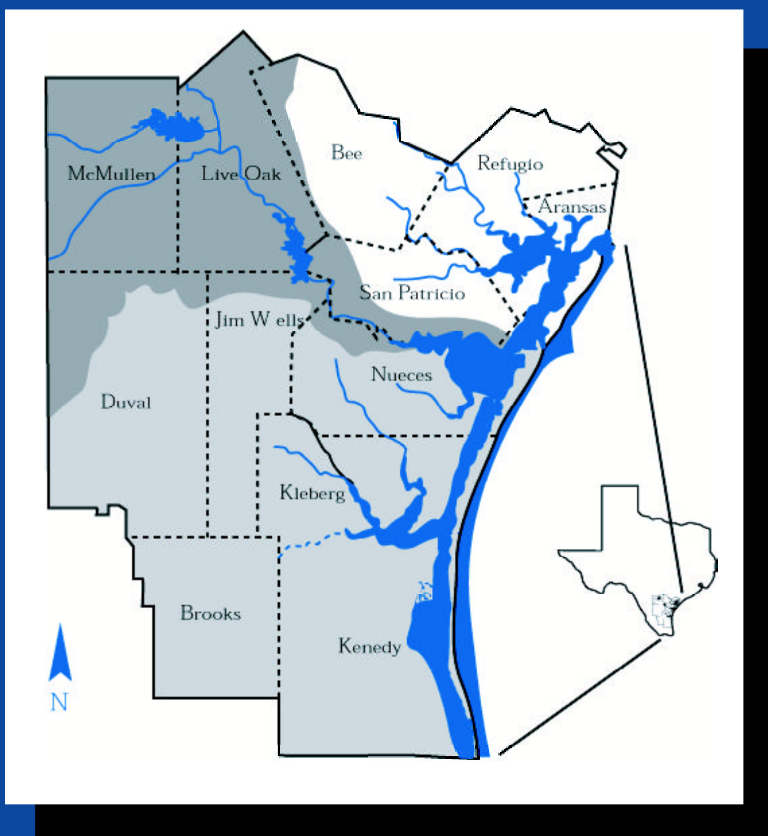
Status, Trends, and Changes in Freshwater Inflows to Bay Systems in the Corpus Christi Bay National Estuary Program Study Area



Corpus Christi Bay National Estuary Program
CCBNEP-17 • September 1997

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Status, Trends and Changes in Freshwater Inflows To Bay Systems in the Corpus Christi Bay National Estuary Program Study Area

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CORPUS CHRISTI BAY NATIONAL ESTUARY PROGRAM

The Corpus Christi Bay National Estuary Program (CCBNEP) is a four-year, community based effort to identify the problems facing the bays and estuaries of the Coastal Bend, and to develop a long-range, Comprehensive Conservation and Management Plan. The Program's fundamental purpose is to protect, restore, or enhance the quality of water, sediments, and living resources found within the 600 square mile estuarine portion of the study area.

The Coastal Bend bay system is one of 28 estuaries that have been designated as an **Estuary of National Significance** under a program established by the United States Congress through the Water Quality Act of 1987. This bay system was so designated in 1992 because of its benefits to Texas and the nation. For example:

- Corpus Christi Bay is the gateway to the nation's sixth largest port, and home to the third largest refinery and petrochemical complex. The Port generates over $1 billion of revenue for related businesses, more than $60 million in state and local taxes, and more than 31,000 jobs for Coastal Bend residents.
- The bays and estuaries are famous for their recreational and commercial fisheries production. A study by Texas Agricultural Experiment Station in 1987 found that these industries, along with other recreational activities, contributed nearly $760 million to the local economy, with a statewide impact of $1.3 billion, that year.
- Of the approximately 100 estuaries around the nation, the Coastal Bend ranks fourth in agricultural acreage. Row crops -- cotton, sorghum, and corn -- and livestock generated $480 million in 1994 with a statewide economic impact of $1.6 billion.
- There are over 2600 documented species of plants and animals in the Coastal Bend, including several species that are classified as endangered or threatened. Over 400 bird species live in or pass through the region every year, making the Coastal Bend one of the premier bird watching spots in the world.

The CCBNEP is gathering new and historical data to understand environmental status and trends in the bay ecosystem, determine sources of pollution, causes of habitat declines and risks to human health, and to identify specific management actions to be implemented over the course of several years. The 'priority issues' under investigation include:

- altered freshwater inflow
- declines in living resources
- loss of wetlands and other habitats
- bay debris
- degradation of water quality
- altered estuarine circulation
- selected public health issues

The **COASTAL BEND BAYS PLAN** that will result from these efforts will be the beginning of a well-coordinated and goal-directed future for this regional resource.

STUDY AREA DESCRIPTION

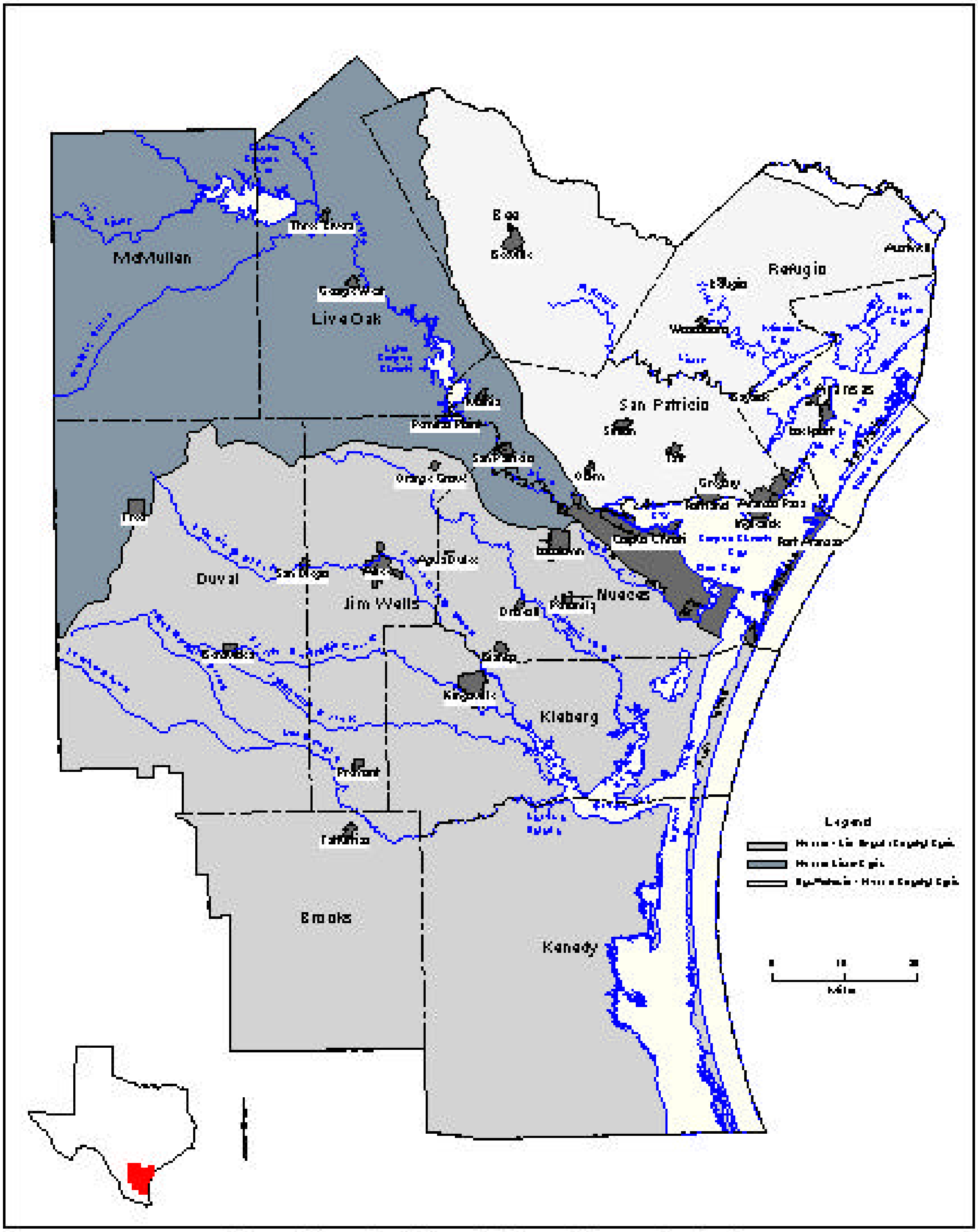
The CCBNEP study area includes three of the seven major estuary systems of the Texas Gulf Coast. These estuaries, the Aransas, Corpus Christi, and Upper Laguna Madre are shallow and biologically productive. Although connected, the estuaries are biogeographically distinct and increase in salinity from north to south. The Laguna Madre is unusual in being only one of three hypersaline lagoon systems in the world. The study area is bounded on its eastern edge by a series of barrier islands, including the world's longest -- Padre Island.

Recognizing that successful management of coastal waters requires an ecosystems approach and careful consideration of all sources of pollutants, the CCBNEP study area includes the 12 counties of the Coastal Bend: Refugio, Aransas, Nueces, San Patricio, Kleberg, Kenedy, Bee, Live Oak, McMullen, Duval, Jim Wells, and Brooks.

This region is part of the Gulf Coast and South Texas Plain, which are characterized by gently sloping plains. Soils are generally clay to sandy loams. There are three major rivers (Aransas, Mission, and Nueces), few natural lakes, and two reservoirs (Lake Corpus Christi and Choke Canyon Reservoir) in the region. The natural vegetation is a mixture of coastal prairie and mesquite chaparral savanna. Land use is largely devoted to rangeland (61%), with cropland and pastureland (27%) and other mixed uses (12%).

The region is semi-arid with a subtropical climate (average annual rainfall varies from 25 to 38 inches, and is highly variable from year to year). Summers are hot and humid, while winters are generally mild with occasional freezes. Hurricanes and tropical storms periodically affect the region.

On the following page is a regional map showing the three bay systems that comprise the CCBNEP study area.



Corpus Christi Bay National Estuary Program Study Area

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Status, Trends, and Changes in Freshwater Inflows to Bay Systems in the Corpus Christi Bay National Estuary Program Study Area

By **William H. Asquith, John G. Mosier,** ***and*** **Peter W. Bush**

Executive Summary

This report presents the results of a study to quantify current (1983–93) mean freshwater inflows to the six bay systems (open water and wetlands) in the Corpus Christi Bay National Estuary Program study area, to test for historical temporal trends in inflows, and to quantify historical and projected changes in inflows. The report also addresses the adequacy of existing data to estimate freshwater inflows.

The six bay systems are the St. Charles, Copano, Redfish, Nueces and Corpus Christi, upper Laguna Madre, and Baffin. Each bay system has one or more adjacent contributing watersheds, for a total of 13 watersheds for purposes of this study, that together comprise about 6,000 square miles. All freshwater runoff to each bay system except the Nueces and Corpus Christi originates in adjacent watersheds. Freshwater that enters the Nueces and Corpus Christi Bay system is a combination of water that originates in the adjacent contributing watersheds and water that originates in the large regional watershed of the Nueces River (greater Nueces River Basin) upstream of the adjacent contributing watersheds.

The watershed simulation model Hydrologic Simulation Program—Fortran (HSPF) was used to generate simulated flow (runoff) from the 13 watersheds to the six bay systems because adequate gaged streamflow data from which to estimate freshwater inflows are not available; only about 23 percent of the adjacent contributing watershed area is gaged. The model was calibrated for the gaged parts of three watersheds—that is, selected input parameters (meteorologic and hydrologic properties and conditions) that control runoff were adjusted in a series of simulations until an adequate match between model-generated flows and a set (time series) of gaged flows was achieved. The primary model input is rainfall and evaporation data and the model output is a time series of runoff volumes. After calibration, simulations driven by daily rainfall for a 26-year period (1968–93) were done for the 13 watersheds to obtain runoff under current (1983–93), predevelopment (pre-1940 streamflow and pre-urbanization), and future (2010) land-use conditions for estimating freshwater inflows and for comparing runoff under the three land-use conditions; and to obtain time series of runoff from which to estimate time series of freshwater inflows for trend analysis.

The assumption was made that the principal factor responsible for change in freshwater inflows (other than changes in climatic conditions, return and diversion flows, and reservoirs) is change in the percentage of urban area. To estimate the amount of urban area under current conditions, the urban area on a 1973 land-use map in and around Corpus Christi and other parts of the study area where appreciable development has occurred since 1973 (primarily near the coast) was increased on the basis of urban development shown on recent (early 1990s) city maps. For the simulations of predevelopment conditions, all urban area was considered as nonexistent. For the simulations of future conditions, the urban area estimated for current conditions in the simulated watersheds was increased on the basis of county population projections from 1990 to 2010.

To estimate current freshwater inflows to each of the six bay systems, the simulated daily runoff (excluding return and diversion flows) under current land-use conditions for each watershed was aggregated by month for 1983–93. Monthly net differences between return and diversion flows (net defined as return minus diversion) for 1983–93 that were computed from return and diversion flow data and that were compiled by the Texas Water Development Board were added to the monthly simulated flows. The monthly sums of simulated runoff and net return and diversion flow were aggregated annually and seasonally by receiving bay system. For the Nueces and Corpus Christi Bay system, monthly streamflow measured at the streamflow-gaging station Nueces River near Mathis was added to the 1983–93 monthly simulated flows and net return and diversion flows to account for the inflow to the Nueces and Corpus Christi Bay system that originates in the greater Nueces River Basin upstream of the adjacent contributing watersheds. The mean annual and mean seasonal inflows for 1983–93 are considered current inflows.

A statistical test, the Mann-Kendall test, was used to determine whether gaged and simulated freshwater inflows have historical trends with time. The time-series data were tested to determine whether a hypothesis about the data—the null hypothesis that there is no trend—can be substantiated by the strength of the evidence provided by the data. The outcome of the test is a decision to reject or not to reject the null hypothesis in favor of an alternate hypothesis, which is that there is either an upward or downward trend.

Trend tests were done on gaged streamflows—time series of annual and seasonal volumes of streamflow measured at 5 streamflow-gaging stations in the adjacent contributing watersheds and 4 in the greater Nueces River Basin. Trend tests were done on rainfall—time series of annual and seasonal volumes of rainfall for three "index" stations in the study area for comparison of results to those of trend tests on streamflow. Trend tests also were done on estimated inflows—the time series of annual and seasonal volumes of inflow for 1977–93 for each receiving bay system were estimated by summing simulated runoff, net return and diversion flows, and (for the Nueces and Corpus Christi Bay system) streamflow measured at the Nueces River near Mathis gaging station. The 1977–93 period was selected for trend tests on estimated inflows because the pre-1977 return and diversion flow data are judged to be inconsistent with the post-1976 data. Trend tests were done on net return and diversion flows—the time series of annual and seasonal volumes of net return and diversion flows for 1977–94.

The estimated current mean annual freshwater inflow to all six bay systems combined is 1,200,000 acre-feet per year. About 26 percent of that amount (about 314,000 acre-feet per year) is flow that originates upstream of the adjacent contributing watersheds, as measured at the Nueces River near Mathis streamflow-gaging station. About 74 percent (about 886,000 acre-feet per year) is a combination of runoff that originates in the adjacent contributing watersheds and net return and diversion flows; net return and diversion flows (about -51,500 acre-feet per year) result in a loss of freshwater inflow of about 4 percent. The Copano Bay system receives the largest share of the total inflow to the bay systems, about 53 percent (about 634,000 acre-feet per year). The Nueces and Corpus Christi Bay system receives the next largest share, about 32 percent (about 378,000 acre-feet per year)—most of which (about 83 percent) is streamflow that originates outside the adjacent contributing watersheds.

Runoff per unit area, which ranges from 0.52 cubic foot per second per square mile for the watersheds of the St. Charles Bay system to 0.042 cubic foot per second per square mile for the watersheds of the Baffin Bay system, decreases appreciably in a southwesterly direction across the study area. The pattern of decrease reflects the decrease in annual rainfall in that direction, the generally flatter topography in the southwestern part of the study area, and the generally more permeable soils in the southern part of the study area than in the northern part.

In the watersheds of the Nueces and Corpus Christi Bay system, which have by far the largest net difference between return and diversion flows, diversion flows exceed return flows. Consumption of water by municipal and industrial users in the greater Corpus Christi area and agricultural users in rural areas reduces freshwater inflow to the Nueces and Corpus Christi Bay system by about 14 percent from what it would be without return and diversion flows.

Complete-year records for the two long-term streamflow-gaging stations in the study area, Mission River at Refugio and Nueces River near Mathis, begin in 1940. Mann-Kendall trend tests on 1940–96 time series of annual and mean seasonal streamflow volumes for the Mission River at Refugio gaging station show no strong evidence for a trend in annual streamflow for the 57-year period. The winter data show some indication of an upward trend, but the evidence from the data is not considered strong enough to conclude with certainty that there is a trend.

The Nueces River near Mathis data show strong evidence for a downward trend in annual streamflow for the 57-year period. The downward trend is more of a "step trend" than a linear trend. Post-Choke Canyon Reservoir (1983–96) mean annual streamflow (about 279,000 acre-feet per year) is about 337,000 acre-feet per year less than pre-Choke Canyon (1940–82) mean annual streamflow (about 616,000 acre-feet per year), which represents a decrease of about 55 percent. Water-budget and streamflow analyses show that storage in and evaporation from Choke Canyon Reservoir accounts for an annual streamflow reduction of about 95,800 acre-feet per year, or about 28 percent of the total 337,000 acre-feet per year post-Choke Canyon decrease in annual streamflow. Other factors besides Choke Canyon Reservoir account for the major part of the post-Choke Canyon streamflow decrease. One factor is decreasing streamflow in the greater Nueces River Basin upstream of Choke Canyon Reservoir. Composite streamflow data from four gaging stations considered upstream of Choke Canyon Reservoir in the greater Nueces River

Basin show a downward trend of about 1.8 percent per year for 1965–96. A previous investigation indicates that increased surface-water withdrawals in the greater Nueces River Basin could account for some of the downward trend in the composite streamflow. Another factor that could contribute to the downward trend in streamflow, were it to be confirmed, is a decrease in rainfall. Development of a representative index of rainfall for the greater Nueces River Basin is complex and beyond the scope of this report.

