LONG-TERM CHANGES

IN RIVER SYSTEM WATER BUDGET IN TEXAS

A Thesis

by

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ABSTRACT

Climate change and water resources development are recognized as the two key factors that change long-term water budget, flow-frequency, and storage-frequency characteristics of different river systems. However, quantifying long-term changes is difficult due to the great natural variations in flows that hide long-term trends. This thesis investigates the relative impacts of various factors on long-term changes in river flows, reservoir storage, evaporation volumes, water use, and other components of river system water budgets in different regions of Texas to develop a better understanding of changes in river system hydrology.

The beginning part of this research includes a literature review based assessment of quantifying the impacts of urbanization, agricultural practices, dams and reservoirs, human water use, and climate change on stream flow. The literature review assessment provides an overview of past studies of quantifying the impacts of stream flow studies performed using either statistical trend analyses of gauged stream flow data or watershed precipitation-runoff simulation models. The overview provides a summary on the variable effects of human activities and climate change on stream flow trends.

The thesis research is based on using the Texas Commission on Environmental Quality (TCEQ) modeling system and Texas Water Development Board (TWDB) databases to explore the relative effects of climate change, water resources development, water use, and other factors on long-term changes in river flow, reservoir storage, evaporation, water use, and other components of the water budgets of different river basins of Texas.

Observed stream flow at 31 gaging stations showed an upward trend in stream flow at 14 stations and downward trend at 17 stations, most of them in the west Texas, during the simulation period. Long-term precipitation and reservoir surface evaporation trends in Texas are minimal, therefore, compared with climate change, human activity plays a major role on water budget change.

DEDICATION

To all those who have supported me through the course of my graduate studies

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NOMENCLATURE

GIS	Geographic Information Systems
IF	In Stream Flow
IPCC	Intergovernmental Panel on Climate Change
IBWC	International Boundary and Water Commission
TCEQ	Texas Commission on Environmental Quality
TPWD	Texas Parks and Wildlife Department
TWDB	Texas Water Development Board
USGS	United States Geological Survey
WAM	Water Availability Modeling
WR	Water Right
WRAP	Water Rights Analysis Package

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CHAPTER I

INTRODUCTION

1.1 Changes in Climate, Hydrology and Water Management

Population and economic growth and accompanying water resources development projects such as dams and reservoirs, diversions to supply agricultural, municipal, and industrial water needs, and return flows from surface and groundwater sources have greatly impacted river flows throughout Texas and the world. The impacts of climate change associated with global warming on hydrology and water management has been being investigated extensively by the scientific and water management communities. Natural flows in rivers are highly variable with daily, seasonal, and multiple-year fluctuations reflecting the extremes of floods and droughts as well as less severe variations. Quantifying long-term changes is difficult due to the great natural variations in flows that hide long-term trends. The impacts of human activities on low flows are typically very different than on high flows. For example, regulation of rivers by dams reduces floods flows but increases low flows at downstream locations. Likewise, climate change can have varying effects on different aspects of river system water budgets.

The Texas Water Availability Modeling (WAM) System maintained by the Texas Commission on Environmental Quality (TCEQ) and databases maintained by the Texas Water Development Board (TWDB) provide a unique opportunity to analyze changes in river system water budgets that have occurred in Texas over the period primarily from 1940 to the present. The thesis research outlined in this proposal is based on using the TCEQ modeling system and TWDB databases to explore the relative effects of climate change, water resources development and use, and other factors on long-term changes in river flow, reservoir storage, evaporation, water use, and other components of the water budgets of the different river basins of Texas.

Climate, hydrology, geography, economic development, and water management vary dramatically across the 15 major river basins and 8 coastal basins of Texas, from the arid western desert to humid eastern forests, from sparsely populated rural regions in the western and eastern extremes of the state to the metropolitan areas of Dallas and Fort Worth, Austin, San Antonio, and Houston. Mean annual precipitation ranges from 20 cm at El Paso on the Rio Grande in west Texas to 142 cm in the Sabine River Basin on the eastern border. The population of the state increased from 5.8 million people in 1930 to 25.4 million in 2010 and is projected to increase to 29.6 million in 2020 and 46.3 million by 2060 (Texas Water Development Board, 2012).

The TWDB maintains databases of monthly precipitation and reservoir surface evaporation rates for the 92 one-degree quadrangles that encompass the state for each month from January 1940 to the present. Statistical trend analyses of these precipitation and evaporation data will be performed in the thesis research to quantify the long-term impacts of climate change.

Long-term changes in stream flow, reservoir storage, reservoir evaporation, water use, and other variables due to human water resources development will be investigated using the WAM System. The TCEQ WAM System consists of the generalized Water Rights Analysis Package (WRAP) modeling system developed at Texas A&M University and input datasets for all of the river basins of Texas. Activities of an array of water management entities operating 3,400 reservoirs in accordance with a water right permit system with about 6,000 active permits, five interstate compacts, international treaty, federal storage contracts, and other institutional arrangements are modeled. Naturalized river flows from the WAM system represent natural conditions without human water development and use. Simulated regulated flows represent a specified condition of water resources development and use. Long-term changes in naturalized flows represent the effects of factors that are not included in converting actual observed gauged flows to naturalized flows.

1.2 Research Objectives and Scope

The primary question to be addressed by the thesis research is stated as follows.

How have (1) climate change, (2) water resources development and water use, and (3) land use changes and other factors changed long-term water budget, flow-frequency, and storage-frequency characteristics of the different river systems of Texas?

A primary motivation for the research is to take advantage of TWDB datasets and modeling capabilities provided by the TCEQ WAM System to develop a better understanding of changes in river system hydrology. The objectives and primary tasks of the proposed research are as follows.

Climate change will be investigated based on performing trend analyses of monthly and annual means and annual minima and maxima for the 1940-2012 monthly precipitation and reservoir evaporation rates for each of the 92 one-degree quadrangles encompassing Texas provided by the TWDB datasets. The objective is to quantify the long-term changes in precipitation and reservoir surface evaporation rates. Preliminary results indicate that long-term trends are minimal.

The river basins of Texas will be simulated with the WRAP/WAM System to quantify long-term changes in overall river system water budgets, with a particular focus on changes in frequency characteristics of river flows and reservoir storage volumes. Observed flows at selected gauges will also be compared with naturalized and simulated regulated flows. The objective is to quantify the long-term changes in stream flows and other components of river system water budgets attributable to water resources development and use.

Statistical trend analyses of the naturalized flows from the WAM System at selected sites be performed to assess the effects of factors that were not included in converting actual observed gauged flows to naturalized flows. Information regarding population, geography, land use, and water resources development in each of the river basins will be obtained from the statewide and regional planning documents available at the TWDB website and other sources.The analyses noted above will be analyzed and synthesized to develop conclusions regarding the relative impacts of various factors on long-term changes in river flows, reservoir storage, evaporation volumes, water use, and other components of river system water budgets in the different regions of Texas.

1.3 Water Resources of Texas

Water resource means water available for human use which on the Earth is only a little more than one-half of 1 percent of the total freshwater. Existing water resources could be categorized as surface water, groundwater, and reuse water. The water resources for Texas are about 17.0 million acre-feet in 2010. According to the Texas Water Development Board (TWDB), 8.4 million acre-feet of surface water and about 8.1 million acre-feet of available groundwater had been supplied as of 2010. Furthermore, about 482,000 acre-feet of reclaimed or reused water were available in 2010, with strategies to increase this amount to about 614,000 acre-feet per year by 2060 (2012 State Water Plan).

Surface water is an important source of water for Texas and is growing more and more in significance. Texas' approximately 191,000 miles of rivers and streams provide about 40 percent of the total water used in the state of the 16.1 million acre-feet of water used in Texas in 2008 (2012 State Water Plan). Texas has 23 surface water basins and 196 major reservoirs with each of them have varying hydrological regimes and abilities to supply water. Texas has 3,450 reservoirs with 196 controlled storage capacities of 5,000 acre-feet or more (TWDB 2012). The 23 surface water basins are illustrated in Figure 1.1, which is including 15 major river basins and 8 coastal river basins along the Gulf of Mexico between the lower reaches of the major river basins. Several of the major river systems shown in Figure 1.2 are shared with neighboring states or Mexico. The unique features of each of these basins are influenced by many factors, for instance, evaporation, vegetation, soil type, surface slope, geology, land use practices, and runoff, but one of the most critical factor is precipitation. Eleven of the 15 major rivers begin and end within Texas' boundaries, another 4 major rivers are shared with neighboring states and governed by interstate agreements and commissions. For example, the Canadian River in the Panhandle, the Red River in the North, and the Pecos River in West Texas and the Sabine River in the East are governed by these agreements and commissions. In addition, the Rio Grande River is both an interstate and an international river managed by both United States and Mexico. Most rivers flow into estuaries, bays and eventually the Gulf of Mexico. According to the 2012 State Water Plan, surface water is expected to increase from about 8.4 million acre-feet in 2010 to about 9.0 million acre-feet which will meet needs in 2060 and account for 51% of the recommended volume of water.

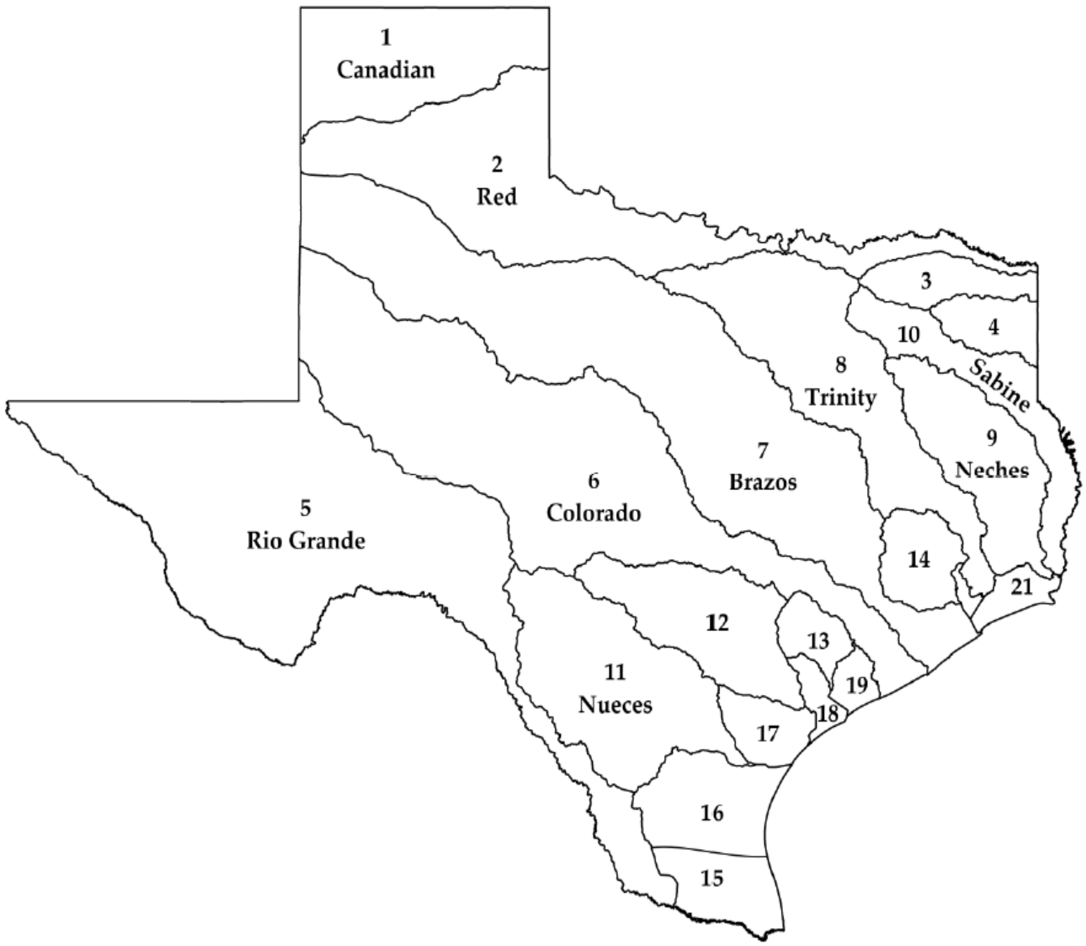


Figure 1.1 Texas WAM System River Basins (Wurbs, 2013a)

Figure 1.2 Major Rivers in Texas (Wurbs, 2013a)

Groundwater is another major source of water in Texas, which exists in underground formations called aquifers. The TWDB monitor groundwater levels and groundwater quality in both 9 major aquifers and 21 minor aquifers. Groundwater provides about 60 percent of the 16.1 million acre-feet of water used in the state. Texas has numerous aquifers capable of producing groundwater for households, municipalities, industry, farms, and ranches. About 82 percent of all groundwater is used for irrigation, or 6.0 million acre-feet per year. Since the 1970s, according to TWDB data, groundwater consistently has accounted for more than half of all Texas water use (TWDB, 2007). Using of groundwater in the Ogallala aquifer is substantial, which lies beneath portions of eight states, including much of the Texas Panhandle. In 2000, for example, about 65 percent of the estimated 10 million acre-feet of groundwater used in

Texas came from this aquifer. However, replenishment rate for this aquifer is not keeping up with pumping (NPGCD, 2007). As a result of its depletion over time, reduced groundwater supplies are projected to decrease by 30 percent, from about 8 million acre-feet in 2010 to about 5.7 million acre-feet in 2060 (2012 State Water Plan). Therefore, TWDB projects that the amount of groundwater that can be used under current permits with existing pumping facilities will decrease by almost a third in the next 50 years (2007 Water for Texas).

1.4 Water Resources Development and Management in Texas

Water resources are needed to be shared by many communities who use the water for a variety of purposes. Water resources are allocated differently between nations by different treaties and other agreements (Wurbs 2013). With a population of 26 million people and land area of 696,000 km^2, Texas is a large state located in the south-central U.S. with diverse geography, climate, hydrology, and water management practices. Therefore, Texas has a rich heritage of planning and developing water allocation strategies. Preparing for extended droughts in Texas is the major driving force for the development of water resources management. Three state agencies have authority over Texas water issues. The goals for TWDB is planning and funding water availability projects in an effective and efficient manner. The Texas Commission on Environmental Quality (TCEQ) is more focused on protecting the state’s water quality, and the Texas Parks and Wildlife Department (TPWD) is responsible for the state’s wildlife to have sustainable supplies of fresh water.

The main purpose of water allocation systems is to apportion water resources to all users equitably and facilitate efficient water use. As the water demands increase with population and economic growth, effective water allocation becomes particularly significant which should protect existing water users from having their supplies diminished by new users and govern the sharing of limited water during droughts when supplies are inadequate to meet all needs. The Texas Water Development Board (TWDB) projects that water demands will increase about 22 percent between 2010 and 2060. (TWDB 2012). However, available water supplies will decrease about 10 percent during this period due to reservoir sedimentation and depletion of groundwater aquifers (TWDB 2012). The 1997 Senate Bill I addressed a wide range of water management issues including expanding statewide water availability modeling capabilities in support of regulatory and planning activities (Wurbs, 2001).

In Texas, water is allocated between states through interstate compacts. Water supply entities service their customers in accordance with contracts and other commitments. The Rio Grande basin is shared with Mexico, and several major river basins are shared with neighboring states in the U.S. The state has progressed significantly in recent years in improving its international water allocation systems (Wurbs 2013).

1.5 Texas Water Availability Modeling (WAM) System

The TCEQ, with its partner agencies and contractors developed a Water Availability Modeling (WAM) System pursuant to the 1997 Senate Bill 1 (Wurbs 2001). The water availability modeling system was implemented during the years of 1997-2003 and provides a consistent set of databases and modeling tools for use both in planning studies and in preparing and evaluating water rights permits applications (Wurbs 2011).

The Texas Water Availability Modeling (WAM) System consists of the Water Rights Analysis Package (WRAP) modeling system, 21 sets of WRAP input files covering the 23 river basins of the state, geographical information system (GIS) tools, and other databases (Wurbs, 2005). WRAP is generalized for application anywhere, subject to input files being developed for the river basins of concern. Applications in Texas consist of executing WRAP with the WAM System data files altered as appropriate to reflect proposed changes in water use or operating practices, construction of new facilities, or other water management strategies of interest.

The TCEQ WAM system has two sets of input files for each of the river basins, full authorized and current use. The fully authorized use input dataset is based on the following premises. Water use targets are the full amounts authorized by the permits. Full reuse with no return flow is assumed. Reservoir storage capacities are those specified in the permits, which typically reflect no sediment accumulation. Term permits are not included (Wurbs 2011).

The Current Use input dataset is based on the following premises. The water use target for each right is based on the maximum annual amount used in any year during a recent ten year period. Best estimates of actual return flows are adopted. Reservoir storage capacities and elevation-area-volume relationships for major reservoirs reflect year 2000 conditions of sedimentation. Term permits are included (Wurbs 2011).

Table 1.1 lists the period of record, number of primary control points, total control points, water rights (WR), in stream flow (IF) records, and the number of reservoirs for each of the 21 river or coastal basins in the Texas WAM system. Theses information are input datasets for the WRAP modeling.

Form Table 1.1, The San Jacinto- Brazos river basins combine with Brazos river basins to become Brazos river basin in WAM dataset. Brazos-Colorado river basins and Colorado River basins combine together to Colorado River basins dataset. Therefore, instead of 23 river basin, there are 21 WAM datasets.

Table 1.1 WRAP Input Datasets in the Texas WAM System

Map ID	Major River Basin or Coastal Basin	Period of Analysis	Number of: Primary Control Points	Total Control Points	WR Record Rights	IF Record Rights	Model Reser-voirs	Reservoir Storage Capacity (acre-feet)	WAM File Name
	Major River Basins								
1	Canadian River Basin	1948-98	12	85	56	0	47	966,000	CRUN3
2	Red River Basin	1948-98	47	447	494	101	245	4,124,000	red3
3	Sulphur River Basin	1940-96	8	83	85	10	57	753,000	sulphur3
4	Cypress Bayou Basin	1948-98	10	147	163	1	91	902,000	cyp3
5	Rio Grande Basin	1940-00	55	957	2,584	4	113	23,918,000	RG3
6	Colorado River Basin and Brazos-Colorado Coastal	1940-98	45	2,395	1,922	86	511	4,763,000	C3
7	Brazos River Basin and San Jacinto-Brazos Coastal	1940-97	77	3,842	1,634	122	678	4,695,000	Bwam3
8	Trinity River Basin	1940-96	40	1,343	1,027	35	700	7,504,000	Trin3
9	Neches River Basin	1940-96	20	306	328	19	180	3,904,000	Neches3
10	Sabine River Basin	1940-98	27	376	310	21	207	6,401,000	Sabine3
11	Nueces River Basin	1934-96	41	542	373	30	121	1,040,000	N_RUN3
12	Guadalupe San Antonio River	1934-89	46	1,338	848	200	238	808,000	gsa_run3
13	Lavaca River Basin	1940-96	7	185	72	30	22	235,000	lav3
14	San Jacinto River Basin	1940-96	17	412	150	15	114	637,000	sjarun3
	Coastal Basins								
15	Lower Nueces-Rio Grande	1948-98	16	119	70	6	42	101,700	LowerNrg3
16	Upper Nueces-Rio Grande	1948-98	13	81	34	2	22	11,000	UpperNRG3
17	San Antonio-Nueces	1948-98	9	53	12	2	9	1,480	SAN_R3
18	Lavaca-Guadalupe Coastal	1940-96	2	68	10	0	0	0	lavgua3
19	Colorado-Lavaca Coastal	1940-96	1	111	27	4	8	7,230	col-lav3
20	Trinity-San Jacinto Coastal	1940-96	2	94	24	0	13	4,880	TSJ3
21	Neches-Trinity Coastal	1940-96	4	245	138	9	31	58,000	NT3
	Total		499	13,229	10,361	697	3,449	60,834,290	

CHAPTER II

LITERATURE REVIEW

The literature review will provide an overview of changes in climate, climate changes due to water resources development and use, and methods for analyzing stream flow changes. Past climate change studies can provide a basis for assessing the capabilities for quantifying the impacts of urbanization, agricultural practices, dams and reservoirs, human water use, and climate change on stream flow. A majority of the discussion will center on the effects of climate change and development and management of water resources.

2.1 Change in Climate

Climate change, which refers to any significant change in measures of climate indicators, is one of the inescapable themes of current times. Strong scientific consensus highlights that anthropogenic effects of climate change are already occurring and will be substantial (Intergovernmental Panel on Climate Change 2007). Using some indicators is one of the effective ways to track and communicate the causes and effects of climate change. The climate change indicators usually chosen to present compelling evidence of climate change are the compositions of the atmosphere and many fundamental measures of climate. For example, temperatures are rising, snow and rainfall patterns are shifting, and more extreme climate events—like heavy rainstorms and record high temperatures—are taking place around the world (EPA, 2012). Scientific evaluation of the effects of global climate change as documented by the Intergovernmental Panel on

Climate Change (IPCC) Fourth Assessment Report (AR4), new studies in the peer-reviewed scientific literature (e.g., Allison et al.2009), and assessments by the U.S. Global Change Research Program, the U.S. National Research Council, and other scientific bodies provide strong evidence of ongoing changes in the Earth climate system. The findings reflect that global-average surface temperature has increased by about 0.74°C (0.56-0.92°C) over the 20th century (IPCC 2007, pg. 10), and also, that every decade in the late 20th century has been warmer than the preceding decades provided by long-term temperature records (NOAA NCDC 2011; Hansen et al. 2010; Jones et al. 2012). Additionally, the most recent 50 years likely have been the warmest worldwide in at least the last 1,300 years (IPCC 2007, pg. 9), and 10 of the 11 warmest years on record have occurred since 2001 (NOAA NCDC 2011; Hansen et al. 2010). In winter, temperatures have increased more rapidly than summer temperatures, and nighttime minimum temperatures have warmed more than the daytime maxima. Across the United States (and elsewhere), the observed number of record high temperatures is about three times higher than the number of record cold events (IPCC 2007; Meehl et al. 2009). Deep storage of heat together with the higher heat capacity of water is causing the ocean surface to warm more slowly than the land surface, and at depths of at least 3,000 meters, the average temperature of the global ocean has increased since 1961 (IPCC 2007). Increasing temperature leads to global sea level increase as well as glaciers melting. The record shows that during the 20th century the sea level has increased about 12-22 centimeters (cm), and also that the rate of sea level rising has now almost doubled to about 3.4 millimeters (mm) per year (IPCC 2007; Allison et al. 2009). Both the

Greenland and Antarctic ice sheets are now losing mass at increasing rates, and lakes and rivers are freezing later in the fall and melting earlier in the spring (IPCC 2007; Allison et al. 2009). Precipitation is highly variable and trends are more difficult to isolate, but overall precipitation and heavy precipitation events have increased in most regions; at the same time the occurrence of drought has also been on the rise, particularly since 1970 (IPCC 2007; Allison et al. 2009).

