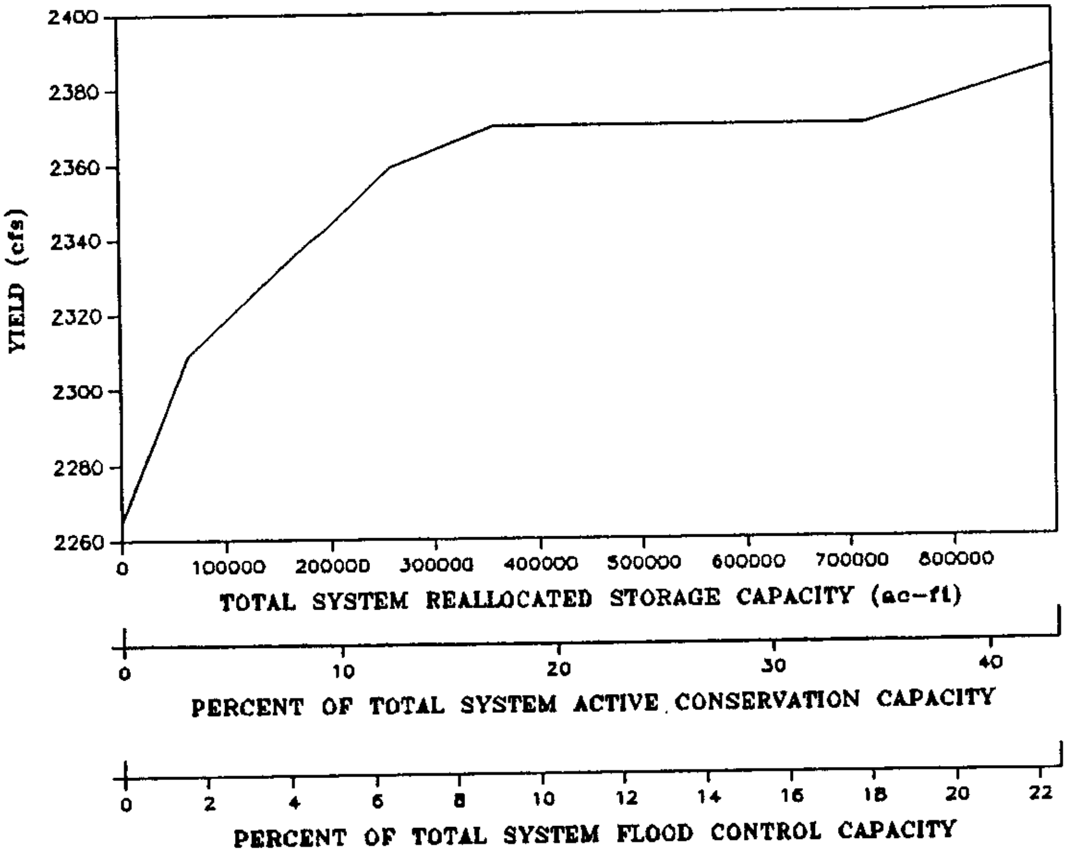


Figure 7.24 12-Reservoir System Firm Yield Versus Storage Capacity, 7-Reservoir Storage Reallocation, 1984 Sedimentation

Table 7.27
SYSTEM FIRM YIELD FOR ALTERNATIVE PERMANENT AND SEASONAL REALLOCATIONS
1984 Sediment Condition

	7-Reservoir Reallocation (% Conservation Capacity)				
	Decrease	Increase Capacity			
Reallocation Plan	Capacity	5%	10%	15%	20%
12-Reservoir System Firm Yield Excluding Unregulated Flows (cfs)					
Permanent	-0-	1,728	1,742	1,772	1,786
Raise Apr-Oct	-0-	1,727	1,740	1,749	1,758
Raise May-Oct	-0-	1,727	1,739	1,748	1,753
Raise May-Oct, Lower Apr	5%	1,727	1,739	1,747	1,753
Raise May-Oct, Lower Apr	10%	1,727	1,738	1,745	1,753
Raise May-Oct, Lower Apr	15%	1,726	1,737	1,743	1,750
Raise May-Oct, Lower Apr	20%	1,716	1,731	1,734	1,738
12-Reservoir System Firm Yield Including Unregulated Flows (cfs)					
Permanent	-0-	2,309	2,326	2,3432	2,359
Raise Apr-Oct	-0-	2,308	2,323	2,333	2,344
Raise May-Oct	-0-	2,308	2,323	2,333	2,344
Raise May-Oct, Lower Apr	5%	2,308	2,323	2,333	2,344
Raise May-Oct, Lower Apr	10%	2,307	2,322	2,332	2,343
Raise May-Oct, Lower Apr	15%	2,307	2,321	2,329	2,338
Raise May-Oct, Lower Apr	20%	2,297	2,310	2,316	2,323

For reallocation of small amounts of storage capacity, a seasonal rule curve will increase the system firm yield almost as much as a permanent reallocation. Lowering the conservation pool during April to enhance flood control has relatively little impact on firm yield as long as the amount of conservation capacity reallocated to flood control is relatively small. For example, permanently increasing the conservation capacity of the seven reservoirs by 10% increases the 12-reservoir system firm yield by 2.65% to 1,742 cfs. Seasonally increasing the conservation capacity of the seven reservoirs by 10% during April through October or during May through October results in firm yields of 1,740 cfs or 1,739 cfs, respectively, which are increases of 2.53 % and 2.47 % over the standard operating plan. Seasonally lowering the conservation capacity by 10% during April and then raising the conservation capacity 10% over the standard operating plan in May through October results in a firm yield of 1,738 cfs which is still a 2.42 % increase.

The firm yields, including unregulated flows, tabulated in Table 7.27 are plotted in Figure 7.25. System firm yields are graphically related to storage reallocation amounts expressed both in acre-feet and as a percent of the original conservation capacity. The April through October and May through October seasonal rule curves are identical and thus represented by a single curve. The graph shows that adopting either of the three seasonal rule curve plans will increase the system firm yields almost as much as a permanent reallocation.

System Firm Yields for Permanent and Seasonal Reallocations for USACE Approval Limit

The Corps of Engineers (USACE) has authority to reallocate storage capacity in their reservoirs without obtaining Congressional approval as long as the reallocation does not exceed the lesser of 50,000 acre-feet or 15% of the flood control capacity. The 15% applies to the total storage for all federal purposes, which in Texas essentially means flood control.

Simulation results for a series of storage reallocation plans based on the 50,000 acre-feet or 15 % criterion are presented in Chapter 6. System firm yields for these reallocation plans are presented in Table 7.28. The alternative plans involve reallocations of 50,000 acre-feet or 15% of the flood control capacity in the seven reservoirs. The storage reallocations are tabulated in Table 7.29 in units of acre-feet and as a percent of the flood control and conservation storage capacities, based on 1984 conditions of sedimentation.

All of the firm yields previously cited in this chapter are based on not including flood control criteria in the simulation model. With the storage at top of conservation pool, flood control releases equal inflows. However, the firm yields presented in Table 7.28 were computed with the flood control allowable discharge rates shown in Table 6.7 included in the model. The elevation versus storage and area tables inputed to HEC-3 were also modified to facilitate including the flood control pool.