No evidence for trends in annual streamflow volumes is indicated for time-series data for gaging stations Copano Creek near Refugio for 1971–93, Aransas River near Skidmore for 1968–93, and Oso Creek at Corpus Christi for 1973–93. Some evidence is indicated for trends in a few time series of seasonal streamflow for these stations.

Trend tests on time series of annual and seasonal rainfall data for the three "index" stations for 1968–93 show little evidence for trends. The results of trend tests on rainfall time series generally are consistent with the results of trend tests on annual and seasonal streamflow data for the same, or nearly the same, periods.

No evidence for trends in estimated annual inflow volumes for any bay system for 1977–93 is indicated. The only seasonal time series that shows some evidence for a trend (downward) is the summer data for the Redfish Bay system. If a trend is present, it could be rainfall-related, or it could be related to an apparent downward trend in net return and diversion flows for the Redfish system.

The addition of urban area to the watersheds from 0 to 3.3 percent of total area to represent the change from predevelopment to current land-use conditions increases simulated annual runoff to all bay systems combined by about 8 percent.

For the Nueces and Corpus Christi Bay system, an approximately 11-percent increase in runoff due to increased urban area since predevelopment (about 12,000 acre-feet per year) is offset by the negative net return and diversion flow (about -60,400 acre-feet per year) and the post-Choke Canyon decrease in Nueces River flow [about 305,000 acre-feet per year (1983–93); about 337,000 acre-feet per year (1983–96)]. The combination of these changes results in a decrease in estimated freshwater inflow to the Nueces and Corpus Christi Bay system from about 731,000 acre-feet per year under predevelopment conditions to about 378,000 acre-feet per year under current conditions, a decrease of about 48 percent.

For all bay systems combined, a change from the estimated predevelopment inflow of 1,490,000 acre-feet per year to the estimated current inflow of 1,200,000 acre-feet per year is a decrease in total freshwater inflow of about 19 percent. The approximately 8-percent increase in runoff from the watersheds to all the bay systems combined since predevelopment (about 69,000 acre-feet per year) virtually offsets the negative net return and diversion flows for all the bay systems combined (about -51,500 acre-feet per year); the decrease in Nueces River flow [305,000 acre-feet per year (1983–93)] virtually accounts for the 19-percent decrease in total freshwater inflow.

For practical purposes, assuming that the flow of the Nueces River is unchanged in 2010 from what it was during 1983–93, total freshwater inflow to all bay systems combined in 2010 is projected to be about the same as current total inflow, 1,200,000 acre-feet per year.

The available data for estimating freshwater inflows into the bay systems in the study area are adequate but not optimum. Gaged streamflows are the optimum data for estimating freshwater inflows because they represent an integration, or synthesis, over time of all the climatic and hydrologic processes and human activities that affect freshwater inflows. New technology now makes gaging the discharge in tidally influenced streams practical. Thus streamflow-gaging stations can be located closer to the mouths of streams than was practical when most, if not all, of the active gaging stations in the study area were established. Streamflow-gaging stations at seven potential sites would expand the gaged area that contributes inflow to the bay systems from about 23 to 70 percent.

I. INTRODUCTION

The Corpus Christi Bay area was designated as an estuary of national significance by the U.S. Environmental Protection Agency (USEPA) in 1992. The Texas Natural Resource Conservation Commission (TNRCC) and the USEPA funded a program in 1992 to obtain information about the current status of the estuary and develop a long-term management plan for conservation of the estuary. In 1994, the U.S. Geological Survey (USGS), in cooperation with the Corpus Christi Bay National Estuary Program (CCBNEP), began a study to characterize the current status, historical trends, and historical and projected changes in freshwater inflows to six bay systems (open water and wetlands) in the CCBNEP study area (Fig. I.1). Freshwater inflows into the bay systems affect biological, chemical, and physical processes and are vital to the health of the estuarine ecosystem. Freshwater inflows to the bay systems show considerable annual and seasonal variation in response to climatic variations. Gradual changes in climatic conditions, in amounts of water diverted from streams for industrial, municipal, or agricultural purposes (diversion flows), in amounts of irrigation water and wastewater discharged to streams (return flows), and in land use can cause long-term trends in freshwater inflows. Reservoir construction or changes in reservoir operation can cause discrete changes in freshwater inflows.

Purpose and Scope

This report presents the results of a study to (1) quantify current (1983–93) mean freshwater inflows to the six bay systems in the CCBNEP study area, (2) test for historical temporal trends in inflows, and (3) quantify historical and projected changes in inflows. After a summary of related previous studies and pertinent data, the report describes an application of the Hydrologic Simulation Program—Fortran (HSPF) watershed simulation model to estimate runoff from 13 contributing watersheds adjacent to the six bay systems on the basis of current, predevelopment (pre-1940 streamflow and pre-urbanization), and future (2010) land-use conditions; and statistical tests for historical trends (Mann-Kendall tests) in time series of gaged streamflows, selected rainfall data, estimated freshwater inflows, and net return and diversion flows.

Figure I.1. Adjacent contributing watersheds of bay systems, Corpus Christi Bay National Estuary Program study area, Texas.

Estimated freshwater inflows are the sum of simulated runoff, net return and diversion flows, and gaged streamflow that originates outside the 13 contributing watersheds adjacent to the six bay systems. Estimated predevelopment freshwater inflows are compared to estimated current inflows, and current inflows are compared to projected future inflows. The report also addresses the adequacy of existing data to estimate freshwater inflows.

Description of the Study Area

The CCBNEP study area (Fig. I.1) contains six bay systems—St. Charles, Copano, Redfish, Nueces and Corpus Christi, upper Laguna Madre, and Baffin. Each bay system has one or more adjacent contributing watersheds, for a total of 13 watersheds for purposes of this study, which together comprise about 6,000 mi^2 (Table I.1). All freshwater runoff to each bay system except the Nueces and Corpus Christi originates in the adjacent watersheds of the bay system. Freshwater inflow to the Nueces and Corpus Christi Bay system is a combination of water that originates in the adjacent watersheds and water that originates in the large (16,700 mi^2) regional watershed of the Nueces River, Frio River, San Miguel Creek, and Atascosa River (greater Nueces River Basin) upstream of the adjacent watersheds (Fig. I.2).

From northeast to southwest, the study area has a subhumid to semiarid climate. Annual rainfall ranges from about 40 inches per year (in/yr) in the northeast to about 24 in/yr in the southwest. Winter generally is the season of least rainfall, and fall is the season of next-to-least. Spring and summer generally have similar amounts and together account for about 60 percent of annual rainfall in the study area.

The typical topography of the watersheds is nearly flat, especially in the southern part of the study area, with low-gradient stream networks. The watersheds of the southern part of the Baffin Bay system are characterized by numerous closed depressions and intermittent playa lakes.

Soils in the northern part of the study area generally are more clayey than soils in the southern part, which proportionately are more sandy. Thus, soils in the northern part of the study area generally are less permeable than soils in the southern part, which likely enhances runoff in the northern part relative to runoff in the southern part for a given rainfall event.

The largest streams in the study area north of the Nueces River—the Mission and Aransas Rivers and Copano Creek of the Copano Bay system—typically maintain base flow much of the year, except during drought conditions. Oso Creek in the Nueces and Corpus Christi Bay system is perennial; but most of the streams in the study area south of the Nueces River are intermittent, which is consistent with topographic, soil, and rainfall conditions in the study are

Figure I.2. Greater Nueces River Basin, Texas.

The Nueces River is the largest stream in the study area. It is regulated upstream of the Nueces and Corpus Christi Bay system by Lake Corpus Christi and further upstream by Choke Canyon Reservoir, which is on the Frio River and drains into the Nueces River by way of the Atascosa River. Lake Corpus Christi, with a storage capacity (pool at top of south spillway gates) of about 241,000 acre-feet (acre-ft) (City of Corpus Christi, written communication, unreferenced), provides water supply for Corpus Christi and several smaller communities. The reservoir was impounded in July 1934 and enlarged in April 1958. Choke Canyon Reservoir was impounded in October 1982 and has a storage capacity at conservation level of about 689,000 acre-ft (J.F.

Giles, Bureau of Reclamation, written communication, unreferenced).

Table I.1. Bay systems and adjacent contributing watersheds, Corpus Christi Bay National Estuary Program study area

[mi^2, square miles]

Bay system (adjacent contributing watershed area)	Adjacent contributing watersheds to bay system	Watersheds as subdivided or grouped for simulation
St. Charles (205 mi^2)	St. Charles Bay	St. Charles Bay
Copano (2,090 mi^2)	Copano Creek Mission River Aransas River Port Bay	Copano Creek Mission River Aransas River Port Bay
Redfish (35.0 mi^2)	Redfish Bay	Redfish Bay
Nueces and Corpus Christi[1] (636 mi^2)	Nueces River Portland Oso Creek	Nueces River Portland Oso Creek
Upper Laguna Madre (61.5 mi^2)	Upper Laguna Madre	Upper Laguna Madre
Baffin (2,980 mi^2)	Petronila Creek Cayo del Mazon Cayo del Infernillo	Petronila Creek
	San Fernando Creek Jaboncillos Creek	San Fernando Creek
	Los Olmos Creek	Los Olmos Creek

[1] Freshwater that enters the Nueces and Corpus Christi Bay system is a combination of water that originates in the adjacent contributing watersheds (636 mi^2) and water that originates in the greater Nueces River Basin (16,700 mi^2) upstream of the adjacent contributing watersheds (upstream of streamflow-gaging station Nueces River near Mathis). Streamflow from the greater Nueces River Basin was not simulated.

Land use in the watersheds of the study area predominantly is farming and ranching. Although urban areas of the study area have increased, particularly near the coast, since the available land-use map (Fig. I.3) was made, the map conveys the general distribution of land use on a regional scale.

On the basis of 1994 county water-use data (Norman Alford, Texas Water Development Board, written communication, unreferenced), surface-water sources account for about one-half the water supplied for industrial, municipal, and agricultural purposes in the study area, excluding the greater Corpus Christi area; and ground-water sources account for the other one-half. In the greater Corpus Christi area, surface water from the Nueces River supplies all but a small fraction of the water used in the area.

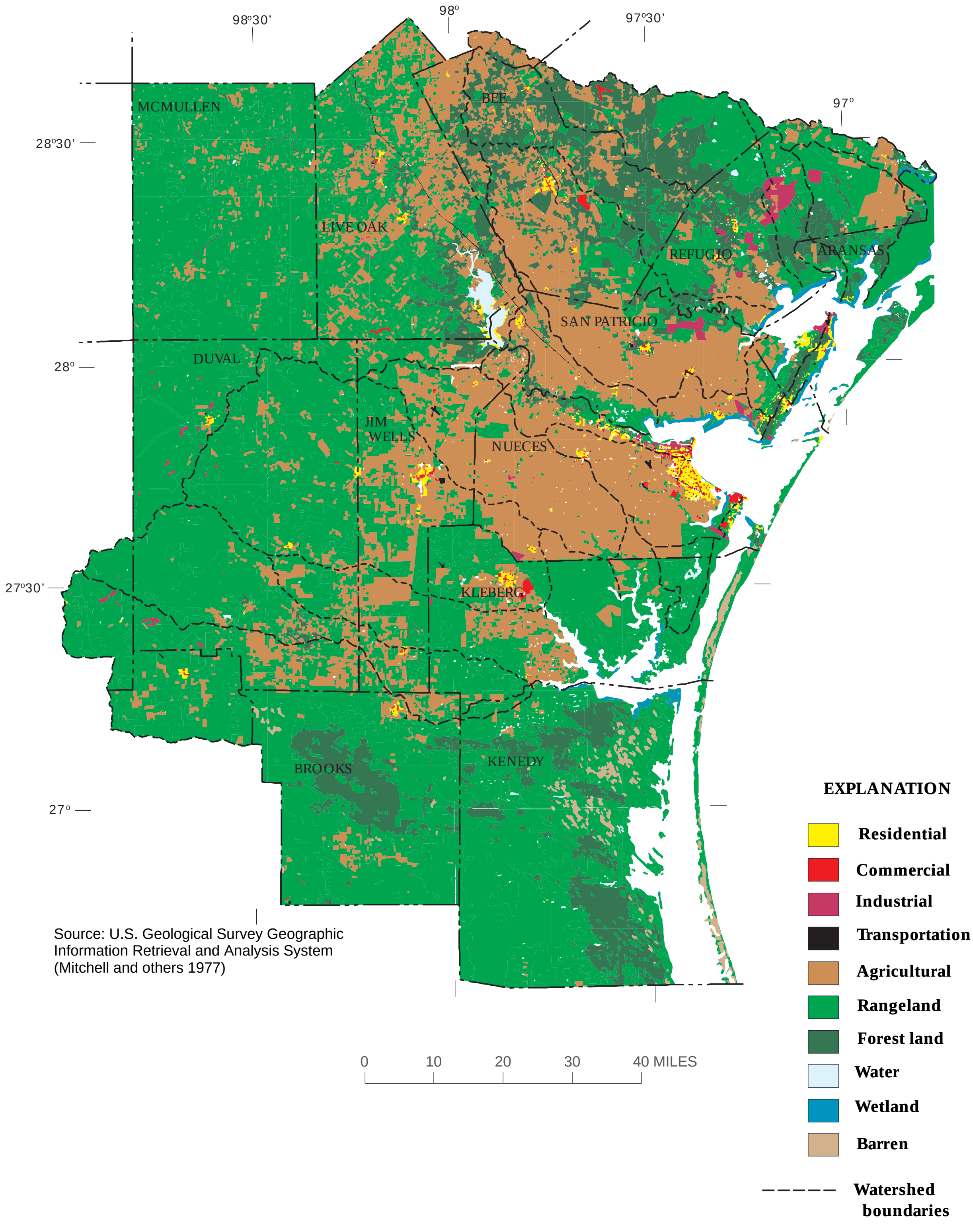

Figure I.3. Land use, Corpus Christi Bay National Estuary Program study area, Texas, 1973.

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II. LITERATURE AND HISTORICAL DATA REVIEW

In 1975, the 64th Texas Legislature enacted Senate Bill 137, which mandated comprehensive studies of the effects of freshwater inflows on the bays and estuaries of Texas. A series of reports resulted from the Senate Bill 137 mandate. Two reports in that series by the Texas Department of Water Resources (TDWR) [now the Texas Water Development Board (TWDB)] deal with the CCBNEP study area: The first report (Texas Department of Water Resources 1981), specifically addresses monthly freshwater inflows from 1941 to 1976 for the Nueces and Mission-Aransas estuaries. Freshwater inflows consisted of (1) gaged flow, (2) ungaged flow, (3) return and diversion flows for municipal, industrial, and agricultural purposes, and (4) direct rainfall on and evaporation from the surface of the estuaries. For ungaged flow, a daily water-yield model was used to estimate freshwater contributions. In the second report (Texas Department of Water Resources 1983), similar methods were used to estimate freshwater inflows to the Laguna Madre estuary.

In response to further directives from the Texas Legislature in subsequent sessions [Texas Water Code 16.058(1)], the TWDB and the Texas Parks and Wildlife Department combined efforts to conduct bay and estuary studies. A comprehensive report (Longley 1994) documents the work of these two agencies. Longley (1994) updates the earlier reports and extends freshwater inflow data bases through 1987. The methods of computing inflows in the Longley (1994) report are virtually the same as in the two TDWR reports (1981, 1983). Longley (1994) reported a significant trend—a 2.1-percent-per-year increase—in freshwater inflows of the Mission-Aransas estuary for the 47 years 1941–87. However, TWDB now reports a corrected trend of 0.2-percent-per-year increase, which is nonsignificant (Ruben Solis, Texas Water Development Board, personal communication, unreferenced). No other significant trends in freshwater inflows to Texas estuaries are reported for the 47-year period.

Greene and Slade (1995, Fig. 48) graphically indicate temporal trends in annual mean streamflow at USGS streamflow-gaging station Nueces River near Mathis for 1940–88. Temporal trends in associated rainfall also are indicated for 1940–88. For the period of record, the graph of Greene and Slade (1995, Fig. 48) shows a downward trend in annual mean streamflow. The graph of annual mean streamflow bears some relation to the graph of associated rainfall, but the extent to which rainfall influences the trend in annual mean streamflow is unclear. Based on a water-budget analysis, Greene and Slade (1995, p 49) report that the impoundment of Choke Canyon Reservoir (Fig. I.1) reduced long-term annual mean streamflow at the Mathis gaging station by 24 percent. Greene and Slade (1995, p 46) estimate annual evaporation from Choke Canyon Reservoir to be 84,000 acre-ft when storage is at 90 percent of capacity. Greene and Slade (1995, p 46) also report that annual evaporation from Lake Corpus Christi is about 62,000 acre-ft when storage is at 90 percent of capacity.

Longley (1995, Table 5.2) estimates the percent change in inflow to selected Texas estuaries (including the Mission-Aransas) under four climate-change scenarios for the projected population of 2040. The analysis projects no increase in inflow to the Mission-Aransas estuary if rainfall does not increase; a 36-percent increase in inflow if rainfall increases 20 percent; and a 65-percent decrease if rainfall decreases 20 percent.

