QUANTIFYING LONG TERM CHANGES IN STREAMFLOW CHARACTERISTICS IN TEXAS

A Thesis

by

GAURAV GARG

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

December 2004

Major Subject: Civil Engineering

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ABSTRACT

Quantifying Long Term Changes in Streamflow

Characteristics in Texas. (December 2004)

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Streamflow characteristics change over time as a result of water resources development and management projects, water use, watershed land use changes, and climate changes. The main objective of this thesis is to assess the significance of the impacts of human activities such as construction of reservoirs, water supply diversions, increased water use and return flows on streamflows by the recently completed Texas WAM (Water Availability Modeling) system. The major river basins in the state of Texas were selected as suitable study basins. The particular objective is accomplished by the assessment of WAM monthly and annual naturalized and regulated flows, based on using the WRAP (Water Rights Analysis Package) model, which represents the river/reservoir management model. WAM flow frequency analysis was performed for the simulated flows. The flow ratio indices developed showed the divergence of the actual flows from their natural behavior for the entire monthly flow frequency flow spectrum ranging from minimum flows to high flows. This study describes the combined effects of reservoir construction, increased water use, water resources development projects and land use changes on the river flow regime.

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1 INTRODUCTION

1.1 Motivation

Water is described as the most precious natural resource. With increasing population over time there is more and more stress on the same sources of water. Over the years humans have built dams, reservoirs and diversions so as to have the most efficient use of the available water. Major dams, diversions and reservoirs have changed the river flow regime. In the present conditions it is difficult to meet the in-stream flow needs for the sustenance of aquatic life and riparian habitat.

Streamflow characteristics change over time as a result of water resources development and management projects, water use, watershed land use changes, and climate changes. The impacts of human activities on low flows are typically very different than on high flows. For example, regulation of streamflows by dams may reduce flood flows but increase low flows at downstream locations. Streamflow variability is attributable to both climatic and non-climatic factors. Climatic factors are related to daily, seasonal, and multiple-year variations in precipitation, evapo-transpiration, temperature, and other climatic variables that include the extremes of floods and droughts as well as less severe fluctuations. Non-climatic factors are due to

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human activities such as changes in land use and water resources development projects such as reservoirs, water supply diversions, and return flows from surface and groundwater sources.

Changes in streamflows have important consequences from the perspectives of environmental in-stream flow needs, freshwater inflows to bays and estuaries, impacts on other environmental resources, aesthetics, river recreation, water supply and multiple-purpose water resources management. The natural flow regime of rivers and streams may be greatly altered by water development and management projects, significantly affecting fish and wild life habitat and other environmental resources. Decreasing flow levels also affect the assimilative capacity of streams to absorb pollutants, which result in increasing costs for waste-water treatment and nonpoint source pollution prevention activities. Aesthetics, recreation, and various other aspects of water management and use are also affected.

Understanding changes in streamflow characteristics is fundamental to environmental management and restoration programs and various other water resources planning and management activities. For the effective management of the Texas water the 1997 Texas legislature enacted Senate Bill, which directs the Texas Natural Resource conservation Commission (TNRCC)/ Texas Commission on Environmental Quality (TCEQ) to develop water availability models for all the river basins of the state. The WAM system was developed during 1997-2003 which can calculate the streamflows subject to various hydrologic principles, reservoir storage capacities and in-stream flow requirements.

The development of the Texas WAM database has offered the prospect to conduct a wide scale assessment of the streamflow alterations in the major rivers and streams of the state of Texas. The evaluation used the results from the Texas WAM system which included the naturalized and regulated streamflow database developed for periods ranging from 50 to 61 years for the different basins of the state. The simulations were performed using the Water Rights Analysis Package (WRAP).

Quantifying long term changes in streamflows is difficult due to the great natural variations which hide these long term trends. Many studies had been performed in the past to quantify these long term changes, but previously the long term changes had not been considered in the TCEQ WAM. The goal of this study is to assess the long term streamflow changes in the rivers of Texas with the WAM system and to compare these results with the historical streamflow data from the United States Geological Survey (USGS) and International Boundary Water Commission (IBWC) gauging stations. The proposed research focuses on an approach based on analyzing the naturalized and regulated flows developed using WRAP simulation model with datasets from the recently implemented Texas WAM system.

1.2 Objectives

The research focuses on calculating the long term trends in the streamflows for the state of Texas. The main goal of the study is to calculate the naturalized and regulated stream flows from the Texas WAM datasets. One of the concerns is also to compare the Texas WAM results with the gauged historical streamflows from the USGS and IBWC gauging stations. The focus is on the changes in monthly and annual flows over time periods of many years.

The objectives of the research are as follows:

1. To develop improved methodologies for evaluating long term changes in streamflow characteristics.
2. To develop an improved understanding of changes in flow characteristics of the major rivers of Texas.

2 TEXAS WAM SYSTEM AND WRAP MODEL

2.1 Texas WAM System

Article 7 of Senate Bill 1 enacted by the Texas Legislature in 1997 directed the TNRCC to develop water availability models for all of the river basins of the state. The TNRCC was renamed the TCEQ in 2002. The Water Availability Modeling (WAM) System was developed during 1997-2003 by the TNRCC/TCEQ in collaboration with the Texas Water Development Board and Texas Park and Wildlife Department, with most of the technical work being performed by consulting engineering firms and university researchers. (Sokulsky et al, 1998).

The Texas WAM System consists of the generalized WRAP model, WRAP hydrology and water rights input datasets for all the river basins of the state, a geographic information system, and other supporting data management systems. The WAM System includes WRAP datasets covering the entire state subdivided by river basins, but a few datasets include two river basins. The WRAP input files can be downloaded from the TCEQ WAM website (TNRCC, 2003). For each river basin or combination of basins listed in Table 1, datasets are available at the TCEQ WAM web site for two water use scenarios: (1) current conditions and (2) full authorization. Current conditions reflect maximum reported use of water within the last ten years and minimum return flow of last 5 years. Full authorization means the full amount of water allowed by the water right permits is used with no return flows.

Table 1. River Basin Models in the Texas WAM System (Wurbs, 2004).

Major River Basin or Coastal Basin	Area in Texas (km²)	Area Outside Texas (km²)	Number of Control Points	Number of Water Rights	Number of Reser-Voirs	Storage Capacity (10^6 m³)	Analysis Period	Mean Flows Natur-alized (10^6 m³/year)	Mean Flows Unappro-priated (10^6 m³/year)
Brazos River	115,000	6,660	3,818	1,606	650	5,758	1940-97	7,845	5,583
Canadian River	32,900	90,700	85	56	47	1,192	1948-98	235	220
Colorado River	108,000	5,100	2,263	1,591	503	5,878	1940-98	3,701	1,300
Cypress Bayou	7,280	259	158	132	85	1,078	1948-98	2,154	1,598
Guadalupe-San Ant	26,500	-0-	1,334	853	233	997	1934-89	2,593	2,522
Lavaca River	5,980	-0-	176	71	22	290	1940-96	1,203	978
Neches River	25,900	-0-	304	327	175	4,818	1940-96	7,694	5,589
Nueces River	43,900	-0-	544	376	122	1,284	1934-96	1,071	14,739
Red River	63,400	61,000	443	447	240	4,965	1948-98	19,173	18,623
Sabine River	19,200	6,040	373	308	206	7,873	1940-98	8,499	4,320
San Jacinto River	14,500	-0-	386	164	111	787	1940-96	2,723	2,279
Sulphur River	9,220	492	77	82	51	930	1940-96	3,083	2,562
Trinity River	46,500	-0-	1,329	1,176	702	9,254	1940-96	8,489	5,258
Rio Grande	125,000	347,000	974	2,562	90	16,149	1940-00	5,345	1,307
Coastal Basins									
Lavaca-Guadalupe	2,590	-0-	68	10	-0-	-0-	1940-96	194	192
Neches-Trinity	1,990	-0-	216	134	31	40	1940-96	749	649
Nueces-Rio Grande	27,000	-0-	197	105	64	140	1948-98	307	302
San Antonio-Nueces	6,860	-0-	49	12	9	2	1948-98	697	695
Trinity-San Antonio	648	-0-	83	21	14	6	1940-96	223	207
Colorado-Lavaca	2,440	-0-	105	26	10	67	1940-96	167	150

The WRAP model simulates capabilities for meeting specified water management and usage requirements during a hypothetical repetition of historical hydrology. The generalized simulation model provides an accounting system for tracking streamflow sequences, subject to reservoir storage capacities and diversion, hydropower, and in-stream flow requirements (Wurbs, 2003a). Water balance computations are performed in each monthly time step of the simulation.

Simulation results include sequences of monthly naturalized, regulated, and unappropriated flows, reservoir storage contents, reservoir net evaporation volumes, water supply diversions, hydropower generated, and other variables. Naturalized streamflows are flows that would have occurred without the water users and facilities reflected in the water rights input data set. Naturalized flows are developed by adjusting gauged flows to remove the effects of reservoirs and water use throughout the river basin. Regulated flows are physical flows at a location after considering all water rights. Unappropriated flows represent water still available for further appropriation. Unappropriated flows may be less than regulated flows due to some of the water being committed to in-stream flow requirements at that location or committed to other diversion, storage, and in-stream flow rights at downstream locations.

The spatial configuration of a river/reservoir/use system is modeled as a set of control points. All system components are assigned control point locations. Naturalized, regulated, and unappropriated flows are developed for all control points. Algorithms in the model are based on each control point having its next downstream control point defined in the input. Environmental in-stream flow requirements are modeled as a special type of water right.

A WRAP simulation combines information describing natural hydrology and human water management. Hydrology is represented by monthly naturalized stream flows spanning periods of many years that reflect the hydrologic characteristics of the river basin including severe droughts. Hydrology also includes net evaporation less precipitation rates from reservoir water surfaces. In WRAP, a water right is a set of water management and use requirements. A typical water right could include water supply diversion or hydroelectric energy generation requirements and storage in any number of reservoirs. In the Texas WAM System, model water rights correspond directly to water right permits, but many of the complex permits are modeled with multiple model water rights. Thus, the 10,059 model water rights noted in Table 1 is greater than the approximately 8,000 actual water right permits. Environmental in-stream flow requirements are modeled as a special type of water right.

2.2 Structure of WRAP

The generalized WRAP simulation model includes the FORTRAN programs. There are three executable programs with which the WRAP is composed. The main simulation program WRAP-SIM starts the computations with known naturalized flows provided in the hydrology input file using the monthly time step. WRAP-HYD helps to adjust gaged flows to obtain naturalized flows and then distributes the naturalized flows from gaged locations to ungaged locations. The simulated results are compiled based on the selections by the user and then written to the WRAP-SIM output file, which is read by program TABLES.

2.3 International WAM Structure for the Rio Grande

The Rio Grande from El Paso to the river's mouth at the Gulf of Mexico near Brownsville forms the international border between the U.S. and Mexico. It has been necessary to incorporate into WAM, the essential provisions of international agreements between the United States and Mexico. The two agreements of the past include the 1944 treaty, which addresses the flow distribution downstream of Fort Quitman and the 1906 convention, which describes the flow sharing above Fort Quitman. One of the most important features of the 1944 treaty is the transfer of one third of Mexican water from certain Mexican tributaries to the U.S. segment of tributaries. In the WAM the Rio Grande is modeled as two different water courses, one for the U.S. flows and one for Mexican flows, which are flowing parallel to each other but are interlinked. The model is structured in a manner with the intention that the tributaries in the Texas portion are linked to the U.S. and the tributaries in the Mexican portion are linked to Mexico.

The state of Texas distributes water to the water rights according to the prior appropriation doctrine (allocates the right to use water on a first come first serve basis). However, the Rio Grande is distinct from the other basins regarding the water right priorities. Upstream of Amistad Reservoir, the upper basin follows the prior appropriation system. However, the water rights in the middle and lower basin are primarily dependent on the water stored in the Amistad and the Falcon Reservoirs. Water is allocated in the middle and lower basins based on the type-of-use.

Mexico does not follow the prior appropriation doctrine. But for WAM purposes the water allocation is done based on type of use (municipal first and then irrigation) and reservoir storage is done based on the river order from upstream to downstream.

2.4 Recent WAM Studies

The Texas Parks and Wildlife Department (TPWD) has recently compared naturalized and regulated flows from the TCEQ WAM System to assess alterations in in-stream flows (Trungale et al., 2004). Monthly flows are converted to daily flows for comparison with benchmarks. The exceedance of the in-stream flow benchmarks under full authorization were compared to naturalized flow conditions.

3 LITERATURE REVIEW

Several studies in the past have explicititdly shown that streamflow characteristics are continuously altering slowly over time due to natural and human induced changes. Streamflow variations occur due to the climate changes, urbanization, agricultural practices, construction of reservoirs and diversions and clearing of forest areas. Models indicate a noticeable increase in the annual minimum, median and maximum daily stream flows around 1970 for the rivers in conterminous United States (McCabe and Wolock, 2002).

Generally speaking, the changes in stream flows are due to both climatic and non-climatic influences. Climatic influences are due to the combination of various factors such as precipitation, temperature, evaporation, wind speed and direction etc. Non-climatic influences which affect the stream flows are due to water resources development and management projects. While managing and forecasting the river discharges, the effects of climate and human induced changes on the streamflows should be clearly separated. As Texas Rivers are affected both by rapid economic changes and the moisture from Gulf of Mexico, the role of climate and humans on the streamflows should be studied separately.

3.1 Human Impacts

3.1.1 Urbanization

Most of the natural disasters in United States are due to floods and droughts. The flood damage increase stems from continuing urban and suburban development on flood plains and drought vulnerability is in the regions of lower renewable water supplies. (Lins and Slack, 1998). The most dominant factor in altering the hydrology of the area is considered to be urbanization. Urbanization is primarily defined as the increase in the impervious area due to the construction activities. Imperviousness is defined as the inability of water to penetrate in the land surface. Stankowski (1972) developed a quantitative index of urban and suburban land use characteristics for application in water resources analysis. He found that the population density is the only independent variable which can be used to calculate empirically the proportion of impervious area resulting from different degrees of urban and suburban development. The secondary effect of the urbanization is the decrease in the vegetative cover due to the urban/residential growth. Urbanization begins with the occupancy of rural land by small concentrated communities. Further growth is characterized by large residential sub-divisions. Further industrial growth starts which convert a rural land area into suburban land area and further into urban area.

Studies had been done in the past relating the time series of monthly, mean daily and maximum instantaneous stream flows with the effects of the urbanization.

Continued urbanization causing increased runoff may generate flooding problems in the future (Leith and Whitfield, 2000). Urbanization effects have proven to be severe in low lying watersheds, which receive heavy precipitation. A slight level increase in the runoff has incremented the flooding problems in these watersheds. The indices which were developed to study the effects of the urbanization were census data, building permits and air photos. Estimates of land use and land cover were made by delineating the drainage basins based on air photos. Monthly runoff from two time periods, the first before intense urbanization 1918-1972 and the second during the intense urbanization 1980-1984, were compared to study the effects of urbanization. The results indicated that a small amount of concentrated urbanization leads to the alteration of flow regimes.

Moore (1990) had studied the effects of urbanization on a watershed in the Lower Fraser Valley in Canada. He indicated that the period between 1981 and 1986 had experienced one of the fastest growth rates for Lower Fraser Valley. The effects of this increase had resulted in the change of the natural hydrologic regime. The hydrology of the basin is largely impacted by the urbanization because of the creation of impervious surfaces, removal of vegetation, changes in consumptive use of water and inter-basins transfer of water. Studies were conducted to show the effects of urbanization on mean and annual stream flows by comparing the historical stream flow, climate and population data for the urbanizing and nearby rural basins.

Urbanization increases the mean annual streamflows in rough proportion to average cumulative changes in population density on the basins. Urbanization also reduces the sensitivity of mean annual streamflow to temperature changes compared to the mean flow response on rural basins. (Dewalle et al, 2000). They further reported that the effects of population density change on mean annual streamflow for the rural basins were negligible. The mean annual stream flow changes in rural basins were responsive to climate scenarios. The results pointed that maximum positive change in annual streamflow of +25% occurred for precipitation changes of +20% and air temperature changes of +2 ^{0}C on rural basins. In case of urban basins, even at the initial population densities, the predicted changes in annual streamflows were higher as compared to rural basins.

Topography of forest and agricultural land uses could have played a major role in changing the streamflows but the analysis showed that the rural and urban basins responded similarly to precipitation changes. The population density in each basin was calculated by determining the average population density in each minor cell division within the basin and calculating a weighted mean density based on the fractional coverage for each minor civil division in the basin. The analysis included four population density scenarios for each climate change scenario:

1. Initial population density at the beginning of the period of reach for each basin.
2. Final population density at the end of the period of reach for each basin.
3. Hypothetical 50% urban development.
4. Hypothetical 100% urban development.

The effects of urbanization were more prominent in case of 50% and 100% urban development. In case of 50% urban development the changes in mean annual stream flows are predicted to be 46% relative to rural basin purposes. And in case of 100%

urban development, the changes in mean annual streamflows were predicted to be 112% relative to rural basin responses.

3.1.2 Agricultural Practices

Changes in agricultural practices over time have resulted in the alterations in the amount of runoff from agricultural land. Different agricultural practices result in changes in evapo-transpiration rates which ultimately affect streamflows. Improved agricultural practices over time that reduce overland flow and increase infiltration and evapo-transpiration rates had found to decrease stream flows on agricultural basins (Gebert and Krug, 1996). Szilagyi (2001) estimated the average annual water balance of the Republican River basin shared by three states Colorado, Nebraska and Kansa to show that the observed decline in the runoff is not only attributed to climate changes but also due to the human activities such as crop irrigation, change in vegetation cover, water conservation practices and construction of reservoirs and artificial ponds. The decline in runoff is due to the increase in the amount of water being evaporated over the basin, thereby reducing the amount of water available to runoff. The study illustrated the various changes that had occurred in the past 50 years. Vegetation cover had been transformed drastically from a predominantly rangeland type landscape (i.e. grass) to dry and irrigated cropland. A number of artificial reservoirs and ponds have been constructed in the basin. The most important factor which resulted in the change of the natural hydrologic regime was the change in the irrigation practices. He further explained that the irrigation itself does not alter the long term runoff in the basin, but the change in evapo- transpiration rate due to the irrigation practice is the predominant factor. The model explained that the adoption of the center pivot irrigation in the basin has caused a small increase in the basins evapo-transpiration in addition to the naturally occurring evapo-transpiration. The assertion was proved to the fact that in 1973 there were only 600 center pivot system but in 1985, they were grown to 2700. The model used in the study estimated the relationships between climate, soil-water storage, and average annual water balance. The model assumed that the

1. Soil is permeable enough to exclude ‘saturation from above’ of the soil during storm events.
2. Evapo-transpiration occurs at its potential level while soil moisture is above permanent wilting point of the vegetation.
3. Any soil moisture in excess of field capacity of soil will contribute to runoff.
4. There is no water contribution to runoff from the soil when its soil moisture content is below its field capacity value.

3.1.3 Reservoir and Artificial Pond Construction

Reservoir regulation plays a significant role in changing the hydrologic regime of the river. The sharp and widespread increase in dam construction since 1960’s in Texas had produced significant changes in stream flows. While dams and artificial ponds can reduce the water shortage problems related with agriculture and human consumption, but the regulations produced due to these reservoirs have resulted in the widespread impact on the downstream users and the environment. Ye et al (2003) found that the upper stream of the Lena River watershed, without much human impact, experience a runoff increase in winter, spring and summer seasons and a discharge decrease in fall season. The results indicated that the reservoir regulation have significantly altered the monthly discharge regime in lower parts of Lena River. Due to the dam construction in West Lena River, summer (high flows) reduced by up to 55% and winter (low flows) increased by up to 30 times.

The study showed that before the dam construction at the Chernyshevskyi station on the Lena River, winter low and summer high discharges were 10-180 and 3000-5800 m^3/s respectively. But after the completion of the dam in 1967, winter monthly discharge at the station increased by up to 700-900 m^3/s until late 1970's, and the summer peak flows decreased by 1200-2500 m^3/s. Reservoir impact on stream flow regime is easier to detect in winter low flow season as compared to summer high flow season. This is due to the huge runoff contributions from the unregulated regions during summer. To better assess the reservoir effects, long term means of monthly discharge between pre dam and post dam period were calculated. This was the period when the reservoir was being filled for full operation. To assess the actual effects it was necessary to minimize the impacts due to other human factors. This was achieved by the reconstruction (naturalization) of monthly and yearly streamflows.

Peters and Prowse (2001) used a combination of hydrologic and hydraulic flow models to generate the naturalized flow series for investigating the effects of reservoir regulation on the lower Peace River in Canada. The changes noticed were the increase in average winter flows by 250%, lowering of annual peaks by the order of 35-39% and the decrease in daily flows. They demonstrated that there were significant changes in the hydrograph even at 1100 Km downstream of the river. The results showed the extensive changes to the hydrology and ecology produced at the downstream of the Peace River, Canada due to the three year filling of the reservoir which extracted about 1.2 years worth of flow from the river. This was achieved by developing an all season naturalized flow record for the downstream reach of the Peace River. The simulated record was compared with the actual observed records to evaluate the effects of regulation. They had considered the conditions that would have existed after 1968 without the effect of the regulation as compared to previous studies which compare the pre to post regulation stream flow records.

3.1.4 Forest Cover Changes

Human activities can dramatically change the land cover characteristics which further can alter the hydrology of the area. Land cover changes such as forest cover strongly affect the hydrological processes by affecting the evapo-transpiration; snow accumulation and snow melt processes. (Bosch and Hewlett, 1982; Stednick, 1996). Land use and plant cover changes are the only non-climatic factors which can explain the loss of around 30% of the average annual discharge (Begueria et al, 2003). The spatial extent of the forested area is generally more than that of agricultural area and urbanized area. The removal of forest cover increases streamflow due to the reduction in evapo-transpiration (Matheussen et al, 2000).

Studies were done on the interior Columbia River basin, in which substantial changes in land cover had occurred due to the conversion of native grassland and shrub lands to agriculture. To study the forest cover related effects on stream flows, there was a need to use a model which should consider only the vegetation cover and vegetation related parameters. The model used in the study was the variable infiltration capacity (VIC) model of Liang et al (1994). It is a physically based, macro scale hydrological model, which divides the incoming solar radiation at land surface into latent and sensible heat, and divides the precipitation (snowmelt) into direct runoff and infiltration. The model uses three types of data: topography, time-series meteorological data and characterization of land cover vegetation. The results suggested that flows would have been lower in the interior Columbia River basin if the conditions of historical vegetation regime would have existed.

Trimble and Weirich (1978) showed that reforestation in the southern United Stated has reduced the stream flows. The reforestation generally induces a decline of 4% to 21% decline in annual stream flow discharges. The results also depicted that the stream flow reductions due to reforestation were more in dry areas as compared to wet areas. Experiments on smaller basins had proved that more forested area leads to additional evapo-transpiration and thus decrease in runoff.

3.2 Climate Changes

Global climate is continuously changing in a slow motion with time. The potential effects of climate changes are on watershed hydrology (soil moisture and stream flow) and on major water uses including water supply, recreation, drought management, hydropower, environmental and ecological protection. Floods and droughts, which are the most costly and naturally occurring disasters, are the results of the severe climate changes. The average global temperature on earth has increased by 0.5^0C-0.7^0C due to the greenhouse effect produced due to the greenhouse gases. The greenhouse effect takes place due to the warming of the earth’s surface. The warming is due to the absorption of the earth’s infrared radiation by the greenhouse gases. The predominant greenhouse gases which accounts for 95% of the greenhouse effect are water vapor and carbon dioxide.

Global climate changes have major effects on precipitation, evapo-transpiration and runoff. A slight change in precipitation produces large impacts on water supplies. In mountainous watersheds, a slight increase in temperature accelerates the rate of snowmelt during spring, which leads to greater spring runoff. To understand the effects of increasing Greenhouse effect on the climate, several models such as Energy Balance Models (EBMs) and General Circulation Models (GCMs) had been developed. The GCMs are detailed, time dependent, three dimensional numerical solutions. The ongoing national assessment of the impacts of climate changes on the U.S. is evaluating the implications of two different models - Hadley and Canadian GCMs. (Frederick and Gleick, 1999).

Both the models depict significant changes in precipitation, potential evaporation and temperature changes. By 2030, the Hadley model projects an increase in precipitation whereas the Canadian model projects a decrease in precipitation. Felden (2002) combined the general circulation global climate model and water hydrology model with WRAP to assess the impacts of potential future climate change on water availability. He found that in the Brazos River basin, some parts of the basin experienced increase in the floods and high flows due to the climate change and some parts experienced decrease in the low flows.

Wurbs et al (2004) used the climate model and watershed hydrology model to adjust the hydrology input to a river/reservoir system water allocation model to reflect anomalous climate during 2040-2060. The impacts of climate change on Texas WAM system estimates of water availability and reliability were investigated from two perspectives: 1) past effects of climate change on the historical hydrology data 2) future effects requiring adjustments to the streamflow and reservoir net evaporation rates to make river basin hydrology representative of future climate.

Georgakakos and Yao (2000) explained that the climate change impacts vary with the choice of GCM scenario, but some common results were:

1. Soil moisture and streamflow variability are expected to increase.
2. Flexible and adaptive water sharing agreements, management strategies, and institutional processes are best suited to cope with the uncertainty associated with

future climate change scenario.

3.3 Procedures for Quantifying Stream Flow Changes

3.3.1 Statistical Trend Analysis

Stream flow time series and trends have been extensively studied. Many studies had been conducted to show the trends in various stream flow statistics. In the past documentation of trends in streamflows had been done on the daily, monthly and annual mean discharges. McCabe and Wolock (2002) analyzed the ranks of annual streamflow statistics for 400 streams in the counterminous states. They found a noticeable increase in the number of sites with high rank annual minimum, median and maximum daily stream flow events after 1970. Moreover, they also indicated that the increase is a step change rather than a gradual trend.

Different statistical tests were used on the data to detect the trends. Trends in stream flow were calculated for selected quantiles of discharge, from 0^{th} to the 100^{th} percentile to evaluate the differences between low, median and high flow regimes for 395 stream flow gaging stations using non parametric Mann Kendall test. (Lins and Slack, 1998). Student t-tests were used to identify the sites with significant differences in the mean rank of monthly and annual daily stream flow statistics. (McCabe and Wolock 2002).

Felden (2002) used various statistical techniques to detect trends and /or cycles using the 1900-1997 sequences of naturalized streamflows. Hubert's segmentation procedure was performed on three time-series: (1) series of mean annual flows obtained by averaging twelve monthly values (2) annual series of minimum yearly flows (3) annual series of maximum yearly flows. Linear and stepwise trend analysis was performed to detect the trends. Cycles of low flow and high flow events were detected using the Fast Fourier transform procedure.

Koltun and Kunze (2002) used a variety of graphical and statistical techniques such as time series plots, box plots, locally weighted scatter plot smoothing and Mann Kendall tests to assess the trends in stream flow. Stogner (2000) used Kendall test, which provides a probability of precipitation or stream flow to increase or decrease over time. Statistical trends were done on the daily, seasonal and annual precipitation data to determine the changes in precipitation after 1977. Streamflow changes after 1977 were determined from statistical trend tests on high and low streamflow statistics. Dewalle et al (2000) developed the regression equations to assess the stream flow changes due to the several different climate and population change scenarios.

3.3.2 SWAT Precipitation Run Off Models

Watershed models serve as a means for organizing and interpreting research data. Various watershed models had been developed in the past to quantify the streamflow changes. Soil and Water Assessment Tool (SWAT) a watershed runoff model was developed by USDA agricultural Research service (ARS). SWAT was developed to compute the sequences of streamflows, given precipitation and other climate input and specified conditions of watersheds such as land use and development. (Neitsch, et al 2002). SWAT is a continuous, physically based, time model which simulates the hydrological processes occurring in the watershed. The input information required for modeling is grouped into the following categories: climate, Hydrologic response units or HRUs, ponds/wetlands, groundwater and the main channel drawing the subbsin. HRUs are land areas within the basin which are comprised of unique land cover, soil and management combinations.

SWAT provides the methods for estimating the surface runoff- the SCS curve number and the Green Ampt infiltration method. SWAT uses Muskingum River routing or variable storage routing method for calculating the routing of water through the channel network. The major components of SWAT are sub basin, reservoir routing and channel routing. Neitsch et al (2002) showed that the hydrologic cycle simulated by SWAT is based on the water balance equation:

$$SW_t = SW_0 + \sum_{i=1}^{t} \left(R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw} \right) \tag{1}$$

Where, SWt is the final soil water content (mm H2O), $SW0$ is the initial soil content on day i (mm H2O), t is the time (days), $Rday$ is the amount of precipitation on day i (mm H2O), $Qsurf$ is the amount of surface runoff on day i (mm H2O), E_a is the amount of evapo-transpiration on day i (mm H2O), $wseep$ is the amount of water entering the vadose zone from the soil profile on day *i* (mm H2O), *Qgw* amount of return flow on day *i* (mm H2O).

Srinivisan et al (1997) used the SWAT model to simulate the hydrology from 1960 to 1989 in the Rio Grande basin located in the parts of United States and New Mexico. The simulated average annual flows were compared with the streamflow records obtained from the USGS records. Spruill et al (2001) found that the SWAT model can be an effective tool for describing monthly runoff from small watersheds however calibration data is necessary to account for solution channels draining into or out of the topographic watershed.

4 RIVER BASIN DEVELOPMENT

4.1 History of Texas

Texas is a vast and diverse state with different levels of water availability, economics, water and environmental issues. Texas encompasses 685,000 km^2 and has a population of 21 million people. Climate, geography, and water management vary dramatically across the state from the arid west to humid east, from sparsely populated rural regions to the Dallas-Fort Worth, Houston, and San Antonio metropolitan areas. Mean annual precipitation varies from 20 cm at El Paso on the Rio Grande to 140 cm in the lower Sabine River Basin. The primary source of the moisture for the state of Texas is Gulf of Mexico. In 1957, after extremely damaging floods ended the state's most severe drought of record in 1950's, the TWDB was created by state legislature. There are defined nine major and 20 minor aquifers in the state. There are about 211 major reservoirs with capacities exceeding 5000 acre-feet that have been constructed in the state of Texas. By 1900, Texas had only one major reservoir. But by 1950 the number grew to 62. The most abundant reservoir development was seen in the period from 1950 to 1970. The growth in number and storage capacity of the major reservoirs in Texas from 1900 to 2000 is presented in Table 2 and Figure 1.The state population is expected almost to double by year 2050 (TWDB, 1997). The growth in the population in the state of Texas from 1960 to 2000 is presented in Table 3 and Figure2.

Table 2. Growth in Number and Storage Capacity of Major Reservoirs in Texas.

Year	Number of Reservoirs	Total Controlled Capacity (Million acrefeet)
Before 1900	1	0.022
Before 1910	5	0.11
Before 1920	13	2.63
Before 1930	28	3.133
Before 1940	49	6.446
Before 1950	70	14.044
Before 1960	113	20.954
Before 1970	166	41.342
Before 1980	190	44.168
Before 1990	208	49.586
Before 2000	214	50.666

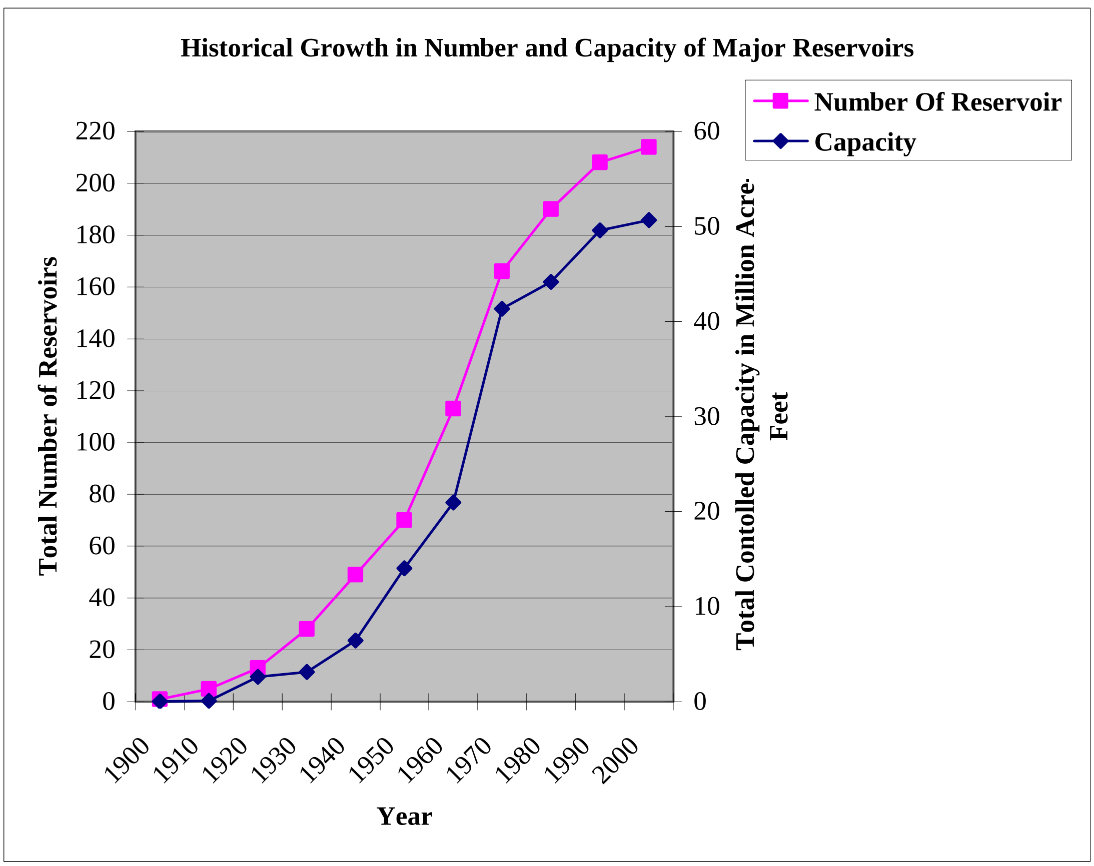

Figure 1. Historical Growth in Number and Storage Capacity of Reservoirs

Table 3. Growth in Population in State of Texas (Census Scope, 2004).

Year	1960	1970	1980	1990	2000
Population	9,579,677	11,198,655	14,229,191	16,986,510	20,851,820

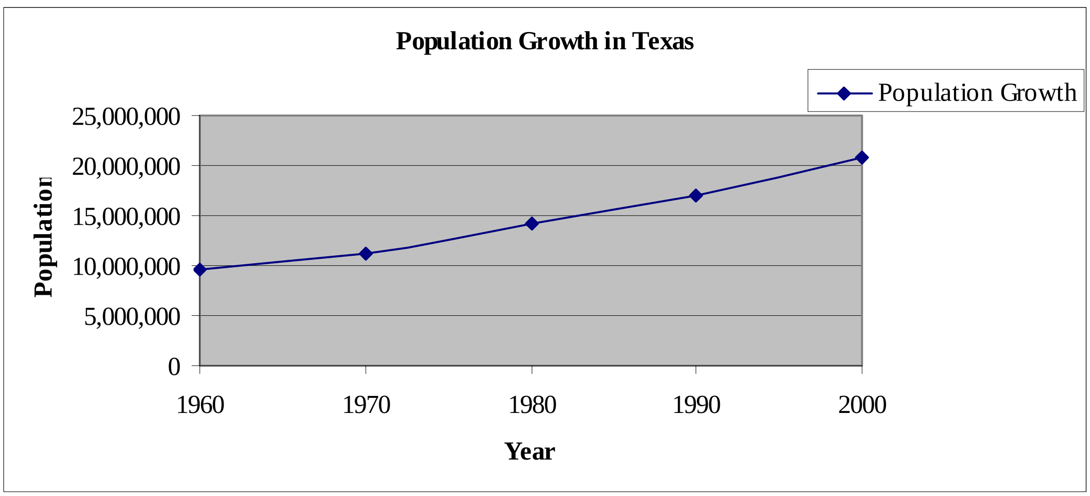

Figure 2. Population Growth in State of Texas (Census Scope, 2004)

4.2 Texas River Basins

There are 15 river basins and 8 coastal basins which traverse the state of Texas. There are about 3700 named streams and rivers that flow more that 80,000 miles of Texas landscape. (TWDB, 1997). Each of the river basins is critical for flow studies because during the past years a lot of ecological changes had been made which had affected the fish, wildlife and recreation. Various human activities have provoked the state agencies to determine the freshwater inflows in the Texas Rivers so as to conserve the natural resources and to maintain the healthy environment. Several studies have been undergoing in each of the basins to study the effects of human activities such as effects of existing reservoirs, effects of proposed reservoirs, dams and diversions. Figure 3 shows the river basins, existing reservoirs and the major rivers in the state of Texas.

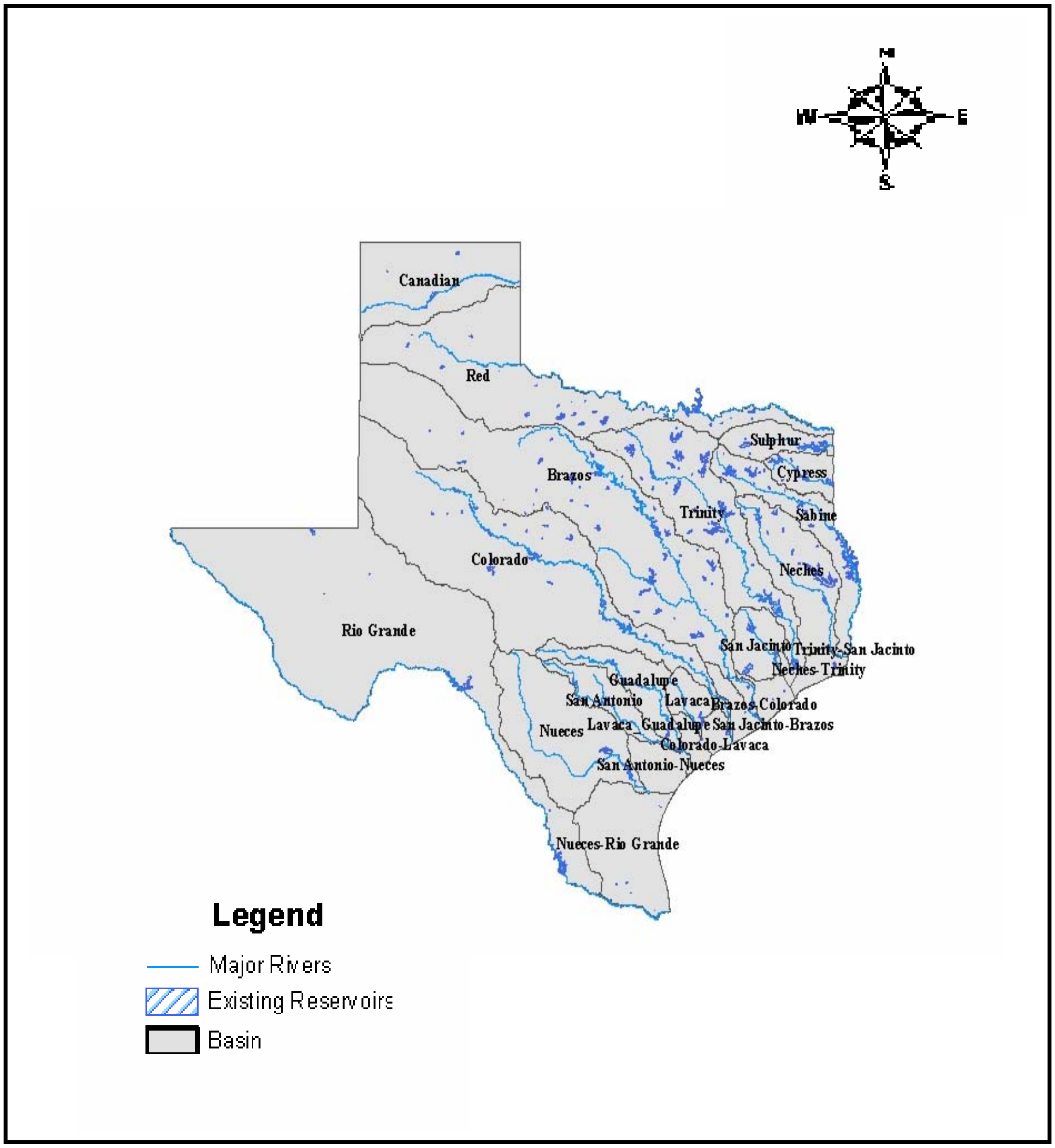

Figure 3. River Basins, Existing Reservoirs and Major Rivers in State of Texas

4.2.1 Brazos River Basin

The most diverse basin in the state due to its size and climatic variations is the Brazos River basin. The Brazos River basin is bounded on north by the Red River basin, on the east by the Trinity River basin, San Jacinto River basin, and the San Jacinto-Brazos coastal basin, and on the south and west by the Colorado River basin and Brazos-Colorado coastal basin. The total water use of about 82% is supplied by ground water resources. Irrigated agriculture is the largest water use category in the basin and accounts for nearly 77 percent of all water used. There are about 31 major reservoirs in the basin accounting for a total of 891,000 acre-feet supplies per year. The basin experiences about 15 inches per year of precipitation near the confluence of Salt Fork and Double Mountain Fork in Stonewall County to 50 inches per year near the Gulf Coast. Sub basin studies are needed so as to study the effects of several minor reservoirs constructed on the tributary streams of the Brazos River. Presently, four water surface projects are recommended for future development in the basin. The projects are Post reservoir project, Paluxy reservoir, Allens Creek reservoir and Lake Whitney relocation. Most of the Brazos is forever changed by the series of reservoirs constructed near Possum Kingdom, Whitney, Granbury, Hubbard creek and Waco. The largest city on the river is the city of Waco.

4.2.2 Canadian River Basin

The Canadian River originates from north eastern New Mexico and flows eastward across the Texas panhandle into Oklahoma and merge with the Arkansas River in eastern Oklahoma. The annual basin water use of about 99% is supplied from ground water resources. Most of the groundwater supplies are fulfilled by the large multistate Ogallala aquifer, which ranges in the thickness from 20 to 540 feet. The basin contains three major surface water reservoirs Lake Meredith, Lake Palo Duro and Rita Blanca Lake. Studies are being conducted to determine the in stream flow conditions upstream of Lake Meredith reservoir under the agreements between New Mexico and Texas governments. The Canadian River at New-Mexico stateline is saline during low flow conditions. Rita Blanca Lake faces increased bacterial concentrations and elevated pH levels due to domestic waste water discharges from the city of Dalhart.

4.2.3 Colorado River Basin

The basin is bounded on the north and east by the Brazos River basin and Brazos-Colorado Coastal basin and on the south and west by Lavaca, Guadalupe, Nueces and Rio Grande basins and the Colorado-Lavaca Coastal Basin. The total water use of about 71% is supplied from the ground water supplies. The largest water use category in the basin is irrigated agriculture which accounts for about 71 percent of all water use. The major aquifers in the state are Ogala aquifer, Edwards Trinity and

Dockum aquifers. There are about 26 major reservoirs in the state. Mansfield Dam and Travis Lake have protected the downstream reaches of the lower Colorado basin by reducing the impact of floods.

4.2.4 Guadalupe River Basin

The basin is bounded on north by the Colorado River basin, on the east by Lavaca River basin and Lavaca-Guadalupe coastal basin, and on the west and south by the Nueces and San-Antonio River basin. The total water use of about 52% is supplied by surface water resources and the rest by ground water resources. Municipal is the largest water use category which accounts for about 45 percent of total water use. The headwaters of the Guadalupe are west of Kerrville on the Edward's plateau. The Trinity, Edwards-Trinity and Edwards-Balcones aquifers are the major sources of ground water supplies.

4.2.5 San-Antonio River Basin

The San-Antonio River basin is bounded on the north and east by Guadalupe River basin and on the west and south by the Nueces River basin and the San-Antonio Nueces coastal basin. The total water use of about 88% is supplied by Ground water resources. The major aquifer in the state is Edward's aquifer which supplies most of the water. There are four major reservoirs in the basin. The major water issues in the basin are poor water quality particularly during periods of low flow and over pumping of ground water. Municipal waste water discharges are the primary source of concern in the basin.

4.2.6 Neches River Basin

The Neches River basin is bounded on the north and east by the Sabine River basin, on the west by the Trinity River basin and on the south by the Neches-Trinity Coastal basin. The annual basin water use of about 55% is supplied by surface water and the remaining 45% by ground water resources. There are about ten major water supply reservoirs. Sam Rayburn is the only reservoir which contains 84 percent of the total storage capacity. The basin has got abundant water resources which can be used both inside and outside of the basin. The development in the Beaumont-Port Arthur-Orange metropolitan area has produced a large scale impact on the streamflows. Upstream diversions, particularly during the rice growing season had resulted in the lower reaches of river being composed of treated waste water industrial discharges

4.2.7 Nueces River Basin

The basin is bounded on the north and east by the Colorado, San Antonio, Guadalupe River basin and San Antonio-Nueces coastal basins and on the west and south by Rio Grande basin and the Nueces Rio Grande coastal basin. The basin's water use of about 76% is supplied by the ground water resources. The basin predominantly has an agriculture based land use. Three major reservoirs had been constructed in the basin. The city of Corpus Christi is the single largest user of water from the basin. The city of Corpus Christi operates Choke Canyon reservoir and Lake Corpus Christi for its water needs.

4.2.8 Red River Basin

The Red River basin is bounded on the north by the Canadian River basin and on the south by Brazos, Trinity and Sulphur River basins. The Red River extends from the northeast corner of the state, along the Texas/Arkansas and Texas/Oklahoma state borders to its headwaters in eastern New Mexico. The annual basin water use of about 88% is supplied from surface water resources and the remaining 12% is supplied by ground water resources. There are about 32 surface reservoirs in the basin which regulate the rivers and streams of the basin. Various salt pollution areas are located in the basin. A lot of site specific studies have been going to study the impacts of the chloride control projects on the water resources.

4.2.9 Sabine River Basin

The Sabine River basin is bounded on the north by the Sulphur River and the Cypress creek basins, on the west by Trinity and Neches River basin and on the east by Texas-Louisiana border. The annual basin water use of about 81% is supplied from surface water and the remaining 19% is supplied from ground water resources. There are about 12 major reservoirs in the state of Texas. The basin is studied for its potential for substantial water transfers. Water conservation practices are implemented in areas of rapid population growth so as to fulfill the demands in water poor areas. The growth of the oil industry in the Beaumont-Port Arthur-Orange metropolitan area had led to the clean waters becomes increasingly polluted. Upstream diversions had resulted in the lower reaches of river being frequently composed of a large %age of treated municipal and industrial effluent.

4.2.10 Sulphur River Basin

The Sulphur River basin in the northeast Texas is bounded on the north by the Red River basin, on the west by Trinity River basin, and on the south by the Sabine and Cypress River basin and on the east by Texas-Arkansas border. The annual basin water use of about 91% is supplied by surface water resources. The existing major reservoirs are Lake Sulphur springs, Lake Wright Patman and Lake Cooper. The large portion of the basin is rural in nature. Studies are being conducted to study the impacts of future reservoir projects such as Marvin Nicholos Reservoir I on streamflows and the fish communities in the downstream river reaches.

4.2.11 Trinity River Basin

The Trinity River basin is bounded on the north by Red River basin, on the east by the Sabine River basin and on the west by the Brazos and San Jacinto River basins. The annual basin water use of about 90% is supplied form the surface water resources. The largest water use category in the basin is municipal which accounts for 75 percent of all the water used in the basin. There are about 30 major reservoirs in the basin. A lot of water reuse projects needs to be evaluated so as to study the in-stream flow needs. The municipal supplies in the basin are provided by the reservoirs in the upper branches which were constructed to control the floods. The runoffs from the Dallas-Fort worth metroplex have caused severe deterioration water quality problems.

4.2.12 Cypress River Basin

The Cypress River basin is bounded on the north by Sulphur River basin, on the west and south by the Sabine River basin, and on the east by Texas-Arkansas and Texas-Louisiana border. The annual basin water use of about 89% is supplied from surface water resources and the remaining 11% is supplied by ground water resources. There are about eight major water supply reservoirs. In future reuse is considered as the source of water for steam electric generation and industrial water needs. Streams in the cypress River basin exhibit low dissolved oxygen concentrations.

4.2.13 Lavaca River Basin

The Lavaca River basin is bounded on the north and east by the Colorado River basin or the west by Guadalupe River basin, and on the southwest by Lavaca-Guadalupe coastal basin, and on the southwest by Lavaca-Guadalupe coastal basin. The total water use of about 59% is supplied by ground water resources. The basin's water needs are met by Gulf Coast aquifer, Lake Texana and imports of surface water from Colorado basin. The major water supply problems in the basin are the over pumping of the Gulf Coast aquifer and inadequate water releases from the reservoir for bay and estuary flow needs.

4.2.14 San Jacinto River Basin

The San Jacinto River basin is bounded on the north and east by the Trinity River basin and Trinity-San Jacinto Coastal basin, on the west by Brazos River and on the south by San-Jacinto Brazos Coastal basin. The annual basin water use of about 59% is supplied by ground water resources and about 41% is supplied by surface water. San Jacinto is the second most populated basins in Texas. The basin has got two water supply reservoirs, Lake Conroe and Lake Houston. Major water related problems in the basin are flooding, poor quality of surface and ground water, environmental concerns for wetlands and Galveston bay. The basin included the most highly urbanized and industrialized portions of the Houston metropolitan area. The future water supplies are expected to be met from the additional supplies of water from Sabine and Trinity River basins.

4.2.15 Rio Grande River Basin

The Rio Grande basin is bounded on the east by the Colorado and Nueces River basins and the Nueces-Rio Grande Coastal basin, on the north by the state of New Mexico, and on the south by Mexico. The total basins water use is supplied from surface water resources which accounts for about 66% of water. About 75% of water consumption accounts for the irrigated agriculture. There are two large international projects on the Rio Grande River. International Falcon and Amistad reservoirs were constructed under the terms of 1944 treaty between United States and New Mexico. El Paso County, one of the most populated portions of the basin gets water from the Rio Grande project of New Mexico- Texas with water from Elephant Butte reservoir in New Mexico. El Paso is facing severe irrigation deficit nowadays. The city’s future water sources would be the reuse of municipal waste water reuse and desalination technology to desalt groundwater.

5 RESEARCH METHODOLOGY

5.1 Outline

The research is outlined as follows:

1. The central focus of the research was the development of indices describing changes in streamflow characteristics at selected locations throughout Texas based on sequences of monthly naturalized and regulated flows from the WAM system.
2. Trend analysis of measured monthly and annual flows at selected gauging stations provided the comparative measures of long-term trends or changes.
3. The results of the analysis explained where, how, and to what extent stream flow characteristics have changed in Texas over the past several decades.
4. The literature review covered:
    - watershed modeling, statistical, and other methodologies for quantifying changes in streamflow characteristics
    - studies quantifying changes in streamflow characteristics in particular river basins or regions throughout the world
    - information regarding hydrology and water resources development in the river basins of Texas.

5.2 Data Collection

The basic procedure in analyzing the changes in streamflow characteristics in a particular river basin involves the development of the naturalized and regulated stream flows throughout the basin from historical hydrologic data and other gathered information. The monthly naturalized flows for the Texas basins were developed by private consulting firms and various research entities from the period 1997-2003. The monthly naturalized database covers the 50-61 year period for the basins of Texas. These long duration datasets included several wet periods and the dry periods of 1950's and 1990's.

The hydrologic data for the most of the basins is available in three regulated flow scenarios- WAM run 1, WAM run 3 and WAM run 8. WAM run 1 considers a full permitted use and current return flows. WAM run 3 adopts full permitted use and no return flows. In WAM run 8 (current conditions), maximum reported use of water within the last ten years and minimum return flows for the last five years. The naturalized and regulated flows were determined using the Texas WAM system for the current condition flow scenario. The simulations were performed by the computer program WRAP that was developed at Texas A&M University.

Historical streamflow records for the gages were downloaded from the USGS and IBWC sites. USGS maintains the daily, monthly and annual streamflow records for most of the streamflow gaging stations in the U.S (USGS, 2003). IBWC maintains the daily records for the streamflow gaging stations whose flows are shared by the state of Texas and Mexico (IBWC, 2004).

5.3 Study Area

Fifteen river basins located in the state of Texas were selected as suitable study basins. The state of Texas was chosen as the study region so as to compare the results of the Texas WAM system with the monthly and annual USGS and IBWC streamflows. The study had taken into account six time series of streamflows corresponding to six streamflow gauging stations for the Brazos River basin, eight time series of streamflows corresponding to eight streamflow gauging stations for the Rio Grande basin and one times series for each of the selected streamflow gaging station for the rest of the basins. The gaging stations selected for the study are listed in Table 4 with their locations, WAM control points and USGS gage numbers.

Table 4. Location of Gaging Stations with their WAM Control Point and USGS Gage Number.

River	Basin Name	Location	WAM Control Point	USGS Gage Number
Brazos	Brazos	Southbend	BRSB23	8088000
Brazos	Brazos	Aquilla	BRAQ33	8093100
Little	Brazos	Cameroon	LRCA58	8106500
Brazos	Brazos	Bryan	BRBR59	8109000
Brazos	Brazos	Hempstead	BRHE68	8111500
Brazos	Brazos	Richmond	BRRI70	8114000
Canadian	Canadian	Near Canadian	B10000	7228000
Colorado	Colorado	Columbus	J10000	8161000
Guadalupe	Guadalupe	Victoria	CP37	8176500
San Anatonio	San Anatonio	Goliad	CP15	8188500
Neches	Neches	Evadale	NEEV	8041000
Nueces	Nueces	Mathis	CP30	8211000
Red	Red	Index,Arkansas	Y10000	7337000
Sabine	Sabine	Near Bon Weir	SRBW	8028500
Sulphur	Sulphur	Near Talco	E250	7343200
Trinity	Trinity	Romayor	8TRRO	8066500
Little Cypress creek	Cypress	Near Jefferson	E10000	7346070
Lavaca	Lavaca	Near Edna	WQ002	8164000
W Fk San Jacinto	San Jacinto	Near Conroe	WSCN	8068000
Pecos	Rio Grande	Red Bluff, New Mexico	GT5000	8407500
Pecos	Rio Grande	Girvin	GT2000	8446500
Rio Grande	Rio Grande	EL Paso	AM/AT2000	8364000
Rio Grande	Rio Grande	Fort Quitman	AM/AT1000	8370500
Rio Grande	Rio Grande	Johnson Ranch Near Castolon	CM/CT4000	8375000
Rio Grande	Rio Grande	Laredo	DM/DT3000	8459000
Rio Grande	Rio Grande	Below Anzalduas Dam	EM/AT1000	8469200
Rio Grande	Rio Grande	Brownsville	EM/AT0000	8475000

The WAM control point, ‘ET0000/EM0000’, is the basin outlet. The streamflow gaging station ‘Rio Grande’ at Brownsville is the most downstream gaging station near the outlet having historical records for a significant period of time. Considering their close proximity in the river basin, for all practical purposes these points are considered to be the same.

All these gaging stations were selected because of their strategic locations and relatively long periods of streamflow records. The goal is to choose the control point which is on the major river near the outlet of the basin and has the longest time series. Available USGS and WAM period of records for the selected control points are listed in Table 5. Figure 4 shows the location of the selected control points in the Texas river basins.

Table 5. USGS and WAM Period of Records.

River	Location	Period of Records	
		USGS	WAM
Brazos	Southbend	1940-2000	1940-1997
Brazos	Aquilla	1940-2000	1940-1997
Little	Cameroon	1920-1999	1940-1997
Brazos	Bryan	1920-1992	1940-1997
Brazos	Hempstead	1940-2000	1940-1997
Brazos	Richmond	1930-2000	1940-1997
Canadian	Near Canadian	1940-1999	1948-1998
Colorado	Columbus	1920-2000	1940-1998
Guadalupe	Victoria	1940-2000	1934-1989
San Anatonio	Goliad	1940-2000	1934-1989
Neches	Evadale	1930-2000	1940-1996
Nueces	Mathis	1940-2000	1934-1996
Red	Index,Arkansas	1940-2000	1948-1998
Sabine	Near Bon Weir	1930-2000	1940-1998
Sulphur	Near Talco	1957-2000	1940-1996
Trinity	Romayor	1930-2000	1940-1996
Little Cypress creek	Near Jefferson	1947-2000	1948-1998
Lavaca	Near Edna	1940-2000	1940-1996
W Fk San Jacinto	Near Conroe	1940-2000	1940-1996
Pecos	Red Bluff, New Mexico	1940-2000	1940-2001
Pecos	Girvin	1940-2000	1940-2001
Rio Grande	EL Paso	1921-2000	1940-2001
Rio Grande	Fort Quitman	1923-2000	1940-2001
Rio Grande	Johnson Ranch Near Castolon	1941-2000	1940-2001
Rio Grande	Laredo	1931-2000	1940-2001
Rio Grande	Below Anzalduas Dam	1952-2002	1940-2001
Rio Grande	Brownsville	1934-2000	1940-2001

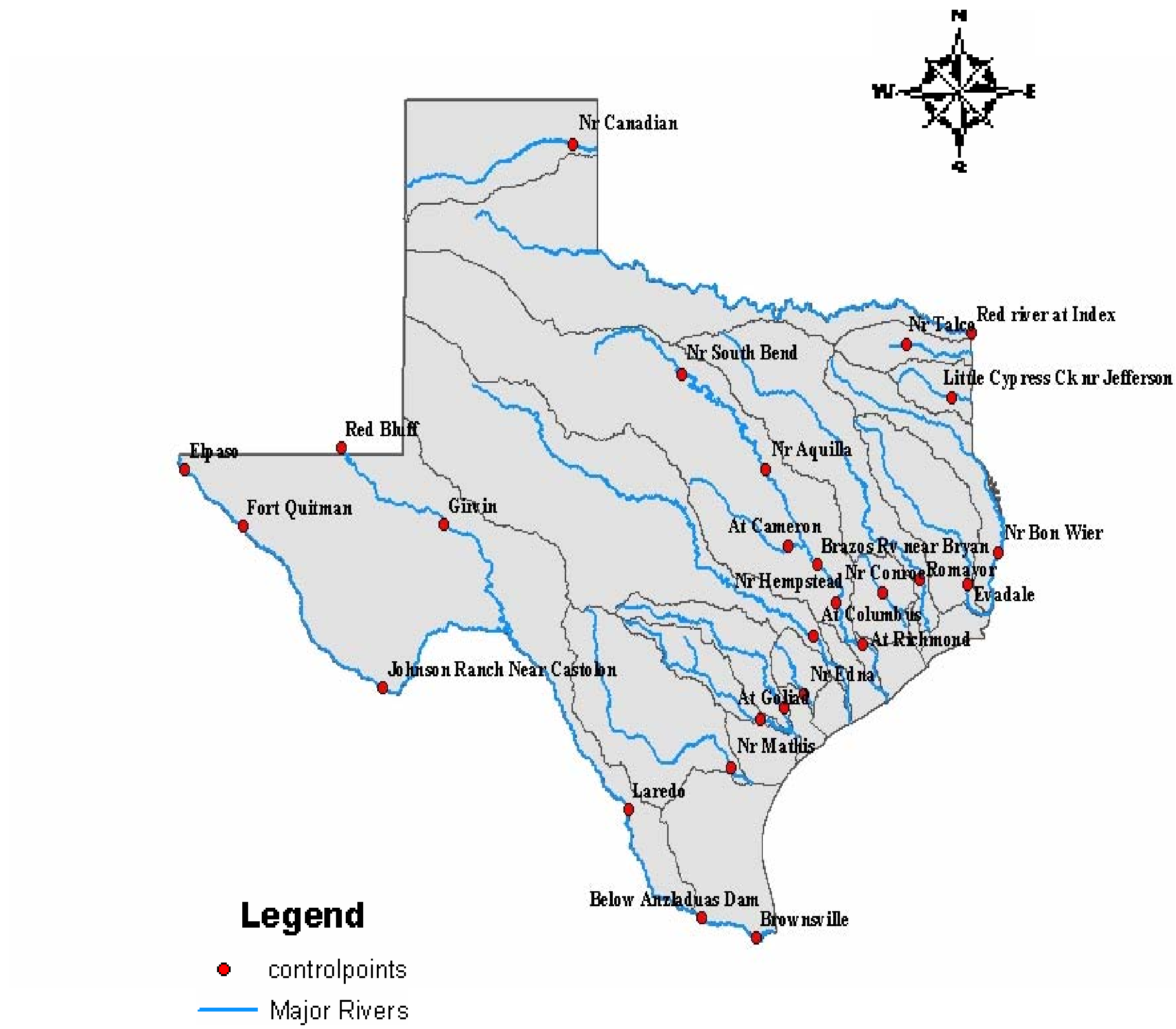

Figure 4. Location of the Selected Control Points in the Texas River Basins

5.4 Naturalized Flows

Long term changes in streamflow characteristics were analyzed by comparing naturalized and regulated flows determined using the Texas WAM system. As previously discussed, naturalized flow is defined as the flow in the stream that would have been present with no water resources development and use.