With the exceptions noted above, the standard operating plan was followed in formulating the reallocation plans outlined in Tables 7.28 and 7.29. Firm yields for the 12-reservoir system are presented in Table 7.28 in cfs and as a percentage of the firm yield assuming no reallocation for 1984 conditions of

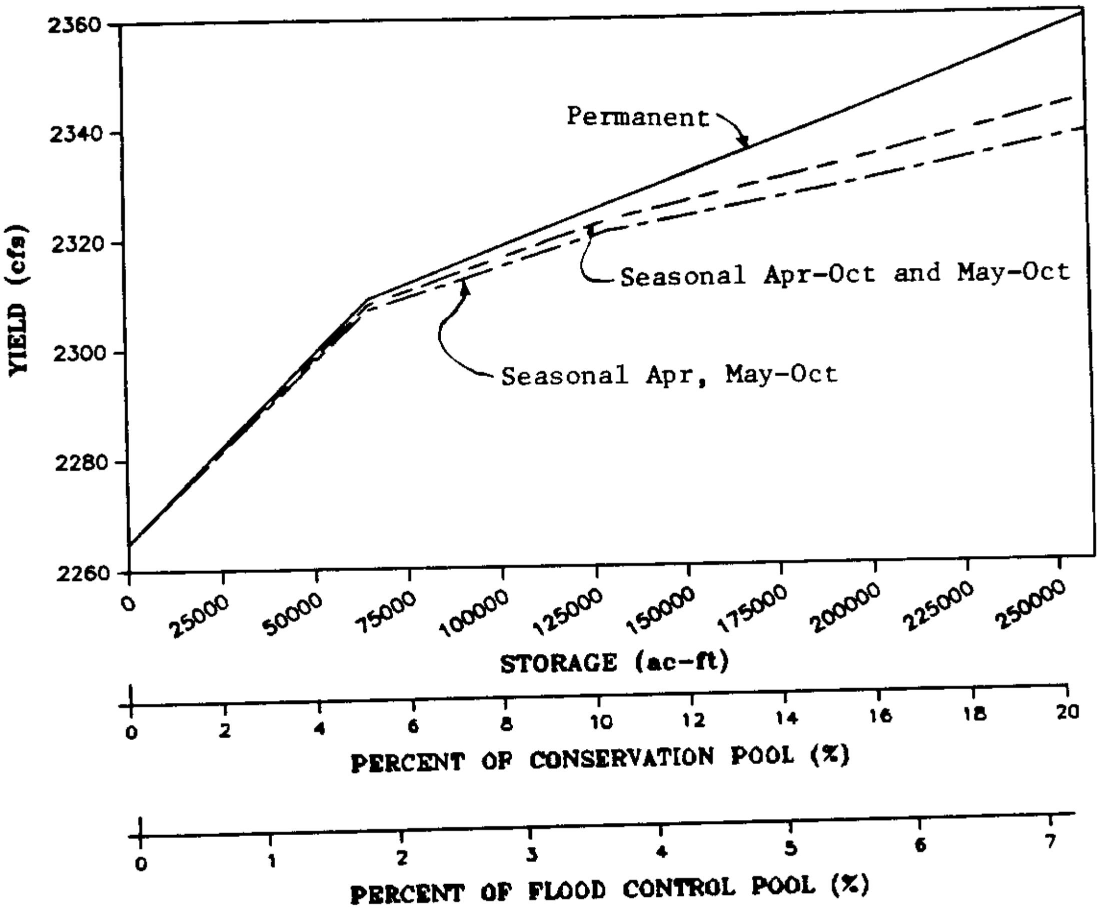


Figure 7.25 **12-Reservoir System Firm Yield for Permanent and Seasonal Storage Reallocations, 7-Reservoir Storage Reallocation, 1984 Sedimentation**

sedimentation, with and without including the unregulated flows. With no reallocation, the computed firm yield is 1,732 cfs and 2,294 cfs, respectively, excluding and including unregulated flows.

The first reallocation plan consist of a permanent reallocation of 50,000 acre-feet from flood control to water supply in Waco Reservoir, with all other reservoirs remaining unchanged. The resulting firm yield is 1,745 cfs and 2,307 cfs, excluding and including unregulated flows.

The second plan is a permanent reallocation of the lesser of 50,000 acre-feet or 15% of the flood control capacity in seven reservoirs. The resulting 12-reservoir system firm yield is 1,800 cfs and 2,387 cfs, excluding and including unregulated flows.

The remaining two plans consist of implementing seasonal rule curves. The top of conservation pool is raised alternatively from April through October or May through October in seven reservoirs to seasonally increase the conservation capacity by the lesser of 50,000 acre-feet or 15% of the flood control capacity. The resulting firm yields are included in Table 7.28.

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 period 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).

Table 7.28
SYSTEM FIRM YIELDS FOR ALTERNATIVE REALLOCATION PLANS
Reallocation of USACE Approval Limit in 7 Reservoirs
1984 Sediment Conditions
Richmond Gage Firm Yield

Reallocation Plan	System Firm Yield			
	Including Unregulated Flows		Excluding Unregulated Flows	
	(cfs)	(%)	(cfs)	(%)
No Reallocation	2,294	100.0	1,732	100.0
Permanent Reallocation				
Waco Reservoir Only	2,307	100.6	1,745	100.8
Seven Reservoirs	2,387	104.1	1,800	104.0
Seasonal Reallocation				
Apr-Oct	2,372	103.4	1,785	103.1
May-Oct	2,364	103.1	1,777	102.6

Table 7.29
STORAGE CAPACITY REALLOCATIONS BASED ON 1984 SEDIMENTATION

	1984 Capacity Before Reallocation		Capacity Reallocated		
Reservoir	Active Conservation (acre-feet)	Flood Control (acre-feet)	(acre-feet)	(% F.C.)	% Cons
P.K. (inactive 875 ft)	544,510	-0-	-0-	-0-	-0-
Granbury (inactive 675 ft)	137,400	-0-	-0-	-0-	-0-
Whitney (inactive 520 ft)	238,170	1,368,400	50,000	3.7	21.0
Aquilla	52,210	93,530	14,030	15.0	26.9
Waco (conservation 455 ft)	133,750	566,030	50,000	8.8	37.4
Proctor	46,850	312,700	-0-	-0-	-0-
Belton	428,250	642,900	50,000	7.8	11.7
Stillhouse Hollow	225,320	393,380	50,000	12.7	22.2
Georgetown	36,540	93,480	-0-	-0-	-0-
Granger	64,190	178,000	26,700	15.0	41.0
Limestone	218,050	-0-	-0-	-0-	-0-
Somerville	154,450	344,110	50,000	14.5	32.4
Total	2,279,680	3,992,530	290,730	7.3	14.0

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.

<u>Reliability Analysis Results</u>

Individual reservoir reliabilities for the reallocation plans outlined in Tables 7.28 and 7.29 are presented in Table 7.30. Reliabilities for the standard operating plan are tabulated in Table 7.31. Diversions range from 100% to 200% of the previously computed system firm yields. The model computes the number of months in which the specified diversion is not met 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.

The relationships between yield, expressed as a percentage of firm yield, and reliability are similar for the several storage allocation plans. A diversion of 125% the firm yield can be maintained more than 96% or 97% of the time. A diversion of 200% of the firm yield can be maintained more than 84% or 85% of the time with each of the alternative storage allocations.

Buffer Pool Operation and Secondary Yield

Conservation operations may include designation of one or more buffer pools. Full demands are met as long as the reservoir water surface is above the top of the buffer pool, with certain demands being curtailed whenever the water in storage falls below this level. Buffer pool operations have not been employed to any significant extent in Texas, but are used elsewhere. The HEC-3 and HEC-5 programs contain capabilities for modeling buffer zone operations.

The concepts of buffer pool operations and secondary yield are combined. The firm yield is released continuously during a simulation. The secondary yield is released whenever reservoir storage is above the top of buffer zone. Secondary yield reliability refers to the percentage of time that the secondary yield can be provided. In the present study, secondary yield is the percentage of months during the 1,020-month simulation for which a specified secondary yield level can be met. For a given top of conservation pool elevation and firm and secondary yield, there is a top of buffer pool elevation which maximizes the secondary yield reliability. Firm yield reliability is, by definition, 100%.