Several reports, for example Shafer (1968, 1970), Shafer and Baker (1973), and Woodman and others (1973), document ground-water conditions in the CCBNEP study area. On the basis of flow-net analyses, Woodman and others (1973, Table 8) estimate the amount of freshwater moving through shallow aquifers of Refugio, San Patricio, and Nueces Counties and discharging into bays to range from about 1,500 to 4,500 acre-feet per year (acre-ft/yr).

The USGS has 6 streamflow-gaging stations with more than 10 years of record in the adjacent contributing watersheds of the study area, 4 in the watersheds of the Copano Bay system and 2 in the watersheds of the Nueces and Corpus Christi Bay system (Table II.1; Fig. II.1). The National Weather Service (NWS) has 19 rainfall stations with more than 30 years of daily record in the study area, some with hourly and 15-minute data as well (Table II.1; Fig. II.1). Also, NWS daily evaporation data are available from two stations in the study area for periods of 15 and 11 years (Table II.1; Fig. II.1).

The USGS has additional long-term streamflow-gaging stations in the greater Nueces Basin upstream of the contributing watersheds in the study area. Locations of four of these streamflow-gaging stations that are pertinent to the study of this report are shown in Figure I.2, along with the Nueces River near Mathis station.

A report by the TNRCC (1994) provides information on freshwater return and diversion flows. However, more detailed information on return and diversion flows has been compiled by the TWDB and is contained in TNRCC files. TWDB return and diversion flow data are aggregated by three bay systems (labeled estuaries by TWDB)—Mission-Aransas, Nueces, and Laguna Madre (W.L. Longley, Texas Water Development Board, written communication, unreferenced). The watersheds that contribute to the Mission-Aransas estuary of TWDB correspond to (are coincident with) the watersheds that contribute to the St. Charles, the Copano, and the eastern part of the Redfish Bay systems of this report. The watersheds that contribute to the Nueces estuary of TWDB correspond to the watersheds that contribute to the Nueces and Corpus Christi Bay system and the western part of the Redfish Bay system of this report; and the watersheds that contribute to the Laguna Madre estuary correspond to the watersheds that contribute to the upper Laguna Madre and the Baffin Bay systems of this report. Return and diversion flow data are available for all three estuaries of TWDB (and thus all six bay systems of this report) by month for 1977–94. Monthly return and diversion flow data for the Mission-Aransas and Nueces estuaries also are available for 1941–76. Mission-Aransas had no diversions during 1941–76 and no returns during 1941–55. The pre-1977 return and diversion flow data are judged to be inconsistent with and (or) of lesser quality than the post-1976 data.

Digital land-use maps (scale 1:250,000) that were compiled as a part of the USGS Geographic Information Retrieval and Analysis System (GIRAS) program (Mitchell and others 1977) are available for the study area for 1973.

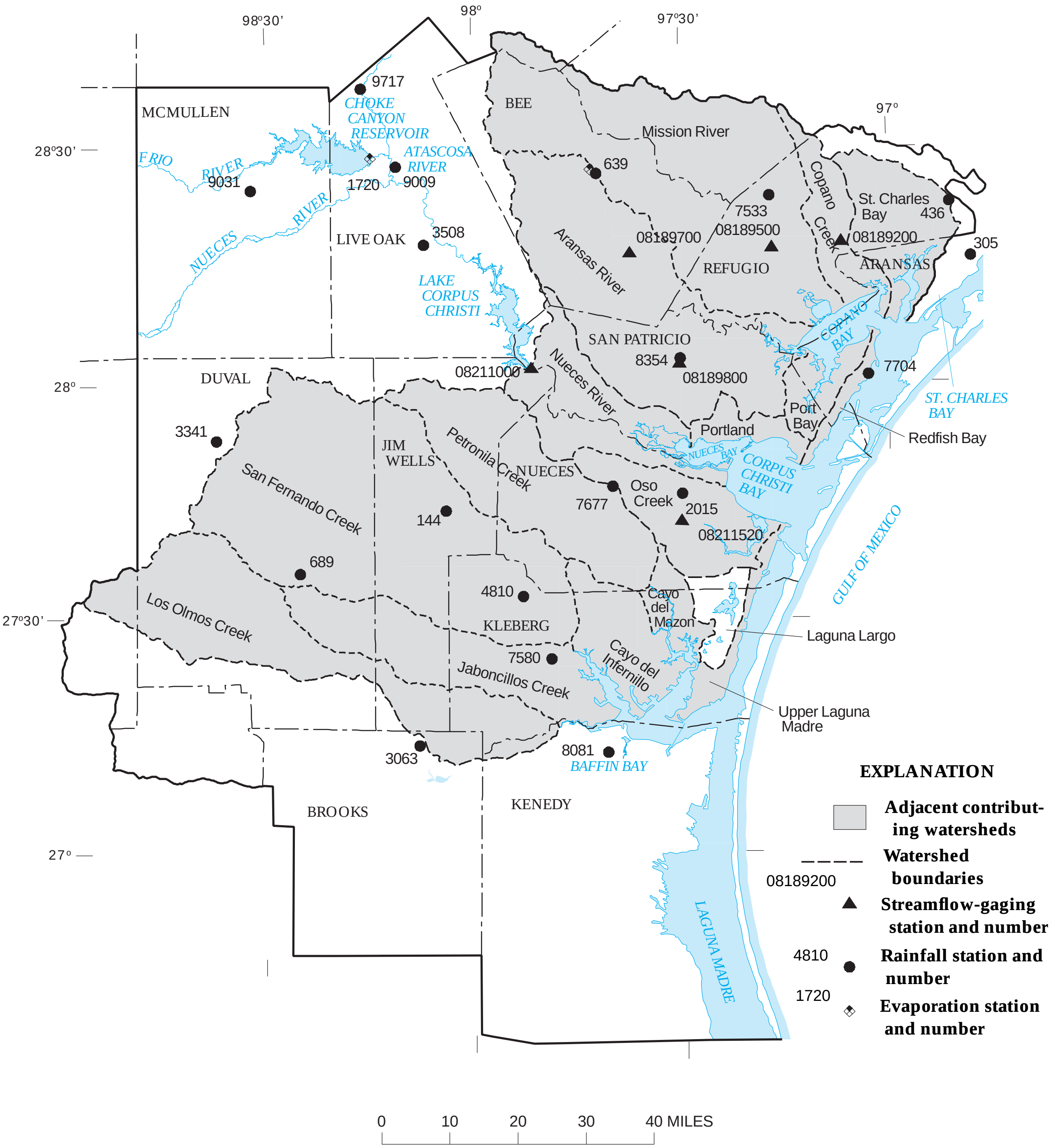

Figure II.1. Locations of long-term U.S. Geological Survey streamflow-gaging stations and National Weather Service rainfall and evaporation gages, Corpus Christi Bay National Esturary Program study area, Texas.

Table II.1. Selected U.S. Geological Survey continuous streamflow-gaging stations and National Weather Service rainfall and evaporation stations in the Corpus Christi Bay National Estuary Program study area

[USGS, U.S. Geological Survey; mi^2, square miles; NWS, National Weather Service; in, inches]

USGS station number	Station name	Drainage area (mi^2)	Receiving bay system	County	Period of record
08189200	Copano Creek near Refugio	87.8	Copano	Refugio	1971–
08189500	Mission River at Refugio	690	Copano	Refugio	1940–
08189700	Aransas River near Skidmore	247	Copano	Bee	1964–
08189800	Chiltipin Creek at Sinton	128	Copano	San Patricio	1971–91
08211000	Nueces River near Mathis	16,700	Nueces and Corpus Christi	San Patricio	1940–
08211520	Oso Creek at Corpus Christi	90.3	Nueces and Corpus Christi	Nueces	1973–

NWS station number	Station name	County	Years of data	Period of record	Mean annual rainfall (in) [1]
436	Austwell	Refugio	52	1897–1960	33.46
[2]305	Aransas Wildlife Refuge	Aransas	54	[3]1940–93	40.46
[2]7533	Refugio 7 North	Refugio	46	[3]1948–93	40.27
[2]7704	Rockport	Aransas	62	[3]1901–93	36.74
639	Beeville 5 North-East	Bee	92	[3]1901–93	31.42
9717	Whitsett	Live Oak	79	[3]1914–93	27.33
9009	Three Rivers	Live Oak	66	1922–87	26.42
3508	George West 2 SSW	Live Oak	78	[3]1916–93	27.63
[2]8354	Sinton	San Patricio	69	[3]1921–93	32.85
9031	Tilden	McMullen	46	[3]1903–93	24.02
[2]2015	Corpus Christi WSO AP	Nueces	46	[3]1948–93	29.94
[2]7677	Robstown	Nueces	54	[3]1922–93	30.79
3341	Freer	Duval	47	[3]1947–93	24.08
689	Benavides 2	Duval	54	[3]1940–93	24.05
[2]4810	Kingsville	Kleberg	77	[3]1902–93	26.62
7580	Ricardo	Kleberg	67	1909–75	25.26
3063	Falfurrias	Brooks	87	[3]1907–93	24.33
[2]8081	Sarita 7 East	Kenedy	94	[3]1900–93	27.19
[2]144	Alice	Jim Wells	77	[3]1911–93	26.85

NWS station number	Station name	County	Years of data	Period of record	Mean annual evaporation (in) [1]
[2]639	Beeville 5 North-East	Bee	15	[3]1979–93	3.15
[2]1720	Choke Canyon Dam	Live Oak	11	[3]1983–93	81.20

[1] For period of record indicated.
[2] Station used for simulation.
[3] Station active as of 1996.

III. METHODS OF ANALYSIS

If the majority of streams that flow into the bays of the CCBNEP study area had streamflow-gaging stations close to the points of stream entry into the bay systems, estimating freshwater inflows to the bay systems primarily would be a matter of summing the gaged flows. However, in 1997 only four continuous[1] streamflow-gaging stations measure flow in the adjacent contributing watersheds of the study area (Table II.1; Fig. II.1), which leaves a substantial part of the watersheds (about 77 percent) ungaged. The Nueces River near Mathis is not included here because its flow originates upstream of the adjacent contributing watersheds. Accordingly, watershed simulation was used to generate simulated flow (runoff) to the bay systems in the CCBNEP study area because adequate gaged streamflow data are not available.

Watershed Simulation

The general approach in using a watershed simulation model to estimate runoff (and the approach used in this study[2]) is to adjust selected input parameters (meteorologic and hydrologic properties and conditions that control runoff) in a series of simulations for a gaged area until an adequate match between model-generated flows and some set (time series) of gaged flows is achieved. The process of obtaining a match between model output and gaged data is called calibration, or history matching. The calibration can be tested by simulating a different set of gaged flows for the calibration area than were used for the calibration. Once the model is adequately calibrated for a gaged area, the model can be used to estimate flows from ungaged areas with climatic and hydrologic characteristics similar to those of the gaged area.

The HSPF watershed simulation model (Bicknell and others 1993) applied in this study is a comprehensive, continuous (in time) model designed to simulate all the water-quantity and water-quality processes that occur in a watershed. The model, which was used to simulate only water-quality processes in this study, represents the various hydrologic processes as flows and storages and maintains a water budget by solving the equation, runoff equals rainfall minus evapotranspiration plus change in storage. Accordingly, the primary input is rainfall and evaporation data, and the output is a time series of runoff. Spatial variability of properties and conditions in the simulated area is accounted for by dividing the area into hydrologically similar segments and simulating runoff for each segment independently—that is, using different input parameters for each segment. Land areas that have enough infiltration capacity to influence the water budget are considered pervious; otherwise they are considered impervious. Pervious and impervious areas are simulated independently because the hydrologic processes that occur on each are not the same: Pervious areas can have precipitation, overland flow, shallow subsurface

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[1] In addition, two low-flow streamflow-gaging stations are located on the Nueces River downstream of the Nueces River near Mathis station (Figure VII.1).

[2] A watershed model was used in this study only to obtain average runoff. Estimating the frequency of wet or dry periods on the basis of an analysis of the distributional characteristics of annual or seasonal simulated runoff is not appropriate with a watershed model because the distributional characteristics of simulated flow often convey little information about the distributional characteristics of actual flow.

flow (interflow), ground-water flow, and evapotranspiration; whereas impervious areas can have precipitation, overland flow, and evaporation.

The parts of the CCBNEP study area that contribute freshwater to bay systems were divided for simulation into 13 watersheds (Table I.1; Fig. III.1) on the basis of drainage characteristics. Data from 10 of the 19 long-term rainfall stations (Table II.1; Fig. III.1) were used for simulation. Four of the 19 stations are too far from the simulated area and 5 of the 19 have too much missing data. Rainfall was distributed over the simulated area using the Thiessen method (Linsley and others 1975). Data from both evaporation stations (Table II.1; Fig. III.1) were used.

Model Calibration

Model calibration was done for the gaged areas of three watersheds—Copano Creek and Aransas River, which drain into the Copano Bay system; and Oso Creek, which drains into the Nueces and Corpus Christi Bay system (Fig. III.1). These watersheds were selected for calibration primarily because of the availability of gaged continuous streamflow data; and also the proximity of meteorologic data-collection sites with continuous data. The objective of the calibrations was to match simulated annual, winter (January, February, March), and summer (July, August, and September) streamflow volumes to gaged annual and seasonal streamflow volumes. (The software used to calibrate the model does not produce calibration statistics for spring and fall.) Through the calibration process, confidence was developed in the resulting basin parameters that were to be applied in simulations of ungaged watersheds. In each watershed, at least 10 years of data were used for calibration. The calibration period for the Copano Creek watershed is 14 years, January 1971–December 1984; 12 years for the Aransas River watershed, January 1975–December 1986; and 11 years for the Oso Creek watershed, January 1981–December 1991. These calibration periods were selected to coincide with available periods of continuous meteorologic and streamflow record (periods with minimal missing record) and to be as close as possible to the period of available land-use data (1973). The model does not account for land-use changes during the calibration periods. Daily rainfall and evaporation data (from which evapotranspiration is estimated) were entered into the model to simulate daily runoff.

A drawback of the HSPF model is that large data sets are required for calibration. To ease the process, an expert system software for handling HSPF parameters is available (Lumb and others 1994) and was used in this study. The expert system software, called HSPEXP, prompts the modeler according to a set of hierarchical rules designed to guide calibration of the model through a systematic evaluation of model parameters. Various watershed parameters—for example, retention storage capacity of soil; infiltration capacity of soil; length and slope of overland flow plane; and parameters that affect water storage, evapotranspiration, and base-flow recession rate—were adjusted to achieve adequate calibration.

Return and diversion flows were not simulated in the model because (1) the available return and diversion flow data are aggregated monthly rather than daily, (2) the pre-1977 return and diversion flow data are not considered compatible with the post-1976 data, and (3) the projected

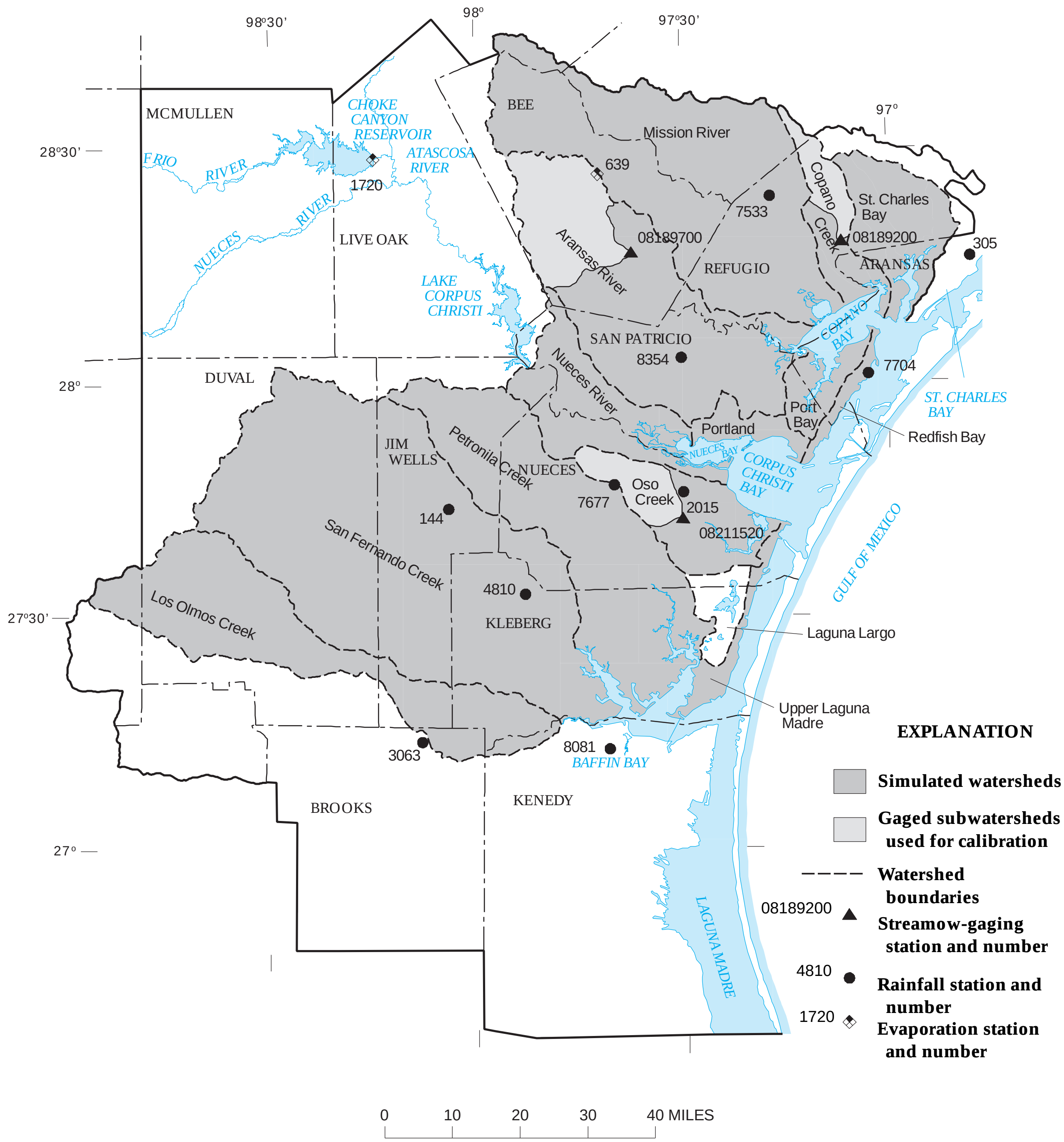

Figure III.1. Simulated watersheds, subwatersheds, and streamow-gaging stations used for calibration, and rainfall and evaporation gages used for calibration and simulation, Corpus Christi Bay National Estuary Program study area, Texas.

future return and diversion flow data are unknown. Monthly net differences between return and diversion flows (net defined as return minus diversion) computed from return and diversion flow data that were compiled by the TWDB (W.L. Longley, Texas Water Development Board, written communication, unreferenced) were added to simulated monthly streamflow volumes to estimate freshwater inflows.