“Streamflow naturalization” is the process of removing the various human related impacts from the historical streamflows. The purpose of streamflow naturalization process is to develop a homogeneous set of flows representing a specified condition of river basin development. The sequences of historical monthly natural flows are developed by adjusting the recorded flow at gaging stations. This is achieved by removing the past impacts of upstream major reservoirs, water supply diversions, return flows from surface and ground water resources and other related factors (Wurbs, 2003b). The naturalized flows were developed from the most upstream gage to the downstream gage. The naturalized flows for the Texas WAM were developed by various private consulting firms and research entities with the help of USGS/IBWC electronic records, TCEQ’s central records file and by contacting individual water right holders.

The various concerns regarding the development of the streamflow naturalization process are listed below:

1. The inaccuracies of the USGS/IBWC streamflow gaging data, storage records, channel losses and reported and estimated diversions and return flows.

2. Since the Rio Grande is shared between the Mexico and the state of Texas, one of the concerns was to model the Mexican portion of the basin. Mexico does not have an organized system to allocate water; therefore, the quality of data from sources in Mexico is poor. (Brandes, 2004).

5.5 Overview of Analysis

5.5.1 WAM Analysis

For each of the gaging stations the current condition scenario (WAM run 8) was executed for the Texas WAM and the naturalized and regulated flows were extracted from the output file. USGS and IBWC gage numbers were related with the WAM control points. The selection of the control points was done with the help of ArcGIS and maps showing streamflow gaging stations, reservoir stations and river stream networks.

For the control points which are on the Rio Grande, the naturalized and regulated flows were divided between the Mexico portion and the portion lying within the state of Texas. The monthly and annual values of the regulated and naturalized flows obtained for the Mexico and portion within Texas were added to get the total flows at these control points. Frequency analysis was performed for the simulated flows to determine the flow that is equaled or exceeded in 10%, 25%, 50%, 75%, 90% and 100% of the months of the hydrologic period-of-analysis. This can be performed by arranging the annual series of flows in the order of their magnitude and the percent of time each annual flow is equaled or exceeded. Flow change indices for the selected sites were computed as the ratio of regulated flows to the naturalized flows. At a given site, for a specified exceedance frequency, the index was computed as

$$index = \frac{regulatedflow(amount)}{naturalizedflow(amount)}(100\%) \tag{2}$$

where both the regulated and the naturalized flow amounts are for the same specified exceedance probability.

5.5.2 Trend Analysis

Urbanization over the past years and the resulting increase in flooding has necessitated the need for new statistical methods. Watershed characteristics have altered drastically due to the changes associated with the human activities. Watershed changes can produce an abrupt change or a secular trend in the flow series. An abrupt change (such as channelization of a stream reach) occurs in very short time duration as compared to the flow series record. Secular trend happens when the changes (such as gradual urbanization) in watershed occurs over a long period of time. It is a tendency to increase or decrease continuously for an extended period of time. In hydrologic analysis, secular changes are more common as compared to abrupt changes.

The flow series contains considerable amount of random variation which generates the non-homogeneity. The effects of non-homogeneity can be assessed by both graphical presentations and statistical testing of the data. (McCuen, 2003). The graphical analysis allows the hydrologist to incorporate physical processes associated with the independent variable into the decision making process. The limitation of graphical analysis is that it is largely limited to two or three dimensions at a time. The best technique to study the non-stationary, non-homogeneous data is using the statistical tests. The limitation of the test is that it only decides whether a significant effect exists or not. It does not model the effect. Time series are analyzed to predict the magnitude of a random variable with respect to the independent variable i.e. time.

The annual gaged flows from USGS and daily gaged flows from IBWC were used for the analysis. The annual gaged flows from USGS were converted to acre feet from cubic feet per second. The daily gaged flows from IBWC were aggregated to get an annual value and were converted to acre feet from cubic meters per second. Time series analyses were performed for each of the control points and represented as (1) naturalized flows (2) regulated flows (3) historical streamflows. Linear or long term trend analyses were performed on the flow series. Linear Trend analysis consists of the process in which the mean value varies linearly over the data record.

Stepwise trend analysis was performed on the historical flow series. Traditional methods were adopted for calculating the step wise trend. Ten year mean value was calculated for the flow series. Step wise trend consists of a step change in the means. A lot of non-homogeneity and random variation was observed in the step-wise trend analysis. Therefore, not much of the further analysis was performed.

6 TREND ANALYSIS

Streamflow characteristics vary tremendously over time. Both, human and climatic factors have changed streamflows in a slow and continuous manner. Various WRAP simulations had been made for different locations to show the alterations in streamflows. These simulations include monthly and annual hydrologic conditions. This section describes the summary of the results from different WRAP runs and performs a trend analysis on historical flow series.

To illustrate the alterations in the streamflows in the Texas river basins, different simulation results are graphically displayed. These graphs include the naturalized flow series, regulated flow series, and historical flow series at locations throughout the state of Texas. Flow series were analyzed for any significant trends over the time period of analysis. Figures are included to show the annual quantities of the flows for the analysis period.

Several control points were chosen on the rivers in the state of Texas to show the annual amounts of the simulated naturalized and regulated flows and the actual historical flows. The annual quantities of the historical flows are for the period of years for which the continuous data, without any missing values, is available on the USGS and IBWC sites. As expected, these results indicate that the streamflows are altering with time.

6.1 Brazos River Basin

Six control points were chosen on the rivers in the Brazos River basin. The annual quantities of the naturalized and regulated flows are for the 1940-2000 period. Figure 5 shows the location of the control points in the Brazos River basin.

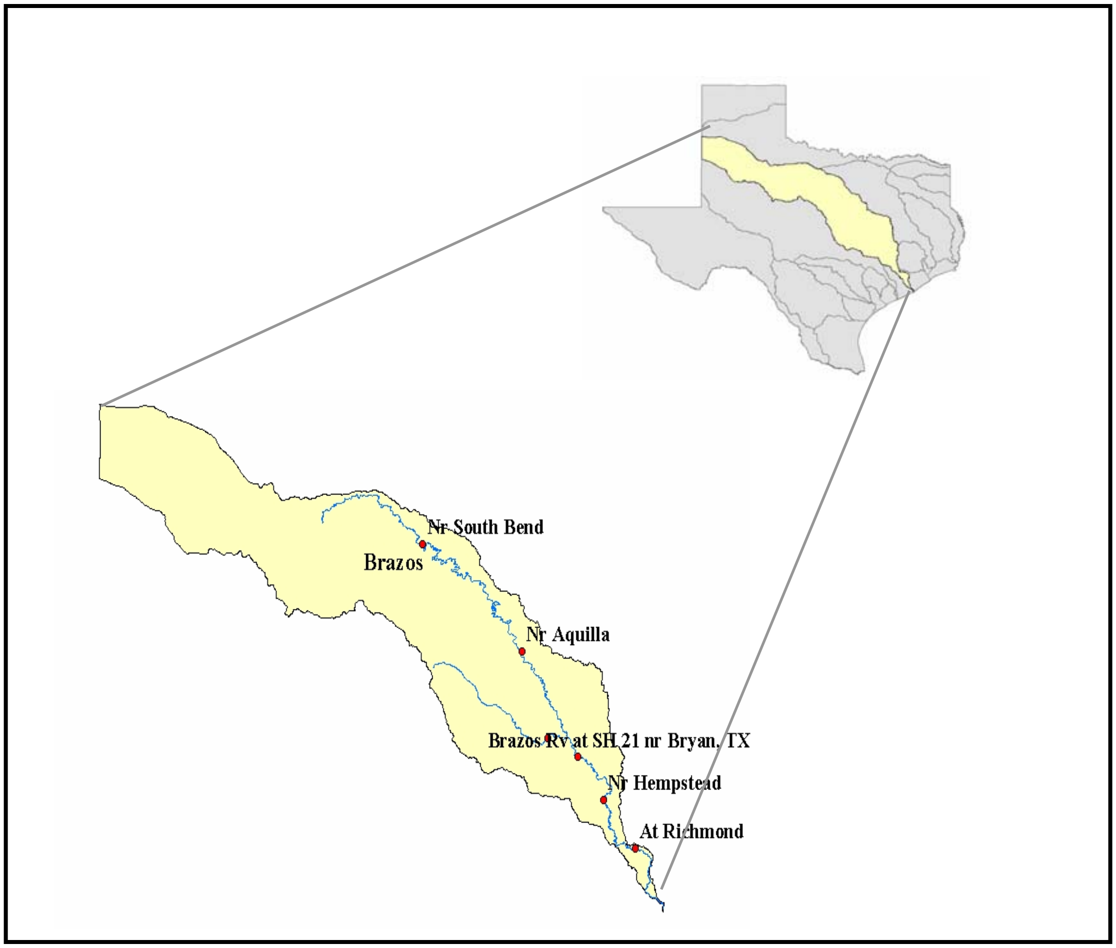

Figure 5. Location of Control Points in Brazos River Basin for Trend Analysis

The plots illustrate the changes in the streamflows brought over a period of years as a result of human activities in the watershed. All the flow series for this basin show high flows during early 1940’s, late 1950’s and early 1990’s and low flows during mid 1950’s and mid 1990’s.

1. Southbend is downstream of the confluence of Brazos River and Clean Fork Brazos River. The flows at this control point are controlled largely by the Hubbard Creek reservoir. The flow series of naturalized, regulated and historical flows do not show any significant linear trend.
2. The flows at Aquilla are controlled largely by the Lake Whitney. The flow series of naturalized, regulated and historical flows do not show any significant linear trend.
3. The flows at Cameroon on the Little River do not show any significant linear trend. The flows at this location are controlled by the Belton Lake. The flows at this location face severe water shortage problems during the length of the flow series.
4. Bryan is downstream of the confluence of the Brazos and Little River. The flow series do not show any significant linear trend.
5. Hempstead is downstream of the confluence of the Brazos and Yegua creek. The flow series do not show any significant linear trend.
6. Richmond is near the outlet of the Brazos River basin. No significant linear trend is observed. Figures 6 to 29 contrasts the naturalized, regulated and observed historical flows for the selected control points in Brazos River basin.

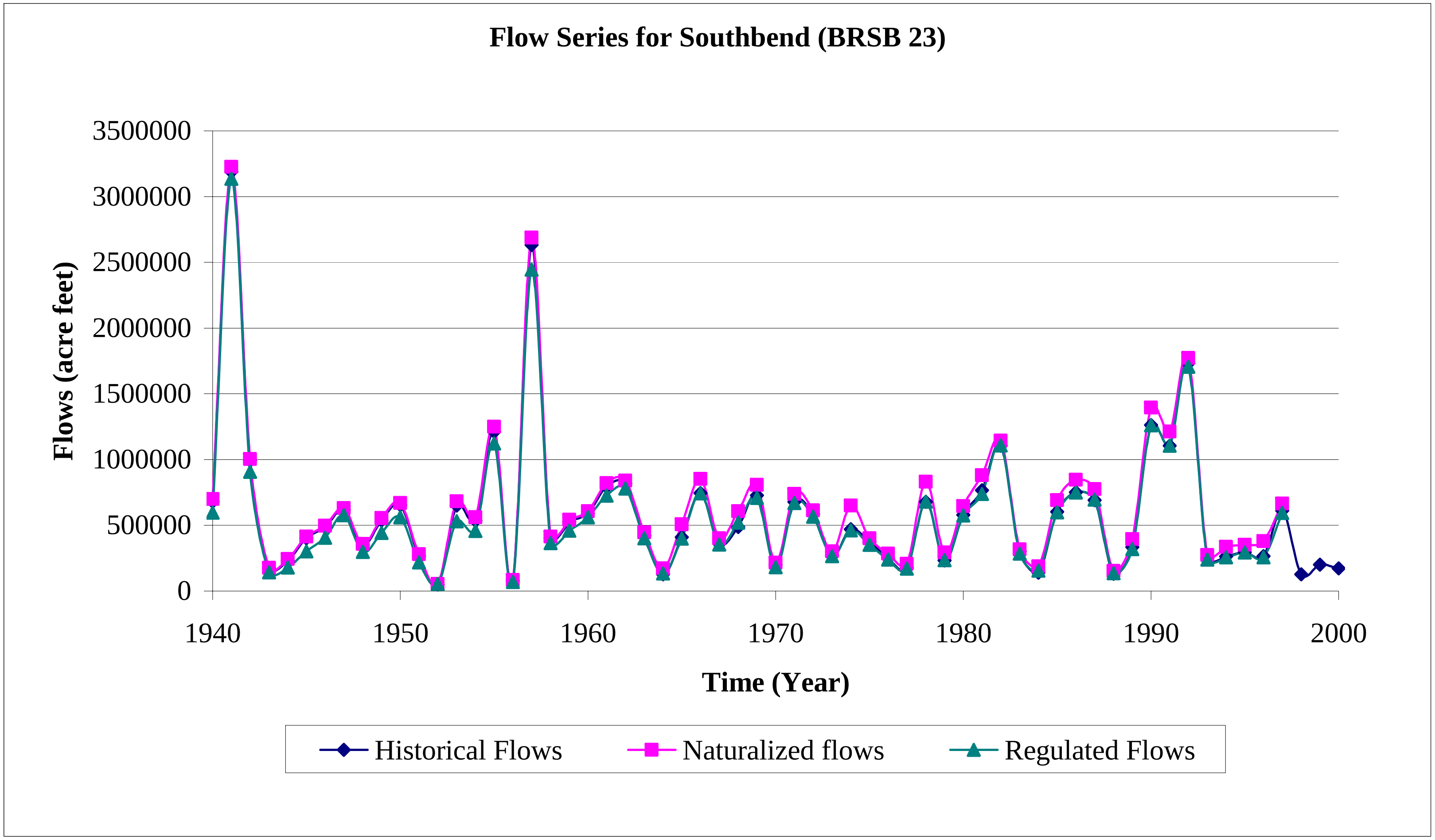

Figure 6. Flow Series for Southbend

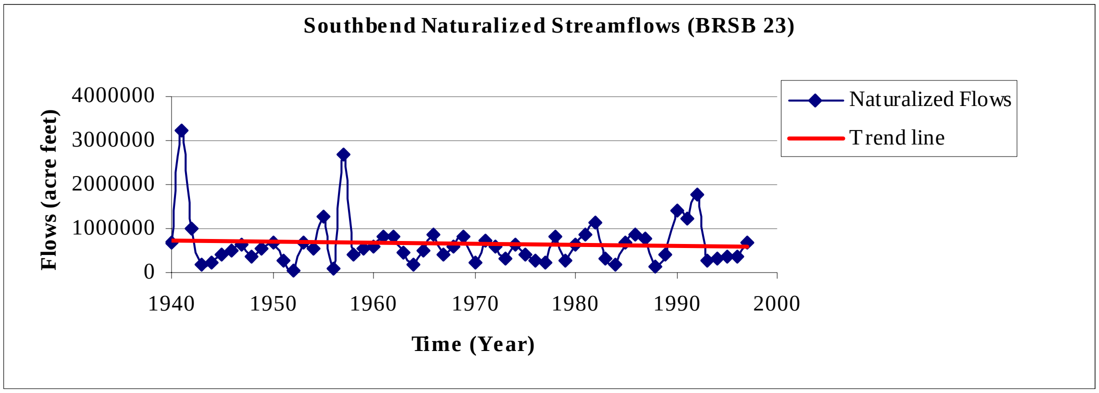

Figure 7. Naturalized Streamflows for Southbend

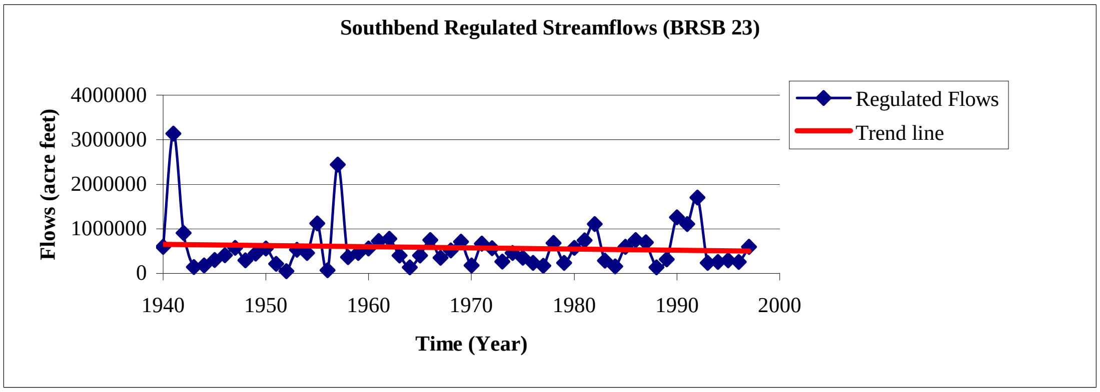

Figure 8. Regulated Streamflows for Southbend

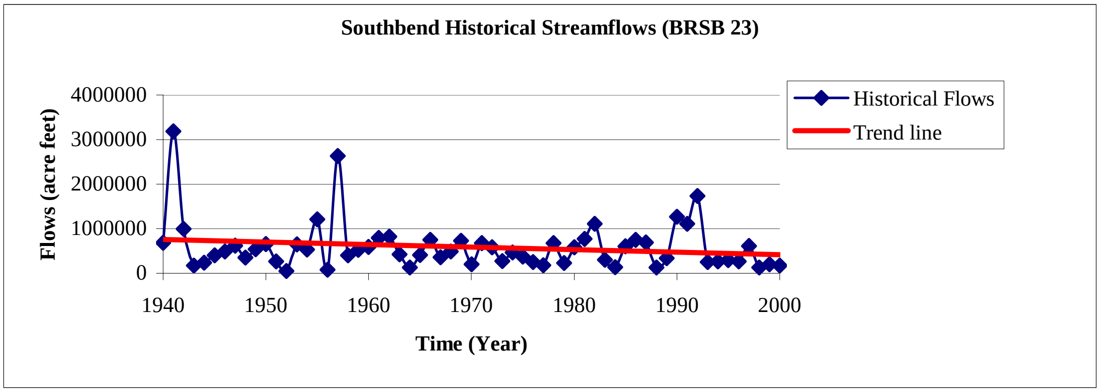

Figure 9. Historical Streamflows for Southbend

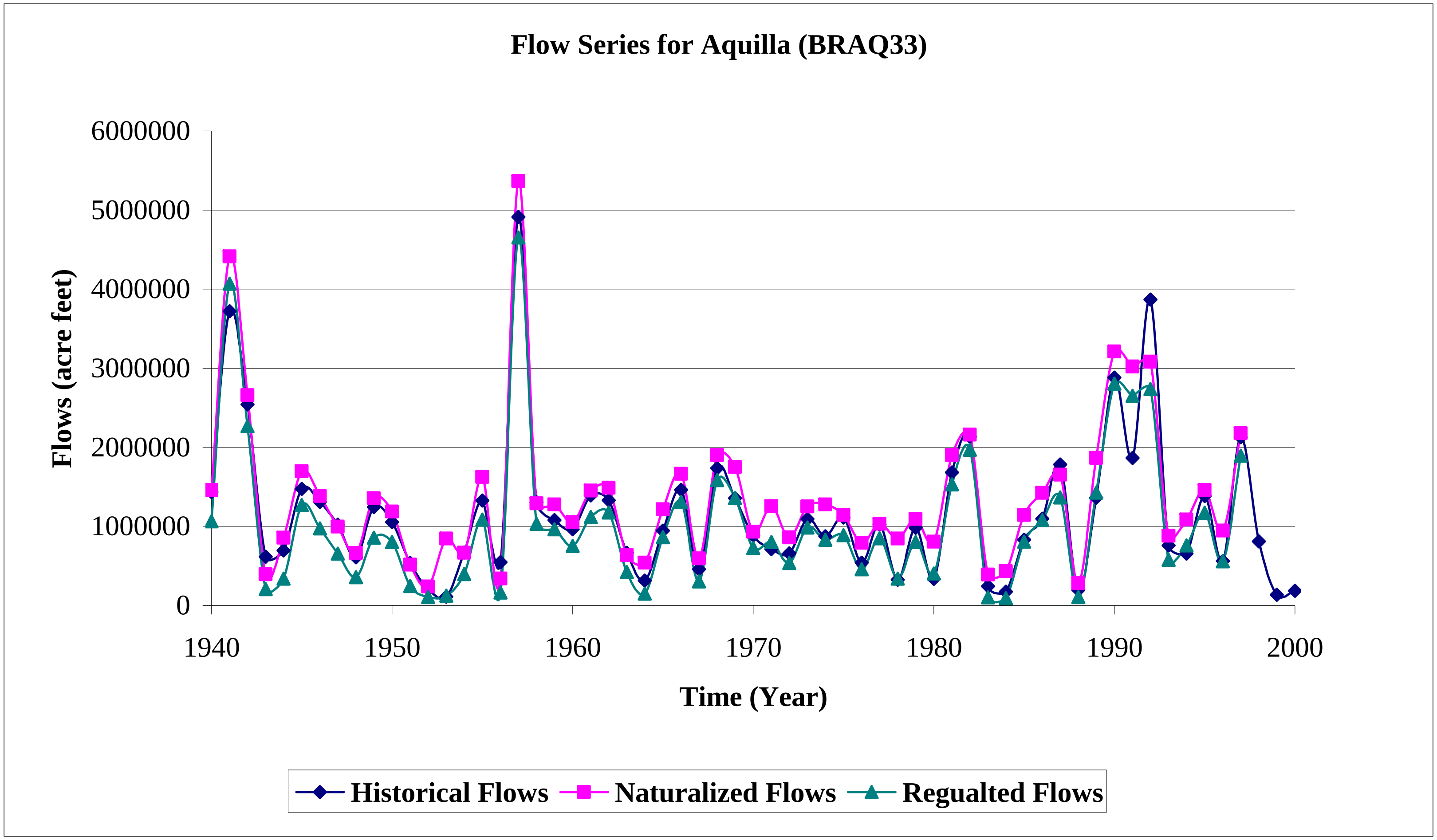

Figure 10. Flow Series for Aquilla

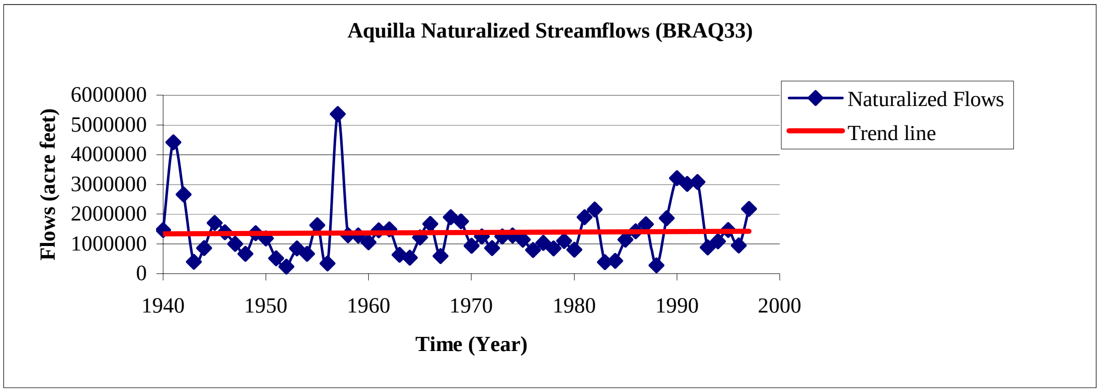

Figure 11. Naturalized Streamflows for Aquilla

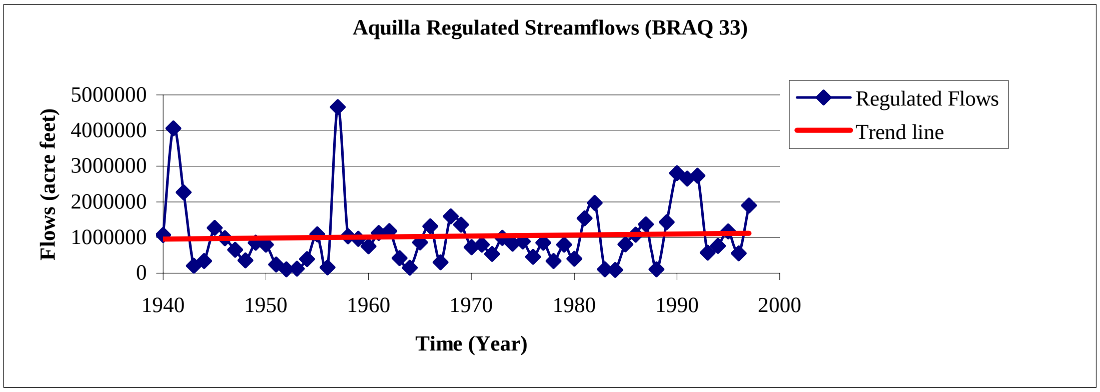

Figure 12. Regulated Streamflows for Aquilla

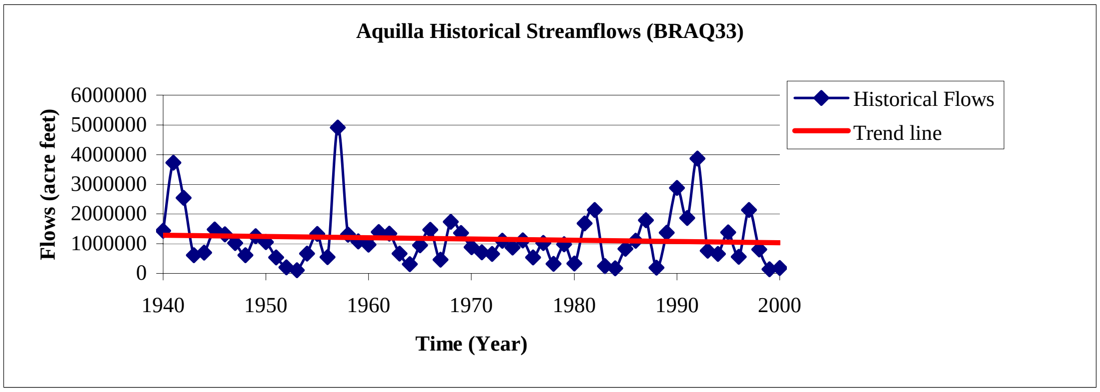

Figure 13. Historical Streamflows for Aquilla

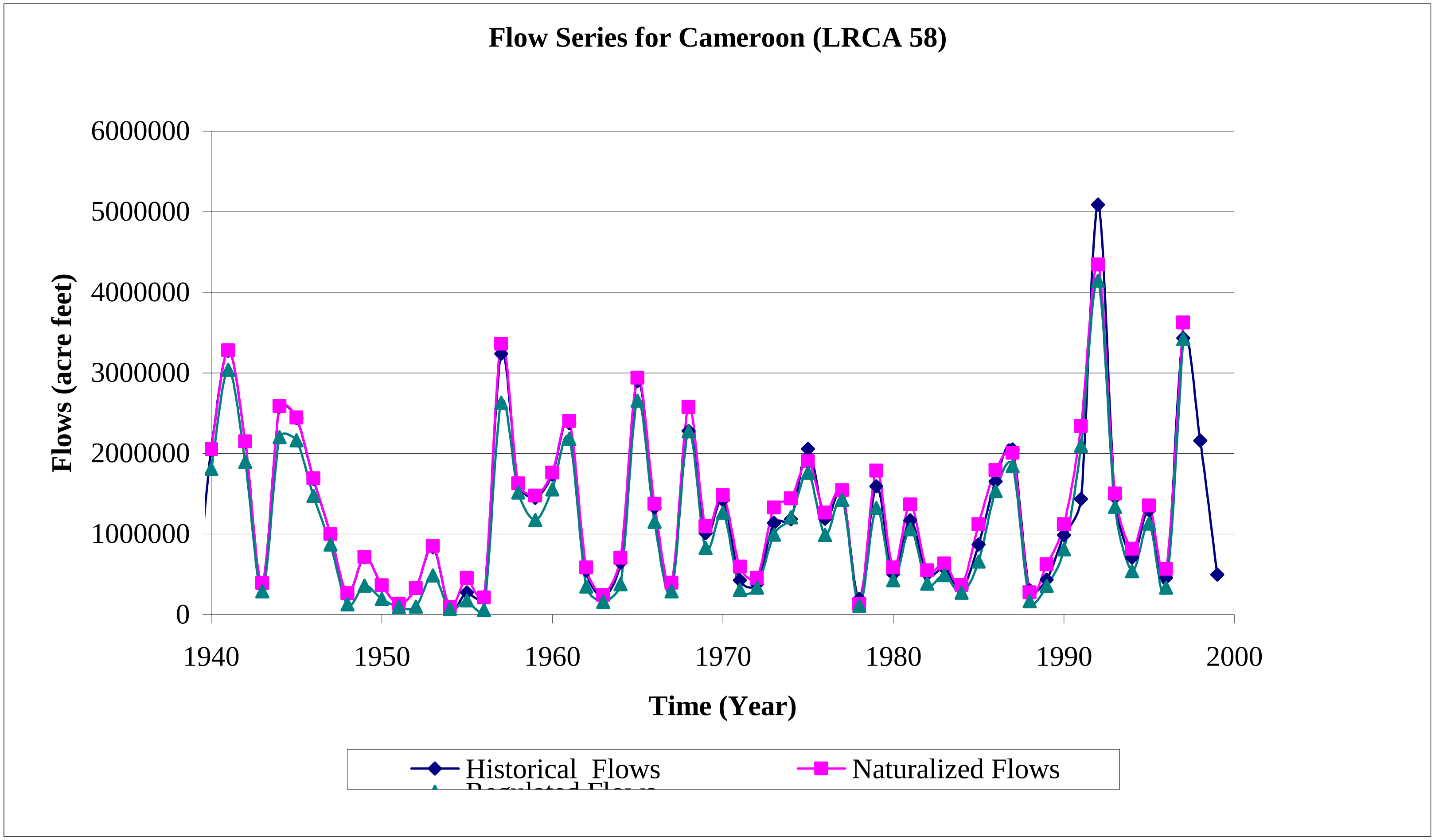

Figure 14. Flow Series for Cameroon

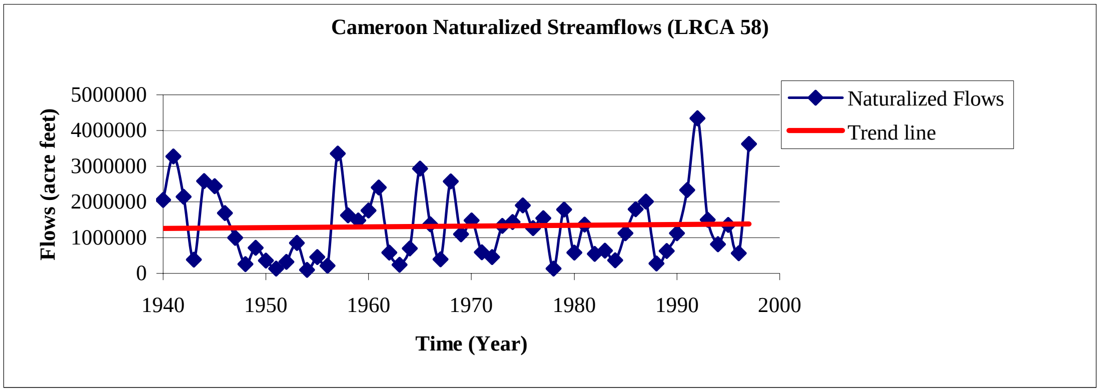

Figure 15. Naturalized Streamflows for Cameroon

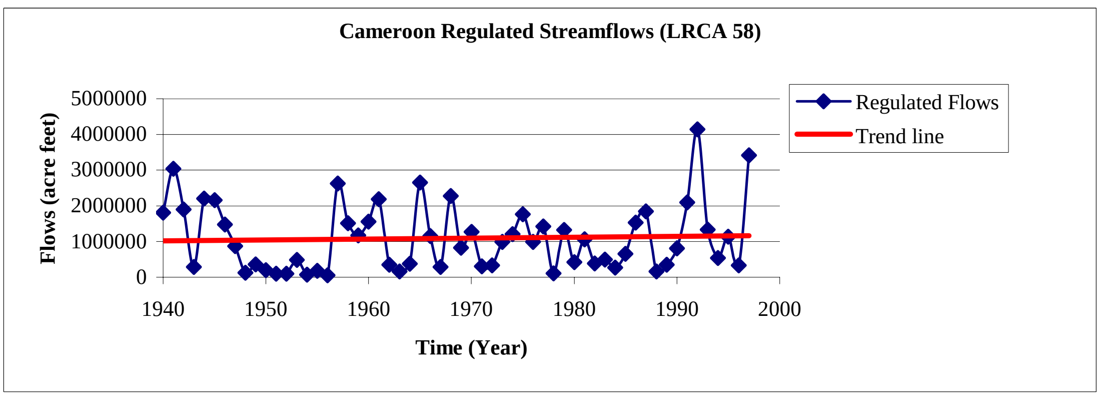

Figure 16. Regulated Streamflows for Cameroon

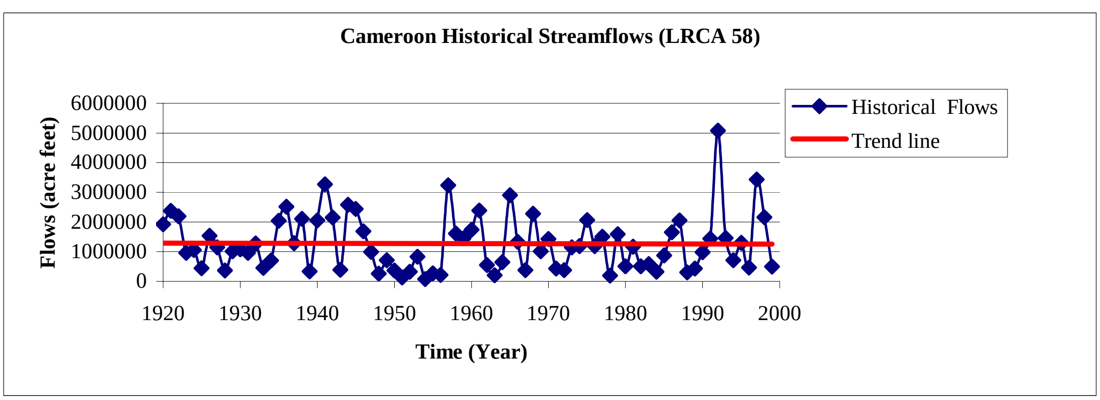

Figure 17. Historical Streamflows for Cameroon

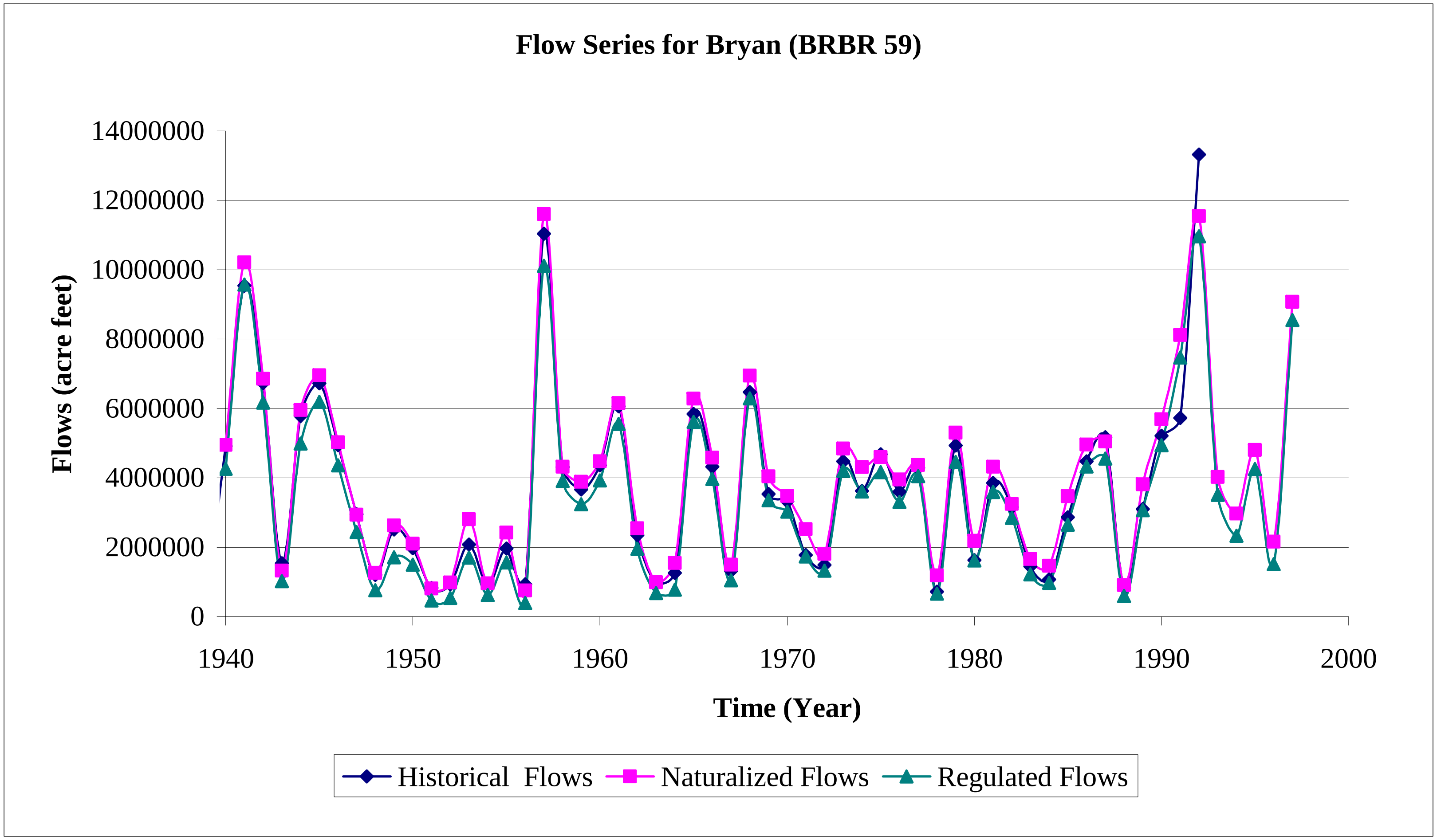

Figure 18. Flow Series for Bryan

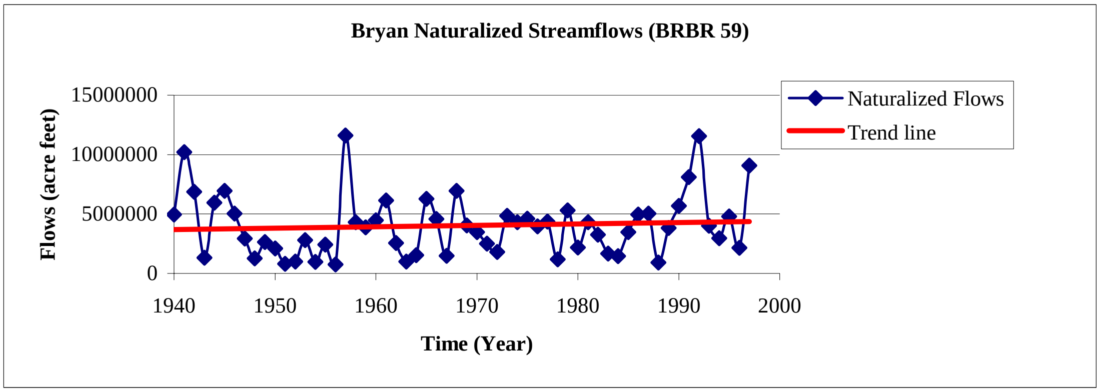

Figure 19. Naturalized Streamflows for Bryan

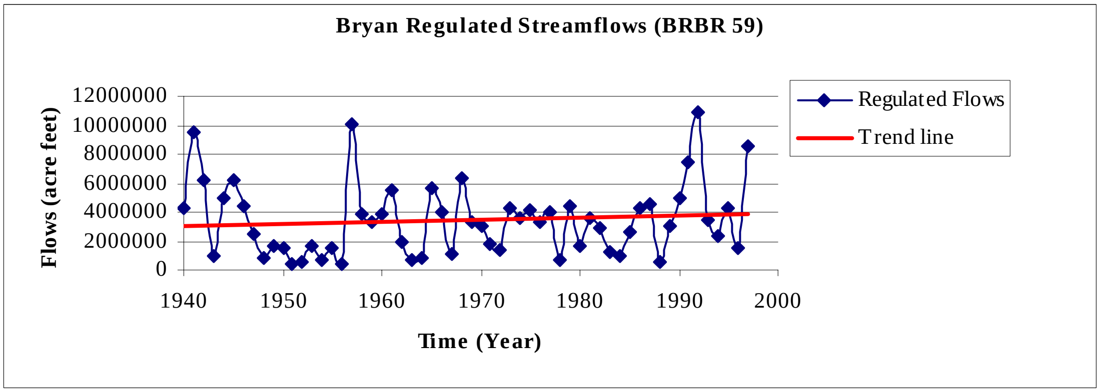

Figure 20. Regulated Streamflows for Bryan

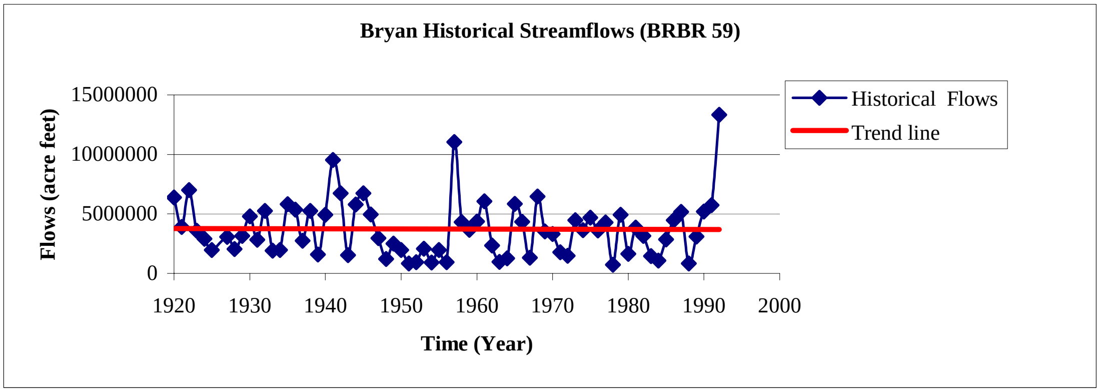

Figure 21. Historical Streamflows for Bryan

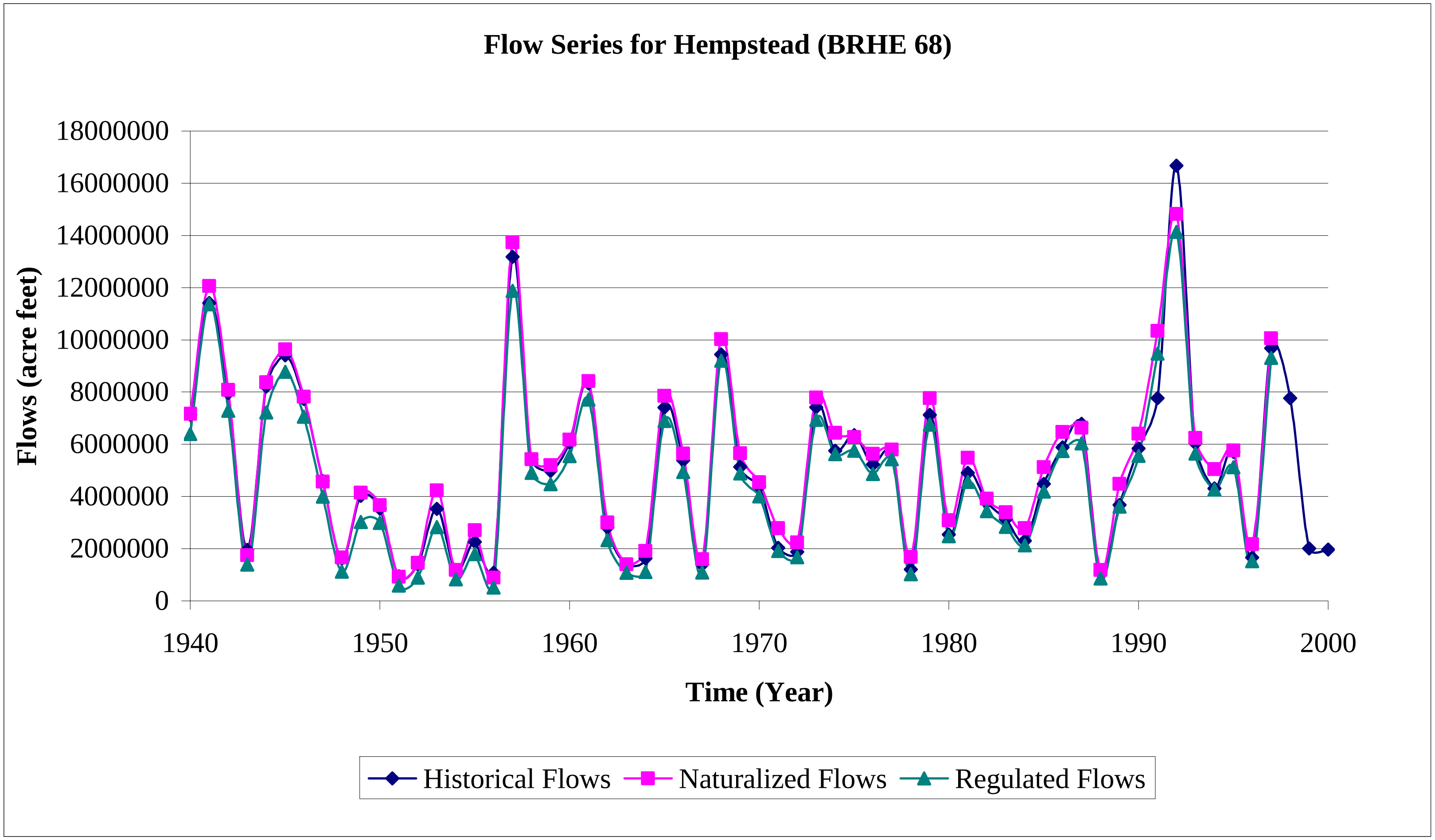

Figure 22. Flow Series for Hempstead

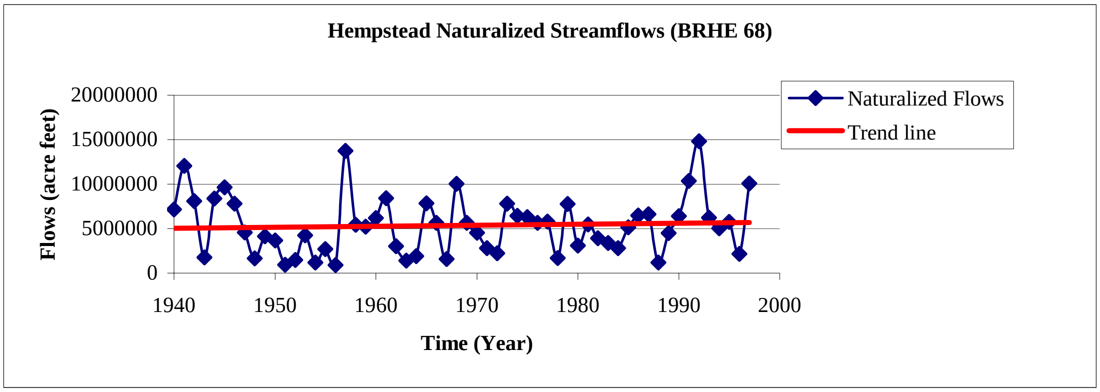

Figure 23. Naturalized Streamflows for Hempstead

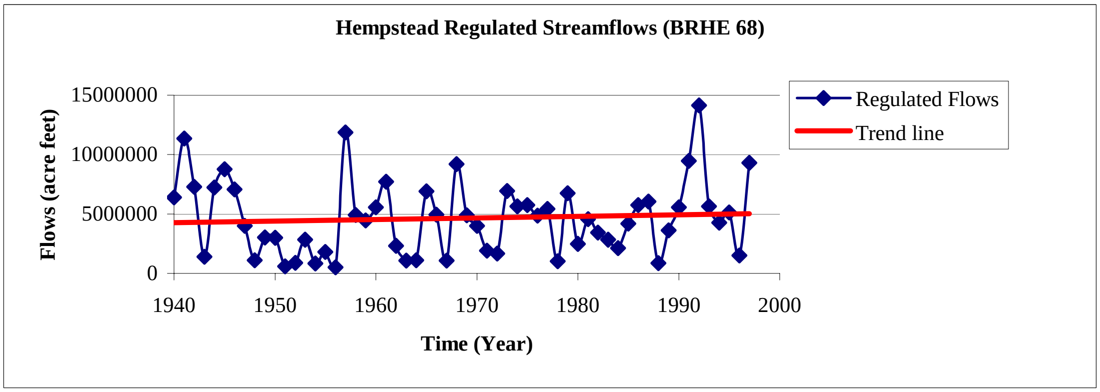

Figure 24. Regulated Streamflows for Hempstead

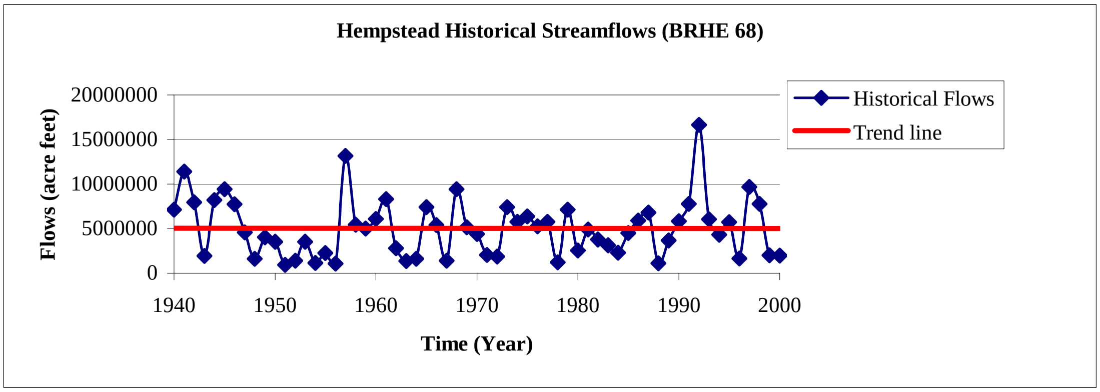

Figure 25. Historical Streamflows for Hempstead

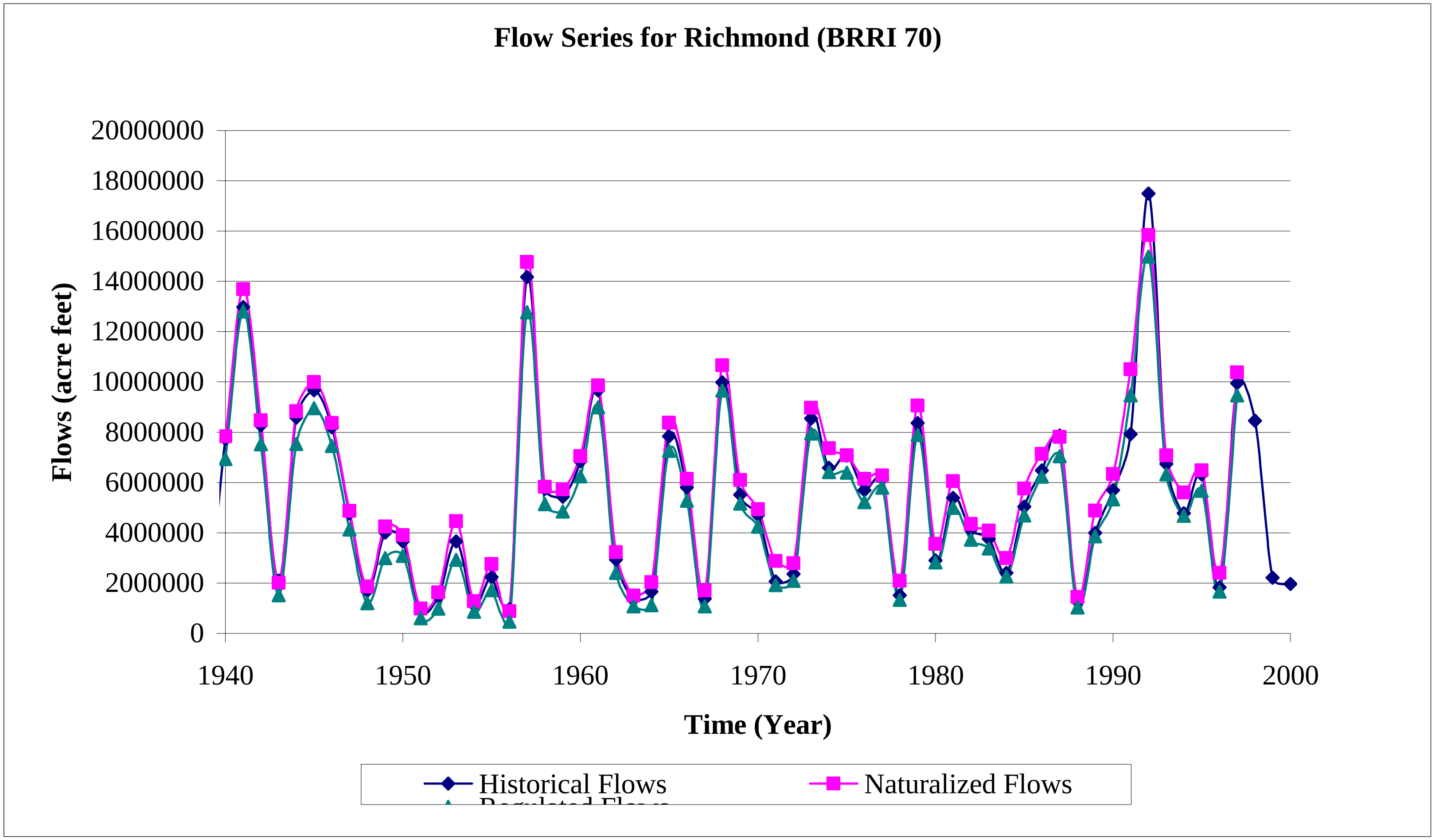

Figure 26. Flow Series for Richmond

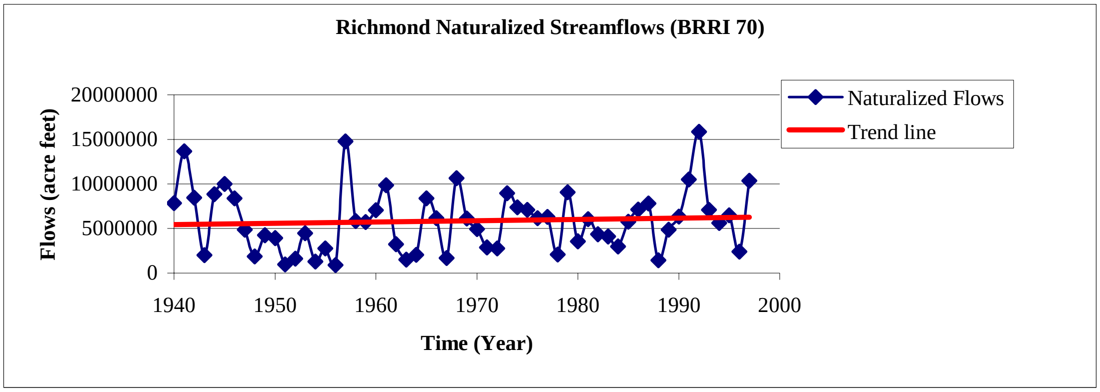

Figure 27. Naturalized Streamflows for Richmond

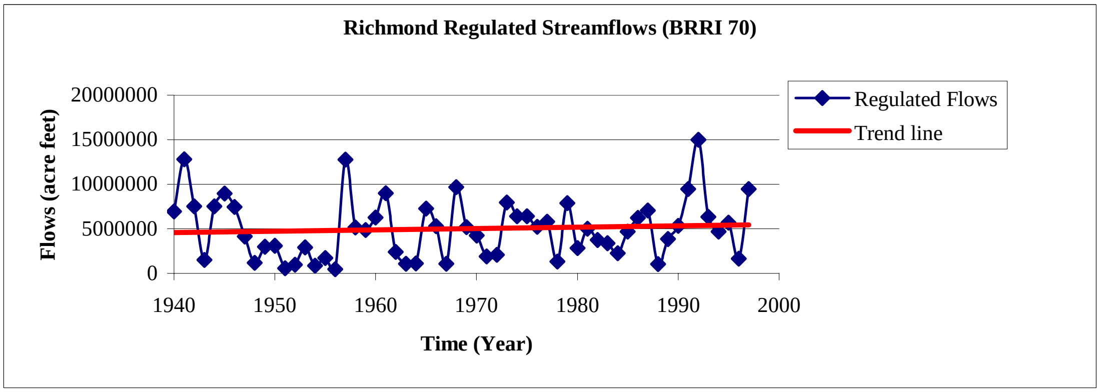

Figure 28. Regulated Streamflows for Richmond

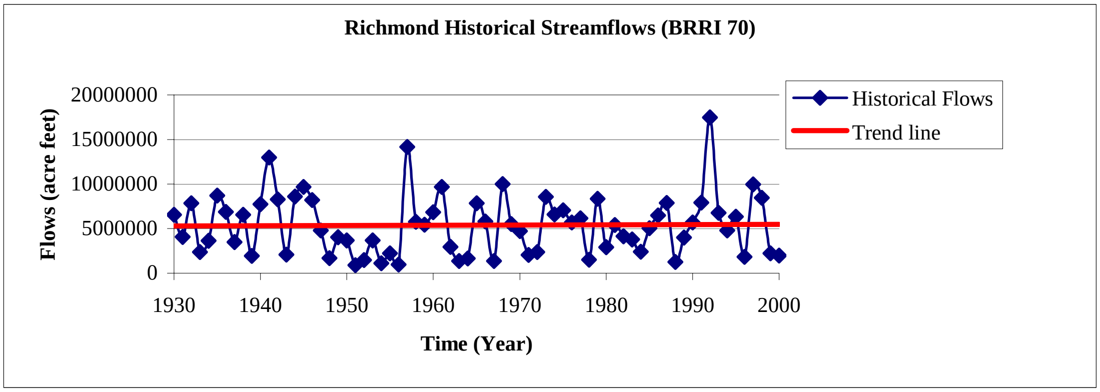

Figure 29. Historical Streamflows for Richmond

6.2 Canadian River Basin

One control point was chosen on the Canadian River in the Canadian River basin. The annual quantities of the naturalized and regulated flows are for the 1948-1998 period. Figure 30 shows the location of the control point in the Canadian River basin. Figures 31 to 34 contrasts the naturalized, regulated and observed historical flows for the selected control point in the Canadian River basin. The naturalized and regulated flow series for this basin show high flows during late 1950's. The flow series depicts very low flows after 1965's. The flows at Canadian, located near the outlet of the Canadian River basin shows a decrease in linear trend. The mean flows are decreasing with time.