2.2 Climate Changes Due to Water Resources Development and Use

Climate change may result from natural factors, processes and/or human activities. As for human activities, we have substantially increased the amount of greenhouse gases in the atmosphere, which lead to warming of the climate and many other changes around the world. Many of the studies show that effects from the increase in the amount of greenhouse gasses will persist over a long time. At the same time, variations in weather and climate cause changes in temperature, precipitation, and extreme event patterns, which can directly or indirectly affect many aspects of society (EPA, 2012).

Ye, Yang, and Kane (2003) analyzed long-term monthly flow records at gauging stations on the Lena River in Siberia to show the effects of climate change and human activities. Construction of a major dam accounted for most of the flow changes thereby reducing summer flows and increasing winter flows. Peters and Prowse (2001) also found that reservoir regulation on the Pease River in Canada greatly increased winter flows and decreased summer flows downstream. Trimble and Weirich (1978), Bosch and

Hewlett (1982), Stednick (1996), and Matheussen et al. (2000) are among the many investigators who have explored the effects of changes in forest cover on stream flow. Stankowski (1972) developed a quantitative index of urban land use characteristics based on population density to estimate impervious area as a determinant of changes in runoff. Dewalle and Swistock (2000) investigated gauge records for 39 urbans and 21 rural regions in the U.S. to study the effects of climate change and urbanization on mean annual flows. They found that urbanization increases the mean annual flow roughly in proportion to cumulative changes in population density. Szilagyi (2001) describes application of statistical trend analyses and watershed precipitation-runoff modeling to investigate declines in flows over several decades in the Republican River of Kansas, Nebraska, and Colorado, and concludes that the combined effects of agricultural activities and construction of dams and reservoirs have significantly reduced the flow of the river.

In China, the effects of human activities on the stream flow in the Da River are close to or more than 60% (Wanga, Ishidairaa, and Xub, 2012). Ye, Yang and Kane (2003) also show that although both climate change and human activities affect the long-term monthly flow records, in most cases, human impact plays a more important role due to changes in land use, construction of dams and water reuse which causes more flow changes in stream flow.

2.3 Methods for Analyzing Stream Flow Changes

A number of studies are reported in the literature related to quantifying the impacts of urbanization, agricultural practices, dams and reservoirs, human water use, and climate change on stream flow. Many studies deal specifically with flood events or low flows, while other studies explore long-term water balances. Some investigations are limited to analyzing means, while others consider the full flow-frequency relationship. Essentially all of the investigations are based on either statistical trend analyses of gauged stream flow data or watershed precipitation-runoff simulation models.

The U.S. Geological Survey has applied least-squares linear regression, the Kendall tau test, and other standard trend analysis methods (Kendall and Gibbons, 1990; Helsel and Hirsch, 1992) to long series of daily, monthly, and/or annual stream flow data observed at gauging stations to detect long-term trends in low, high, and median flows for various rivers. Such investigations include the Chagrin River in Ohio (Koltun and Kunze 2002), Puyallup River Basin of Washington (Sumioka 2004), St. Croix River in Wisconsin and Minnesota (Bernard N. Lenz 2004), Chesapeake Bay Basin (Langland, et al. 2004), and Red River of Texas and Oklahoma (Smith and Wahl 2003). Lettenmaier et al. (1994) investigated trends in monthly and annual stream flow at gauging stations across the United States. Lins and Slack (1999) examined trends using the non-parametric Mann-Kendall test for daily flows at selected frequency percentiles ranging from the annual minimum daily flow to annual maximum daily flow at 395 gauging stations located throughout the United States. They found that flows at low to median flow percentiles have increased across broad sections of the U.S. but decreased in some areas. Systematic patterns were found to be less apparent for high flow percentiles. McCabe and Wolock (2002) examined annual minimum, median, and maximum daily flows at 400 gauges measured during 1941-1999 and found a noticeable increase in annual minimum and median daily stream flow around 1970, and a less significant pattern of increases and decreases in annual maximum daily flows.

The LOWESS Trend Line (Cleveland, 1979; Cleveland and Devlin, 1988) and other trend analysis methods show long-term trends in peak and median flows for various rivers. Trends in mean annual-flow were analyzed for a 36-year period (1968–2003), within and near Oklahoma (Tortorelli, 2005), with the analysis showing an upward trend in stream flow at 14 stations and downward trend at 4 stations. Trends in historical runoff have been analyzed by statistical methods in the north and south areas of China. The Yellow river is an example of a large northern catchment, sensitive to drying trends and conjugated with intense human withdrawal. The Yangtze River, on the other hand, is frequently flooded by monsoon rains (Piao, Ciais, Huang, 2010).

In China, results from the Soil and Water Assessment Tool (SWAT) watershed (precipitation-runoff) model indicate that the effects of climate change on the stream flow in the Da River basin, the largest branch of the Red River, located in the humid region in the mountainous Yunnan Province, has contributed less than 30% of the changes of stream flow.

The impacts of global warming on hydrology and water resources have been addressed extensively in the literature. Major global, regional, and national assessments have been reported by Frederick et al. (1997), van Dam (1999), Lattenmaier et al.

(1999), Gleick (2000), National Assessment Synthesis Team (2000), and the Inter-Governmental Panel on Climate Change (2001). Various combinations of global circulation models simulating climate processes and watershed models representing precipitation-runoff processes have been used to predict the effects of climate change on water resources in various regions of the world (Miller and Russell, 1992; Brumbelow and Georgakakos, 2001; Arora and Boer, 2001; Matondo and Msibi, 2001).

Wurbs, Muttiah, and Felden (2005) describe an assessment of potential impacts of global warming on water management in the Brazos River Basin of Texas. The Canadian Center for Climate Modeling and Analysis global circulation model (Flato et al., 2000), SWAT watershed model, and WRAP water management model with the Brazos River Basin input dataset from the Texas WAM System were combined to predict the impacts of global warming on water supply capabilities in the year 2050. The future climate scenario generally resulted in decreased mean stream flows and greater variability. However, the effects on water availability vary significantly in different regions of the Brazos River Basin and among water users. Effects on individual water supply entities depend greatly on available reservoir storage capacity. Climate, watershed, and water management components of the modeling process all reflect approximations and uncertainties. However, the greatest uncertainty is associated with representing future climate using precipitation and temperature data from a global model.

CHAPTER III

PRECIPITATION AND RESERVOIR SURFACE EVAPORTATION RATES

The precipitation and reservoir surface evaporation vary widely geographically and seasonally. Besides the wetter, eastern portion of the state, in most parts of Texas evaporation exceeds precipitation yielding a semiarid climate. The climate becomes arid in far west Texas. Most of the annual rainfall in Texas occurs during rain storms. A large amount of precipitation falls in a short period of time, in pronounced rainy spring and fall. In order to quantify the long-term changes in the precipitation and reservoir surface evaporation rates, simulations were performed using TWDB input datasets and the recently developed PrecipEvap program. Additionally, the HEC-DSSVue, a Java-based visual utility program, is used to plot the precipitation and reservoir surface evaporation rate graphs. The DSS files which are input files of the HEC-DSSVue are prepared by the PrecipEvap program. The 92 one-degree quadrangles in Texas are used to quantify long-term effects of climate change on river system water budgets. Preliminary results indicate that long-term trends are minimal.

3.1 Texas Water Development Board Precipitation and Evaporation Datasets

The Texas Water Development Board (TWDB) was created in 1957 which goals is planning for the Texas water resources, providing affordable water and wastewater services. The TWDB provides water planning, data collection, dissemination, financial assistance and technical assistance services to the citizens of Texas (Texas Water Development Board, 2012). Climate change was investigated based on performing trend analyses of monthly and annual means, annual minima and maxima monthly precipitation, and reservoir evaporation rates during 1940-2012 for each of the 92 one-degree quadrangles encompassing Texas provided by the TWDB datasets. The PrecipEvap Program provides capabilities for trend analysis by reading the Texas Water Development Board (TWDB) precipitation and evaporation datasets. The HEC-DSSVue program is used to compute and plot monthly and annually precipitation and reservoir evaporation rates database for the each 92 quadrangles. The raw data have been prepared into monthly and annually datasets after collecting from both TWDB and other state or local agencies since the early 1900's. There are more precipitation gauges than evaporation pans. The periods-of-record of the observed data vary in gauge sites. Both average monthly precipitation and evaporation are computed year by year based on a geographic information system based on a program called ThEvap. However, prior to 1954, WD0300, the older program, used pan evaporation data from non-standard pans, which allowed for a much larger evaporation dataset. The monthly historical precipitation and pan evaporation rates for Texas are compiled data are showed by one-degree quadrangles of latitude and longitude for the period since 1940. The input datasets for the PrecipEvap Program by each 92 quadrangles are included in two files named Precipitation PPP and Evaporation EEE in inches. These input data are directly obtained from datasets maintained by TWDB. The PrecipEvap Program computes the mean annual precipitation and reservoir surface evaporation volume for each quadrangle. The DSS files as input data for the HEC-DSSVue are provided at the end of trend analysis. The HEC-DSS results will be displayed as time series plots and tables of trend analysis.

The statewide datasets of reservoir surface evaporation and historical observed monthly precipitation datasets are maintained by TWDB at the following website:

http://midgewater.twdb.state.tx.us/Evaporation/evap.html

There are 92 one-degree quadrangles covering Texas and are shown in the Figure 3.1. The monthly precipitation and evaporation depths for Texas have been updated by TWDB each year since 1940 to near the present.

Texas and adjacent surrounding land areas extending 12 degrees longitude and 14 degrees latitude are divided into 168 quadrangles. Each quadrangle is 1 degree latitude and 1 degree longitude in size. The monthly precipitation and evaporation data can be traced back to1940 and updated each year. The grid consist of 168 one-degree quadrangles and consists of 12 rows and 14 columns. The three or four digit quadrangle identifiers consist of the row and column numbers. Each quadrangle covers about 4,000 square miles, though areas vary a little between quadrangles. There are additional 76 quadrangles located outside Texas, however, there are periods of data missed for these areas. Therefore, these quadrangles will not be focused on in this thesis.

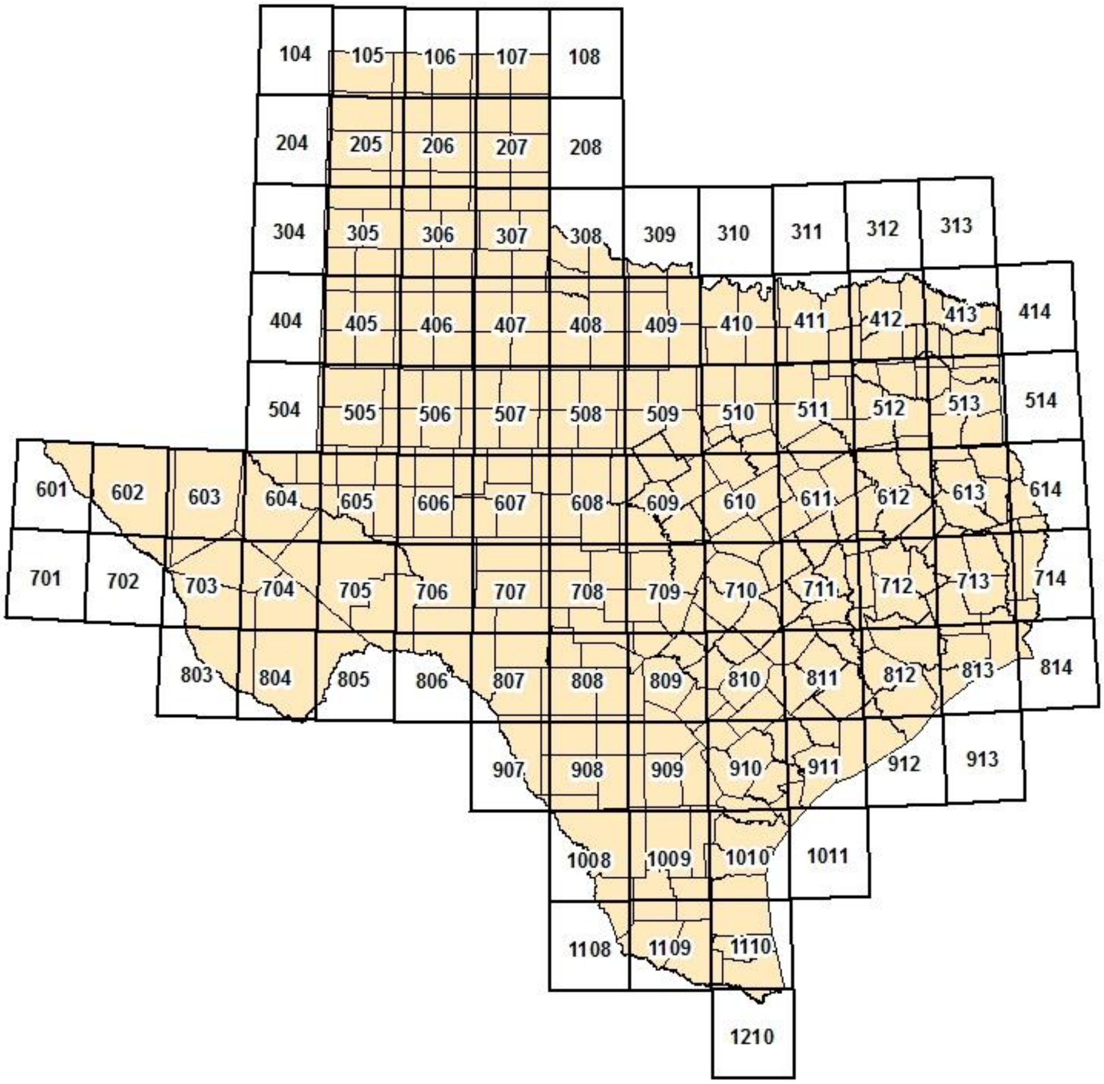


Figure 3.1 Grid of One Degree Quadrangles Encompassing Texas

3.2 Analyses of Precipitation Data

Precipitation in Texas varies very dramatically across the 15 major river basins and 8 coastal basins of Texas, from the arid western desert to humid eastern. Mean annual precipitation ranges from 20 cm at El Paso on the Rio Grande in west Texas to 142 cm in the Sabine River Basin on the eastern border (Texas Water Development Board, 2012). The precipitation datasets from the Texas Water Development Board (TWDB) for the years 1940-2012 are used as input into the program PrecipEvap. Simulations were performed based on the statistical trend analyses method of liner regression. The output data for annual precipitation form analysis does not show any significant change.

It can be seen from the Figure 3.2 that monthly precipitation fluctuates are quite significantly during the years. For Texas as a whole, the maximum monthly precipitation is 6.312 inches per month in May, 2004, and the minimum value is 0.0713 inches per month in September, 1952. However, there are no observed improved or decrease in overall trends on Texas monthly precipitation.

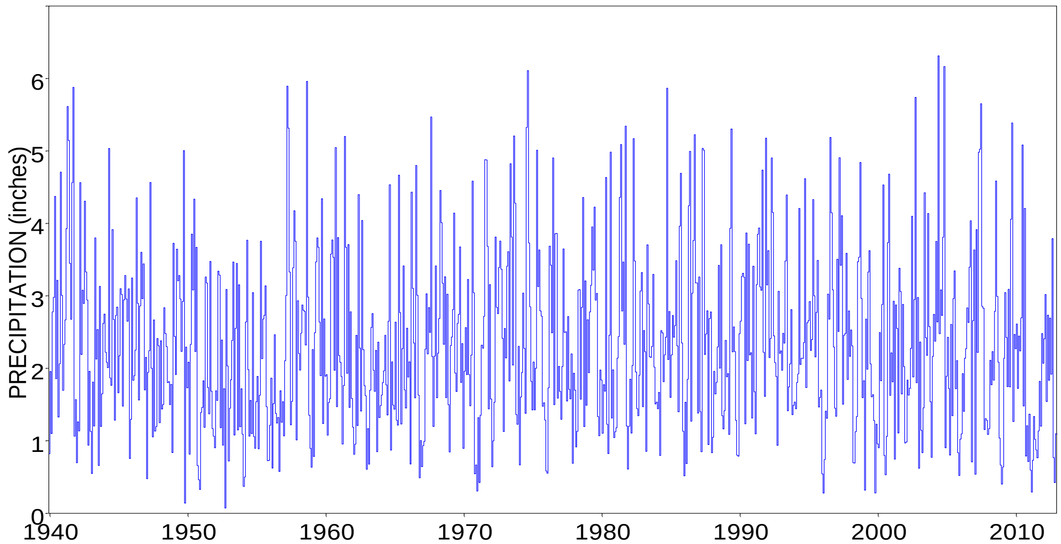


Figure 3.2 Monthly Precipitation for the 92 Quadrangles

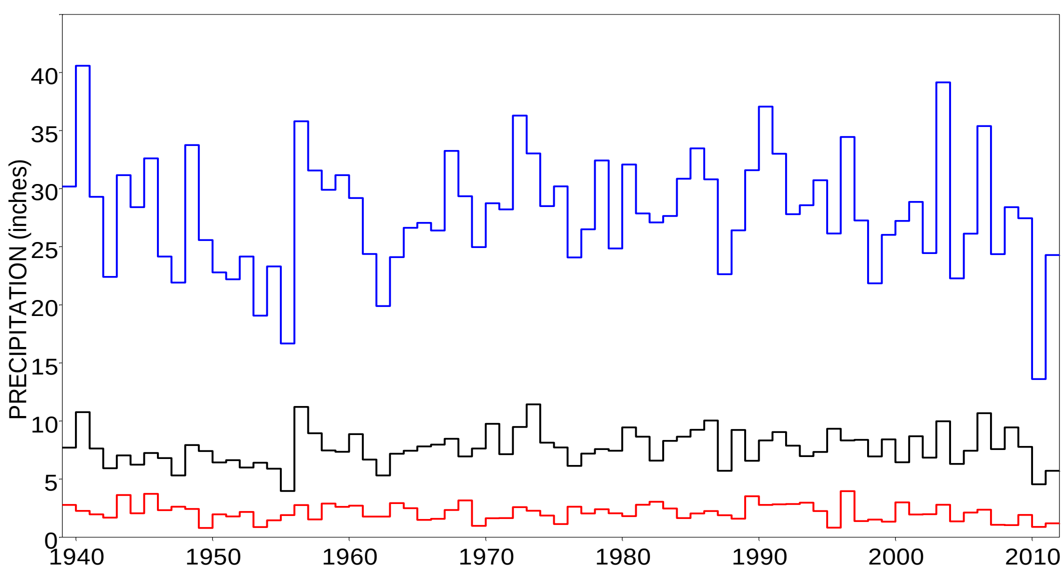


Figure 3.3 Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for the 92 Quadrangles

According to annual total precipitation for Texas in Figure 3.3, the largest annual precipitation value is 40.575 inches in 1940, and the lowest annual precipitation values is 13.6 inches in 2010. The biggest drought, on a statewide basis, happened in the 1950s which remains the most severe drought the state has ever experienced and lead to relatively low annual precipitation. Based on recorded measurements of precipitation, other significant droughts in Texas occurred in the late 1800s and the 1910s, 1930s, and 1960s.What is more, at the end of 2011, the drought may have ranked among the most intense one-year droughts on record in many climatic divisions.

Figure 3.3 also indicates 2-Month maximum, and 2-month minimum precipitation for the 92 quadrangles. In Figure 3.3, the blue line indicates annual precipitation, the black line indicates 2-month maximum precipitation and the red line means 2-month minimum precipitation. Compared with 2-month minimum precipitation, 2-month maximum precipitation has more fluctuation. The biggest change happened in the 1950s. The reason is that following this most intense drought, in the spring of 1957, massive rains resulted in the flooding of every major river and tributary in the state.