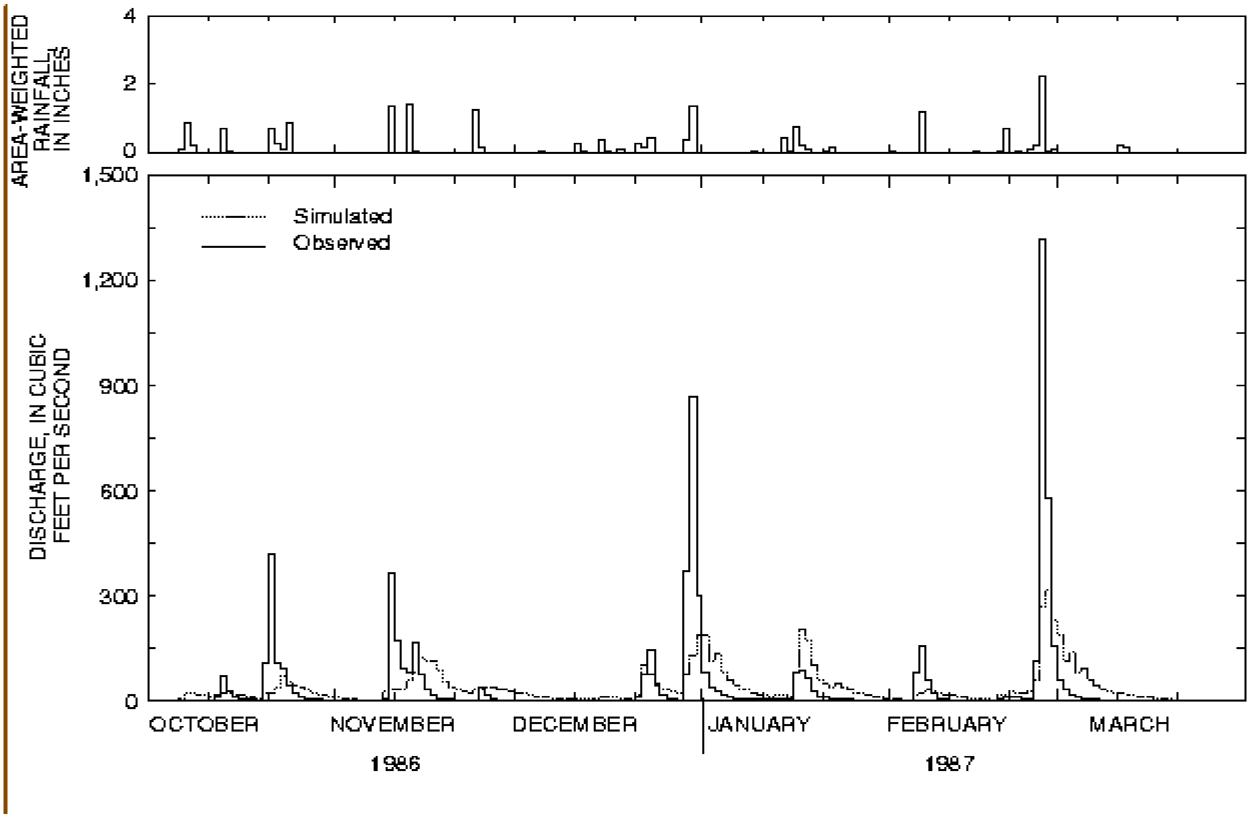

Figure III.2. Simulated and observed daily mean discharge for streamflow-gaging station Oso Creek at Corpus Christi (08211520), Corpus Christi Bay National Estuary Program study area, October 1986–March 1987.

The calibration of the Oso Creek watershed was tested by simulating runoff for the period January 1975–December 1985. The calibrations of the Copano Creek and Aransas River watersheds were not tested by simulating periods different from the calibration periods because the quality of the calibrations (the match between simulated and measured annual and winter streamflow volumes) for those watersheds was judged to be similar to that for the Oso Creek watershed.

Close calibrations of annual and winter streamflow volumes were achieved in each of the three watersheds (Table III.1). Calibrations of summer streamflow volumes are not as close; simulated summer volumes are larger than measured volumes in all three watersheds. The matches between simulated and measured magnitudes of storm peak flows (peaks) are close for the Copano Creek watershed, but not close for the Aransas and Oso (Fig. III.2) watersheds. Typically, the magnitudes of simulated storm peaks are substantially less than the measured magnitudes for Aransas and Oso; and the simulated peaks often lag (in time) the measured peaks in all three watersheds.

Several factors can account for the differences in simulated and measured flow conditions. Inherent error is a part of any hydrologic model because complex processes (for example, evapotranspiration) are simplified so they can be represented mathematically in the model. The

Table III.1. Calibration statistics—simulated and observed flow characteristics—for the Copano Creek, Aransas River, and Oso Creek watersheds, Corpus Christi Bay National Estuary Program study area

[winter comprises January, February, March; summer comprises July, August, September (the expert system software used for calibration does not produce statistics for spring or fall); mi^2, square miles; in/yr, inches per year; ft^3/s, cubic feet per second; ΔQ/t, change in discharge per unit time; --, not available]

Copano Creek
Gaged drainage area: 87.8 mi^2
Calibration period: 14 years, January 1971–December 1984

	Simulated	Measured
Mean annual runoff (in/yr)	5.6	5.4
Largest 10 percent of flows (in/yr)	5.4	4.9
Smallest 50 percent of flows (in/yr)	.01	0
Mean winter runoff (in/yr)	.60	.59
Mean summer runoff (in/yr)	2.2	1.2
Average of storm peaks for calibration period (ft^3/s)	211	220
Average base-flow recession rate for calibration period (ΔQ/t)	.94	.83
Mean annual evapotranspiration (in/yr)	32	--

Aransas River
Gaged drainage area: 247 mi^2
Calibration period: 12 years, January 1975–December 1986

	Simulated	Measured
Mean annual runoff (in/yr)	1.1	1.2
Largest 10 percent of flows (in/yr)	.90	.91
Smallest 50 percent of flows (in/yr)	.01	.08
Mean winter runoff (in/yr)	.15	.17
Mean summer runoff (in/yr)	.65	.37
Average of storm peaks for calibration period (ft^3/s)	196	685
Average base-flow recession rate for calibration period (ΔQ/t)	.64	.94
Mean annual evapotranspiration (in/yr)	32	--

Oso Creek
Gaged drainage area: 90.3 mi^2
Calibration period: 11 years, January 1981–December 1991

	Simulated	Measured
Mean annual runoff (in/yr)	3.2	3.3
Largest 10 percent of flows (in/yr)	2.2	2.9
Smallest 50 percent of flows (in/yr)	.13	.11
Mean winter runoff (in/yr)	1.1	.96
Mean summer runoff (in/yr)	.74	.65
Average of storm peaks for calibration period (ft^3/s)	101	323
Average base-flow recession rate for calibration period (ΔQ/t)	.89	.91
Mean annual evapotranspiration (in/yr)	30	--

complex spatial distributions of parameters necessitate simplification for input to the model. The spatial distribution of rainfall is crude compared to the actual distribution. How well the calibrated parameters represent conditions in the ungaged watersheds is unknown. The specific factors that cause the less-than-ideal match between simulated and measured summer streamflow volumes, and between simulated and measured storm peaks, are not known. The model as calibrated is judged acceptable for providing gross estimates of annual and winter runoff volumes for ungaged watersheds in the study area. However, the ability of the model as calibrated to provide adequate estimates of runoff volumes in the other seasons is questionable.

Application of Calibrated Model

Simulations were done to obtain runoff under current, predevelopment, and future land-use conditions for estimating freshwater inflows and for comparing runoff under the three land-use conditions; and to obtain time series of runoff from which to estimate time series of freshwater inflows for trend analysis. Runoff (excluding return and diversion flows) from each of the watersheds of the CCBNEP study area (Fig. III.1) was simulated by using basin-specific measured or estimated parameters and calibrated parameters from 1 of the 3 calibrated watersheds. The decision as to which of the three sets of calibrated parameters to use in a particular watershed was made on the basis of similarity in watershed characteristics between a calibrated watershed and the particular watershed.

The assumption was made that the principal factor responsible for change in freshwater inflows (other than changes in climatic conditions, return and diversion flows, and reservoirs) is change in the amount of urban area. Tillage practices associated with agricultural development probably have reduced runoff to some extent, but no practical way to quantify the reduction was available within the scope of the project. Thus, "predevelopment" actually means "pre-urbanization."

Three sets of simulations driven by daily rainfall for the period 1968–93 were done in which the amount of urban area in each watershed (except in the virtually undeveloped St. Charles Bay watershed, the eastern part of which is the western part of the Aransas National Wildlife Refuge) was estimated to represent current, predevelopment, and future land-use conditions. To estimate the amount of urban area under current conditions, the urban area on the 1973 land-use map in and around Corpus Christi and other parts of the study area where appreciable development has occurred since 1973 (primarily near the coast) was increased on the basis of urban development shown on recent (early 1990s) city maps. For the simulations of predevelopment conditions, all urban area was removed. For the simulations of future conditions, the urban area estimated for current conditions in the simulated watersheds was increased on the basis of county population projections from 1990 to 2010 (Texas Natural Resource Conservation Commission 1994, Appendix D). It was assumed that development, hence urban area, increases at about the same rate as population. Because watersheds are not coincident with counties, the increase in urban area in each watershed was computed as an area-weighted average of the projected population increases in the counties that are in part coincident with the watershed.

The estimated amount of urban area of the simulated watersheds under current conditions is small, about 3.3 percent of the area of all watersheds combined (Table III.2). After an average 20-percent increase in the urban area of the watersheds to represent future conditions, the estimated amount of urban area under future conditions is still small, about 4.0 percent of the area of all watersheds combined.

Table III.2. Amount of urban area of calibrated and simulated watersheds, Corpus Christi Bay National Estuary Program study area

[current, 1983–93; future, 2010; --, not applicable]

Watershed	Total area (acres)	Urban area (acres)				
		Current/percent of total		Predevelopment	Future/percent increase	
Gaged/calibrated						
Copano Creek	46,000	1,920	4.2	--	--	--
Aransas River	155,000	5,090	3.3	--	--	--
Oso Creek	60,700	5,780	9.5	--	--	--
Ungaged/simulated						
St. Charles Bay	131,000	negligible	--	--	--	--
Copano Creek	85,500	2,280	2.7	0	2,850	25
Mission River	580,000	11,200	1.9	0	14,000	25
Aransas River	613,000	15,500	2.5	0	17,800	15
Port Bay	57,400	3,750	6.5	0	4,430	18
Redfish Bay	22,400	6,040	27	0	7,550	25
Nueces River	189,000	6,460	3.4	0	7,620	18
Portland	43,200	5,500	13	0	6,550	18
Oso Creek	175,000	52,400	30	0	61,300	17
Upper Laguna Madre	39,400	1,650	4.2	0	2,060	25
Petronila Creek	422,000	2,880	.68	0	3,860	34
San Fernando Creek	1,060,000	19,100	1.8	0	23,500	23
Los Olmos Creek	419,000	1,500	.36	0	1,860	24
Total	3,840,000	128,000	3.3	0	153,000	20

Estimation of Freshwater Inflows

To estimate freshwater inflows to each of the six bay systems, the simulated daily runoff (excluding return and diversion flows) under current land-use conditions for each watershed was aggregated by month for 1983–93. The 1983–93 period was selected because that period is after impoundment of Choke Canyon Reservoir, which, as will be discussed later in the report, appreciably affects freshwater inflows. The 1983–93 period is thus a period (1) of equal length for each of the six bay systems that receive inflow, (2) of consistent flow conditions long enough to average annual variability and (to a lesser extent[1]) seasonal variability, and (3) recent enough to represent "current" conditions. Monthly net differences between return and diversion flows (net defined as return minus diversion) for 1983–93 computed from return and diversion flow data compiled by the TWDB (W.L. Longley, Texas Water Development Board, written communication, unreferenced) were added to the monthly simulated flows. The monthly sums of simulated runoff and net return and diversion flow were aggregated annually and seasonally by

[1] Annual streamflows intrinsically contain more data than seasonal streamflows. Therefore annual averages are expected to be more accurate than seasonal averages.

bay system and computed mean flows. For the Nueces and Corpus Christi Bay system, monthly streamflow measured at the streamflow-gaging station Nueces River near Mathis was added to the 1983–93 monthly simulated flows and net return and diversion flows before aggregating annually and seasonally and computing mean flows to account for the inflow to the Nueces and Corpus Christi Bay system that originates upstream of the adjacent contributing watersheds. The mean annual and mean seasonal inflows for 1983–93 are considered current inflows.

Analysis of Trends

A statistical test, the Mann-Kendall test (Helsel and Hirsch 1992; Hollander and Wolfe 1973), was used to determine whether gaged and simulated freshwater inflows have historical trends[4] with time. The Mann-Kendall test is a nonparametric, rank-based, two-sided (for this application[5]) hypothesis test. That is, no assumption of normally distributed data is required, and the test is based on the ranks of the data rather than the actual data. The data are tested to determine whether a hypothesis (the null hypothesis) about the data that there is no trend can be substantiated by the strength of the evidence provided by the data. The outcome of the test is a [6]decision to reject or not to reject the null hypothesis in favor of an alternate hypothesis, which is that there is either an upward or downward trend. The decision to reject the null hypothesis in favor of the alternate hypothesis is made on the basis of the p-value[6] from the test. The p-value indicates the strength of the evidence against the null hypothesis, which is that there is no trend—the smaller the p-value, the stronger the evidence. Accordingly, p-values are documented in the report to allow the reader to judge the strength of the evidence. When deciding whether to reject the null hypothesis, the following should be considered: If the null hypothesis is true, then the probability of obtaining the computed test statistic (the test yields a test statistic), or one even less likely, is equal to the p-value. So if the p-value is small, say 0.08, then there is a good chance (92 in 100) that the null hypothesis is not true; thus, it might be reasonable to reject it. Commonly, p-values less than about 0.05 are considered strong evidence that the hypothesis of no trend should be rejected. Failing to reject the null hypothesis does not prove that there is no trend; it just means that the evidence available is not sufficient to conclude that there is a trend (Helsel and Hirsch 1992, p 325).

The Mann-Kendall test also yields a correlation coefficient, Kendall's tau. Tau is a measure of the strength of a trend (strength of the correlation between discharge and time). The sign of tau

[4] "Trend" in the context of this report means "statistically significant trend." Thus, a conclusion of "no trend" actually means "no statistically significant trend."

[5] A two-sided hypothesis test applies because the data are equally likely to have an upward or downward trend. A one-sided test would apply if it is suspected beforehand that either an upward or downward trend is more likely.

[6] The p-value is the "attained significant level" (the significance level attained by the data), which is the probability of obtaining the computed test statistic, or one even less likely, when the null hypothesis is true (Helsel and Hersch 1992, p 108).

indicates the direction of the trend: A positive tau indicates an upward trend, and a negative tau indicates a downward trend.

Trend tests were done on time series of annual and seasonal volumes of gaged streamflow. Trend tests on streamflow from the two long-term stations, Mission River at Refugio and Nueces River near Mathis (Table II.1; Fig. II.1), were done for the periods of complete-year record, both 1940–1996. Trend tests were done on period-of-record streamflow for each of, and the composite of, four streamflow-gaging stations considered to be upstream of Choke Canyon Reservoir in the greater Nueces River Basin; for Copano Creek near Refugio streamflow for 1971–93; for Aransas River near Skidmore streamflow for 1968–93; and for Oso Creek at Corpus Christi streamflow for 1973–93. Trend tests were not done on data from the discontinued gaging station Chiltipin Creek at Sinton because the station was used to gage flow to the Copano Bay system; and 3 of the 5 trend tests done are on gaged flow to the Copano Bay system.

Trend tests were done on time series of annual and seasonal volumes of rainfall for three "index" stations—that is, a station in the northern part of the study area (Refugio 7 North), a station in the middle part (Corpus Christi WSO AP), and a station in the southern part (Sarita 7 East)—for comparison of results to those of trend tests on streamflow.

Trend tests were done on time series of annual and seasonal volumes of inflow for each receiving bay system for 1977–93. To obtain time series of inflows for trend analysis, the two components of inflow—simulated runoff and net return and diversion flow, and gaged Nueces River flow near Mathis for the Nueces and Corpus Christi bay system—were aggregated annually and seasonally for 1977–93. The 1977–93 period was selected because (1) pre-1977 return and diversion data are considered not compatible with post-1976 return and diversion data, and (2) the authors believe the trade-off between the shorter but consistent (all post-Choke Canyon Reservoir Nueces River flow) 1983–93 period and the longer but inconsistent (some pre- and some post-Choke Canyon Reservoir Nueces River flow) 1977–93 period favors the longer period.