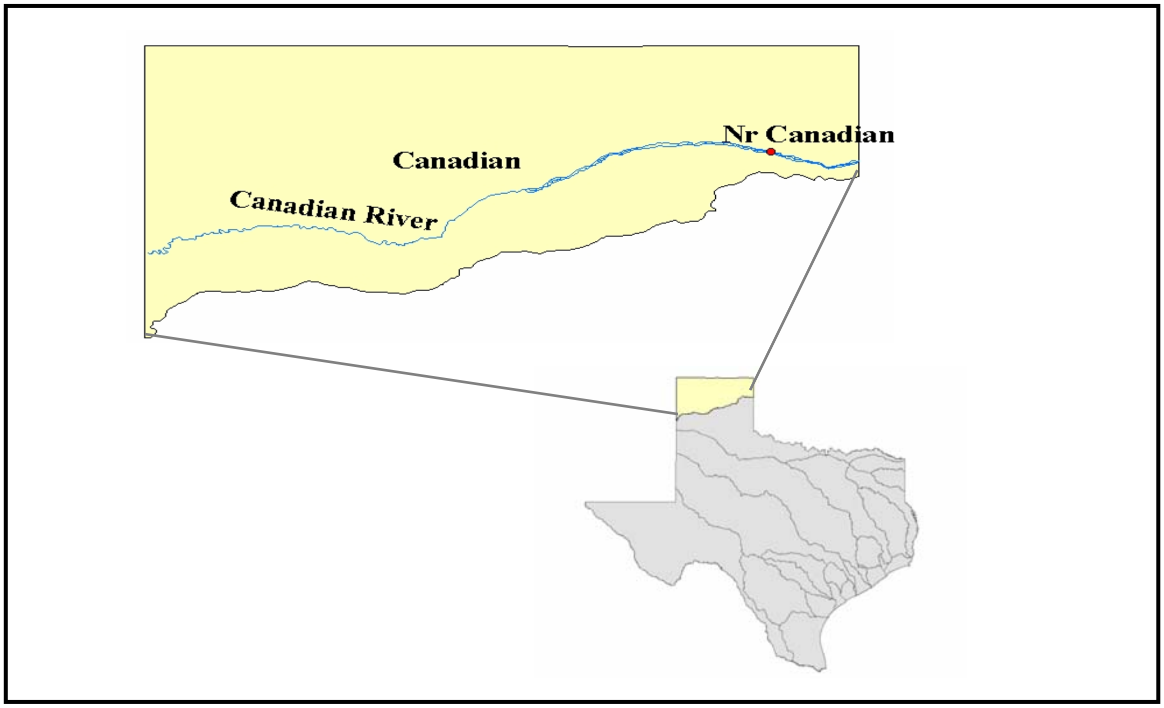

Figure 30. Location of Control Points in Canadian River Basin for Trend Analysis

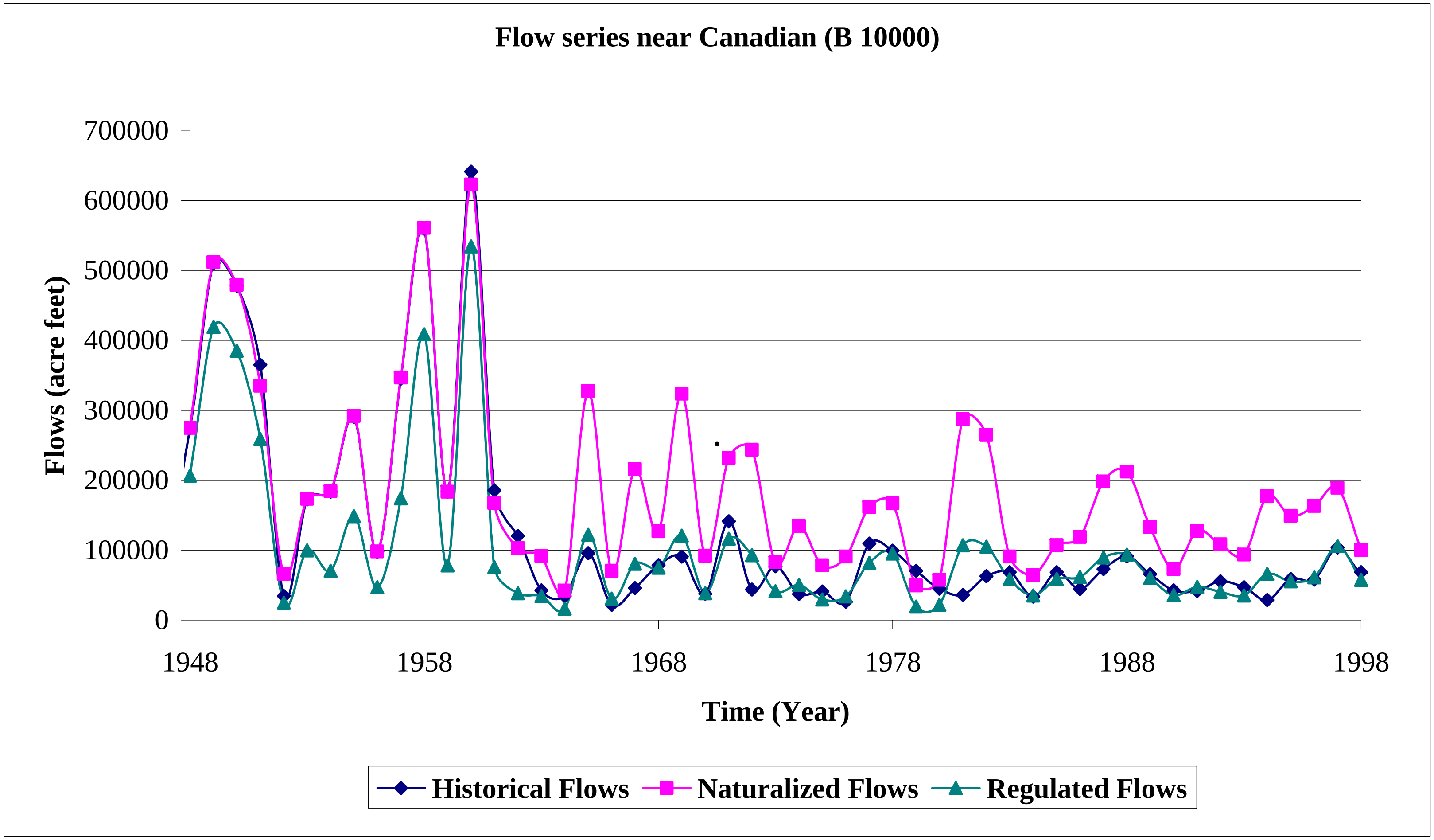

Figure 31. Flow Series near Canadian

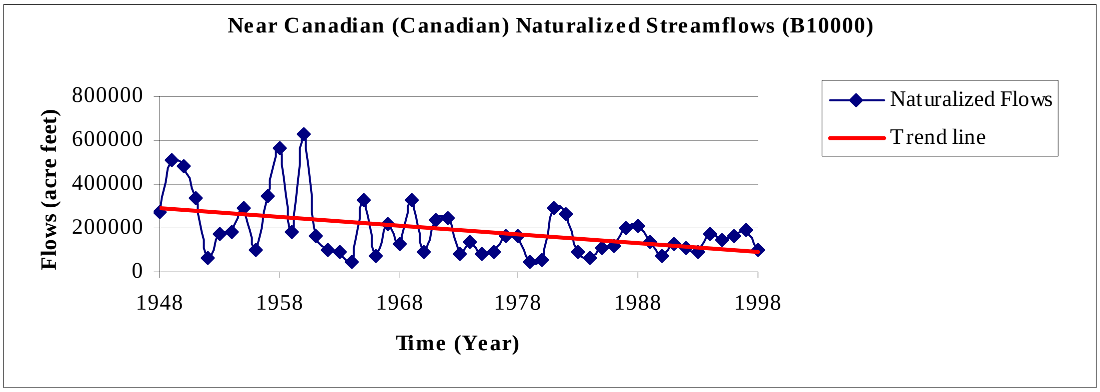

Figure 32. Naturalized Streamflows near Canadian

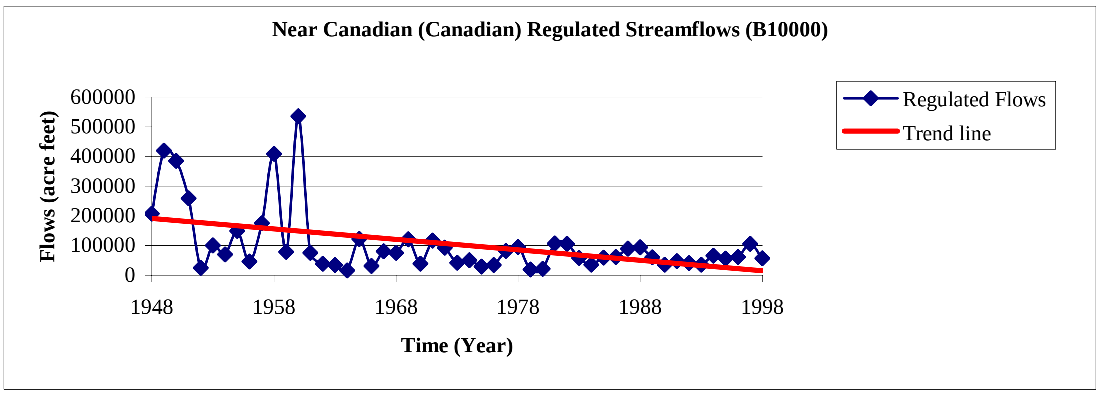

Figure 33. Regulated Streamflows near Canadian

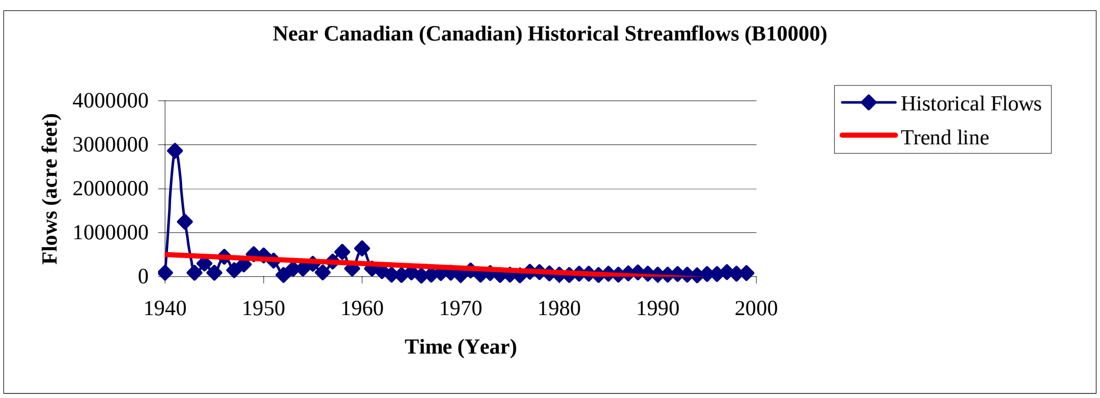

Figure 34. Historical Streamflows near Canadian

6.3 Colorado River Basin

One control point was chosen on the Colorado River in the Colorado River basin. The annual quantities of the naturalized and regulated flows are for the 1940-2000 period. Figure 35 shows the location of the control point in the Colorado River basin. Figures 36 to 39 contrasts the naturalized, regulated and observed historical flows for the selected control point in the Colorado River basin. The flow series for this basin show high flows during early 1940's, late 1950's and early 1990's. The period of early 1950's illustrates low flows. The flows at Columbus, Colorado located near the outlet of the Canadian River basin do not show any significant linear trend.

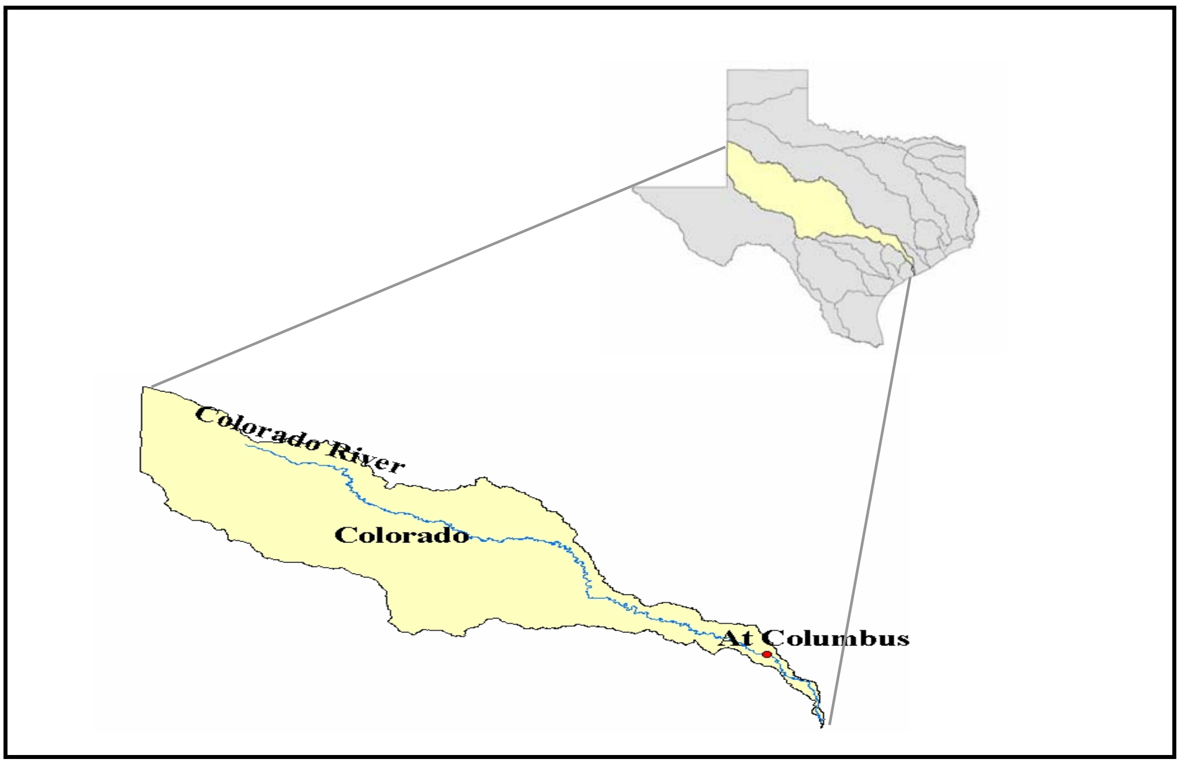

Figure 35. Location of Control Points in Colorado River Basin for Trend Analysis

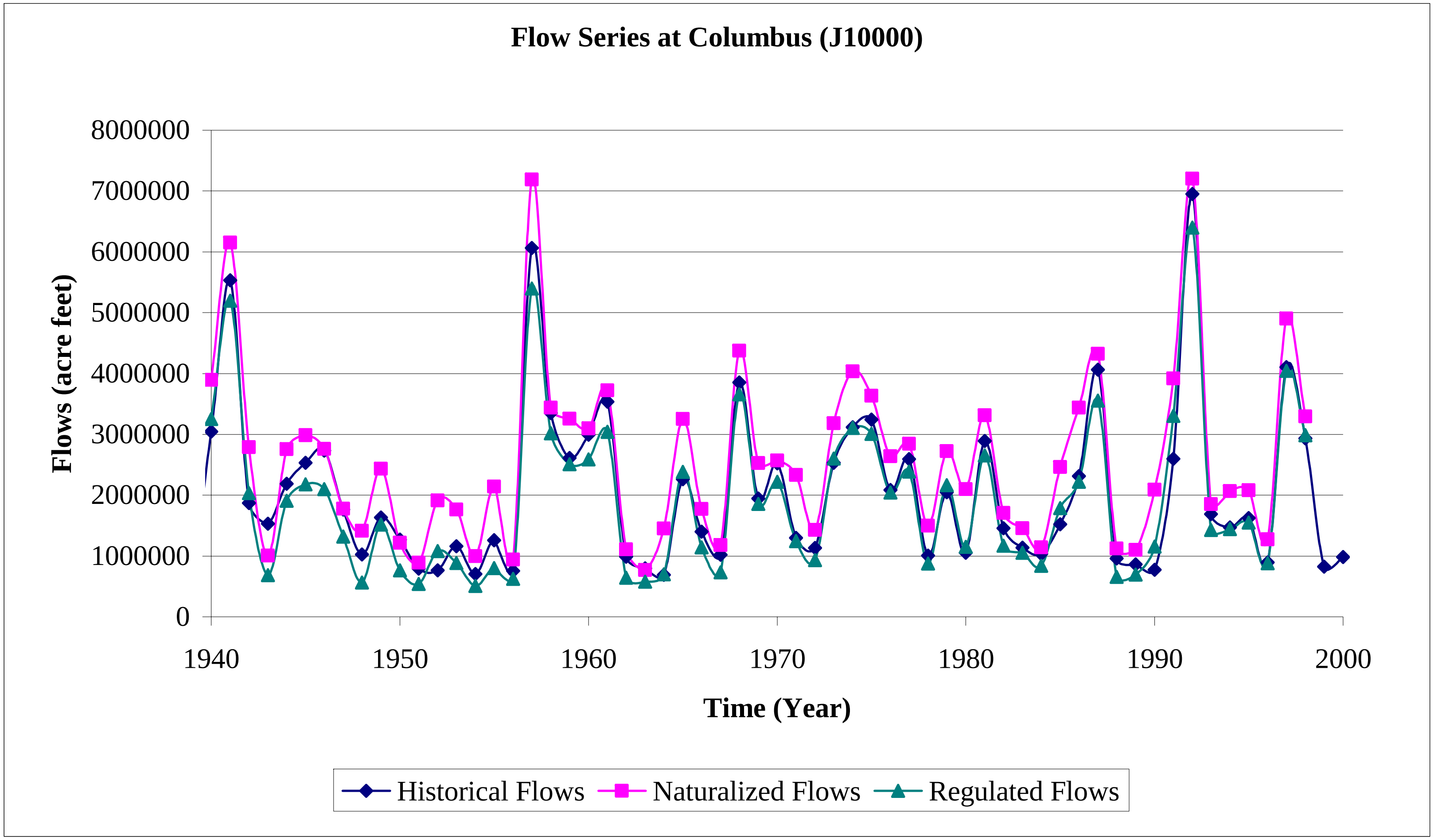

Figure 36. Flow Series at Columbus

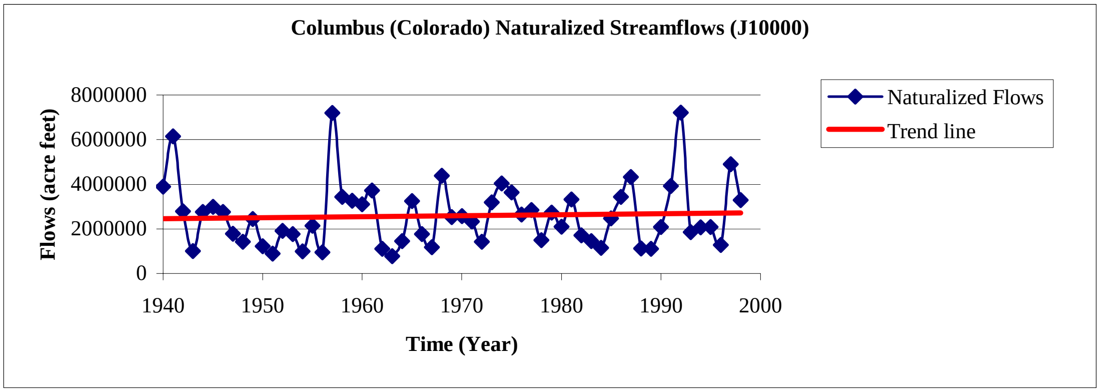

Figure 37. Naturalized Streamflows for Columbus

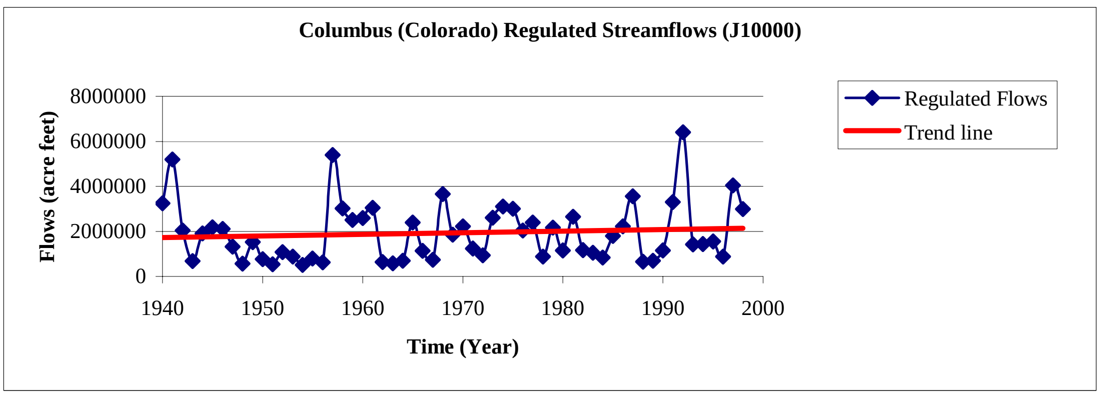

Figure 38. Regulated Streamflows for Columbus

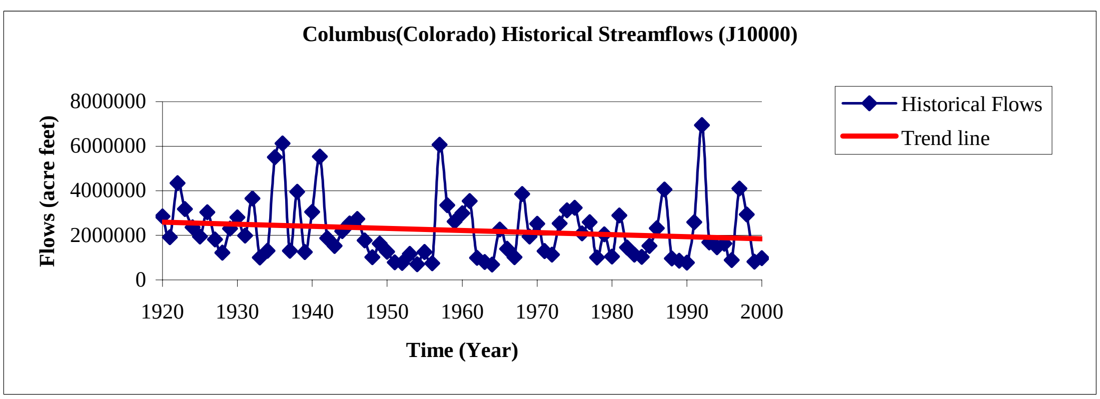

Figure 39. Historical Streamflows for Columbus

6.4 Guadalupe River Basin

One control point was chosen on the Guadalupe River in the Guadalupe River basin. The annual quantities of the naturalized and regulated flows are for the 1934-1989 period. Figure 40 shows the location of the control point in the Guadalupe River basin. Figures 41 to 44 contrasts the naturalized, regulated and observed historical flows for the selected control point in the Guadalupe River basin. The flow series for this basin show high flows after 1985's. The period of mid 1950's illustrates low flows. The flows at Victoria, Guadalupe located near the outlet of the Guadalupe River basin show an upward increasing linear trend.

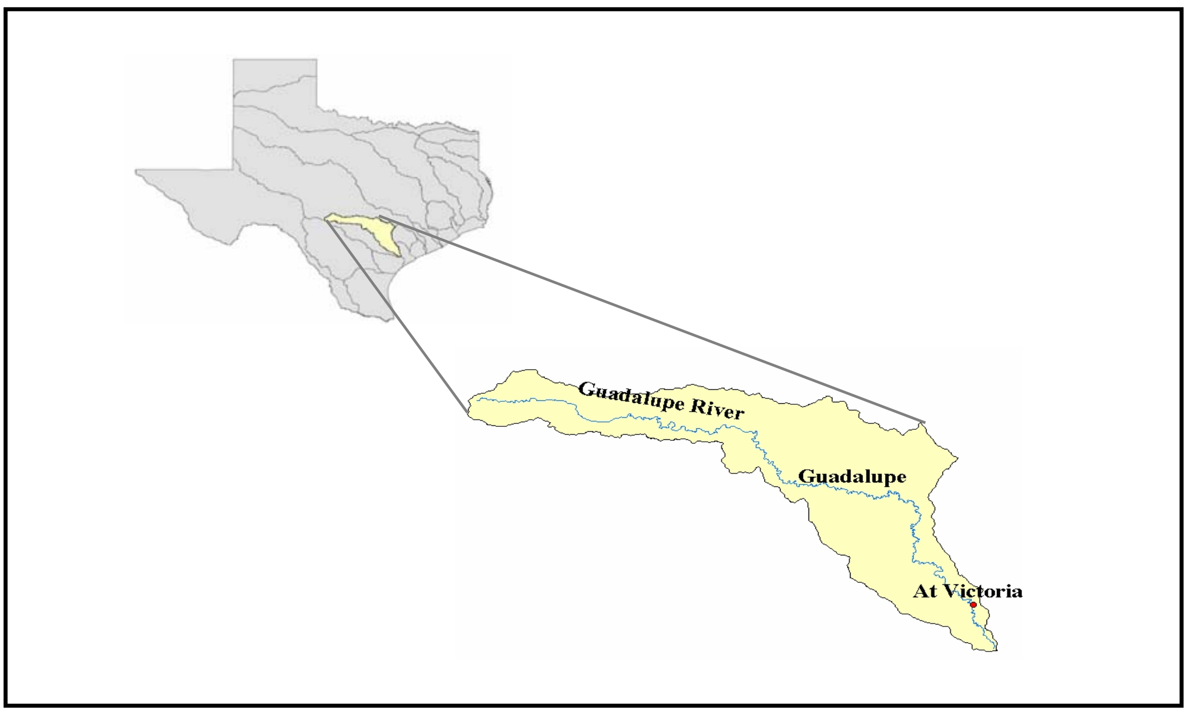

Figure 40. Location of Control Points in Guadalupe River Basin for Trend Analysis

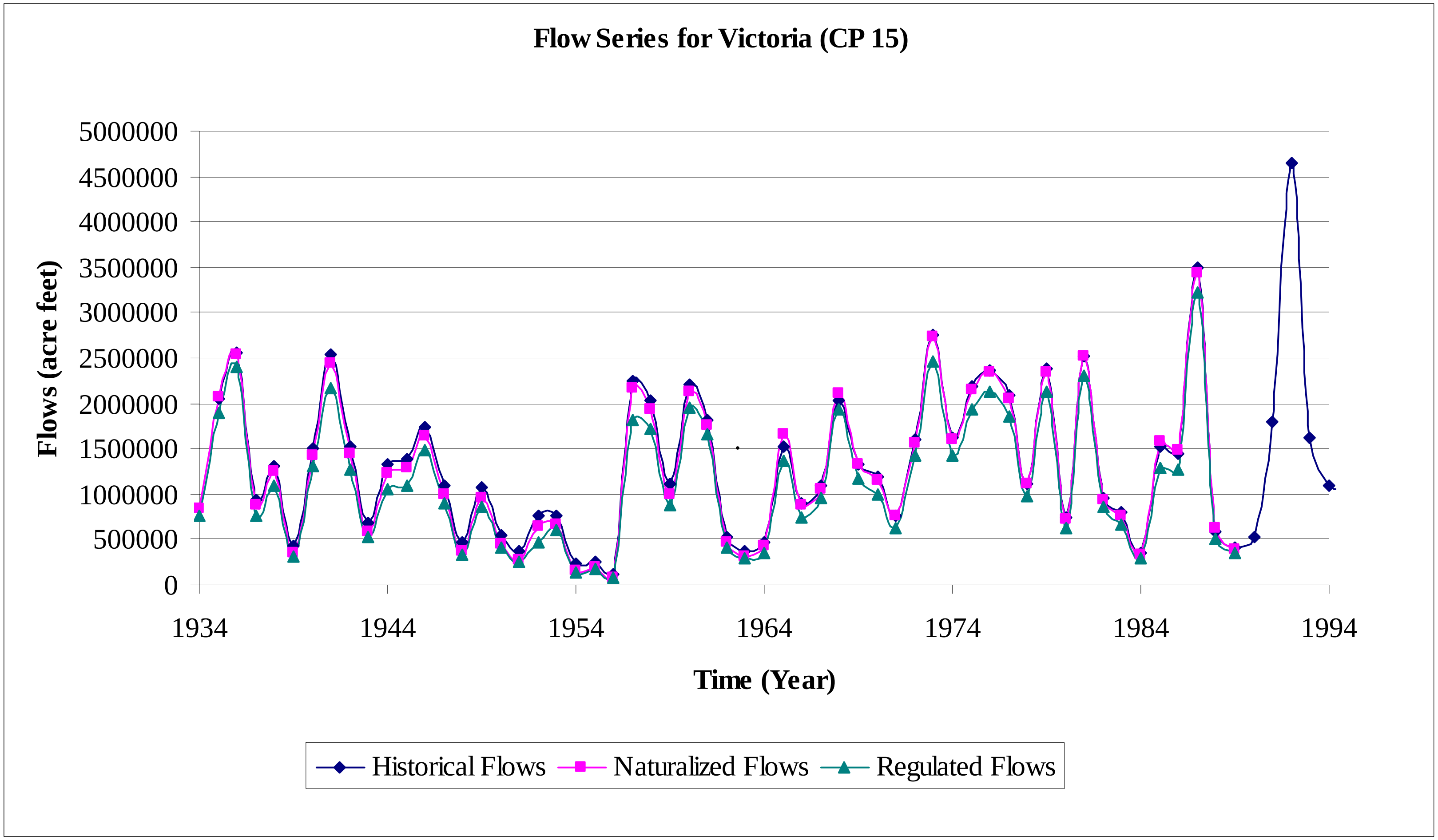

Figure 41. Flow Series for Victoria

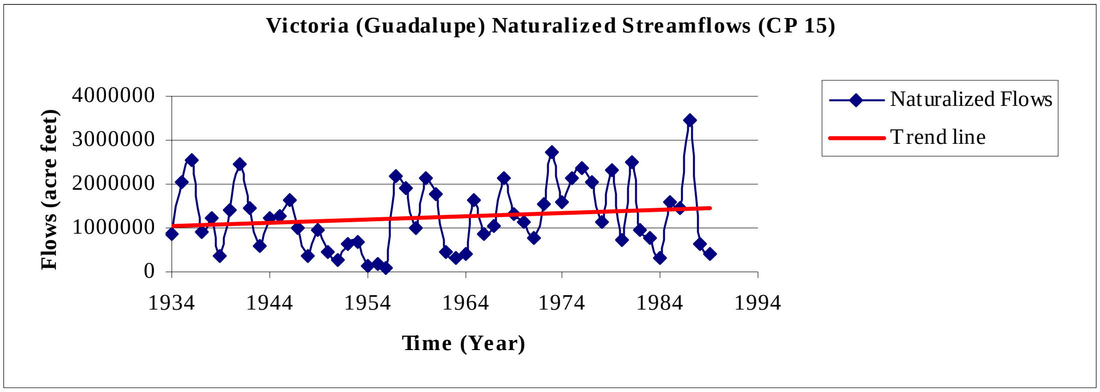

Figure 42. Naturalized Streamflows for Victoria

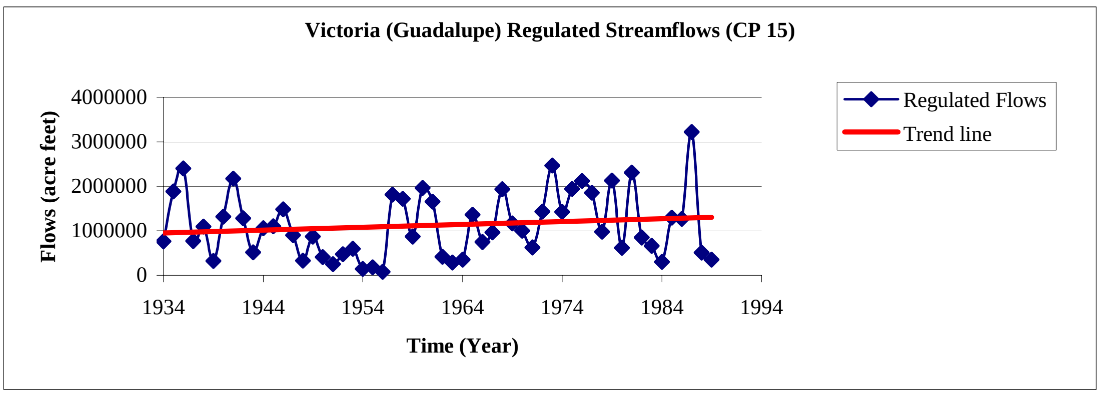

Figure 43. Regulated Streamflows for Victoria

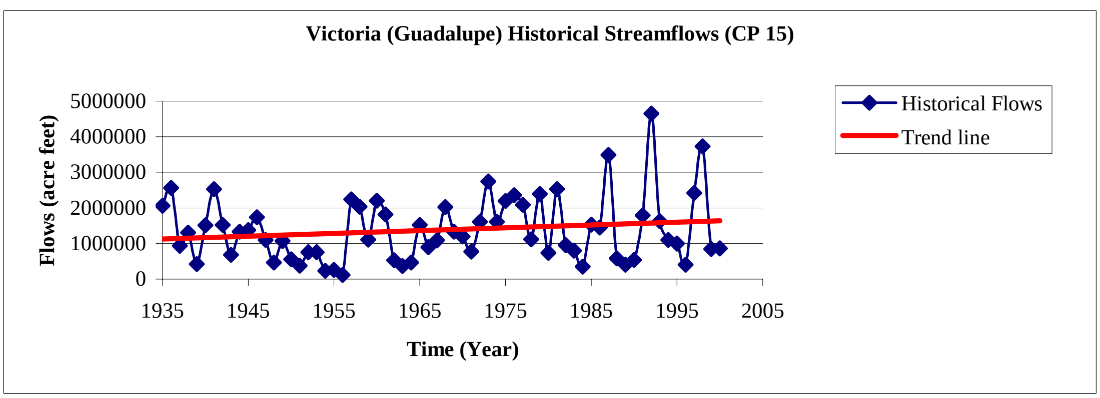

Figure 44. Historical Streamflows for Victoria

6.5 San Antonio River Basin

One control point was chosen on the San Antonio River in the San Antonio River basin. The annual quantities of the naturalized and regulated flows are for the 1934-1989 period. Figure 45 shows the location of the control point in the San Antonio River basin. Figures 46 to 49 contrasts the naturalized, regulated and observed historical flows for the selected control point in the San Antonio River basin. The flow series for this basin show high flows during early 1970's and early 1990's. The period from 1950's-1960 show low flows. The flows at Goliad, San Antonio located near the outlet of the San Antonio River basin show an upward increasing linear trend.

Figure 45. Location of Control Points in San Antonio River Basin for Trend Analysis

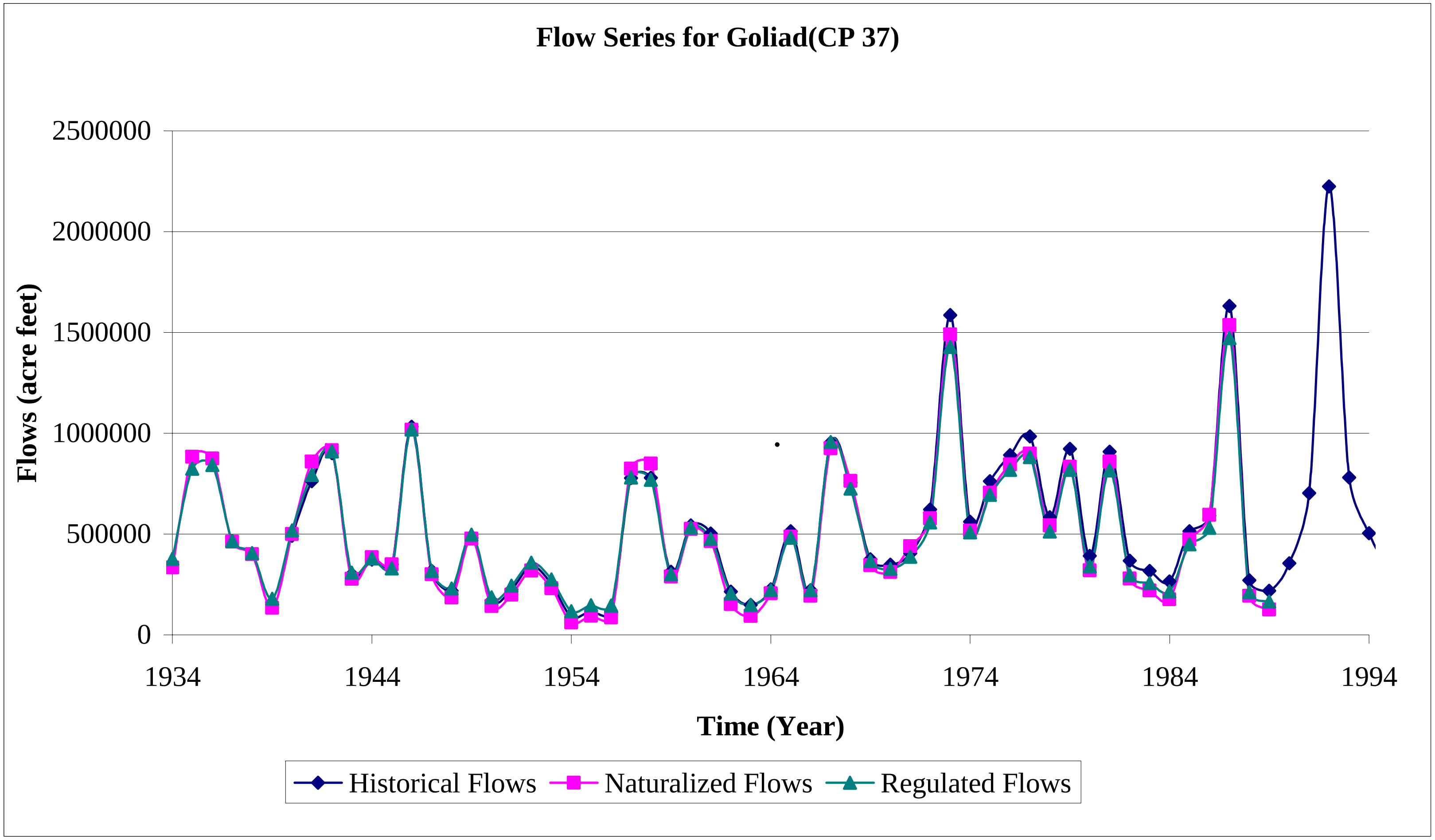

Figure 46. Flow Series for Goliad

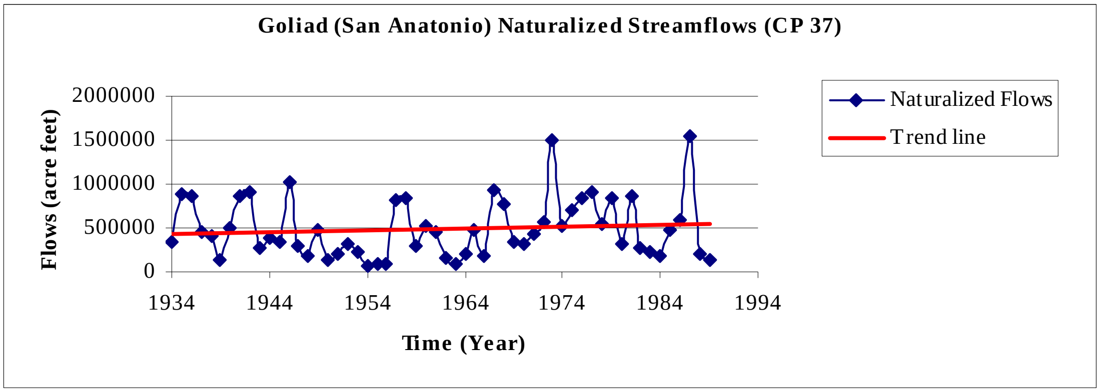

Figure 47. Naturalized Streamflows for Goliad

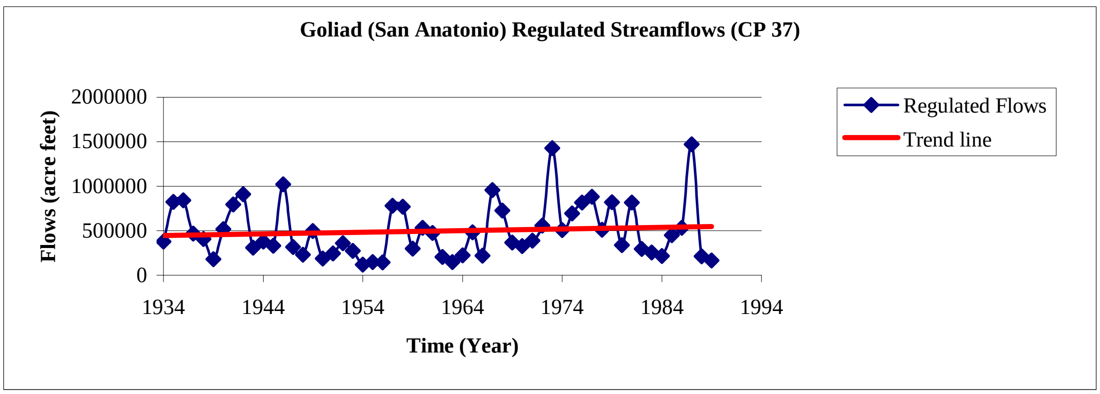

Figure 48. Regulated Streamflows for Goliad

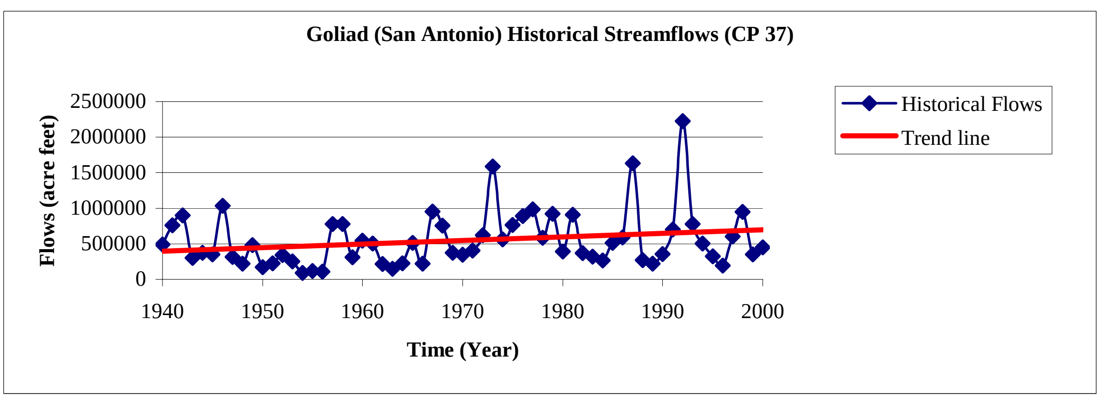

Figure 49. Historical Streamflows for Goliad

6.6 Neches River Basin

One control point was chosen on the Neches River in the Neches River basin. The annual quantities of the naturalized and regulated flows are for the 1940-2000 period. Figure 50 shows the location of the control point in the Neches River basin. Figures 51 to 54 contrasts the naturalized, regulated and observed historical flows for the selected control point in the Neches River basin. The flow series for this basin show high flows during mid 1940's, mid 1970's and early 1990's. The period during mid 1950's and mid 1960's show low flows. The flows at Evadale, Neches located near the outlet of the Neches River basin show no significant linear trend.

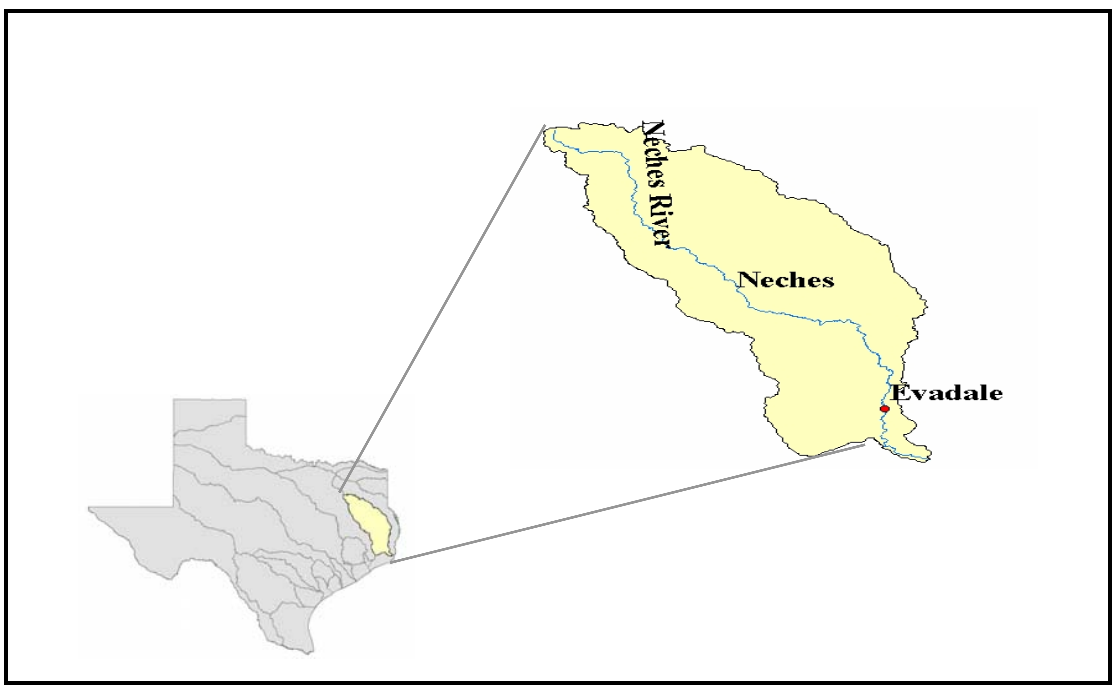

Figure 50. Location of Control Points in Neches River Basin for Trend Analysis

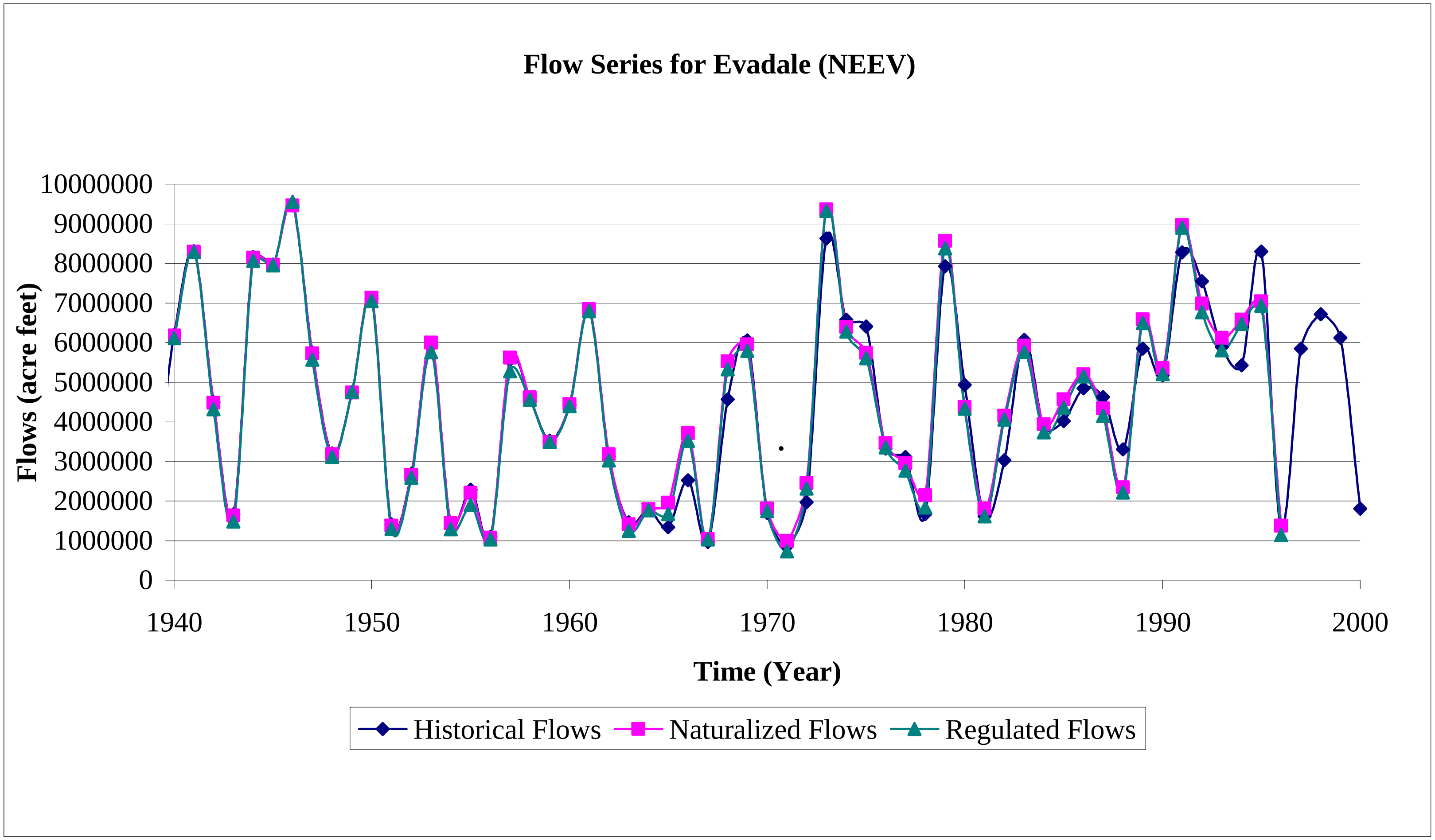

Figure 51. Flow Series for Evadale

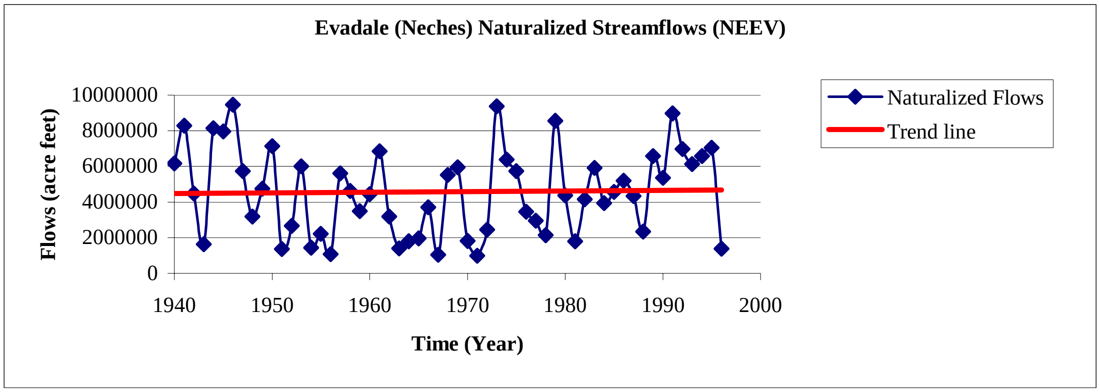

Figure 52. Naturalized Streamflows for Evadale

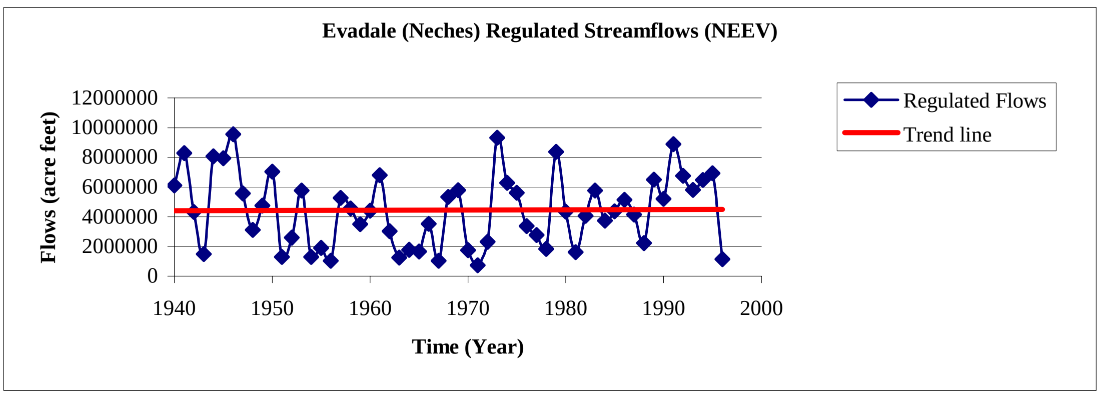

Figure 53. Regulated Streamflows for Evadale

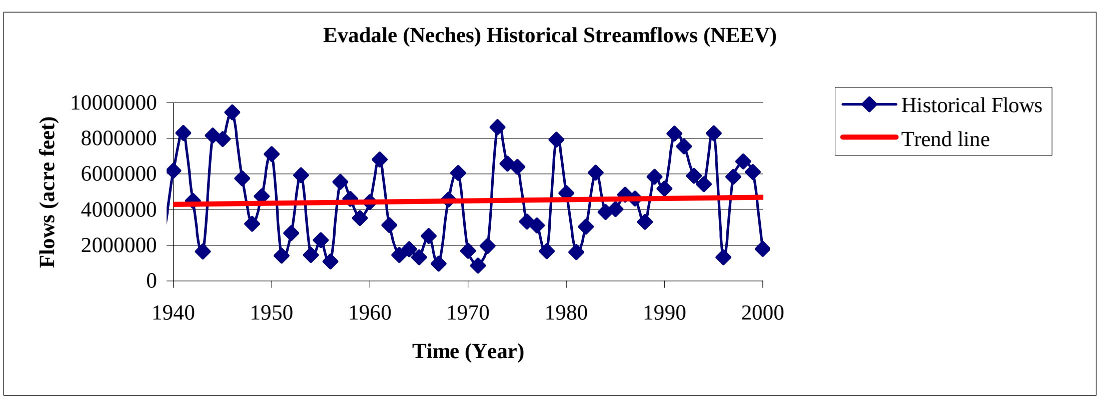

Figure 54. Historical Streamflows for Evadale

6.7 Nueces River Basin

One control point was chosen on the Nueces River in the Nueces River basin. The annual quantities of the naturalized and regulated flows are for the 1934-1996 period. Figure 55 shows the location of the control point in the Nueces River basin. Figures 56 to 59 contrasts the naturalized, regulated and observed historical flows for the selected control point in the Nueces River basin. The flow series for this basin show high flows during 1935 and early 1970’s. The flow series illustrates several low flow periods throughout its length. The flows at Mathis, Nueces located near the outlet of the Nueces River basin show decreasing linear trend. Mathis is located few miles downstream of the Lake Corpus Christi. The flows at this location are controlled largely by the lake.

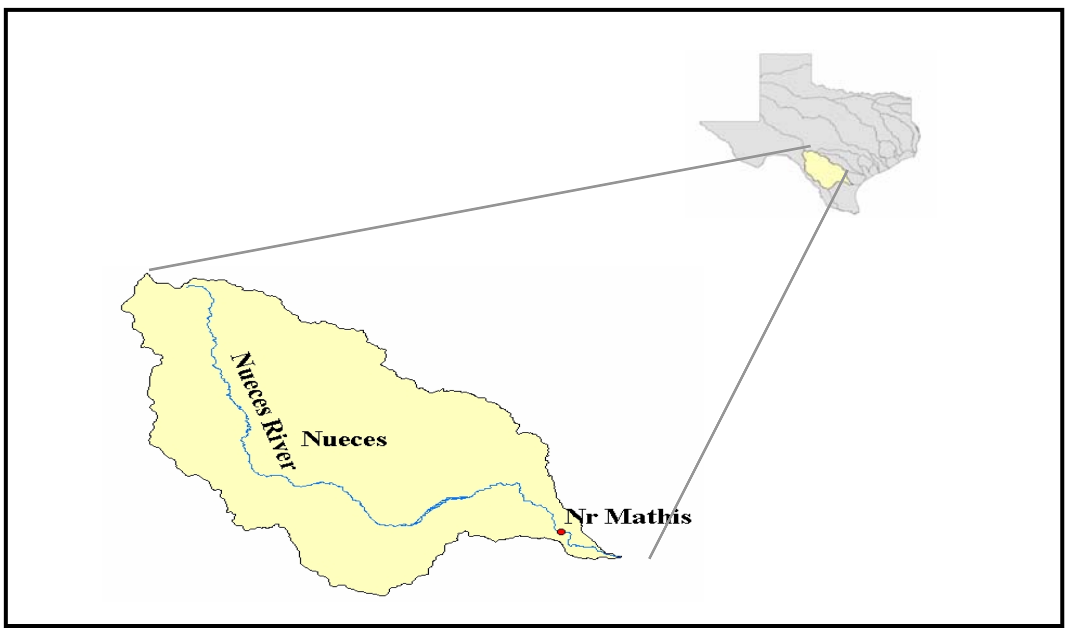

Figure 55. Location of Control Points in Nueces River Basin for Trend Analysis

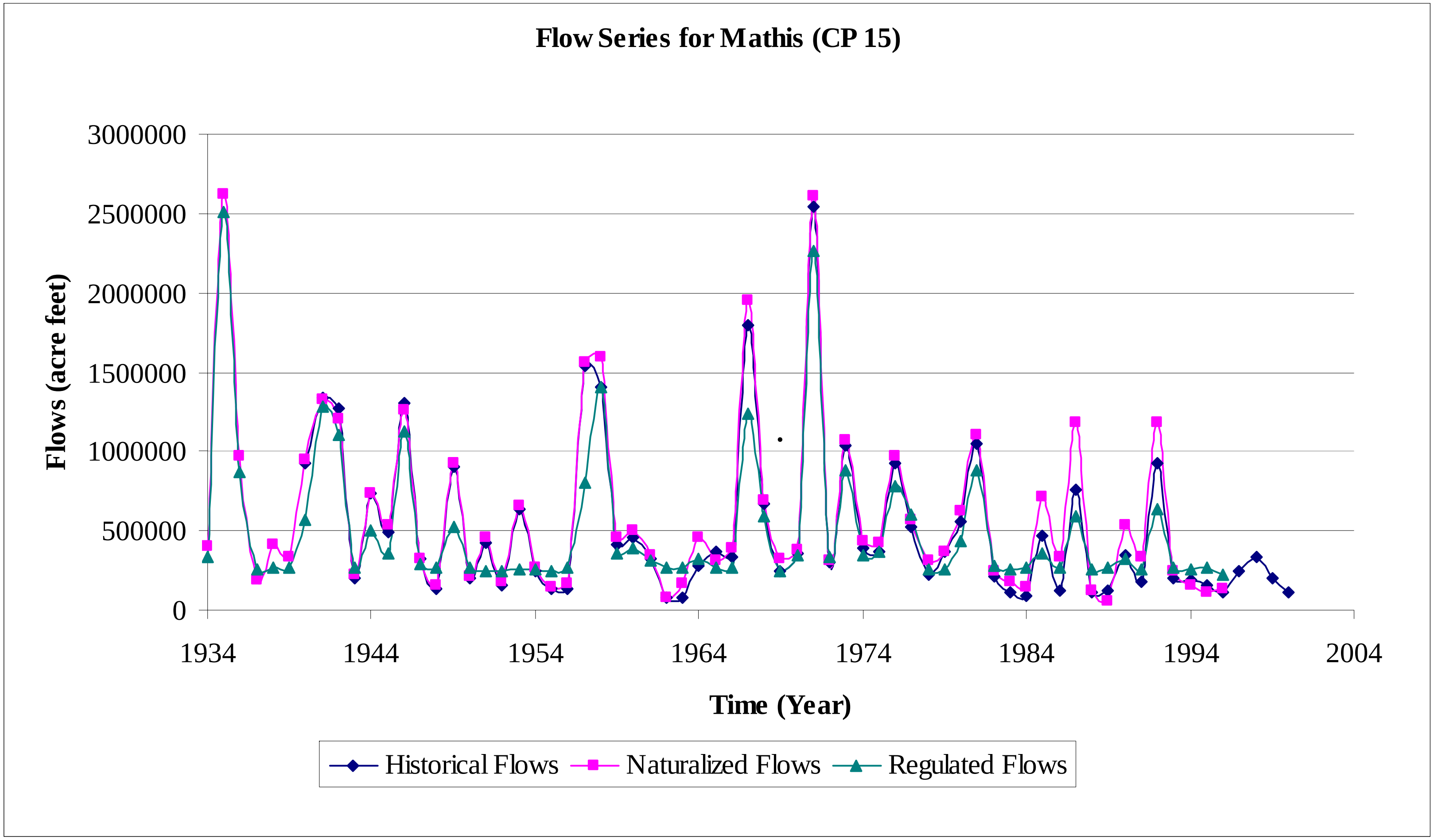

Figure 56. Flow Series for Mathis

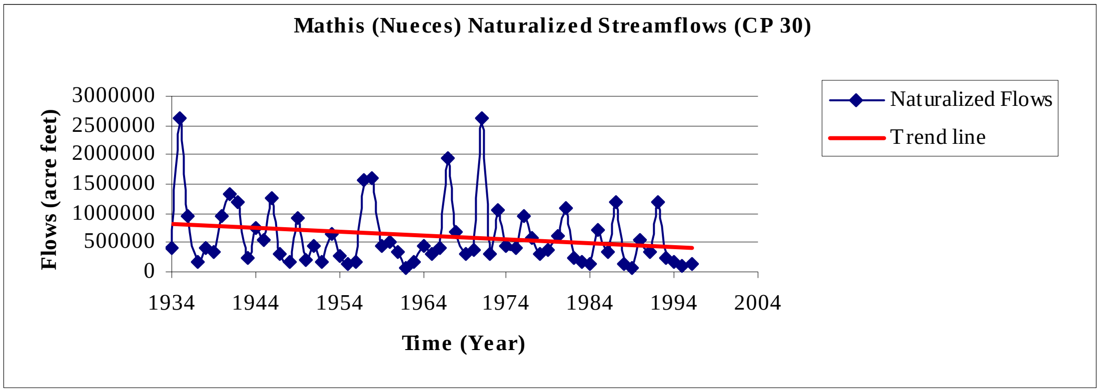

Figure 57. Naturalized Streamflows for Mathis

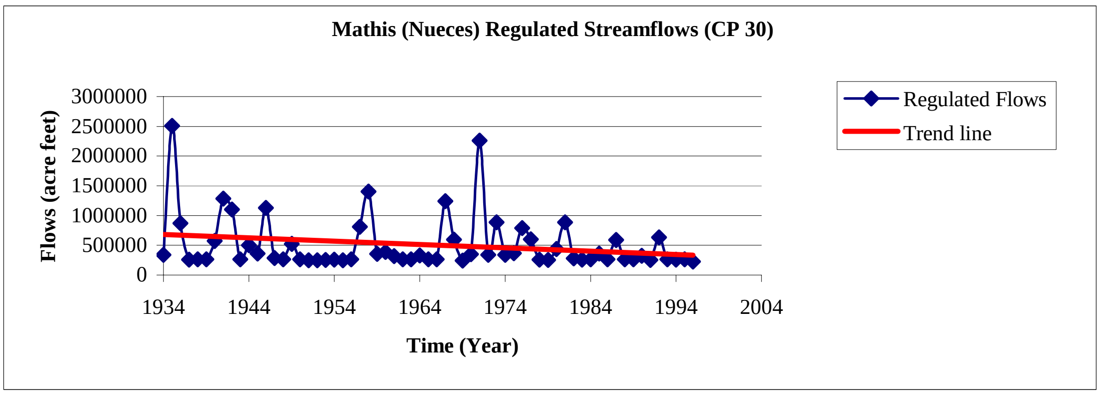

Figure 58. Regulated Streamflows for Mathis

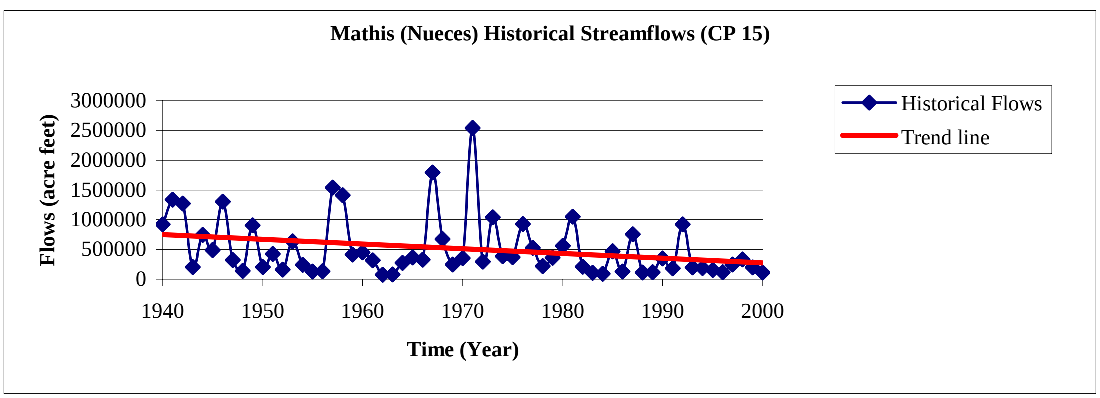

Figure 59. Historical Streamflows for Mathis

6.8 Red River Basin

One control point was chosen on the Red River in the Red River basin. The annual quantities of the naturalized and regulated flows are for the 1948-1998 period. Figure 60 shows the location of the control point in the Red River basin. Figures 61 to 64 contrasts the naturalized, regulated and observed historical flows for the selected control point in the Red River basin. The flow series for this basin show high flows during late 1950's and early 1990's. The flows at Index, Arkansas located near the outlet of the Red River basin show increasing upward linear trend.