Table 7.30
RESERVOIR SYSTEM RELIABILITY FOR ALTERNATIVE REALLOCATION PLANS
1984 Sediment Conditions

Diversion		Shortage Periods	Average Shortage	Shortage Index	Period Reliability	Volume Reliability
% Firm Yield	cfs	(months)	(cfs month)	-	(%)	(%)
No Reallocation						
100%	2,294	0	0	0.00	100.00	100.00
105%	2,409	10	14	0.04	99.02	99.38
110%	2,523	15	27	0.14	98.53	98.86
125%	2,868	33	77	0.71	96.76	97.16
150%	3,441	68	194	2.04	93.33	94.10
175%	4,015	110	363	3.93	89.21	90.60
200%	4,588	157	589	6.14	84.61	86.71
Waco Reservoir Reallocation						
100%	2,307	0	0	0.00	100.00	100.00
105%	2,422	5	9	0.05	99.50	99.96
110%	2,538	10	20	0.14	99.00	99.16
125%	2,884	27	35	0.71	97.35	98.71
150%	3,461	68	196	2.07	93.33	94.05
175%	4,037	112	368	3.99	89.02	90.50
200%	4,614	157	596	6.22	84.61	86.60
Permanent Reallocation in 7 Reservoirs						
100%	2,387	0	0	0.00	100.00	100.00
105%	2,506	8	8	0.05	99.22	99.65
110%	2,626	11	19	0.12	98.92	99.22
125%	2,984	28	65	0.62	97.25	97.68
150%	3,581	64	186	1.87	93.72	94.53
175%	4,177	99	354	3.60	90.29	91.14
200%	4,774	147	581	5.62	85.60	87.35
Seasonal Reallocation in 7 Reservoirs, April-October						
100%	2,372	0	0	0.00	100.00	100.00
105%	2,491	7	9	0.05	99.31	99.61
110%	2,609	10	19	0.13	99.00	99.22
125%	2,965	25	64	0.61	97.54	97.71
150%	3,558	60	185	1.88	94.18	94.53
175%	4,151	102	354	3.57	90.00	91.11
200%	4,744	150	582	5.65	85.29	87.27

Table 7.30 (continued)
RESERVOIR SYSTEM REALIABILITY FOR ALTERNATIVE REALLOCATION PLANS

Seasonal Reallocation in 7 Reservoirs, May-October						
100%	2,364	0	0	0.00	100.00	100.00
105%	2,482	7	9	0.05	99.31	99.61
110%	2,600	11	19	0.13	98.92	99.22
125%	2,955	25	66	0.62	97.54	97.62
150%	3,546	64	187	1.94	93.72	94.46
175%	4,137	113	357	3.75	88.92	91.00
200%	4,728	150	585	5.67	85.29	87.56

Table 7.31
SYSTEM RELIABILITY FOR STANDARD OPERATING PLAN
2010 Sediment Conditions

Diversion		Shortage Periods	Shortage Volume	Shortage Index	Period Reliability	Volume Reliability
% Firm Yield:	cfs	(months)	(cfs mon)	-	(%)	(%)
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

The concepts of buffer pool operations and secondary yield are illustrated by Tables 7.32 through 7.35 and the accompanying figures. Four alternative operating scenarios are presented, with two involving multireservoir system operation and the other two involving only Waco Reservoir. In each case, the top of conservation pool and firm yield is fixed. A secondary yield versus reliability relationship is developed for alternative buffer pool levels by multiple runs of HEC-3.

Table 7.32 presents the results of an analysis of the reservoir system based on existing top of conservation pool elevations. The 12-reservoir system firm yield is somewhat arbitrarily assumed to be 1,812 cfs, which is 80% of the standard operating plan firm yield of 2,265 cfs. Thus, the firm yield is reduced 453 cfs, from 2,265 cfs to 1,812 cfs. With a firm yield of 1,812 cfs, a secondary yield of 453 cfs has a reliability of 100%. Greater secondary yields have lesser reliabilities. Thus, Table 7.32 shows the secondary yields and associated reliabilities which can be obtained by sacrificing 20% of the firm yield. Buffer pools are included in Aquilla, Belton, Stillhouse Hollow, Granger, Limestone, and Somerville Reservoirs. Operations are otherwise identical to the standard operating plan.

Table 7.33 involves combining a permanent storage reallocation with buffer zone operations. The firm yield is set equal to the standard operating plan firm yield of 2,265 cfs. Thus, the storage reallocation provides secondary yield rather than increasing the firm yield. Buffer pools are again included in Aquilla, Belton, Stillhouse Hollow, Granger, Limestone, and Somerville Reservoirs.

Table 7.34 presents the results of an analysis of Waco Reservoir with a permanent storage reallocation. The top of conservation pool is raised to elevation 462 feet instead of the existing 455 feet. The firm yield is set equal to 116 cfs, which is the firm yield for a top of conservation pool elevation of 455 feet and no buffer zone. Thus, the reallocation of storage capacity from flood control to water supply provides secondary yield rather than increases the firm yield.

Table 7.35 is also for Waco Reservoir operated alone. However, the top of conservation pool is a seasonal rule curve. The top of conservation pool elevation is 462 feet from April through October and 455 feet from November through March. The firm yield is set at 116 cfs as in the previous analysis.

For each of the four analyses represented by Tables 7.32 through 7.35 and Figures 7.26 through 7.29, a secondary yield versus reliability relationship is presented for alternative top of buffer pool elevations. The smallest reliability shown for each buffer pool is associated with the maximum secondary yield which can be achieved by this buffer. The same secondary yield can be provided by higher top of buffer pool elevations, but the reliability will be less. Thus, for a given secondary yield, a buffer level can be determined which will maximize the reliability. If the top of buffer and conservation pools are the same, the secondary yield versus reliability relationship is the flow-duration curves for spills.

Table 7.32
SECONDARY YIELD VERSUS RELIABILITY FOR ALTERNATIVE BUFFER POOLS FOR EXISTING TOP OF CONSERVATION POOL ELEVATIONS AND 20% REDUCTION IN FIRM YIELD

Secondary Yield (cfs)	Buffer Pool as Percent of Conservation Pool				
	0%	25%	50%	75%	100%
	Secondary Yield Reliability (%)				
453	100.0%	99.8%	99.1%	98.1%	97.1%
500		99.4%	98.9%	98.0%	96.9%
557		99.2%	98.7%	97.9%	96.8%
600			98.5%	97.7%	96.7%
652			98.3%	97.6%	96.6%
675				97.5%	96.5%
708				97.3%	96.4%
750					96.3%
768					96.2%

Notes:

1. 12-Reservoir system firm yield of 1,812 cfs (80% of 2,265 cfs).
2. Buffer pools in Aquilla, Belton, Stillhouse, Granger, Limestone and Somerville Reservoirs.
3. Existing top of conservation pool elevations.
4. Firm and secondary yields include unregulated flows.
5. 1984 sediment conditions.

Table 7.33

SECONDARY YIELD VERSUS RELIABILITY FOR ALTERNATIVE BUFFER POOLS SYSTEM YIELD FOR PERMANENT STORAGE REALLOCATION

Secondary Yield (cfs)	Buffer Pool as Percent of Conservation Pool				
	0%	25%	50%	75%	100%
	Secondary Yield (%)				
77	100.0%	99.9%	99.2%	98.8%	96.1%
100		99.6%	99.1%	98.7%	95.9%
125		99.5%	99.0%	98.6%	95.8%
150		99.4%	98.9%	98.5%	95.7%
173		99.3%	98.8%	98.2%	95.6%
198			98.4%	97.7%	95.5%
224				97.3%	95.4%
250					95.3%
272					95.2%

Notes:

1. 12-Reservoir system firm yield of 2,265 cfs.
2. 12-Reservoir system firm yield of 2,342 cfs without buffer pool operation.
3. Buffer pools in Aquilla, Belton, Stillhouse, Granger, Limestone and Somerville Reservoirs.
4. Permanent storage reallocation of 15% conservation capacity in seven reservoirs.
5. Firm and secondary yields include unregulated flows.
6. 1984 sediment conditions.