Trend tests were done on time series of annual and seasonal volumes of net return and diversion data for 1977–94 for comparison of results to those of trend tests on inflow.

IV. STATUS OF FRESHWATER INFLOWS

The estimated current (1983–93) mean annual freshwater inflow to all six bay systems combined is 1,200,000 acre-ft/yr (Table IV.1). About 26 percent of that amount is flow that originates upstream of the adjacent contributing watersheds, as measured at the Nueces River near Mathis streamflow-gaging station. About 74 percent is a combination of runoff that originates in the adjacent contributing watersheds and net return and diversion flows; net return and diversion flows result in a loss of freshwater inflow of about 4 percent. The Copano Bay system has the

Table IV.1. Estimated mean annual and seasonal freshwater inflows to bay systems in the Corpus Christi Bay National Estuary Program study area, 1983–93

[winter, January, February, March; spring, April, May, June; summer, July, August, September; fall, October, November, December; acre-ft/yr, acre-feet per year; acre-ft/season, acre-feet per season; mi^2, square miles; [6.5], percent of total mean annual for all bay systems combined; (47), percent of mean annual; $ft^3/s•mi^2$, cubic feet per second per square mile. Component inflows and percentages might not equal totals due to rounding.]

Bay system (adjacent contributing watershed area)	Mean annual inflow (acre-ft/yr)	Mean winter inflow (acre-ft/ season)	Mean spring inflow (acre-ft/ season)	Mean summer inflow (acre-ft/ season)	Mean fall inflow (acre-ft/ season)
St. Charles (205 mi^2)	77,700 [6.5]	36,200 (47)	10,100 (13)	13,200 (17)	18,200 (23)
Runoff (0.52 $ft^3/s•mi^2$)	7,700	36,200	10,100	13,200	18,200
Return flow minus diversion flow[1]	20	5	5	5	5
Copano (2,090 mi^2)	634,000 [53]	199,000 (31)	157,000 (25)	107,000 (17)	171,000 (27)
Runoff (0.42 $ft^3/s•mi^2$)	632,000	198,000	156,000	107,000	171,000
Return flow minus diversion flow[1]	2,120	554	540	507	516
Redfish (35.0 mi^2)	11,300 [.9]	3,320 (29)	2,710 (24)	2,520 (22)	2,710 (24)
Runoff (0.41 $ft^3/s•mi^2$)	10,300	3,060	2,460	2,270	2,460
Return flow minus diversion flow[1]	1,010	259	252	248	250
Nueces and Corpus Christi (636 mi^2)	378,000 [31]	81,200 (21)	160,00 (42)	74,100 (20)	63,100 (17)
Nueces River near Mathis inflow	314,000	56,800	139,000	68,200	49,600
Runoff (0.27 $ft^3/s•mi^2$)	124,000	36,300	37,000	24,900	27,000
Return flow minus diversion flow[1]	-60,400	-11,900	-16,000	-19,000	-13,500
Upper Laguna Madre (61.5 mi^2)	4,850 [.4]	1,380 (28)	1,470 (30)	945 (19)	1,050 (22)
Runoff (0.095 $ft^3/s•mi^2$)	4,240	1,220	1,310	805	903
Return flow minus diversion flow[1]	611	161	163	140	147
Baffin (2,980 mi^2)	98,100 [8.2]	46,300 (47)	24,300 (25)	10,000 (10)	17,600 (18)
Runoff (0.042 $ft^3/s•mi^2$)	90,900	44,600	22,400	8,180	15,800
Return flow minus diversion flow[1]	7,180	1,720	1,870	1,820	1,770
Totals (6,000 mi^2)	1,200,000	365,000 (30)	356,000 (30)	208,000 (17)	274,000 (23)
Nueces River near Mathis inflow	314,000	56,800	139,000	68,200	49,600
Runoff (0.22 $ft^3/s•mi^2$)[2]	938,000	317,000	230,000	156,000	235,000
Return flow minus diversion flow[1]	-51,500	-9,200	-13,200	-16,600	-10,800

[1] Net return and diversion flows are means for 1977–94.
[2] Area-weighted average.

largest share of the total inflow to the bay systems, about 53 percent (Fig. IV.1). The Nueces and Corpus Christi Bay system has the next largest share, about 32 percent—most of which (about 83 percent) is streamflow that originates outside the adjacent contributing watersheds.

Runoff on a per-unit-area basis is largest for the watersheds of the St. Charles Bay system [0.52 cubic foot per second per square mile ($ft^3/s•mi^2$)] and smallest for the watersheds of the Baffin Bay system (0.042 $ft^3/s•mi^2$). Runoff per square mile decreases appreciably in a southwesterly

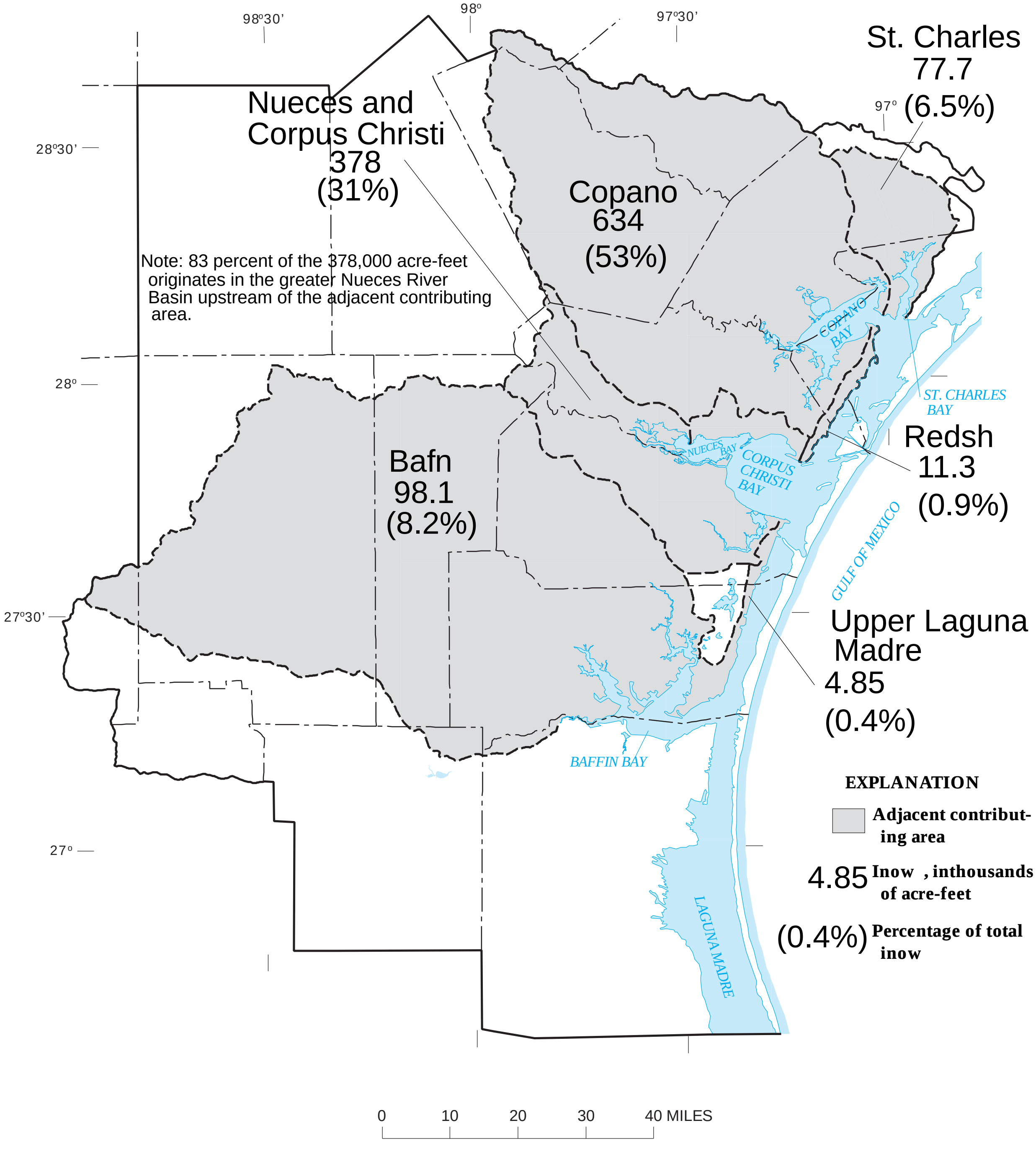

Figure IV.1. Estimated annual freshwater inows to bay systems, Corpus Christi Bay National Estuary Program study area, Texas.

direction across the study area, which reflects the decrease in annual rainfall in that direction, the generally flatter topography in the southwestern part of the study area, and the generally more permeable soils in the southernpart of the study area than in the northern part.

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Return flows exceed diversion flows in the watersheds of the Copano, Redfish, upper Laguna Madre, and Baffin Bay systems. The excess of return flows over diversion flows to these bay systems could be accounted for by ground-water pumpage that ultimately becomes runoff and (or) inaccuracies in the data base of return and diversion flows. In the watersheds of the Nueces and Corpus Christi Bay system, which have by far the largest net difference between return and diversion flows, diversion flows exceed return flows. Consumption of water by municipal and industrial users in the greater Corpus Christi area and agricultural users in rural areas reduces freshwater inflow to the Nueces and Corpus Christi Bay system by about 14 percent from what it would be without return and diversion flows. Net return and diversion flow is negligible in the undeveloped watershed of the St. Charles Bay system.

Seasonal flows, and thus the percentages of annual inflow that occur in each season, are highly variable (more variable than annual totals) and depend on the period of record for which mean flows are computed. Therefore, the seasonal percentages of annual inflow shown for 1983–93 (Table IV.1) might not be representative of long-term seasonal percentages. The smaller percentages of annual inflow to the Nueces and Corpus Christi Bay system in winter and fall, and the larger percentage in spring, than to the other bay systems could be the result of streamflow regulation at Lake Corpus Christi and Choke Canyon Reservoir. Winter and fall generally are the seasons of least and next-to-least rainfall; it is likely that proportionately more of the greater Nueces River Basin flow is retained in the reservoirs for water supply during the drier seasons, and proportionately less is retained during the generally wetter spring and summer seasons.

V. TRENDS IN FRESHWATER INFLOWS

Trends in Gaged Streamflows

On average, gaged streamflows account for about 40 percent of estimated total freshwater inflow to the bay systems of the study area. Because time series of gaged streamflows reflect the combined effects of climatic variations and changes and human activities on runoff, the results of trend tests on gaged streamflows can be an accurate, although partial, indicator of changes in freshwater inflows with time. Complete-year records for the two long-term streamflow-gaging stations, Mission River at Refugio and Nueces River near Mathis, begin in 1940. Mann-Kendall trend tests on 1940–96 time series of annual and mean seasonal streamflow volumes for both stations show somewhat different results (Table V.1). The Mission River at Refugio data show no strong evidence for a trend in annual streamflow for the 57-year period. The winter data show some indication of an upward trend, but the evidence (p-value = 0.084) is not considered strong enough to conclude with certainty that there is a trend. Streamflow data for the other seasons do not indicate trends.

Trend tests on time series of annual and seasonal rainfall data for three "index" stations for 1968–93 show little evidence for trends (Table V.2). The Refugio 7 North winter rainfall data show some evidence of an upward trend (p-value = 0.071), and the Corpus Christi WSO AP

Table V.1. Results of trend analyses on time series of annual and seasonal gaged streamflow, Corpus Christi Bay National Estuary Program study area

["maybe" means some evidence against "no trend" hypothesis but decision is considered uncertain]

Station name (time series tested)	Time period	p-value (Is there a trend?)	Kendall's tau (direction of trend)
Mission River at Refugio (1940–96)	Annual	0.150 (no)	
	Winter	.084 (maybe)	0.158 (upward)
	Spring	.179 (no)	
	Summer	.885 (no)	
	Fall	.162 (no)	
Nueces River near Mathis (1940–96)	Annual	.024 (yes)	-.206 (downward)
	Winter	.001 (yes)	.296 (upward)
	Spring	.437 (no)	
	Summer	.143 (no)	
	Fall	.989 (no)	
Copano Creek near Refugio (1971–93)	Annual	.369 (no)	
	Winter	.196 (no)	
	Spring	.616 (no)	
	Summer	.096 (maybe)	-.253 (downward)
	Fall	.077 (maybe)	-.269 (downward)
Aransas River near Skidmore (1968–93)	Annual	.928 (no)	
	Winter	.064 (maybe)	.261 (upward)
	Spring	.860 (no)	
	Summer	.290 (no)	
	Fall	.860 (no)	
Oso Creek at Corpus Christi (1973–93)	Annual	.566 (no)	
	Winter	.319 (no)	
	Spring	.695 (no)	
	Summer	.027 (yes)	-.352 (downward)
	Fall	.216 (no)	

winter rainfall data show stronger evidence of an upward trend (p-value = 0.050). Results of a trend test on Mission River winter streamflow for 1968–93 (not shown in Table V.1), the same period as the rainfall time series, show an upward but insignificant trend. Trend-test results for the Mission River annual and spring, summer, and fall time series for 1968–93 (not shown in Table V.1) are consistent with the results of trend tests on time series of annual and seasonal rainfall data for the Refugio 7 North and the Corpus Christi WSO AP stations.

The Nueces River near Mathis data show strong evidence (p-value = 0.024) for a downward trend in annual streamflow for the 57-year period. Although Table V.1 shows no trend for spring, summer, or fall streamflow, Kendall's tau for each of those seasons (not shown in Table V.1) is negative. The three seasons thus have nonsignificant but downward trends which, taken together, probably result in the significant downward trend in annual streamflow.

Table V.2. Results of trend analyses on time series of annual and seasonal rainfall for three "index" stations, Corpus Christi Bay National Estuary Program study area

["maybe" means some evidence against "no trend" hypothesis but decision is considered uncertain]

Station name (time series tested)	Time period	p-value (Is there a trend?)	Kendall's tau (direction of trend)
Refugio 7 North (1968–93)	Annual	0.311 (no)	
	Winter	.071 (maybe)	0.255 (upward)
	Spring	.454 (no)	
	Summer	.172 (no)	
	Fall	.628 (no)	
Corpus Christi WSO AP (1968–93)	Annual	.251 (no)	
	Winter	.050 (yes)	.277 (upward)
	Spring	.860 (no)	
	Summer	.064 (maybe)	-.262 (downward)
	Fall	.860 (no)	
Sarita 7 East (1968–93)	Annual	.826 (no)	
	Winter	.311 (no)	
	Spring	.826 (no)	
	Summer	.252 (no)	
	Fall	.290 (no)	

A hydrograph of the annual streamflow time series of the Nueces River near Mathis (Fig. V.1) shows that the downward trend in annual streamflow appears to be more of a "step trend" than a linear trend. A noticeable decrease in annual flow after impoundment of Choke Canyon Reservoir in 1982 is confirmed by the superposition on the Nueces River near Mathis data of the mean annual flow under three upstream reservoir conditions: (1) 1940–57, Lake Corpus Christi operating as originally impounded in 1934 (mean and median annual flow 619,000 and 459,000 acre-ft/yr); (2) 1958–82, after enlargement of Lake Corpus Christi that began in April 1958 and before impoundment of Choke Canyon Reservoir that began in October 1982 (mean and median annual flow 614,000 and 374,000 acre-ft/yr); and (3) 1983–96, after impoundment of Choke Canyon Reservoir (mean and median annual flow 279,000 and 168,000 acre-ft/yr). The change in annual streamflow after enlargement of Lake Corpus Christi is negligible, but the change in annual streamflow after impoundment of Choke Canyon Reservoir is large. Post-Choke Canyon mean annual streamflow is about 337,000 acre-ft/yr less than pre-Choke Canyon mean annual streamflow, which represents a decrease of about 55 percent.

Another way to illustrate the post-Choke Canyon decrease in streamflow of the Nueces River near Mathis is to distribute annual streamflows for the entire period of record on the basis of annual nonexceedance probability (Fig. V.2): Only 3 of the 14 post-Choke Canyon annual volumes plot above the entire-period-of-record 50-percent annual nonexceedance probability.