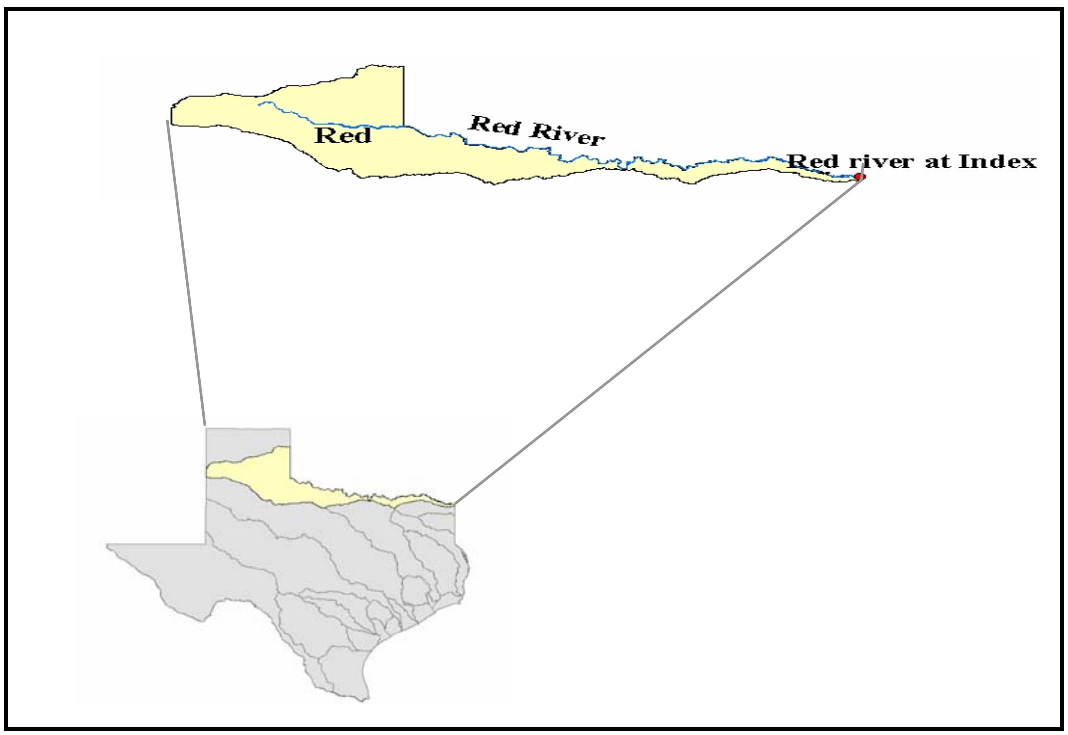

Figure 60. Location of Control Points in Red River Basin for Trend Analysis

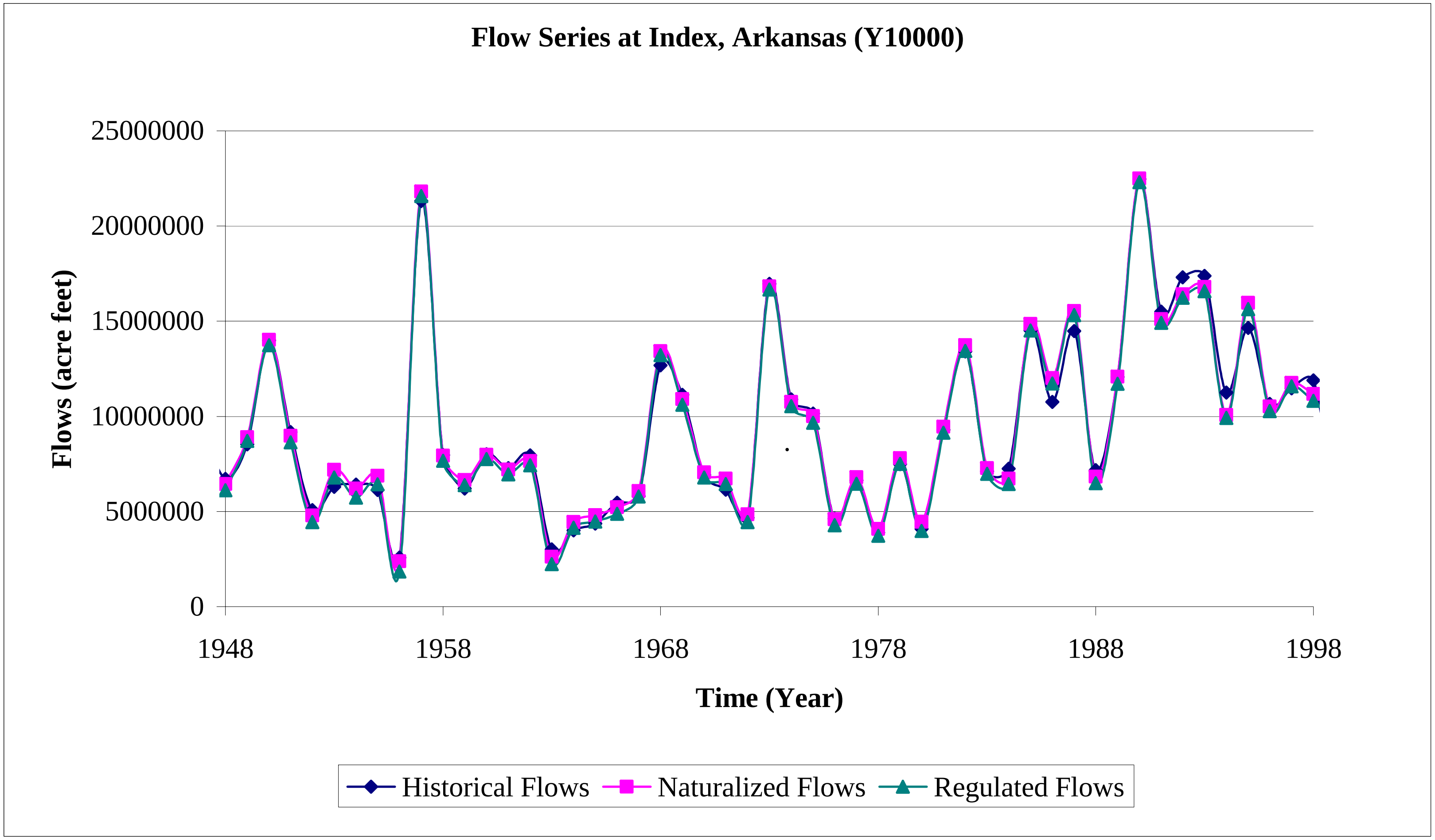

Figure 61. Flow Series at Index, Arkansas

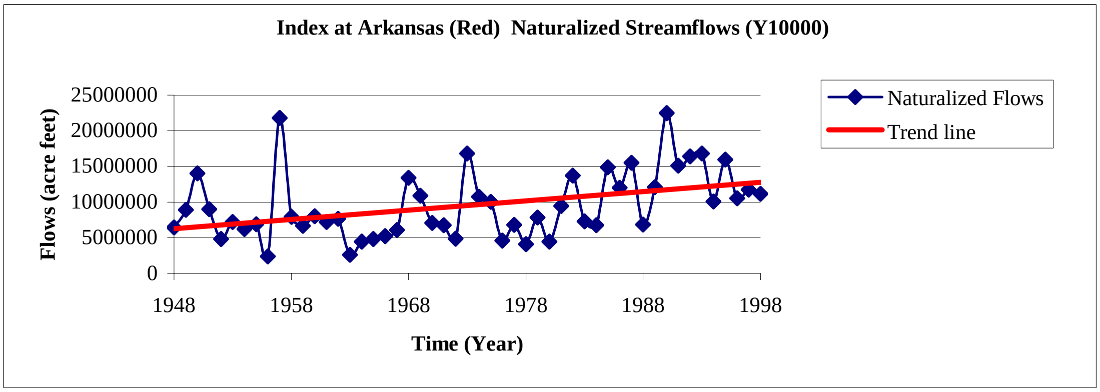

Figure 62. Naturalized Streamflows for Index

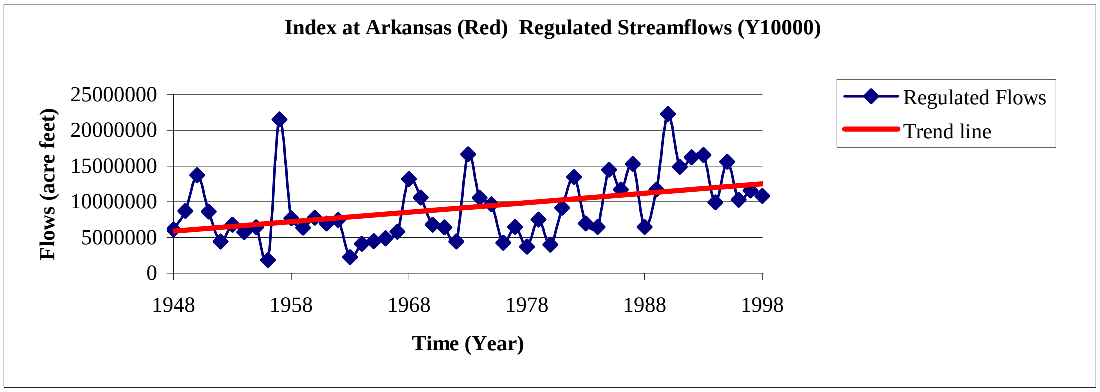

Figure 63. Regulated Streamflows for Index

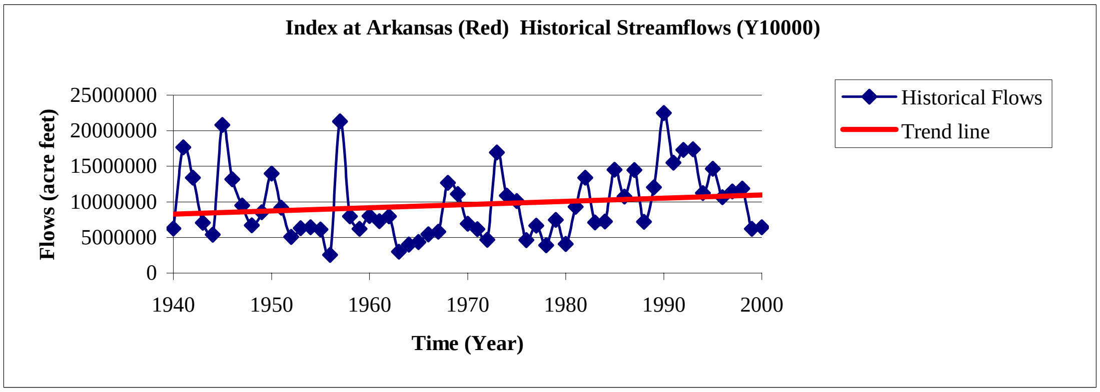

Figure 64. Historical Streamflows for Index

6.9 Sabine River Basin

One control point was chosen on the Sabine River in the Sabine River basin. The annual quantities of the naturalized and regulated flows are for the 1940-1998 period. Figure 65 shows the location of the control point in the Sabine River basin. Figures 66 to 69 contrasts the naturalized, regulated and observed historical flows for the selected control point in the Sabine River basin. The flows near Bon Weir, Sabine located near the outlet of the Sabine River basin do not show any significant linear trend. Bon Weir is located few miles downstream of the Toledo Bend Reservoir. The flows at this location are controlled largely by the reservoir.

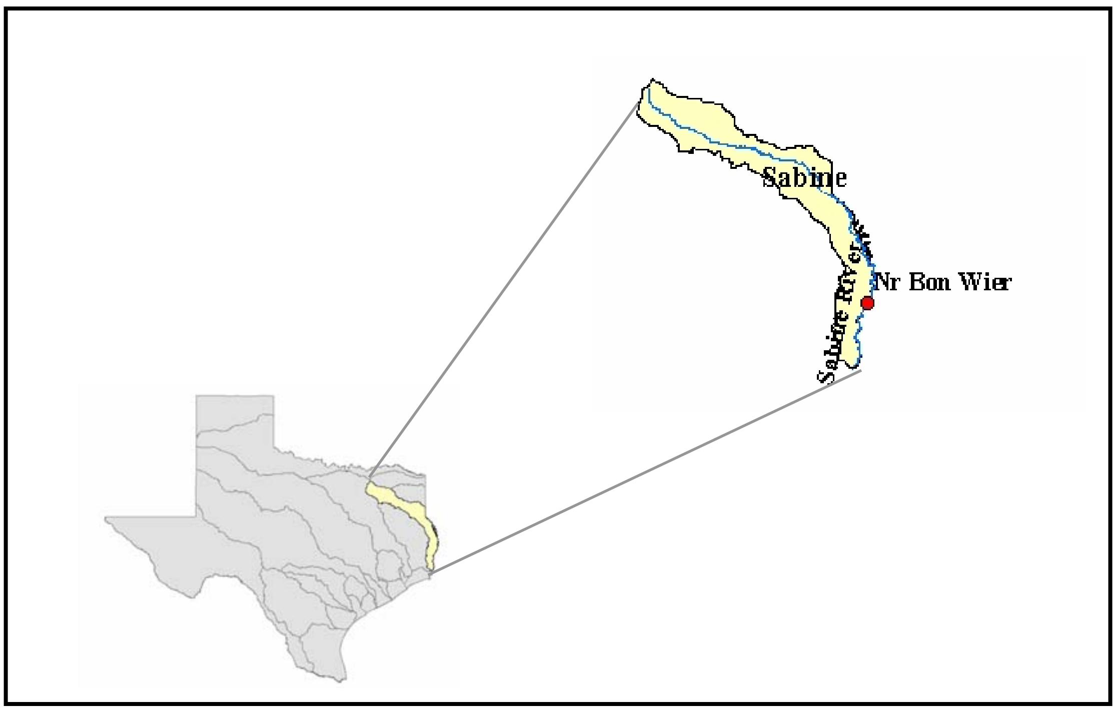

Figure 65. Location of Control Points in Sabine River Basin for Trend Analysis

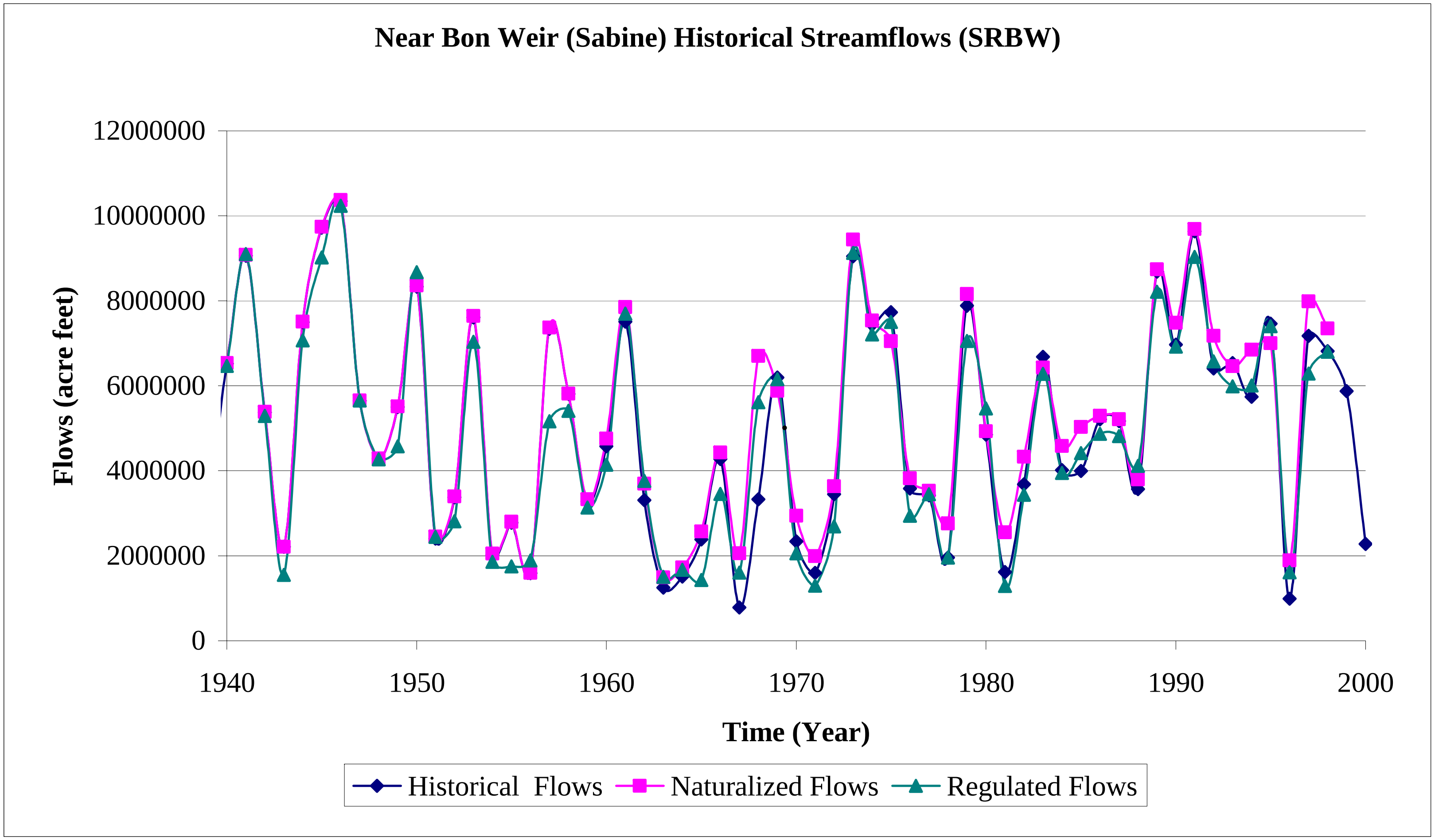

Figure 66. Flow Series near Bon Weir

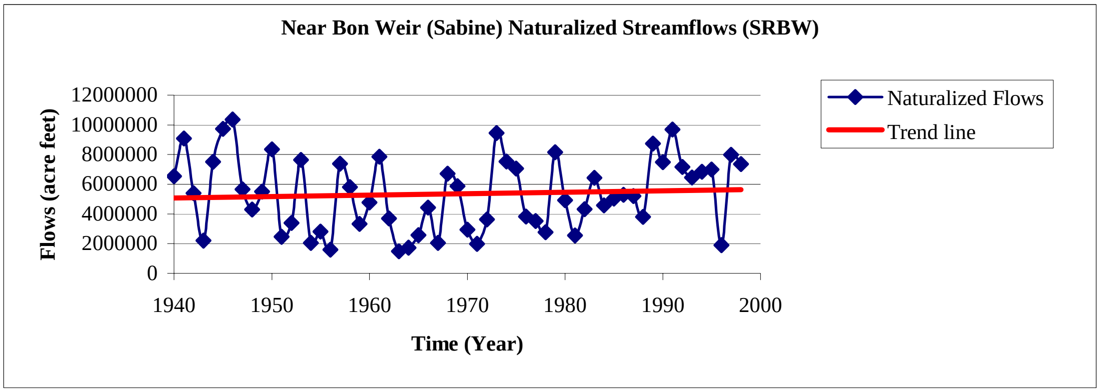

Figure 67. Naturalized Streamflows near BonWeir

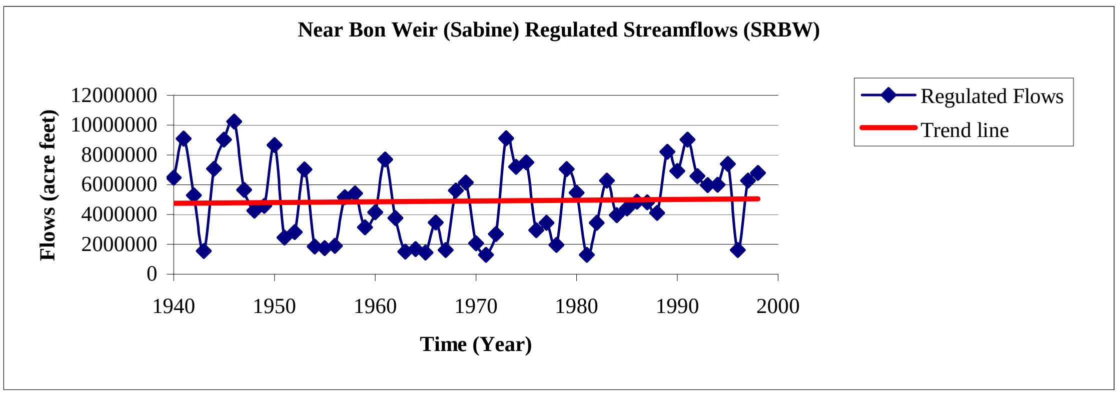

Figure 68. Regulated Streamflows near BonWeir

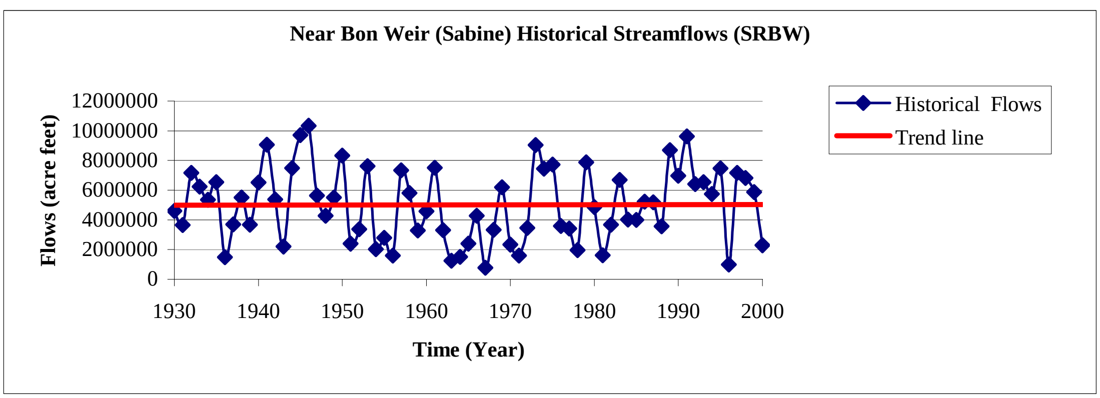

Figure 69. Historical Streamflows near BonWeir

6.10 Sulphur River Basin

One control point was chosen on the Sulphur River in the Sulphur River basin. The annual quantities of the naturalized and regulated flows are for the 1940-1996 period. Figure 70 shows the location of the control point in the Sulphur River basin. Figures 71 to 74 contrasts the naturalized, regulated and observed historical flows for the selected control point in the Sulphur River basin. The flows at Talco, Sulphur show increasing upward linear trend. Talco is located few miles downstream of River Crest Reservoir. The period after 1953 shows the low flow period because of the construction of the reservoir. The period of late 1950's and mid 1970's show high flow period.

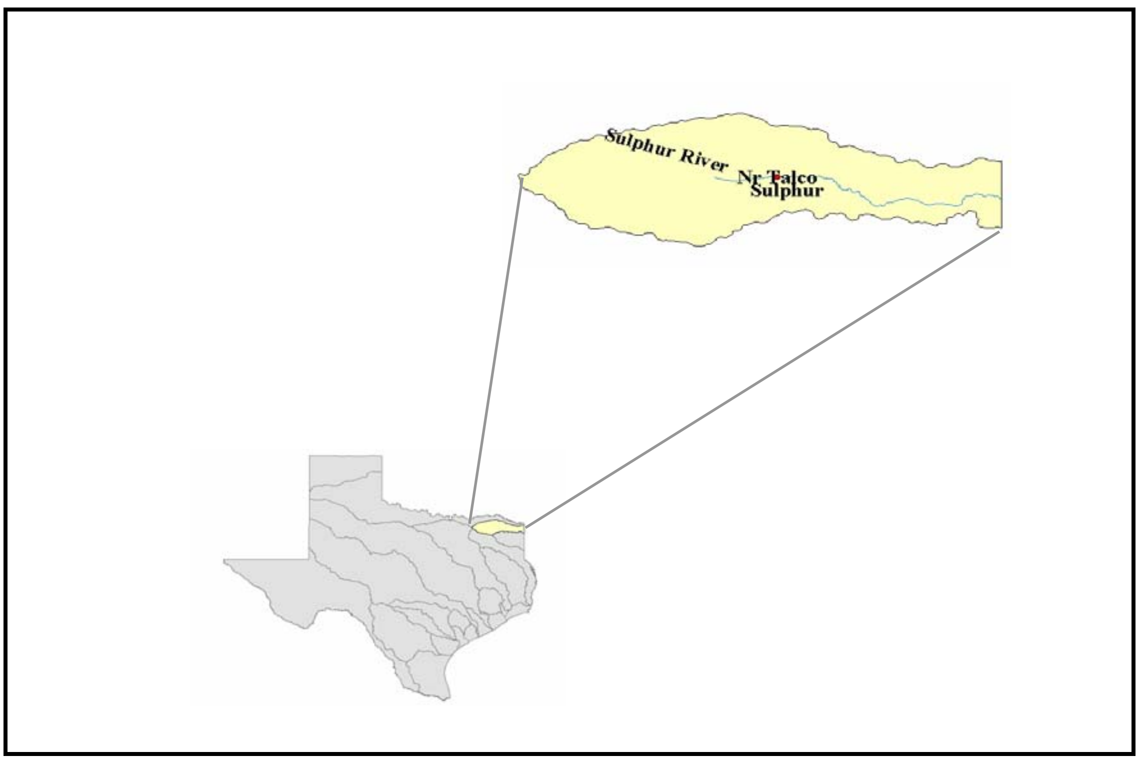

Figure 70. Location of Control Points in Sulphur River Basin for Trend Analysis

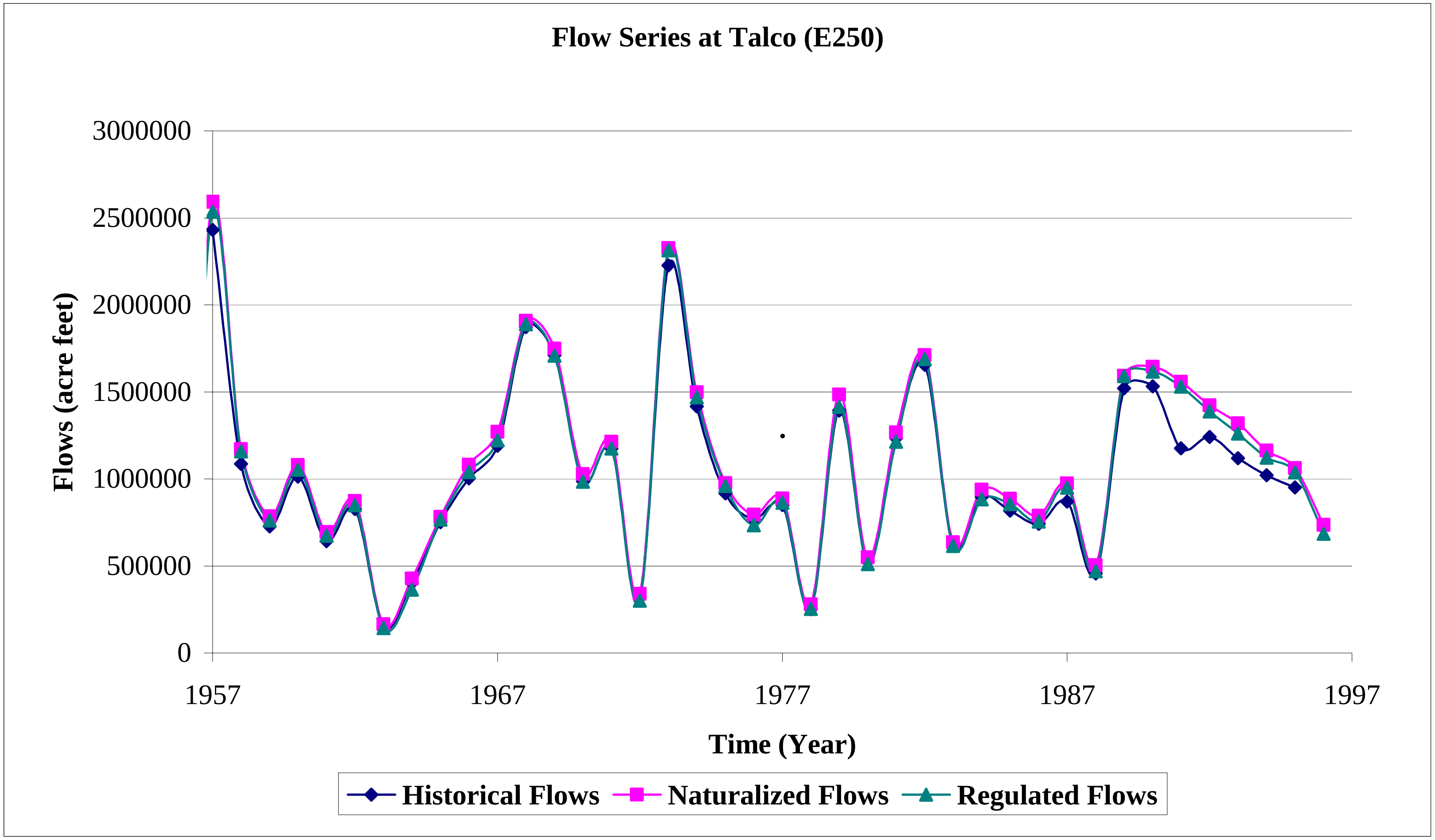

Figure 71. Flow Series for Talco

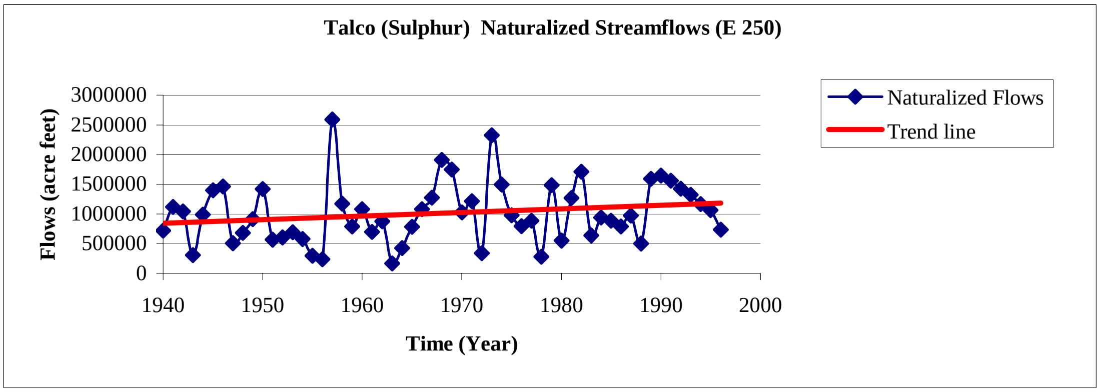

Figure 72. Historical Streamflows for Talco

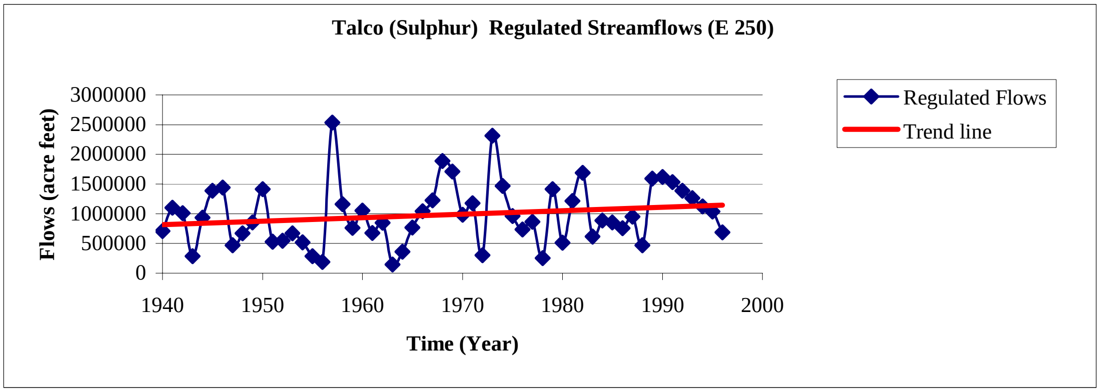

Figure 73. Regulated Streamflows for Talco

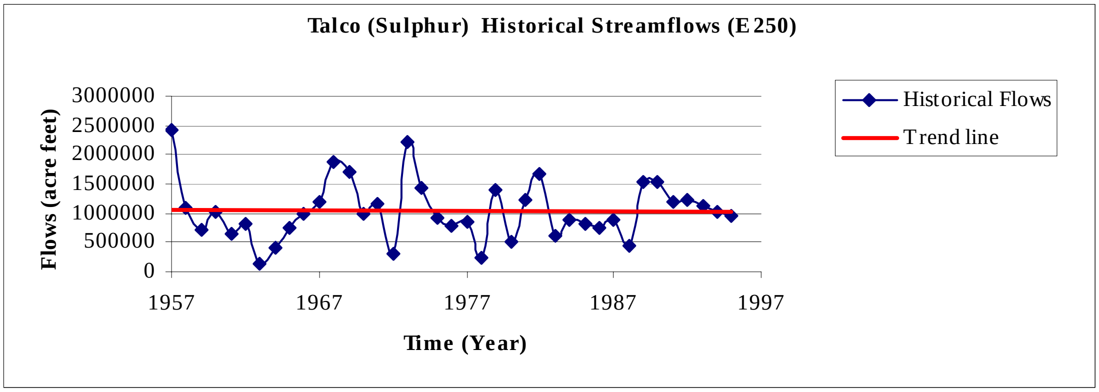

Figure 74. Historical Streamflows for Talco

6.11 Trinity River Basin

One control point was chosen on the Trinity River in the Trinity River basin. The annual quantities of the naturalized and regulated flows are for the 1940-1996 period. Figure 75 shows the location of the control point in the Trinity River basin. Figures 76 to 79 contrasts the naturalized, regulated and observed historical flows for the selected control point in the Trinity River basin. The flows at Romayor, Trinity show increasing upward linear trend. Romayor is located few miles downstream of Livingston Reservoir. The period of early and mid 1950's shows the low flow period. The river water in this basin is under the effects of regulation due to the large number of reservoirs being constructed in the basin.

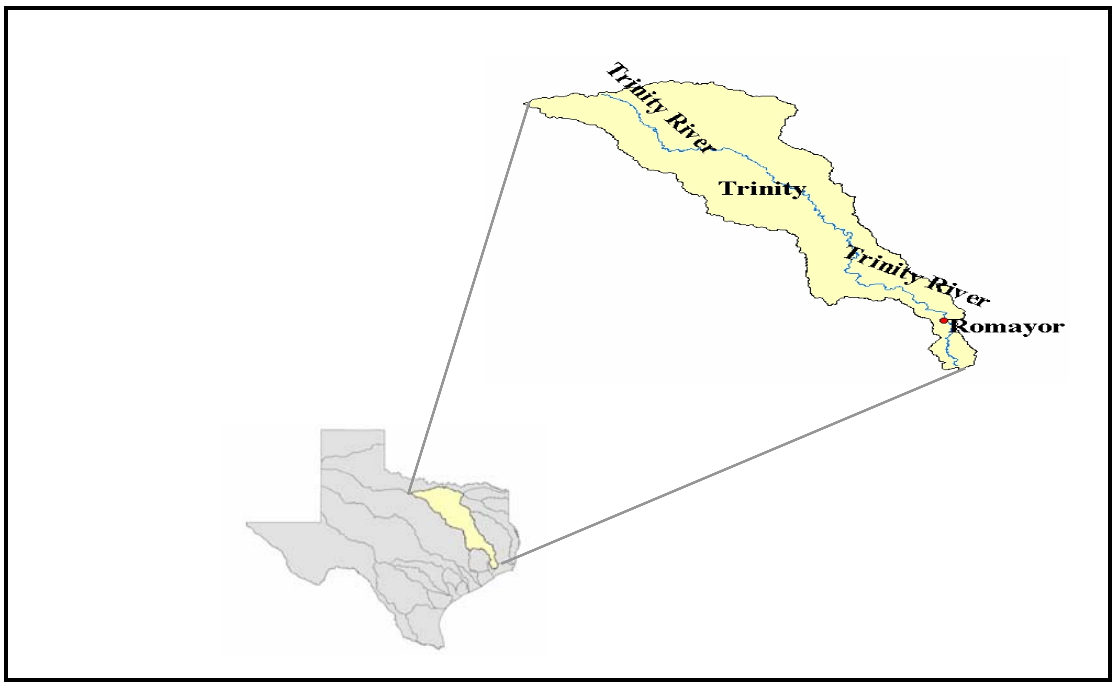

Figure 75. Location of Control Points in Trinity River Basin for Trend Analysis

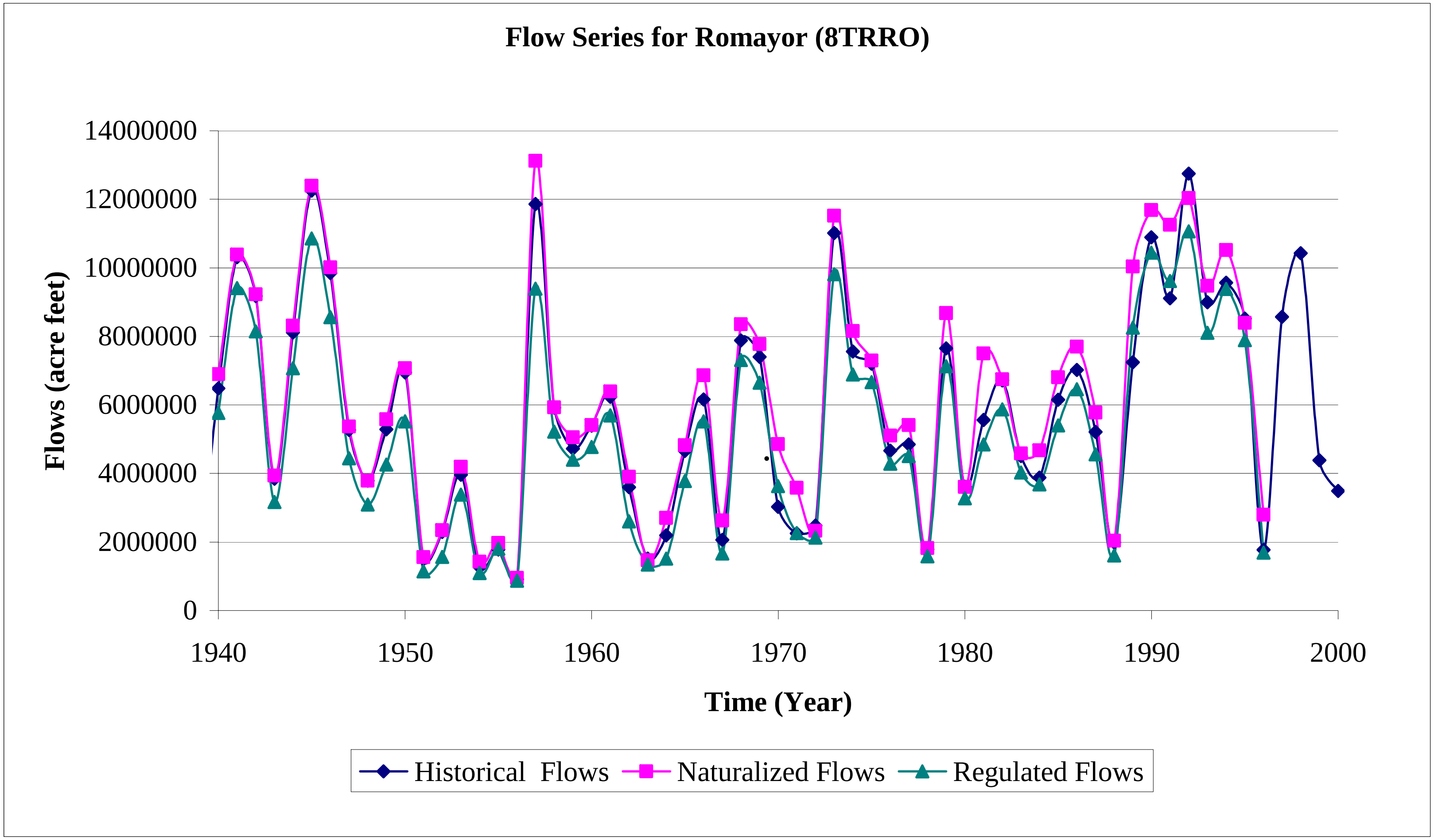

Figure 76. Flow Series for Romayor

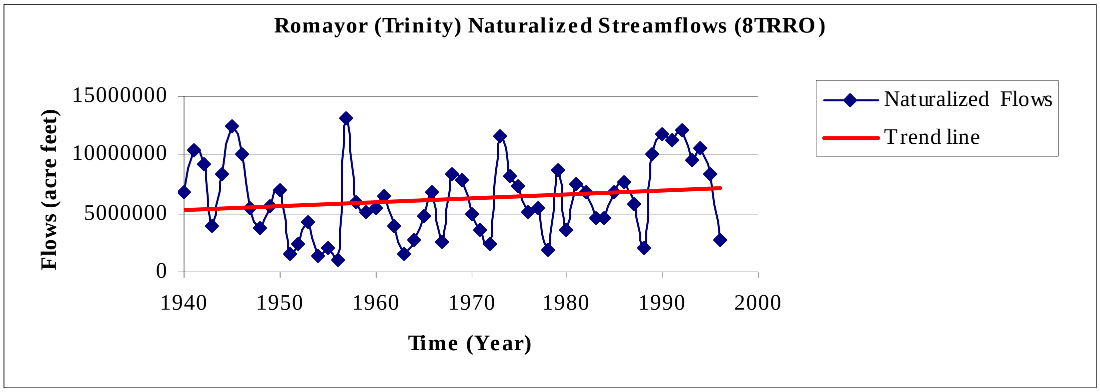

Figure 77. Naturalized Streamflows for Romayor

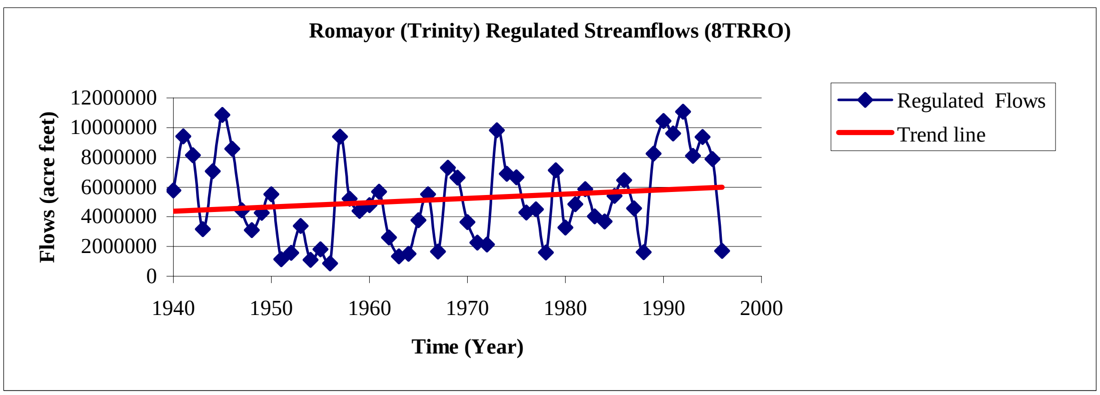

Figure 78. Regulated Streamflows for Romayor

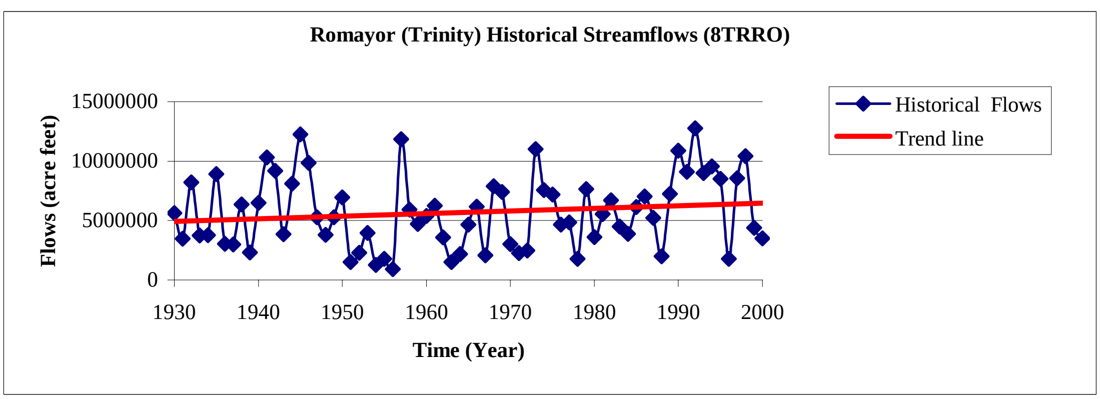

Figure 79. Historical Streamflows for Romayor

6.12 Cypress River Basin

One control point was chosen on the Little Cypress Creek in the Cypress River basin. The annual quantities of the naturalized and regulated flows are for the 1948-1998 period. Figure 80 shows the location of the control point in the Cypress River basin. Figures 81 to 84 contrasts the naturalized, regulated and observed historical flows for the selected control point in the Cypress River basin. The flows at Little Cypress Creek near Jefferson do not show any significant linear trend.

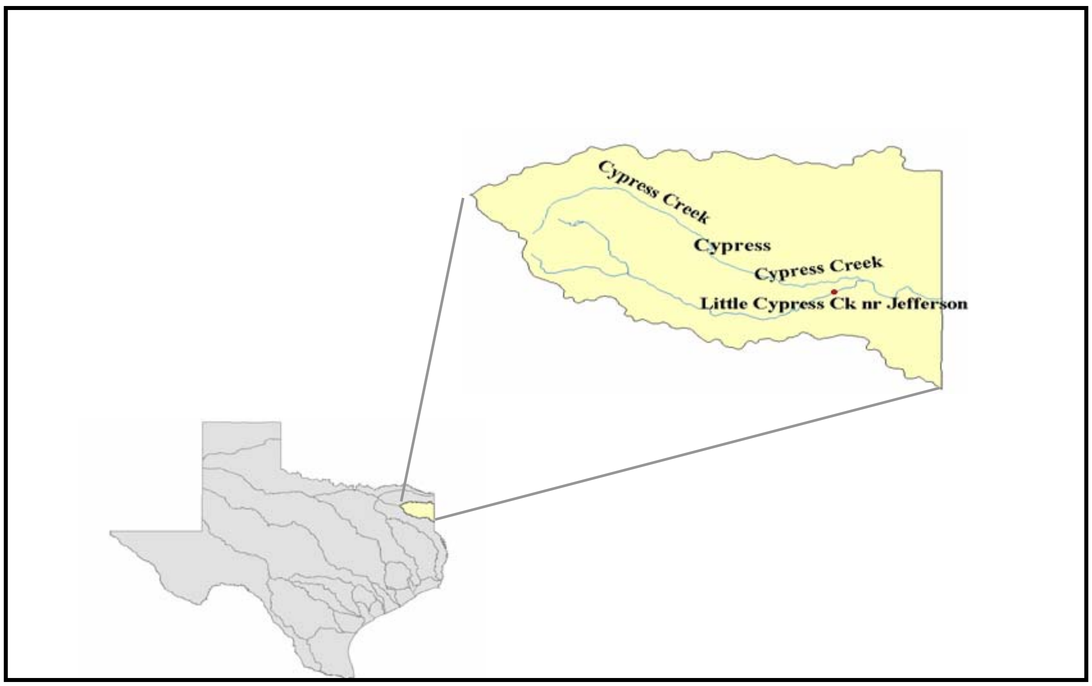

Figure 80. Location of Control Points in Cypress River Basin for Trend Analysis

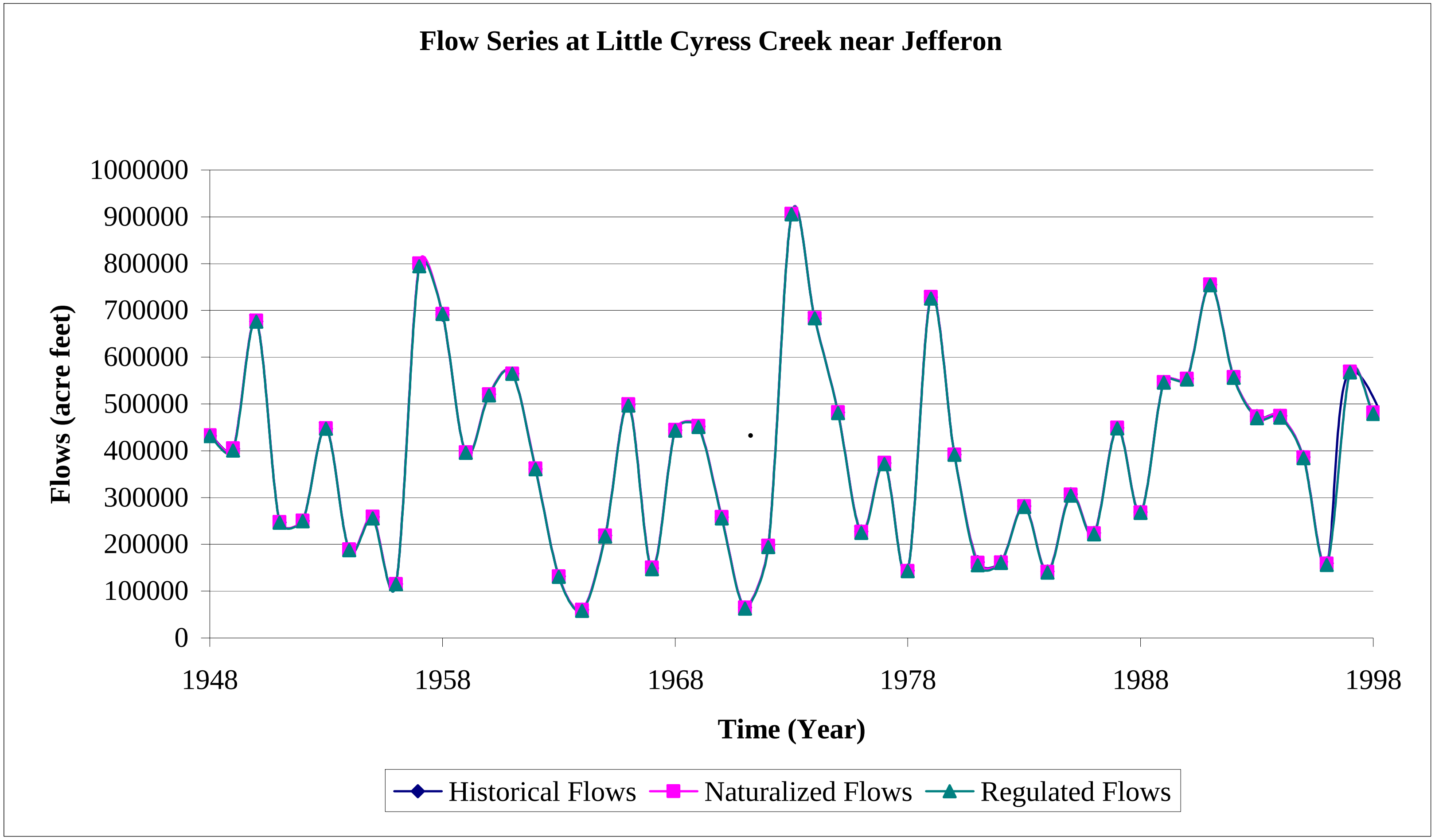

Figure 81. Flow Series at Little Cypress Creek near Jefferson

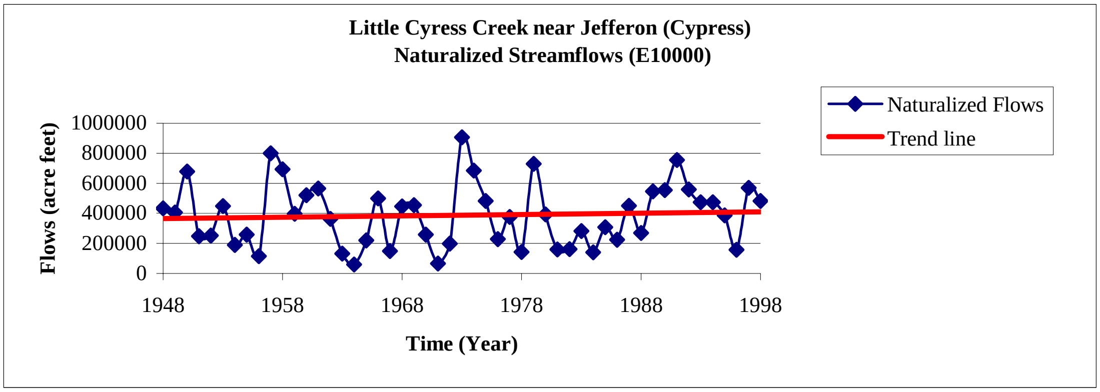

Figure 82. Naturalized Streamflows for Little Cypress Creek near Jefferson

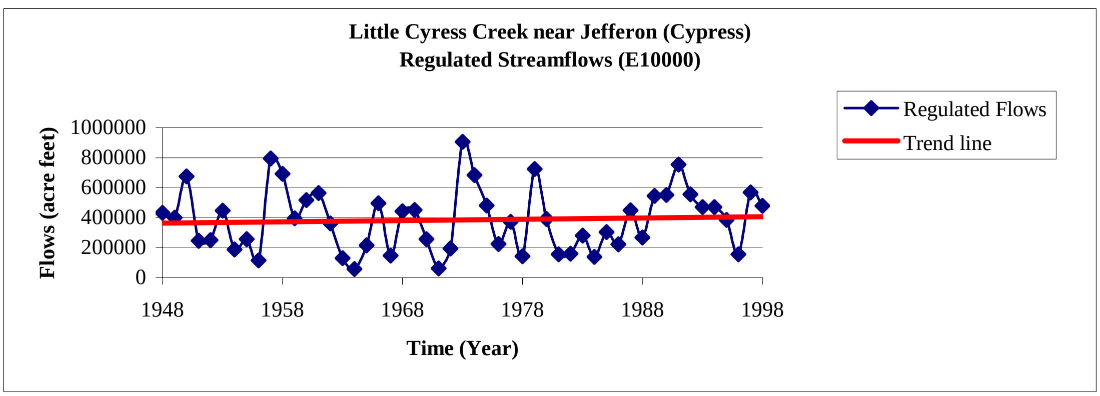

Figure 83. Regulated Streamflows for Little Cypress Creek near Jefferson

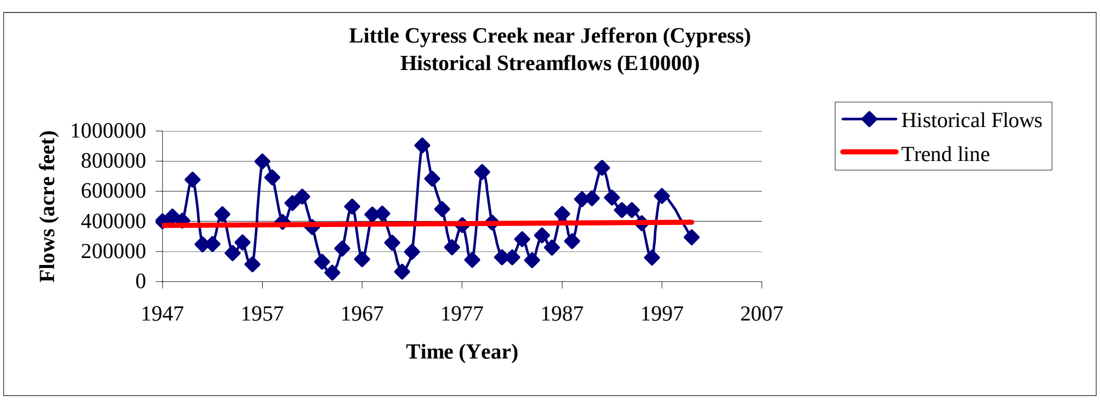

Figure 84. Historical Streamflows for Little Cypress Creek near Jefferson

6.13 Lavaca River Basin

One control point was chosen on the Lavaca River in the Lavaca River basin. The annual quantities of the naturalized and regulated flows are for the 1940-1996 period. Figure 85 shows the location of the control point in the Lavaca River basin. Figures 86 to 89 contrasts the naturalized, regulated and observed historical flows for the selected control point in the Lavaca River basin. The flows near Edna, Lavaca show increasing upward linear trend. The period of early and mid 1950's and late 1980's shows the low flow period. The period of early 1970's and 1990's show high flow period.