Table 3.1
Linear Regression Analysis of 1940-2012 Monthly Precipitation

Quad	Mean (inches)	Intercept (inches)	Slope (inch/month)	Intercept % Mean	Slope % Mean	Mean % Mean
104	1.390	1.4451	-0.000125	103.941	-0.00899	4.9762
105	1.479	1.6335	-0.000352	110.420	-0.02376	5.2951
106	1.545	1.6843	-0.000317	108.995	-0.02051	5.5310
107	1.732	1.7251	0.000016	99.584	0.00095	6.2005
108	1.996	1.9697	0.000059	98.697	0.00297	7.1432
204	1.398	1.589	-0.000436	113.663	-0.03116	5.0038
205	1.525	1.5821	-0.000131	103.760	-0.00857	5.4575
206	1.693	1.7405	-0.000108	102.807	-0.0064	6.0598
207	1.994	1.9726	0.000048	98.940	0.00242	7.1363
208	2.321	2.4021	-0.000186	103.510	-0.008	8.3063
304	1.383	1.3429	0.000092	97.095	0.00662	4.9504
305	1.504	1.4868	0.000039	98.852	0.00262	5.3834
306	1.714	1.7045	0.000021	99.472	0.00121	6.1332
307	1.829	1.7557	0.000167	95.998	0.00913	6.5460
308	2.150	2.1085	0.000095	98.069	0.0044	7.6955
309	2.559	2.5341	0.000056	99.036	0.0022	9.1586
404	1.330	1.3448	-0.000035	101.142	-0.0026	4.7589
405	1.499	1.4563	0.000098	97.135	0.00653	5.3661
406	1.909	2.0362	-0.000290	106.658	-0.01518	6.8332
407	1.909	1.7451	0.000374	91.416	0.01958	6.8327
408	2.101	2.0513	0.000113	97.649	0.00536	7.5190
409	2.450	2.3985	0.000117	97.908	0.00477	8.7685
410	2.845	2.7529	0.000209	96.776	0.00735	10.1817
411	3.378	3.2843	0.000213	97.229	0.00632	12.0903
412	3.825	4.0613	-0.000539	106.176	-0.01409	13.6910
413	4.062	4.0496	0.000028	99.695	0.0007	14.5389
414	4.231	4.2891	-0.000132	101.372	-0.00313	15.1440
504	1.302	1.3456	-0.000099	103.321	-0.00757	4.6616
505	1.432	1.509	-0.000176	105.406	-0.01233	5.1241
506	1.735	1.7933	-0.000133	103.350	-0.00764	6.2108
507	1.884	1.8753	0.000020	99.538	0.00105	6.7434
508	2.180	2.1641	0.000035	99.295	0.00161	7.8010
509	2.495	2.3781	0.000267	95.309	0.0107	8.9307
510	2.792	2.7119	0.000182	97.142	0.00652	9.9923
511	3.204	3.1185	0.000195	97.338	0.00607	11.4672
512	3.601	3.707	-0.000241	102.940	-0.00671	12.8894
513	3.950	3.9277	0.000051	99.438	0.00128	14.1378
514	4.205	4.1413	0.000145	98.488	0.00345	15.0504
601	0.925	0.9139	0.000025	98.817	0.0027	3.3101
602	1.244	1.172	0.000165	94.190	0.01325	4.4535
603	1.234	1.2583	-0.000055	101.937	-0.00442	4.4182
604	0.969	0.9196	0.000113	94.867	0.01171	3.4697

Table 3.1 Continued

Quad	Mean (inches)	Intercept (inches)	Slope (inch/month)	Intercept % Mean	Slope % Mean	Mean % Mean
607	1.763	1.7299	0.000076	98.104	0.00432	6.3113
608	2.039	1.8911	0.000338	92.734	0.01657	7.2990
609	2.405	2.2933	0.000254	95.374	0.01055	8.6065
610	2.727	2.4849	0.000551	91.139	0.02021	9.7588
611	3.183	3.0916	0.000209	97.128	0.00655	11.3929
612	3.647	3.643	0.000009	99.896	0.00024	13.0529
613	4.064	4.0316	0.000074	99.199	0.00183	14.5467
614	4.399	4.3906	0.000019	99.815	0.00042	15.7445
701	0.779	0.7427	0.000083	95.315	0.01068	2.7889
702	1.348	1.3478	0.000001	99.956	0.0001	4.8265
703	1.155	1.1178	0.000086	96.741	0.00743	4.1356
704	1.248	1.2727	-0.000056	101.959	-0.00447	4.4680
705	1.139	1.0776	0.000139	94.630	0.01225	4.0758
706	1.581	1.7334	-0.000348	109.665	-0.02204	5.6574
707	1.867	1.812	0.000126	97.048	0.00673	6.6831
708	2.116	2.0539	0.000141	97.079	0.00666	7.5728
709	2.533	2.465	0.000155	97.316	0.00612	9.0664
710	2.727	2.5917	0.000308	95.052	0.01128	9.7593
711	3.285	3.3753	-0.000207	102.757	-0.00629	11.7569
712	3.862	3.9438	-0.000187	102.120	-0.00483	13.8231
713	4.483	4.3752	0.000247	97.585	0.00551	16.0475
714	4.655	4.4934	0.000368	96.536	0.0079	16.6603
803	1.737	3.5505	-0.004136	204.428	-0.23815	6.2166
804	1.240	1.7868	-0.001247	144.089	-0.10054	4.4386
805	0.975	1.0213	-0.000106	104.746	-0.01082	3.4899
806	1.396	1.3985	-0.000006	100.193	-0.00044	4.9958
807	2.050	1.9635	0.000196	95.800	0.00958	7.3359
808	2.215	2.0309	0.000419	91.703	0.01892	7.9268
809	2.608	2.4948	0.000259	95.645	0.00993	9.3363
810	2.871	2.7393	0.000300	95.412	0.01046	10.2761
811	3.466	3.377	0.000203	97.435	0.00585	12.4054
812	3.903	3.6237	0.000637	92.848	0.01631	13.9693
813	4.021	3.5207	0.001141	87.558	0.02837	14.3923
814	4.687	4.676	0.000026	99.760	0.00055	16.7770
907	1.737	1.7927	-0.000127	103.211	-0.00732	6.2171
908	1.833	1.8843	-0.000117	102.802	-0.00639	6.5608
909	2.118	2.0875	0.000070	98.548	0.00331	7.5817
910	2.945	2.971	-0.000058	100.869	-0.00198	10.5425
911	3.308	3.274	0.000078	98.971	0.00235	11.8406
912	3.649	3.4825	0.000380	95.437	0.01041	13.0610
1008	1.697	1.6784	0.000043	98.877	0.00256	6.0755
1009	1.989	1.9388	0.000115	97.455	0.0058	7.1207
1010	2.441	2.3302	0.000253	95.449	0.01038	8.7381
1011	2.890	2.9454	-0.000126	101.911	-0.00436	10.3449

Table 3.1 Continued

Quad	Mean (inches)	Intercept (inches)	Slope (inch/month)	Intercept % Mean	Slope % Mean	Mean % Mean
1108	1.482	1.2752	0.000472	86.043	0.03183	5.3049
1109	1.811	1.7686	0.000096	97.686	0.00528	6.4803
1110	2.157	2.1447	0.000029	99.419	0.00132	7.7212
1210	2.170	2.0782	0.000210	95.757	0.00968	7.7683
Averages	2.325	2.3219	0.000008	100.688	-0.00157	8.3232
Total	2.328	2.3243	0.000009	99.834	0.00038	8.3333

Mean annual precipitation for the total 92 quadrangles is 27.93 inches. The total slope for liner regression is 0.00031. Although slopes vary dramatically between quadrangles, each quadrangles' slope near 0. The monthly precipitation simulation results for each of the 92 quadrangles from the Program PrecipEvap are reported together in Table 3.1, and annual simulation results are contained in Table 3.2. Table 3.3 shows regression intercept and slope as percentages of mean annual precipitation in grid of one degree quadrangles encompassing Texas.

Table 3.2
Linear Trend Regression Analysis of 1940-2012 Annual Precipitation

Quad	Mean (in/yr)	Intercept (inches)	Slope (inches/yr)	Intercept % Mean	Slope % Mean	Mean % Mean
104	16.68	17.3777	-0.018769	104.163	-0.11250	59.7142
105	17.75	19.6416	-0.051056	110.641	-0.28760	63.5411
106	18.54	20.2505	-0.046142	109.207	-0.24883	66.3717
107	20.79	20.7145	0.001982	99.647	0.00953	74.4054
108	23.95	23.6404	0.008326	98.714	0.03477	85.7184
204	16.78	19.1355	-0.063770	114.065	-0.38013	60.0462
205	18.30	19.0306	-0.019824	104.009	-0.10834	65.4906
206	20.32	20.9216	-0.016359	102.979	-0.08052	72.7178
207	23.93	23.6861	0.006461	99.001	0.02700	85.6351
208	27.85	28.8402	-0.026815	103.563	-0.09629	99.6761
304	16.60	16.1672	0.011616	97.410	0.06999	59.4053
305	18.05	17.8879	0.004341	99.110	0.02405	64.6007
306	20.56	20.4794	0.002240	99.597	0.01089	73.5984
307	21.95	21.0736	0.023583	96.024	0.10746	78.5515
308	25.80	25.3141	0.013133	98.117	0.05090	92.3455
309	30.71	30.4269	0.007522	99.094	0.02450	109.9026
404	15.95	16.2005	-0.006640	101.540	-0.04162	57.1067
405	17.99	17.5161	0.012819	97.364	0.07125	64.3927
406	22.91	24.4800	-0.042452	106.856	-0.18530	81.9989
407	22.91	20.9437	0.053072	91.428	0.23168	81.9920
408	25.21	24.6332	0.015542	97.719	0.06166	90.2274
409	29.40	28.7970	0.016229	97.957	0.05521	105.2221
410	34.14	33.0315	0.029838	96.766	0.08741	122.1805
411	40.53	39.3957	0.030771	97.191	0.07591	145.0835
412	45.90	48.7689	-0.077516	106.249	-0.16888	164.2920
413	48.74	48.5867	0.004240	99.678	0.00870	174.4669
414	50.77	51.4500	-0.018319	101.335	-0.03608	181.7281
504	15.63	16.2071	-0.015637	103.702	-0.10005	55.9388
505	17.18	18.1625	-0.026581	105.725	-0.15473	61.4886
506	20.82	21.5682	-0.020156	103.582	-0.09680	74.5295
507	22.61	22.5350	0.001976	99.677	0.00874	80.9207
508	26.15	25.9936	0.004335	99.387	0.01658	93.6125
509	29.94	28.5203	0.038404	95.254	0.12827	107.1681
510	33.50	32.5244	0.026378	97.087	0.07874	119.9074
511	38.45	37.4028	0.028176	97.288	0.07329	137.6067
512	43.21	44.4951	-0.034639	102.966	-0.08016	154.6730
513	47.40	47.1115	0.007769	99.394	0.01639	169.6541
514	50.46	49.6328	0.022308	98.364	0.04421	180.6042
601	11.10	11.0095	0.002383	99.206	0.02147	39.7217
602	14.93	14.1002	0.022454	94.436	0.15039	53.4421
603	14.81	15.1679	-0.009606	102.399	-0.06485	53.0180
604	11.63	11.0725	0.015135	95.186	0.13011	41.6359

Table 3.2 Continued

Quad	Mean (in/yr)	Intercept (inches)	Slope (inches/yr)	Intercept % Mean	Slope % Mean	Mean % Mean
605	13.53	13.4844	0.001151	99.685	0.00851	48.4169
606	18.06	19.4448	-0.037338	107.648	-0.20670	64.6536
607	21.16	20.7811	0.010230	98.211	0.04835	75.7362
608	24.47	22.6862	0.048235	92.707	0.19711	87.5885
609	28.85	27.5004	0.036595	95.307	0.12683	103.2780
610	32.72	29.7865	0.079221	91.041	0.24214	117.1058
611	38.20	37.0914	0.029861	97.107	0.07818	136.7154
612	43.76	43.7267	0.000945	99.920	0.00216	156.6353
613	48.77	48.3726	0.010730	99.186	0.02200	174.5601
614	52.79	52.6553	0.003515	99.754	0.00666	188.9337
701	9.35	8.9555	0.010666	95.779	0.11407	33.4668
702	16.18	16.2307	-0.001334	100.305	-0.00825	57.9177
703	13.87	13.4827	0.010333	97.242	0.07453	49.6270
704	14.98	15.3421	-0.009802	102.421	-0.06544	53.6157
705	13.66	12.9655	0.018894	94.884	0.13827	48.9092
706	18.97	20.8545	-0.051007	109.950	-0.26892	67.8892
707	22.41	21.7659	0.017298	97.143	0.07720	80.1970
708	25.39	24.6598	0.019705	97.128	0.07761	90.8741
709	30.40	29.5907	0.021769	97.350	0.07162	108.7965
710	32.72	31.1051	0.043630	95.066	0.13335	117.1121
711	39.42	40.5453	-0.030507	102.864	-0.07740	141.0831
712	46.34	47.3876	-0.028213	102.253	-0.06088	165.8772
713	53.80	52.5400	0.034089	97.656	0.06336	192.5699
714	55.86	53.9282	0.052099	96.549	0.09327	199.9240
803	20.84	42.9072	-0.596363	205.871	-2.86138	74.5986
804	14.88	21.5747	-0.180917	144.984	-1.21577	53.2627
805	11.70	12.2965	-0.016111	105.095	-0.13769	41.8791
806	16.75	16.8127	-0.001716	100.379	-0.01024	59.9500
807	24.59	23.5787	0.027452	95.870	0.11162	88.0303
808	26.58	24.3712	0.059583	91.705	0.22420	95.1221
809	31.30	29.9601	0.036244	95.716	0.11579	112.0355
810	34.45	32.8938	0.042114	95.477	0.12224	123.3136
811	41.59	40.5710	0.027560	97.548	0.06626	148.8648
812	46.83	43.5349	0.089164	92.956	0.19038	167.6320
813	48.25	42.2735	0.161582	87.610	0.33487	172.7077
814	56.25	56.1938	0.001437	99.906	0.00255	201.3239
907	20.84	21.5488	-0.019061	103.384	-0.09145	74.6050
908	22.00	22.6522	-0.017737	102.984	-0.08064	78.7295
909	25.42	25.0868	0.008969	98.694	0.03529	90.9805
910	35.35	35.7143	-0.009978	101.045	-0.02823	126.5100
911	39.70	39.3816	0.008528	99.205	0.02148	142.0872
912	43.79	41.8571	0.052199	95.589	0.11921	156.7314
1008	20.37	20.1911	0.004809	99.127	0.02361	72.9065
1009	23.87	23.3163	0.015051	97.667	0.06304	85.4487

Table 3.2 Continued

Quad	Mean (in/yr)	Intercept (inches)	Slope (inches/yr)	Intercept % Mean	Slope % Mean	Mean % Mean
1010	29.30	28.0348	0.034076	95.696	0.11632	104.8573
1011	34.68	35.4652	-0.021154	102.257	-0.06099	124.1384
1108	17.79	15.3364	0.066184	86.231	0.37213	63.6583
1109	21.73	21.2899	0.011791	97.992	0.05427	77.7641
1110	25.89	25.8317	0.001471	99.790	0.00568	92.6539
1210	26.04	25.0492	0.026889	96.180	0.10324	93.2192
Averages	27.90	27.8967	0.000213	100.861	-0.02326	99.8785
Total	27.94	27.9270	0.000314	99.959	0.00112	100.0000

Table 3.1 and Table 3.2 show that the linear regression analysis results of monthly and annual precipitation. The intercept as percentages of mean listed in the fifth column which calculated by the regression intercept in each quadrangle divided by the mean precipitation in each quadrangle. The slope as percentages of mean listed in the sixth column which calculated by the slope in each quadrangle divided by the mean precipitation in each quadrangle. The mean as percentages of mean listed in the last column which calculated by the mean in each quadrangle divided by the annual mean precipitation of total quadrangles.

As shown in Table 3.2, although each quadrangles' long-term trend for the future is different, there is no wide fluctuation trend from 1940-2012. According to Table 3.3, the eastern part of Texas is moister than the western part of Texas. The annual precipitation for each quadrangle varies from 201.32% in the 814 quadrangle, to 33.47% in the 701 quadrangle for the mean annual precipitation. The variability of precipitation generally increases from inland across the state and to the Gulf, while relative humidity generally decreases from east to west and inland away from the coast. In spite of the different climates types in Texas, the regression slopes and intercepts for mean precipitation does not show large variability trend.

The Table 3.2 indicates that the highest positive trend slope is 0.3721 in the1108 quadrangle, and the lowest regression slope is -2.861 in the 803 quadrangle. Table 3.3 show that regression intercept and slope as percentages of annual precipitation. Both of them are used to reflect long-term changes.

According to Table 3.3, the intercept as percentages of mean, listed in the first row of each quadrangle, which calculated by the regression intercept in each quadrangle divided by the mean precipitation in each quadrangle. The slope as percentages of mean, listed in the second row, which calculated by the slope in each quadrangle divided by the precipitation.

Table 3.3
Regression Intercept and Slope as Percentages of Mean Annual Precipitation (from Table 3.2)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
100				104.16 -0.113	110.64 -0.288	109.21 -0.249	99.647 0.0095	98.714 0.0348						
200				114.06 -0.380	104.01 -0.108	102.98 -0.081	99.001 0.0270	103.56 -0.096						
300				97.410 0.0699	99.110 0.0240	99.596 0.0109	96.024 0.1075	98.117 0.0509	99.094 0.0245					
400				101.54 -0.042	97.364 0.0713	106.86 -0.185	91.428 0.2316	97.719 0.0616	97.957 0.0552	96.765 0.0874	97.191 0.0759	106.25 -0.169	99.678 0.0087	101.34 -0.036
500				103.70 -0.100	105.72 -0.155	103.58 -0.097	99.677 0.0087	99.387 0.0166	95.254 0.1283	97.086 0.0787	97.288 0.0732	102.97 -0.081	99.394 0.0164	98.364 0.0442
600	99.206 0.0215	94.435 0.1503	102.39 -0.065	95.186 0.1301	99.685 0.0085	107.65 -0.206	98.211 0.0484	92.707 0.1971	95.307 91.041	91.041 0.2421	97.107 0.0782	99.920 0.0022	99.186 0.0220	99.754 0.0067
700	95.779 0.1141	100.31 -0.008	97.242 0.0745	102.42 -0.065	94.884 0.1383	109.95 -0.269	97.143 0.0772	97.128 0.7761	97.350 0.0716	95.066 0.1333	102.86 -0.071	102.25 -0.061	97.656 0.0634	96.548 0.0933
800			205.87 -2.861	144.98 -1.216	105.09 -0.137	100.38 -0.010	95.870 0.1116	91.704 0.2242	95.716 0.1158	95.477 0.1222	97.548 0.0662	92.956 0.1904	87.609 0.335	99.905 0.0003
900							103.38 -0.091	102.98 -0.081	98.694 0.0353	101.04 -0.028	99.205 0.0215	95.589 0.1192		
1000								99.126 0.0236	97.667 0.0630	95.696 0.1163	102.26 -0.060			
1100								86.231 0.3721	97.992 0.0543	99.789 0.0056				
1200										96.180 0.1032				
	1	2	3	4	5	6	7	8	9	10	11	12	13	14

The linear regression analysis of annual 2-month minimum and 2-month maximum precipitation are computed by The PrecipEvap Program. These metrics show differences between effects on low and high flows. For example, dams usually decrease high flows but often increase low flows. Two months are used rather than one month because a several day flood or low flow event can occur during the last several days of a month continuing into the first several days of the next month.

The regression results of annual 2-month minimum and 2-month maximum precipitation are indicated in Table 3.4 and Table 3.5 respectively. The intercept as percentages of mean listed in the fifth column which calculated by the regression intercept of 2-month minimum or 2-month maximum precipitation in each quadrangle divided by the mean precipitation in each quadrangle. The slope as percentages of mean listed in the sixth column which calculated by the slope of 2-month minimum or 2-month maximum precipitation in each quadrangle divided by the mean precipitation in each quadrangle. The mean as percentages of mean listed in the last column which calculated by the mean of 2-month minimum or 2-month maximum precipitation in each quadrangle divided by the annual mean precipitation in total quadrangles Both the slopes near of zero and intercept approximately equal to the mean, which indicates that there is no significant long-term linear trend in 2-month minimum and 2-month maximum.