The post-Choke Canyon decrease in mean annual streamflow of the Nueces river near Mathis could be caused by several factors, including a decrease in rainfall in the greater Nueces River Basin, an increase in consumption of water withdrawn from streams or shallow aquifers, changes in land use that decrease runoff, and an increase in water storage and evaporation due to Choke

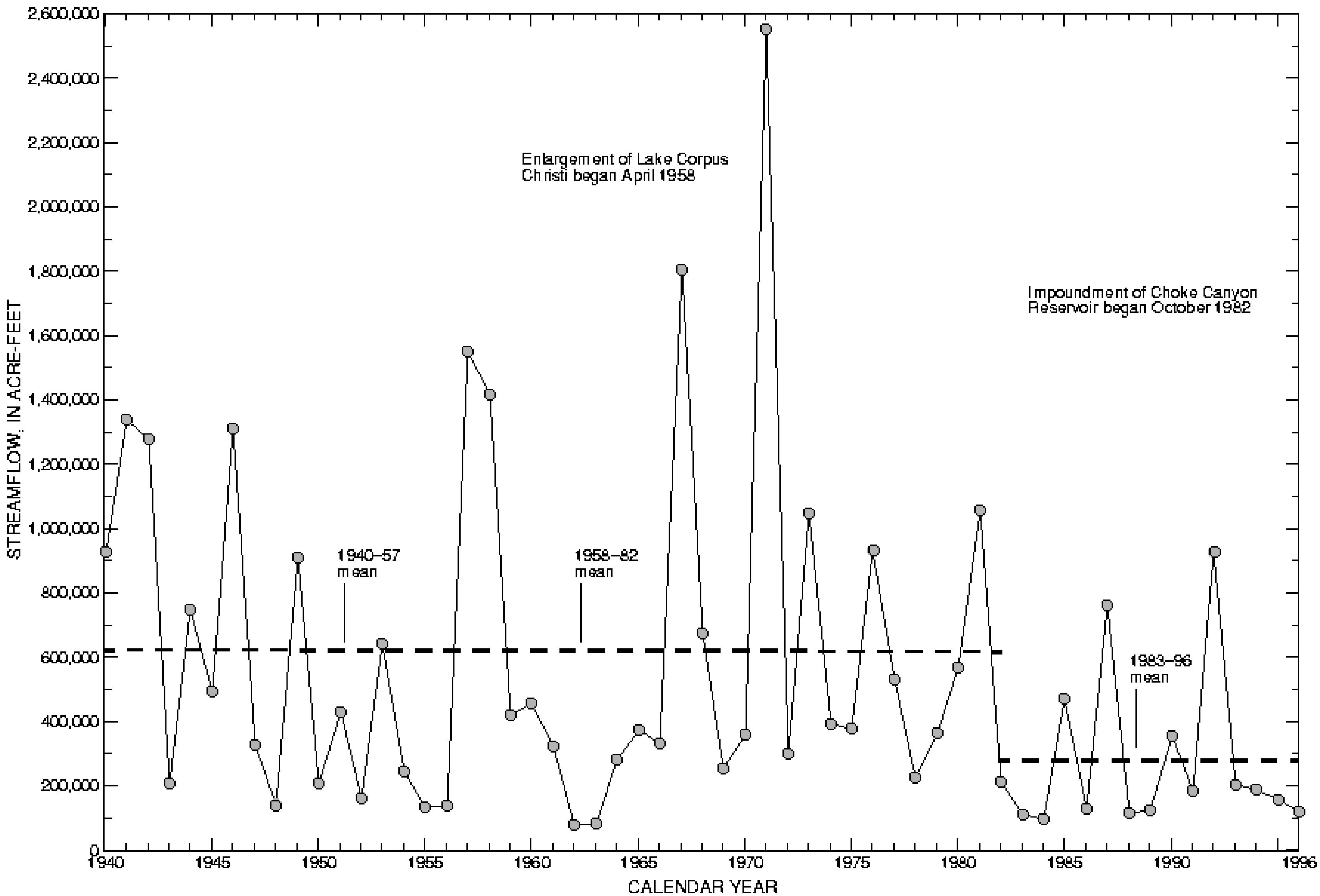

Figure V.1. Time series of annual streamflow for streamflow-gaging station Nueces River near Mathis (08211000), 1940–96, Corpus Christi Bay National Estuary Program study area.

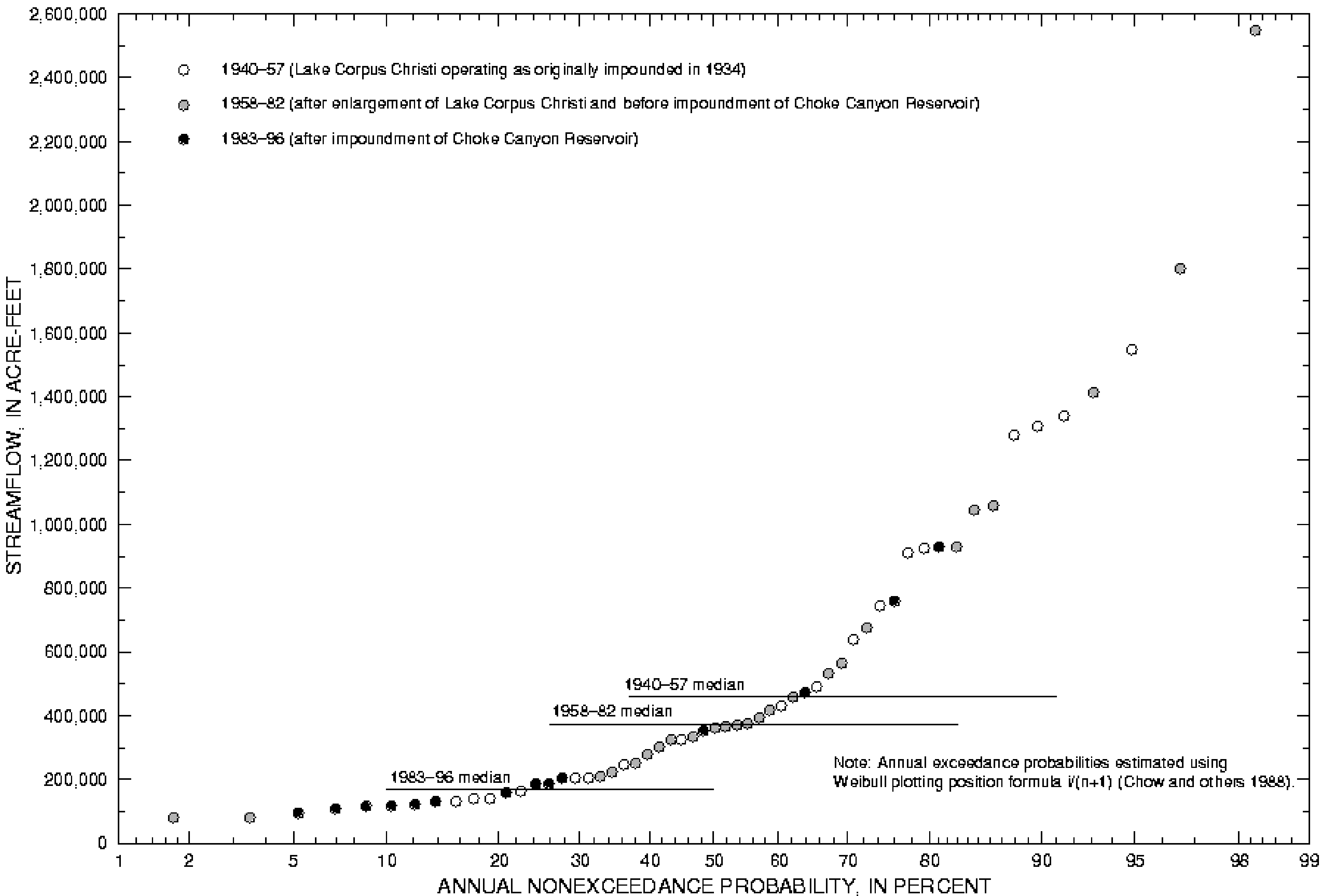

Figure V.2. Distribution of annual streamflow based on annual nonexceedance probability for streamflow-gaging station Nueces River near Mathis (08211000), 1940–96, Corpus Christi Bay National Estuary Program study area.

Canyon. To assess the decrease in mean annual streamflow attributable to storage in Choke Canyon and evaporation from Choke Canyon, a water-budget analysis for Choke Canyon Reservoir was done for the post-impoundment period 1983–96. As a check on the water-budget analysis, an analysis of streamflow in the greater Nueces River Basin was done to compute the streamflow reduction at the Mathis streamflow-gaging station from what would have occurred (according to the assumptions of the analysis) had Choke Canyon not existed during 1983–96. (No water-budget analysis of Lake Corpus Christi was done. Although Lake Corpus Christi has undoubtedly reduced downstream annual Nueces River streamflow from pre-Lake Corpus Christi rates, the reservoir existed throughout the pre- and post-Choke Canyon periods of streamflow record and therefore is assumed not to contribute measurably to the post-Choke Canyon decrease in mean annual streamflow.)

The basis of the 14-year Choke Canyon water budget (Appendix 1) is that the long-term difference between cumulative inflow to and outflow from the reservoir, which represents a reduction in streamflow, equals the change in the volume of water in storage and the estimated evaporation from the reservoir surface. The net change in storage of Choke Canyon Reservoir for 1983–96 is 176,000 acre-ft (12,600 acre-ft/yr). The estimated total evaporation for 1983–96 is 1,210,000 acre-ft (86,600 acre-ft/yr). Summing the two components, the estimated total streamflow reduction due to Choke Canyon for 1983–96 from the water budget is 1,390,000 acre-ft (99,300 acre-ft/yr).

The basis of the streamflow analysis (Appendix 1) is a computation of the difference between the expected annual streamflow of the Nueces River near Mathis without Choke Canyon and the actual streamflow measured near Mathis during the 14-year period. The watersheds of four major streams in the greater Nueces River Basin—the Nueces River, the Frio River, San Miguel Creek, and the Atascosa River (Fig. I.2)—yield most of the streamflow measured in the Nueces River near Mathis. Streamflow-gaging stations on each of these streams—Nueces River near Tilden, Frio River near Derby, San Miguel Creek near Tilden, and Atascosa River at Whitsett—measure flow "upstream" of Choke Canyon Reservoir. (Only the Frio River and San Miguel Creek actually flow into Choke Canyon Reservoir, but all four gaging stations are considered upstream of the reservoir for this analysis.) If Choke Canyon Reservoir were not present, then the composite flow at these four gaging stations (hereafter referred to as composite upstream flow), plus the intervening flow (positive or negative and including change in storage and evaporation from Lake Corpus Christi) between the four upstream gaging stations and the Mathis gaging station, essentially would be the flow measured near Mathis. Accordingly, the expected annual streamflow of the Nueces River near Mathis without Choke Canyon for 1983–96 is estimated by multiplying the annual composite upstream flow times the ratio of the total annual streamflow measured near Mathis to the total annual composite upstream flow for the period 1965–82 (1.05). The cumulative difference between the expected annual streamflow and the actual streamflow measured near Mathis for the 14-year post-Choke Canyon period, 1,340,000 acre-ft (95,800 acre-ft/yr), is the estimated total streamflow reduction due to Choke Canyon from the streamflow analysis during 1983–96. The streamflow reduction due to Choke Canyon computed from the streamflow analysis is within about 4 percent of the streamflow reduction computed from the water-budget analysis (1,390,000 acre-ft).

The estimated reduction in streamflow volume due to Choke Canyon during 1983–96 is about 26 percent of the expected total volume of streamflow that would have been measured near Mathis during the period. In a similar analysis, Greene and Slade (1995, p 49) estimated that the reduction in streamflow measured in the Nueces River near Mathis during 1985–90 was 24 percent of the long-term annual mean streamflow near Mathis. The estimated reduction in streamflow volume of 1,340,000 acre-ft during 1983–96 on an annual basis, about 95,800 acre-ft/yr, only accounts for about 28 percent of the decrease in annual streamflow after impoundment Choke Canyon Reservoir of 337,000 acre-ft/yr; thus other factors besides Choke Canyon must account for some of the decrease. Mann-Kendall trend tests on the entire period of streamflow record for each of the four upstream gaging stations in the greater Nueces River Basin indicate some evidence for downward trends in annual streamflow for the Nueces River near Tilden (p-value = 0.069) and San Miguel Creek near Tilden (p-value = 0.054) (Table V.3). Additionally, the tests indicate some evidence for downward trends in streamflow for one or more seasons for the Nueces River near Tilden, San Miguel Creek near Tilden, and the Atascosa River at Whitsett; and strong evidence for upward trends for winter and fall for the Frio River near Derby. The mean annual composite upstream flow in the greater Nueces River Basin for 1965–82, 651,000 acre-ft/yr, decreased about 45 percent to 351,000 acre-ft/yr for 1983–96. Trend tests on the composite upstream flow for the common period of record for the component stations, 1965–96, indicate strong evidence (p-value = 0.026) for a downward trend in annual streamflow.

Hydrographs of the annual streamflow time series illustrate downward trends in annual streamflow for the Nueces River near Tilden, which represents about 53 percent of the composite upstream flow, and for the composite upstream flow (Fig. V.3). An estimate of the straight-line slope of the trend [Kendall-Theil robust line (Helsel and Hirsch 1992)] superimposed on each hydrograph shows that the downward trend in the composite upstream flow is larger than the downward trend in the Nueces River near Tilden streamflow, which is consistent with the strength of the evidence for trends (p-values) from the respective Mann-Kendall tests (Table V.3). The straight-line slope of the trend in the composite upstream flow is about 9,600 acre-ft/yr, which represents an annual streamflow reduction during 1965–96 of about 1.8 percent per year.

One factor that could account for some of the downward trend in the composite upstream flow is increased surface-water withdrawals in the greater Nueces River Basin. Greene and Slade (1995, Fig. 49) show a long-term (1940–90) time series of reported surface-water withdrawals that indicates an increase in withdrawals of about 60 percent from 1965 to 1990. Another factor that could contribute to the downward trend in streamflow, were it to be confirmed, is a decrease in rainfall. Development of a representative index of rainfall for the greater Nueces River Basin is complex and beyond the scope of this report; however, Greene and Slade (1995, Figs. 41–48) present several rainfall indices (variable start dates but before 1940 through 1990) for large parts of the greater Nueces River Basin. Variable declines in the majority of indices are shown from about 1970 through about 1990; but Greene and Slade (1995, Table 7) report only one long-term downward trend (greater than 3 percent for 50 years of record) in an annual rainfall index developed for the Atascosa River at Whitsett streamflow-gaging station.

Table V.3. Results of trend analyses on time series of annual and seasonal gaged streamflows considered upstream of Choke Canyon Reservoir, greater Nueces River Basin

["maybe" means some evidence against "no trend" hypothesis but decision is considered uncertain]

Station name (time series tested)	Time period	p-value (Is there a trend?)	Kendall's tau (direction of trend)
Nueces River near Tilden (1943–96)	Annual	0.069 (maybe)	-0.171 (downward)
	Winter	.375 (no)	
	Spring	.052 (maybe)	-.182 (downward)
	Summer	.110 (no)	
	Fall	.693 (no)	
Frio River near Derby (1916–96)	Annual	.226 (no)	
	Winter	.008 (yes)	.202 (upward)
	Spring	.729 (no)	
	Summer	.491 (no)	
	Fall	.033 (yes)	.161 (upward)
San Miguel Creek near Tilden (1965–96)	Annual	.054 (maybe)	-.242 (downward)
	Winter	.961 (no)	
	Spring	.168 (no)	
	Summer	.043 (yes)	-.254 (downward)
	Fall	.446 (no)	
Atascosa River at Whitsett (1933–96)	Annual	.631 (no)	
	Winter	.054 (maybe)	-.165 (downward)
	Spring	.421 (no)	
	Summer	.055 (maybe)	-.165 (downward)
	Fall	.279 (no)	
Composite upstream flow[1] (1965–96)	Annual	.026 (yes)	-.278 (downward)
	Winter	.733 (no)	
	Spring	.189 (no)	
	Summer	.140 (no)	
	Fall	.661 (no)	

[1] Composite upstream flow is sum of flows for Nueces River near Tilden, Frio River near Derby, San Miguel Creek near Tilden, and Atascosa River at Whitsett.

The Nueces River near Mathis data show strong evidence (p-value = 0.001) for an upward trend in winter streamflow for the 57-year period. This upward trend could be related to the upward trends in winter and fall streamflow for the Frio River near Derby, although that stream contributes a minor fraction of the streamflow of the Nueces River near Mathis. Whether the trend in Mathis winter streamflow is related to Choke Canyon Reservoir is difficult to determine. Summary statistics for Mathis winter streamflow in acre-feet relative to previously described reservoir conditions are as follows:

1940–57 mean 26,700; median 10,500
1958–82 mean 79,300; median 20,118
1983–96 mean 50,200; median 25,545

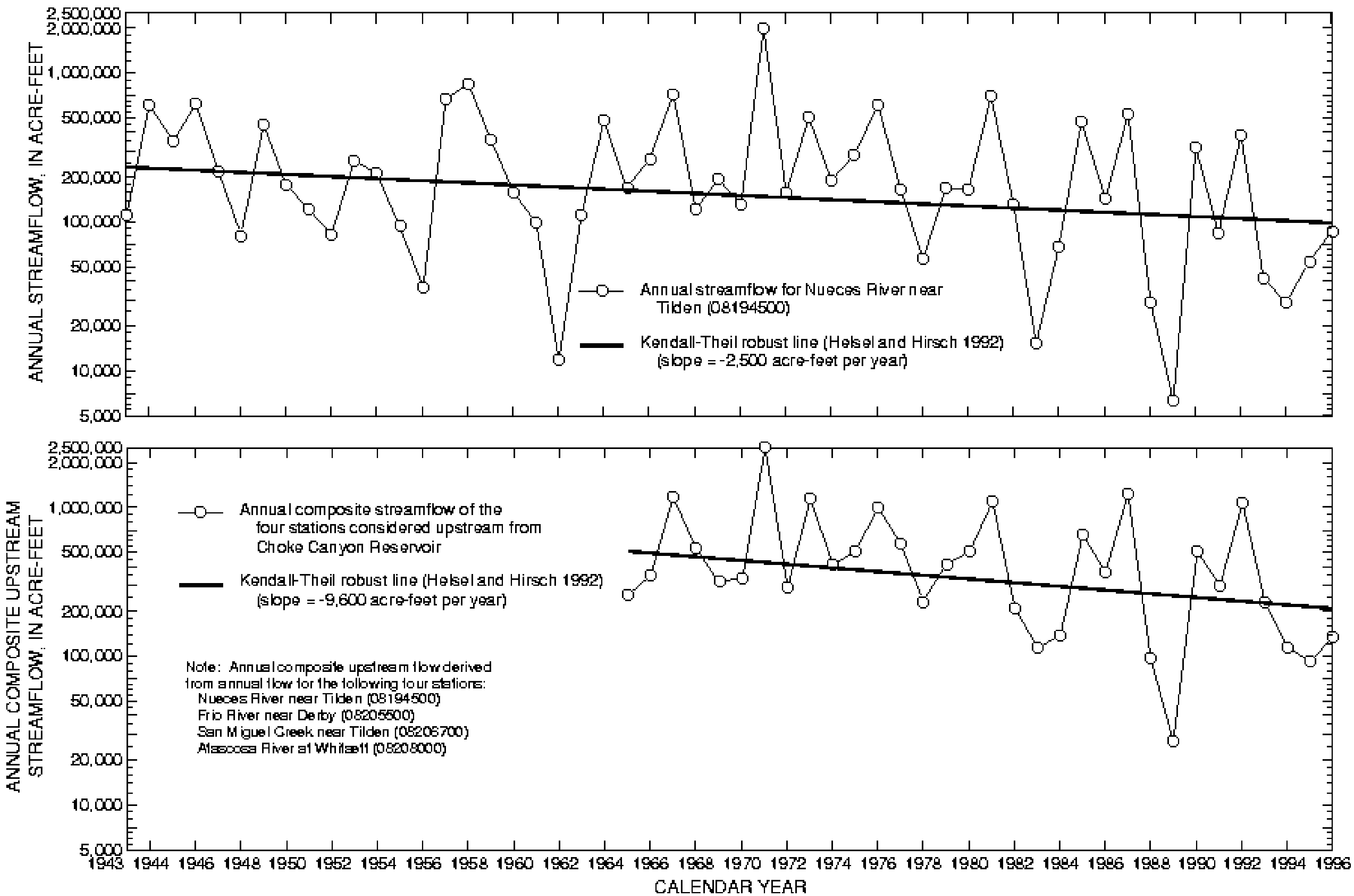

Figure V.3. Time series of annual streamflow for streamflow-gaging station Nueces River near Tilden (08194500), 1943–96, and composite flow from four streamflow-gaging stations considered upstream from Choke Canyon Reservoir, 1965–96, greater Nueces River Basin.