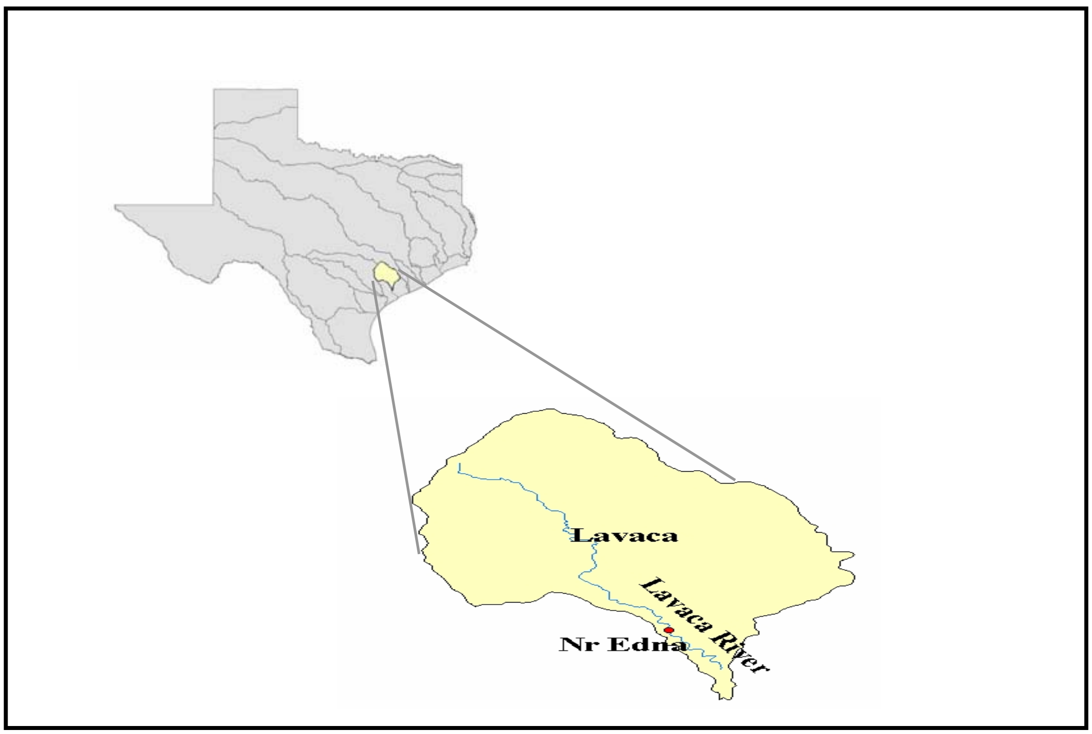

Figure 85. Location of Control Points in Lavaca River Basin for Trend Analysis

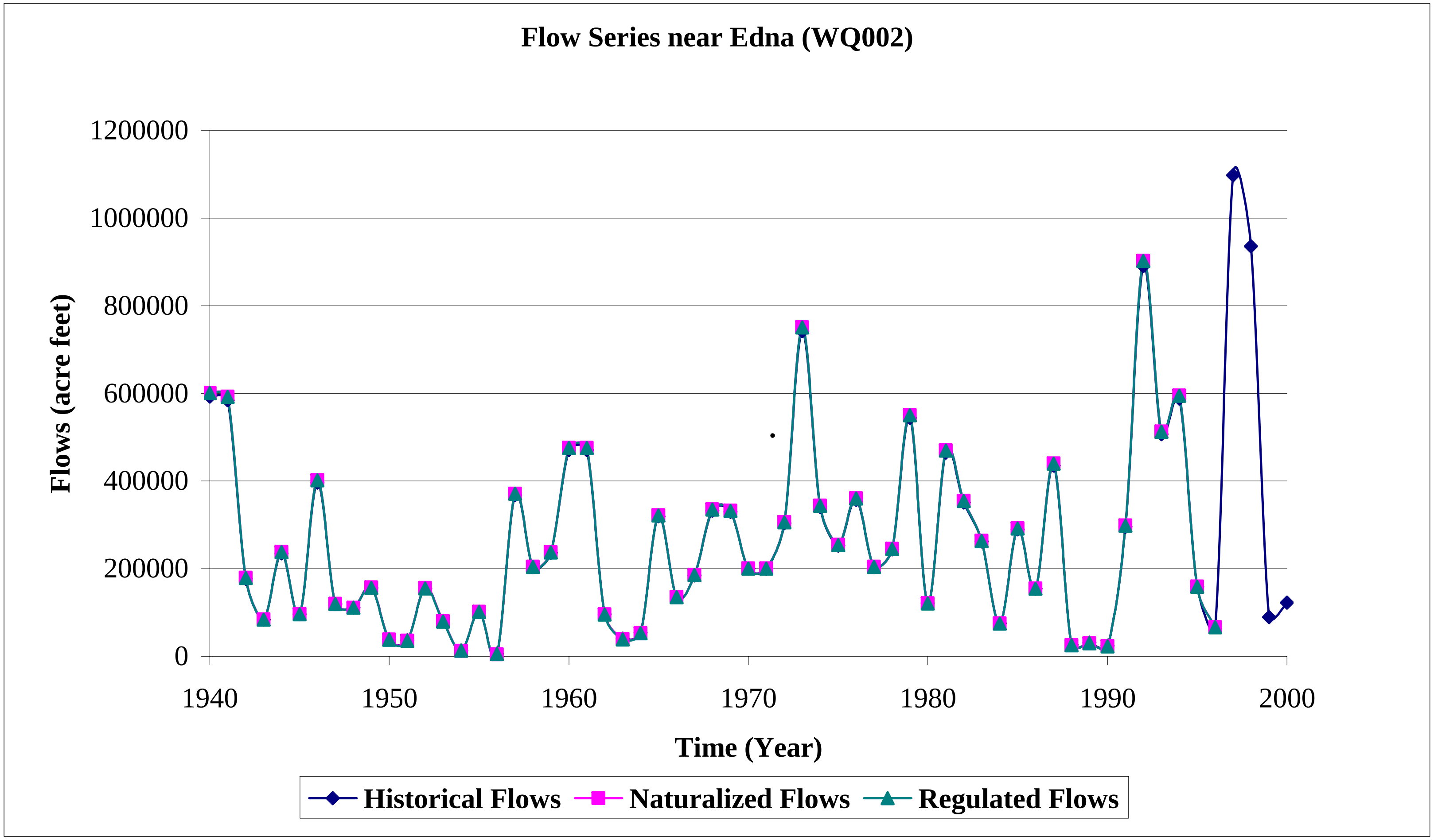

Figure 86. Flow Series near Edna

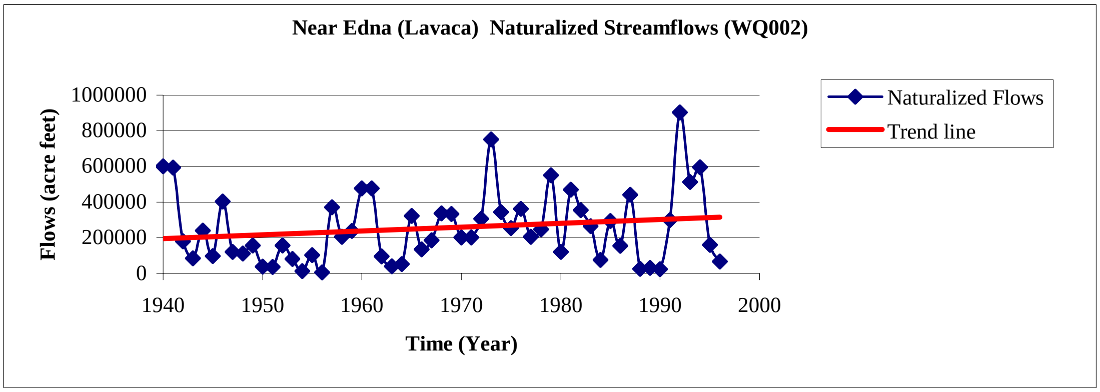

Figure 87. Naturalized Streamflows near Edna

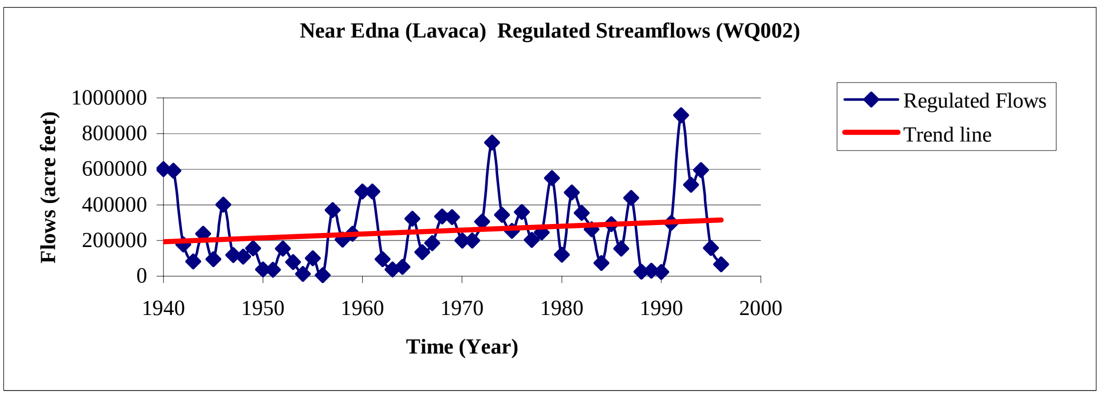

Figure 88. Regulated Streamflows near Edna

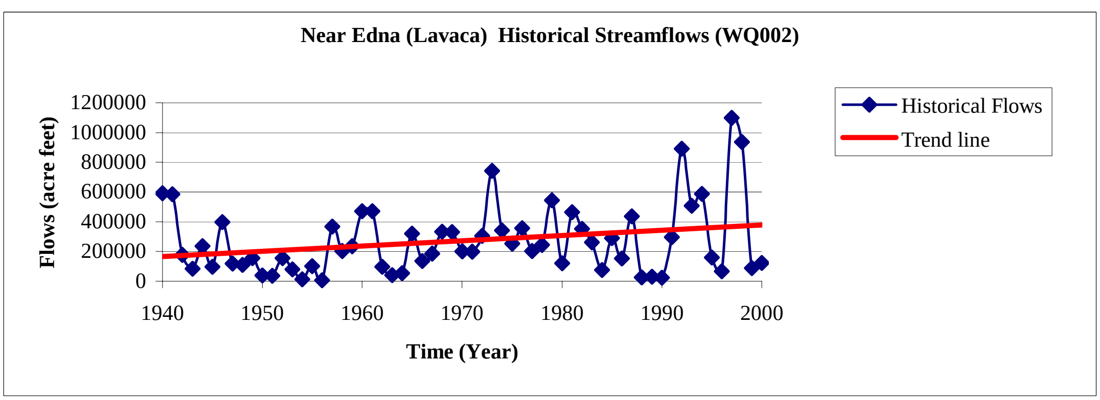

Figure 89. Historical Streamflows near Edna

6.14 San Jacinto River Basin

One control point was chosen on the San Jacinto River in the San Jacinto River basin. The annual quantities of the naturalized and regulated flows are for the 1940-1996 period. Figure 90 shows the location of the control point in the San Jacinto River basin. Figures 91 to 94 contrasts the naturalized, regulated and observed historical flows for the selected control point in the San Jacinto River basin. The flows near Conroe, San Jacinto do not show any significant linear trend. The control point is located few miles downstream of the Lake Conroe. The flows at this location are controlled largely by the operations of the lake. The period of early and mid 1950's and early 1970's shows the low flow period.

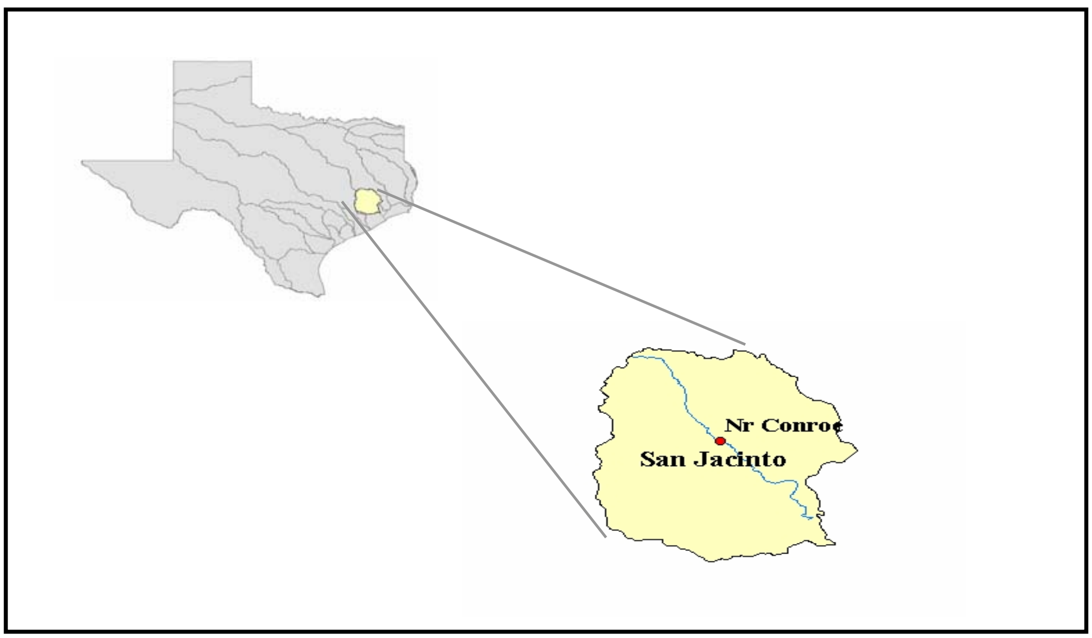

Figure 90. Location of Control Points in San Jacinto River Basin for Trend Analysis

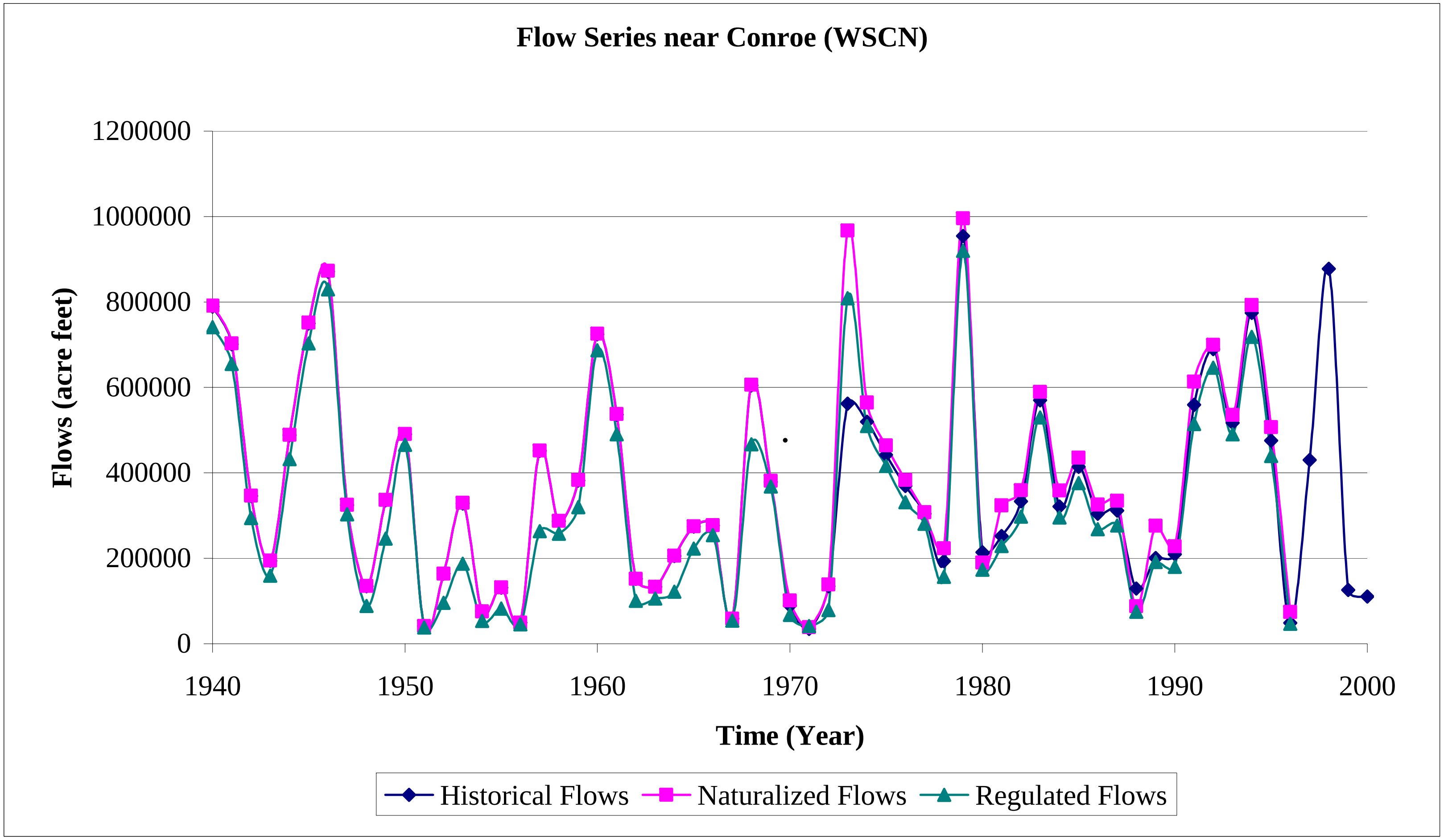

Figure 91. Flow Series near Conroe

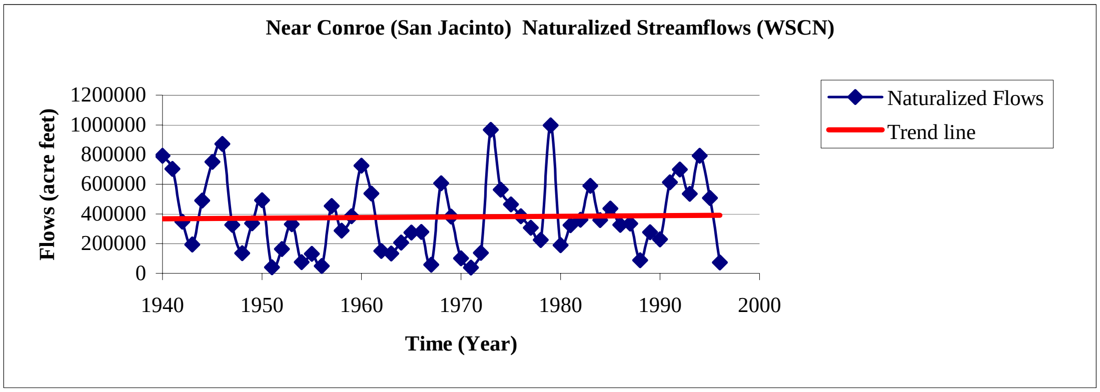

Figure 92. Naturalized Streamflows near Conroe

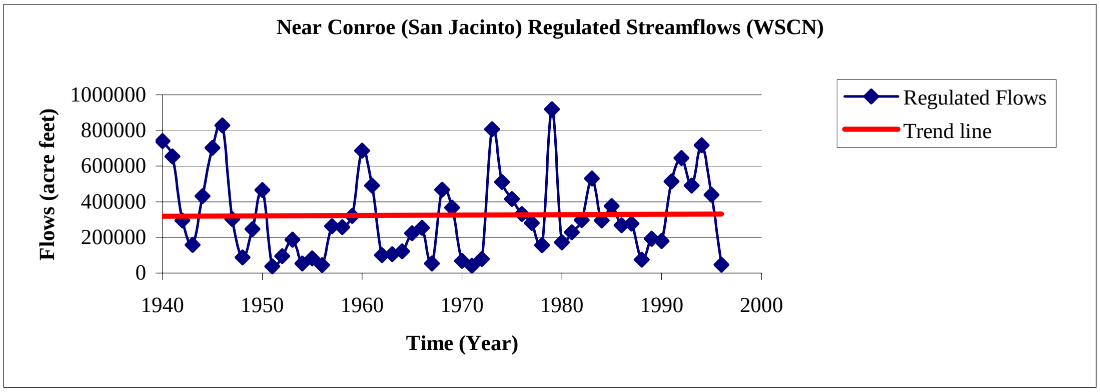

Figure 93. Regulated Streamflows near Conroe

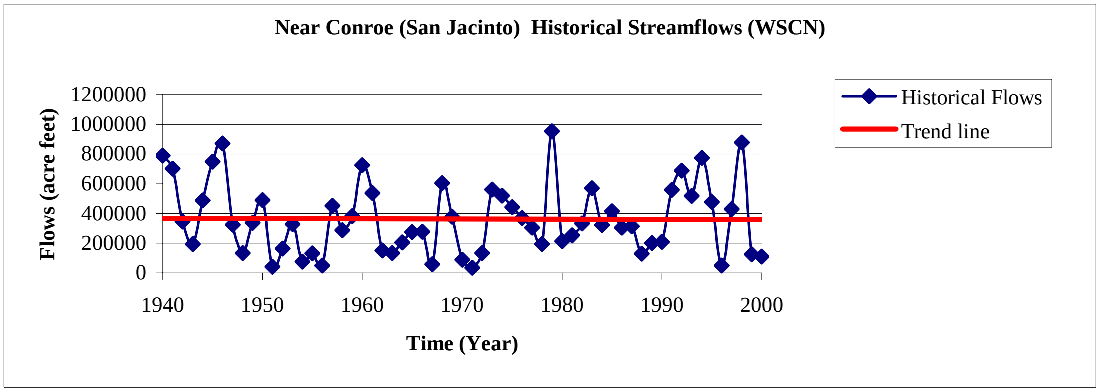

Figure 94. Historical Streamflows near Conroe

6.15 Rio Grande River Basin

Eight control points were chosen on the rivers in the Rio Grande basin. The annual quantities of the naturalized and regulated flows are for the 1940-2000 period. Figure 95 shows the location of the control points in the Rio Grande basin.

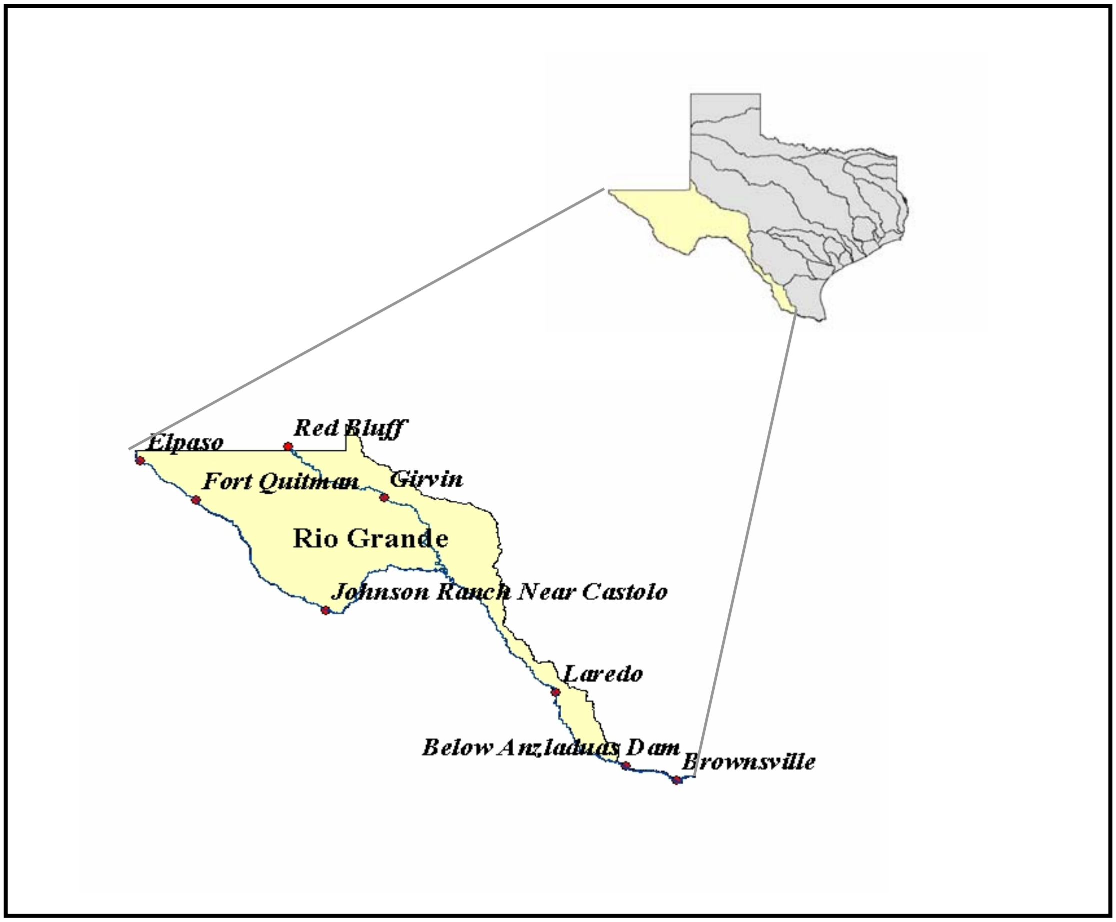

Figure 95. Location of Control Points in Rio Grande River Basin for Trend Analysis

The graphs illustrate the changes in the streamflows as a result of human activities in the watershed.

1. The plots for the control points of the Rio Grande Basin showed that the early 1940’s was the wet period as compared to other periods. The early 1940’s experienced high flows below the elephant Butte reservoir for the Rio Grande basin. The basin also experienced hydrological droughts during the 1950’s, 1960’s and 1990’s. The combined natural and regulated flows for the U.S. and Mexico portion at El Paso gaging station do not show any significant linear trend. The historical flows at this location show a decreasing linear trend.
2. The historical flows at Girvin on Pecos River have a decreasing linear trend. At this site the excessive use of the river water has resulted in very low flows, leading to no water for further appropriation.
3. The combined naturalized and regulated flows for the Texas and Mexico portion at Fort Quitman do not show any significant linear trend. The location faces severe drought problems during many years of its hydrological history. However, the plots for the historical flows show a decreasing linear trend.
4. The historical flows for the Texas and Mexico portion at Johnson Ranch near Castolon underwent decreasing linear trend. The site faces high flows during early 1940’s and early 1990’s.
5. The historical flows at Laredo for the state of Texas portion follow the decreasing trend. The decreasing flows for the Texas portion can be due to highly populated and industrial areas at this location.

6. The historical flows below Anzalduas dam for the state of Texas show decreasing linear trend. The site experiences high flow conditions during several years of its hydrological period. This might be due to the releases from the diversion dam. But the period from 1990-2000 is relatively dry for the site.

7. The historical flows at Brownsville, located near the outlet of the basin underwent downward linear trend. The low flow conditions exist most of time except the period from 1970's-1980.

Figures 96 to 127 contrasts the naturalized, regulated and observed historical flows for the selected control point in the Rio Grande basin.

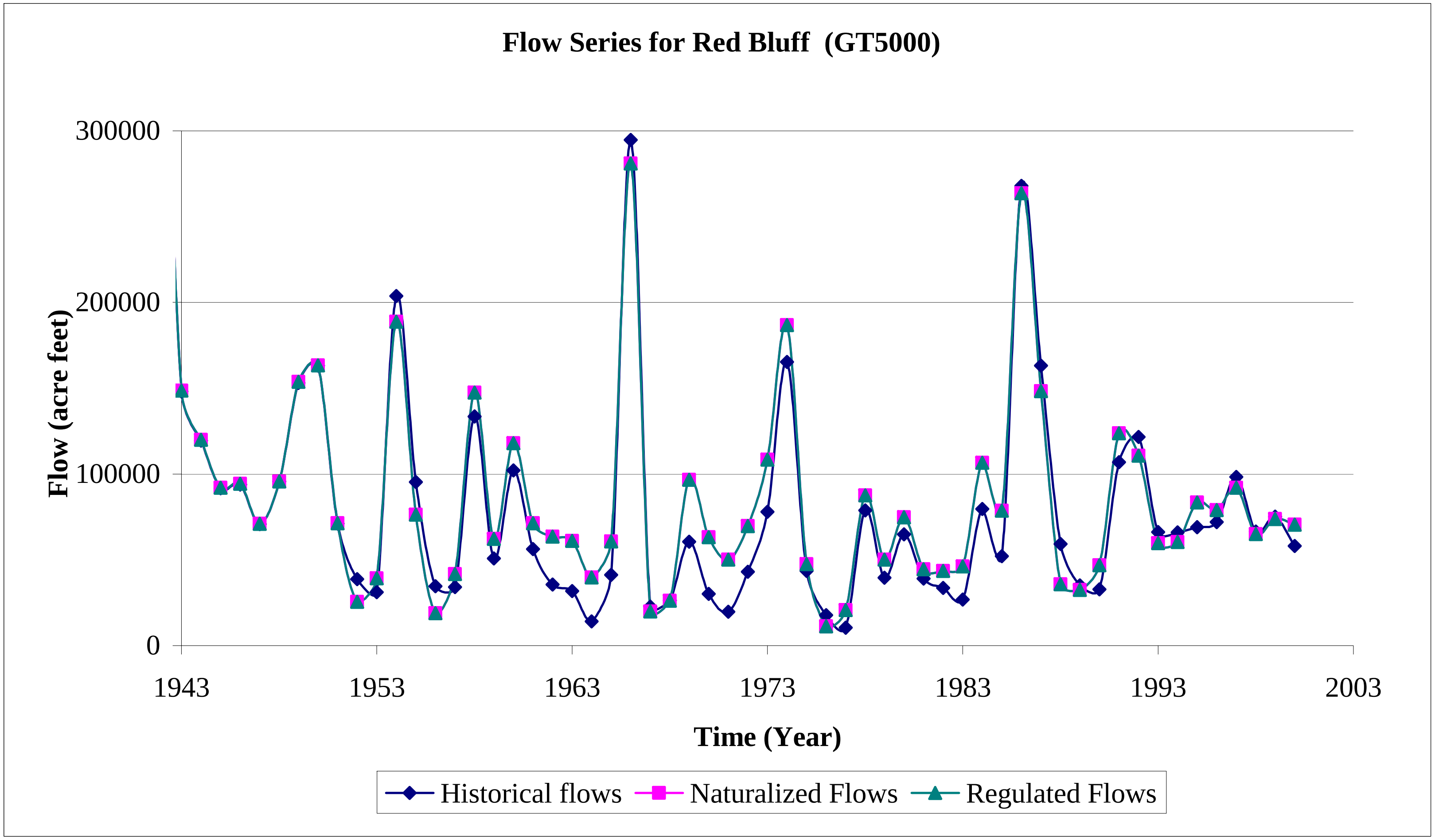

Figure 96. Flow Series for Red Bluff

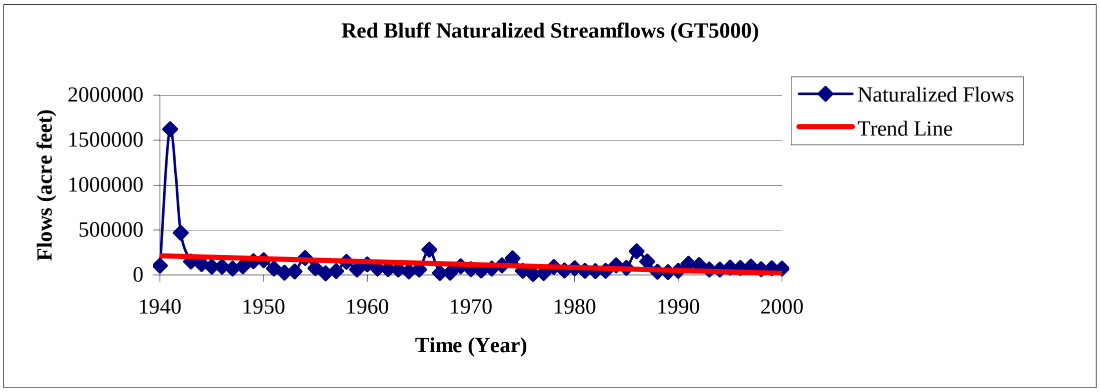

Figure 97. Naturalized Streamflows at Red Bluff

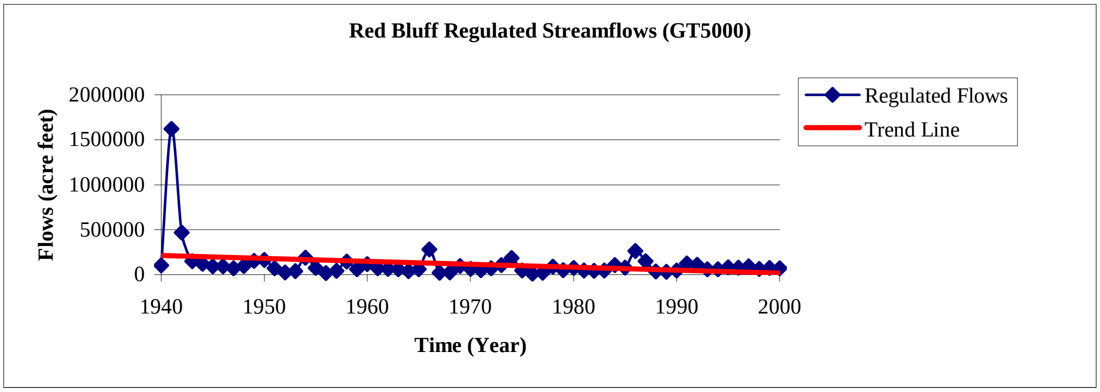

Figure 98. Regulated Streamflows at Red Bluff

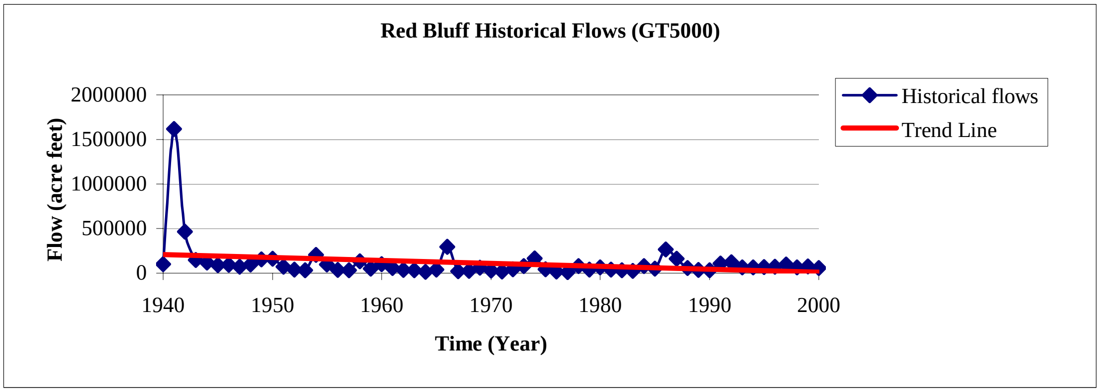

Figure 99. Historical Streamflows at Red Bluff

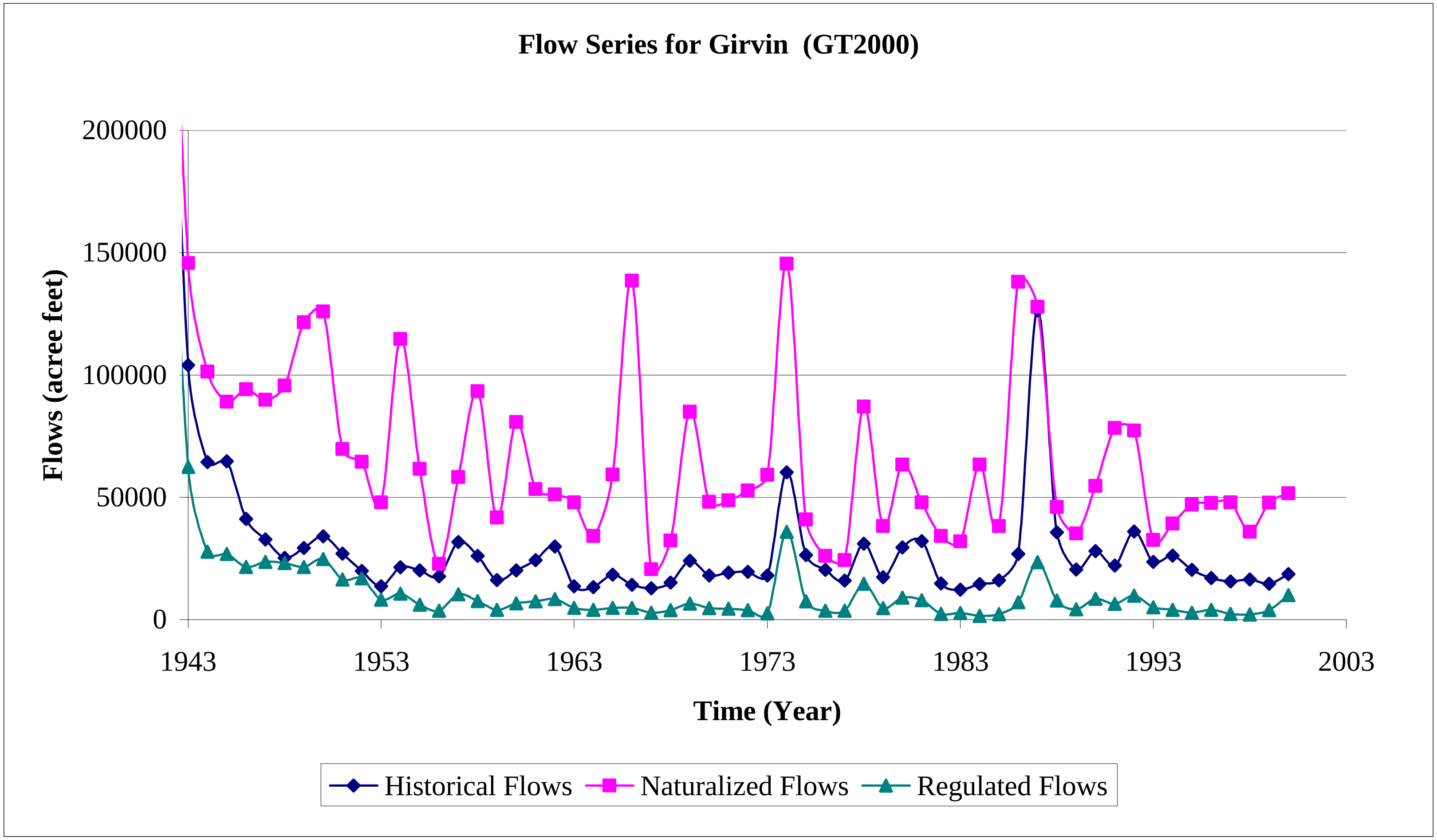

Figure 100. Flow Series for Girvin

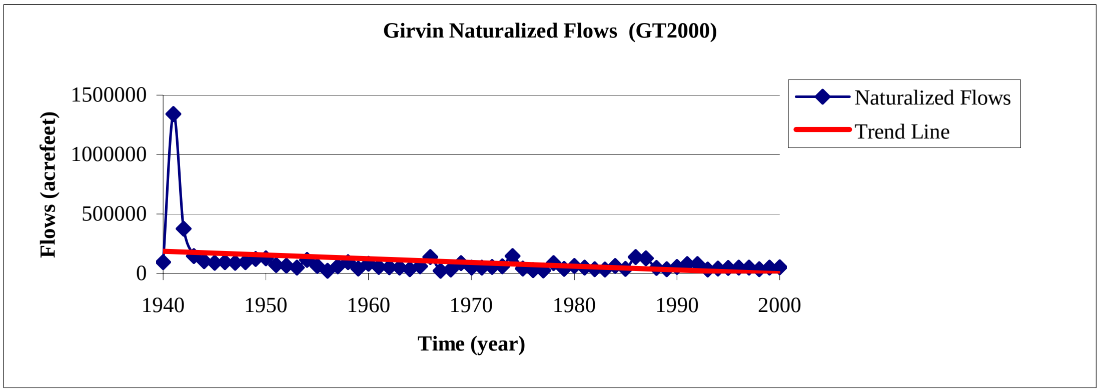

Figure 101. Naturalized Streamflows for Girvin

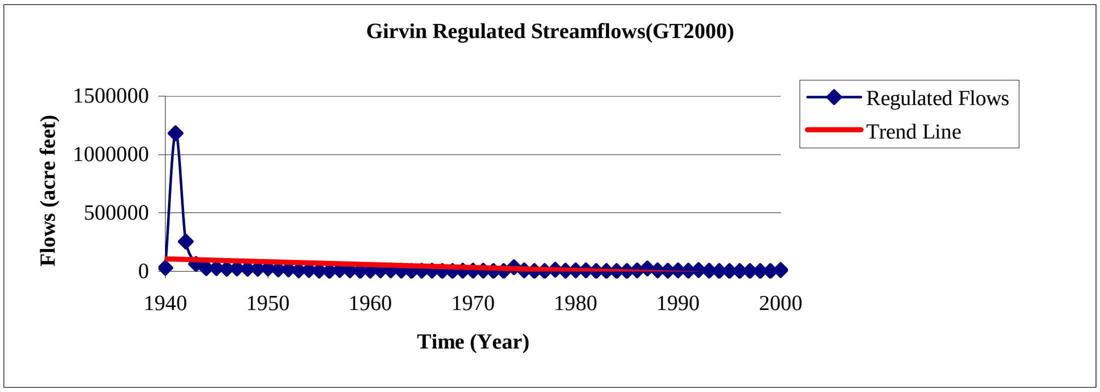

Figure 102. Regulated Streamflows for Girvin

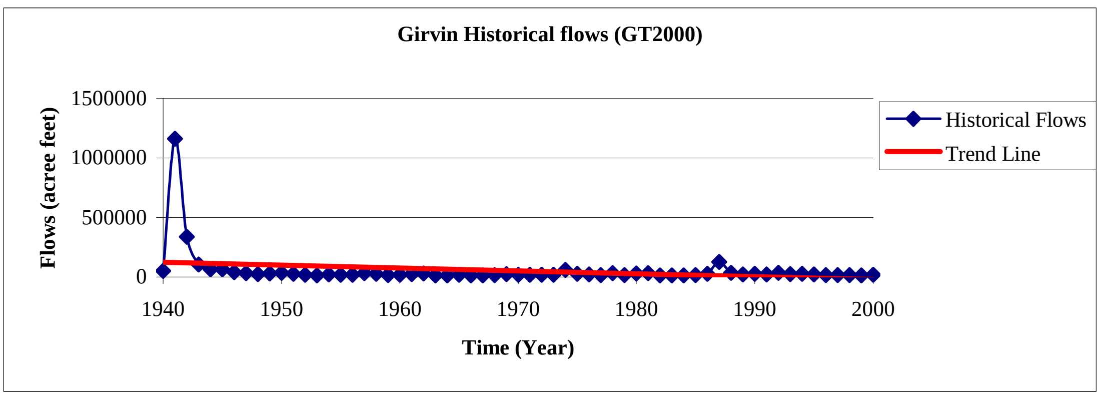

Figure 103. Historical Streamflows for Girvin

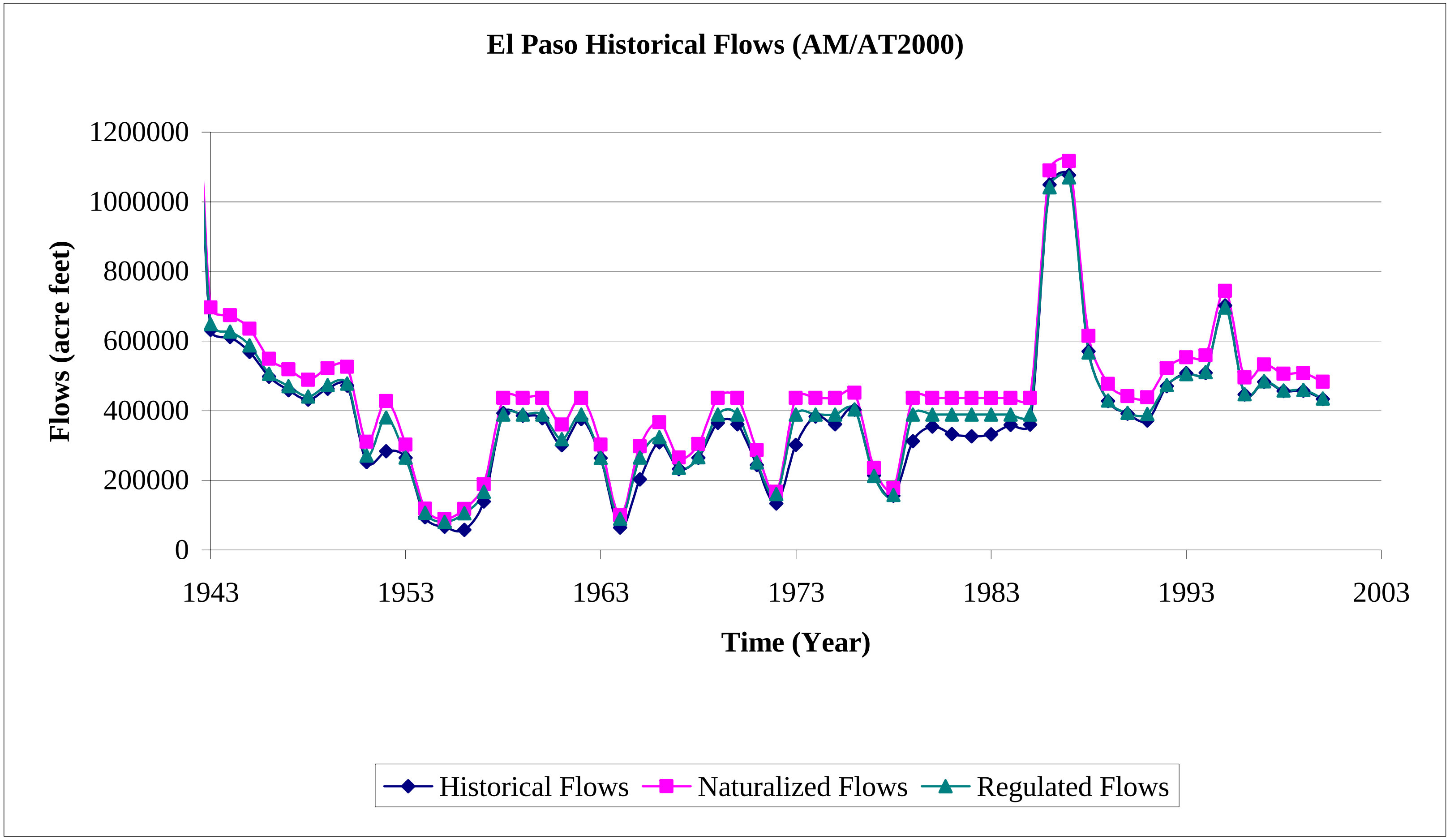

Figure 104. Flow Series for El Paso

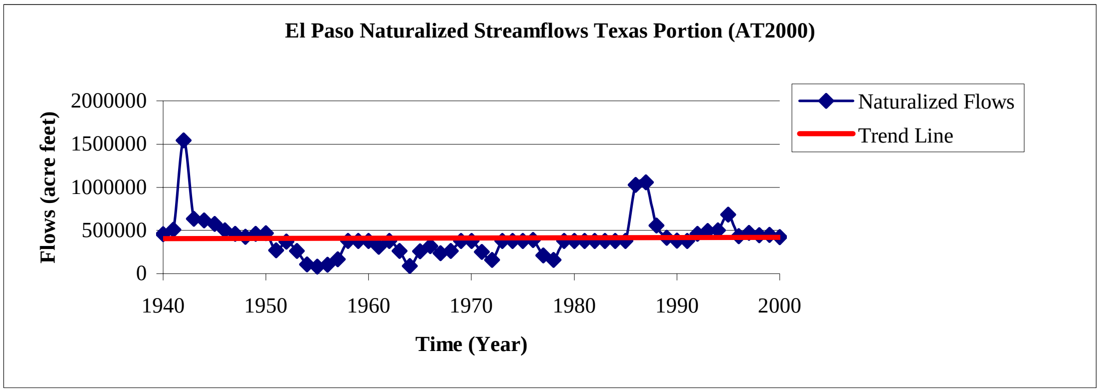

Figure 105. Naturalized Streamflows for El Paso for Texas Portion

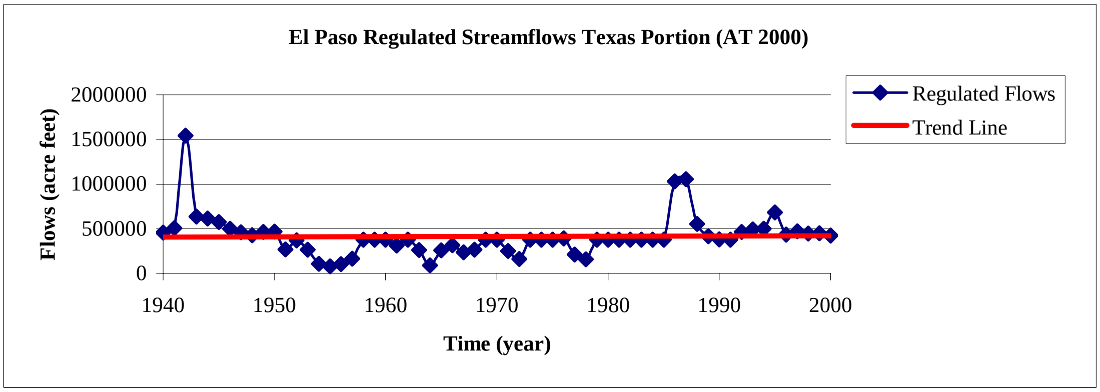

Figure 106. Regulated Streamflows for El Paso for Texas Portion

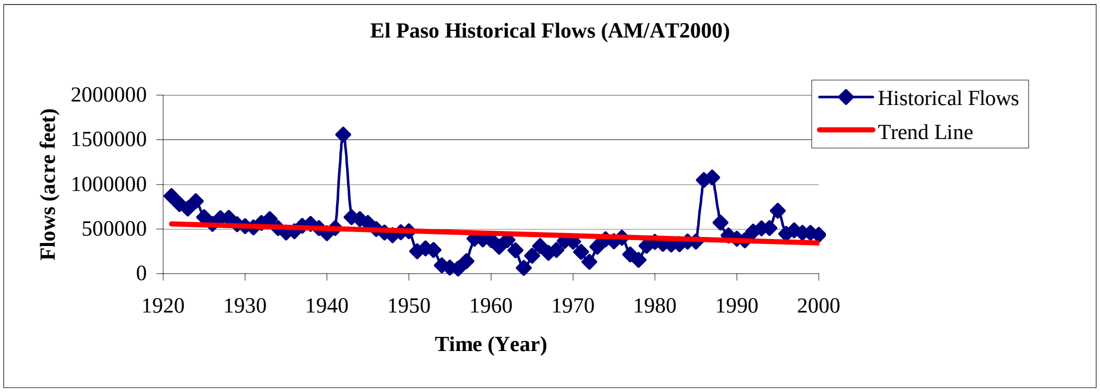

Figure 107 . Historical Streamflows for El Paso for Texas Portion

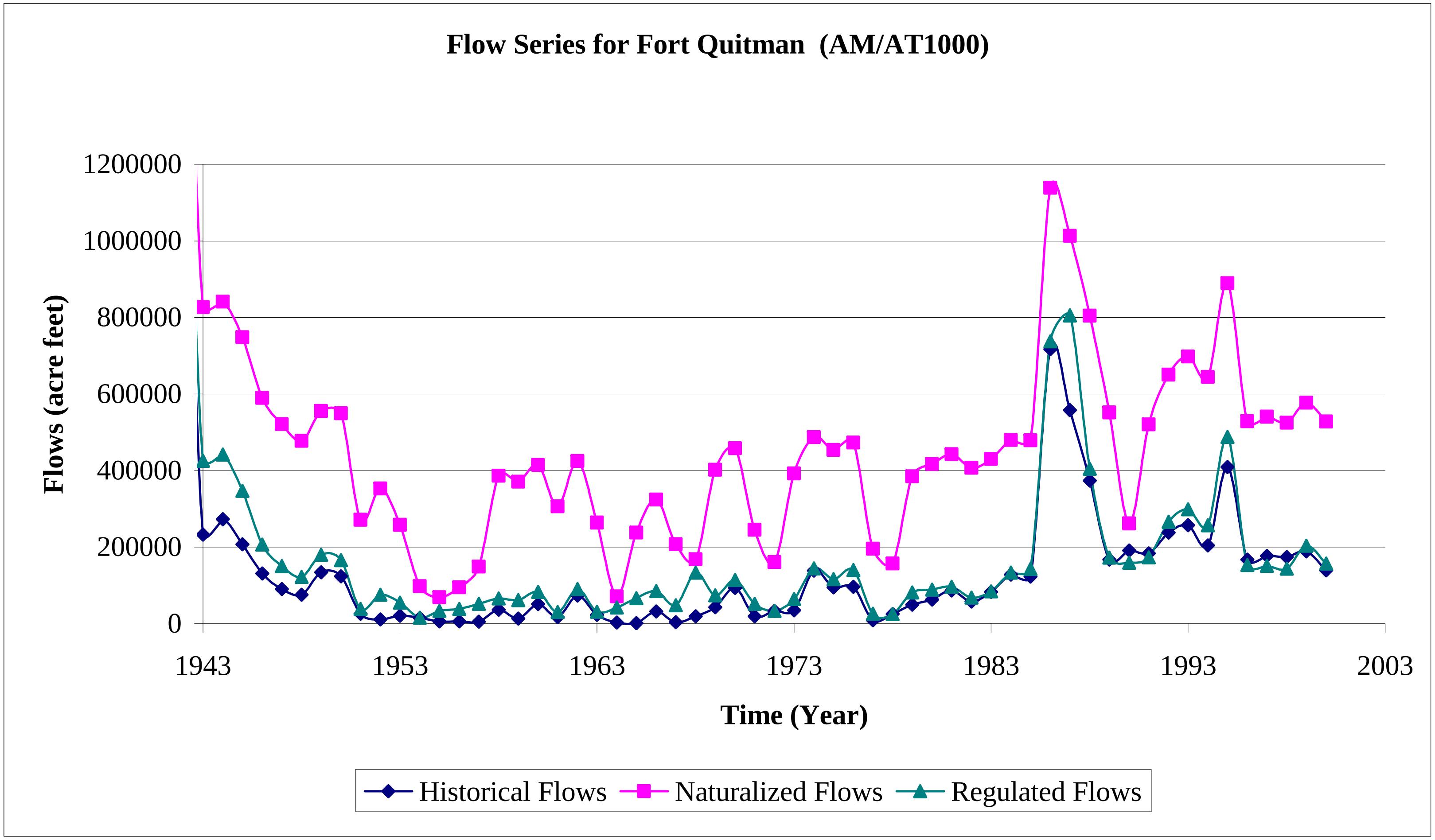

Figure 108. Flow Series for Fort Quitman

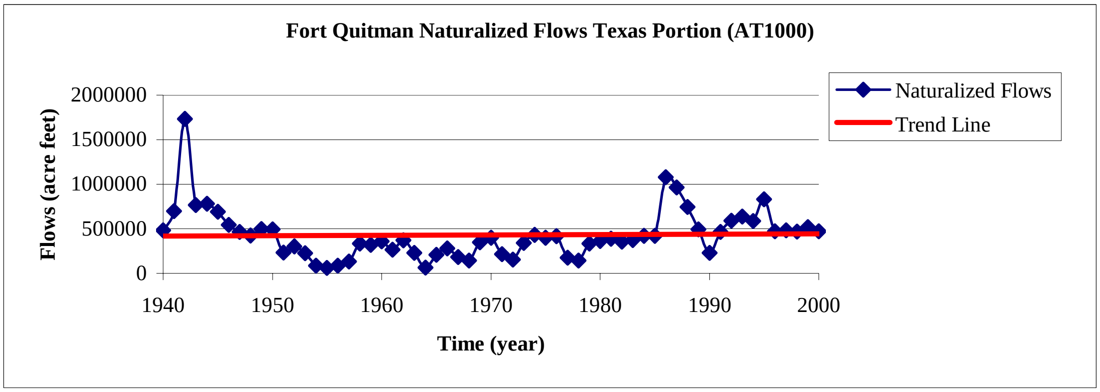

Figure 109. Naturalized Streamflows for Fort Quitman for Texas Portion

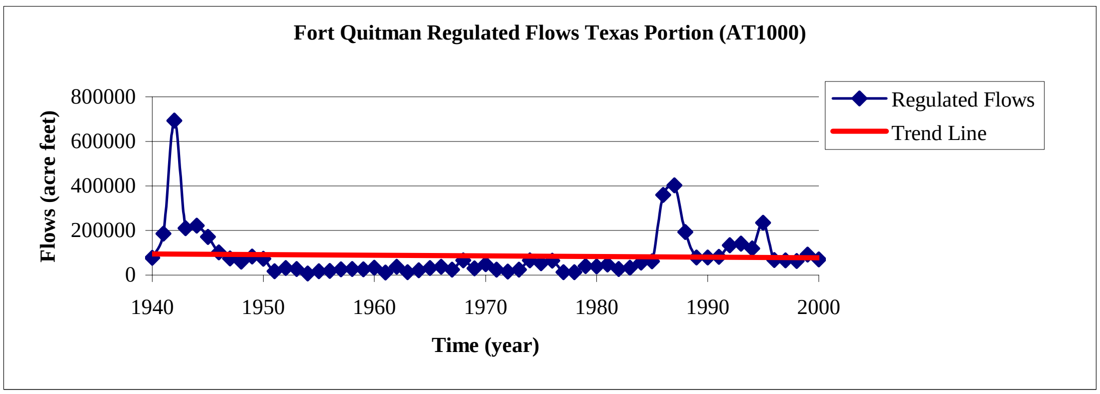

Figure 110. Regulated Streamflows for Fort Quitman for Texas Portion

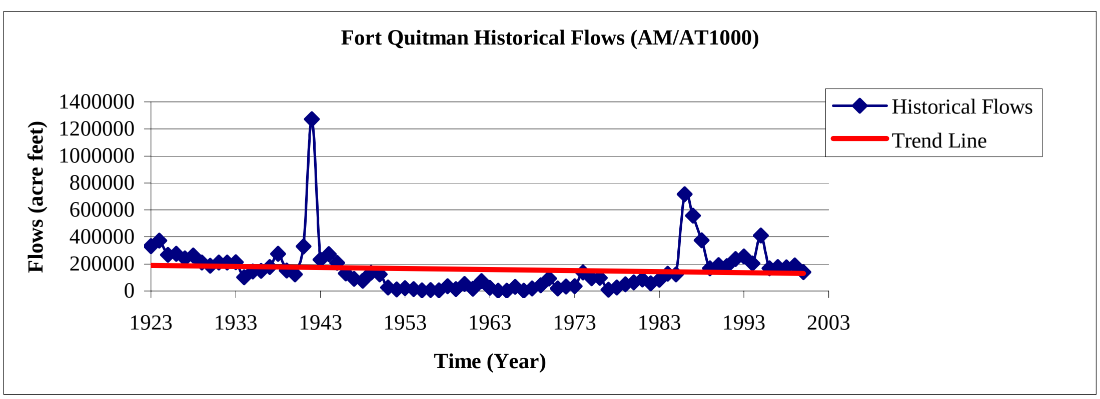

Figure 111. Historical Streamflows for Fort Quitman for Texas Portion

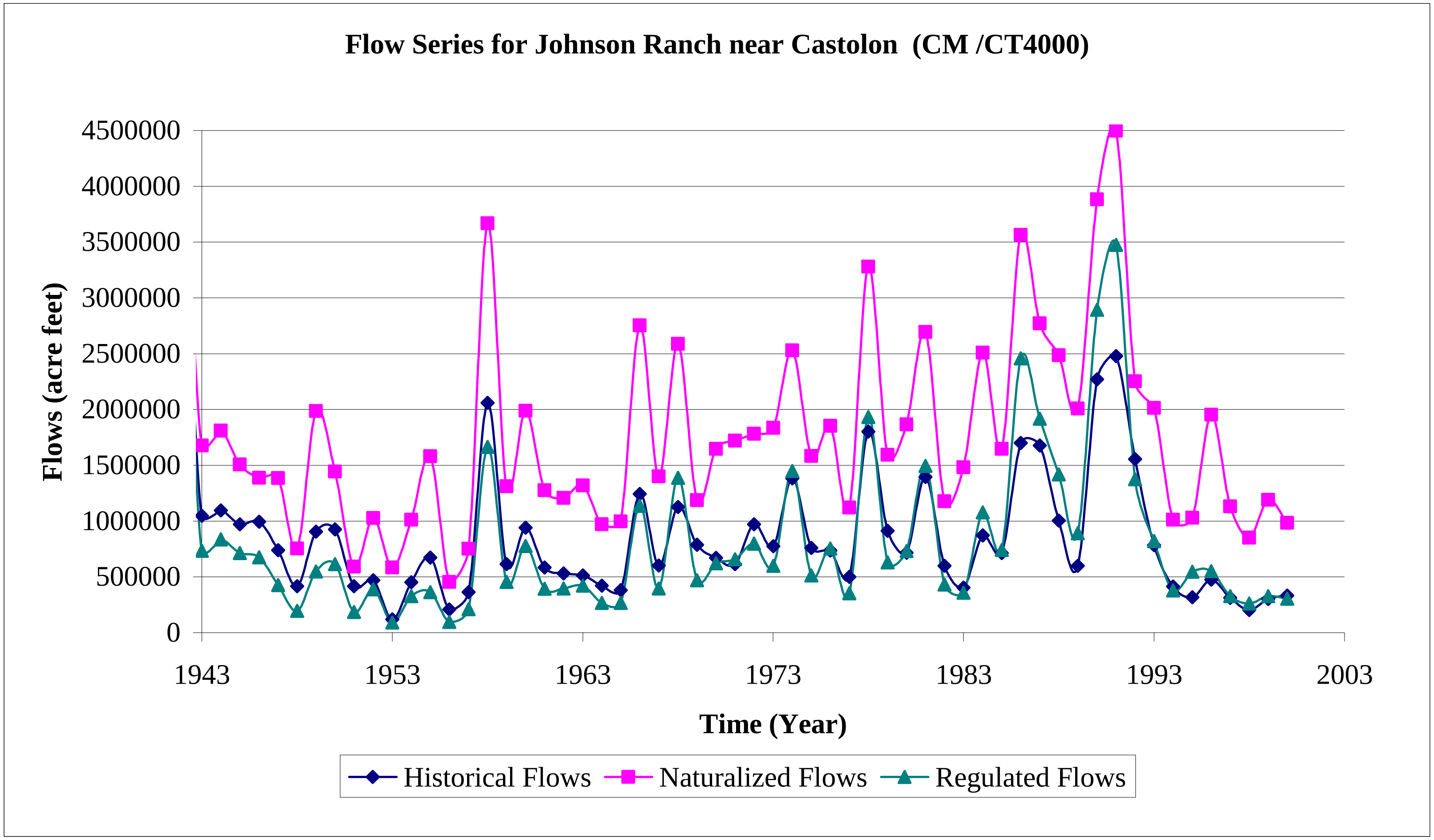

Figure 112. Flow Series for Johnson Ranch near Castolon

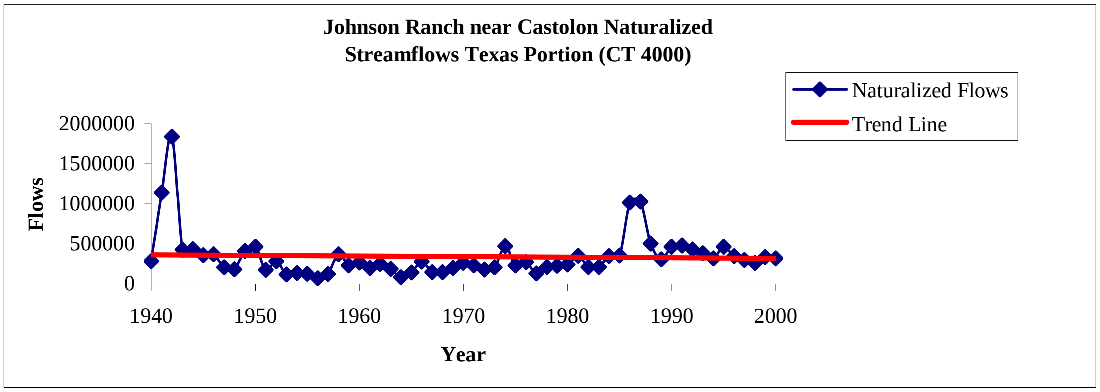

Figure 113. Naturalized Streamflows for Johnson Ranch near Castolon for Texas Portion