Table 7.34
SECONDARY YIELD VERSUS RELIABILITY FOR ALTERNATIVE BUFFER POOLS WACO RESERVOIR WITH PERMANENT REALLOCATION

Secondary Yield (cfs)	Top of Buffer Pool Elevation (feet msl)				
	400	445	450	452	455
	Secondary Yield (%)				
13	100.0%	91.8%	87.9%	82.9%	77.8%
15		91.3%	87.3%	82.3%	77.2%
22		90.2%	86.6%	81.5%	76.1%
25			85.6%	80.7%	74.4%
33			84.2%	79.1%	73.1%
35				78.8%	71.3%
45				78.4%	68.6%
53				78.0%	65.6%
65					63.5%
75					61.2%
86					59.5%

Notes:

1. Firm yield of 116 cfs.
2. Firm yield of 129 cfs without buffer pool operation.
3. Top of conservation pool elevation of 462 feet.
4. 1984 sediment conditions.

Table 7.35
SECONDARY YIELD VERSUS RELIABILITY FOR ALTERNATIVE BUFFER POOLS WACO RESERVOIR WITH SEASONAL RULE CURVE

Secondary Yield (cfs)	Top of Buffer Pool Elevation (feet msl)				
	400	445	450	452	455
	Secondary Yield (%)				
13	100.0%	87.4%	83.3%	75.3%	60.0%
14		86.9%	83.1%	74.9%	59.8%
20			82.1%	73.9%	59.3%
25			81.2%	72.8%	58.0%
32			79.7%	72.4%	57.3%
35				71.3%	56.4%
45				70.4%	55.1%
55				69.2%	53.4%
65				67.3%	52.0%
75				66.4%	50.4%
83				65.2%	49.0%
89					48.5%
95					47.7%
130					43.5%
142					41.5%

Notes:

1. Firm yield of 116 cfs.
2. Firm yield of 120 cfs without buffer pool operation.
3. Top of conservation pool elevation of 462 feet from April through October and 455 feet from November through March.
4. 1984 sediment conditions.

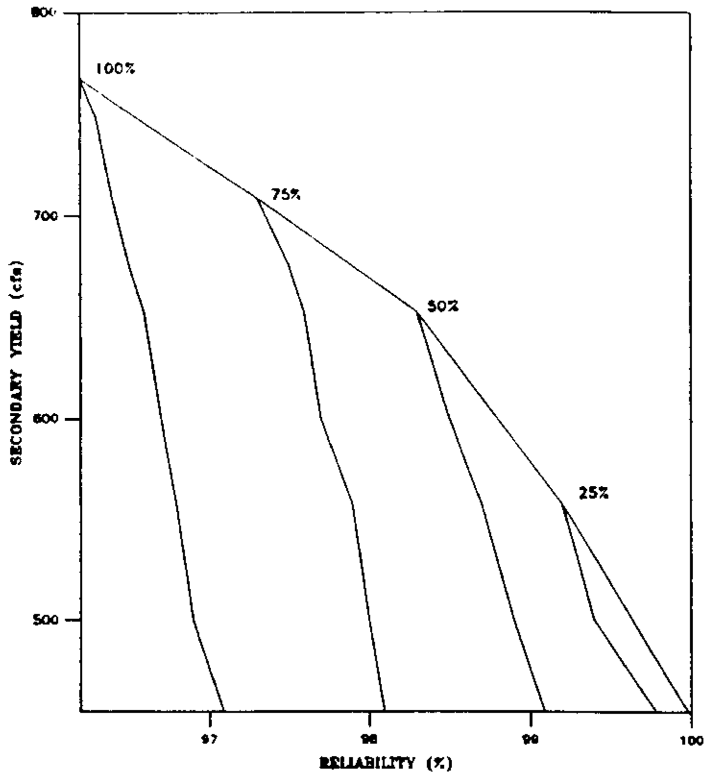


Figure 7.26 Secondary Yield Versus Reliability for Alternative Buffer Pools for Existing Top of Conservation Pool Elevations and 20% Reduction in Firm Yield

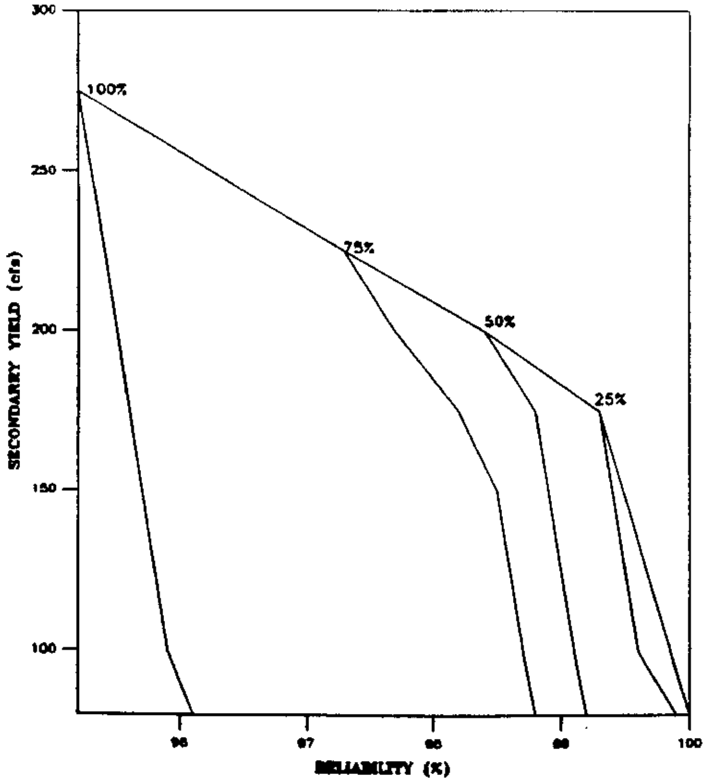


Figure 7.27 Secondary Yield Versus Reliability for Alternative Buffer Pools, System Yield for Permanent Storage Reallocation

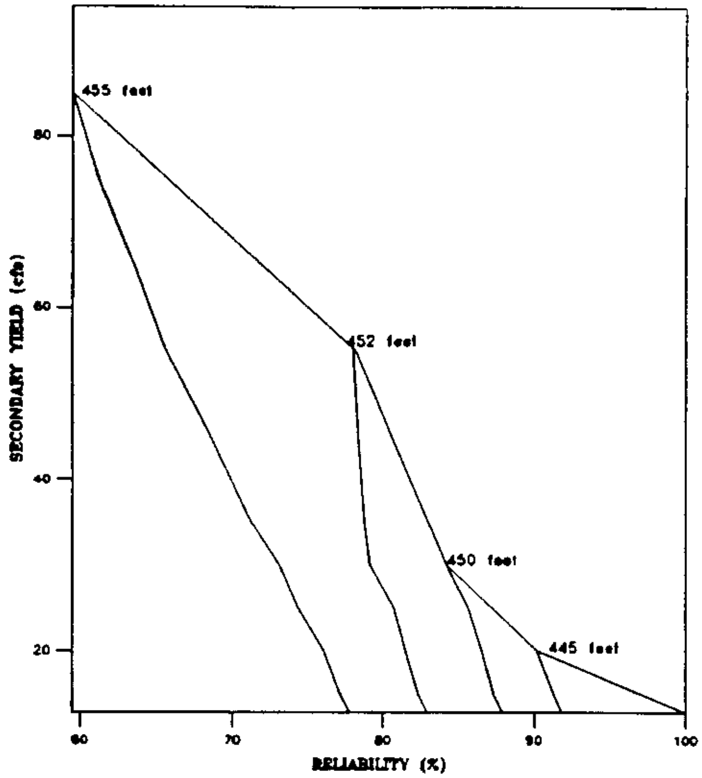


Figure 7.28 **Secondary Yield Versus Reliability for Alternative Buffer Pools, Waco Reservoir with Permanent Reallocation**