The Mann-Kendall trend test is a rank-based test [and therefore resistant to the effect of a small number of unusual values (outliers)]; the median is a rank-based statistic. Thus the trend-test result is more a reflection of how the medians, rather than the means, change from the first reservoir condition to the second and from the second to the third; but the means more accurately reflect the amount of streamflow—that is, the streamflow expressed as a volume—during the respective periods.

No evidence for trends in annual streamflow volumes is indicated for time-series data for gaging stations Copano Creek near Refugio for 1971–93, Aransas River near Skidmore for 1968–93, and Oso Creek at Corpus Christi for 1973–93. The summer and fall data for Copano Creek near Refugio show some indication of downward trends, but the evidence (p-values = 0.096 and 0.077, respectively) is not considered strong enough to conclude with certainty that there is a trend in either time series. The winter data for Aransas River near Skidmore shows some evidence for an upward trend (p-value = 0.064). If a trend is present, it could be related to rainfall; as previously discussed, both the Refugio 7 North and Corpus Christi WSO AP winter rainfall data also show evidence of upward trends for 1968–93. The summer data for Oso Creek at Corpus Christi show strong evidence (p-value = 0.027) of a downward trend, which also could be related to rainfall, as indicated by the evidence for a downward trend in the Corpus Christi WSO AP summer rainfall data (p-value = 0.064). However, the fact that the Oso Creek streamflow time series (1973–93) and the Corpus Christi WSO AP rainfall time series (1968–93) are not for the same periods makes any conclusion regarding the relation between trends in streamflow and rainfall tenuous.

Trends in Estimated Inflows

In this study, the trend tests on freshwater inflows estimated by summing simulated runoff, net return and diversion flows, and (for the Nueces and Corpus Christi Bay system) the streamflow measured at the Nueces River near Mathis gaging station in large part indicate trends in rainfall distributed on the watersheds of the bay systems. This is because simulated runoff is the largest component of estimated total freshwater inflow to all bay systems combined, and simulated runoff primarily is based on rainfall. The time-series data of simulated runoff do not reflect the effects of land-use changes during 1977–93 because the amounts of urban area in the watersheds were not changed in the simulations that produced the time-series data. Nevertheless, net return and diversion flows, although a small fraction of inflows to each bay system, could cause or contribute to a trend in bay system inflows if net return and diversion flows have a significant enough trend and are more than a minor fraction of the magnitude of simulated runoff. The same applies to the streamflow measured at the Mathis gaging station, which represents a larger fraction of inflow to the Nueces and Corpus Christi Bay system than net return and diversion flows.

No evidence for trends in estimated annual inflow volumes for any bay system for 1977–93 is indicated (Table V.4), not even for the Nueces and Corpus Christi Bay system, the time series for which contains 6 years of pre-Choke Canyon and 11 years of post-Choke Canyon Nueces River flow data. The only seasonal time series that shows some evidence for a trend (downward) is the

Table V.4. Results of trend analyses on 1977–93 time series of annual and seasonal estimated freshwater inflows by bay system, Corpus Christi Bay National Estuary Program study area

["maybe" means some evidence against "no trend" hypothesis but decision is considered uncertain]

Bay system	Time period	p-value (Is there a trend?)	Kendall's tau (direction of trend)
St. Charles	Annual	0.303 (no)	
	Winter	.232 (no)	
	Spring	.387 (no)	
	Summer	.901 (no)	
	Fall	.901 (no)	
Copano	Annual	.484 (no)	
	Winter	.537 (no)	
	Spring	.149 (no)	
	Summer	.592 (no)	
	Fall	.901 (no)	
Redfish	Annual	.837 (no)	
	Winter	.232 (no)	
	Spring	.387 (no)	
	Summer	.083 (maybe)	-0.316 (downward)
	Fall	.773 (no)	
Nueces and Corpus Christi	Annual	.484 (no)	
	Winter	.650 (no)	
	Spring	.434 (no)	
	Summer	.650 (no)	
	Fall	.387 (no)	
Upper Laguna Madre	Annual	.901 (no)	
	Winter	.837 (no)	
	Spring	.773 (no)	
	Summer	.592 (no)	
	Fall	.837 (no)	
Baffin	Annual	.592 (no)	
	Winter	.773 (no)	
	Spring	.592 (no)	
	Summer	.901 (no)	
	Fall	.266 (no)	

summer data for the Redfish Bay system (p-value = 0.083). If a trend is present, it could be rainfall-related, as indicated by the evidence noted above for a downward trend in the Corpus Christi WSO AP summer rainfall data. A downward trend in summer inflows to the Redfish Bay system also could be related to an apparent downward trend in net return and diversion flows for the Redfish system, for which there is strong evidence (p-value = 0.006) (Table V.5). Although there is strong evidence of downward trends in annual and other seasonal net return and diversion flows for the Redfish system, those trends apparently are not significant enough to cause trends in the annual and other seasonal estimated inflows for Redfish. The same applies to the summer return and diversion flows for the upper Laguna Madre system and to the fall return and diversion

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Table V.5. Results of trend analyses on 1977–94 time series of annual and seasonal net return and diversion flows[1] by bay system, Corpus Christi Bay National Estuary Program study area

["maybe" means some evidence against "no trend" hypothesis but decision is considered uncertain]

Bay system	Time period	p-value (Is there a trend?)	Kendall's tau (direction of trend)
St. Charles (net return and diversion flows negligible)			
Copano	Annual	0.198 (no)	
	Winter	.120 (no)	
	Spring	.185 (no)	
	Summer	.384 (no)	
	Fall	.705 (no)	
Redfish	Annual	.049 (yes)	-0.346 (downward)
	Winter	.049 (yes)	-.346 (downward)
	Spring	.289 (no)	
	Summer	.006 (yes)	-.477 (downward)
	Fall	.003 (yes)	-.516 (downward)
Nueces and Corpus Christi	Annual	.405 (no)	
	Winter	.596 (no)	
	Spring	.705 (no)	
	Summer	.096 (maybe)	-.294 (downward)
	Fall	.495 (no)	
Upper Laguna Madre	Annual	.103 (no)	
	Winter	.970 (no)	
	Spring	.384 (no)	
	Summer	.000 (yes)	-.706 (downward)
	Fall	.426 (no)	
Baffin	Annual	.225 (no)	
	Winter	.161 (no)	
	Spring	.970 (no)	
	Summer	.256 (no)	
	Fall	.063 (maybe)	-.327 (downward)

[1] Net return and diversion flow equals return flow minus diversion flow; thus, a downward trend indicates an increase in water consumption over time.

flows for the Baffin Bay system—each indicates some evidence of downward trends that apparently are not significant enough to cause trends in the respective estimated inflows.

VI. CHANGES IN FRESHWATER INFLOWS

The increase in urban area of the adjacent contributing watersheds from 0 to 3.3 percent of total area to represent the change from predevelopment to current land-use conditions increases simulated annual runoff to all bay systems combined about 8 percent (Table VI.1). The watersheds of the two small coastal bay systems, Redfish and upper Laguna Madre, show the largest historical increases in simulated annual runoff (79 and 53 percent), which reflect a result of the urbanization that is common in coastal areas.

Table VI.1. Increases in simulated annual and seasonal runoff due to increases in urban area from predevelopment to current (1983–93) and current to future (2010) land-use conditions by bay system, Corpus Christi Bay National Estuary Program study area

[mi^2, square mile; --, not applicable]

Bay system (adjacent contributing watershed area)	Increase in urban area (percent)	Increase in simulated runoff (percent)				
		Annual	Winter	Spring	Summer	Fall
St. Charles[1] (205 mi^2)						
Predevelopment to current	--	0	0	0	0	0
Current to future	0	0	0	0	0	0
Copano (2,090 mi^2)						
Predevelopment to current	--	4.2	3.7	5.5	4.4	3.4
Current to future	19	1.2	.95	1.6	1.2	.89
Redfish (35.0 mi^2)						
Predevelopment to current	--	79	72	93	82	70
Current to future	25	20	18	23	20	18
Nueces and Corpus Christi (636 mi^2)						
Predevelopment to current	--	11	16	10	11	10
Current to future	17	1.7	2.3	1.6	1.7	1.5
Upper Laguna Madre (61.5 mi^2)						
Predevelopment to current	--	53	43	58	63	45
Current to future	25	13	11	15	16	11
Baffin (2,980 mi^2)						
Predevelopment to current	--	26	20	42	29	18
Current to future	24	6.5	4.8	10	7.2	4.5
All bay systems combined (6,000 mi^2)						
Predevelopment to current	--	[2]7.9	[2]7.3	[2]11	[2]78	[2]5.7
Current to future	[3]20	[2]1.9	[2]1.8	[2]2.7	[2]1.0	[2]1.4

[1] St. Charles Bay system is virtually undeveloped and, therefore, not simulated for this comparison.
[2] Bay system weighted average is based on 1983–93 mean runoff (Table IV.1).
[3] Bay system weighted average is based on area.

Simulation provides estimates of historical (and projected) changes in runoff. To estimate the historical change in freshwater inflow, the changes in runoff are combined with the historical changes in streamflow of the Nueces River and net return and diversion flows. For the Nueces and Corpus Christi Bay system, the estimated change in freshwater inflow since predevelopment is computed as follows (Appendix 2): The mean annual flow of the Nueces River near Mathis for 1940–57, 619,000 acre-ft/yr (Fig. V.1), is considered the predevelopment mean (although it is less than the actual predevelopment mean because of storage in and evaporation from Lake Corpus Christi). If the current (1983–93 mean) annual runoff from the watersheds to the bay system is 124,000 acre-ft/yr (Table IV.1) and that rate represents an 11-percent increase over the predevelopment rate (Table VI.1), then predevelopment runoff was about 10 percent less than 124,000, or about 112,000 acre-ft/yr. Net return and diversion flow is zero under predevelopment conditions. Adding the estimates of predevelopment Nueces River flow (619,000 acre-ft/yr) and predevelopment runoff to the bay system (112,000 acre-ft/yr) yields an estimate of predevelopment freshwater inflow of 731,000 acre-ft/yr. Estimated current freshwater inflow to the bay system (378,000 acre-ft/yr) (Table IV.1) is the sum of 1983–93 mean annual flow of the Nueces River near Mathis (314,000 acre-ft/yr), 1983–93 mean annual runoff from the adjacent contributing watersheds to the bay system (124,000 acre-ft/yr), and the 1983–94 mean annual net return and diversion flow (-60,400 acre-ft/yr). The change in freshwater inflow since predevelopment from about 731,000 to about 378, 000 acre-ft/yr is a decrease in freshwater inflow to the Nueces and Corpus Christi Bay system of 353,000 acre-ft/yr, which represents a decrease of about 48 percent. The approximately 11-percent increase in runoff since predevelopment (about 12,000 acre-ft/yr) is offset by the negative net return and diversion flow (about -60,400 acre-ft/yr) and the decrease in Nueces River flow (about 305,000 acre-ft/yr).

Similar computations yield an estimate of total predevelopment inflow to all bay systems combined of 1,490,000 acre-ft/yr (Appendix 2). The change from 1,490,000 acre-ft/yr to the estimated total current inflow of 1,200,000 acre-ft/yr (Table IV.1) is a decrease in total freshwater inflow to all bay systems of about 19 percent. The approximately 8-percent increase in runoff from the watersheds to all the bay systems combined since predevelopment (about 69,000 acre-ft/yr) virtually offsets the negative net return and diversion flows for all the bay systems combined (about -51,500 acre-ft/yr); the decrease in Nueces River flow (about 305,000 acre-ft/yr) virtually accounts for the 19-percent decrease in total freshwater inflow.

The projected increase in annual runoff to all bay systems combined by 2010, based on an increase in urban area in the adjacent contributing watersheds of the bay systems of 20 percent (from 3.3 to 4.0 percent of total area), is about 2 percent (Table VI.1), which is considerably smaller than the estimated historical increase in runoff (8 percent) that has already occurred. As with bay system historical increases, the Redfish and upper Laguna Madre systems show the largest projected increases (20 and 13 percent).

Assuming that the flow of the Nueces River is unchanged in 2010 from the 1983–93 mean flow, the projected 2-percent increase in runoff, to the extent that it is not offset by greater consumption of water (larger negative net return and diversion flow), could result in a slight increase in total freshwater inflow to all bay systems combined in 2010. However, annual variability in Nueces River flow is appreciably greater than the projected increase in runoff and likely would make such a slight increase difficult to document. For practical purposes, total freshwater inflow to all bay systems combined in 2010 is projected to be about the same as current total inflow, 1,200,000 acre-ft/yr.

VII. ADEQUACY OF AVAILABLE DATA FOR ESTIMATING FRESHWATER INFLOWS

The available data for estimating freshwater inflows into the bay systems in the study area are adequate but not optimum. The need to use a watershed model to obtain runoff as was done in this study, with its limitations and deficiencies, results in reasonably accurate estimates of

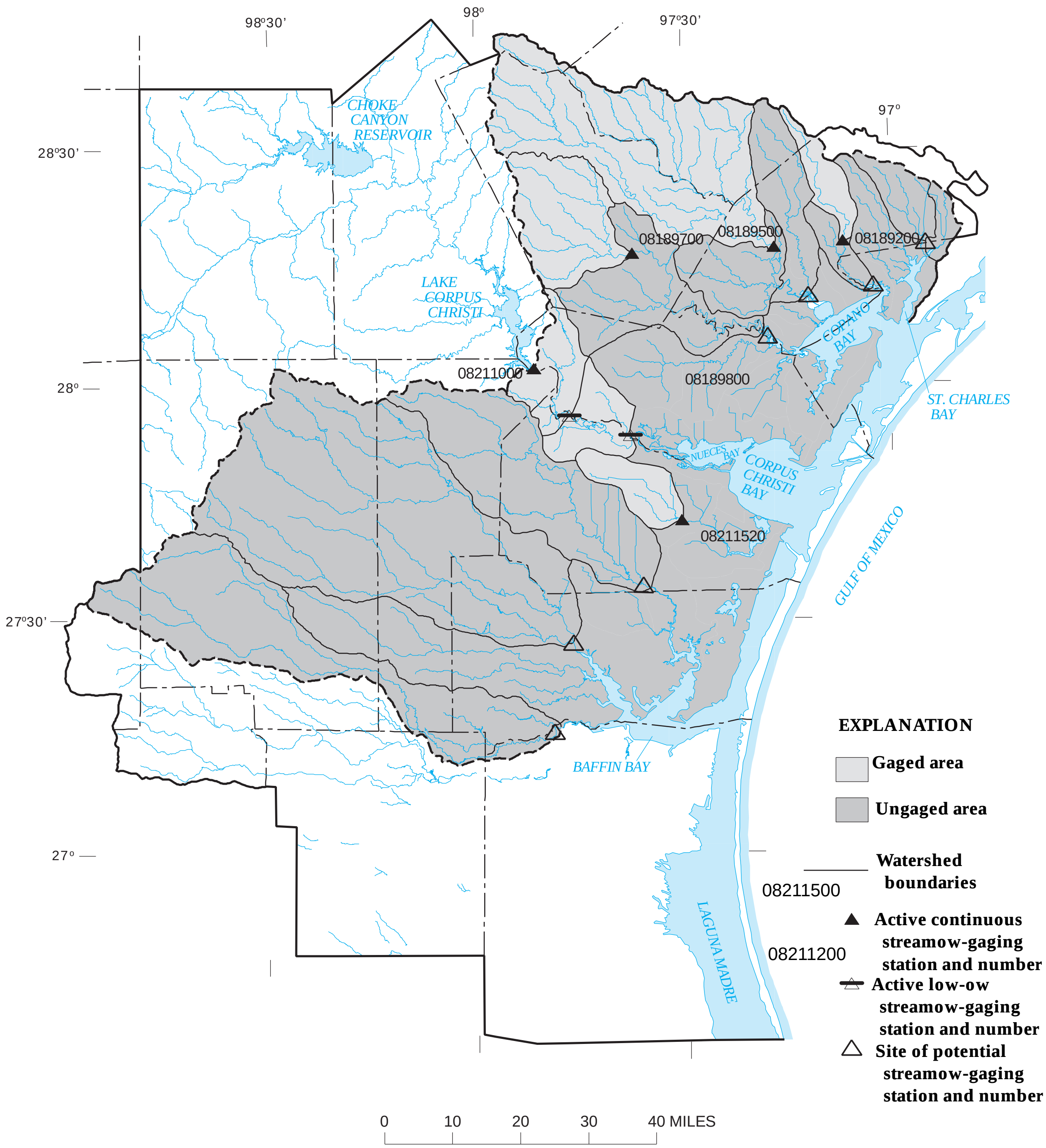

Figure VII.1. Gaged and ungaged areas, active streamow-gaging stations, and sites of potential streamow-gaging stations, Corpus Christi National Estuary Program study area, Texas.

freshwater inflows; however, improved estimates could be obtained from an expanded streamflow-gaging station network. Gaged streamflows represent an integration, or synthesis, over time of all the climatic and hydrologic processes and human activities that affect freshwater inflows. Runoff generated by a sophisticated watershed model with more accurate input parameters than were available for this study is more likely to match gaged streamflows in terms of accuracy; however, the level of accuracy achieved by the model would not match that of measured streamflows.