Table 3.4
Linear Trend Regression Analysis of Annual 2-Month Minimum Precipitation

Quad	Mean (inches)	Intercept (inches)	Slope (inch/year)	Intercept % Mean	Slope % Mean	Mean % Mean
104	0.3895	0.4030	-0.00037	103.4794	-0.09404	1.3940
105	0.6205	0.9489	-0.00887	152.9066	-1.42991	2.2211
106	0.4271	0.4848	-0.00156	113.5049	-0.36500	1.5288
107	0.5747	0.5915	-0.00045	102.9281	-0.07914	2.0569
108	0.7785	0.9158	-0.00371	117.6432	-0.47684	2.7864
204	0.4458	0.6367	-0.00516	142.8447	-1.15796	1.5955
205	0.5945	0.7188	-0.00336	120.9083	-0.56509	2.1280
206	0.5784	0.5652	0.000355	97.7282	0.06140	2.0701
207	0.8923	0.8979	-0.00015	100.6191	-0.01673	3.1939
208	1.3237	1.7938	-0.01271	135.5161	-0.95989	4.7379
304	0.3903	0.3948	-0.00012	101.1582	-0.03130	1.3969
305	0.5545	0.6709	-0.00315	120.9877	-0.56723	1.9848
306	0.591	0.5557	0.000953	94.033	0.16127	2.1152
307	0.6293	0.5763	0.001432	91.5815	0.22753	2.2525
308	0.8841	0.8766	0.000203	99.1491	0.02300	3.1645
309	1.3471	1.2282	0.003214	91.1718	0.23860	4.8217
404	0.3542	0.4094	-0.00149	115.5678	-0.42075	1.2679
405	0.411	0.3314	0.002151	80.6334	0.52342	1.4709
406	1.0082	1.3638	-0.00961	135.2648	-0.95310	3.6087
407	0.8807	0.7859	0.002561	89.2402	0.29081	3.1522
408	0.9421	0.8765	0.001771	93.0432	0.18802	3.3719
409	1.3379	1.1780	0.004323	88.0439	0.32314	4.7889
410	1.8603	1.5369	0.008741	82.6154	0.46985	6.6584
411	2.4858	2.3063	0.004851	92.7793	0.19515	8.8972
412	3.1723	3.4206	-0.00671	107.826	-0.21151	11.3547
413	3.4637	3.2527	0.005703	93.9078	0.16465	12.3976
414	3.8271	3.8561	-0.00078	100.7582	-0.02049	13.6984
504	0.5426	0.7040	-0.00436	129.7484	-0.80401	1.9421
505	0.5438	0.6235	-0.00215	114.6474	-0.39588	1.9465
506	0.8304	1.0541	-0.00605	126.9355	-0.72799	2.9723
507	0.8381	0.9117	-0.00199	108.7787	-0.23726	2.9997
508	1.1041	1.0913	0.000345	98.8441	0.03124	3.9519
509	1.4145	1.3282	0.002334	93.894	0.16503	5.0630
510	1.8962	1.6588	0.006414	87.4843	0.33826	6.7869
511	2.4726	2.3698	0.00278	95.8407	0.11241	8.8501
512	2.9908	2.9818	0.000242	99.7	0.00811	10.7050
513	3.4756	3.1344	0.009222	90.1824	0.26534	12.4402
514	3.7885	3.4405	0.009404	90.8157	0.24822	13.5601
601	0.4782	0.5338	-0.0015	111.6299	-0.31432	1.7117
602	0.7284	0.6942	0.000923	95.309	0.12678	2.6070
603	0.4611	0.5128	-0.0014	111.2077	-0.30291	1.6504
604	0.2134	0.1675	0.00124	78.5034	0.58099	0.7639

Table 3.4 Continued

Quad	Mean (inches)	Intercept (inches)	Slope (inch/year)	Intercept % Mean	Slope % Mean	Mean % Mean
606	0.6127	1.0913	-0.01293	178.1056	-2.11096	2.1932
607	0.7084	0.7920	-0.00226	111.811	-0.31922	2.5354
608	0.9896	0.9670	0.000612	97.7125	0.06182	3.5420
609	1.4212	1.4843	-0.00171	104.4409	-0.12002	5.0870
610	1.8518	1.8990	-0.00127	102.5473	-0.06884	6.6280
611	2.5229	2.7374	-0.0058	108.5035	-0.22982	9.0301
612	3.2853	3.5766	-0.00787	108.8667	-0.23964	11.7592
613	3.7785	3.8564	-0.00211	102.0617	-0.05572	13.5243
614	4.0704	4.1324	-0.00167	101.5223	-0.04114	14.5692
701	0.1763	0.1825	-0.00017	103.5354	-0.09555	0.6310
702	0.7436	0.7805	-0.001	104.9727	-0.13440	2.6614
703	0.2512	0.2127	0.001042	84.66	0.41459	0.8992
704	0.2873	0.3331	-0.00124	115.9515	-0.43112	1.0282
705	0.324	0.3530	-0.00078	108.9641	-0.24227	1.1596
706	0.7281	1.2805	-0.01493	175.8717	-2.05059	2.6060
707	0.8834	0.9430	-0.00161	106.7465	-0.18234	3.1620
708	1.0222	1.2123	-0.00514	118.5965	-0.50261	3.6587
709	1.4488	1.7395	-0.00786	120.069	-0.54240	5.1855
710	1.9171	2.1044	-0.00506	109.7695	-0.26404	6.8619
711	2.5958	2.8493	-0.00685	109.7679	-0.26400	9.2909
712	3.6542	4.0287	-0.01012	110.2462	-0.27692	13.0796
713	4.1601	4.4609	-0.00813	107.2291	-0.19538	14.8903
714	4.4314	4.5097	-0.00212	101.7677	-0.04778	15.8611
803	0.9353	2.7345	-0.04863	292.3562	-5.19882	3.3479
804	0.4749	1.1132	-0.01725	234.4005	-3.63245	1.6999
805	0.279	0.3853	-0.00287	138.0912	-1.02949	0.9988
806	0.4536	0.5294	-0.00205	116.7245	-0.45201	1.6234
807	1.2092	1.2562	-0.00127	103.8896	-0.10513	4.3280
808	1.171	1.5489	-0.01021	132.2746	-0.87229	4.1912
809	1.4595	2.0354	-0.01557	139.4633	-1.06658	5.2238
810	1.9158	2.2397	-0.00876	116.911	-0.45705	6.8570
811	2.7814	3.0856	-0.00822	110.9367	-0.29559	9.9553
812	3.2138	3.4200	-0.00557	106.4153	-0.17339	11.5032
813	3.2504	3.3771	-0.00342	103.8975	-0.10534	11.6341
814	4.0029	4.2993	-0.00801	107.4051	-0.20014	14.3274
907	0.5297	0.7387	-0.00565	139.4578	-1.06643	1.8960
908	0.7164	0.9307	-0.00579	129.9029	-0.80819	2.5643
909	1.1167	1.3599	-0.00657	121.776	-0.58854	3.9970
910	2.1096	2.7720	-0.0179	131.3994	-0.84863	7.5508
911	2.0988	2.3746	-0.00746	113.1431	-0.35522	7.5121
912	2.9837	3.7529	-0.02079	125.78	-0.69676	10.6795
1008	0.5597	0.6521	-0.0025	116.5035	-0.44604	2.0034
1009	0.7599	0.9159	-0.00422	120.5411	-0.55517	2.7198
1010	1.0933	1.1577	-0.00174	105.8941	-0.15930	3.9132

Table 3.4 Continued

Quad	Mean (inches)	Intercept (inches)	Slope (inch/year)	Intercept % Mean	Slope % Mean	Mean % Mean
1011	1.4305	1.8947	-0.01254	132.4428	-0.87683	5.1203
1108	0.547	0.5091	0.001023	93.0816	0.18698	1.9578
1109	0.6996	0.6412	0.001579	91.6471	0.22575	2.5040
1110	0.9722	1.1170	-0.00391	114.8983	-0.40266	3.4797
1210	0.8055	0.8961	-0.00245	111.2528	-0.30413	2.8830
Averages	1.4381	1.5700	-0.00356	113.7301	-0.37108	5.1472
Total	2.1232	2.3126	-0.00512	108.9189	-0.24105	7.5995

The linear regression analysis for the 92 quadrangles indicated that total regression intercept and slope are 108.92% and -0.241% for mean annual 2-month minimum precipitation. The total regression intercept are 94.63% and 0.145% for mean annual 2-month maximum precipitation.

Precipitation plots by monthly and annual means and annual minima and maxima during the 1940-2012 for each of the 92 quadrangles can be found in Appendix A.

Table 3.5
Linear Trend Regression Analysis of Annual 2-Month Maximum Precipitation

Quad	Mean (inches)	Intercept (inches)	Slope (inch/year)	Intercept % Mean	Slope % Mean	Mean % Mean
104	6.6555	6.9354	-0.00757	104.2062	-0.11368	23.8218
105	6.4078	6.4807	-0.00197	101.1380	-0.03076	22.9354
106	7.3100	8.1798	-0.02351	111.8982	-0.32157	26.1646
107	7.7160	8.0988	-0.01035	104.9611	-0.13408	27.6178
108	8.6573	9.0080	-0.00948	104.0513	-0.10949	30.9868
204	6.4812	6.9843	-0.01360	107.7619	-0.20978	23.1982
205	6.7612	7.1078	-0.00937	105.1256	-0.13853	24.2004
206	7.7449	8.5324	-0.02128	110.1679	-0.27481	27.7213
207	8.5996	9.0119	-0.01114	104.7949	-0.12959	30.7804
208	9.3710	9.3394	0.00085	99.6632	0.00910	33.5413
304	6.6734	6.7643	-0.00246	101.3614	-0.03680	23.8861
305	6.8262	6.6708	0.00420	97.7245	0.06150	24.4328
306	7.7784	8.0652	-0.00775	103.6883	-0.09968	27.8409
307	8.2345	8.4412	-0.00559	102.5097	-0.06783	29.4737
308	9.4890	9.8784	-0.01052	104.1037	-0.11091	33.9640
309	10.5586	10.3465	0.00573	97.9908	0.05430	37.7923
404	6.5014	6.3260	0.00474	97.3025	0.07291	23.2702
405	7.1882	7.3486	-0.00433	102.2312	-0.06030	25.7287
406	7.7530	7.6894	0.00172	99.1797	0.02217	27.7502
407	8.0466	7.2528	0.02145	90.1357	0.26660	28.8010
408	8.9855	8.6969	0.00780	96.7884	0.08680	32.1616
409	9.9230	9.7759	0.00398	98.5177	0.04006	35.5173
410	11.0499	10.7692	0.00758	97.4602	0.06864	39.5506
411	12.6212	12.0453	0.01556	95.4370	0.12332	45.1750
412	13.2886	13.5417	-0.00684	101.9041	-0.05146	47.5638
413	14.0492	14.0194	0.00081	99.7878	0.00574	50.2860
414	14.3503	14.0805	0.00729	98.1201	0.05081	51.3637
504	6.0516	5.8851	0.00450	97.2478	0.07438	21.6605
505	6.4923	6.4208	0.00193	98.8981	0.02978	23.2379
506	7.2771	7.2237	0.00145	99.2653	0.01986	26.0469
507	7.9700	7.8525	0.00318	98.5256	0.03985	28.5269
508	8.8107	8.9031	-0.00250	101.0489	-0.02835	31.5359
509	9.8203	9.3030	0.01398	94.7330	0.14235	35.1495
510	10.7053	10.2377	0.01264	95.6314	0.11807	38.3174
511	11.8775	11.6830	0.00526	98.3621	0.04427	42.5130
512	12.8966	13.3175	-0.01138	103.2638	-0.08821	46.1605
513	13.5810	13.0272	0.01497	95.9223	0.11021	48.6101
514	14.3323	13.2334	0.02970	92.3327	0.20722	51.2994
601	4.1822	3.8759	0.00828	92.6771	0.19792	14.9692
602	5.2360	4.9524	0.00767	94.5832	0.14640	18.7412
603	5.7025	5.5670	0.00366	97.6241	0.06421	20.4107
604	4.8378	4.3549	0.01305	90.0189	0.26976	17.3159

Table 3.5 Continued

Quad	Mean (inches)	Intercept (inches)	Slope (inch/year)	Intercept % Mean	Slope % Mean	Mean % Mean
606	6.4078	6.4679	-0.00162	100.9370	-0.02533	22.9354
607	7.3866	7.3263	0.00163	99.1835	0.02207	26.4386
608	8.2695	7.7932	0.01287	94.2407	0.15566	29.5987
609	9.1021	8.6525	0.01215	95.0610	0.13349	32.5788
610	10.1514	8.7587	0.03764	86.2812	0.37078	36.3346
611	11.2590	10.4808	0.02103	93.0882	0.18681	40.2993
612	12.5036	12.2464	0.00695	97.9433	0.05559	44.7538
613	13.9249	13.6584	0.00720	98.0861	0.05173	49.8413
614	15.1573	14.9281	0.00619	98.4881	0.04086	54.2521
701	4.3108	4.0385	0.00736	93.6820	0.17076	15.4297
702	5.7608	5.6355	0.00339	97.8247	0.05879	20.6196
703	5.9926	5.6651	0.00885	94.5351	0.14770	21.4492
704	6.2289	5.9914	0.00642	96.1875	0.10304	22.2950
705	5.4219	4.8202	0.01626	88.9025	0.29993	19.4066
706	6.8756	6.9359	-0.00163	100.8762	-0.02368	24.6098
707	7.7322	7.6072	0.00338	98.3840	0.04368	27.6757
708	8.5062	8.0985	0.01102	95.2073	0.12953	30.4460
709	9.7349	8.3893	0.03637	86.1771	0.37359	34.8441
710	10.1821	8.5322	0.04459	83.7961	0.43794	36.4445
711	11.7986	11.2370	0.01518	95.2396	0.12866	42.2306
712	13.4658	12.6295	0.02260	93.7897	0.16785	48.1977
713	15.2999	14.3707	0.02511	93.9268	0.16414	54.7625
714	15.7360	14.9023	0.02253	94.7017	0.14320	56.3237
803	7.5470	13.4069	-0.15838	177.6455	-2.09853	27.0128
804	5.7279	7.1902	-0.03952	125.5292	-0.68998	20.5019
805	4.6767	4.4695	0.00560	95.5685	0.11977	16.7393
806	6.9396	7.0771	-0.00372	101.9817	-0.05356	24.8388
807	8.3225	8.2999	0.00061	99.7289	0.00733	29.7885
808	9.2045	7.9322	0.03439	86.1772	0.37359	32.9456
809	10.5260	8.7578	0.04779	83.2014	0.45402	37.6756
810	11.2268	9.9093	0.03561	88.2640	0.31719	40.1841
811	12.7038	11.4742	0.03323	90.3204	0.26161	45.4706
812	14.0042	12.6098	0.03769	90.0430	0.26911	50.1252
813	14.6059	12.5417	0.05579	85.8673	0.38196	52.2786
814	16.6681	16.0849	0.01576	96.5015	0.09455	59.6598
907	8.3701	8.8786	-0.01374	106.0748	-0.16418	29.9591
908	8.1903	8.7902	-0.01621	107.3249	-0.19797	29.3153
909	8.8451	8.4264	0.01131	95.2668	0.12792	31.6590
910	11.2295	10.6619	0.01534	94.9461	0.13659	40.1934
911	13.3196	13.0446	0.00743	97.9354	0.05580	47.6746
912	13.2670	11.3829	0.05092	85.7987	0.38382	47.4863
1008	7.8125	8.2824	-0.01270	106.0153	-0.16258	27.9630
1009	9.0526	9.1056	-0.00143	100.5852	-0.01582	32.4018
1010	11.2105	10.6553	0.01501	95.0472	0.13386	40.1257

Table 3.5 Continued

Quad	Mean (inches)	Intercept (inches)	Slope (inch/year)	Intercept % Mean	Slope % Mean	Mean % Mean
1011	12.8545	12.4392	0.01122	96.7692	0.08732	46.0100
1108	6.9449	5.8622	0.02926	84.4093	0.42137	24.8579
1109	8.7141	8.2563	0.01237	94.7469	0.14198	31.1903
1110	9.9581	9.6328	0.00879	96.7330	0.08830	35.6428
1210	10.6158	10.3097	0.00827	97.1174	0.07791	37.9968
Average	9.3238	9.0955	0.00617	98.2381	0.04762	33.3726
Total	7.6912	7.2782	0.01116	94.6305	0.14512	27.5288

3.3 Analyses of Evaporation Data

Similar to precipitation, evaporation also varies by geography. It changes from less than 50 inches per year in east Texas to more than 75 inches per year in the Trans-Pecos region when using the precipitation and evaporation datasets for the years 1940-2012 prepared by the Texas Water Development Board (TWDB) as input data. There are two methods used by TWDB to calculate evaporation rate. Evaporation rates prior to 1954 were only run by an older program named WD0300. Since WD0300 used pan evaporation data from non-standard pans, this method allowed for a much larger dataset than the data calculated by ThEvap from 1954. Since 1954, evaporation data has been recalculated by ThEvap, which is based on a geographic information system and developed by using ARC Macro Language (AML) in 1998. The WD0300 only computes pan evaporation for an area of the Thiessen polygon. Different with WD0300, the ThEvap computes the area surrounding a station, and also converts the Thiessen polygon data to quadrangular data by the area-weighted average divided by the intersected

Thiessen polygons. By applying the updated evaporation pan-to-lake coefficients, the ThEvap converts pan evaporation rate to reservoir surface evaporation rate for each quadrangle (Texas Water Development Board, 2012).The linear regression analysis results of monthly evaporation are shown in Table 3.6, and the annual results are in Table 3.7. There is some missing data in the information provided by TWDB. For Example, quadrangles 108, 208, and 701 have no data for 1999-2000, and quadrangle 414 has no data for year 2000. For the missing data occurring in quadrangles 108, 208, 701 and 414, we used the mean monthly evaporation for each month to replace the blank space. Therefore, the input data for the PrecipEvap is integrated, which will elimate computed mistakes. In order to compute accurate mean and trend slopes, trend analysis for evaporation rates data is only from 1954 to 2012. As a result, there is also no significant trend shown from the historical data.

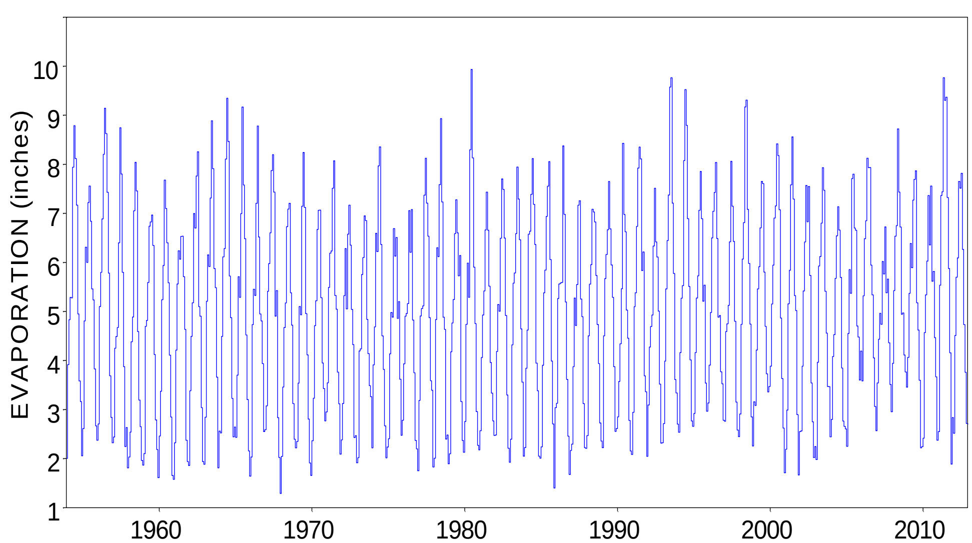


Figure 3.4 1954-2012 Monthly Reservoir Evaporation for the 92 Quadrangles

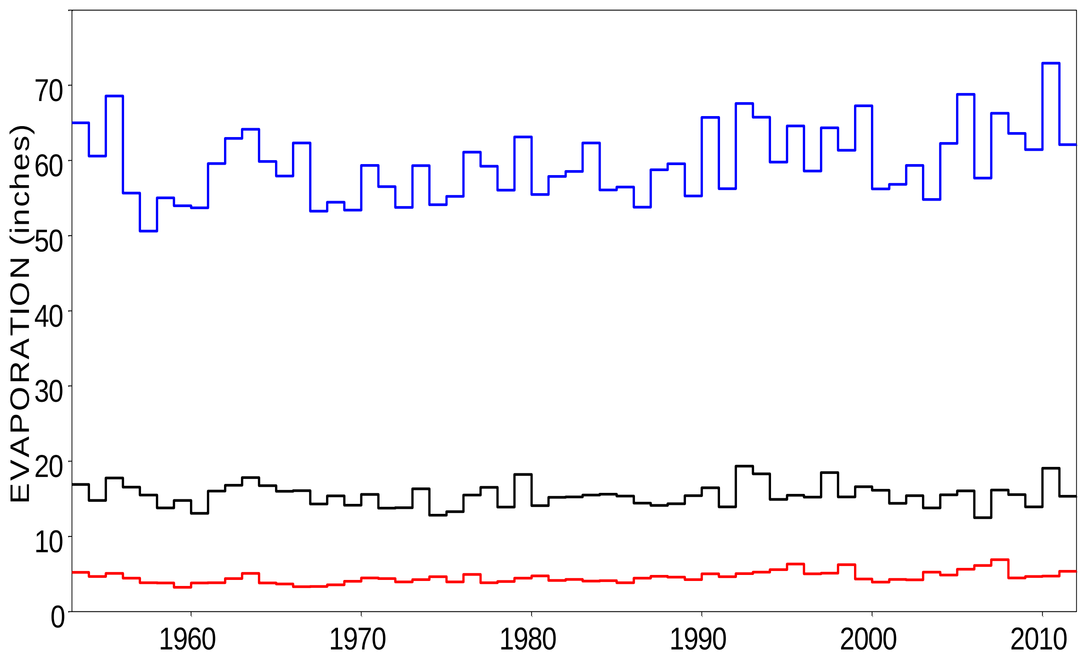


Figure 3.5 1954-2012 Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for the 92 Quadrangles

Unlike trend analysis, the plots begin with either 1940 or 1954 depending on when the evaporation data been recorded. Besides that, 0 is used to show missing data in quadrangles 108, 208, 701 and 414. Therefore, these plots reflect the evaporation rates fluctuations from year to year directly. Both seasonal and spatial variation of evaporation rate are distributed in these plots. We find that approximately two-thirds (68.7%) of evaporation occurs during the summer months, April to September, and one-third (31.3%) during the remaining months of the year. In spite of the fact that evaporation rates data prior to 1954 are a little larger due to a different method, there is no long-term trend on annual evaporate rate.

A significant amount of fluctuation is shown in Figure 3.4 for the monthly evaporation of all quadrangles. There are nearly four wave crests in the figure. Usually, June or July witness the most maximum evaporation recorded during a year, which may be up to nearly 3-4 times as much as the minimum evaporation that occurred in November or December. Evaporation can be influenced by many factors. The first reason is that the high temperature in the summer months make the water molecules move faster, therefore increasing evaporation rates. The maximum monthly evaporation value is 9.3 inches per month in June 1998, and the minimum monthly evaporation value is 1.2869 inches per month in December 1967. The highest annual evaporation data (63.16 inches) was recorded in 1999. The lowest annual evaporation data (35.28 inches) was recorded in 1955.

Figure 3.5 shows annual total evaporation (blue line), 2-month maximum evaporation (black line), and 2-month minimum evaporation (red line) for all of the quadrangles. Compared with the annual total, the 2-month maximum and the 2-month minimum evaporation for all of the quadrangles indicates less fluctuation. In conclusion, the long-term overall evaporation trends are minimal.