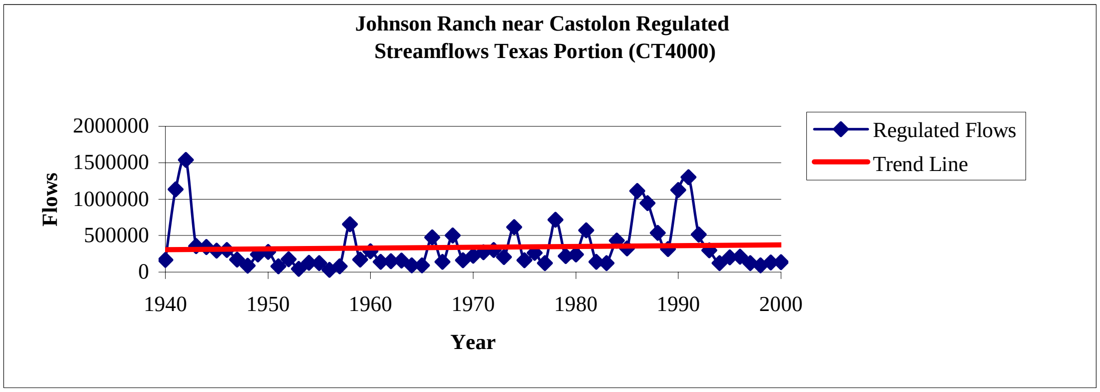

Figure 114. Regulated Streamflows for Johnson Ranch near Castolon for Texas Portion

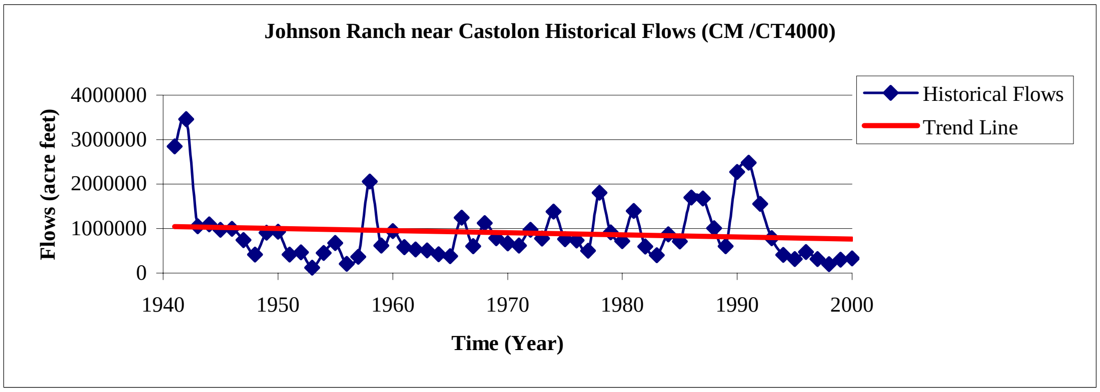

Figure 115. Historical Streamflows for Johnson Ranch near Castolon for Texas Portion

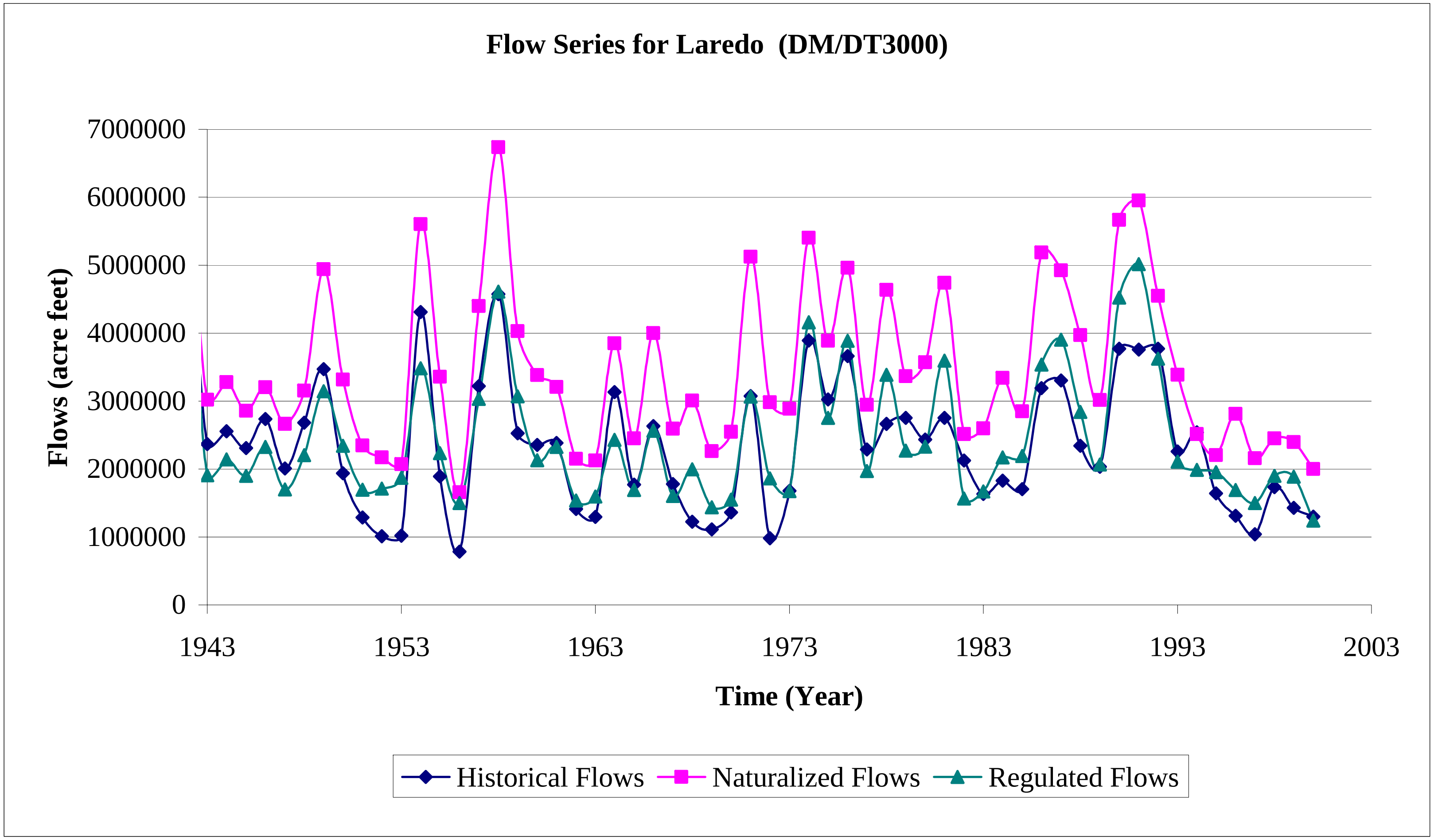

Figure 116. Flow Series for Laredo

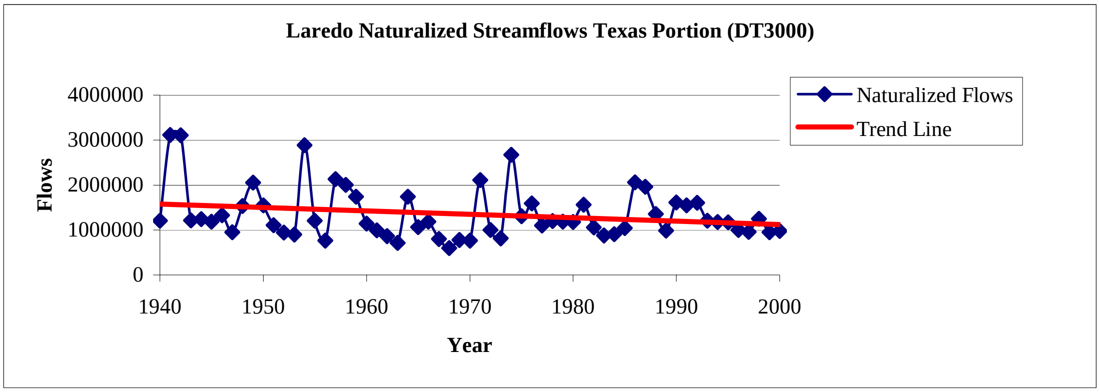

Figure 117. Naturalized Streamflows for Laredo for Texas Portion

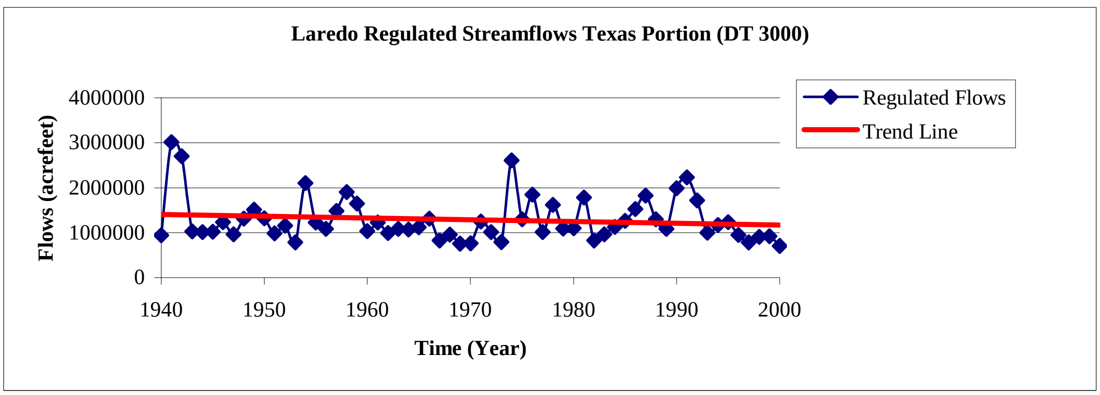

Figure 118. Regulated Streamflows for Laredo for Texas Portion

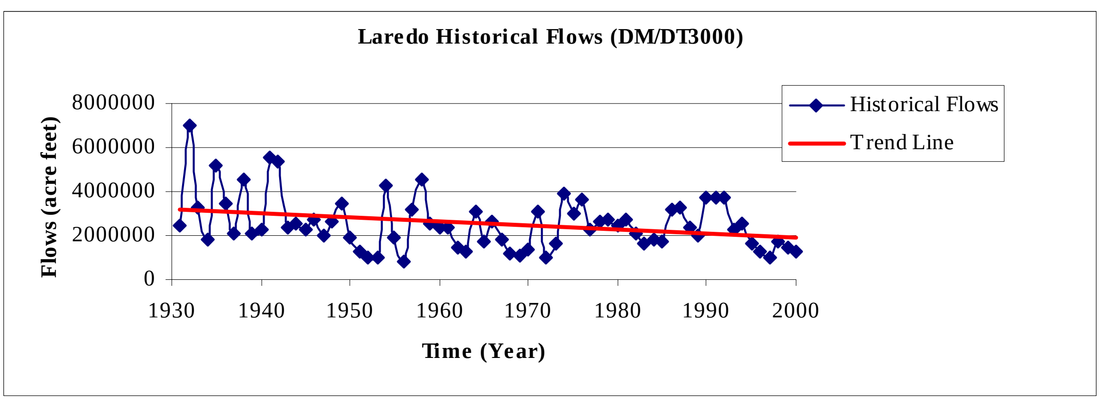

Figure 119. Historical Streamflows for Laredo for Texas Portion

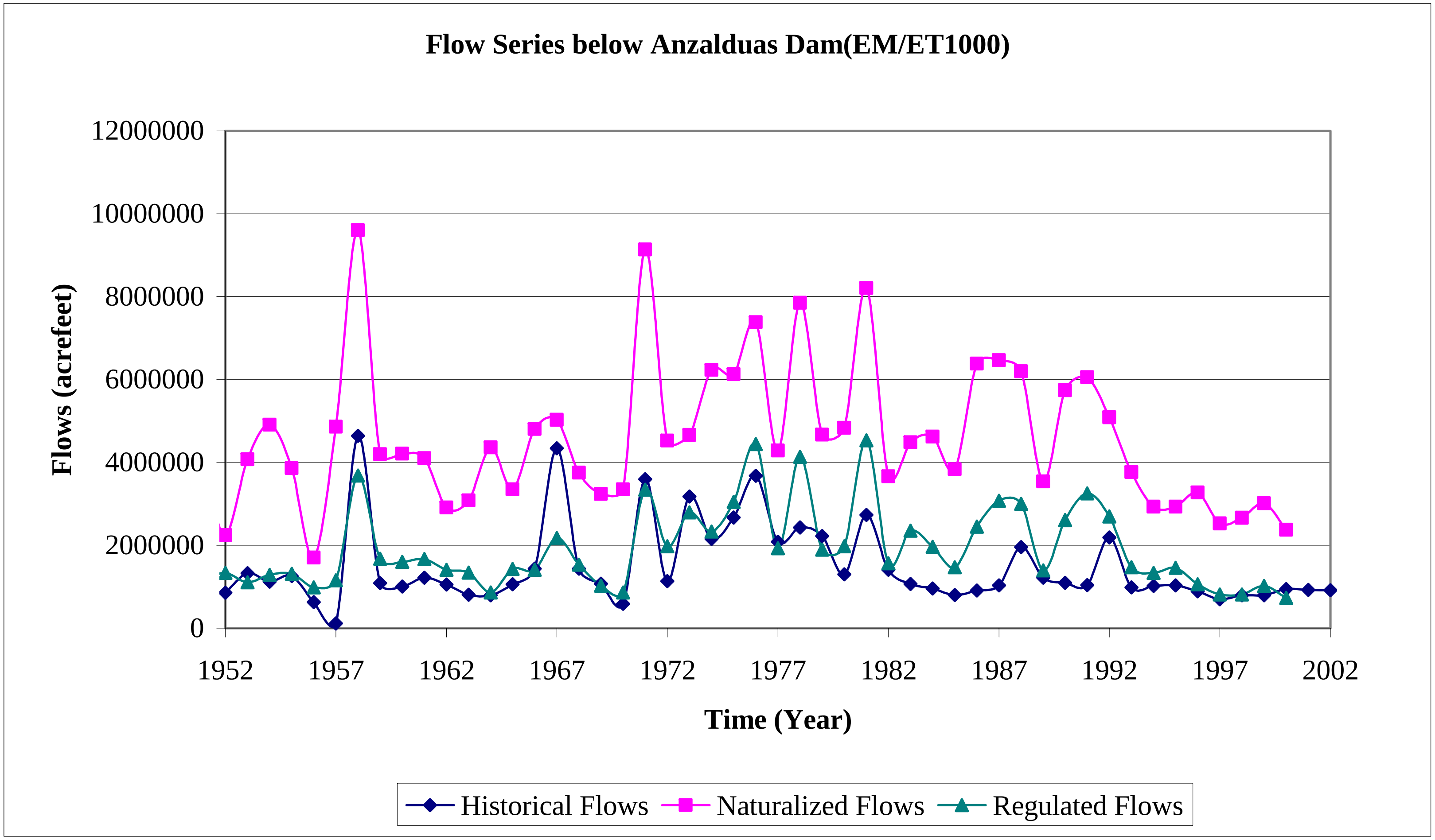

Figure 120. Flow Series below Anzalduas Dam

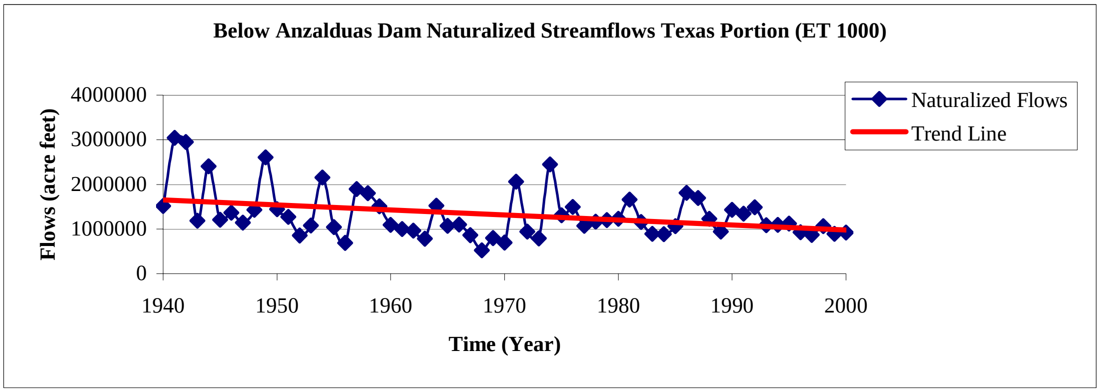

Figure 121. Naturalized Streamflows below Anzalduas Dam for Texas Portion

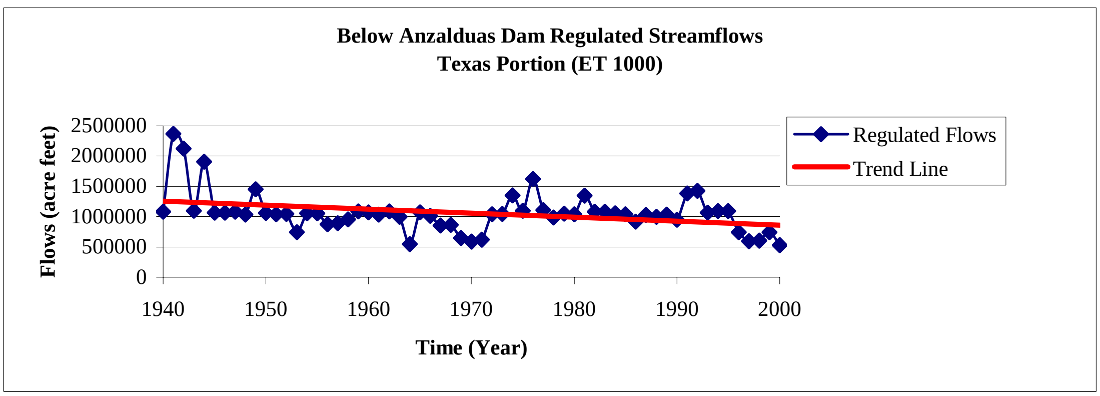

Figure 122. Regulated Streamflows below Anzalduas Dam for Texas Portion

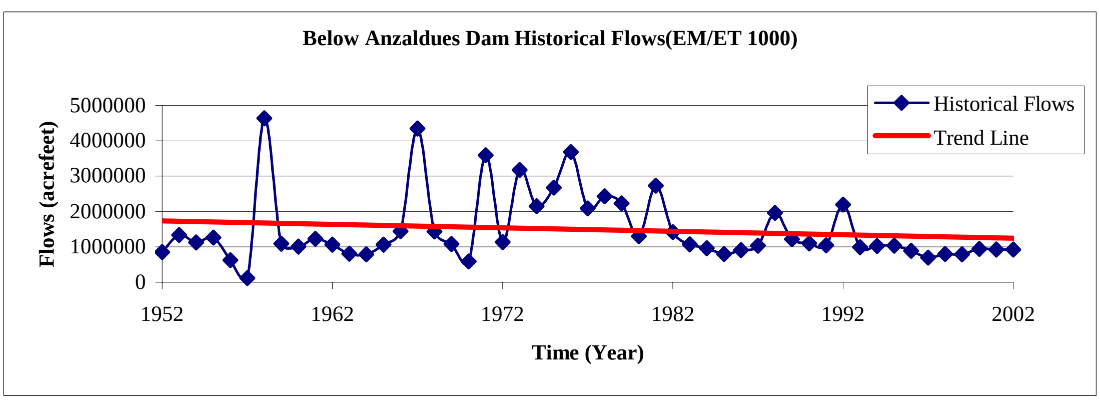

Figure 123. Historical Streamflows below Anzalduas Dam for Texas Portion

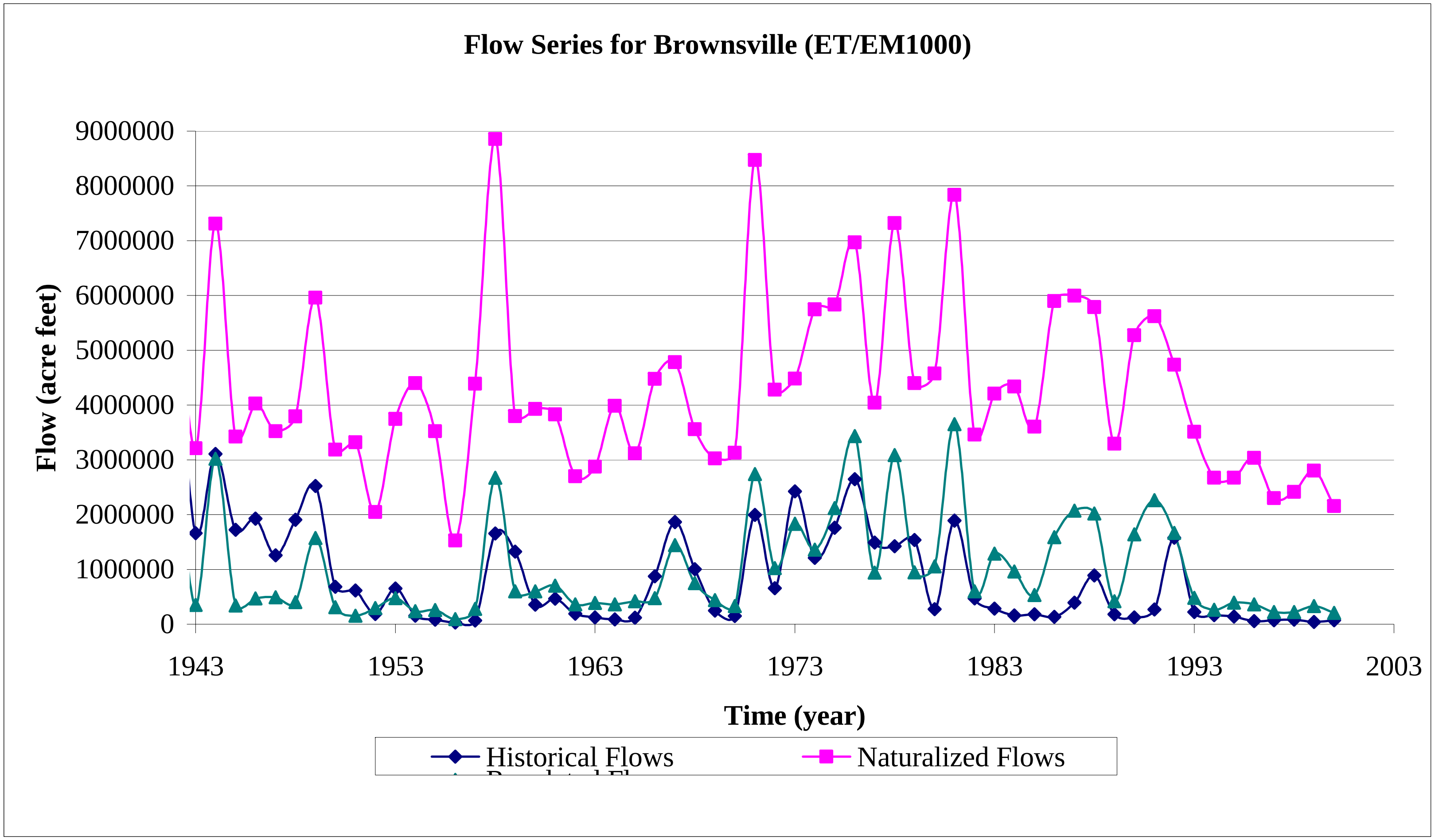

Figure 124. Flow Series for Brownsville

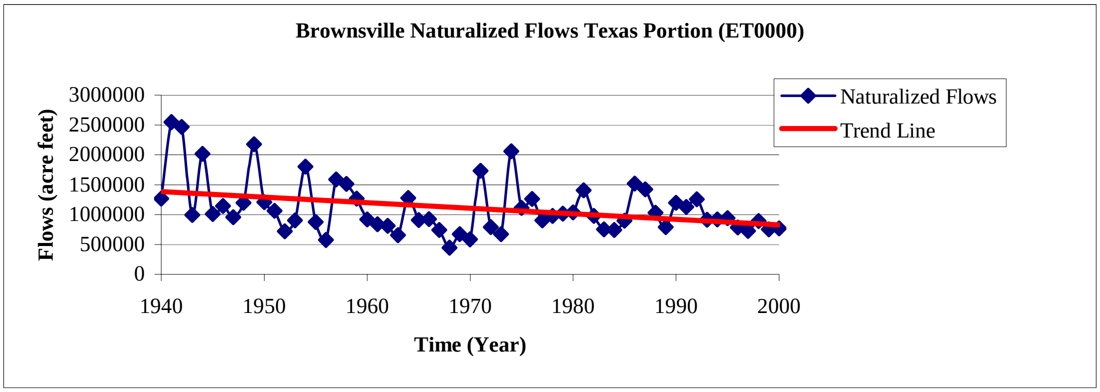

Figure 125. Naturalized Streamflows for Brownsville for Texas Portion

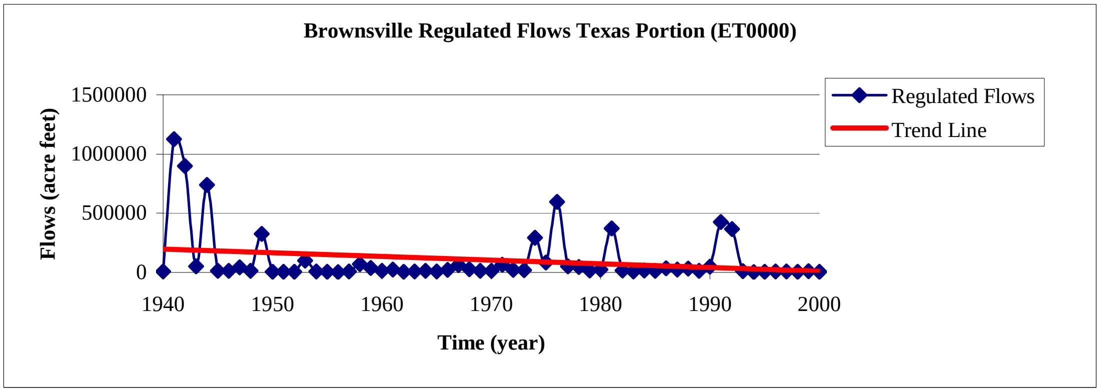

Figure 126. Regulated Streamflows for Brownsville for Texas Portion

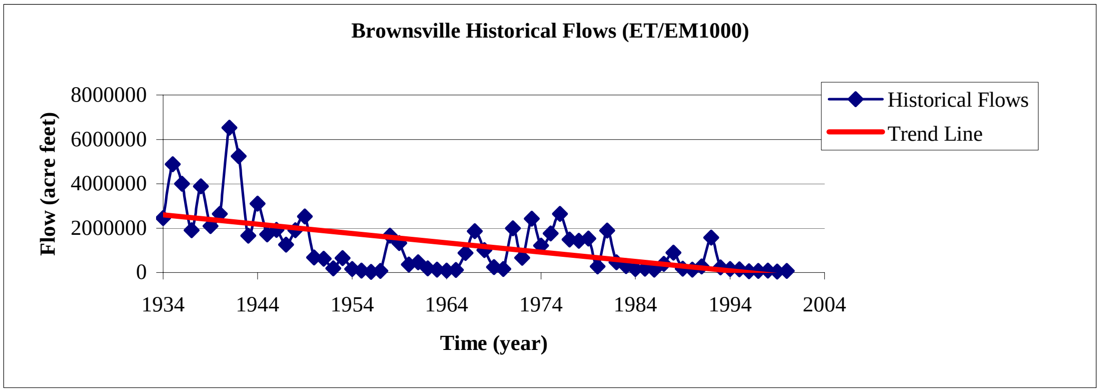

Figure 127. Historical Streamflows for Brownsville for Texas Portion

7 WAM FLOW FREQUENCY ANALYSIS

As discussed in section 5, equation 2, at a given site, for a specified exceedance frequency, the index was computed as

$$index = \frac{regulatedflow(amount)}{naturalizedflow(amount)}(100\%) \tag{3}$$

where both the regulated and the naturalized flow amounts are for the same specified exceedance probability. If the value of the index is less than 1, then the human related developments have reduced the flows at these locations and restoration needs to be done to preserve the habitat. If the value of index is greater than 1, then the water is being added to the streams as return flows or from releases from the reservoirs.

Several control points were chosen in the state of Texas to perform the flow frequency analysis. WAM flow frequency analysis was done to calculate the amount by which the streamflows during high flows (25% of the flows), median flows (50% of the flows) and the low flows (75% of the flows) have been altered by various human activities. Appendix A shows the list of the control points with their WAM flow frequency analysis of the simulated flows. Table A1 shows the flow frequencies for the naturalized flows, table A2 shows the flow frequencies for the regulated flows and table A3 shows the ratio of the flow frequencies for the regulated to the naturalized flows. The selection criterion of the control points was very critical to determine the streamflow changes.

7.1 Brazos River Basin

Twenty two control points were chosen on the rivers in the Brazos River basin for WAM frequency analysis. Figure 128 shows the location of the selected control points in the basin.

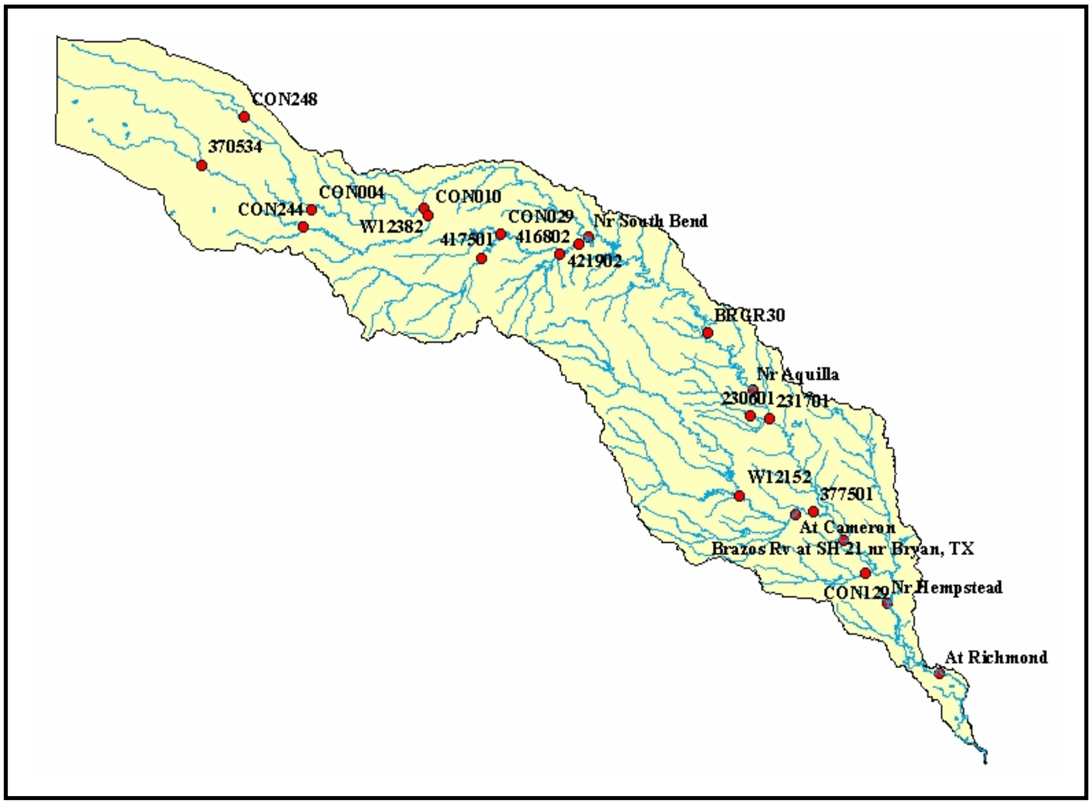

Figure 128. Location of Control Points in Brazos River Basin for WAM Analysis

The flows at control point CON004 on the White River are altered due to the regulation effects produced by the White River Lake. The ratio of the regulated to the naturalized flows for the control point CON 244 on the North Fork Double Mountain Fork Brazos River is small for low, median and high flows. This is due to the regulation effects produced by the Alen Henry Reservoir which is constructed few miles upstream of the control point. The flows at control point W12382 on Salt Fork Brazos River and control point CON 010 on Double Mountain Fork Brazos River does not show any major alterations in the streamflows. This might be explained due to a very few number of water rights in this area.

The control point 230601 on North Bosque River is upstream of the Lake Waco and the control point 231701 on Bosque River is downstream of the Lake Waco. The flows upstream of the lake are not altered too much. The index value is nearly close to 1. But at the downstream of the Lake Waco a very low index value is noticed. This explains the effects of the construction of the reservoirs on the streamflows.

Southbend is downstream of the confluence of Brazos River and Clear Fork Brazos River. A high index value for the low, median and high flows indicate that the flows at this location are not much affected. The control point BRGR30 on Brazos River is downstream of the Lake Granbury. A low index value is due to regulation effects produced by the construction of the lake. The flows at Aquilla on Brazos River are largely affected by Lake Whitney. The flows at Bryan on Brazos River are affected due to the large number of water right allocations in surrounding area of Bryan. The low index value at Richmond on Brazos River is due to the large amount of supplies of water for municipal needs. Table 6 shows the ratio of the flow frequencies for regulated to naturalized flows for Brazos River basin.

Table 6. Ratio of Flow Frequencies for Regulated to Naturalized Flows for Brazos River Basin.

CONTROL POINT	River Name	PERCENTAGE OF MONTHS WITH FLOWS EQUALING OR EXCEEDING VALUES SHOWN IN THE TABLE		
		75%	50%	25%
370534	Yellow House Draw	1.00	1.00	1.00
CON248	White River	9.30	2.03	1.26
CON004	White River	0.79	0.74	0.71
CON244	North Fork Double Mountain Fork	0.57	0.54	0.49
W12382	Salt Fork Brazos	0.94	0.96	0.93
CON010	Double Mountain Fork Brazos	0.92	0.88	0.84
CON029	Paint Creek	1.41	0.74	0.61
416802	Clear Fork Brazos	0.94	0.74	0.63
421902	Gunsolus Creek	0.62	0.55	0.33
231701	Bosque River	0.01	0.38	0.85
417501	Clear Fork Brazos	1.44	0.83	0.55
BRSB23	Brazos at Southbend	0.94	0.89	0.83
BRGR30	Brazos River	0.09	0.37	0.72
BRAQ33	Brazos at Aquilla	0.25	0.35	0.63
230601	North Bosque River	1.05	0.96	0.95
231701	Bosque River	0.01	0.38	0.85
W12152	Leon River	0.36	0.38	0.54
LRCA58	Brazos at Cameroon	0.64	0.54	0.76
BRBR59	Brazos at Bryan	0.67	0.66	0.82
BRHE68	Brazos at Hempstead	0.72	0.69	0.87
CON129	Yegua creek	0.49	0.41	0.64
BRRI70	Brazos at Richmond	0.62	0.66	0.85

7.2 Canadian River Basin

Five control points were chosen on the rivers in the Canadian River basin for WAM frequency analysis. Figure 129 shows the location of the selected control points in the basin.

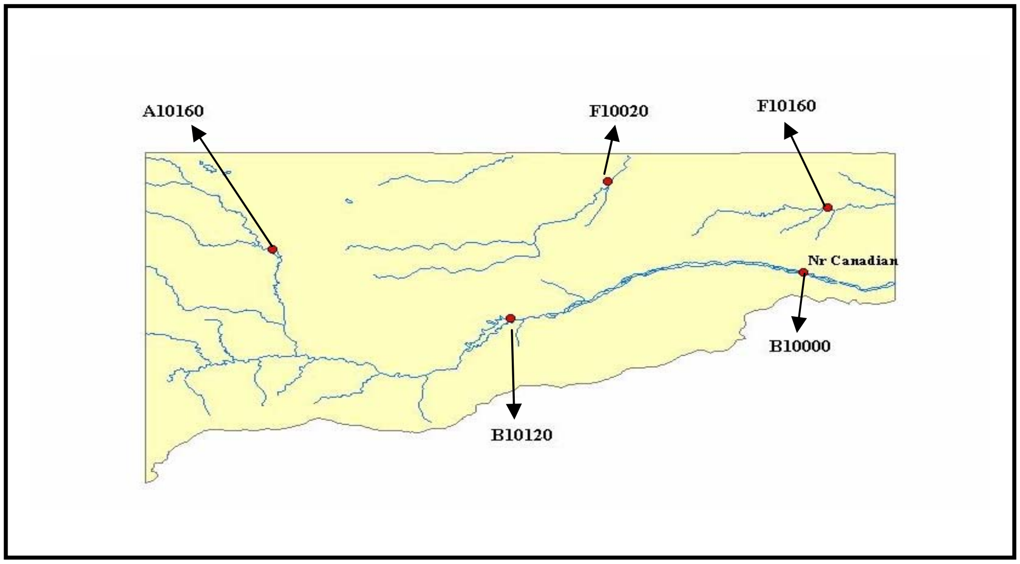

Figure 129. Location of Control Points in Canadian River Basin for WAM Analysis

The control point A10160 on the Rita Blanca Creek has got low index value for low, median and high flows. The regulated low flows are decreased by a considerable amount. The regulated flows for the 100%, 95%, 90% and 75% of the months are almost equal too zero. The flows are controlled by the Lake Rita Blanca. The Canadian River at B10120 has gone almost dry due to the regulation effects produced by the construction of Lake Meredith. The flows at Palo Duro creek are reduced due to the construction of the Palo Duro reservoir. Table 7 shows the ratio of the flow frequencies for regulated to naturalized flows for Canadian River basin.

Table 7. Ratio of Flow Frequencies for Regulated to Naturalized Flows for Canadian River Basin.

CONTROL POINT	River Name	PERCENTAGE OF MONTHS WITH FLOWS EQUALING OR EXCEEDING VALUES SHOWN IN THE TABLE		
		75%	50%	25%
A10160	Rita Blanca Creek	0.00	0.59	0.79
B10120	Canadian River	0.0001	0.0000	0.0001
F10020	Palo Duro Creek	0.00	0.00	0.00
F10160	Wolf Creek	0.77	0.92	0.98
B10000	Canadian River near Canadian	0.40	0.52	0.43

7.3 Colorado River Basin

Fourteen control points were chosen on the rivers in the Colorado River basin for WAM frequency analysis. Figure 130 shows the location of the selected control points in the basin.

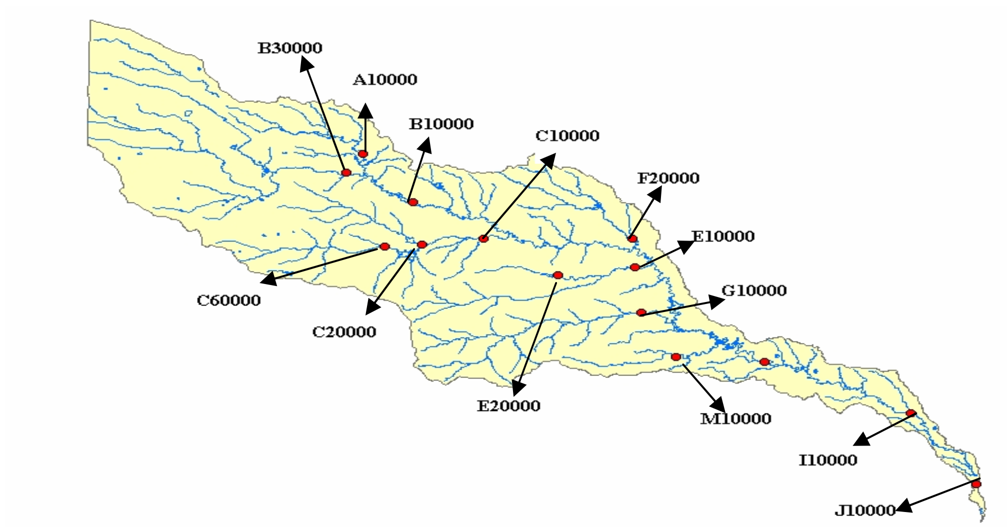

Figure 130. Location of Control Points in Colorado River Basin for WAM Analysis

The flows at control point A10000 on the Colorado River have been altered due to the regulation effects produced by the Lake J.B. Thomas. The low, median and high flows have decreased due to the construction of the lake. The flows at location B10000 on the Colorado River have reduced due to the construction of E.V. Spence reservoir. The flows at control points K10000, I10000 and J10000 are controlled by Lake Travis. All these locations exhibit decrease in low, median and high flows.

The low flows at E20000 on the Brady creek has increased by a large volume. This is due to releases from the Brady Creek reservoir during the low flow period. But the median and high flows at this location have decreased. There are no major alterations in the streamflows on the Middle Concho River. However, the flows on the Concho River are altered due to the regulation effects produced by the O.C. Fisher Lake and Twin Buttes reservoir. Table 8 shows the ratio of the flow frequencies for regulated to naturalized flows for Colorado River basin.

Table 8. Ratio of Flow Frequencies for Regulated to Naturalized Flows for Colorado River Basin.

CONTROL POINT	River Name	PERCENTAGE OF MONTHS WITH FLOWS EQUALING OR EXCEEDING VALUES SHOWN IN THE TABLE		
		75%	50%	25%
A10000	Colorado river	0.01	0.01	0.42
B30000	Beals Creek	*	0.19	0.63
C20000	Concho River	0.08	0.25	0.37
C60000	Middle Concho River	*	1	1
B10000	Colorado River	0	0.04	0.19
C10000	Concho River	0.32	0.46	0.46
E20000	Brady Creek	17.0	0.55	0.44
F20000	Pecan Bayou	0.66	0.48	0.65
E10000	San Saba river	0.86	0.9	0.9
G10000	Llano river	0.94	0.95	0.97
M10000	Pedernales River	0.08	0.26	0.53
K10000	Colorado river	0	0.3	0.58
I10000	Colorado river	0.56	0.72	0.6
J10000	Colorado river at Columbus	0.67	0.7	0.66

* Naturalized flow is zero.

7.4 Guadalupe River Basin

Four control points were chosen on the rivers in the Guadalupe River basin for WAM frequency analysis. Figure 131 shows the location of the selected control points in the basin.

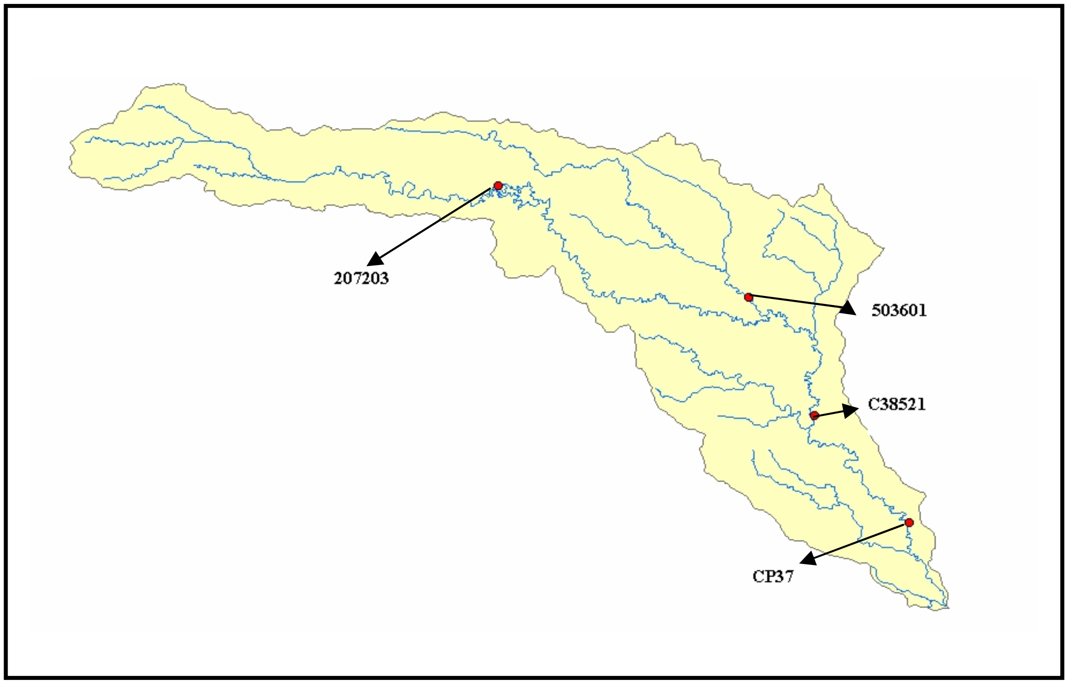

Figure 131. Location of Control Points in Guadalupe River Basin for WAM Analysis

The flows at location 207203 on the Guadalupe River do not show any significant alterations. The flows at CP37 on the Guadalupe River show an increase in the low and median flows and no major alterations in the high flows. The flows in the

San Marcos River do not show any significant alterations. The index value for low, median, and high flows is close to one. Table 9 shows the ratio of the flow frequencies for regulated to naturalized flows for Guadalupe River basin.

Table 9. Ratio of Flow Frequencies for Regulated to Naturalized Flows for Guadalupe River Basin.

CONTROL POINT	River Name	PERCENTAGE OF MONTHS WITH FLOWS EQUALING OR EXCEEDING VALUES SHOWN IN THE TABLE		
		75%	50%	25%
207203	Guadalupe River	0.98	0.98	0.95
503601	San Marcos River	0.99	0.92	0.93
C38521	Guadalupe River	0.94	0.87	0.85
CP37	Guadalupe River at Victoria	1.26	1.07	0.97

7.5 San Antonio River Basin

Four control points were chosen on the rivers in the San Antonio River basin for WAM frequency analysis. Figure 132 shows the location of the selected control points in the basin.

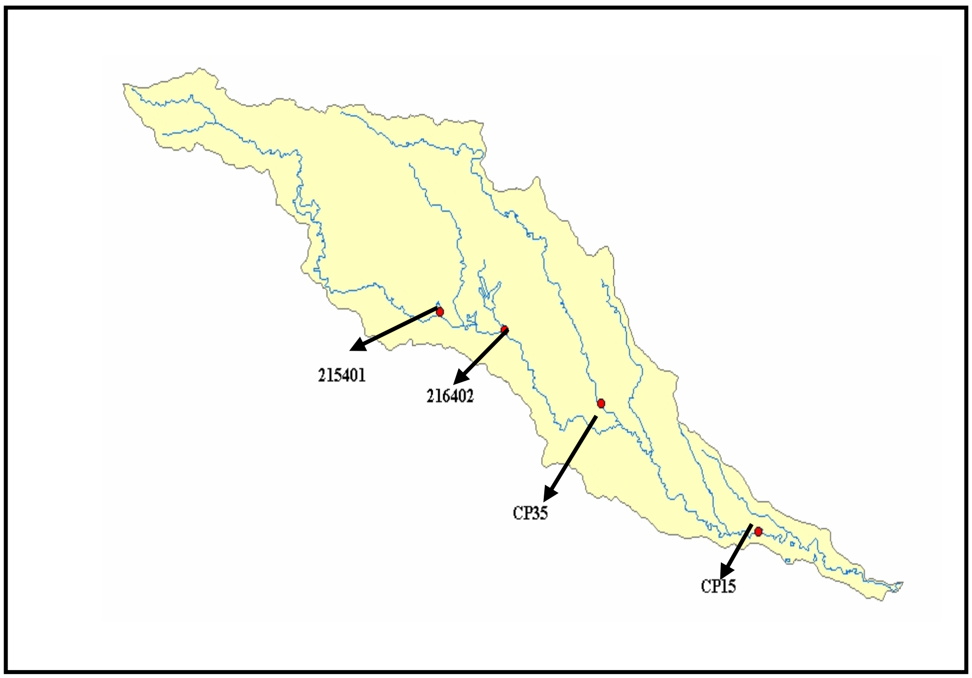

Figure 132. Location of Control Points in San Antonio River Basin for WAM Analysis

The flows at the different locations in the rivers and streams of San Antonio River basin do not show any major alterations. The flows at the control point 216402 on San Antonio River have increased due to the releases from the Calaveras Lake. The flows at Goliad near the outlet of the San Antonio River basin do not show major changes in the streamflows. Table 10 shows the ratio of the flow frequencies for regulated to naturalized flows for San Antonio River basin.

Table 10. Ratio of Flow Frequencies for Regulated to Naturalized Flows for San Antonio River Basin.

CONTROL POINT	River Name	PERCENTAGE OF MONTHS WITH FLOWS EQUALING OR EXCEEDING VALUES SHOWN IN THE TABLE		
		75%	50%	25%
215401	Medina River	0.69	0.76	0.87
216402	San Antonio	1.72	1.23	0.98
CP35	Cibolo Creek	1.35	1.17	1.00
CP15	San Antonio at Goliad	0.85	0.86	0.86

7.6 Neches River Basin

Four control points were chosen on the rivers in the Neches river basin for WAM frequency analysis. Figure 133 shows the location of the selected control points in the basin.

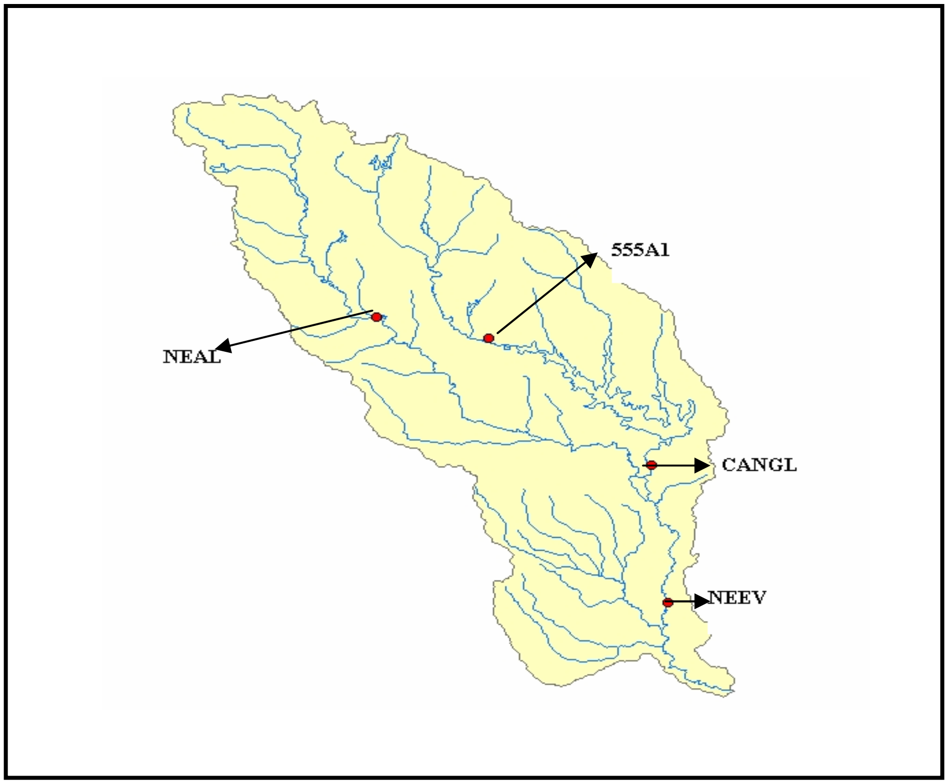

Figure 133. Location of Control Points in Neches River Basin for WAM Analysis

The control points chosen for the Neches River Basin are on the Neches River and Angelina River. No major alterations have been noticed at all the selected locations for the high flows. The low flows at these locations have been altered due to the water rights allocation in the region. The control point CANGL on Angelina River is downstream of the Sam Rayburn reservoir. The flows at this location are controlled by the releases from the reservoir. The control point NEEV on Neches River is near the outlet of the basin. The location faces severe water shortage problems in the rivers during low flows. Table 11 shows the ratio of the flow frequencies for regulated to naturalized flows for Neches River basin.

Table 11. Ratio of Flow Frequencies for Regulated to Naturalized Flows for Neches River Basin.

CONTROL POINT	River Name	PERCENTAGE OF MONTHS WITH FLOWS EQUALING OR EXCEEDING VALUES SHOWN IN THE TABLE		
		75%	50%	25%
NEAL	Neches	0.59	0.84	0.99
5555A1	Angelina	0.68	0.98	1.00
CANGL	Angelina	0.37	0.83	1.00
NEEV	Neches at Evadale	0.72	0.91	0.99

7.7 Nueces River Basin

Seven control points were chosen on the rivers in the Nueces River basin for WAM frequency analysis. Figure 134 shows the location of the selected control points in the basin.

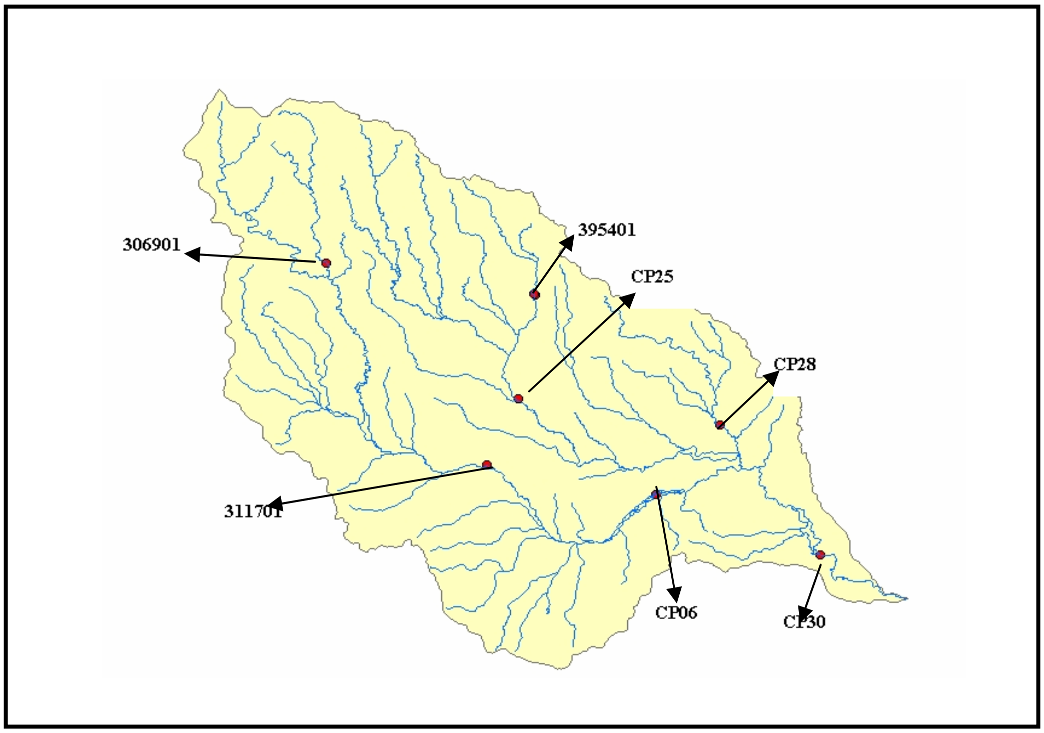

Figure 134. Location of Control Points in Nueces River Basin for WAM Analysis

Frio River, Hondo creek, and Atascosa River do not show any alterations in the median and high flows. The low flows in these streams have increased due to the return flows. Nueces River Basin has predominantly agriculture based economy. The reduction in the flows at 311701 on Nueces River is due to the extra irrigational requirements. The low flows and median flows at CP30 on Nueces River have increased due to the releases from Lake Corpus Christi which is just upstream of the control point. Table 12 shows the ratio of the flow frequencies for regulated to naturalized flows for Nueces River basin.