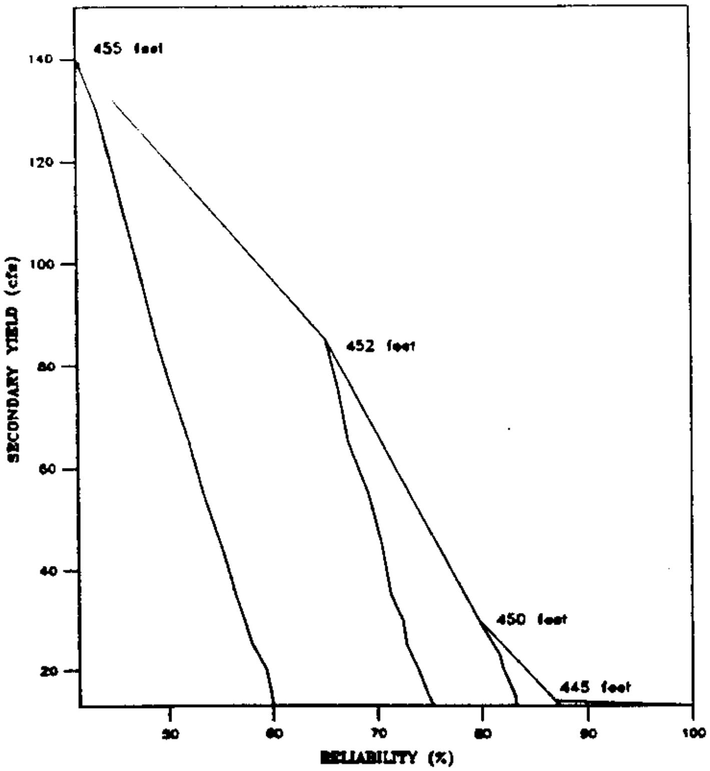


Figure 7.29 **Secondary Yield Versus Reliability for Alternative Buffer Pools, Waco Reservoir with Seasonal Rule Curve**

CHAPTER 8
COMPARATIVE EVALUATION OF REALLOCATION POTENTIALITIES

This chapter summarizes the results of the simulation modeling studies documented by the previous two chapters, from the perspective of a comparative evaluation of the several reservoir operation strategies considered. The objective of the study was to investigate general potentialities for optimizing reservoir operations, not develop detailed operating plans. No attempt is made to recommend implementation of specific storage reallocation plans or other changes in operating policies. This chapter simply highlights several key observations regarding the case study results.

Several indicators of water supply capabilities are adopted in Chapters 6 and 7. Yield is quantified by firm yields and reliabilities as well as by diversion shortages and drawdown frequencies associated with specified water use conditions. The present chapter focuses primarily on firm yield. Reliabilities computed for alternative yield levels expressed as percentages of firm yield were found to be similar for the alternative operating plans analyzed. Changes in firm yield and changes in reliability are closely correlated. Statements made below regarding differences in firm yield achieved by alternative operating plans are generally equally valid if expressed in terms of reliabilities or other measures of water availability.

Overview of Storage Reallocation and Related Reservoir Operation Strategies

The following reservoir management strategies were addressed, to various degrees, in the Brazos River Basin study:

1. multiple reservoir system operation,
2. use of unregulated flows entering the river below the dams in combination with reservoir releases,
3. temporary use of sediment reserve for other purposes,
4. permanent reallocation of storage capacity between flood control and conservation purposes,
5. seasonal rule curve operation,
6. reallocation of storage capacity between conservation purposes, and
7. buffer zone operation and secondary yield.

The first, second and last strategies listed are actually not storage reallocations, but are important considerations in the study. Multireservoir system operations, coordination of reservoir releases and downstream unregulated flows, and buffer zone operations are potentially beneficial operating strategies independently of storage reallocation and can also be utilized in conjunction with storage reallocation plans. The other four operation strategies listed above are alternative types of storage reallocations.

System Operation

System operation is an integral part of the actual operation of the USACE/BRA system for both flood control and conservation purposes. Flood control release decisions are based on discharges at downstream control points common to several or all of the reservoirs. Conservation releases through the hydroelectric power turbines at Possum Kingdom and Whitney Reservoirs are withdrawn at downstream locations for water supply uses. Water demands at downstream locations are met by releases from any of a combination of several reservoirs. As discussed by Wurbs, Bergman, Carriere, and Walls (1988), the BRA holds an excess flow water right permit which allows diversion of unregulated flows from the lower reach of the Brazos River, as long as other water rights holders are not adversely affected.

Water supply planning and management studies and decisions have traditionally been based on estimated individual reservoir firm yields. The results of the present study indicate that firm yields reflecting system operation are much greater than the sum of individual reservoir firm yields. For the USACE/BRA system, the increases in estimated firm yield are achieved primarily by properly crediting existing operating policies rather than by changing operating policies. The increases in yield which result from system operation are much larger than the increases achieved by any of the other operation strategies considered in the study.

The yield studies presented by Wurbs, Bergman, Carriere, and Walls (1988) and by Chapter 7 of the present report demonstrate the increases in firm yield achieved by multireservoir system operation rather than operating each reservoir individually. System firm yield is greater than the sum of the individual reservoir firm yields because the timing of the critical low flow periods do not perfectly coincide at the reservoir sites. Operated individually, the reservoirs empty at different times, with some reservoirs empty while significant storage still remains in other reservoirs. Unregulated streamflow also contributes to system yield. A significant amount of runoff enters the river below the dams. The unregulated flows have zero firm yield but provide a significant increase in firm yield if supplemented by reservoir releases during low flow periods.

A comparison of system and individual reservoir firm yields is presented in Table 7.15. The 12-reservoir system firm yield, excluding unregulated flows, is about 28% higher than the sum of the individual reservoir firm yields. If the unregulated flows originated below the dams is included, the system firm yield is about 172% of the sum of the individual reservoir firm yields. Thus, operating the reservoirs as a system, rather than individually, can increase firm yield excluding unregulated flows, by up to 28%. Utilizing the unregulated flow below the dams can further increase the system firm yield by up to 34%. The total increase is 72% of the sum of the individual reservoir firm yields.

These are hydrologic firm yields, without consideration of other water users in the basin. Wurbs, Bergman, Carriere, and Walls (1988) present a comparable analysis including the effects of priority water rights, which similarly demonstrates the benefits of system operation.

In the present case study, release decisions in the model were based on balancing the percentage 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.

Temporary Use of Sediment Reserve for Other Purposes

The reservoirs were originally designed with storage capacities sized to include 50 to 100 years of sedimentation. Prior to being filled with sediment, the sediment reserves can be used for other purposes. Sediment reserve capacity in flood control pools automatically provide additional flood control storage. The BRA uses sediment reserve capacity in conservation pools for temporary water supply commitments. Sediment reserves represent a significant amount of storage capacity available for many years.

The present study did not directly address the temporary use of sediment reserve for other purposes prior to depletion by sediment deposition. However, firm yields were computed for alternative conditions of sedimentation. Table 7.4 is a tabulation of individual reservoir firm yields for alternative conditions of sedimentation. The sum of the individual reservoir firm yields for ultimate conditions is 9.6% lower than the sum for initial conditions. The individual reservoir firm yield estimates are 5.4% lower for 2010 sediment conditions than for 1984 sediment conditions. System firm yields shown in Table 7.15 are about 4.7% lower for 2010 than for 1984 conditions of sedimentation.

Permanent Reallocation of Storage Capacity Between Flood Control and Conservation Purposes

Permanent reallocation of flood control capacity to water supply was a major focus of the study. The impacts of reallocations on flood control capabilities are quantified in terms of the recurrence interval of the flood which just fills the flood control pool to capacity. Tables 6.15, 6.18, 6.19, and 6.20 show the recurrence intervals estimated for permanent storage reallocations of various magnitudes.