Table 3.6
Linear Regression Analysis of 1954-2012 Monthly Evaporation

Quad	Mean (inches)	Intercept (inches)	Slope (inch/month)	Intercept % Mean	Slope % Mean	Mean % Mean
104	4.9680	4.6043	0.0010	92.6789	0.0207	8.3340
105	5.6136	4.9483	0.0019	88.1485	0.0334	9.4171
106	5.6266	5.0199	0.0017	89.2159	0.0304	9.4389
107	5.3557	4.8579	0.0014	90.7039	0.0262	8.9845
108	4.9557	4.4115	0.0015	89.0195	0.0310	8.3134
204	5.2493	4.6038	0.0018	87.7037	0.0347	8.8059
205	5.5510	4.6387	0.0026	83.5652	0.0464	9.3120
206	5.5485	4.7477	0.0023	85.5674	0.0407	9.3078
207	5.3081	4.7404	0.0016	89.3058	0.0302	8.9045
208	4.9202	4.3900	0.0015	89.2255	0.0304	8.2537
304	5.2167	4.7658	0.0013	91.3565	0.0244	8.7512
305	5.3532	4.5546	0.0023	85.0807	0.0421	8.9802
306	5.5322	4.5847	0.0027	82.8720	0.0483	9.2805
307	5.5211	5.0377	0.0014	91.2453	0.0247	9.2618
308	5.3990	5.0842	0.0009	94.1697	0.0165	9.0570
309	4.9437	4.4377	0.0014	89.7645	0.0289	8.2933
404	5.3133	4.7733	0.0015	89.8362	0.0287	8.9132
405	5.4970	4.6696	0.0023	84.9479	0.0425	9.2215
406	5.6761	4.7142	0.0027	83.0549	0.0478	9.5218
407	5.8110	4.9627	0.0024	85.4014	0.0412	9.7481
408	5.3824	4.8439	0.0015	89.9955	0.0282	9.0291
409	5.0535	4.4020	0.0018	87.1075	0.0364	8.4775
410	4.6189	3.9450	0.0019	85.4095	0.0412	7.7484
411	4.5042	4.3810	0.0003	97.2661	0.0077	7.5559
412	4.4509	4.3124	0.0004	96.8886	0.0088	7.4665
413	3.6559	3.6995	-0.0001	101.1931	-0.0034	6.1329
414	3.2641	3.0558	0.0006	93.6167	0.0180	5.4757
504	5.6400	5.3983	0.0007	95.7147	0.0121	9.4613
505	5.9807	5.4423	0.0015	90.9987	0.0254	10.0328
506	5.8518	5.2573	0.0017	89.8422	0.0287	9.8165
507	5.3737	5.0735	0.0008	94.4150	0.0158	9.0145
508	5.2564	5.2559	0.0000	99.9899	0.0000	8.8178
509	4.9523	4.9473	0.0000	99.8990	0.0003	8.3077
510	4.8331	4.9795	-0.0004	103.0298	-0.0086	8.1077
511	4.7801	4.7724	0.0000	99.8379	0.0005	8.0188
512	4.6118	4.3444	0.0008	94.2018	0.0164	7.7365
513	4.1234	3.9010	0.0006	94.6073	0.0152	6.9171
514	3.8114	3.5666	0.0007	93.5770	0.0181	6.3937
601	5.8650	6.0145	-0.0004	102.5491	-0.0072	9.8387
602	5.9653	5.8223	0.0004	97.6028	0.0068	10.0070
603	5.4073	5.4386	-0.0001	100.5785	-0.0016	9.0710
604	5.6673	5.7194	-0.0001	100.9189	-0.0026	9.5072

Table 3.6 Continued

Quad	Mean (inches)	Intercept (inches)	Slope (inch/month)	Intercept % Mean	Slope % Mean	Mean % Mean
606	5.7979	5.5887	0.0006	96.3923	0.0102	9.7262
607	5.5028	5.7010	-0.0006	103.6010	-0.0102	9.2311
608	5.4457	5.3465	0.0003	98.1787	0.0051	9.1354
609	4.7743	4.7848	0.0000	100.2205	-0.0006	8.0091
610	4.7195	4.5659	0.0004	96.7448	0.0092	7.9171
611	4.9362	4.6200	0.0009	93.5958	0.0181	8.2806
612	4.4243	3.9917	0.0012	90.2227	0.0276	7.4218
613	3.8801	3.6302	0.0007	93.5608	0.0182	6.5090
614	4.1128	3.6235	0.0014	88.1030	0.0336	6.8994
701	5.9723	5.8735	0.0003	98.3452	0.0047	10.0188
702	5.2426	5.6365	-0.0011	107.5118	-0.0212	8.7947
703	4.5814	5.1401	-0.0016	112.1956	-0.0344	7.6854
704	4.8250	5.2961	-0.0013	109.7651	-0.0276	8.0941
705	5.3621	5.1730	0.0005	96.4731	0.0100	8.9952
706	5.3672	5.0369	0.0009	93.8453	0.0174	9.0038
707	5.1742	5.3946	-0.0006	104.2596	-0.0120	8.6799
708	4.8481	4.6099	0.0007	95.0877	0.0139	8.1328
709	4.5746	4.2630	0.0009	93.1889	0.0192	7.6740
710	4.4276	4.4077	0.0001	99.5495	0.0013	7.4275
711	4.4284	4.2252	0.0006	95.4115	0.0129	7.4288
712	4.1810	3.7220	0.0013	89.0213	0.0310	7.0138
713	3.7321	3.5040	0.0006	93.8860	0.0173	6.2608
714	3.8861	3.5591	0.0009	91.5853	0.0237	6.5191
803	4.6395	5.2150	-0.0016	112.4028	-0.0350	7.7830
804	4.5977	5.0634	-0.0013	110.1288	-0.0286	7.7129
805	5.4149	5.0423	0.0011	93.1183	0.0194	9.0837
806	5.6918	5.2509	0.0012	92.2522	0.0219	9.5483
807	5.5080	5.3315	0.0005	96.7966	0.0090	9.2398
808	4.8445	4.6064	0.0007	95.0851	0.0139	8.1269
809	4.5117	4.4196	0.0003	97.9587	0.0058	7.5685
810	4.4105	4.5489	-0.0004	103.1385	-0.0089	7.3988
811	4.1655	3.9621	0.0006	95.1179	0.0138	6.9877
812	3.9012	3.4743	0.0012	89.0567	0.0309	6.5444
813	3.8353	3.4326	0.0011	89.5015	0.0296	6.4339
814	3.8048	3.4404	0.0010	90.4228	0.0270	6.3827
907	5.4952	5.0591	0.0012	92.0644	0.0224	9.2184
908	4.9590	4.6504	0.0009	93.7767	0.0176	8.3189
909	4.7145	4.4963	0.0006	95.3718	0.0131	7.9088
910	4.4404	4.4589	-0.0001	100.4184	-0.0012	7.4489
911	4.2302	4.0520	0.0005	95.7879	0.0119	7.0962
912	4.0867	3.5469	0.0015	86.7921	0.0373	6.8556
1008	5.5354	5.3375	0.0006	96.4248	0.0101	9.2858
1009	5.3200	5.7177	-0.0011	107.4751	-0.0211	8.9245
1010	4.9786	4.9949	0.0000	100.3282	-0.0009	8.3518

Table 3.6 Continued

Quad	Mean (inches)	Intercept (inches)	Slope (inch/month)	Intercept % Mean	Slope % Mean	Mean % Mean
1011	4.5690	4.4119	0.0004	96.5615	0.0097	7.6647
1108	5.4970	5.9059	-0.0012	107.4369	-0.0210	9.2215
1109	5.2506	5.5326	-0.0008	105.3711	-0.0152	8.8080
1110	5.1945	4.9090	0.0008	94.5046	0.0155	8.7139
1210	5.1179	4.7885	0.0009	93.5642	0.0182	8.5854
Average	4.9707	4.7185	0.0007	94.9788	0.0142	8.3385
Total	4.9676	4.7201	0.0007	95.0169	0.0141	8.3333

Table 3.6 and Table 3.7 show that the regression analysis results of monthly and annual evaporation. The intercept as percentages of mean listed in the fifth column which calculated by the regression intercept in each quadrangle divided by the mean evaporation in each quadrangle.

Table 3.7
Linear Regression Analysis of 1954-2012 Annual Evaporation

Quad	Mean (inches)	Intercept (inches)	Slope (inch/year)	Intercept % Mean	Slope % Mean	Mean % Mean
104	59.6159	55.2298	0.1462	92.6427	0.2452	100.0079
105	67.3637	59.3770	0.2662	88.1439	0.3952	113.0051
106	67.5197	60.2488	0.2424	89.2315	0.3590	113.2667
107	64.2690	58.3202	0.1983	90.7439	0.3085	107.8136
108	59.4683	52.9492	0.2173	89.0377	0.3654	99.7603
204	62.9915	55.1757	0.2605	87.5923	0.4136	105.6706
205	66.6117	55.5902	0.3674	83.4542	0.5515	111.7436
206	66.5817	56.9291	0.3218	85.5026	0.4833	111.6932
207	63.6971	56.8913	0.2269	89.3153	0.3562	106.8542
208	59.0419	52.6908	0.2117	89.2431	0.3586	99.0449
304	62.6005	57.1267	0.1825	91.2560	0.2915	105.0146
305	64.2388	54.5628	0.3225	84.9374	0.5021	107.7630
306	66.3866	54.9235	0.3821	82.7328	0.5756	111.3660
307	66.2529	60.4838	0.1923	91.2923	0.2903	111.1416
308	64.7880	61.0836	0.1235	94.2823	0.1906	108.6842
309	59.3246	53.2687	0.2019	89.7920	0.3403	99.5191
404	63.7595	57.1800	0.2193	89.6807	0.3440	106.9589
405	65.9644	55.9057	0.3353	84.7513	0.5083	110.6577
406	68.1127	56.4490	0.3888	82.8758	0.5708	114.2616
407	69.7317	59.5023	0.3410	85.3304	0.4890	116.9775
408	64.5883	58.1481	0.2147	90.0288	0.3324	108.3492
409	60.6422	52.8254	0.2606	87.1099	0.4297	101.7295
410	55.4268	47.3274	0.2700	85.3873	0.4871	92.9804
411	54.0498	52.6530	0.0466	97.4157	0.0861	90.6706
412	53.4105	51.8380	0.0524	97.0558	0.0981	89.5981
413	43.8708	44.4743	-0.0201	101.3756	-0.0459	73.5950
414	39.1695	36.6680	0.0834	93.6137	0.2129	65.7082
504	67.6802	64.7320	0.0983	95.6439	0.1452	113.5360
505	71.7681	65.2486	0.2173	90.9158	0.3028	120.3937
506	70.2210	63.0233	0.2399	89.7500	0.3417	117.7983
507	64.4839	60.8937	0.1197	94.4323	0.1856	108.1741
508	63.0771	63.1607	-0.0028	100.1325	-0.0044	105.8142
509	59.4278	59.4694	-0.0014	100.0701	-0.0023	99.6923
510	57.9971	59.9086	-0.0637	103.2957	-0.1099	97.2923
511	57.3615	57.3934	-0.0011	100.0556	-0.0019	96.2261
512	55.3419	52.2035	0.1046	94.3291	0.1890	92.8380
513	49.4803	46.8507	0.0877	94.6854	0.1772	83.0051
514	45.7366	42.8024	0.0978	93.5846	0.2139	76.7248
601	70.3798	72.1501	-0.0590	102.5152	-0.0838	118.0648
602	71.5834	69.7822	0.0600	97.4838	0.0839	120.0837
603	64.8878	65.2347	-0.0116	100.5346	-0.0178	108.8516
604	68.0080	68.6201	-0.0204	100.9001	-0.0300	114.0858

Table 3.7 Continued

Quad	Mean (inches)	Intercept (inches)	Slope (inch/year)	Intercept % Mean	Slope % Mean	Mean % Mean
605	71.7607	67.6643	0.1365	94.2917	0.1903	120.3811
606	69.5746	67.0619	0.0838	96.3886	0.1204	116.7139
607	66.0336	68.4888	-0.0818	103.7182	-0.1239	110.7737
608	65.3488	64.2152	0.0378	98.2652	0.0578	109.6250
609	57.2917	57.5191	-0.0076	100.3969	-0.0132	96.1089
610	56.6339	54.8893	0.0582	96.9195	0.1027	95.0054
611	59.2339	55.5007	0.1244	93.6974	0.2101	99.3670
612	53.0910	47.9018	0.1730	90.2258	0.3258	89.0621
613	46.5608	43.5701	0.0997	93.5767	0.2141	78.1075
614	49.3537	43.4447	0.1970	88.0272	0.3991	82.7927
701	71.6680	70.4034	0.0422	98.2354	0.0588	120.2256
702	62.9119	67.6502	-0.1579	107.5317	-0.2511	105.5369
703	54.9764	61.7320	-0.2252	112.2882	-0.4096	92.2250
704	57.8997	63.6016	-0.1901	109.8480	-0.3283	97.1288
705	64.3456	62.0478	0.0766	96.4289	0.1190	107.9421
706	64.4070	60.4376	0.1323	93.8370	0.2054	108.0450
707	62.0905	64.8270	-0.0912	104.4072	-0.1469	104.1591
708	58.1770	55.3426	0.0945	95.1280	0.1624	97.5940
709	54.8949	51.2012	0.1231	93.2713	0.2243	92.0882
710	53.1315	52.9926	0.0046	99.7385	0.0087	89.1301
711	53.1407	50.7676	0.0791	95.5343	0.1489	89.1454
712	50.1724	44.6512	0.1840	88.9955	0.3668	84.1660
713	44.7858	42.0591	0.0909	93.9118	0.2029	75.1297
714	46.6331	42.7043	0.1310	91.5752	0.2808	78.2287
803	55.6746	62.6339	-0.2320	112.5000	-0.4167	93.3961
804	55.1729	60.8218	-0.1883	110.2386	-0.3413	92.5545
805	64.9788	60.4911	0.1496	93.0936	0.2302	109.0043
806	68.3022	63.0098	0.1764	92.2516	0.2583	114.5794
807	66.0954	64.0234	0.0691	96.8650	0.1045	110.8775
808	58.1342	55.3017	0.0944	95.1276	0.1624	97.5223
809	54.1398	53.1067	0.0344	98.0918	0.0636	90.8215
810	52.9259	54.7073	-0.0594	103.3657	-0.1122	88.7852
811	49.9856	47.5924	0.0798	95.2122	0.1596	83.8526
812	46.8146	41.6732	0.1714	89.0176	0.3661	78.5332
813	46.0236	41.1781	0.1615	89.4718	0.3509	77.2062
814	45.6580	41.2779	0.1460	90.4068	0.3198	76.5929
907	65.9424	60.7099	0.1744	92.0651	0.2645	110.6207
908	59.5081	55.8264	0.1227	93.8130	0.2062	99.8271
909	56.5746	53.9984	0.0859	95.4465	0.1518	94.9059
910	53.2842	53.6008	-0.0106	100.5942	-0.0198	89.3862
911	50.7619	48.6876	0.0691	95.9138	0.1362	85.1549
912	49.0405	42.5450	0.2165	86.7548	0.4415	82.2672
1008	66.4244	64.0711	0.0784	96.4571	0.1181	111.4294
1009	63.8403	68.7631	-0.1641	107.7110	-0.2570	107.0945

Table 3.7 Continued

Quad	Mean (inches)	Intercept (inches)	Slope (inch/year)	Intercept % Mean	Slope % Mean	Mean % Mean
1010	59.7432	60.0370	-0.0098	100.4917	-0.0164	100.2214
1011	54.8281	53.0178	0.0603	96.6982	0.1101	91.9762
1108	65.9646	70.9804	-0.1672	107.6038	-0.2535	110.6580
1109	63.0069	66.4935	-0.1162	105.5336	-0.1845	105.6964
1110	62.3339	58.9185	0.1138	94.5207	0.1826	104.5674
1210	61.4142	57.4633	0.1317	93.5667	0.2144	103.0246
Average	59.6478	56.6402	0.1003	95.0131	0.1662	100.0615
Total	59.611	56.659	0.098	95.048	0.165	100.000

According to Table 3.6 and Table 3.7, the slope as percentages of mean listed in the sixth column which calculated by the slope in each quadrangle divided by the mean evaporation in each quadrangle. The mean as percentages of mean listed in the last column which calculated by the mean in each quadrangle divided by the annual mean evaporation of total quadrangles. Mean annual evaporation for the total of the 92 quadrangles is 59.61 inches. The overall linear regression trend slope is 0.0984. The total slope is 0.165% for mean annual evaporation. Although slopes vary geographically and seasonally, each quadrangles' long-trend trend slopes are approximately equal 0, which means none of the evaporation rates are changing observably. The simulated regression intercept and slope as percentages of mean annual evaporation for each of the 92 quadrangles from the Program PrecipEvap is reported together in Table 3.8.

According to Table 3.7, the highest regression trend slope is 0.3888 in the 406 quadrangle, and the lowest trend slope is -0.232 in the 803 quadrangle. The quadrangles in the southwest indicate a little more change as shown in Table 3.8. The possible reason for this phenomena is the climate may be influenced by hurricanes from the Gulf of Mexico. Most quadrangles in the eastern part of Texas have less than 100% of statewide mean annual evaporation, while in the western part of Texas this number is higher than 100%. The highest mean annual evaporation is 120.38% of the statewide mean in the 505 quadrangle, and the lowest is 65.708% of the statewide mean in the 414 quadrangle. The trend regression slopes vary from -0.25703% for mean annual evaporation in the quadrangle 1009 to 0.57557% in the quadrangle 306. As a result, no trend variation in the future has been found by data of monthly or annual evaporation from years 1954 to 2012.

According to Table 3.3, the intercept as percentages of mean, listed in the first row of each quadrangle, which calculated by the regression intercept in each quadrangle divided by the mean evaporation in each quadrangle. The slope as percentages of mean, listed in the second row, which calculated by the slope in each quadrangle divided by the evaporation.

Table 3.8
Regression Intercept and Slope as Percentages of Mean Annual Evaporation (from Table 3.7)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
100				0.245 92.64	0.3952 88.14	0.3590 89.23	0.3085 90.74	0.3654 89.04						
200				0.4135 87.59	0.5515 83.45	0.4832 85.50	0.3562 89.32	0.3586 89.24						
300				0.2914 91.26	0.5021 84.94	0.5756 82.73	0.2902 91.29	0.1905 94.28	0.3402 89.79					
400				0.3439 89.68	0.5082 84.75	0.5708 82.88	0.4889 85.33	0.3324 90.03	0.4296 87.11	0.4871 85.39	0.0861 97.42	0.0981 97.06	-0.045 101.38	0.2128 93.61
500				0.1452 95.63	0.3028 90.92	0.3416 89.75	108.17 0.1856	-0.004 100.10	-0.002 100.07	-0.109 103.3	-0.002 100.1	0.1890 94.32	0.1772 94.68	0.2138 93.58
600	-0.0838 102.5	0.0838 97.48	-0.0178 100.5	-0.300 100.9	0.1902 94.29	0.1203 96.39	-0.124 103.7	0.0578 98.26	-0.013 100.4	0.1026 96.92	0.2101 93.69	0.3258 90.23	0.2141 93.58	0.3990 88.03
700	0.0588 98.23	-0.251 107.5	-0.409 112.3	-0.328 109.8	0.119 96.42	0.2054 93.83	-0.147 104.4	0.1624 95.13	0.2243 93.27	0.0087 99.73	0.1488 95.54	0.3668 88.99	0.2029 93.91	0.2808 91.57
800			-0.416 112.5	-0.342 110.2	0.2302 93.09	0.2582 92.25	0.1045 96.86	0.1624 95.12	0.0636 98.09	-0.112 103.4	0.1596 95.21	0.3660 89.02	0.3509 89.47	0.3197 90.41
900							0.2645 92.07	0.2062 93.81	0.1518 95.45	-0.019 100.6	0.1362 95.91	0.4415 86.75		
1000								0.1181 96.46	-0.257 107.7	-0.016 100.5	0.1100 96.69			
1100								-0.253 107.6	-0.184 105.5	0.1826 94.52				
1200										0.2144 93.56				
	1	2	3	4	5	6	7	8	9	10	11	12	13	14

The linear regression analysis for annual 2-month minimum and 2-month maximum evaporation are computed also by The PrecipEvap Program. The results are reflected in Table 3.9 and Table 3.10 respectively. The intercept as percentages of mean listed in the fifth column which calculated by the regression intercept of 2-month minimum or 2-month maximum evaporation in each quadrangle divided by the mean evaporation in each quadrangle. The slope as percentages of mean listed in the sixth column which calculated by the slope of 2-month minimum or 2-month maximum evaporation in each quadrangle divided by the mean evaporation in each quadrangle. The mean as percentages of mean listed in the last column which calculated by the mean of 2-month minimum or 2-month maximum evaporation in each quadrangle divided by the annual mean evaporation of total quadrangles. The linear regression analysis for the 92 quadrangles as a whole indicated total intercept and slope of the annual 2-month minimum evaporation are 3.846 and 0.023 which is a little higher than the 2-month minimum precipitation value. For the annual 2-month maximum evaporation in Texas the intercept and slope are 15.4065 and 0.0026, reflecting no significant long-term trend.