Six active streamflow-gaging stations[7] (4 continuous, 2 low-flow) now measure runoff from about 23 percent of the adjacent area that contributes inflow to the six bay systems combined (Fig. VII.1). Until the late 1980s, gaging tidally influenced streams was extremely difficult because stage-discharge ratings could not be developed. Accordingly, streamflow-gaging stations were located miles upstream from the mouths of streams that drain into bay systems to avoid tidal effects. New technology—for example, the vessel-mounted, broadband acoustic doppler current profiler to measure discharge and the acoustic velocity meter to measure velocity—now makes gaging tidally influenced streams practical; velocity-stage-discharge ratings can replace the traditional stage-discharge rating (D.D. Dunn, U.S. Geological Survey, written communication, unreferenced). As a result of the new technology available, streamflow-gaging stations can now be located closer to the mouths of streams than was possible when most, if not all, of the active gaging stations in the study area were originally established.

Streamflow-gaging stations at seven potential sites shown in Figure VII.1 would expand the gaged area that contributes inflow to the bay systems to about 70 percent; only those return and diversion flows downstream of the potential gaging-station sites would need to be estimated when estimating total freshwater inflows. Additionally, the increase in gaged watershed areas provides improved estimates of runoff per unit area for areas that are immediately adjacent to ungaged areas. These estimates could then be used to estimate runoff for adjacent ungaged areas with more confidence than if the estimates of runoff per unit area were based on data from gaged watersheds remote from the ungaged areas.

VIII. CONCLUSIONS

Regarding status of freshwater inflows:

About 26 percent (about 314,000 acre-ft/yr) of the estimated current (1983–93) mean annual freshwater inflow to all six bay systems combined, 1,200,000 acre-ft/yr, is flow that originates in the greater Nueces River Basin upstream of the adjacent contributing watersheds, as measured at the Nueces River near Mathis streamflow-gaging station. About 74 percent (about 886,000 acre-ft/yr) is a combination of runoff that originates in the adjacent contributing watersheds and net return and diversion flows; net return and diversion flows (about -51,500 acre-ft/yr) result in a loss of freshwater inflow of about 4 percent.

The Copano Bay system receives the largest share of the total inflow to the bay systems, about 53 percent (about 634,000 acre-ft/yr). The Nueces and Corpus Christi Bay system has the next largest share, about 32 percent (about 378,000 acre-ft/yr)—most of which (about 83 percent) is streamflow that originates in the greater Nueces River Basin outside the adjacent contributing watersheds.

[7] A seventh active streamflow-gaging station, the Nueces River near Mathis (08211000), measures flow that originates outside the adjacent contributing watersheds.

Regarding trends in freshwater inflows:

The annual streamflow volumes for the Mission River at Refugio streamflow-gaging station have no trend for the 57 years 1940–96. The winter data might have an upward trend.

The annual streamflow volumes for the Nueces River near Mathis streamflow-gaging station have a downward trend for the 57 years 1940–96. The downward trend in annual streamflow near Mathis is more of a "step trend" than a linear trend. Post-Choke Canyon (1983–96) mean annual streamflow (about 279,000 acre-ft/yr) is about 337,000 acre-ft/yr less than pre-Choke Canyon (1940–82) mean annual streamflow (about 616,000 acre-ft/yr), which represents a decrease of about 55 percent.

Water-budget and streamflow analyses show that storage in and evaporation from Choke Canyon Reservoir account for an annual streamflow reduction of about 95,800 acre-ft/yr, or about 28 percent of the total 337,000 acre-ft/yr post-Choke Canyon (1983–96) decrease in annual streamflow.

Composite streamflow data from four gaging stations considered upstream of Choke Canyon Reservoir in the greater Nueces River Basin show a downward trend of about 1.8 percent per year for 1965–96.

Annual streamflow volumes for streamflow-gaging stations Copano Creek near Refugio for 1971–93, Aransas River near Skidmore for 1968–93, and Oso Creek at Corpus Christi for 1973–93 have no trends. A few time series of seasonal streamflow for these stations might have trends, some of which could be rainfall-related.

Estimated annual inflow volumes—the sum of simulated runoff, net return and diversion flows, and, for the Nueces and Corpus Christi Bay system, gaged streamflow for the Nueces River near Mathis—for each of the six bay systems have no trends for 1977–93. The only seasonal time series of estimated annual inflow volumes that might have a trend (downward) is the summer data for the Redfish Bay system. If a trend is present, it could be rainfall-related, or it could be related to an apparent downward trend in net return and diversion flows for the Redfish system.

Regarding changes in freshwater inflows:

An increase in urban area of the adjacent contributing watersheds associated with development from 0 (predevelopment) to 3.3 percent of total area (early 1990s) increased runoff to all bay systems by an estimated 8 percent, from about 869,000 to about 938,000 acre-ft/yr.

The 8-percent increase in runoff to all bay systems (about 69,000 acre-ft/yr) is approximately offset by greater diversion flows than return flows (returns minus diversions for all bay systems for 1983–94 were about -51,500 acre-ft/yr); that is, the increase in runoff is offset by water consumption in the study area, primarily in the watersheds that contribute to the Nueces and Corpus Christi Bay system.

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The post-Choke Canyon decrease in Nueces River flow due to storage in and evaporation from Choke Canyon and other factors in the greater Nueces River Basin upstream of the study area [about 305,000 acre-ft/yr (1983–93), about 337,000 acre-ft/yr (1983–96)], essentially accounts for an estimated decrease in inflow to all bay systems of about 290,000 acre-ft/yr; which represents a decrease of about 19 percent from 1,490,000 acre-ft/yr (predevelopment estimate) to 1,200,000 acre-ft/yr (1983–93 estimate).

For the Nueces and Corpus Christi Bay system, an estimated 11-percent increase in runoff due to increased urban area since predevelopment, from about 112,000 to about 124,000 acre-ft/yr, is offset by water consumption in the contributing watersheds (returns minus diversions for the Nueces and Corpus Christi Bay system for 1983–94 were about -60,400 acre-ft/yr), and by the decrease in Nueces River flow [about 305,000 acre-ft/yr (1983–93); about 337,000 acre-ft/yr (1983–96)]. The combination of these changes results in an estimated decrease in freshwater inflows to the Nueces and Corpus Christi Bay system of about 353,000 acre-ft/yr; which represents a decrease of about 48 percent from 731,000 acre-ft/yr (predevelopment estimate) to 378,000 acre-ft/yr (1983–93 estimate).

Assuming that flow of the Nueces River in 2010 is about the same as it was during 1983–93, total freshwater inflow to all bay systems combined in 2010 is projected to be about the same as total inflow during 1983–93, 1,200,000 acre-ft/yr.

Regarding the adequacy of available data:

The available data for estimating freshwater inflows into the bay systems in the study area are adequate but not optimum. Runoff generated by a sophisticated watershed model with more accurate input parameters than were available for this study is more likely to match gaged streamflows in terms of accuracy; however, the level of accuracy achieved by the model would not match that of measured streamflows. The optimum data for obtaining freshwater inflows are gaged streamflows.

Streamflow-gaging stations at seven potential sites would expand the gaged area that contributes inflow to the bay systems from about 23 to about 70 percent.

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Appendix 1. Water-budget and streamflow analyses for reduction in total streamflow resulting from change in storage and evaporation at Choke Canyon Reservoir, greater Nueces River Basin, 1983–96

[acre-ft, acre-feet; in/yr, inches per year; --, not applicable]

Calendar year	Water-budget analysis: End-of-year storage of Choke Canyon Reservoir (acre-ft)	Water-budget analysis: Change in storage of Choke Canyon Reservoir (acre-ft)[1]	Water-budget analysis: Annual mean storage of Choke Canyon Reservoir (acre-ft)	Water-budget analysis: Annual pan evaporation at Choke Canyon dam, station 1720 (in/yr)	Water-budget analysis: Mean surface area of Choke Canyon Reservoir (acre)[2]	Water-budget analysis: Estimated evaporation from Choke Canyon Reservoir (acre-ft)[3]	Streamflow analysis: Annual composite upstream streamflow (acre-ft)[4]	Streamflow analysis: Actual streamflow at station 08211000 (acre-ft)	Streamflow analysis: Expected annual streamflow at station 08211000 (acre-ft)[5]	Streamflow analysis: Annual streamflow reduction at station 08211000 (acre-ft)
1965	--	--	--	--	--	--	255,296	369,229	--	--
1966	--	--	--	--	--	--	343,497	331,109	--	--
1967	--	--	--	--	--	--	1,166,840	1,800,345	--	--
1968	--	--	--	--	--	--	529,772	672,908	--	--
1969	--	--	--	--	--	--	316,445	250,003	--	--
1970	--	--	--	--	--	--	332,465	358,342	--	--
1971	--	--	--	--	--	--	2,485,979	2,547,379	--	--
1972	--	--	--	--	--	--	288,688	298,251	--	--
1973	--	--	--	--	--	--	1,122,160	1,042,572	--	--
1974	--	--	--	--	--	--	408,855	389,821	--	--
1975	--	--	--	--	--	--	501,259	373,716	--	--
1976	--	--	--	--	--	--	983,233	928,234	--	--
1977	--	--	--	--	--	--	558,105	528,746	--	--
1978	--	--	--	--	--	--	229,399	222,670	--	--
1979	--	--	--	--	--	--	409,015	363,492	--	--
1980	--	--	--	--	--	--	497,976	562,345	--	--
1981	--	--	--	--	--	--	1,084,593	1,055,812	--	--
1982	--	--	--	--	--	--	208,001	209,143	--	--
1983	0	--	--	--	--	--	113,503	107,629	119,144	11,515
1984	53,210	53,210	26,605	87.68	3,078	17,542	134,602	93,714	141,291	47,577
1985	199,800	146,590	126,505	77.27	9,024	45,253	645,929	469,731	678,030	208,299
1986	309,800	110,000	254,800	80.49	14,260	74,606	363,816	127,597	381,897	254,300
1987	686,000	376,200	497,900	75.92	21,055	103,902	1,223,750	757,335	1,284,568	527,233
1988	616,600	-69,400	651,300	82.35	25,367	135,783	95,252	114,571	99,986	-14,585
1989	348,100	-268,500	482,350	93.91	20,725	126,509	26,777	120,599	28,108	-92,491
1990	396,600	48,500	372,350	85.57	17,885	99,455	496,386	352,026	521,055	169,029
1991	398,600	2,000	397,600	80.22	18,593	96,871	291,763	182,489	306,263	123,774
1992	670,700	272,100	534,650	76.61	21,814	108,865	1,043,982	924,885	1,095,866	170,981

PRIOR TO CHOKE CANYON RESERVOIR

Appendix 1. Water-budget and streamflow analyses for reduction in total streamflow resulting from change in storage and evaporation at Choke Canyon Reservoir, greater Nueces River Basin, 1983–96—Continued

	Water-budget analysis						Streamflow analysis			
Calendar year	End-of-year storage of Choke Canyon Reservoir (acre-ft)	Change in storage of Choke Canyon Reservoir[1] (acre-ft)	Annual mean storage of Choke Canyon Reservoir (acre-ft)	Annual pan evaporation at Choke Canyon dam, station 1720 (in/yr)	Mean surface area of Choke Canyon Reservoir[2] (acre)	Estimated evaporation from Choke Canyon Reservoir[3] (acre-ft)	Annual composite upstream streamflow[4] (acre-ft)	Actual streamflow at station 08211000 (acre-ft)	Expected annual streamflow at station 08211000[5] (acre-ft)	Annual streamflow reduction at station 08211000 (acre-ft)
1993	599,300	-71,400	635,000	81.28	24,976	131,990	229,027	201,424	240,409	38,985
1994	446,600	-152,700	522,950	77.18	21,574	108,210	112,472	186,429	118,062	-68,367
1995	273,000	-173,600	359,800	86.40	14,564	81,791	90,301	154,355	94,789	-59,566
1996	175,900	-97,100	224,450	96.66	13,046	81,967	133,545	116,078	140,182	24,104
TOTALS (acre-ft)										
1965–82	--	--				--	11,700,000	12,300,000	--	--
1983–96	--	176,000			+	1,210,000	5,000,000	3,910,000	5,250,000	1,340,000
MEANS (acre-ft/year)										
1965–82	--	--				--	651,000	684,000	--	--
1983–96	--	12,600				86,600	357,000	279,000	375,000	95,800
Percent change[6]							-45	-59		
Estimated total streamflow reduction due to Choke Canyon Reservoir (1983–96) (acre-ft)					1,390,000		1,340,000			
Estimated mean annual streamflow reduction due to Choke Canyon Reservoir (1983–96) (acre-ft/year)					99,300		95,800			

[1] Change in storage of Choke Canyon Reservoir is difference between end-of-calendar-year storage in reservoir for consecutive years.

[2] Mean surface area of Choke Canyon Reservoir is the surface area corresponding to the yearly mean storage determined from area-stage and capacity-stage tables for reservoir dated 1983 (James F. Giles, Bureau of Reclamation, written communication, unreferenced). The yearly mean storage is calculated as average of end-of-calendar-year storage in reservoir for consecutive years.

[3] Estimated evaporation from Choke Canyon Reservoir is the product of annual pan evaporation and mean surface area multiplied by a pan coefficient of 0.78 (Kane 1967, p 15).

[4] The annual composite upstream streamflow is computed as the sum of annual streamflow for stations Nueces River near Tilden (08194500); Frio River near Derby (082055000); San Miguel Creek near Tilden (08206700); and Atascosa River at Whitsett (8208000).

[5] The expected annual streamflow at Nueces River near Mathis (08211000) is 1.05 times the annual composite upstream streamflow. This multiplier is the ratio of total annual streamflow at station 08211000 to total annual cumulative upstream streamflow for the four stations for the period 1965–82. Because station 08211000 is downstream of Lake Corpus Christi, this multiplier intrinsically accounts for: (1) the streamflow originating from the intervening watersheds between the four stations and station 08211000, (2) the change in storage in Lake Corpus Christi, and (3) the evaporation from Lake Corpus Christi.

[6] Percent change between time periods 1965–82 and 1983–96.

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Appendix 2. Computation of estimated reduction in mean annual freshwater inflows, predevelopment to current (1983–93) conditions, for Nueces and Corpus Christi Bay system and all bay systems combined, Corpus Christi Bay National Estuary Program study area

Nueces and Corpus Christi Bay system

Predevelopment inflow (acre-feet/year):

Nueces River near Mathis streamflow—619,000 (1940–57 mean assumed to be close to predevelopment) (Fig. V.1)

Runoff—

$$\frac{124{,}000 \text{ (1983–93 mean) (Table IV.I)}}{1.11 \text{ (11-percent increase, predevelopment to current) (Table VI.1)}} =$$

112,000 (predevelopment runoff)

0	(net return and diversion)
619,000	(Mathis flow)
112,000	(runoff)
731,000	(predevelopment inflow)

Current inflow (acre-feet/year):

314,000	(1983–93 mean Mathis flow) (Table IV.1)
124,000	(1983–93 mean runoff) (Table IV.1)
-60,400	(1983–94 net return and diversion) (Table IV.1)
378,000	(total) (Table IV.1)

Percent decrease, predevelopment to current:

$$\left[\frac{731{,}000 - 378{,}000}{731{,}000}\right] \text{X } 100 = 48$$

All bay systems combined

Predevelopment inflow (acre-feet/year):

Nueces River near Mathis streamflow—619,000 (1940–57 mean assumed to be close to predevelopment) (Fig. V.1)

Runoff—

$$\frac{938{,}000 \text{ (1983–93 mean) (Table IV.1)}}{1.079 \text{ (7.9-percent increase, predevelopment to current) (Table VI.1)}} =$$

869,000 (predevelopment runoff, all bay systems)

0	(net return and diversion)
619,000	(Mathis flow)
869,000	(runoff)
1,490,000	(predevelopment inflow)

Current inflow (acre-feet/year):

314,000	(1983–93 mean Mathis flow) (Table IV.1)
938,000	(1983–93 mean runoff) (Table IV.1)
-51,500	(1983–94 net return and diversion) (Table IV.1)
1,200,000	(total) (Table IV.1)

Percent decrease, predevelopment to current:

$$\left[\frac{1{,}490{,}000 - 1{,}200{,}000}{1{,}490{,}000}\right] \text{X } 100 = 19$$

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