Water supply capabilities provided by alternative storage allocations are quantified in Chapter 6 in terms of diversion shortages and drawdown frequencies based on year 2010 conditions of water use and the 85-year hydrologic simulation period. With present storage allocations, reservoir drawdowns and diversion shortages are relatively small during the 85-year simulation for 1984 water use conditions but become severe for projected 2010 water use conditions. Table 6.10 indicates that the permanent reallocations analyzed in Chapter 6 have little impact on diversion shortages associated with 2010 water use. However, the frequency and severity of drawdowns is significantly affected as indicated by Tables 6.22, 6.23, and 6.24.

Firm yields and reliabilities are presented in Chapter 7. Tables 7.24 and 7.25 demonstrate the relationships between storage capacity and single reservoir firm yields. System firm yields for permanent reallocations are presented in Table 7.26 and Figure 7.24. Significant increases in firm yield can be achieved by permanently raising top of conservation pool elevations. However, the firm yield versus storage capacity relationship is highly nonlinear, with incremental increases in firm yield rapidly decreasing with further increases in storage capacity. A 6% increase in conservation capacity will result in roughly a 3% increase in firm yield. However, after the conservation storage capacity is increased by about 15%, further increases in storage capacity result in relatively little additional increase in firm yield. As indicated by Tables 6.15, 6.18, 6.19, and 6.20, significant losses in flood control storage capacity result in correspondingly significant increases in the risk of the flood control capacity being exceeded by an extreme flood event. Consequently, plans for reallocation of storage capacity from flood control to water supply can be expected to involve limited proportions of the total storage capacity and relatively small increases in firm yield. Small-scale storage reallocations are a potentially viable strategy for obtaining additional water supply yield. However, in general, drastic increases in firm yield likely will not be achieved by reallocation of practical amounts of flood control capacity.

Development of procedures for detailed evaluation of the trade-offs between flood control and conservation purposes is a major area of needed research.

Seasonal Rule Curve Operation

Permanent reallocations between flood control and conservation storage capacity result in tradeoffs between purposes. Permanent loss of significant amounts of flood control capacity increases the risk of a major flood event overtopping the flood control pool. The objective of seasonal rule curve operation is to simultaneously enhance both flood control and water supply or to enhance one purpose while minimizing adverse impacts on the other.

Seasonal rule curve operation involves varying the top of conservation pool elevation as a function of time of the year. In the simulation modeling study, simplified "block" rule curves were adopted in which the top of conservation pool elevation is constant throughout a given month but can vary between months. In the actual detailed design of a rule curve, the top of conservation pool elevation can be varied within each month.

As indicated by Table 6.27, most of the conservation drawdowns occurring during the simulation begin in June, July, or August. The seasonal rule curve captures additional May inflows to minimize storage depletions from the summer drawdowns.

In designing rule curves, May is the key month from the perspective of both water supply and flood control. The top of conservation pool would typically be raised in late April or sometime in May. A rule curve could involve gradually raising the pool during May, with the timing and magnitude of the pool change being dependent upon forecasted flooding and water supply conditions. The pool would normally be lowered in the Fall. The precise timing of the pool lowering is probably not as important as the timing of the Spring pool raise.

Seasonal rule curves were found in the simulation study to increase firm yield essentially as much as a corresponding permanent reallocation, but with little or no adverse impacts on flood control. Tables 7.25 and 7.27 and Figure 7.25 demonstrate that increases in firm yield achieved by a seasonal rule curve are almost the same as a permanent reallocation of the same magnitude, as long as the amount of storage reallocated is relatively small. The simulation analysis indicates that the seasonal rule curve plans included in Table 6.15 result in little or no increase in the risk of overtopping a flood control pool.

Flood control operations are normally based on specified maximum allowable discharges at downstream control points. If the flood control pool storage capacity is exceeded or expected to be exceeded, releases are based on not exceeding a specified reservoir water surface elevation, rather than downstream discharge constraints. Storage reallocations will normally not affect downstream flooding conditions except for extreme flood events which exceed the flood control storage capacity.

Although not considered in the present study, flood release rates as well as top of conservation pool elevations can be varied. Releases from a flood control pool are often maintained below the maximum allowable to prevent inconvenience and damages to downstream floodplain activities which can occur at the maximum allowable discharges. Seasonally or otherwise varying allowable discharges and seasonal rule curves can be used in combination.

Flood control operations in the Brazos River Basin and other basins in Texas involve reducing damages at locations which may be several days travel time below the dams. If releases are made to the allowable downstream discharge, rainfall occurring during the release travel time can result in the release contributing to flooding several days later at the downstream control point. Seasonal rule curve operation and/or reduced release rates decrease the risk of contributing to downstream flooding due to imperfect forecasting. The present study did not include daily simulations required to analyze these aspects of flood control operations.

Real-time collection of precipitation and streamflow data, streamflow forecasting, and associated modeling capabilities have received considerable attention throughout the water management community during the past several years. Technological advances in real-time forecasting of streamflow and other variables could significantly enhance the feasibility of seasonal rule curve and related reservoir management strategies.

Reallocation of Storage Capacity Between Conservation Purposes

The consideration of reallocations between conservation purposes focused on the inactive storage capacity contained in Possum Kingdom, Granbury, and Whitney Reservoirs, particularly Whitney Reservoir. The inactive pools in Possum Kingdom and Whitney Reservoirs provide head for hydroelectric power. The inactive pool in Granbury Reservoir facilitates withdrawals of cooling water for a steam-electric power plant.

Individual reservoir firm yields for alternative top of inactive pool elevations are tabulated in Tables 7.4 through 7.8. System firm yields for alternative conservation reallocations are presented in Table 7.19. Converting the inactive storage in Possum Kingdom Reservoir to water supply increases the 12-reservoir system firm yield from between 3.9% and 8.7% depending on which of the conditions including in Table 7.19 is assumed. Likewise, increases in system firm yield achieved by using the Granbury Reservoir inactive pool for water supply range from roughly 0.5% to 3.2%. Converting the entire Whitney conservation pool to water supply, with no hydropower, increases the system firm yield approximately 10% to 16.5% for the alternative conditions included in Table 7.19.

The objective of the Whitney Reservoir drought contingency storage plan is to take advantage of the potential increase in system firm yield available from the Whitney inactive pool, while minimizing adverse impacts on hydroelectric power generation. The plan was formulated to illustrate the potential benefits of coordinating water supply and hydroelectric power operations. In this plan, the inactive pool at Whitney Reservoir is treated as a contingency water supply to be used only during severe drought conditions after the conservation pools in the other reservoirs have been emptied. The Whitney Reservoir drought contingency storage plan results in almost the same increase in firm yield as permanently converting the entire Whitney conservation storage capacity to water supply.

Buffer Zone Operation and Secondary Yield

Conservation operations may include designation of buffer pools. Full demands are met as long as the reservoir water surface is above the top of the buffer pool, with certain demands being curtailed whenever the water in storage falls below this level. Thus, firm and secondary yields can be differentiated. Water supply contracts may be based on either firm or secondary yields or both. For certain water users, obtaining a relatively large quantity of water with some risk of shortage may be of more value than a supply of greater reliability but smaller quantity. Implementation of drought contingency plans may be triggered by the storage falling below a specified buffer level. An analysis was performed in the present study to illustrate the relationship between firm yield, secondary yield, and reliability.

Comparison of Several Storage Allocation Plans

The storage reallocation strategies outlined above are further discussed by comparing seven specific allocation plans. The previously listed strategies 3,4, and 5 are represented by the seven plans. The selected plans are considered to be illustrative of the potentialities of storage reallocation.

Alternative Plans

The discussion below is a comparative evaluation of the following storage allocation plans:

1. standard operating plan,
2. Possum Kingdom inactive pool set at 970 feet,
3. Whitney Reservoir drought contingency storage,
4. April, May-October 15% seasonal rule curve at 7 reservoirs,
5. plans 3 and 4 combined,
6. permanent reallocation to USACE approval limit at 7 reservoirs, and
7. May-October seasonal rule curve to USACE approval limit at 7 reservoirs.