Table 12. Ratio of Flow Frequencies for Regulated to Naturalized Flows for Nueces River Basin.

CONTROL POINT	River Name	PERCENTAGE OF MONTHS WITH FLOWS EQUALING OR EXCEEDING VALUES SHOWN IN THE TABLE		
		75%	50%	25%
306901	Nueces	0.96	0.98	0.98
311701	Nueces	0.67	0.75	0.82
CP25	Frio River	1.77	1.06	1.01
395401	Hondo Creek	0.98	1.00	0.98
CP28	Atascosa River	1.15	1.07	1.02
CP06	Nueces River	0.84	0.81	0.96
CP30	Nueces River at Mathis	5.46	2.05	0.66

7.8 Red River Basin

Eleven control points were chosen on the rivers in the Red River basin for WAM frequency analysis. Figure 135 shows the location of the selected control points in the basin.

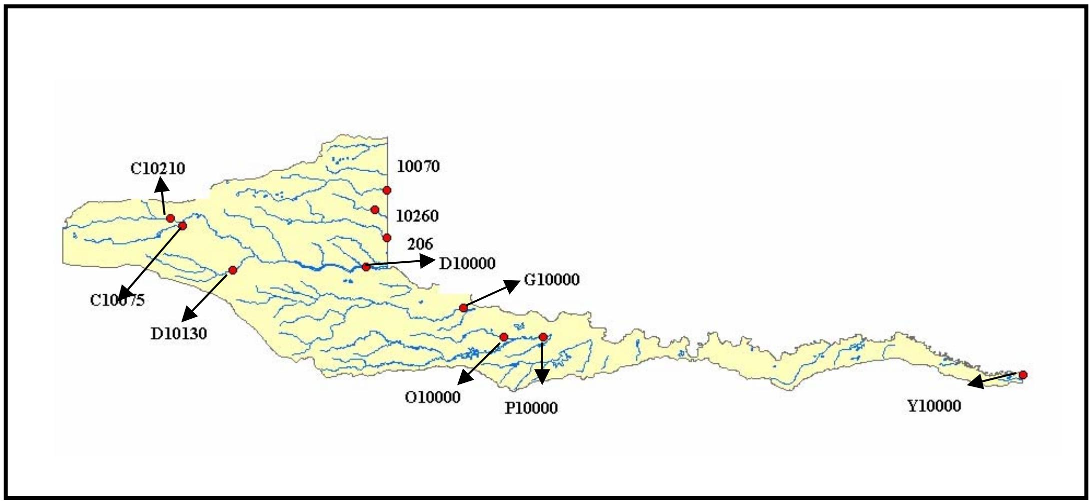

Figure 135. Location of Control Points in Red River Basin for WAM Analysis

The low, median, and high flows at control point C10210 on Palo Duro creek have altered due to the regulation effects produced by the Bivins Lake. The flows at control point D10130 on Tule creek has been decreased to almost zero due to regulation effects produced by the Mackenzie reservoir. No significant changes in the flows have been noticed in the Elm creek, Salt Fork Red River, Tierra Blanca creek and North Fork Red River. The flows at control point P10000 on the Wichita River have decreased due to upstream diversions made by Lake Kemp and Lake Diversion. No reduction in the streamflows has been observed at Index on Red River, Arkansas. The river is discharging full volume of water at its outlet to the state of Arkansas. Table 13 shows the ratio of the flow frequencies for regulated to naturalized flows for Red River basin.

Table 13. Ratio of Flow Frequencies for Regulated to Naturalized Flows for Red River Basin.

CONTROL POINT	River Name	PERCENTAGE OF MONTHS WITH FLOWS EQUALING OR EXCEEDING VALUES SHOWN IN THE TABLE		
		75%	50%	25%
C10210	Palo Duro Creek	0.00	0.00	0.14
C10075	Teirra Blanca Creek	1.00	1.00	1.00
D10130	Tule Creek	0.00	0.00	0.35
D10000	Prairie Dog Town Fork	0.82	0.86	0.90
P10000	Wichita River	0.40	0.42	0.46
O10000	Beaver Creek	0.60	0.68	0.86
G10000	Pease River	0.99	0.99	0.99
206	Salt Fork Red River	1.00	1.00	1.00
10260	Elm Creek	0.94	0.94	0.99
10070	North Fork Red River	0.76	0.87	0.91
Y10000	Red River at Index, Arkansas	0.92	0.95	0.98

7.9 Sabine River Basin

Four control points were chosen on the rivers in the Sabine River basin for WAM frequency analysis. Figure 136 shows the location of the selected control points in the basin.

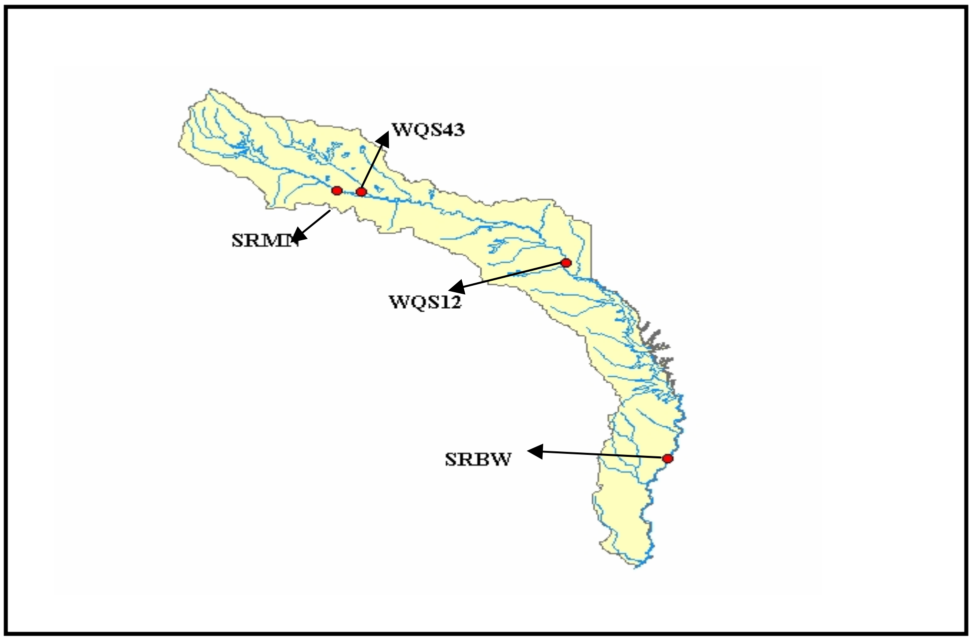

Figure 136. Location of Control Points in Sabine River Basin for WAM Analysis

The low, median, and high flows at control point SRMN on Sabine River have reduced due to the regulation effects produced by the Lake Tawakoni. The flows at control point WQS43 on Turkey River have reduced due to the regulation effects produced by the Lake Fork Reservoir. The low and median flows at Bon Weir on Sabine

River have increased due to the releases from the Toledo Bend reservoir and the high flows have reduced due to the regulation effects produced by the reservoir upstream of the control point. Table 14 shows the ratio of the flow frequencies for regulated to naturalized flows for Sabine River basin.

Table 14. Ratio of Flow Frequencies for Regulated to Naturalized Flows for Sabine River Basin.

CONTROL POINT	River Name	PERCENTAGE OF MONTHS WITH FLOWS EQUALING OR EXCEEDING VALUES SHOWN IN THE TABLE		
		75%	50%	25%
SRMN	Sabine River	0.39	0.41	0.58
WQS43	Turkey Creek	0.39	0.47	0.69
WQS12	Sabine River	0.67	0.70	0.82
SRBW	Sabine River near Bon Weir	1.19	1.04	0.76

7.10 Sulphur River Basin

Three control points were chosen on the rivers in the Sabine River basin for WAM frequency analysis. Figure 137 shows the location of the selected control points in the basin.

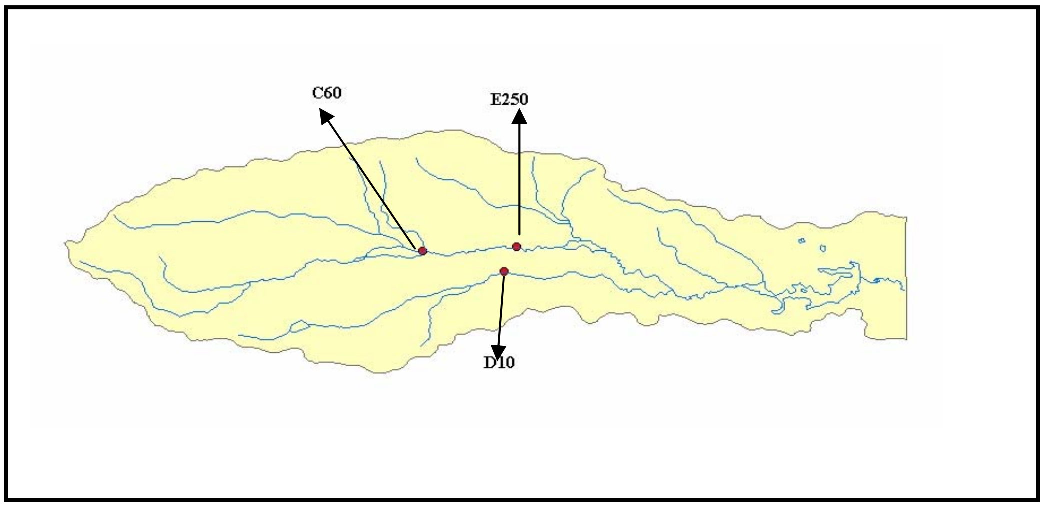

Figure 137. Location of Control Points in Sulphur River Basin for WAM Analysis

The low, median, and high flows are not altered much in the rivers and streams of Sulphur River basin. The basin is discharging full volume of water at its outlet. Cooper Lake and Wright Patman Lake are the major lakes which produce the regulation effects in Sulphur River basin. Table 15 shows the ratio of the flow frequencies for regulated to naturalized flows for Sulphur River basin.

Table 15. Ratio of Flow Frequencies for Regulated to Naturalized Flows for Sulphur River Basin.

CONTROL POINT	River Name	PERCENTAGE OF MONTHS WITH FLOWS EQUALING OR EXCEEDING VALUES SHOWN IN THE TABLE		
		75%	50%	25%
C60	Sulphur River	0.90	0.84	0.93
D10	White Oak Creek	1.00	0.92	0.93
E250	Sulphur River near Talco	0.90	0.86	0.96

7.11 Trinity River Basin

Nine control points were chosen on the rivers in the Trinity River basin for WAM frequency analysis. Figure 138 shows the location of the selected control points in the basin.

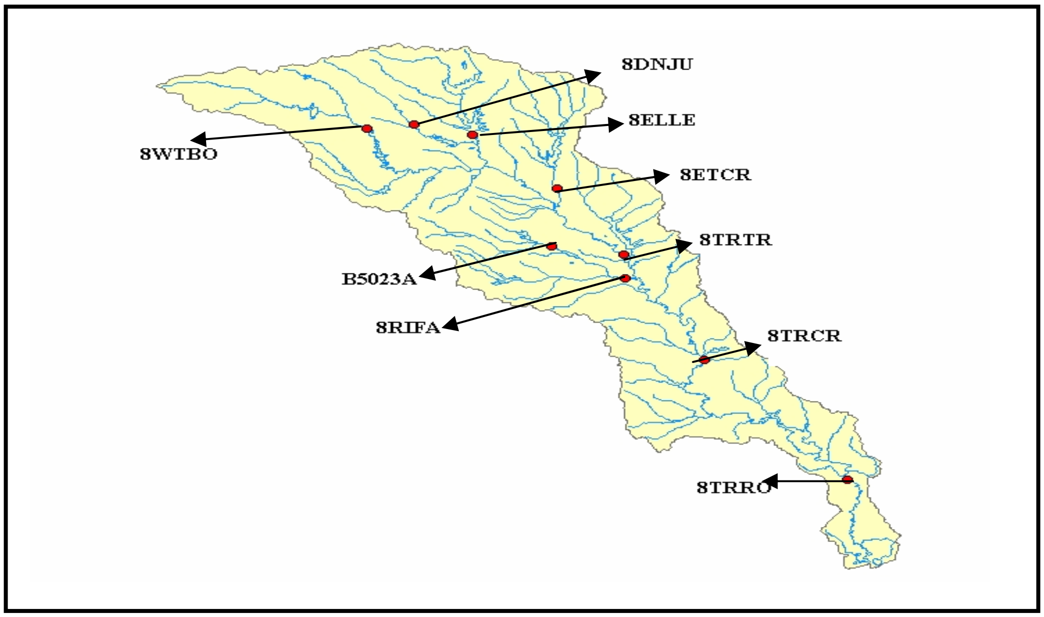

Figure 138. Location of Control Points in Trinity River Basin for WAM Analysis

The low and median flows at control point 8WTBO on the Trinity River have increased due to the releases from the Lake Bridgeport, but the high flows have decreased. The median and high flows at 8TRTR on the Trinity River have decreased due to the regulation effects produced by the Cedar Creek Reservoir, but the low flows have increased due to the releases from the reservoir. The flows near the outlet of the basin at control point 8TRRO have decreased due to the regulation effects produced by Lake Livingston.

The flows at control point 8RIFA on Richland creek faces severe water shortage problems due to the regulation effects produced by the Richland-Chamber reservoir. Elm Fork Trinity and East Fork Trinity Rivers face water shortage problems during median and high flows. Table 16 shows the ratio of the flow frequencies for regulated to naturalized flows for Trinity River basin.

Table 16. Ratio of Flow Frequencies for Regulated to Naturalized Flows for Trinity River Basin.

CONTROL POINT	River Name	PERCENTAGE OF MONTHS WITH FLOWS EQUALING OR EXCEEDING VALUES SHOWN IN THE TABLE		
		75%	50%	25%
8WTBO	Trinity River	8.01	1.86	0.80
8DNJU	Denton Creek	1.00	1.00	1.00
8ELLE	Elm Fork Trinity	6.39	0.08	0.03
8ETCR	East Fork Trinity	1.95	0.40	0.47
8TRTR	Trinity River	1.72	0.86	0.69
B5023A	Chambers Creek	0.66	0.80	0.91
8RIFA	Richland Creek	0.14	0.02	0.46
8TRCR	Trinity River	1.07	0.73	0.70
8TRRO	Trinity River at Romayor	0.71	0.72	0.78

7.12 Cypress River Basin

Five control points were chosen on the rivers in the Trinity River basin for WAM frequency analysis. Figure 139 shows the location of the selected control points in the basin.

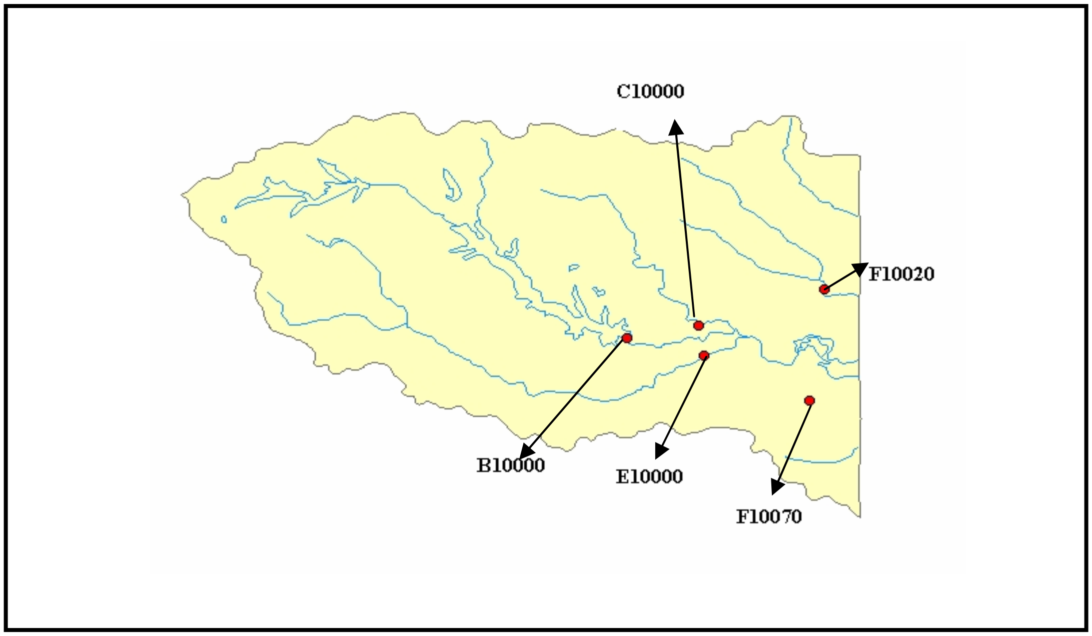

Figure 139. Location of Control Points in Cypress River Basin for WAM Analysis

B10000 on big Cypress creek is downstream of the Lake O' The Pines. The low, median and high flows have reduced due to the regulation effects of the lake. The flows in Black Cypress Bayou, James Bayou, Harrison Bayou and little Cypress creek do not observe any significant alterations in the streamflows. Table 17 shows the ratio of the flow frequencies for regulated to naturalized flows for Cypress River basin.

Table 17. Ratio of Flow Frequencies for Regulated to Naturalized Flows for Cypress River Basin.

CONTROL POINT	River Name	PERCENTAGE OF MONTHS WITH FLOWS EQUALING OR EXCEEDING VALUES SHOWN IN THE TABLE		
		75%	50%	25%
B10000	Big Cypress creek	0.60	0.72	0.74
C10000	Black Cypress Bayou	1.00	1.00	1.00
E10000	Little Cypress creek Near Jefferson	0.99	0.98	0.99
F10020	James Bayou	0.94	1.00	1.00
F10070	Harrison Bayou in Harrison	1.00	1.00	1.00

7.13 Lavaca River Basin

One control points was chosen on the rivers in the Lavaca River basin for WAM frequency analysis. Figure 140 shows the location of the selected control points in the basin.

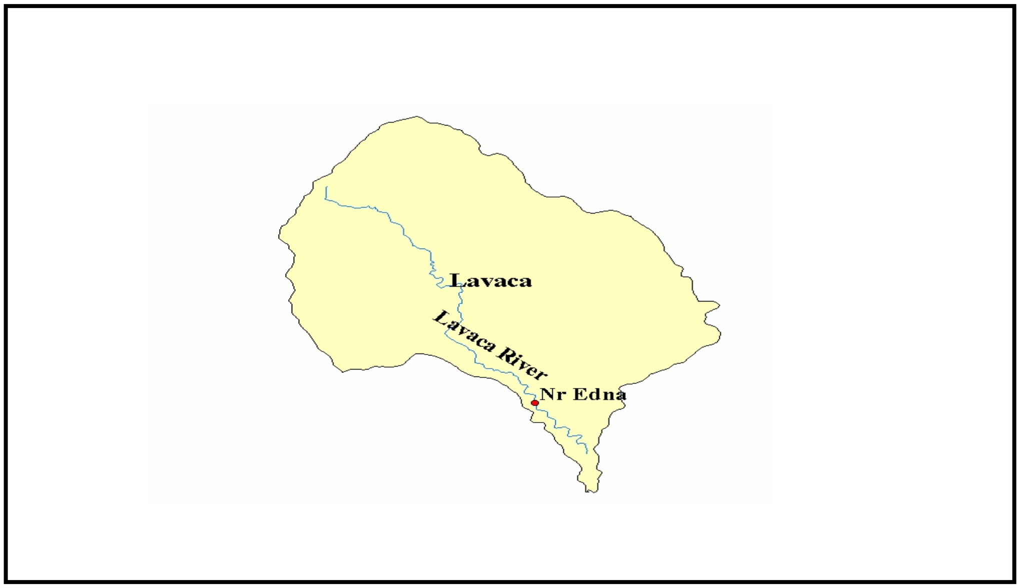

Figure 140. Location of Control Points in Lavaca River Basin for WAM Analysis

The flows at the outlet of Lavaca River basin near Edna do not faces severe alterations in the streamflows. The index value for low, median and high flows is close to one. Table 18 shows the ratio of the flow frequencies for regulated to naturalized flows for Lavaca River basin.

Table 18. Ratio of Flow Frequencies for Regulated to Naturalized Flows for Lavaca River Basin.

CONTROL POINT	River Name	PERCENTAGE OF MONTHS WITH FLOWS EQUALING OR EXCEEDING VALUES SHOWN IN THE TABLE		
		75%	50%	25%
WQ002	Lavaca River near Edna	1.01	0.99	1

7.14 San Jacinto River Basin

Three control points were chosen on the rivers in the Lavaca River basin for WAM frequency analysis. Figure 141 shows the location of the selected control points in the basin.

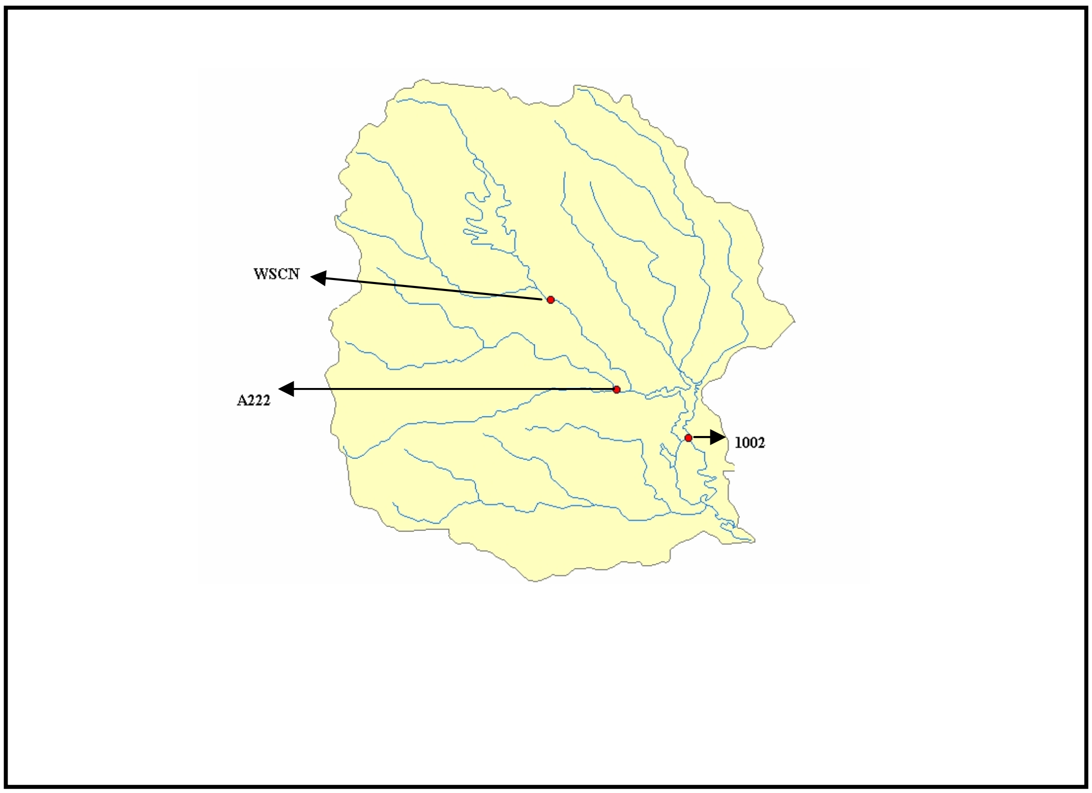

Figure 141. Location of Control Points in San Jacinto River Basin for WAM Analysis

WSCN on San Jacinto River is downstream of Lake Conroe. No alterations have been observed in the low flows but the median and high flows at this location have decreased. 1002 is downstream of the Lake Houston. In spite of the large water allocations in this area the flows have not much altered. This might be due to the releases from lake operations. Spring creek observes increase in the low, median and high flows. Table 19 shows the ratio of the flow frequencies for regulated to naturalized flows for San Jacinto River basin.

Table 19. Ratio of Flow Frequencies for Regulated to Naturalized Flows for San Jacinto River Basin.

CONTROL POINT	River Name	PERCENTAGE OF MONTHS WITH FLOWS EQUALING OR EXCEEDING VALUES SHOWN IN THE TABLE		
		75%	50%	25%
A222	Spring Creek	1.45	1.19	1.05
1002	San Jacinto River	1.2	0.91	0.94
WSCN	San Jacinto near Conroe	1.01	0.63	0.76

7.15 Rio Grande River Basin

Eight control points were chosen on the rivers in the Rio Grande basin for WAM frequency analysis. Figure 142 shows the location of the selected control points in the basin.

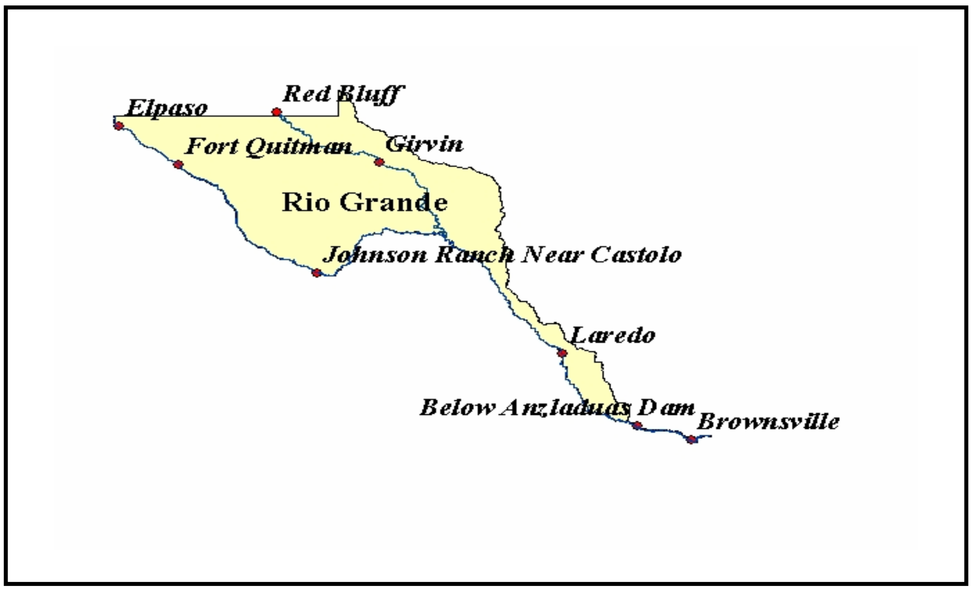

Figure 142. Location of Control Points in Rio Grande River Basin for WAM Analysis

For the Rio Grande basin, the results showed that the stream at Girvin, Pecos River has been affected a lot by excessive pumping of the water. A very low index gives the indication that due to extra usage of water the stream has gone almost dry. At Fort Quitman few miles downstream of El Paso a very low index value is noted. This low value indicates that a lot of pumping is done in the El Paso area due to which a very little water is left downstream of El Paso. For El Paso on the Mexico side of the basin, a low index value indicates that the water allocation is not proper on the Mexican side. However, at Fort Quitman, for the Mexico side, a high index value for the high flows indicates that the flows are added to the Rio Grande below the El Paso. The flows upstream of Laredo are greatly affected by the releases of the Amistad International reservoir. Laredo has got large population centers and industrial areas. The index value for the Texas portion is near to one for high flows but the index value is low for low flows. The Mexico portion has got low index value for both low and high flow values.On the U.S. side the flows below the Anzalduas dam has high index value. This might be due to the releases from the diversion dam. Downstream of the Anzalduas dam, all the water withdrawn from the Rio Grande for irrigation and municipal purposes is returned to the Rio Grande. The outlet of the basin is at the Gulf of Mexico near Brownsville. This point reflects the total outflows of the basin to the Gulf of Mexico. At the outlet a low index value indicates that a river is discharging very less water in the Gulf of Mexico. On the U.S. side of the basin upstream of Brownsville, reflect the demand of huge amounts of irrigated water needed for agricultural purposes. Also, the Mexico side of the basin at the outlet is discharging very less water to Gulf of Mexico. Table 20 shows the ratio of the flow frequencies for regulated to naturalized flows for Rio Grande basin.

Table 20. Ratio of Flow Frequencies for Regulated to Naturalized Flows for Rio Grande Basin.

CONTROL POINT	River Name	PERCENTAGE OF MONTHS WITH FLOWS EQUALING OR EXCEEDING VALUES SHOWN IN THE TABLE		
		75%	50%	25%
GT2000	Pecos River atGirvin, TX	0	0.07	0.14
AT1000	Rio Grande River at Fort Quitman, TX	0.1	0.13	0.16
CT4000	Rio Grande River atJohnson Ranch Near Castolon,TX	0.43	0.56	0.77
DT3000	Rio Grande River atLaredo, TX	1.04	1.05	0.97
ET1000	Rio Grande River Below Anzalduas Dam, TX	1.05	0.99	0.85
ET0000	Rio Grande River atBrownsville,Tx	0.01	0.01	0.02

8 CONCLUSIONS

The goal of this research is to assess changes in flow characteristics of the rivers of Texas. Population and economic growth in Texas during the 20th century has been accompanied by increased water use, construction of reservoirs and other water resources development projects, and land use changes. These activities have altered the river flow regime. Changes in flows vary with proximity to reservoirs, water supply diversions, wastewater treatment plant discharges, and watershed land use changes and with the magnitude and characteristics of these activities. For example, the impacts of reservoir construction on downstream flows are most pronounced immediately below the dam. Changes in flow also vary greatly for different ranges of the flow-frequency relationship. Reservoir projects typically reduce flood flows but increase low flows.

Population growth and economic development and accompanying changes in watershed land cover and water resources management/use vary greatly between different regions of the state. Urbanization in the metropolitan areas of Houston, Dallas-Fort Worth, El Paso, and other cities has significantly altered the natural flow regime. Increased watershed runoff and increases in municipal and industrial water use and return flows are major factors in these urban areas. Agricultural irrigation accounts for most of the stream flow changes in the Rio Grande and various other stream reaches across the state.

The flow plots and linear trend lines of annual historical gauged flows provide a convenient visual display of long-term trends in total annual volumes. The historical annual flows exhibit great year-to-year variability. The 1950-1957 drought is the most hydrologically severe drought-of-record for much of Texas. However, long-term trends are not dramatic. Some gauging stations exhibit an increasing trend line while others show a decreasing trend.

The annual naturalized and regulated flows show negligible if any long-term trends, which should be the case. If the naturalized flows exhibit no long-term trends, the corresponding regulated flows computed within WRAP should likewise exhibit no long-term trends. The naturalized flows were developed for the Texas WAM System by the TCEQ and its contractors by adjusting gauged flows to remove the effects of human water management activities. The trend analyses of annual naturalized flows confirm that the flow naturalization achieved its objective, at least from the perspective of annual volumes.

Monthly low flows and high flows are logically expected to be much more sensitive, relative to annual totals, to reservoir construction, increased water use, and other human activities. The flow ratio indices developed by the WAM flow frequency analysis demonstrate this to be the case. The ratios of regulated to naturalized flows show the divergence of actual flows from natural flows for an assumed repetition of historical hydrology for the entire monthly flow frequency spectrum ranging from minimum flows to high flows.

Results show the percentage by which the streamflows have increased or decreased over time. The analyses confirmed that reservoir regulations have significantly altered the monthly discharge regimes. The effects of regulation are clearly seen in the downstream locations. A comparison of the indices between the upstream and downstream locations of the reservoirs confirmed very significant changes in the discharges. This is clearly evident in case of Lake Waco in Brazos River basin. Upstream of Lake Waco the flows are not altered. However, downstream of the lake, a low index value indicates that the reservoir construction has regulated the flows. Reservoir construction accounts for most of the streamflow changes in the river segments. A system of more than 200 major reservoirs and numerous numbers of small reservoirs have significantly altered the streamflow characteristics of Texas Rivers.

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APPENDIX A

NATURALIZED AND REGULATED STREAMFLOW DATASET

TABLE A1. Flow Frequency for Naturalized Flows (acre-feet).

Control Point	Basin Name	River Name	Percentage of Months with Flows Equaling or Exceeding Values Shown in the Table										
			Mean	Standard Deviation	100%	98%	95%	90%	75%	50%	25%	10%	MAXIMUM
CON248	Brazos	White River	415.3	1136.6	0	0	0	0	8.4	65	265	963	11392
CON004	Brazos	White River	2679.4	6439	0	0	3.7	15.4	124.5	424	1981	6974	55814
CON244	Brazos	North Fork Double Mountain Fork	6067.4	13286.8	0	0	6.2	43.9	265.3	1157	5213	16603	112426
W12382	Brazos	Salt Fork Brazos	7563.1	16930.1	0	13	74.2	159.6	604.1	1526	6260	18750	155844
CON010	Brazos	Double Mountain Fork Brazos	9870.5	20983.3	0	22.8	114.9	213.9	535.1	2083	8976	26812	189522
CON029	Brazos	Paint Creek	15637.9	39353.9	0	0	6.7	50.2	625.9	3082	12852	38252	508860
416802	Brazos	Clear Fork Brazos	25125.1	58520.8	0	4.1	148.8	479.2	1712.5	5804	22470	63988	741228
421902	Brazos	Gunsolus Creek	10514.5	26999.8	0	0	0	78	584	1933	8744	28305	305117
231701	Brazos	Bosque River	29611.3	52967.3	0	0	0	466.5	2833.5	9898	34310	79443	524738
417501	Brazos	Clear Fork Brazos	9778.4	22030.3	0	0	1.2	253.3	779.8	2670	9816	24409	342751
BRSB23	Brazos	Brazos at Southbend	54688.3	116202.6	0	119.4	785	2083	4889	13817	52133	145077	1395822
BRGR30	Brazos	Brazos River	93248.2	182476.4	0	527.5	1861.6	4598	445	30585	96926	242476.2	710228
BRAQ33	Brazos	Brazos at Aquilla	114921	204743.8	0	1717	3425.4	6929	16626	46163	131747	280970	981239
230601	Brazos	North Bosque River	17634.4	36067.1	0	37.1	205	517.3	1556.3	4667	16430	47419	428821
231701	Brazos	Bosque River	29611.3	52967.3	0	0	0	466.5	2833.5	9898	34310	79443	524738
W12152	Brazos	Leon River	24295.9	41069.5	0	431.7	782.8	1451	3369.3	8153	27281	66475	352006
LRCA58	Brazos	Brazos at Cameroon	109858	170465.5	0	1249	2706.4	5440	15032	44799	130473	290433	403136
BRBR59	Brazos	Brazos at Bryan	335664	483896.8	0	11162	17707	28173	60717	158629	402271	810073	4704312
BRHE68	Brazos	Brazos at Hempstead	446579	588542.4	1634	17422	30122	44643	89698	229331	581968	1153505	5723482
BRRI70	Brazos	Brazos at Richmond	487519	613001.8	0	25402	39522	53888	111204	257456	653272	1230723	6135975

Table A1 (continued)

Control Point	Basin Name	River Name	Percentage of Months with Flows Equaling or Exceeding Values Shown in the Table										
			Mean	Standard Deviation	100%	98%	95%	90%	75%	50%	25%	10%	MAXIMUM
A10160	Canadian	Rita Blanca Creek	801.1	1510.7	0	5.6	22.8	36	69.5	197	926	2248	12660
B10120	Canadian	Canadian River	13087.8	24469.9	0	90.1	385	604.9	1337.1	3636	14332	35116	200683
F10020	Canadian	Palo Duro Creek	1016.4	3530.4	0	0	0	0	34.8	136	526	2390	58762
F10160	Canadian	Wolf Creek	804.1	2170.3	0	8.6	22.8	37.5	72.3	206	521	1419	25750
B10000	Canadian	Canadian River near Canadian	15768.4	30133	0	93.6	413.2	639.8	1516	4803	17015	39024	267870
A10000	Colorado	Colorado river	4622.3	12234	0	0	2	25.6	140	487	2519	11747	96406
B30000	Colorado	Beals Creek	1792	4667.8	0	0	0	0	0	234	1350	4296	46633
C20000	Colorado	Concho River	7936.2	17964.8	561.6	753.2	1084.1	1408	2305.2	3635	6761	15389	269048
C60000	Colorado	Middle Concho River	1393.2	5041.4	0	0	0	0	0	178	808	3030	70255
B10000	Colorado	Colorado River	9440.9	22846.4	0	11.3	50.4	135	418	1721	6936	26451	234206
C10000	Colorado	Concho River	10519.5	21229.1	549.6	836.6	1167.3	1721	2948.7	5209	9976	20205	315949
E20000	Colorado	Brady Creek	1168.6	4634.9	0	0	0	0	3	154	684	2035	61337
F20000	Colorado	Pecan Bayou	16534.8	33345.2	0	341	689.4	1038	1907	5305	15001	41690	352561
E10000	Colorado	San Saba river	13583.5	20656	865	1917	2395.2	3197	4876	7374	13168	24642	187581
G10000	Colorado	Llano river	23463.7	36062.1	902	1981	2699	4133	7363	11855	22633	47863	275632
M10000	Colorado	Pedernales River	249305	303357.8	9550	28562	36606	47896	78331	141823	312775	546834	2798050
J10000	Colorado	Colorado river at Columbus	215712	262720.8	9539	23381	33585	42051	64526	122957	263434	486731	2232446
K10000	Colorado	Colorado river	243931	294845	9550	28356	36467	47470	75965	141532	304342	543974	2645166
I10000	Colorado	Colorado river	157849	206903.2	8957	19304	26459	32531	49536	87623	177372	367331	2188889
207203	Guadalupe	Guadalupe River	21989.4	31964.2	494.9	1109	1801.6	2839	5737.5	11657	25301	48607	373708
503601	Guadalupe	San Marcos River	35413.4	46063.1	610.1	2565	3653.2	5515	10096	18729	41693	84285	517115
C38521	Guadalupe	Guadalupe River	86792.4	105174.3	261.5	3226	7546.5	13775	30455	54720	105060	197716	259959
CP37	Guadalupe	Guadalupe River at Victoria	40974.8	65826.9	1076	2661	4250.2	6028	11693	21852	43834	90270	895982

Table A1 (continued)

Control Point	Basin Name	River Name	Percentage of Months with Flows Equaling or Exceeding Values Shown in the Table										
			Mean	Standard Deviation	100%	98%	95%	90%	75%	50%	25%	10%	MAXIMUM
215401	San Antonio	Medina River	133	221.1	0	0	15.7	25.4	52.1	80	124	261	3361
216402	San Antonio	San Antonio	22914	34670.9	118.8	304.4	548.5	2574	6386.3	12963	25353	52693	506192
CP35	San Antonio	Cibolo Creek	7354.6	15635.2	0	333.8	508.2	688.2	1140	1998	5699	16888	166672
CP15	San Antonio	San Antonio at Goliad	105046	132209.7	1446	4753	9776	17243	35811	63624	124670	241390	598310
NEAL	Neches	Neches	74299.2	85859.4	0	259.9	1680	3819	12651	40508	110599	191522	624597
5555A1	Neches	Angelina	2722.8	3558.7	0	0	0	0	151.6	1198	4177	7818	24057
CANGL	Neches	Angelina	168314	207338.3	657	3041	4232	6496	23711	83224	249746	457097.1	594634
NEEV	Neches	Neches at Evadale	381354	429030.4	3406	8910	15873	25463	69527	221640	576099	956729	3061346
306901	Nueces	Nueces	9280.9	18579.5	289.5	574.1	1099	1547	2849	4836	6029	17681	326727
311701	Nueces	Nueces	16382.7	44209.5	1	124.5	214.2	400.5	1143.3	2678	4192	39521	642171
CP25	Nueces	Frio River	8305.4	29869.6	0	1.1	8	18	110	1260	2148	18449	480100
395401	Nueces	Hondo Creek	1886.6	7329.6	0	0	0	0	9	169	341	3942	99486
CP28	Nueces	Atascosa River	7717.5	21816.5	0	29.4	109.6	211.4	514	1240	1910	17498	297942
CP06	Nueces	Nueces River	25812.9	67539	21	187.2	296	545.6	1238	4299	6751	70174	763190
CP30	Nueces	Nueces River at Mathis	50704.9	124433	0	334.5	527	1051	3604	10799	17428	136778	632553
C10210	Red	Palo Duro Creek	109.7	357.9	0	0	0	0	9.5	32	88	250	7123
C10075	Red	Teirra Blanca Creek	154	502.3	0	0	0	0	13.4	44	124	351	9997
D10130	Red	Tule Creek	923.5	1672.4	0	19.3	36.8	56.9	147	333	939	2396	16629
D10000	Red	Prairie Dog Town Fork	6145.8	11084.1	0	136	296.8	447.6	1033	2194	6302	16463	113017
P10000	Red	Wichita River	26524.7	39509.1	950	1720	705.6	3532	5855	11398	29966	71749	354221
O10000	Red	Beaver Creek	5520.8	11656.4	64	199	352.2	497.2	816	1855	4509	13529	106884
G10000	Red	Pease River	6741.5	13331.3	8	131	252.4	375.8	730	1877	6464	17754	130647

Table A1 (continued)

Control Point	Basin Name	River Name	Percentage of Months with Flows Equaling or Exceeding Values Shown in the Table										
			Mean	Standard Deviation	100%	98%	95%	90%	75%	50%	25%	10%	MAXIMUM
206	Red	Salt Fork Red River	100	0	100	100	100	100	100	100	100	100	100
10260	Red	Elm Creek	478.4	934.4	0	0	17.8	46	124.8	235	421	904	9292
10070	Red	North Fork Red River	1312.7	1419.7	2.9	52	98.7	217.9	775.9	964	1557	2429	20626
Y10000	Red	Red River at Index, Ak	792995	874790.4	54691	84560	114613	139534	215930	473495	1063012	1829818	7633196
SRMN	Sabine	Sabine River	63387.6	92091.4	47	239.3	360.2	626.2	4125	24421	86384	171766	621628
WQS43	Sabine	Turkey Creek	98471.5	137803.6	134.5	515.4	874.6	2431	9138.9	39370	135359	265219	950460
WQS12	Sabine	Sabine River	202421	238772.8	319	2510	6213	10775	32280	115976	296412	536638.1	891108
SRBW	Sabine	Sabine Rv near Bon Weir	446176	479956.5	3346	12497	22951	37912	99357	267456	665069	1141230	3742103
C60	Sulphur	Sulphur River	64427.3	92572.3	0	0	55.2	276.6	3022	23686	91602	181130	612799
D10	Sulphur	White Oak Creek	32255.4	48027.1	0	0	39	228.8	1647	10397	43231	95879	301552
E250	Sulphur	Sulphur River near Talco	84309.6	120392.5	0	12	117.2	435.4	4286	33074	121199	234546	768236
A222	San Jacinto	Spring Creek	29475.7	45932.5	522.1	1052	1597	2013	4229.3	10177	33332	82669	474512
1002	San Jacinto	San Jacinto River	116995	172639.5	2263	4968	6347	8154	15285	46004	151914	331111	1730843
WSCN	San Jacinto	San Jacinto near Conroe	31609.9	49163.8	0	0	375.4	942	2535	10998	41933	97149	486077
8WTBO	Trinity	Trinity River	20577.9	47902	0	0	0	0	869	5467	20380	52434	525070
8DNJU	Trinity	Denton Creek	6923.6	15902.8	0	0	0	2	325	1505	7131	18805	173861
8ELLE	Trinity	Elm Fork Trinity	49747.1	98587.7	0	0	0	0	98	11411	60286	142342	929798
8ETCR	Trinity	East Fork Trinity	53256.9	85734.2	0	0	0	0	2401	17584	64969	158555	662282
8TRTR	Trinity	Trinity River	224511	357119.7	0	0	33	5990	27474	92810	266474	610599	2899825
B5023A	Trinity	Chambers Creek	24121	41287.7	0	0	0	0	612.6	5773	29281	74927	308946
8RIFA	Trinity	Richland Creek	60185.9	103870	0	0	0	22.6	1738	13834	75851	178311	754345
8TRCR	Trinity	Trinity River	397180	534656.1	0	3817	11768	23473	65342	189947	533437	1000375	3805195
8TRRO	Trinity	Trinity River at Romayor	517939	631586.4	0	6117	15785	33719	96273	274907	717208	1341048.	4558105
WQ002	Lavaca	Lavaca River near Edna	21171.5	42602.5	0	0	214.9	750.6	2024.8	5324	17758	63000	443244
B10000	Cypress	Big Cypress creek	45221.1	48974.5	0	1.7	1770	4323	12325	32906	59443	100153	394017
C10000	Cypress	Black Cypress Bayou	21376.4	33342.8	0	3.7	131.2	351.2	1607	8763	28656	55706	285155

Table A1 (Continued)

Control Point	Basin Name	River Name	Percentage of Months with Flows Equaling or Exceeding Values Shown in the Table										
			Mean	Standard Deviation	100%	98%	95%	90%	75%	50%	25%	10%	MAXIMUM
E10000	Cypress	Little Cypress creek Near Jefferson	32241.9	44766.6	0	2.5	52.6	318.4	2886	13707	46144	90464	308654
F10020	Cypress	James Bayou	13902.7	21996	0	0	0	0	450.1	4005	17322	44314	136623
F10070	Cypress	Harrison Bayou in Harrison	22.5	35.5	0	0	0	0	0.7	6	28	72	221
GT2000	Rio Grande	Girvin, TX	7661.8	24185.5	223.1	270.6	289.1	339	1947.3	3938	6814	12480	522870
AT1000	Rio Grande	Fort Quitman, TX	35772.6	33136.1	0	0	0	2521	12430	29752	51652	68814	372048
CT4000	Rio Grande	Johnson Ranch Near Castolon,TX	28433.7	41431.7	112	518.8	1059.6	2551.2	10036	20112	33165	56673	733162
DT3000	Rio Grande	Laredo, TX	112243	112244.4	20706	39182	45101	51618	64185	84826	121505	185383	1377071
ET1000	Rio Grande	Below Anzalduas Dam, TX	109648	101269.7	15483	33205	40936	48052	60780	81282	123833	188771	1132886
ET0000	Rio Grande	Brownsville,Tx	92115.8	84823.6	13026	28028	34241	40288	51175	68620	104168	159607	948227

TABLE A2. Flow frequency for regulated flows (acre-feet).

Control Point	Basin Name	River Name	Percentage of Months with Flows Equaling or Exceeding Values Shown in the Table										
			Mean	Standard Deviation	100%	98%	95%	90%	75%	50%	25%	10%	MAXIMUM
CON248	Brazos	White River	463.5	1065.5	65.8	66.2	67.8	69.7	78.1	132	335	1020	11296
CON004	Brazos	White River	2147.4	5833	0	7.6	9.9	21.1	97.9	312	1402	5174	56075
CON244	Brazos	North Fork Double Mountain Fork	4349.3	11493	5.1	6.4	12.9	34	150	629	2558	10013	112084
W12382	Brazos	Salt Fork Brazos	7216.6	16533	3.1	17.4	78.2	163.6	566.3	1468	5803	17488	155929
CON010	Brazos	Double Mountain Fork Brazos	8975.2	19934	0	23.3	111.6	207.6	492.6	1824	7538	23006	189226
CON029	Brazos	Paint Creek	12379.5	35786	0	304	411.7	501.7	881.1	2283	7783	25824	504370
416802	Brazos	Clear Fork Brazos	19239.2	50912	0	260.8	351.2	608.2	1606.8	4267	14051	44045	734396
421902	Brazos	Gunsolus Creek	5957.2	20551	0	65.8	73.7	126.3	364.3	1059	2866	11780	300202
231701	Brazos	Bosque River	25618.1	52772	0	0	0	0.2	39.9	3781	29296	76446	526956
417501	Brazos	Clear Fork Brazos	7245.1	18934	67	555.8	633.2	742.9	1125.2	2228	5422	14154	337208
BRSB23	Brazos	Brazos at Southbend	48111.4	108934	63.1	394.1	997.5	2179.7	4613.3	12358	43148	119680	1386384
BRGR30	Brazos	Brazos River	72032.9	174366	0	0	44.4	152.7	940.7	11388	70240	199610	696526
BRAQ33	Brazos	Brazos at Aquilla	86206.1	194365	0	0	36.3	405.4	4109.7	16201	83381	237420	932089
230601	Brazos	North Bosque River	17360.6	35930	0	126.9	286.1	601.5	1628.9	4460	15549	47328	428649
231701	Brazos	Bosque River	25618.1	52772	0	0	0	0.2	39.9	3781	29296	76446	526956
W12152	Brazos	Leon River	18091.7	39109	0	0.1	89.1	294.8	1214.3	3133	14684	53815	349151
LRCA58	Brazos	Brazos at Cameroon	90874.9	161553	959.3	2345.2	3461.6	5072.8	9580.7	24357	98628	247987	406179
BRBR59	Brazos	Brazos at Bryan	284827.6	465115	4712	9964.7	14939	20271.2	40948	103978	328009	710774	4626861
BRHE68	Brazos	Brazos at Hempstead	386458.2	565166	10578	18740	24913	35157.4	64360	157393	506163	1074953	5580300
BRRI70	Brazos	Brazos at Richmond	416024.2	590652	8213	23442	30633	40577.6	68825	169722	557293	1129203	5977720

Table A2 (continued)

Control Point	Basin Name	River Name	Percentage of Months with Flows Equaling or Exceeding Values Shown in the Table										
			Mean	Standard Deviation	100%	98%	95%	90%	75%	50%	25%	10%	MAXIMUM
A10160	Canadian	Rita Blanca Creek	703.6	1503.4	0	0	0	0	0	116	733	2075	12576
B10120	Canadian	Canadian River	2038.5	13415	0	0	0	0	0.1	0	1	2	186719
F10020	Canadian	Palo Duro Creek	336	2541.8	0	0	0	0	0	0	0	0	49174
F10160	Canadian	Wolf Creek	787.5	2171.7	0	5.7	15.5	24.7	55.6	189	509	1402	25752
B10000	Canadian	Canadian River near Canadian	8586.1	22038	21.1	82.7	191.2	270.3	609	2494	7344	17477	230261
A10000	Colorado	Colorado river	2345.6	7108.2	0	0	0	0	1.3	6	1068	5821	68047
B30000	Colorado	Beals Creek	1504.3	4437	0	0	0	0	0	44	844	3594	44640
C20000	Colorado	Concho River	2787.5	7803.1	0	7.5	17	27.6	192.3	909	2522	5090	116256
C60000	Colorado	Middle Concho River	1393.2	5041.4	0	0	0	0	0	178	808	3030	70255
B10000	Colorado	Colorado River	3276.2	10847	0	0	0	0	0	74	1312	8496	160010
C10000	Colorado	Concho River	4888.4	10777	0	1.1	77.1	335.9	946.7	2372	4638	10148	165301
E20000	Colorado	Brady Creek	812	3908.9	13.3	37.9	39.7	42.2	51.1	84	299	1109	56088
F20000	Colorado	Pecan Bayou	12377.2	29987	266.1	498.7	644.8	844.2	1254.2	2530	9803	31263	346584
E10000	Colorado	San Saba river	12452.6	19639	801.6	1489	2040.8	2650.7	4217.6	6655	11795	23458	186298
G10000	Colorado	Llano river	22927.7	35900	839.1	1745.1	2248.9	3857.4	6943.9	11302	22012	47574	274868
M10000	Colorado	Pedernales River	143602.2	268455	1360	1576.1	2164.2	2760.8	6481.9	37021	165913	379192	2704376
J10000	Colorado	Colorado river at Columbus	160703.5	228410	877.8	13612	17433	23293.6	43318	85892	174915	371842	2084509
K10000	Colorado	Colorado river	143745.1	261437	0	0	0	25	84.3	42775	175106	371072	2578845
I10000	Colorado	Colorado river	108402.6	167768	5707	12414	14361	16585.6	27741	63039	106186	254639	1747556
207203	Guadalupe	Guadalupe River	21548.5	31700	538.2	1111.7	1732.2	2799.1	5619.3	11469	24036	47146	372852
503601	Guadalupe	San Marcos River	33441.7	43451	1160	3305.8	4396.4	5999.1	10039	17240	38843	79217	493628
C38521	Guadalupe	Guadalupe River	76905.3	96473	1452	4032.7	7751.5	13069	28525	47834	89242	181977	186247
CP37	Guadalupe	Guadalupe River at Victoria	41266.9	61707	4441	7718.7	8795.6	10109.5	14782	23477	42493	89416	856009

Table A2 (continued)

Control Point	Basin Name	River Name	Percentage of Months with Flows Equaling or Exceeding Values Shown in the Table										
			Mean	Standard Deviation	100%	98%	95%	90%	75%	50%	25%	10%	MAXIMUM
215401	San Antonio	Medina River	119.6	221.2	0	1	10.3	18.2	35.8	61	108	240	3338
216402	San Antonio	San Antonio	23937.8	30500	987	4109.5	5757.3	8115.2	10988	15903	24772	45628	487538
CP35	San Antonio	Cibolo Creek	7343.1	14352	0	798.7	966.7	1151.2	1543.3	2338	5705	17104	140443
CP15	San Antonio	San Antonio at Goliad	93785.6	124355	1760	4553.6	9131.4	15902	30361	54438	107578	218239	529516
NEAL	Neches	Neches	70352.4	86669	65.3	435.9	1185.1	2335	7490.4	33896	109580	190247	633891
5555A1	Neches	Angelina	2696.9	3562.2	0	0	0	0	103.2	1179	4165	7806	24068
CANGL	Neches	Angelina	161674.8	212625	5434	6769.6	7253.2	7685.8	8744.1	68921	250300	450674	624522
NEEV	Neches	Neches at Evadale	370499.2	434294	7599	14588	20643	29164.6	50168	202041	569706	950456	3131546
306901	Nueces	Nueces	9107.8	18526	168.4	408.7	943.1	1400.3	2731.3	4741	5916	17115	326236
311701	Nueces	Nueces	15080.7	43174	0	15.2	75.4	206.7	760.6	2012	2927	36676	635930
CP25	Nueces	Frio River	8361	29799	71.7	85.4	96.8	121.3	194.7	1336	2224	18341	479945
395401	Nueces	Hondo Creek	1872.9	7305.7	0	0	0	0	8.8	169	341	3858	99422
CP28	Nueces	Atascosa River	7800.4	21814	82	113.7	193.8	298.6	590	1324	1994	17576	297997
CP06	Nueces	Nueces River	24877.4	66753	0	84.1	139.5	353.7	1041.1	3492	5782	68358	757952
CP30	Nueces	Nueces River at Mathis	42129.2	94560	3551	13051	17684	17749.7	19671	22133	22616	53367.1	561133
C10210	Red	Palo Duro Creek	32.1	203.9	0	0	0	0	0	0	12	38	4007
C10075	Red	Teirra Blanca Creek	154	502.3	0	0	0	0	13.4	44	124	351	9997
D10130	Red	Tule Creek	569.8	1532.9	0	0	0	0	0	0	325	1924	13971
D10000	Red	Prairie Dog Town Fork	5584	10467	42.8	154.7	264.2	374.8	850.2	1882	5651	14365	106605

Table A2 (continued)

Control Point	Basin Name	River Name	Mean	Standard Deviation	100%	98%	95%	90%	75%	50%	25%	10%	MAXIMUM
			Percentage of Months with Flows Equaling or Exceeding Values Shown in the Table										
P10000	Red	Wichita River	15742.6	32010	504.7	672.2	963.1	1298.6	2370.1	4785	13677	39277	319998
O10000	Red	Beaver Creek	5020.6	11469	56.7	117.6	197.5	282.2	491.6	1256	3895	12894	104926
G10000	Red	Pease River	6708.9	13300	7.9	129.4	249.4	371.3	721	1855	6399	17670	130358
206	Red	Salt Fork Red River	100	0	100	100	100	100	100	100	100	100	100
10260	Red	Elm Creek	469.6	934.4	0	0	13.6	37.3	116.7	222	415	890	9290
10070	Red	North Fork Red River	1176.3	1409.2	0	0	35.5	104	587.8	840	1414	2334	20444
Y10000	Red	Red River at Index, Arkansas	768039.2	878254	14762	43988	74486	105623	198522	451353	1E+06	1809480	7600047
SRMN	Sabine	Sabine River	45198	81235	0	25.5	70.6	453.4	1610	9993	50834	135775	578164
WQS43	Sabine	Turkey Creek	75517.1	126908	300.4	646.1	917.2	1499.8	3558.4	18612	93119	220470	971348
WQS12	Sabine	Sabine River	175379.2	230302	1897	2966.6	5549.9	7750	21755	81855	44282	503034	873892
SRBW	Sabine	Sabine River near Bon Weir	408474.1	446853	0	13862	23568	39378.4	117744	279156	502922	41831	3652472
C60	Sulphur	Sulphur River	61745.3	91933	353.3	399.3	456.2	616.1	2740.9	19960	85334	175973	611714
D10	Sulphur	White Oak Creek	30850.9	46790	13.4	47.3	185.9	349	1660.5	9646	40422	92690	300338
E250	Sulphur	Sulphur River near Talco	81581.2	119871	94.6	371	492.1	718.1	3856.6	28608	116361	225141	767533
A222	San Jacinto	Spring Creek	31252	45801	2597	3137.6	3621.9	4039.8	6126.6	12098	35132	83820	475822
1002	San Jacinto	San Jacinto River	114309.3	169141	5478	8238.2	9595.4	11412	18380	42060	143509	320168	704691
WSCN	San Jacinto	San Jacinto near Conroe	27031.7	46122	417.9	531.7	814.8	1432.8	2572.7	6911	31733	87889	458071
8WTBO	Trinity	Trinity River	17692.4	34359	0	276.2	2544.1	3789.7	6956.9	10181	16320	29786	391920
8DNJU	Trinity	Denton Creek	6908.7	15870	0	0	0	2	325	1505	7131	18717	173146
8ELLE	Trinity	Elm Fork Trinity	14230.3	52029	0	0	0	0	626.1	900	1579	33829	613912
8ETCR	Trinity	East Fork Trinity	36896.2	72775	0	3141.2	4019	4059.5	4690.1	7005	30484	108777	633346
8TRTR	Trinity	Trinity River	182257.6	282674	28295	35050	36637	39098.1	47305	80225	185101	422962	2567211

Table A2 (continued)

Control Point	Basin Name	River Name	Percentage of Months with Flows Equaling or Exceeding Values Shown in the Table										
			Mean	Standard Deviation	100%	98%	95%	90%	75%	50%	25%	10%	MAXIMUM
B5023A	Trinity	Chambers Creek	22863.1	40500	0.3	1	1	1	402.8	4594	26611	71990	306951
8RIFA	Trinity	Richland Creek	41582.3	92737	0	0	22.6	230	244	266	35204	150143	659913
8TRCR	Trinity	Trinity River	321448.2	459098	42	37378	41728	47149.5	69860	139499	372312	835405	3546362
8TRRO	Trinity	Trinity River at Romayor	431445.5	562731	33145	48960	51281	51281	68608	197928	560602	1157979	3746411
WQ002	Lavaca	Lavaca River near Edna	21121	42589	17.4	111	310.9	837.6	2045	5250	17751	62769	443309
B10000	Cypress	Big Cypress creek	36212.1	44897	0	4.1	119.4	140.4	14593	51492	165015	334193	372297
C10000	Cypress	Black Cypress Bayou	21372.2	33347	0	0.1	375	1115.6	7351.4	23720	44282	91084	285166
E10000	Cypress	Little Cypress creek Near Jefferson	32060.2	44720	0	2.9	130.3	346.1	1599.2	8727	28668	55728	308827
F10020	Cypress	James Bayou	13890.4	21998	70.6	78.2	128.1	399.1	2849.5	13371	45772	90410	136630
F10070	Cypress	Harrison Bayou	22.5	35.5	0	0	0	0	424	4002	17319	44272	221
GT2000	Rio Grande	Girvin, TX	2796.4	22208	0	0	0	0	0	283	960	2768	513825
AT1000	Rio Grande	Fort Quitman, TX	7203.1	12454	0	0	0	309.7	1194	3721	8322	15243	168366
CT4000	Rio Grande	Johnson Ranch Near Castolon,TX	28289.1	56600	0	119.9	331.5	956.3	4333.8	11235	25455	68397	689790
DT3000	Rio Grande	Laredo, TX	107211.9	91578	15448	27775	34684	43232.8	66775	89396	117598	171224	1139853
ET1000	Rio Grande	Below Anzalduas Dam,	88165.4	58964	11912	20074	32230	47436.3	63556	80671	105552	111667	846851
ET0000	Rio Grande	Brownsville,Tx	8653.8	46696	5.1	30.7	73.3	130	340.2	715	1624	5664	663717

TABLE A3. Ratio of flow frequencies of regulated to naturalized flows.