Table 3.9
Linear Regression Analysis of Annual 2-Month Minimum Evaporation

Quad	Mean (inches)	Intercept (inches)	Slope (inch/year)	Intercept % Mean	Slope % Mean	Mean % Mean
104	4.1347	2.5762	0.0520	62.3053	1.2565	6.9362
105	4.0014	2.6461	0.0452	66.1304	1.1290	6.7124
106	3.9068	2.6912	0.0405	68.8865	1.0371	6.5538
107	3.9198	2.5612	0.0453	65.3396	1.1554	6.5757
108	4.0361	2.5041	0.0511	62.0430	1.2652	6.7707
204	4.3078	2.9745	0.0444	69.0502	1.0317	7.2265
205	4.1634	2.5942	0.0523	62.3104	1.2563	6.9842
206	4.0242	2.6048	0.0473	64.7288	1.1757	6.7508
207	3.9253	2.7677	0.0386	70.5098	0.9830	6.5848
208	4.2366	2.7604	0.0492	65.1551	1.1615	7.1071
304	4.5010	3.4742	0.0342	77.1865	0.7605	7.5506
305	4.4051	3.0684	0.0446	69.6569	1.0114	7.3897
306	4.2298	2.8184	0.0470	66.6309	1.1123	7.0957
307	4.3841	3.3117	0.0357	75.5401	0.8153	7.3544
308	4.3819	3.0438	0.0446	69.4625	1.0179	7.3507
309	4.0336	2.5659	0.0489	63.6132	1.2129	6.7664
404	4.5005	3.4820	0.0340	77.3682	0.7544	7.5498
405	4.7105	3.6466	0.0355	77.4138	0.7529	7.9020
406	4.7217	3.7154	0.0335	78.6887	0.7104	7.9208
407	4.7288	3.9315	0.0266	83.1386	0.5621	7.9328
408	4.5297	3.5752	0.0318	78.9280	0.7024	7.5987
409	4.0714	3.1693	0.0301	77.8439	0.7385	6.8298
410	3.9229	2.8752	0.0349	73.2939	0.8902	6.5808
411	3.8824	3.0145	0.0289	77.6470	0.7451	6.5128
412	3.9778	3.1934	0.0261	80.2796	0.6574	6.6729
413	3.1861	3.0072	0.0060	94.3863	0.1871	5.3448
414	2.8853	2.6306	0.0085	91.1727	0.2942	4.8401
504	4.6059	4.1532	0.0151	90.1706	0.3277	7.7266
505	5.0976	4.1626	0.0312	81.6572	0.6114	8.5515
506	4.9905	4.1482	0.0281	83.1223	0.5626	8.3718
507	4.4942	3.9799	0.0171	88.5562	0.3815	7.5392
508	4.4754	4.1689	0.0102	93.1514	0.2283	7.5077
509	4.4025	4.0725	0.0110	92.5040	0.2499	7.3854
510	4.0151	3.8282	0.0062	95.3453	0.1552	6.7355
511	4.0963	3.5334	0.0188	86.2595	0.4580	6.8716
512	4.1041	3.3640	0.0247	81.9676	0.6011	6.8847
513	3.6105	3.1235	0.0162	86.5106	0.4496	6.0568
514	3.3300	3.1413	0.0063	94.3345	0.1889	5.5862
601	4.9164	5.0678	-0.0050	103.0777	-0.1026	8.2475
602	5.0064	4.9224	0.0028	98.3211	0.0560	8.3985
603	4.6661	4.3092	0.0119	92.3509	0.2550	7.8276
604	4.9076	4.3302	0.0192	88.2343	0.3922	8.2327

Table 3.9 Continued

Quad	Mean (inches)	Intercept (inches)	Slope (inch/year)	Intercept % Mean	Slope % Mean	Mean % Mean
605	5.2336	4.3014	0.0311	82.1889	0.5937	8.7795
606	5.1520	4.2595	0.0298	82.6761	0.5775	8.6427
607	4.6598	4.3799	0.0093	93.9917	0.2003	7.8170
608	4.6634	4.2298	0.0145	90.7019	0.3099	7.8230
609	4.2573	3.9152	0.0114	91.9645	0.2679	7.1418
610	4.0093	3.3352	0.0225	83.1850	0.5605	6.7258
611	4.5295	3.3304	0.0400	73.5263	0.8825	7.5984
612	4.2975	3.0438	0.0418	70.8284	0.9724	7.2091
613	3.6222	3.1518	0.0157	87.0132	0.4329	6.0764
614	3.9392	3.0709	0.0289	77.9572	0.7348	6.6081
701	4.9881	5.1424	-0.0051	103.0926	-0.1031	8.3678
702	4.8381	4.9737	-0.0045	102.8010	-0.0934	8.1161
703	4.5831	4.5473	0.0012	99.2199	0.0260	7.6882
704	4.8153	4.5539	0.0087	94.5723	0.1809	8.0778
705	5.0853	4.2561	0.0276	83.6944	0.5435	8.5307
706	4.8271	4.0906	0.0246	84.7424	0.5086	8.0977
707	4.5432	4.4004	0.0048	96.8566	0.1048	7.6214
708	4.4556	3.9656	0.0163	89.0023	0.3666	7.4744
709	4.1253	3.6653	0.0153	88.8505	0.3717	6.9203
710	4.0542	3.8085	0.0082	93.9388	0.2020	6.8011
711	4.1159	3.7609	0.0118	91.3749	0.2875	6.9046
712	4.1712	3.2476	0.0308	77.8581	0.7381	6.9973
713	3.5044	3.0079	0.0166	85.8311	0.4723	5.8788
714	3.6592	2.9677	0.0230	81.1029	0.6299	6.1384
803	4.6581	4.6688	-0.0004	100.2292	-0.0076	7.8142
804	4.5888	4.4387	0.0050	96.7289	0.1090	7.6979
805	4.7664	4.1560	0.0203	87.1939	0.4269	7.9959
806	4.7753	4.1178	0.0219	86.2321	0.4589	8.0107
807	4.7249	4.1361	0.0196	87.5378	0.4154	7.9262
808	4.3931	3.7870	0.0202	86.2040	0.4599	7.3695
809	4.1627	3.8021	0.0120	91.3366	0.2888	6.9831
810	4.2810	4.1577	0.0041	97.1187	0.0960	7.1816
811	4.0334	3.8828	0.0050	96.2659	0.1245	6.7662
812	3.9503	3.5921	0.0119	90.9317	0.3023	6.6268
813	3.9049	3.5811	0.0108	91.7085	0.2764	6.5506
814	3.6673	3.1637	0.0168	86.2692	0.4577	6.1520
907	4.6829	3.7646	0.0306	80.3898	0.6537	7.8557
908	4.2269	3.6529	0.0191	86.4201	0.4527	7.0909
909	4.0698	3.6785	0.0130	90.3845	0.3205	6.8273
910	4.2542	3.8815	0.0124	91.2394	0.2920	7.1366
911	4.0564	3.8024	0.0085	93.7381	0.2087	6.8048
912	4.0393	3.7839	0.0085	93.6764	0.2108	6.7761
1008	4.7008	4.4162	0.0095	93.9457	0.2018	7.8858
1009	4.9427	5.0207	-0.0026	101.5786	-0.0526	8.2916

Table 3.9 Continued

Quad	Mean (inches)	Intercept (inches)	Slope (inch/year)	Intercept % Mean	Slope % Mean	Mean % Mean
1010	4.8946	4.66400	0.0077	95.28940	0.1570	8.2108
1011	4.4712	3.92750	0.0181	87.83990	0.4053	7.5006
1108	4.7322	4.90870	-0.0059	103.72890	-0.1243	7.9384
1109	4.9837	5.01430	-0.0010	100.61330	-0.0204	8.3604
1110	5.2083	4.83030	0.0126	92.74160	0.2420	8.7371
1210	5.1397	4.71120	0.0143	91.66420	0.2779	8.622
Average	4.3572	3.72230	0.0212	85.13310	0.4956	7.3094
Total	4.5355	3.84590	0.0230	84.79370	0.5069	7.6085

The linear regression intercept and slope are 84.79% and 0.507% for mean annual 2-month minimum evaporation. While the total linear regression intercept and slope are 99.5% and 0.017% for mean annual 2-month maximum evaporation. However, neither annual 2-month maximum, nor 2-month minimum evaporation, have provided noticeable trends between two months in the future.

Evaporation Plots by monthly and annual means and annual minima and maxima during the 1940-2012 for the each 92 quadrangles can be found in Appendix B

Table 3.10
Linear Regression Analysis of Annual 2-Month Maximum Evaporation

Quad	Mean (inches)	Intercept (inches)	Slope (inch/year)	Intercept % Mean	Slope % Mean	Mean % Mean
104	15.1931	15.2292	-0.0012	100.2376	-0.0079	25.4869
105	18.9671	17.7659	0.0400	93.6667	0.2111	31.8180
106	19.3614	18.4577	0.0301	95.3326	0.1556	32.4794
107	18.2634	17.8014	0.0154	97.4706	0.0843	30.6375
108	16.6597	15.9581	0.0234	95.7888	0.1404	27.9472
204	16.3510	14.9271	0.0475	91.2913	0.2903	27.4294
205	18.0458	15.4602	0.0862	85.6720	0.4776	30.2724
206	18.2544	15.8531	0.0800	86.8456	0.4385	30.6224
207	17.5014	16.4051	0.0365	93.7359	0.2088	29.3592
208	16.4353	15.5932	0.0281	94.8763	0.1708	27.5707
304	16.3993	15.5260	0.0291	94.6745	0.1775	27.5105
305	16.8471	15.0052	0.0614	89.0670	0.3644	28.2617
306	17.5954	15.1285	0.0822	85.9800	0.4673	29.5170
307	18.1903	17.5925	0.0199	96.7134	0.1096	30.5150
308	18.3200	18.3487	-0.0010	100.1566	-0.0052	30.7325
309	16.5381	15.8126	0.0242	95.6132	0.1462	27.7433
404	16.7003	15.8972	0.0268	95.1907	0.1603	28.0154
405	17.0707	14.8254	0.0748	86.8469	0.4384	28.6367
406	17.9064	15.4488	0.0819	86.2750	0.4575	30.0387
407	18.9353	16.7455	0.0730	88.4355	0.3855	31.7646
408	17.9703	16.8232	0.0382	93.6163	0.2128	30.1459
409	17.0075	15.4550	0.0517	90.8720	0.3043	28.5306
410	15.2864	13.7377	0.0516	89.8683	0.3377	25.6436
411	14.8334	15.4223	-0.0196	103.9703	-0.1323	24.8836
412	14.3653	14.7931	-0.0143	102.9781	-0.0993	24.0982
413	11.9041	12.2583	-0.0118	102.9761	-0.0992	19.9695
414	10.5588	9.8377	0.0240	93.1707	0.2276	17.7128
504	17.9486	17.5589	0.0130	97.8285	0.0724	30.1095
505	18.8400	17.4410	0.0466	92.5742	0.2475	31.6048
506	18.5688	17.1370	0.0477	92.2893	0.2570	31.1499
507	17.1973	16.7539	0.0148	97.4215	0.0860	28.8491
508	16.7995	17.6292	-0.0277	104.9392	-0.1646	28.1818
509	16.2468	16.7565	-0.0170	103.1374	-0.1046	27.2546
510	16.3115	17.3575	-0.0349	106.4125	-0.2138	27.3632
511	15.8247	16.4370	-0.0204	103.8689	-0.1290	26.5466
512	14.8580	14.6625	0.0065	98.6844	0.0439	24.9248
513	13.1675	12.6398	0.0176	95.9929	0.1336	22.0889
514	12.1712	11.4340	0.0246	93.9434	0.2019	20.4176
601	18.6849	19.1761	-0.0164	102.6286	-0.0876	31.3446
602	18.8210	18.4114	0.0137	97.8238	0.0725	31.5729
603	16.8853	17.3029	-0.0139	102.4733	-0.0824	28.3256
604	17.7698	18.2817	-0.0171	102.8808	-0.0960	29.8095

Table 3.10 Continued

Quad	Mean (inches)	Intercept (inches)	Slope (inch/year)	Intercept % Mean	Slope % Mean	Mean % Mean
605	18.6912	18.2064	0.0162	97.4066	0.0865	31.3551
606	18.3471	18.5330	-0.0062	101.0131	-0.0338	30.7780
607	17.8912	19.4650	-0.0525	108.7969	-0.2932	30.0131
608	17.5488	18.1360	-0.0196	103.3459	-0.1115	29.4388
609	15.6441	16.4617	-0.0273	105.2266	-0.1742	26.2435
610	15.8722	16.1661	-0.0098	101.8517	-0.0617	26.6262
611	15.9169	16.2007	-0.0095	101.7827	-0.0594	26.7013
612	13.7675	13.5830	0.0061	98.6604	0.0447	23.0954
613	12.1761	11.5617	0.0205	94.9544	0.1682	20.4259
614	12.5598	11.6850	0.0292	93.0346	0.2322	21.0696
701	19.1008	18.6280	0.0158	97.5245	0.0825	32.0424
702	16.1410	17.5747	-0.0478	108.8821	-0.2961	27.0771
703	13.8103	16.1424	-0.0777	116.8862	-0.5629	23.1674
704	14.6400	17.0180	-0.0793	116.2430	-0.5414	24.5591
705	16.5864	16.7529	-0.0055	101.0033	-0.0334	27.8244
706	17.4434	17.0683	0.0125	97.8495	0.0717	29.2619
707	16.9598	18.3974	-0.0479	108.4766	-0.2826	28.4507
708	15.6654	15.8863	-0.0074	101.4102	-0.0470	26.2793
709	15.0644	14.6895	0.0125	97.5116	0.0830	25.2711
710	14.5485	15.0868	-0.0179	103.6999	-0.1233	24.4056
711	14.2073	13.7948	0.0137	97.0966	0.0968	23.8332
712	12.5124	11.7869	0.0242	94.2023	0.1933	20.9900
713	11.3714	11.3478	0.0008	99.7930	0.0069	19.0759
714	11.8444	11.5046	0.0113	97.1307	0.0956	19.8694
803	14.1071	16.6986	-0.0864	118.3702	-0.6123	23.6652
804	14.1151	16.6307	-0.0839	117.8224	-0.5941	23.6786
805	17.3739	17.0043	0.0123	97.8727	0.0709	29.1453
806	18.9095	18.2637	0.0215	96.5850	0.1138	31.7214
807	18.2207	18.4842	-0.0088	101.4460	-0.0482	30.5659
808	15.7993	15.9874	-0.0063	101.1905	-0.0397	26.5039
809	14.6934	15.0730	-0.0127	102.5834	-0.0861	24.6487
810	13.9080	15.0702	-0.0387	108.3567	-0.2786	23.3311
811	12.7480	12.3475	0.0133	96.8587	0.1047	21.3852
812	11.4636	10.3703	0.0364	90.4635	0.3179	19.2305
813	11.2603	10.5481	0.0237	93.6751	0.2108	18.8896
814	11.4142	11.0021	0.0137	96.3889	0.1204	19.1478
907	18.1983	17.6123	0.0195	96.7796	0.1074	30.5283
908	16.5347	16.2277	0.0102	98.1428	0.0619	27.7376
909	15.5239	15.3504	0.0058	98.8823	0.0373	26.0419
910	14.0378	14.9525	-0.0305	106.5161	-0.2172	23.5489
911	13.2297	12.9089	0.0107	97.5756	0.0808	22.1932
912	12.4780	10.8691	0.0536	87.1066	0.4298	20.9322
1008	18.2475	18.1016	0.0049	99.2004	0.0267	30.6108
1009	16.7780	18.7274	-0.0650	111.6192	-0.3873	28.1456

Table 3.10 Continued

Quad	Mean (inches)	Intercept (inches)	Slope (inch/year)	Intercept % Mean	Slope % Mean	Mean % Mean
1010	15.0934	16.1579	-0.0355	107.0528	-0.2351	25.3197
1011	13.9081	14.5229	-0.0205	104.4205	-0.1474	23.3314
1108	17.7934	19.5704	-0.0592	109.9867	-0.3329	29.8491
1109	16.4029	17.4396	-0.0346	106.3202	-0.2107	27.5164
1110	15.6432	15.0886	0.0185	96.4543	0.1182	26.2421
1210	15.5295	14.8250	0.0235	95.4635	0.1512	26.0513
Average	15.9052	15.7239	0.0060	98.9689	0.0344	26.6815
Total	15.4839	15.4065	0.0026	99.5004	0.0167	25.9747

Table 3.11 indicates the mean annual precipitation and evaporation in major river basins or coastal basins. Utilizing mean annual precipitation and evaporation in each of the 92 quadrangles and multiplying by area for the major basins in each of the 92 quadrangles, equals the mean annual precipitation and evaporation in each of river basin. According to Table 3.11, Texas has 263,186 square mile, the mean annual precipitation and evaporation for Texas are 391,285,647 ac-ft and 850,976,710 ac-ft. In most river and coastal basins, mean annual precipitation is lower than mean annual evaporation. Only Neches-Trinity and Trinity-San Jacinto basins have higher precipitation than evaporation.

Table 3.11
Mean Annual Precipitation and Evaporation

Major River Basin or Coastal Basin	Watershed Area TWDB (sq miles)	Area in Texas TWDB (sq miles)	Rolando Computed Area (sq miles)	Mean Annual Precip (inches)	Mean Annual Precip (ac-ft)	Mean Annual Evap (inches)	Mean Annual Evap (ac-ft)
Canadian	47,705	12,865	12,810	19.490	13,372,409	66.154	45,862,949.34
Red	93,450	24,297	24,179	25.566	33,128,908	63.398	83,008,886.52
Sulphur	3,767	3,580	3,561	46.612	8,899,780	50.099	9,665,139.28
Cypress	3,552	2,929	2,909	47.230	7,377,989	48.943	7,725,265.76
Sabine	9,756	7,570	7,371	47.761	19,282,844	50.932	20,776,978.92
Neches	9,937	9,937	9,898	48.664	25,790,700	48.532	25,988,674.96
Neches-Trinity	769	769	1,624	49.558	2,032,559	45.884	1,901,467.86
Trinity	17,913	17,913	17,797	39.382	37,624,284	55.134	53,221,101.14
Trinity-San Jacinto	247	247	391	48.116	633,847	46.457	618,365.67
San Jacinto	3,936	3,936	3,921	46.635	9,789,535	49.004	10,394,147.17
San Jacinto-Brazos	1,440	1,440	1,729	46.988	3,608,696	46.742	3,627,214.38
Brazos	45,573	42,865	42,670	28.854	65,964,941	60.650	140,097,145.47
Brazos-Colorado	1,850	1,850	1,857	44.044	4,345,702	48.631	4,848,257.75
Colorado	42,318	39,428	39,227	23.549	49,518,698	63.727	135,402,607.85
Colorado-Lavaca	939	939	1,259	40.045	2,005,438	50.619	2,561,395.80
Lavaca	2,309	2,309	2,302	39.720	4,891,348	50.756	6,315,542.73
Lavaca-Guadalupe	998	998	1,280	39.605	2,108,064	50.812	2,732,734.38
Guadalupe	5,953	5,953	5,921	32.652	10,366,746	53.966	17,312,198.60
San Antonio	4,180	4,180	4,163	31.788	7,086,603	54.332	12,238,585.30
San Antonio-Nueces	2,652	2,652	3,013	35.054	4,958,103	53.869	7,698,663.94
Nueces	16,700	16,700	16,625	24.810	22,097,548	59.583	53,621,631.97
Nueces-Rio grande	10,442	10,442	11,405	25.291	14,084,821	62.289	35,050,600.04
Rio Grande	182,215	49,387	49,101	16.065	42,316,084	63.991	170,307,155.20
Total	508,601	263,186	265,013	27.876	391,285,647	60.626	850,976,710.02

3.4 Summary and Conclusions

Associated with global warming the climate change has been considered plays an important role on long-term changes in river system water budgets. In this chapter, climate change has been investigated based on performing trend analyses for monthly and annual means, annual minima and maxima precipitation, and reservoir evaporation rates for each of the 92 one-degree quadrangles encompassing Texas provided by the TWDB datasets during 1940-2012. The programs PrecipEvap and HEC-DSS are used to quantify the long-term changes in precipitation and reservoir surface evaporation. The results demonstrated that precipitation and reservoir evaporation rates vary dramatically, geographically and seasonally, however, the long-term trends in Texas are minimal.

CHAPTER IV

OBSERVED STREAM FLOW

Texas is one of the largest states with 10 climatic regions. Water resources across the state include 3,700 named streams, 20 major aquifers, and 3,450 permitted reservoirs including 196 major reservoirs with controlled storage capacities of 5,000 acre-feet or more (TWDB 2012). This chapter investigates long-term climate change effects based on analysis from observed stream flow data which is derived from TWDB daily observed stream flow datasets.

4.1 River Systems of Texas

River systems are crucial aquatic ecosystems, which play a major role in protecting water quality, preventing erosion, and providing nutrients and habitats for fish and wildlife. There are 3,700 named streams and 15 major rivers that meander through 191,000 miles of Texas landscape. According to the major rivers, Texas has been divided into 15 major river basins and 8 coastal basins. The fifteen major river basins of Texas are illustrated in Figure 4.1, and major rivers and largest cities of Texas are shown in Figure 4.2. Based on the U.S. Geological Survey in 2008, the longest river is the Rio Grande with a total length of 1,900 miles from its headwaters to its mouth on the Gulf of Mexico. This river forms the boundary of Texas and the international U.S.-Mexican border for either 889 or 1,254 river miles, depending upon method of measurement. With a drainage area of about 42,865 square miles, the Brazos River is the second-largest river basin in Texas, after the Rio Grande. It flows directly into the Gulf southwest of Freeport in Brazoria County. The average annual flow for the Brazos River is 6,074,000 acre-feet the largest volume of almost all the rivers in the Texas.

Besides the Rio Grande River, several of the river systems in Texas shown in Figure 4.2 are shared with neighboring states. For example, the Red River is shared with Oklahoma, and the Sabine is shared with Louisiana. For these interstate and international river basins, it is necessary for Texas to analyze hydrology data, assess water availability and develop water resources management collaborate with neighboring states and Mexico. Along the way, water eventually flows into seven major estuaries, five minor estuaries, supports over 212 reservoirs, countless riparian habitats, wetlands, and terrestrial areas. The 23 river systems supply nearly 40% of the drinking water, irrigation for crops, generation of electricity, and other needs in Texas (TWDB 2012).

Figure 4.1 Fifteen Major River Basins of Texas

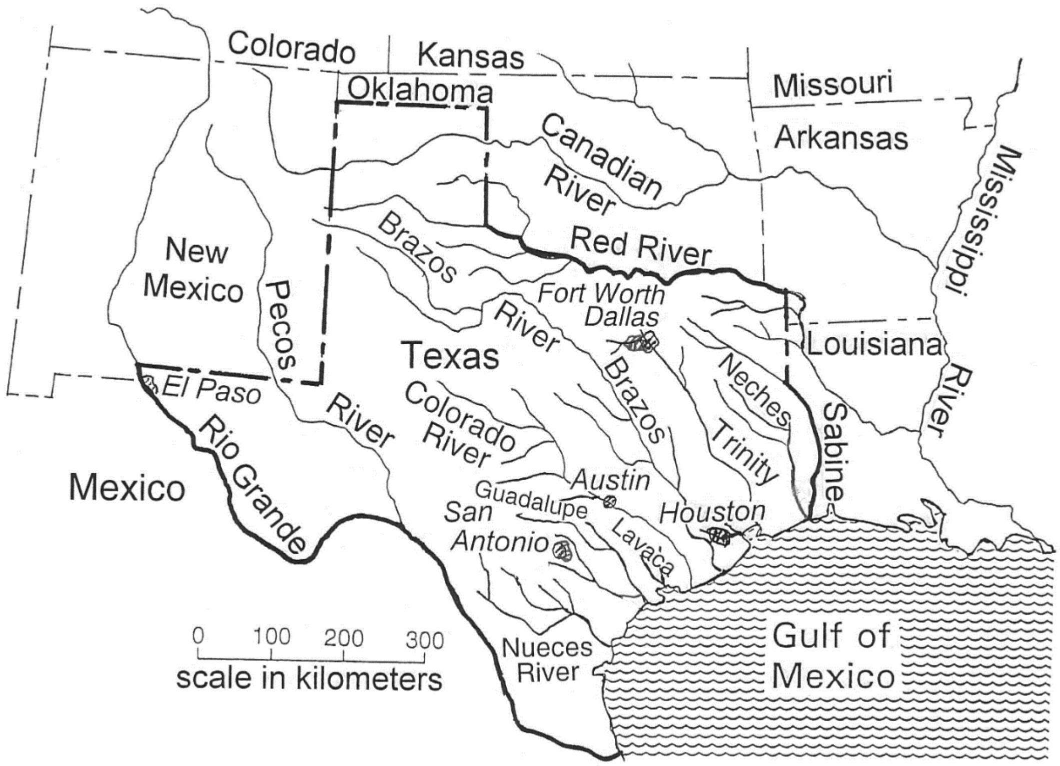


Figure 4.2 Major Rivers and Largest Cities of Texas

4.2 Analysis of Observed Daily Flows at Selected Gaging Station

Stream flow measures the amount of water carried by rivers and streams. It represents a critical resource for people and the local environment. Changes in stream flow can directly influence the water management (EPA, 2012). In addition, stream flow plays an important role in the ecosystem, which is the habitat of many plants and animals.