The standard operating plan is outlined in Table 7.10 and accompanying text in Chapter 7. The standard operating plan provides a base for comparison, with the other plans being specific deviations thereof. The standard operating plan is a hypothetical set of pool elevations and release rules incorporated in the model, which are generally, but not totally, representative of the actual system operating procedures.

Possum Kingdom Reservoir has a top of inactive pool elevation of 875 feet in the standard operating plan. In actual operation, the top of inactive pool has been set at 970 feet to facilitate hydroelectric power generation. Plan 2 listed above consists of setting the inactive pool at elevation 970 feet at Possum Kingdom Reservoir to be more representative of actual operations. All other model input is identical to the standard operating plan.

Plan 3 consists of using the inactive conservation capacity of Whitney Reservoir as a contingency water supply. Releases are made from the Whitney inactive pool only when the other reservoirs in the system are empty. The objective of plan 4 is to realize the significant increase in water supply firm yield provided by the Whitney inactive pool while minimizing adverse impacts on hydropower.

Plan 4 consists of seasonally lowering and raising the top of conservation pool elevation in Whitney, Aquilla, Waco, Belton, Stillhouse Hollow, Granger, and Somerville Reservoirs. In April, 15% of the present conservation capacity in each of the seven reservoirs is converted to flood control. From May through October, flood control capacity equal to 15% of the present conservation capacity is converted to conservation. The seasonal rule curve is illustrated by Figure 6.4. All other model input data is identical to the standard operating plan. Plan 4 both increases water supply yield and decreases the risk of a major flood event overtopping the flood control pool capacity.

Plan 5 consists of combining the seasonal rule curve (plan 4) with the Whitney Reservoir drought contingency storage (plan 3).

The Corps of Engineers (USACE) has authority to reallocate storage capacity in their reservoirs without obtaining Congressional approval as long as the reallocation does not exceed the lesser of 50,000 acre-feet or 15% of the flood control capacity. Plan 6 consists of a permanent reallocation of 50,000 acre-feet or 15% of the flood control capacity, whichever is less, in Whitney, Aquilla, Waco, Belton, Stillhouse Hollow, Granger, and Somerville Reservoirs. Plan 6 is outlined in Table 7.29.

Plan 7 is identical to plan 6, except the reallocations occur seasonally rather than permanently. The top of conservation pool is raised from May through October to reallocate the storage amounts indicated above for plan 6.

Comparative Evaluation

The system firm yield for the seven alternative storage allocation plans are presented in Table 8.1, based on 1984 sediment conditions, excluding and including unregulated flows entering the river below the dams. The values in Table 8.1 for all plans except plan 5 are reproduced from Tables 7.16, 7.27, and 7.28. Flood control operation criteria were included in the plans 6 and 7 firm yield computations but not the others. System firm yields for the alternative plans are expressed as a percentage of the system firm yield for the standard operating plan. Table 8.1 provides a general overview of the relative magnitude of yield increases resulting from the alternative reallocation plans.

Table 8.1
SYSTEM FIRM YIELD FOR ALTERNATIVE REALLOCATION PLANS
1984 Sediment Conditions

Plan	12-Reservoir System Firm Yield (cfs and % of Plan 1)			
	Excluding Unregulated Flows		Including Unregulated Flows	
	cfs	%	cfs	%
1	1,697	100.0%	2,265	100.0%
2	1,606	94.6%	2,069	91.3%
3	1,838	108.3%	2,538	112.1%
4	1,743	102.7%	2,329	102.8%
5	1,890	111.4%	2,586	114.2%
6	1,800	106.1%	2,387	105.4%
7	1,777	104.7%	2,364	104.4%

Plan 1	-	standard operating plan as outlined in Table 7.10
Plan 2	-	Possum Kingdom inactive pool set at 970 feet, instead of 875 feet in standard operating plan
Plan 3	-	Whitney Reservoir drought contingency storage
Plan 4	-	Seasonal rule curve involving 15% conservation storage capacity of 7 reservoirs, with pool lowered in April and raised May-Oct as illustrated by Figure 6-4
Plan 5	-	Plans 3 and 4 combined
Plan 6	-	permanent reallocation to USACE approval limit in 7 reservoirs as outlined in Table 7.29
Plan 7	-	May-Oct seasonal rule curve to USACE approval limit in 7 reservoirs as outlined in Table 7.29

The contract between the Southwestern Power Administration and Brazos Electric Power Cooperative provides for generation of 36,000 megawatt-hours of electricity annually at Whitney Reservoir. Hydroelectric power operations at Whitney Reservoir were based in the model on the annual energy demand of 36,000 megawatt-hours. Energy generated to meet this demand is primary energy. Secondary energy is also generated incidental to flood control and water supply releases. The effectiveness of plans 1, 3, and 5 in meeting the energy demand during the 85-year simulation period is summarized in Table 8.2. The results of system firm yield simulations alternatively excluding and including unregulated flows are presented.

Recurrence intervals for filling the flood control pools are presented in Table 8.3 for several of the plans.

Using the inactive storage capacity in Possum Kingdom, Granbury, and/or Whitney Reservoirs as a contingency water supply source; permanent reallocation of flood control capacity to water supply in any or all of the nine flood control reservoirs; or seasonal rule curve operations are all viable potential management strategies. The alternative plans and measures of effectiveness included in Tables 8.1, 8.2, and 8.3 illustrate general potentialities.

The Whitney drought contingency plan (plan 3) increases the system firm yield more than the permanent reallocation of flood control capacity to water supply at the USACE approval limit in the seven reservoirs (plan 6). The permanent reallocation of flood control capacity does significantly increase the risk of the flood control pools being overtopped, as illustrated by Table 8.3. The Whitney drought contingency plan does not significantly affect flood control operations but does adversely impact hydroelectric power generation. However, the impact on hydroelectric power is not severe. As indicated by Table 8.2, the standard operating plan and Whitney drought contingency plan result in shortages during 1 month and 15 months, respectively, of the 1020-month simulation period. The Whitney drought contingency plan shortages, averaged over the simulation period, are 203 megawatt-hours/year or 0.56% of the 36,000 megawatt-hours/year energy demand, based on the firm yield simulation excluding unregulated flows. Natural salt contamination problems, not addressed by the present study, could greatly impact the feasibility of the Whitney drought contingency plan or similar plans involving water supply from the main stem of the Brazos River.

Plan 7 illustrates the use of a seasonal rule curve to increase firm yield while minimizing adverse impacts on flood control. Plan 4 was included to demonstrate that both water supply, as measured by system firm yield, and flood control as measured by the recurrence intervals, could be enhanced simultaneously. The plan 4 seasonal rule curve increases the system firm yield almost as much as a permanent reallocation of the same amount of storage capacity.

Table 8.2
HYDROELECTRIC POWER GENERATED AT WHITNEY RESERVOIR
1984 Sediment Condition

Measure of Effectiveness	Excluding Unreg. Flows			Including Unreg. Flows		
	Plan 1	Plan 3	Plan 5	Plan 1	Plan 3	Plan 5
water supply firm yield (cfs)	1,697	1,838	1,890	2,265	2,538	2,586
annual energy (megawatt-hrs/yr)	36,000	36,000	36,000	36,000	36,000	36,000
primary energy (megawatt-hrs/yr)	35,991	35,797	35,838	35,900	34,894	35,137
average shortage (megawatt-hrs/yr)	9	203	162	100	1,106	863
maximum shortage (megawatt-hrs/mo)	786	2,041	2,041	1,961	3,000	3,000
months with shortage	1	15	13	9	45	39
power shortage index	0.001	0.075	0.058	0.022	0.957	0.685
secondary energy (megawatt-hrs)	71,082	72,748	73,942	71,559	75,311	76,762

Table 8.3
RECURRENCE INTERVAL FOR FILLING FLOOD CONTROL POOLS
2010 Sediment and Water Use Conditions

Reservoir	No Reallocation	Plan 4 15% Seasonal Rule Curve	Plan 6 Permanent USACE Limit	Plan 7 Seasonal USACE Limit
	Recurrence Interval (years)			
Whitney	38.8	39.8	37.3	38.4
Aquilla	71.6	80.8	56.0	69.2
Waco	131.7	149.5	87.7	130.9
Belton	45.5	71.5	35.3	45.5
Stillhouse	115.3	174.1	62.5	115.3
Granger	111.8	144.8	49.5	111.8
Somerville	51.1	53.1	29.5	43.9

CHAPTER 9
SUMMARY AND CONCLUSIONS

Optimizing the beneficial use of existing reservoirs is becoming a major focus of water supply planning and management. The results of the study documented by this report indicate that storage reallocations and related reservoir management strategies can be effective in responding to changing conditions and increasing demands on limited resources. An enhanced understanding of the effects of changes in operating policies can be developed through simulation modeling studies.