Control Point	Basin Name	River Name	Percentage of Months with Flows Equaling or Exceeding Values Shown in the Table										
			Mean	Standard Deviation	100%	98%	95%	90%	75%	50%	25%	10%	MAXIMUM
CON248	Brazos	White River	1.12	0.94	*	*	*	*	9.30	2.03	1.26	1.06	0.99
CON004	Brazos	White River	0.80	0.91	*	*	2.68	1.37	0.79	0.74	0.71	0.74	1.00
CON244	Brazos	North Fork Double Mountain Fork	0.72	0.86	*	*	2.08	0.77	0.57	0.54	0.49	0.60	1.00
W12382	Brazos	Salt Fork Brazos	0.95	0.98	*	1.34	1.05	1.03	0.94	0.96	0.93	0.93	1.00
CON010	Brazos	Double Mountain Fork Brazos	0.91	0.95	*	1.02	0.97	0.97	0.92	0.88	0.84	0.86	1.00
CON029	Brazos	Paint Creek	0.79	0.91	*	*	61.45	9.99	1.41	0.74	0.61	0.68	0.99
416802	Brazos	Clear Fork Brazos	0.77	0.87	*	63.61	2.36	1.27	0.94	0.74	0.63	0.69	0.99
421902	Brazos	Gunsolus Creek	0.57	0.76	*	*	*	1.62	0.62	0.55	0.33	0.42	0.98
231701	Brazos	Bosque River	0.87	1.00	*	*	*	0.00	0.01	0.38	0.85	0.96	1.00
417501	Brazos	Clear Fork Brazos	0.74	0.86	*	*	527.6 7	2.93	1.44	0.83	0.55	0.58	0.98
BRSB23	Brazos	Brazos at Southbend	0.88	0.94	*	3.30	1.27	1.05	0.94	0.89	0.83	0.82	0.97
BRGR30	Brazos	Brazos River	0.77	0.96	*	0.00	0.02	0.03	2.11	0.37	0.72	0.82	0.98
BRAQ33	Brazos	Brazos at Aquilla	0.75	0.95	*	0.00	0.01	0.06	0.25	0.35	0.63	0.85	0.95
230601	Brazos	North Bosque River	0.98	1.00	*	3.42	1.40	1.16	1.05	0.96	0.95	1.00	1.00
231701	Brazos	Bosque River	0.87	1.00	*	*	*	0.00	0.01	0.38	0.85	0.96	1.00
W12152	Brazos	Leon River	0.74	0.95	*	0.00	0.11	0.20	0.36	0.38	0.54	0.81	0.99
LRCA58	Brazos	Brazos at Cameroon	0.83	0.95	*	1.88	1.28	0.93	0.64	0.54	0.76	0.85	1.01
BRBR59	Brazos	Brazos at Bryan	0.85	0.96	*	0.89	0.84	0.72	0.67	0.66	0.82	0.88	0.98
BRHE68	Brazos	Brazos at Hempstead	0.87	0.96	6.47	1.08	0.83	0.79	0.72	0.69	0.87	0.93	0.97
BRRI70	Brazos	Brazos at Richmond	0.85	0.96	*	0.92	0.78	0.75	0.62	0.66	0.85	0.92	0.97

Table A3 (continued)

Control Point	Basin Name	River Name	Mean	Standard Deviation	100%	98%	95%	90%	75%	50%	25%	10%	MAXIMUM
			Percentage of Months with Flows Equaling or Exceeding Values Shown in the Table										
A10160	Canadian	Rita Blanca Creek	0.88	1.00	*	0.00	0.00	0.00	0.00	0.59	0.79	0.92	0.99
B10120	Canadian	Canadian River	0.16	0.55	*	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.93
F10020	Canadian	Palo Duro Creek	0.33	0.72	*	*	*	*	0.00	0.00	0.00	0.00	0.84
F10160	Canadian	Wolf Creek	0.98	1.00	*	0.66	0.68	0.66	0.77	0.92	0.98	0.99	1.00
B10000	Canadian	Canadian River near Canadian	0.54	0.73	*	0.88	0.46	0.42	0.40	0.52	0.43	0.45	0.86
A10000	Colorado	Colorado river	0.51	0.58	*	*	0.00	0.00	0.01	0.01	0.42	0.50	0.71
B30000	Colorado	Beals Creek	0.84	0.95	*	*	*	*	*	0.19	0.63	0.84	0.96
C20000	Colorado	Concho River	0.35	0.43	0.00	0.01	0.02	0.02	0.08	0.25	0.37	0.33	0.43
C60000	Colorado	Middle Concho River	1.00	1.00	*	*	*	*	*	1.00	1.00	1.00	1.00
B10000	Colorado	Colorado River	0.35	0.47	*	0.00	0.00	0.00	0.00	0.04	0.19	0.32	0.68
C10000	Colorado	Concho River	0.46	0.51	0.00	0.00	0.07	0.20	0.32	0.46	0.46	0.50	0.52
E20000	Colorado	Brady Creek	0.69	0.84	*	*	*	*	17.03	0.55	0.44	0.54	0.91
F20000	Colorado	Pecan Bayou	0.75	0.90	*	1.46	0.94	0.81	0.66	0.48	0.65	0.75	0.98
E10000	Colorado	San Saba river	0.92	0.95	0.93	0.78	0.85	0.83	0.86	0.90	0.90	0.95	0.99
G10000	Colorado	Llano river	0.98	1.00	0.93	0.88	0.83	0.93	0.94	0.95	0.97	0.99	1.00
M10000	Colorado	Pedernales River	0.58	0.88	0.14	0.06	0.06	0.06	0.08	0.26	0.53	0.69	0.97
J10000	Colorado	Colorado river at Columbus	0.74	0.87	0.09	0.58	0.52	0.55	0.67	0.70	0.66	0.76	0.93
K10000	Colorado	Colorado river	0.59	0.89	0.00	0.00	0.00	0.00	0.00	0.30	0.58	0.68	0.97
I10000	Colorado	Colorado river	0.69	0.81	0.64	0.64	0.54	0.51	0.56	0.72	0.60	0.69	0.80
207203	Guadalupe	Guadalupe River	0.98	0.99	1.09	1.00	0.96	0.99	0.98	0.98	0.95	0.97	1.00
503601	Guadalupe	San Marcos River	0.94	0.94	1.90	1.29	1.20	1.09	0.99	0.92	0.93	0.94	0.95

Table A3 (continued)

Control Point	Basin Name	River Name	Percentage of Months with Flows Equaling or Exceeding Values Shown in the Table Mean	Standard Deviation	100%	98%	95%	90%	75%	50%	25%	10%	MAXIMUM
C38521	Guadalupe	Guadalupe River	0.89	0.92	5.55	1.25	1.03	0.95	0.94	0.87	0.85	0.92	0.72
CP37	Guadalupe	Guadalupe River at Victoria	1.01	0.94	4.13	2.90	2.07	1.68	1.26	1.07	0.97	0.99	0.96
215401	San Antonio	Medina River	0.90	1.00	*	*	0.66	0.72	0.69	0.76	0.87	0.92	0.99
216402	San Antonio	San Antonio	1.04	0.88	8.31	13.50	10.50	3.15	1.72	1.23	0.98	0.87	0.96
CP35	San Antonio	Cibolo Creek	1.00	0.92	*	2.39	1.90	1.67	1.35	1.17	1.00	1.01	0.84
CP15	San Antonio	San Antonio at Goliad	0.89	0.94	1.22	0.96	0.93	0.92	0.85	0.86	0.86	0.90	0.89
NEAL	Neches	Neches	0.95	1.01	*	1.68	0.71	0.61	0.59	0.84	0.99	0.99	1.01
5555A1	Neches	Angelina	0.99	1.00	*	*	*	*	0.68	0.98	1.00	1.00	1.00
CANGL	Neches	Angelina	0.96	1.03	8.27	2.23	1.71	1.18	0.37	0.83	1.00	0.99	1.05
NEEV	Neches	Neches at Evadale	0.97	1.01	2.23	1.64	1.30	1.15	0.72	0.91	0.99	0.99	1.02
306901	Nueces	Nueces	0.98	1.00	0.58	0.71	0.86	0.91	0.96	0.98	0.98	0.97	1.00
311701	Nueces	Nueces	0.92	0.98	0.00	0.12	0.35	0.52	0.67	0.75	0.70	0.93	0.99
CP25	Nueces	Frio River	1.01	1.00	*	77.64	12.10	6.74	1.77	1.06	1.04	0.99	1.00
395401	Nueces	Hondo Creek	0.99	1.00	*	*	*	*	0.98	1.00	1.00	0.98	1.00
CP28	Nueces	Atascosa River	1.01	1.00	*	3.87	1.77	1.41	1.15	1.07	1.04	1.00	1.00
CP06	Nueces	Nueces River	0.96	0.99	0.00	0.45	0.47	0.65	0.84	0.81	0.86	0.97	0.99
CP30	Nueces	Nueces River at Mathis	0.83	0.76	*	39.02	33.56	16.89	5.46	2.05	1.30	0.39	0.89
C10210	Red	Palo Duro Creek	0.29	0.57	*	*	*	*	0.00	0.00	0.14	0.15	0.56
C10075	Red	Teirra Blanca Creek	1.00	1.00	*	*	*	*	1.00	1.00	1.00	1.00	1.00
D10130	Red	Tule Creek	0.62	0.92	*	0.00	0.00	0.00	0.00	0.00	0.35	0.80	0.84
D10000	Red	Prairie Dog Town Fork	0.91	0.94	*	1.14	0.89	0.84	0.82	0.86	0.90	0.87	0.94

Table A3 (continued)

Control Point	Basin Name	River Name	Percentage of Months with Flows Equaling or Exceeding Values Shown in the Table										
			Mean	Standard Deviation	100%	98%	95%	90%	75%	50%	25%	10%	MAXIMUM
P10000	Red	Wichita River	0.59	0.81	0.53	0.39	1.36	0.37	0.40	0.42	0.46	0.55	0.90
O10000	Red	Beaver Creek	0.91	0.98	0.89	0.59	0.56	0.57	0.60	0.68	0.86	0.95	0.98
G10000	Red	Pease River	1.00	1.00	0.99	0.99	0.99	0.99	0.99	0.99	0.99	1.00	1.00
206	Red	Salt Fork Red River	1.00	*	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
10260	Red	Elm Creek	0.98	1.00			0.76	0.81	0.94	0.94	0.99	0.98	1.00
10070	Red	North Fork Red River	0.90	0.99	0.00	0.00	0.36	0.48	0.76	0.87	0.91	0.96	0.99
Y10000	Red	Red River at Index, Arkansas	0.97	1.00	0.27	0.52	0.65	0.76	0.92	0.95	0.98	0.99	1.00
SRMN	Sabine	Sabine River	0.71	0.88	0.00	0.11	0.20	0.72	0.39	0.41	0.59	0.79	0.93
WQS43	Sabine	Turkey Creek	0.77	0.92	2.23	1.25	1.05	0.62	0.39	0.47	0.69	0.83	1.02
WQS12	Sabine	Sabine River	0.87	0.96	5.95	1.18	0.89	0.72	0.67	0.71	0.15	0.94	0.98
SRBW	Sabine	Sabine River near Bon Weir	0.92	0.93	0.00	1.11	1.03	1.04	1.19	1.04	0.76	0.04	0.98
C60	Sulphur	Sulphur River	0.96	0.99	*	*	8.26	2.23	0.91	0.84	0.93	0.97	1.00
D10	Sulphur	White Oak Creek	0.96	0.97	*	*	4.77	1.53	1.01	0.93	0.94	0.97	1.00
E250	Sulphur	Sulphur River near Talco	0.97	1.00	*	30.92	4.20	1.65	0.90	0.86	0.96	0.96	1.00
A222	San Jacinto	Spring Creek	1.06	1.00	4.97	2.98	2.27	2.01	1.45	1.19	1.05	1.01	1.00
1002	San Jacinto	San Jacinto River	0.98	0.98	2.42	1.66	1.51	1.40	1.20	0.91	0.94	0.97	0.41
WSCN	San Jacinto	San Jacinto near Conroe	0.86	0.94	*	*	2.17	1.52	1.01	0.63	0.76	0.90	0.94
8WTBO	Trinity	Trinity River	0.86	0.72	*	*	*	*	8.01	1.86	0.80	0.57	0.75
8DNJU	Trinity	Denton Creek	1.00	1.00	*	*	*	1.00	1.00	1.00	1.00	1.00	1.00

Table A3 (continued)

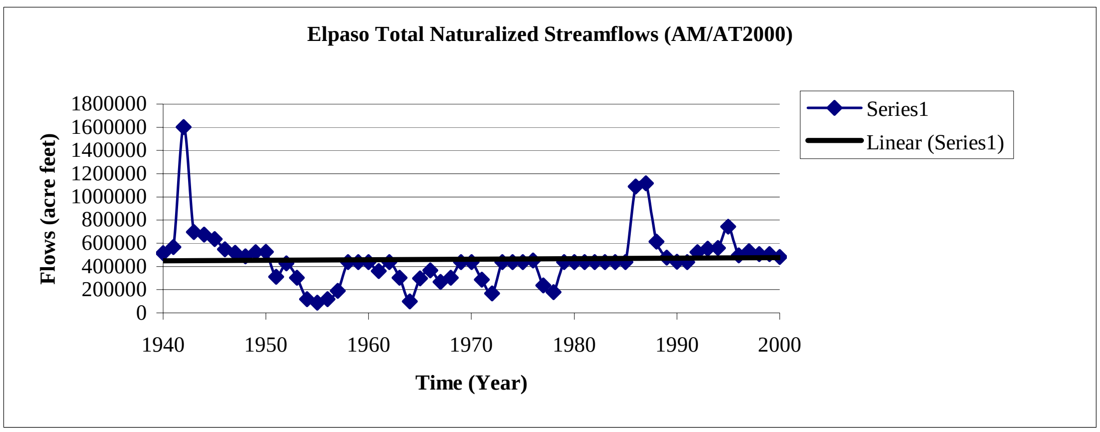
Control Point	Basin Name	River Name	Percentage of Months with Flows Equaling or Exceeding Values Shown in the Table										
			Mean	Standard Deviation	100%	98%	95%	90%	75%	50%	25%	10%	MAXIMUM
8ELLE	Trinity	Elm Fork Trinity	0.29	0.53	*	*	*	*	6.39	0.08	0.03	0.24	0.66
8ETCR	Trinity	East Fork Trinity	0.69	0.85	*	*	*	*	1.95	0.40	0.47	0.69	0.96
8TRTR	Trinity	Trinity River	0.81	0.79	*	*	1110.22	6.53	1.72	0.86	0.69	0.69	0.89
B5023A	Trinity	Chambers Creek	0.95	0.98	*	*	*	*	0.66	0.80	0.91	0.96	0.99
8RIFA	Trinity	Richland Creek	0.69	0.89	*	*	*	10.18	0.14	0.02	0.46	0.84	0.87
8TRCR	Trinity	Trinity River	0.81	0.86	*	9.79	3.55	2.01	1.07	0.73	0.70	0.84	0.93
8TRRO	Trinity	Trinity River at Romayor	0.83	0.89	*	8.00	3.25	1.52	0.71	0.72	0.78	0.86	0.82
WQ002	Lavaca	Lavaca River near Edna	1.00	1.00	*	*	1.45	1.12	1.01	0.99	1.00	1.00	1.00
B10000	Cypress	Big Cypress creek	0.80	0.92	*	0.06	0.21	0.26	0.60	0.72	0.74	0.91	0.94
C10000	Cypress	Black Cypress Bayou	1.00	1.00	*	0.78	0.99	0.99	1.00	1.00	1.00	1.00	1.00
E10000	Cypress	Little Cypress creek Near Jefferson	0.99	1.00	*	31.28	2.44	1.25	0.99	0.98	0.99	1.00	1.00
F10020	Cypress	James Bayou	1.00	1.00	*	*	*	*	0.94	1.00	1.00	1.00	1.00
F10070	Cypress	Harrison Bayou in Harrison	1.00	1.00	*	*	*	*	1.00	1.00	1.00	1.00	1.00
GT2000	Rio Grande	Girvin, TX	0.36	0.92	0.00	0.00	0.00	0.00	0.00	0.07	0.14	0.22	0.98
AT1000	Rio Grande	Fort Quitman, TX	0.20	0.38	*	*	*	0.12	0.10	0.13	0.16	0.22	0.45
CT4000	Rio Grande	Johnson Ranch Near Castolon,TX	0.99	1.37	0.00	0.23	0.31	0.37	0.43	0.56	0.77	1.21	0.94
DT3000	Rio Grande	Laredo, TX	0.96	0.82	0.75	0.71	0.77	0.84	1.04	1.05	0.97	0.92	0.83
ET1000	Rio Grande	Below Anzalduas Dam, TX	0.80	0.58	0.77	0.60	0.79	0.99	1.05	0.99	0.85	0.59	0.75
ET0000	Rio Grande	Brownsville,Tx	0.09	0.55	0.00	0.00	0.00	0.00	0.01	0.01	0.02	0.04	0.70

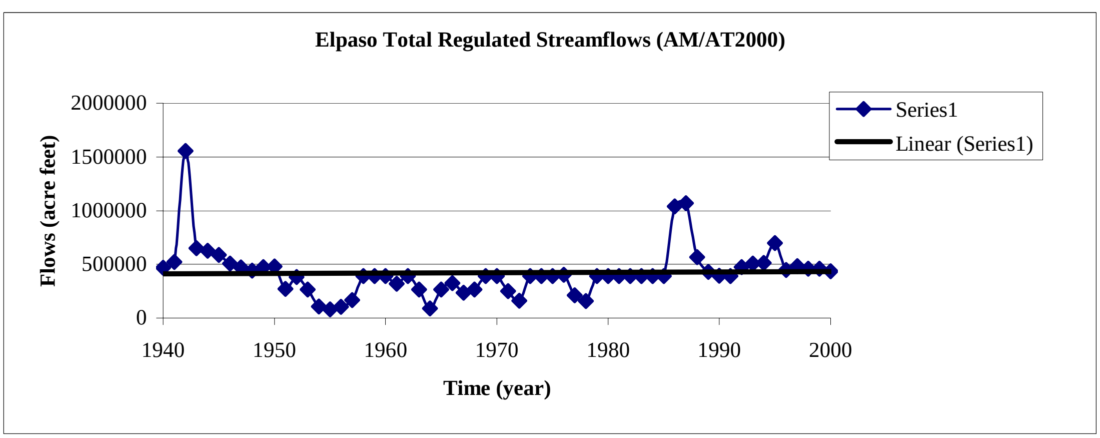
* Naturalized flow is zero.

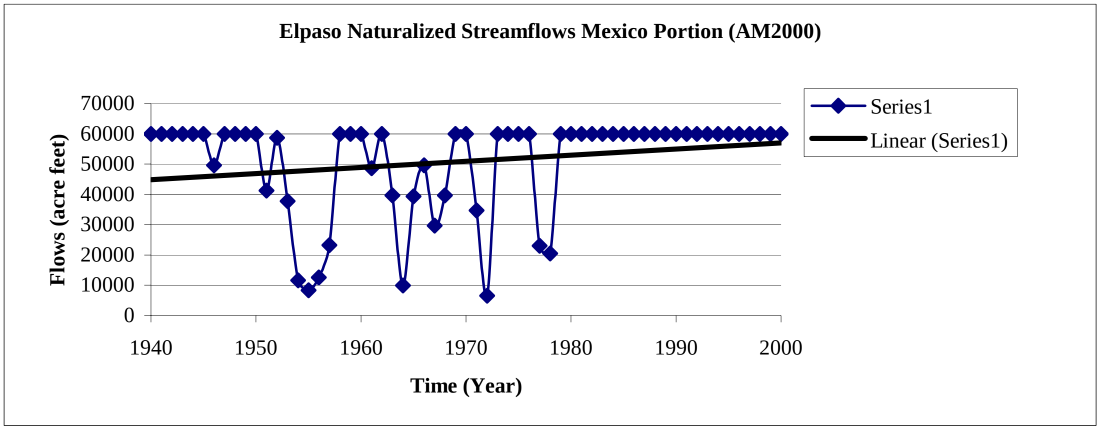
APPENDIX B

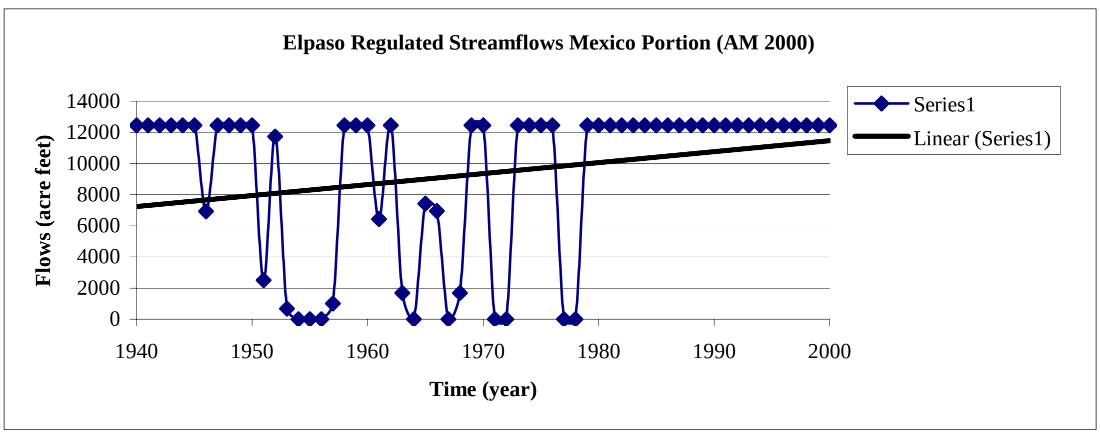
FLOW SERIES PLOTS FOR RIO GRANDE BASIN (TOTAL FLOWS AND FLOWS IN MEXICO PORTION)

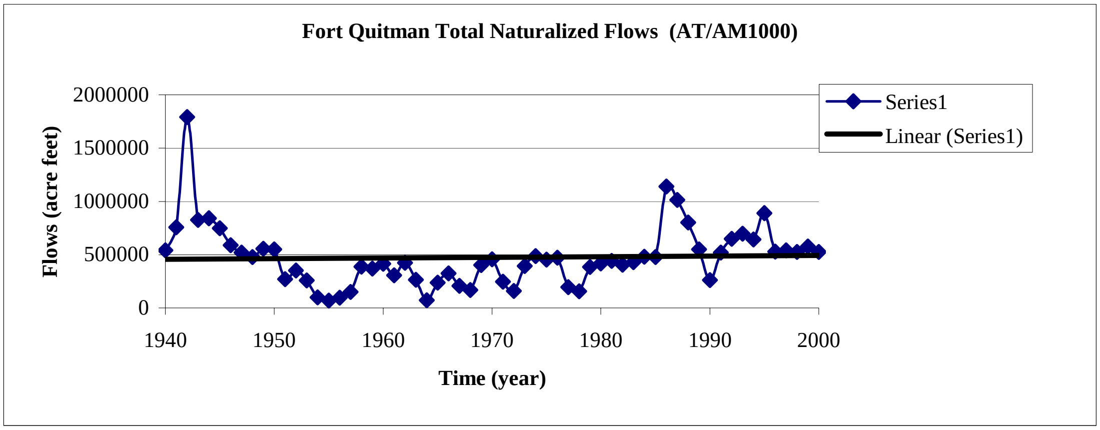
The following figures show the trend analysis of the naturalized and regulated streamflows for the Rio Grande basin. (Total flows and Mexico portion flows).

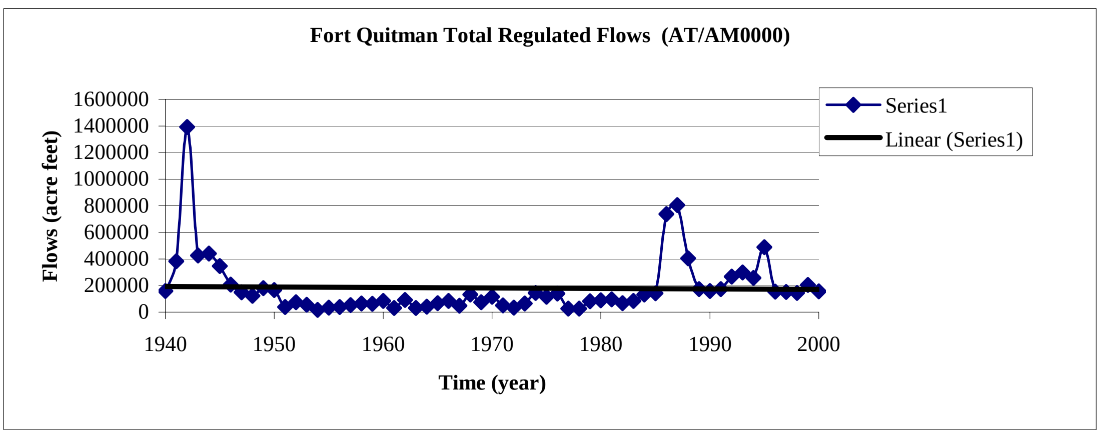


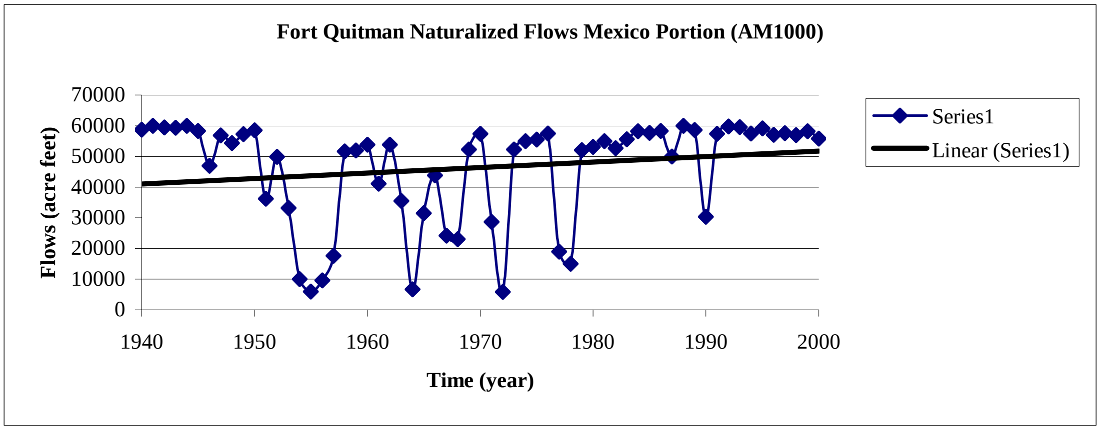


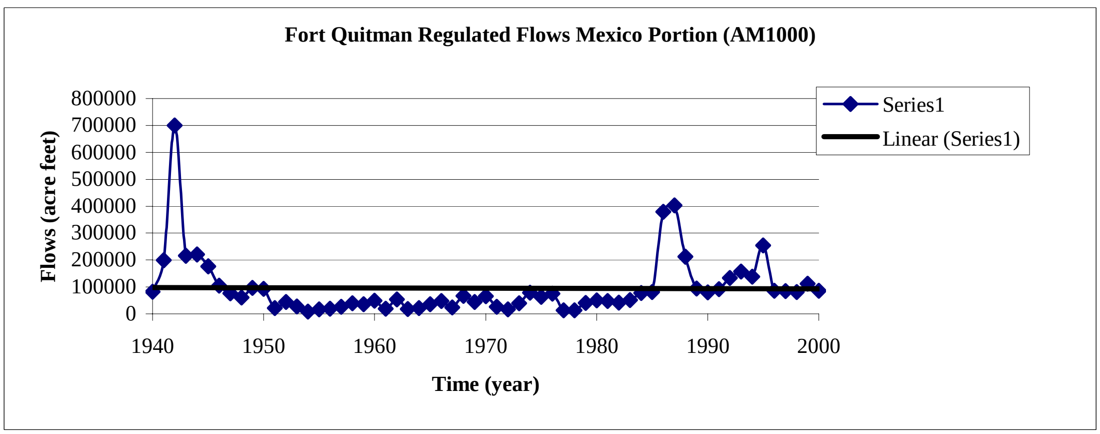

Elpaso Naturalized Streamflows Mexico Portion (AM2000)
Flows (acre feet)
70000
60000
50000
40000
30000
20000
10000
0
1940
1950
1960
1970
1980
1990
2000
Time (Year)
Series1
Linear (Series1)

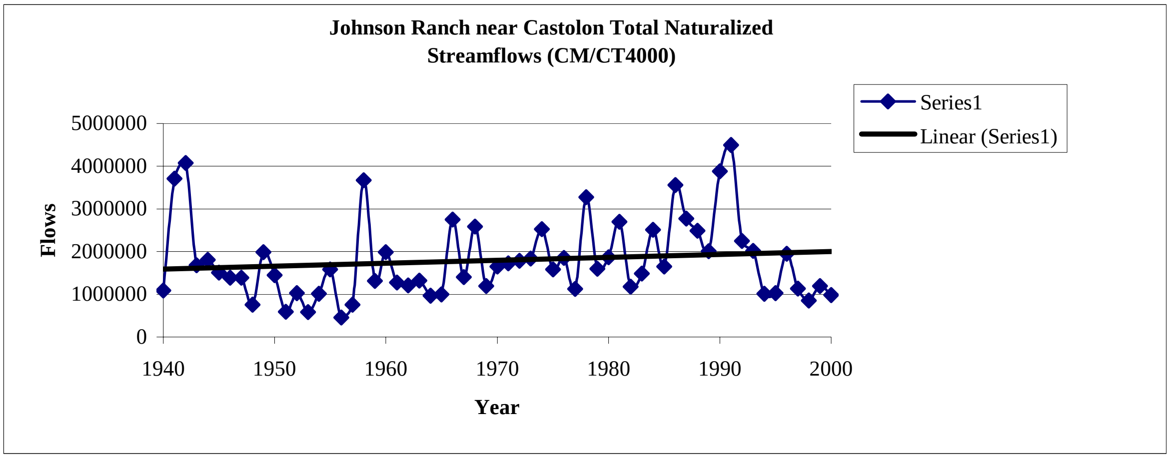

Elpaso Regulated Streamflows Mexico Portion (AM 2000)
Flows (acre feet)
14000
12000
10000
8000
6000
4000
2000
0
1940
1950
1960
1970
1980
1990
2000
Time (year)
Series1
Linear (Series1)

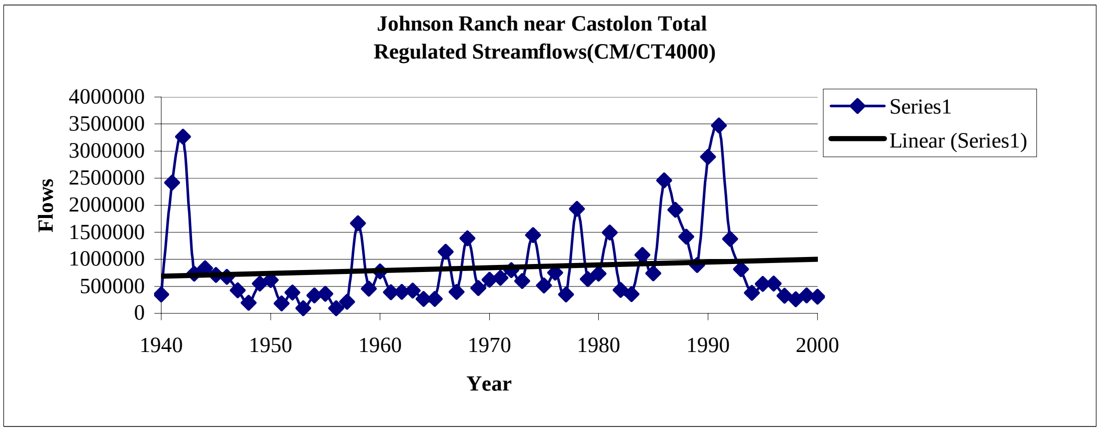

Fort Quitman Total Naturalized Flows (AT/AM1000)
2000000
1500000
1000000
500000
0
Flows (acre feet)
1940
1950
1960
1970
1980
1990
2000
Time (year)
Series1
Linear (Series1)

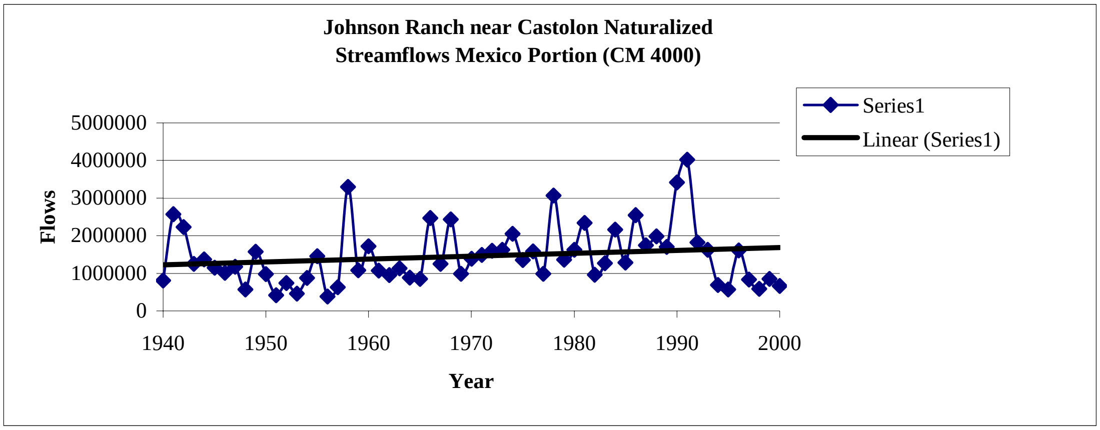

Fort Quitman Total Regulated Flows (AT/AM0000)
1600000
1400000
1200000
1000000
800000
600000
400000
200000
0
Flows (acre feet)
1940
1950
1960
1970
1980
1990
2000
Time (year)
Series1
Linear (Series1)

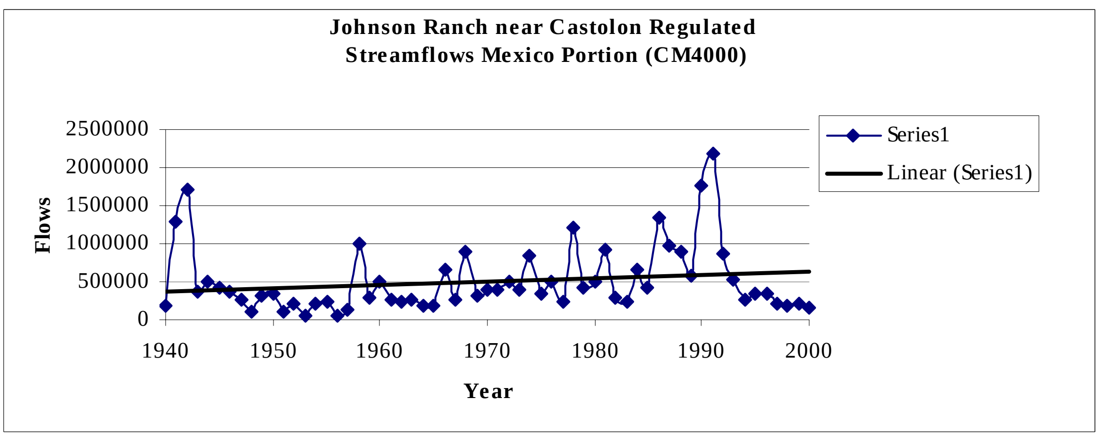

Fort Quitman Naturalized Flows Mexico Portion (AM1000)
Flows (acre feet)
70000
60000
50000
40000
30000
20000
10000
0
1940
1950
1960
1970
1980
1990
2000
Time (year)
Series1
Linear (Series1)

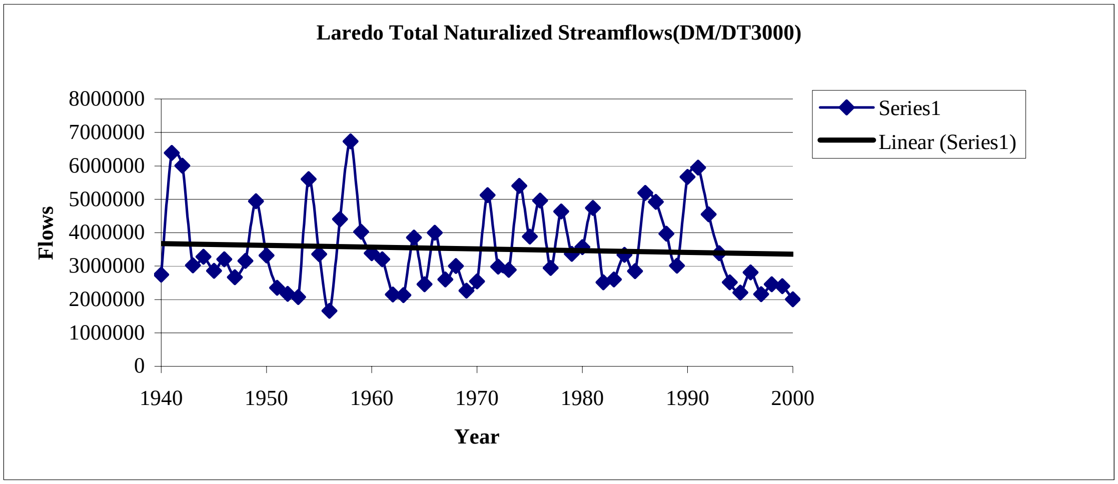

Fort Quitman Regulated Flows Mexico Portion (AM1000)
Flows (acre feet)
800000
700000
600000
500000
400000
300000
200000
100000
0
1940
1950
1960
1970
1980
1990
2000
Time (year)
Series1
Linear (Series1)

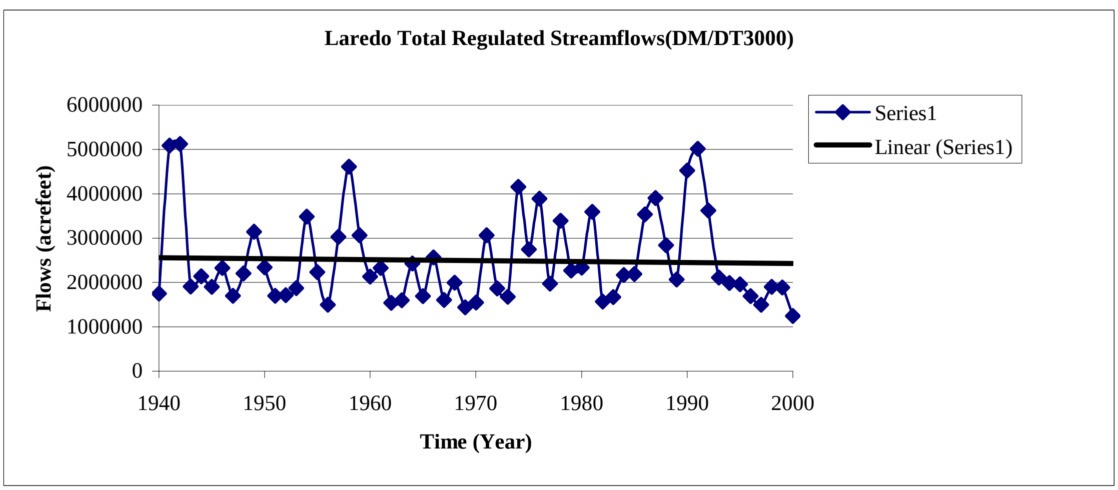

Johnson Ranch near Castolon Total Naturalized Streamflows (CM/CT4000)
Series1
Linear (Series1)
Flows
5000000
4000000
3000000
2000000
1000000
0
1940
1950
1960
1970
1980
1990
2000
Year

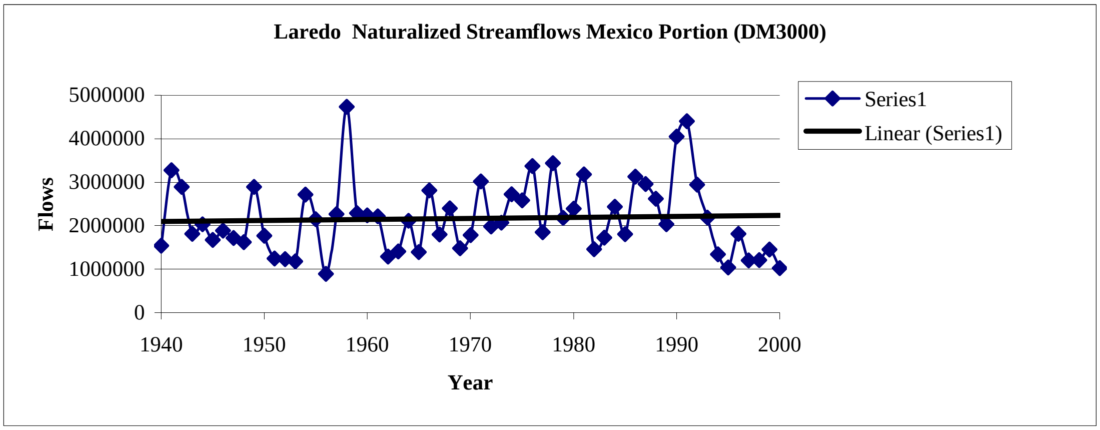

Johnson Ranch near Castolon Total Regulated Streamflows(CM/CT4000)
Series1
Linear (Series1)
Flows
4000000
3500000
3000000
2500000
2000000
1500000
1000000
500000
0
1940
1950
1960
1970
1980
1990
2000
Year

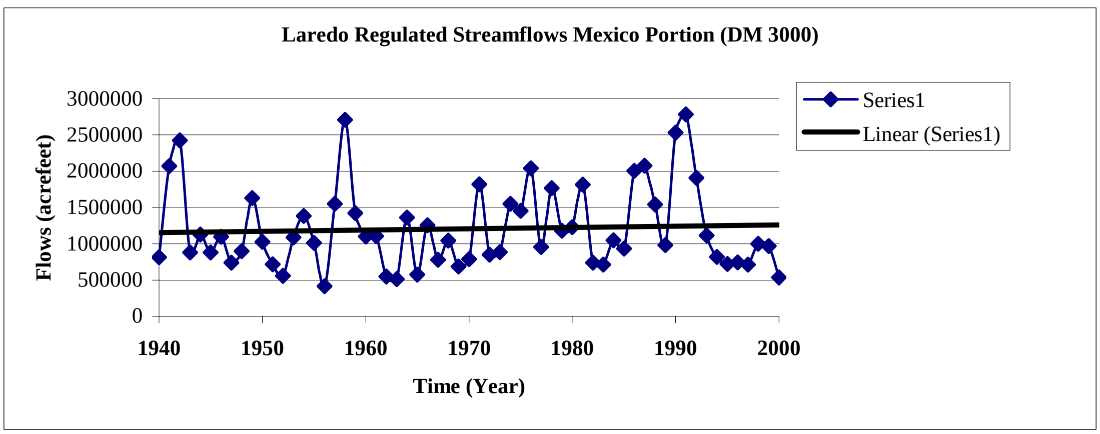

Johnson Ranch near Castolon Naturalized
Streamflows Mexico Portion (CM 4000)
Series1
Linear (Series1)
Flows
5000000
4000000
3000000
2000000
1000000
0
1940
1950
1960
1970
1980
1990
2000
Year

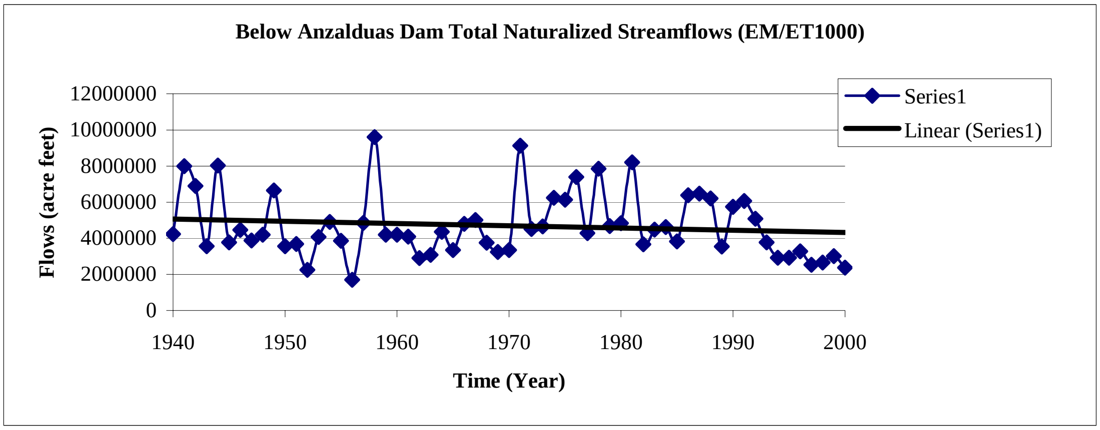

Johnson Ranch near Castolon Regulated
Streamflows Mexico Portion (CM4000)
Series1
Linear (Series1)
Flows
2500000
2000000
1500000
1000000
500000
0
1940
1950
1960
1970
1980
1990
2000
Year

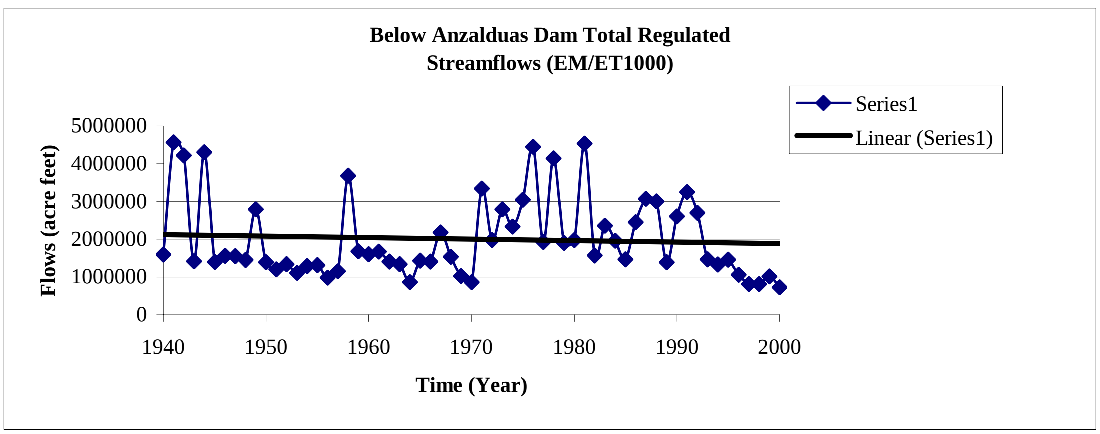

Laredo Total Naturalized Streamflows(DM/DT3000)
8000000
7000000
6000000
5000000
4000000
3000000
2000000
1000000
0
Flows
1940
1950
1960
1970
1980
1990
2000
Year
Series1
Linear (Series1)

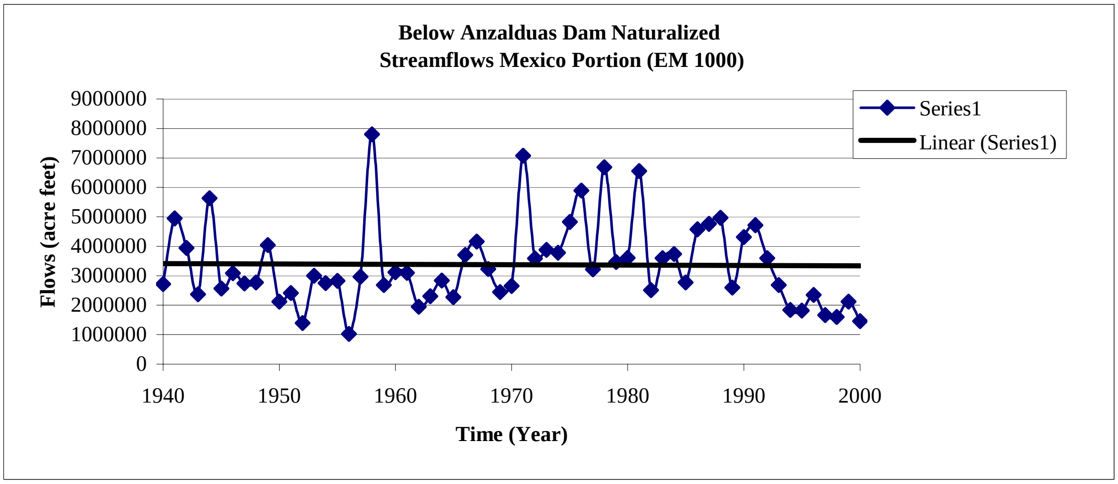

Laredo Total Regulated Streamflows(DM/DT3000)
6000000
5000000
4000000
3000000
2000000
1000000
0
Flows (acrefeet)
1940
1950
1960
1970
1980
1990
2000
Time (Year)
Series1
Linear (Series1)

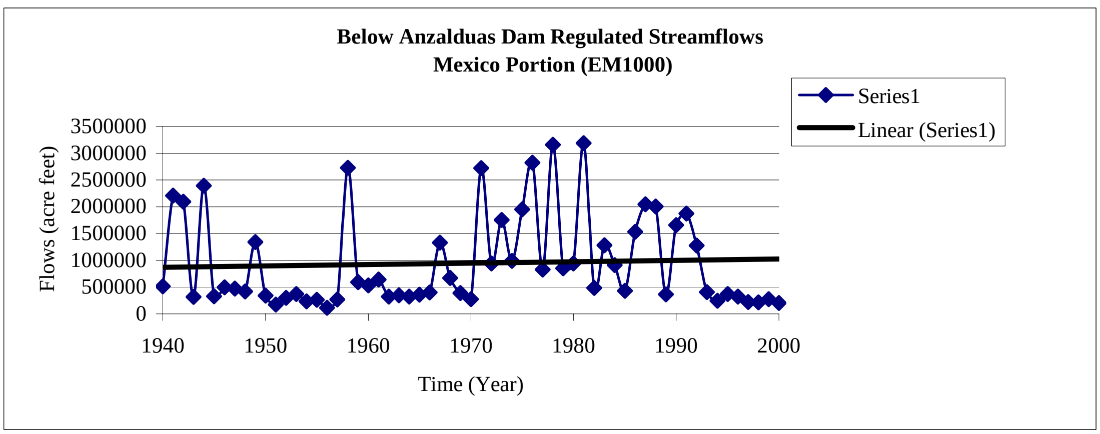

Laredo Naturalized Streamflows Mexico Portion (DM3000)
Series1
Linear (Series1)
Flows
5000000
4000000
3000000
2000000
1000000
0
1940
1950
1960
1970
1980
1990
2000
Year

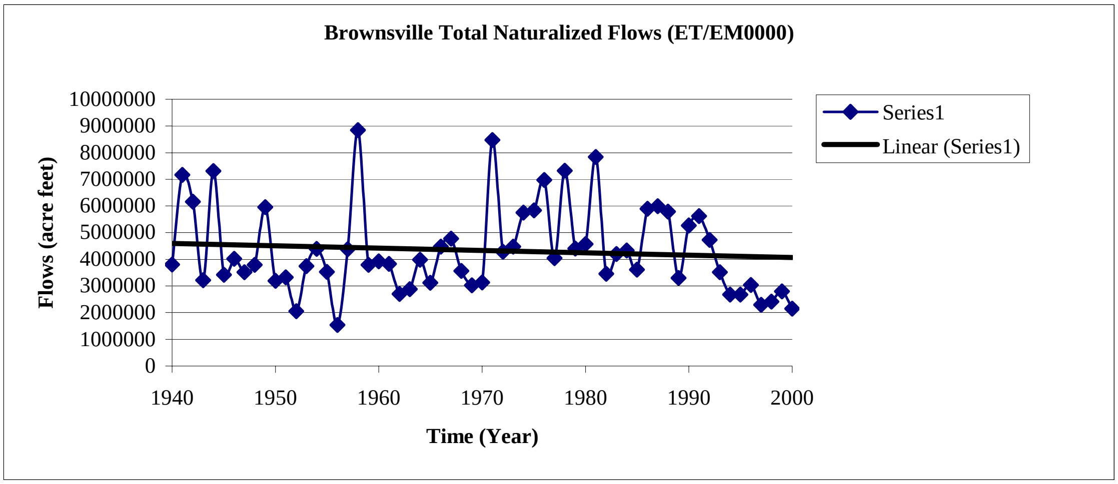

Laredo Regulated Streamflows Mexico Portion (DM 3000)
Series1
Linear (Series1)
Flows (acrefeet)
3000000
2500000
2000000
1500000
1000000
500000
0
1940
1950
1960
1970
1980
1990
2000
Time (Year)


Below Anzalduas Dam Total Naturalized Streamflows (EM/ET1000)
Series1
Linear (Series1)
Flows (acre feet)
12000000
10000000
8000000
6000000
4000000
2000000
0
1940
1950
1960
1970
1980
1990
2000
Time (Year)

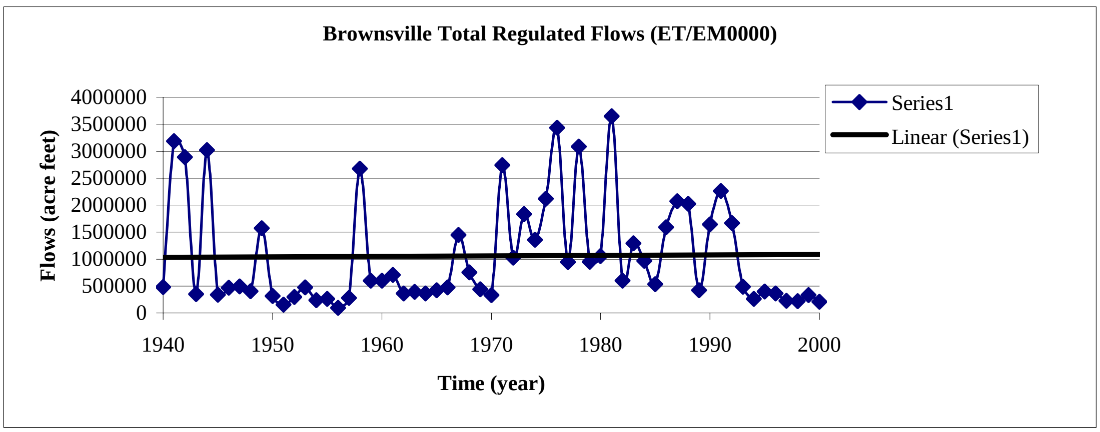

Below Anzalduas Dam Total Regulated Streamflows (EM/ET1000)
Series1
Linear (Series1)
Flows (acre feet)
5000000
4000000
3000000
2000000
1000000
0
1940
1950
1960
1970
1980
1990
2000
Time (Year)


Below Anzalduas Dam Naturalized
Streamflows Mexico Portion (EM 1000)
Flows (acre feet)
9000000
8000000
7000000
6000000
5000000
4000000
3000000
2000000
1000000
0
1940
1950
1960
1970
1980
1990
2000
Time (Year)
Series1
Linear (Series1)

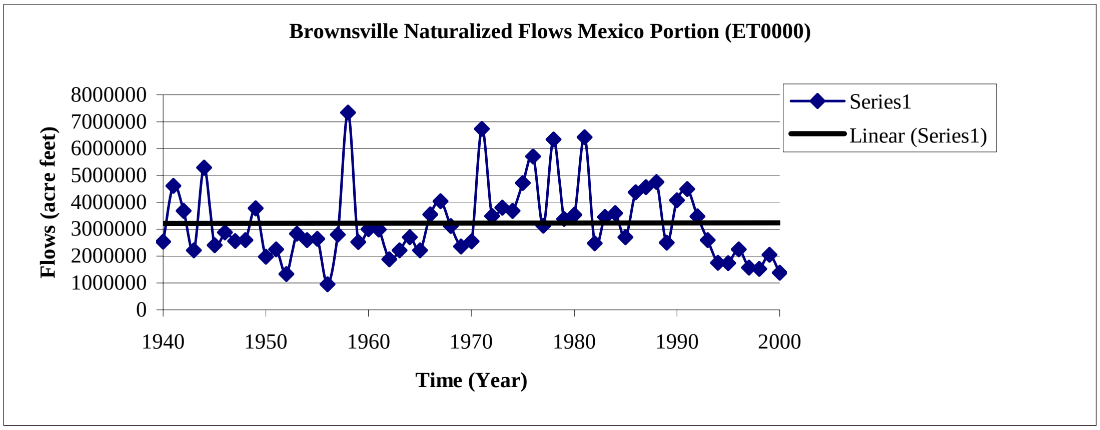

Below Anzalduas Dam Regulated Streamflows
Mexico Portion (EM1000)
Flows (acre feet)
3500000
3000000
2500000
2000000
1500000
1000000
500000
0
1940
1950
1960
1970
1980
1990
2000
Time (Year)
Series1
Linear (Series1)

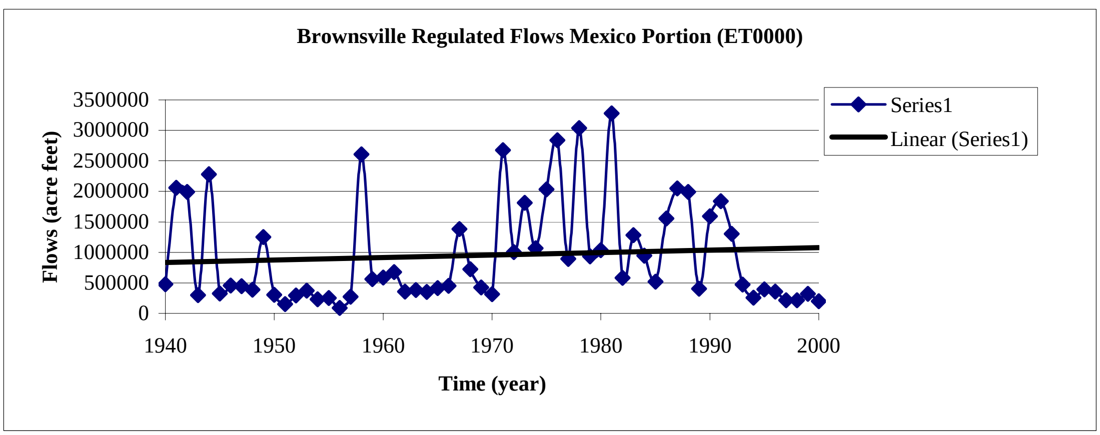


Brownsville Total Naturalized Flows (ET/EM0000)
Flows (acre feet)
10000000
9000000
8000000
7000000
6000000
5000000
4000000
3000000
2000000
1000000
0
1940
1950
1960
1970
1980
1990
2000
Time (Year)
Series1
Linear (Series1)



Brownsville Total Regulated Flows (ET/EM0000)
Flows (acre feet)
4000000
3500000
3000000
2500000
2000000
1500000
1000000
500000
0
1940
1950
1960
1970
1980
1990
2000
Time (year)
Series1
Linear (Series1)


Brownsville Naturalized Flows Mexico Portion (ET0000)
Flows (acre feet)
8000000
7000000
6000000
5000000
4000000
3000000
2000000
1000000
0
1940
1950
1960
1970
1980
1990
2000
Time (Year)
Series1
Linear (Series1)


Brownsville Regulated Flows Mexico Portion (ET0000)
Flows (acre feet)
3500000
3000000
2500000
2000000
1500000
1000000
500000
0
1940
1950
1960
1970
1980
1990
2000
Time (year)
Series1
Linear (Series1)

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