Stream flow may vary naturally from season to season. For example, most rivers and streams fed by snow melts have their highest sustained flow in spring. Climate changes lead to fluctuation in temperature, precipitation, snowpack, and glaciers. These changes can directly affect the amount of water carried by rivers and streams and the timing of peak flow. From the 19^{th} to present, minimum and maximum flows have changed in many rivers of Texas. In some rivers, the flows are higher, but others are lower. Three-fifths of the rivers and streams measured show peak winter-spring runoff occurred at least five days earlier than in the past (EPA, 2012).

Stream flow data were collected by the U.S. Geological Survey. The U.S. Geological Survey measures stream flow in rivers and streams across the United States using continuous monitoring devices called stream gauges. The stream flow data in this thesis is based on a selected 35 (out of total 211) stream gauges located in areas where trends are not artificially influenced by dams, reservoir management, wastewater treatment facilities, or other activities. The selected 35 stream flow gauging stations are shown in Figure 4.3. The data for the gauges on the Rio Grande River are available on the International Boundary and Water Commission (IBWC) website:

http://www.ibwc.state.gov/Water_Data/histflo1.htm

Daily average stream flow data for all of the other gauges is from the US. Geological Survey (USGS) stored in the National Water Information System (NWIS) and is publicly available at:

http://waterdata.usgs.gov/nwis.

A variety of selected stream flow gauging station information is included in Table 4.1. This includes the map ID, gauge ID, location of the river and nearest city, when the record begins, the watershed area, and the mean flow. The mean flow as a contributing watershed depth equivalent in inches/year is computed by dividing the mean flow in cfs by the contributing watershed area in square miles and multiplying by the unit conversion factor of 13.57438.

The Hydrologic Engineering Center's (HEC) Data Storage System Visual Utility Engine (HEC-DESSVue) is a graphical user interface program for viewing, editing and manipulating data in the HEC Data Storage Systen (HEC-Dss) database files (CEIWR-HEC, 2009). Most of data for the observed flow are imported to HEC-DESSVue directly from the USGS website. However, some of them including the data from the gauges on the Rio Grande River are imported by Microsoft Excel. In addition, the HEC-DESSVue not only plots the daily measurements but also computes and plots the monthly, annual and minimum monthly flow for each year.

The details for the 35 gaging stations with the plots of daily, monthly, annual and minimum observed monthly stream flow by HEC-DESSVue can be found in Appendix C.

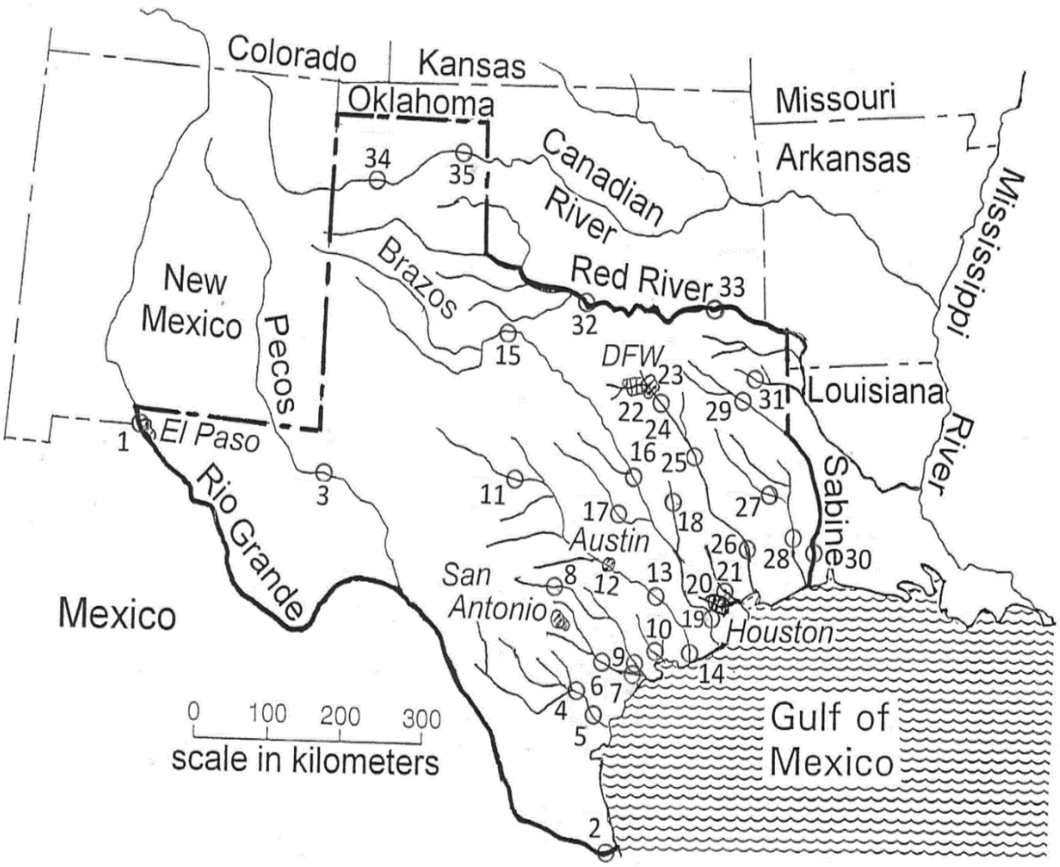


Figure 4.3 Selected Stream Flow Gaging Stations

Table 4.1
Selected Stream Flow Gaging Stations

Map ID	Gage ID	Location River and Nearest City	Record Begins	Watershed Area Total	Watershed Area Contributing	Mean Flow
				(square miles)		(inches/yr)
1	08-3640.00	Rio Grande at El Paso	5/1899		–	
2	08-4750.00	Rio Grande at Brownsville	1/1934		–	
3	08412500	Pecos River at Orla	6/1937	25,070	21,229	0.083
4	08210000	Nueces River at Three Rivers	7/1915	15,427	–	0.662
5	08211000	Nueces River at Mathis	8/1939	16,503	–	0.574
6	08183500	San Antonio River Falls City	5/1925	2,113	–	3.173
7	08188500	San Antonio River at Goliad	7/1939	3,921	–	2.795
8	08167500	Guadalupe River at Spring Branch	6/1922	1,315	–	3.781
9	08176500	Guadalupe River at Victoria	11/1934	5,198	–	5.079
10	08164000	Lavaca River near Edna	8/1938	817	–	6.172
11	08147000	Colorado River near San Saba	11/1915	31,217	19,819	0.686
12	08158000	Colorado River at Austin	3/1898	39,009	27,606	1.055
13	08161000	Colorado River at Columbus	5/1916	41,640	30,237	1.344
14	08162500	Colorado River near Bay City	5/1948	42,240	30,837	1.085
15	08082500	Brazos River at Seymour	12/1923	15,538	5,972	0.760
16	08096500	Brazos River at Waco	10/1898	29,559	19,993	1.596
17	08106500	Little River at Cameron	11/1916	7,065	–	3.352
18	08110500	Navasota River at Easterly	3/1924	968	–	5.857
19	08114000	Brazos River at Richmond	1/1903	45,107	35,541	2.807
20	08074000	Buffalo Bayou in Houston	6/1936	336	–	19.56
21	08068000	West Fork San Jacinto, Conroe	5/1924	828	–	8.137
22	08048000	West Fork Trinity at Fort Worth	10/1920	2,615	–	2.050
23	08057000	Trinity River at Dallas	10/1903	6,106	–	3.803
24	08062500	Trinity River near Rosser	8/1924	8,146	–	5.220
25	08065000	Trinity River near Oakwood	10/1923	12,833	–	5.531
26	08066500	Trinity River at Romayor	5/1924	17,186	–	6.126
27	08033500	Neches River near Rockland	7/1904	3,636	–	8.782
28	08041000	Neches River near Evansdale	8/1922	7,951	–	10.46
29	8022040	Sabine River near Beckville	10/1938	3,589	–	9.442
30	8030500	Sabine River near Ruliff	10/1924	9,329	–	11.81
31	07346000	Big Cypress Bayou at Jefferson	8/1924	850	–	10.04
32	07315500	Red River near Terrel, OK	4/1938	28,723	–	1.106
33	07335500	Red River at Arthur City, Texas	10/1905	44,445	–	2.684
34	07227500	Canadian River near Amarillo	4/1938	19,445	15,376	0.218
35	07228000	Canadian River near Canadian	4/1938	22,866	18,178	0.189

As seen in Table 4.1 there is great diversity between each of the 35 selected stream flow gaging stations. For example, some gauging stations are began record stream flow as early as 1898, while others are begin in 1939. Contributing watershed means the area of land that actually drains all the streams and rainfall to a common outlet such as the outflow of a reservoir, mouth of a bay, or any point along a stream channel. Most river gauges have the same total watershed and contributing watershed, but some river gauges, such as the Pecos River at Oral, Colorado River near San Saba, Brazos River at Richmond, Canadian River near Amarillo, Canadian River near Canadian, the contributing watershed is smaller than the total watershed. According to Table 4.1 the mean flow for each of the 35 gauges vary spatially from 0.083 inches/year in Pecos River at Orla to 19.56 inches/year in Buffalo Bayou River near Houston. The summary statistics for observed daily flows are shown on Table 4.2. Because lack of the exact contributing watershed area for the Rio Grande River at El Paso and the Rio Grande River at Brownsville, the mean flow as a contributing watershed depth equivalent in inches per year is missing in these two gauges.

Table 4.2
Summary Statistics for Observed Daily Flows

	River, Nearest City	First Day	Last Day	Missing Values	Mean	Standard Deviation	Skew Coeff
					(cfs)	(cfs)	(cfs)
1	Rio Grande, El Paso	10May1889	31Dec2011	0	20.1	32.9	6.79
2	Rio Grande, Brownsville	31Dec1933	30Dec2011	0	43.6	94.7	4.09
3	Pecos River, Orla	01Jun1937	01Jun2013	0	130	533	26.3
4	Nueces, Three Rivers	01Jul1915	31Dec2012	0	752	2,822	14.4
5	Nueces, Mathis	05Aug1939	31Dec2012	0	698	2,862	16.2
6	San Antonio, Falls City	01May1925	01Jun2013	0	494	1,220	17.6
7	San Antonio, Goliad	01Jul1939	01Jun2013	0	807	2,128	16.9
8	Guadalupe, Spring Branch	28Jun1922	01Jun2013	0	366	1,454	26.8
9	Guadalupe, Victoria	04Nov1934	01Jun2013	0	1945	4,393	23.5
10	Lavaca, Edna	13Aug1938	01Jun2013	0	371	1,853	20.7
11	Colorado, San Saba	01Nov1915	01Jun2013	513	1002	4,258	17.1
12	Colorado, Austin	01Nov1898	01Jun2013	0	2146	5,719	16.5
13	Colorado, Columbus	22May1916	01Jun2013	0	2995	6,228	8.51
14	Colorado, Bay City	01May1948	01Jun2013	1558	2464	5,295	5.90
15	Brazos, Seymour	01Dec1923	01Jun 2013	0	334	1,609	15.1
16	Brazos, Waco	01 Oct 1898	01Jun 2013	0	2350	5,852	8.05
17	Little River, Cameron	01Nov1916	01Jun 2013	0	1744	4,589	30.4
18	Navasota, Easterly	27Mar1924	01Jun 2013	0	418	1,787	11.2
19	Brazos, Richmond	31Dec1902	08Mar2014	5936	7350	11,779	3.49
20	Buffalo Bayou, Houston	01Jun1936	19May2013	12618	484	820	3.11
21	WF San Jacinto, Conroe	01May1924	01Jun 2013	4322	496	1,822	18.6
22	WF Trinity, Fort Worth	01 Oct1920	01Jun 2013	0	395	1,230	10.5
23	Trinity, Dallas	01 Oct1903	01Jun 2013	0	1711	4,058	8.57
24	Trinity, Rosser	01Aug1924	01Jun 2013	4805	3133	5,686	5.62
25	Trinity, Oakwood	01 Oct1923	01Jun 2013	0	5229	9,095	4.25
26	Trinity, Romayor	01May1924	01Jun 2013	0	7755	11,453	2.73
27	Neches, Rockland	01Jul1904	01Jun 2013	0	2352	3,681	3.52
28	Neches, Evansdale	01Aug1922	01Jun 2013	0	6126	7,460	2.78
29	Sabine, Beckville	01 Oct1938	01Jun 2013	0	2496	4,227	5.96
30	Sabine, Ruliff	01 Oct1924	01Jun 2013	0	8118	9,709	2.70
31	Big Cypress, Jefferson	01 Aug1924	01Jun 2013	7213	629	1,292	10.4
32	Red, Terrel	31Mar1938	09Mar2014	0	2340	6,927	10.4
33	Red, Arthur City	30Sep1905	10Mar2014	9133	8788	14,063	5.65
34	Canadian, Amarillo	01Apr1938	01Jun 2013	0	247	1,292	19.7
35	Canadian, Canadian	01Apr1938	01Jun 2013	0	253	1,488	15.8

According to Table 4.2, some of the 35 gauges have missing values while others are not. The gauge for the Buffalo Bayou in Houston is missing 12,618 data since 01Jun1936 to 19May2013. The missing data is shown as blank to the all plots of daily, monthly, annual and minimum monthly observed stream flow for the 35 gauging stations in Appendix C. As illustrated in Table 4.2, the mean for each 35 gauges vary spatially from 21.0 cfs in the Rio Grande River near El Paso to 8,788 cfs in the Red River near Arthur City. Standard deviation for some gauges are very large, as 14,063 in Red river near Arthur City, which means the steam flow in these gauges are spread out over a large range of mean values and more variable. One of possible reasons is that a lot of missing data may lead to a high standard value. From Table 4.2, the gauges which have a large mean have a larger standard value than the gauges with a smaller mean.

Skewness coefficient in Table 4.2 is referring to the shape of frequency or probability distributions, and asymmetry of the distribution. All skewness coefficients for the 35 observed stream flows are positively skewed, which means distribution with an asymmetric tail extending out to the right. These skewed to the right indicate most of the stream flows are larger than the median value. The maximum value for skewness coefficient is 30.4 in the Little River near Cameron and the minimum value is 2.70 in the Sabine River near Ruliff.

A moving average, also called a moving mean is a calculation to analyze data points by creating a series of averages of different subsets from the full data set. For stream flow, given a series of data and a fixed subset size as 30 days, 90 days, 365 days, and 1,095 days, the first element of the moving minimum flow is obtained by taking the average of the initial fixed subset of the number series. Then the subset is modified by "shifting forward” and creates a new subset of numbers. The minimum moving average is used with time series data to smooth out short-term fluctuations and highlight longer-term trends for stream flow. Forward moving averages are computed for 30 days, 90 days, 365 days, and 1,095 days by HEC-DESSVue.

The minimum mean flows values for durations of 30, 90, 365 and 1,095 days along with the date of the first day of the period having the smallest average flow are entered in the Table 4.3. The Table 4.3 also lists the minimum mean flows (cfs) for durations of 30, 90, 365, and 1,095 days, which are volatile. Most of minimum mean flow for durations of 30 days happened in the beginning of the collected data period, but for the Red River at the Terrel gauge, Pecos River at the Orla and Canadian River at the Amarillo gauges the minimum mean flows occurred nearly the 21th Century.

Table 4.3
Minimum Mean Flows (cfs) for Durations of 30, 90, 365, and 1,095 Days

	River, Nearest City	30 days Mean (cfs)	30 days Date	90 days Mean (cfs)	90 days Date	365 days Mean (cfs)	365 days Date	1,095 days Mean (cfs)	1,095 days Date
1	Rio Grande, El Paso	0	27Aug1889	0	26Oct1889	0	30Jun1894	0	29Jun1896
2	Rio Grande, Brownsville	0	03Apr1952	0	23Aug1953	0.24	26Aug1953	2.14	06Sep1958
3	Pecos River, Orla	0	25Oct2011	0	31Jan2012	0.18	31Jan2012	24.9	31Jan2012
4	Nueces, Three Rivers	0	28Jun1917	0.73	07Dec1931	20.1	17Nov1917	122	08Aug1964
5	Nueces, Mathis	24.3	25Feb1942	27.5	01Mar1940	94.6	13Jul2011	108	02Oct1964
6	San Antonio, Falls City	33.0	19Jun1956	49.5	02Oct1954	78.0	20Aug1956	101	14Oct1956
7	San Antonio, Goliad	20.9	22Aug1956	37.3	23Aug1956	91.3	03Sep1956	136	16Oct1956
8	Guadalupe, Spring Br	0	12Aug1954	0	27Jul1956	9.03	22Feb1957	28.0	22Feb1957
9	Guadalupe, Victoria	31.0	17Oct1956	41.5	17Oct1956	126	18Dec1956	259	24Feb1957
10	Lavaca, Edna	0	05Dec1956	0.128	17Dec1956	5.38	17Dec1956	37.1	08Jan1991
11	Colorado, San Saba	0.037	14Aug1964	4.22	02Oct2011	45.1	08Oct2011	113	01Jun2013
12	Colorado, Austin	31.2	17Dec1989	44.9	13Jan1964	239	11May2013	622	01Jun2013
13	Colorado, Columbus	125.0	29Aug1917	180	29Jan1964	430	27May2013	997	01Jun2013
14	Colorado, Bay City	0.913	18Aug1967	97.2	09Oct2011	286	10Dec2011	328	05Oct2000
15	Brazos, Seymour	0	21Dec1924	0	05Feb1924	3.95	05May2012	105	05Jun2004
16	Brazos, Waco	1.67	4Sep1918	23.3	26Apr1909	179	31Oct1999	636	14Jul1911
17	Little River, Cameron	0.56	10Nov1952	1.73	16Nov1952	87.9	03Feb1955	252	12Mar1957
18	Navasota, Easterly	0	22Aug1924	0.32	14Nov1931	8.93	03Mar1964	55.0	08Jan1965
19	Brazos, Richmond	113	03Sep1934	234	08Sep1934	687	10Dec2011	731	06Oct1922
20	Buffalo Bayou, Houston	2.56	14Dec1938	5.48	01Jun1939	29.1	17Feb1957	35	02Jan1962
21	WF San Jacinto, Conroe	6.23	01Oct1965	8.02	02Nov1956	17.5	09Nov1939	17.5	09Nov1939
22	WF Trinity, Fort Worth	0	11Sep1930	0.048	09Oct1956	10.4	02Feb1955	16.0	17Dec1956
23	Trinity, Dallas	0	30Oct1910	0	29Dec1910	8.22	31Oct1918	132	27Jul1913
24	Trinity, Rosser	32.3	05Nov1924	42.5	23Dec1924	58.3	11Jul1926	58.3	10Jul1928
25	Trinity, Oakwood	45.8	13Sep1925	77.1	13Sep1925	613	29Apr1956	884	01Feb1957
26	Trinity, Romayor	126	29Aug1956	149	25Oct1956	704	31Oct1971	1,766	05Feb1957
27	Neches, Rockland	2.43	20Oct1956	5.23	11Nov1956	217	04Dec2011	690	16Jul1972
28	Neches, Evansdale	84.9	20Dec1956	128	21Jan1957	763	19Dec2011	1,984	01Oct1972
29	Sabine, Beckville	10.6	14Oct1939	15.5	21Oct1956	251	22Nov2011	580	17May2013
30	Sabine, Ruliff	280	23Oct1956	310	08Dec1967	1,031	23Nov2011	2,991	11Apr2013
31	Big Cypress, Jefferson	0	23Oct1939	0.17	10Nov1939	42.1	18Jun1996	83.1	01Jun2013
32	Red, Terrel	14.4	20Aug2012	29.2	29Sep2012	119	18Apr2013	169	09Mar2014
33	Red, Arthur City	170.1	16Dec1956	338	06Feb1940	1,028	15May2013	2,518	26Sep2013
34	Canadian, Amarillo	0	16Sep2000	0.031	13Sep2011	6.16	16Sep2011	12.7	01Jun2013
35	Canadian, Canadian	0	28Sep1983	0.038	12Sep1970	22.3	09May2013	35.0	01Jun2013

In addition, minimum mean flows increase with the durations of days for most gauges. For example, in Nueces River Three Rivers the minimum mean is 0 which happened in 28Jun1917 for the durations is 30 days, the minimum mean increased to 0.73 in 07Dec1931 for the durations is 90 days, the minimum mean change to 20.1 and 122 occurred in 17Nov1917 and 08Aug1964 for the durations is 1 and 3 years. However, in Rio Grande River at El Paso the minimum mean flow is 0 no matter the durations is 30 days or 3 years. According to Appendix C, monthly and annual flows for each gauges are commonly calculated by averaging the daily flows of stream flow over the month and year. The plots of daily, monthly and annual flows for each gauge directly show stream flow conditions that occur over the course of a year. Minimum monthly flow looks at the driest conditions each year which are commonly calculated by the lowest seven consecutive days of stream flow over the year. This plots captures the year's most severe, sustained dry spell. The trends of the 35 selected gauges vary from region to region across the state. For example, streams in the Pecos, Nueces, Colorado, Brazos, Canadian, Sabine, Neches, WF Trinity and WF San Jacinto River have generally seen a decrease or little change in observed stream flows since the first recorded data, while some other streams such as the San Antonio, Guadalupe, Lavaca, Buffalo Bayou, Trinity and Big Cypress River have seen an increase trend. Overall, more sites in the west have seen decreases in stream flows than increases.