Summary

The study focused on simulating storage reallocations and other management strategies for a case study reservoir system, but also included a review of reservoir operation practices and procedures, storage reallocations which have been proposed or implemented in Texas and throughout the nation, seasonal characteristics of factors affecting reservoir operations in Texas, and state-of-the-art modeling capabilities for formulating and evaluating changes in operating policies.

The system of 12 reservoirs in the Brazos River Basin owned and operated by the U.S. Army Corps of Engineers and Brazos River Authority provided a case study representative of operation of major reservoir systems in Texas. A HEC-3/HEC-5 simulation study was performed based on a 85-year period-of-record sequence of monthly streamflows.

Simulation models in general, and HEC-3 and HEC-5 in particular, are useful tools for formulating and evaluating alternative reservoir operating strategies. Computer simulation provides a broad range of capabilities for experimenting with alternative water use scenarios and operating plans. The effectiveness of alternative operating plans under various conditions can be quantified. The case study illustrates approaches for developing model input data, organizing simulation runs, and analyzing model results.

Several indicators of water supply capabilities were adopted in the study. Yield is quantified by firm yield and reliability as well as by diversion shortages and drawdown frequencies associated with specified water use conditions. Hydroelectric firm and secondary energy and shortages associated with a specified energy demand are computed. Flood control capabilities are quantified in terms of the recurrence interval of a flood which just fills the storage capacity of a flood control pool. A procedure was developed for estimating flood control recurrence intervals based on the results of a reservoir system simulation for monthly period-of-record hydrology.

The following reservoir management strategies were considered, to various degrees of detail, in the study:

1. multiple reservoir system operation,
2. use of unregulated flows entering the river below the dams in combination with reservoir releases,
3. temporary use of sediment reserves for other purposes,
4. reallocation of storage capacity between conservation purposes,

5. permanent reallocation of storage capacity between flood control and conservation purposes,
6. seasonal rule curve operations, and
7. buffer zone operations involving secondary yield as well as firm yield.

The reservoir operation policies were analyzed specifically for the case study reservoir system. However, the observations and conclusions presented below are pertinent to other reservoir systems as well.

Conclusions

Water supply planning and management studies and decisions traditionally have been based on individual reservoir firm yield estimates. The results of the present study indicate that firm yields reflecting system operation are much greater than the sum of individual reservoir firm yields. For the Brazos River Authority system, the increases in estimated firm yield are achieved primarily by properly crediting existing operating policies rather than by changing operating policies. The reservoirs are actually operated as a system. The increases in yield which result from system operation are significantly larger than the increases achieved by any of the other operation strategies considered in the study.

System firm yield, as the term is used here, involves coordinated releases from two or more reservoirs to meet a common diversion demand at a downstream location. The system firm yield is larger than the sum of the individual reservoir firm yields from two perspectives. The timing of the individual reservoir firm yield critical drawdown periods vary between the reservoirs. The reservoirs empty at different times, with a reservoir being empty while significant storage still remains in other reservoirs. System operation evens out the storage depletions. Also, a significant amount of runoff enters the river below the dams. The unregulated flows have zero firm yield but provide a significant increase in system firm yield if supplemented by reservoir releases during low flow periods.

Reservoir storage capacity is sized to include a reserve for 50 to 100 years of sedimentation in addition to the usable design capacity. In most water resources planning reports and other documents, yield is viewed in terms of usable storage capacity, excluding sediment reserve. Prior to being filled with sediment, the sediment reserve can be used for other purposes. The BRA uses sediment reserve capacity for temporary water supply commitments. Sediment reserves represent a significant amount of storage capacity available for many years. In the present study, firm yield and other analyses were performed for alternative conditions of sedimentation.

In the case study, reallocation between conservation purposes focused on using hydropower inactive storage capacity for water supply. System firm yields for the BRA reservoir system can be significantly increased in this manner. Adverse impacts on hydroelectric power generation can be minimized by releasing from the inactive pool only after the storage capacity of the other reservoirs in the system has been depleted. Thus, encroachments into the inactive pool occur very infrequently, but the contingency water supply storage significantly increases system firm yield.

An interestingly large proportion of the storage reallocations which have been studied and/or implemented throughout the nation have been in Texas. Most of the storage reallocations implemented or studied in Texas and elsewhere in the nation have involved converting flood control capacity to municipal and industrial water supply. Permanent reallocation of flood control capacity to water supply was a major emphasis of the present study.

Increases in yield can be achieved by permanently raising top of conservation pool elevations. However, the firm yield versus storage capacity relationships are highly nonlinear, with incremental increases in firm yield diminishing with further increases in storage capacity. Significant losses in flood control storage capacity result in correspondingly significant increases in the risk of flood control capacity being exceeded by an extreme flood event. Relatively small storage reallocations are a viable strategy for obtaining additional water supply yield. However, drastic increases in yield will likely be accompanied by significant tradeoffs between purposes. Most of the reallocations which have been actually proposed or implemented either have involved small amounts of storage relative to the total flood control capacity, such that impacts on flood control are minimal, or have been combined with construction of an upstream reservoir.

Permanent reallocations between flood control and conservation storage capacity result in tradeoffs between purposes. The objective of seasonal rule curve operation is to simultaneously enhance both flood control and water supply or to enhance one purpose while minimizing adverse impacts on the other. In many parts of the nation and world, which have distinct flood seasons, seasonal rule curve reservoir operation is common. Seasonal rule curve operations are hindered in Texas by the lack of a distinct flood season. Extreme rainfall events can occur at any time. However, seasonal rule curve operations are still potentially viable in Texas due to the seasonal characteristics of a combination of factors affecting reservoir operations. Streamflow, both mean flows and extreme events, is more seasonal than extreme precipitation events. Reservoir storage, including conservation drawdowns and flood control pool encroachments, appears to be more seasonal than streamflow or precipitation extremes. For relatively small amounts of reallocated storage capacity, certain seasonal rule curves were found in the simulation study to increase firm yield essentially as much as a corresponding permanent reallocation, but with little or no adverse impacts on flood control.

The firm yield is, by definition, met 100% of the time during a historical period-of-record simulation. A reliability analysis indicates that providing alternative means to handle demands a small percentage of the time can significantly increase the overall system dependable yield. Thus, conjunctive management of surface water supplies with groundwater supplies and/or short-term demand management strategies can be potentially effective from a hydrologic water availability perspective.

Buffer pool operations have not been adopted to any significant extent in Texas, but are used elsewhere. Buffer pools allow differentiation between firm and secondary yields from the same reservoir or multireservoir system. Full demands are met as long as the water surface is above the top of the buffer pool, with certain demands being curtailed whenever the water in storage falls below this level. Water supply contracts may be based on secondary as well as firm yield. Implementation of drought contingency plans may be triggered by the storage falling below a specified buffer level. An analysis was performed in the present study to illustrate the relationship between firm yield, secondary yield, and reliability.

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