As seen in Appendix C, the Rio Grande River at EI Paso gauges, which is located on the Rio Grande River 1,256 miles above its outlet at the Gulf of Mexico and 1.7 miles above the American Dam at EI Paso. Although the graphs based on the daily flows of this gauges change frequent and widespread, it still shows an obvious trend of decrease. The largest annual flow in the Rio Grande was 78.7cfs and happened in the year 1905, the second largest annual flow was 75.51cfs in 1891; and the third annual flows was 71.86cfs in 1907. Therefore, most of large annual flows are happened in the end of nineteenth century or at the beginning of the twentieth century. Additionally, the maximum value for minimum is 20.76cfs in 1917, which is even larger than all annual flow in the twenty-first century.In contrast with the decrease trend in the Rio Grande River, Buffalo Bayou near Houston shows an increase trend since 1936 to present. This gauge is at Shepard Drive West (upstream) of downtown Houston three miles east (downstream) of IH 610. The Barker and Addicks Dam are about sixteen miles from the gauge. Based on Appendix C, although there are some missing data in this gauge, the trend in stream flow shows observed increase. The maximum value for the annual flow is 2,041cfs, and the follows have been 1,955cfs and 1,937cfs which has happened in the end of twentieth and twenty-first century.In conclusion, different beginning dates and missing data can affect the trend, and there are no consistent significant trends found from all river flows recorded at the 35 selected gauges stations from the beginning of the record until the present. Some of them show an increase trend while others have decrease or little change in trend.

CHAPTER V

WRAP/WAM MODERING SYSTEM

The WAM simulation model is used in this study for performing river system development of water budget summaries and flow frequency statistics for undeveloped natural flows versus regulated flow, which reflect river basins in the present conditions of water resources development and management. River system water budgets will be developed for the river outlets and other selected locations in the major river basins of Texas. Additionally, the linear trend and frequency statistics analysis of reservoir storage will also be computed in this chapter.

5.1 WRAP/WAM Modeling System

The WRAP simulates the development, management, regulation, allocation, and use of water resources of a river basin or multiple-basin region. The generalized modeling system is designed for assessing hydrologic and institutional water availability and reliability for water supply diversions, environmental in stream flows, hydroelectric energy generation, and reservoir storage. Basin wide interactions among numerous water uses and diverse water management facilities and practices may be modeled. River basin hydrology is represented by sequences of monthly naturalized stream flows and reservoir net evaporation less precipitation depths at all pertinent locations for each sequential month of a hydrologic period-of-analysis. Although WRAP also has daily computational time step capabilities, routine applications with the Texas WAM System use a monthly time step with a hydrologic period-of-analysis of 60 years or more. WRAP is documented in detail by a set of manuals (Wurbs, 2009, 2013a, 2013b, 2013c, 2013d, Wurbs and Hoffpauir, 2013a, 2013b)

A WRAP simulation study involves assessing capabilities for meeting specified water management and use requirements during a hypothetical repetition of historical hydrology. The overall modeling process includes the following tasks. Sequences of monthly naturalized flows covering the specified period-of-analysis at selected gauging stations are developed. Naturalized flows are distributed from gauged to pertinent ungauged locations. The river/reservoir water allocation/management/use system is simulated. Simulation results are organized and water supply reliability indices, flow and storage frequency relationships, and other summary statistics are computed. Task 1 has been completed for all of the river basins in Texas though the hydrologic periods-of-analysis are currently being updated. Tasks 2 and 3 occur each time the simulation model is executed. A post-simulation program is used for task 4.

The Texas WAM System consists of the generalized WRAP model, datasets containing hydrology and water rights input files for the river basins of the state, GIS tools, and other supporting databases. Four of the datasets combine two adjoining basins, and one basin is divided into two datasets. The water rights in the datasets are updated as the TCEQ approves applications to revise existing permits and issues new permits. Other aspects of the datasets also continue to be refined.

Naturalized flows are provided in the WAM System WRAP input files for 499 primary control points, most of which are located at U.S. Geological Survey gauging stations. Naturalized monthly flows are distributed to the 12,730 other sites based on flows at the 499 control points and watershed parameters contained within the WRAP input files for each of the 13,229 control points.

Model water rights correspond directly to water right permits, but many of the complex permits are modeled with multiple model water rights. Thus, the 10,361 model water rights noted in Table 1.1 is greater than the approximately 6,000 actual water right permits. Environmental in-stream flow requirements are modeled as a special type of water right. The datasets contain the 3,340 reservoirs for which a water right permit has been issued. The original hydrologic period-of-analysis shown in Table 1.1 is currently being updated to near the present.

WRAP simulates capabilities for meeting specified water management and use requirements during a hypothetical repetition of historical hydrology. The model combines detailed information describing water resources development, management, allocation, and use with naturalized stream flows, net reservoir evaporation rates, and channel loss parameters describing natural river system hydrology. Simulation results include sequences of naturalized flows, regulated flows, unappropriated flows, reservoir storage, reservoir net evaporation volumes, and incremental changes in channel losses, water supply diversions, hydroelectric power generated, and other quantities. Simulation results are summarized with frequency statistics and reliability indices. In planning and water right regulatory applications in Texas, reliability indices for measuring water supply capabilities are of particular concern. From the perspective of the proposed research project, the WAM System provides: historical naturalized monthly stream flow sequences at over 500 gauging stations and watershed parameters for distributing these flows to several thousand ungauged sites, and simulation capabilities for converting naturalized flows to regulated flows corresponding to specify scenarios of water resources development, management, allocation, and use.

The basic program SIM and TABLES is used for this study. SIM performs the river/reservoir/use system water allocation simulation using a monthly time step. Program TABLES organizes the SIM simulation results and develops frequency relationships, reliability indices, and summary statistics. TABLES organizes simulation results HEC-DSSVue for plots. The basic WAM input datasets developed for the river basins in Texas were used to performing WRAP-SIM simulations, including the DAT, EVA, FLO, and DIS files. The DAT input includes required and optional records for controlling various simulation options and represents the river/reservoir/rights system being modeled (Wurbs 2013b). The EVA input monthly net evaporation-precipitation depths, the FLO monthly naturalized river flows and the DIS file contains all information about flow distributions throughout the reservoir (Wurbs 2013b).

Naturalized stream flows are flows that would have occurred without human water resources development and use. WAM naturalized flows were computed by adjusting recorded flows to remove the historical impacts of upstream reservoirs, water supply diversions, and return flows, adjusted for channel losses, and in some cases other factors (Wurbs and Sisson, 1999; Wurbs 2006). For the Guadalupe, San Antonio, and Nueces River Basins which cross the Edwards Aquifer recharge zone, adjustments developed from a groundwater model were used to adjust flows for the effects of historical groundwater pumping. Changes in forest cover were considered for the Sulphur River Basin. The TCEQ and TWDB collect data submitted by cities, water districts, and other entities on water supply diversions and return flows. Wastewater treatment plant effluent discharges and irrigation return flows to stream systems include water supplied from groundwater as well as surface water sources.

Both regulated flows and unappropriated flows are computed by the WRAP simulation model for a specified water management scenario. Regulated flows are physical flows at a location reflecting the water management scenario by adjustments to naturalized flows for water right requirements. Unappropriated flows represent water still available for further appropriation after all the water rights receive their allocated share. Texas has 15 major river basins and eight coastal basins along the Gulf of Mexico between the lower reaches of the major river basins. Several of the major river systems shown in Figure 5.1 are shared with neighboring states or Mexico. For the interstate and international river basins, hydrology and water management in neighboring states and Mexico are considered in the WAM System to the extent necessary to assess water availability in Texas. The 21 WAM datasets listed in Table 5.1 cover the entire state and is subdivided by the river basins shown in Figure 5.1.

Figure 5.1 Fifteen Major River Basins and Eight Coastal Basins of Texas

Table 5.1
Water Availability Models (WAMs)

Major River Basin and/or Coastal Basin (filename root)	Basin Area (TWDB) In Texas (mile2)	Basin Area (TWDB) outside Texas (mile2)	Original Simulation Period	Updated Simulation Period
Brazos and San Jacinto-Brazos Coastal (bwam8)	44,305	2,708	1940-1997	1940-2012
Canadian River Basin (CRUN8)	12,865	34,840	1948-1998	–
Colorado and Brazos-Colorado Coastal (C8)	41,278	201	1940-1998	1940-2012
Cypress Bayou Basin (cyp08)	2,929	623	1948-1998	–
Guadalupe and San Antonio Basins (gsarun8)	10,133	0	1934-1989	1934-2012
Lavaca River Basin (lav8)	2,309	0	1940-1996	–
Neches River Basin (neches8)	9,937	0	1940-1996	1940-2012
Nueces River Basin (N_Run8)	16,700	0	1934-1996	–
Red River Basin (red8)	24,297	69,153	1948-1998	–
Rio Grande Basin (RG8)	49,387	132,828	1940-2000	–
Sabine River Basin (sabine8)	7,570	2,186	1940-1998	1940-2012
San Jacinto River Basin (sjarun8)	3,936	0	1940-1996	–
Sulphur River Basin (sulphur8)	3,580	187	1940-1996	–
Trinity River Basin (trin8)	17,913	0	1940-1996	1940-2012
Coastal Basins				
Colorado-Lavaca (col-lav8)	939	0	1940-1996	–
Lavaca-Guadalupe (lavguad8)	998	0	1940-1996	–
Neches-Trinity (NT8)	769	0	1940-1996	–
Nueces-Rio Grande (Nrg8)	10,442	0	1948-1998	–
San Antonio-Nueces (SANueces8)	2,652	0	1948-1998	–
Trinity-San Jacinto (TSJ8)	247	0	1940-1996	–

Number of WAM Control Points, Water Rights, and Reservoirs are described in Table 5.1. The 20 data sets (follow with filename root) coving 23 major river basins or coastal basins in Texas are listed in Table 5.1. These datasets were developed by 4 major simulation periods. The data in Brazos and San Jacinto-Brazos Coastal, Colorado and Brazos-Colorado Coastal, Guadalupe and San Antonio, Neches, Sabine, and Trinity

River Basin have been updated to 2012. The simulation period for the Canadian, Cypress, Red, Nueces-Rio Grande, and San Antonio-Nueces Basins are from 1948 to 1998. The data in the Rio Grande River Basin are computed from 1940 to 2000, while other datasets are compiled during 1940-1996.

As seen in Figure 5.1 and Table 5.1, each of the river basins varies in size of area. Some of the larger river basins have large amounts of climate variability and water use consumption. For example, Red, Brazos, Colorado, and Rio Grande river basins have very large drainage areas, and these basins span much of the state. According to Table 5.1, there are 12 river basins or coastal basins beginning and ending in Texas, while other basins have area outside Texas. For example, in the Rio Grande Basin (RG8) there are only 49,387 $mile^2$ in Texas and 132,828 $mile^2$ out of Texas.

Table 5.2
Number of WAM Control Points, Water Rights, and Reservoirs

WAM	Latest Update	Number of Control Points				WR Records	IF Records	Reser-voirs
		Total	Primary	Evap	FA			
Brazos	Sep 2008	3,842	77	67	0	1,734	145	719
Canadian	Jan 2013	85	12	9	0	56	0	47
Colorado	Aug 2007	2,396	45	47	1,180	1,928	93	510
Cypress	Jan 2010	147	10	10	0	159	1	91
GSA	Oct 2008	1,340	46	13	280	872	214	241
Lavaca	Nov 2010	184	8	7	0	65	30	21
Neches	Oct 2012	395	20	12	0	385	78	203
Nueces	Jan 2013	546	41	10	0	393	32	125
Red	Jan 2013	451	47	40	612	508	111	248
Rio Grande	Jun 2007	957	55	25	61	2,597	4	113
Sabine	Aug 2004	387	27	20	0	328	23	213
San Jacinto	Nov 2009	414	17	4	0	158	17	114
Sulphur	Nov 2012	89	8	4	0	85	10	57
Trinity	Oct 2012	1,418	40	50	0	1,067	89	700
Colorado-Lavaca	Jul 2007	111	1	1	0	27	4	8
Lavaca-Guadalupe	Oct 2001	68	2	2	0	12	0	0
Neches-Trinity	Jan 2013	249	4	4	0	139	11	31
Nueces-Rio Grande	Jan 2013	200	29	5	0	109	7	65
San Antonio-Nueces	Jan 2013	53	9	3	0	12	2	9
Trinity-San Jacinto	Jan 2013	94	2	3	0	26	1	13

The 20 WAMP input datasets contain 13,426 total control points and 3,365 reservoirs for which a water right permit has been issued. Information from the WAMP datasets include period of analysis, number of primary and total control points, number of water rights (WR), number of in stream flow (IF) records, and number of reservoirs for each of the 21 WAM river basins is listed in Table 5.2. According to Table 5.2, water

management conditions vary dramatically in each of the 23 Texas river basins modeled by the 21 datasets. Although there are 3,365 reservoirs across Texas, over 90% of the total conservation storage capacity of these reservoirs are contained in the largest 211 reservoirs with conservation capacities exceeding 6,170,000m^3 (5,000 acre-ft). (Wurbs, 2005b). As seen in Table 5.2 some river basins have large number of reservoirs like Brazos which has 719 reservoirs, and Trinity which has 700 reservoirs, while others such as Lavaca-Guadalupe, do not. Therefore, river system water budgets simulations results help provide insight on the sensitivity of water supply availability and reliability to climatic conditions and water use demand changes.

5.2 River System Water Budgets

Conceptually, the water budget is among the simplest and most direct method available for describing the flow change of a river system. The water budget is based on the changes in volume of water stored and the difference between inflow and outflow. The inflow term consists of precipitation on the water surface, runoff, channel inflow, groundwater inflow, and any other diversion into the body of water being studied. Outflow typically is composed of evaporation from the water surface, channel outflow, groundwater outflow (seepage), and any diversion out of the body of water. This thesis research is based on using the TCEQ modeling system and TWDB databases to explore the relative effects of climate change, water resources development, and other factors on long-term changes of the water budgets for the different river basins of Texas.

The water budget table is performed for the individual components of inflows to and outflows from the control point or river basin along with changes in reservoir storage in the WRAP model. A 2BUD record in the Table program activates relatively extensive computations to develop water budgets for control points and the entire river basin. The monthly data are also used to develop a period-of-analysis river basin water budget summary table (Wurbs 2013b).

The descriptive information and volume budgets for river basins are shown in Table 5.3. This table includes the number of reservoirs, basin mean storage capacity, basin mean storage, net evaporation-precipitation, naturalized flows, return flows, diversion targets, channel loss credits, net reservoir evaporation-precipitation, other gains and losses and volume reliabilities. The storage capacity associated with each *Water Storage* record set is the total cumulative capacity, which means the reservoir can be refilled under that right's priority, assuming the reservoir has been drawn down in previous months and stream flow is now available for refilling for future water diverting use. Diversion targets are related to water rights in each of the 19 TCEQ WAM river basins. It represents the total annual diversion volume from all water right records in the DAT file for a particular river basin. The Rio Grande river basin summary includes only the water allocated to the United States pursuant to the 1944 international treaty. Some information is omitted in this summary. For Example: targets, diversions, and return flows for accounting rights, and storage in 21 accounting reservoirs in the Colorado; targets, diversions, and return flows for accounting rights in the Trinity; and diversion targets for accounting FK control points in Neches are omitted from the summary.

Table 5.3
Descriptive Information and Volume Budgets for River Basins

Descriptive Informative for Each WAM River Basin

WAM river basin	Colorado	Brazos	San Jacinto	Trinity	Neches
simulation period for WAM	1940-2012	1940-2012	1940-1996	1940-2012	1940-2012
watershed area (square miles)	41,278	44,305	46.6	17,797	9,937
mean precipitation (inches/year)	24.5	29.4	29.4	39.4	48.7
mean precipitation (ac-ft/year)	53,864,400	69,573,637	9,789,535	37,624,284	25,790,700
mean evaporation (inches/year)	63.05	60.20	49.0	55.13	48.5
number of reservoirs	489	719	114	700	180
storage capacity (acre-feet)	4,709,829	4,015,865	587,529	7,356,200	3,656,259
mean storage (acre-feet)	3,274,978	3,332,800	535,814	5,819,605	3,590,176
mean storage (% of capacity)	69.53%	82.99%	91.20%	79.11%	98.19%
diversion target (acre-feet/year)	2,235,420	1,519,141	520,360	6,617,851	621,609
volume reliability (percent)	82.52%	93.29%	83.18%	86.92%	81.15%
naturalized flow (% of precip)	5.79%	10.42%	23.19%	17.62%	24.13%
regulated flow (% precipitation)	3.54%	8.77%	11.43%	12.83%	21.60%

WAM River System Volume Budget (acre-feet/year)

naturalized flows at outlet	3,118,790	7,246,374	2,270,089	6,630,282	6,223,550
regulated flows at outlet	1,907,890	6,100,112	1,119,168	4,828,743	5,571,735
water supply diversions	1,844,678	1,417,246	432,840	5,752,039	504,452
return flows	808,709	307,849	70,451	3,696,714	310,406
CI record constant inflows	14,420	63,750	544,970	635,934	36,158
net reservoir evaporation	284,690	425,646	34,026	538,291	137,618
(reservoir evaporation)	(628,767)	(1,026,529)	2,197,590	(2,546,026)	(648,870)
(reservoir precipitation)	(344,077)	(600,883)	2,163,547	(2,007,735)	(511,252)
net change in reservoir storage	0	-37.9	0	-731.8	-25.8
(beginning storage)	(2,741,179)	(3,014,288)	(532,785)	(5,292,818)	3,615,774
(ending storage)	(2,741,179)	(3,011,520)	(532,785)	(5,239,394)	3,613,887
channel loss credits	6,903	223,806	0	257,862	0.0
channel loss credit deductions	1,818	26,320	0	87,074	0.9
other gains and losses	90,254	127,545	-1,299,476	-15,377	356,334

Volume Budget Summary (acre-feet/year)

naturalized flows at outlet	3,118,790	7,246,374	2,270,089	6,630,282	6,223,550
return flows and other inflows	823,129	371,599	615,421	4,332,648	346,564
water supply diversions	1,844,678	1,417,246	432,840	5,752,039	504,452
net reservoir evaporation-precip	284,690	425,646	34,026	538,291	137,618
other gains and losses	95,339	325,031	-1,299,476	156,143	-356,309
regulated flows at outlet	1,907,890	6,100,112	1,119,168	4,828,743	5,571,735

Table 5.3 Continued

Descriptive Informative for Each WAM River Basin					
WAM river basin	Rio Grande	Nueces Rio-Grande	Nueces	Guadalupe & San Antonio	Lavaca
simulation period for WAM	1940-2000	1948-1998	1934-1996	1936-2012	1940-1996
watershed area (square miles)	49,387	10,442	16,700	10,133	2,309
mean precipitation (inches/year)	16.1	25.3	24.8	32.3	39.7
mean precipitation (ac-ft/year)	42,316,084	14,084,821	22,097,548	17,453,349	4,891,348
mean evaporation (inches/year)	64.0	62.3	59.6	54.1	50.8
number of reservoirs	113	65	125	241	21
storage capacity (acre-feet)	3,499,068	113,092	959,827	756,527	167,716
mean storage (acre-feet)	1,713,859	39,059	508,744	603,433	155,253
mean storage (% of capacity)	48.98%	34.54%	53.00%	79.76%	92.57%
diversion target (acre-feet/year)	2,228,867	12,146	637,039	420,776	61,620
volume reliability (percent)	81.71%	38.04%	87.37%	90.92%	82.44%
naturalized flow (% of precip)	2.60%	2.13%	2.93%	12.72%	17.59%
regulated flow (% precipitation)	0.18%	2.26%	1.99%	11.82%	16.48%
WAM River System Volume Budget (acre-feet/year)					
naturalized flows at outlet	1,099,597	300,314	647,932	2,220,137	860,402
regulated flows at outlet	75,163	318,006	440,410	2,063,020	806,335
water supply diversions	1,821,216	4,620	556,610	382,559	50,798
return flows	34,651	443	423,900	110,698	1,758
CI record constant inflows	0	53,208	11,241	172,962	16,050
net reservoir evaporation	217,632	12,808	93,002	65,288	21,078
(reservoir evaporation)	(304,111)	(23,982)	(201,597)	(158,119)	(106,652)
(reservoir precipitation)	(86,479)	(11,174)	(108,595)	(92,831)	(85,574)
net change in reservoir storage	0	0	0	871	0
(beginning storage)	(444,488)	(44,967)	(20,268)	572,268	(167,675)
(ending storage)	(444,488)	(44,967)	(20,268)	573,139	(167,675)
channel loss credits	0	1,117	91,984	740,722	0
channel loss credit deductions	0	4,620	21,085	305,638	0
other gains or losses	979,763	-15,028	-63,950	7,070	1
Volume Budget Summary (acre-feet/year)					
naturalized flows at outlet	1,099,597	300,314	647,932	2,220,137	860,402
return flows and other inflows	34,651	53,651	435,141	283,660	17,808
water supply diversions	1,821,216	4,620	556,610	382,559	50,798
net reservoir evaporation-precip	217,632	12,808	93,002	65,288	21,078
other gains and losses	979,763	-18,531	6,949	7,070	1
regulated flows at outlet	75,163	318,006	440,410	2,063,020	806,335

Table 5.3 Continued

Descriptive Informative for Each WAM River Basin

WAM river basin	Canadian	Red	Sulphur	Cypress	Sabine
simulation period for WAM	1948-1998	1948-1998	1948-1996	1948-1998	1948-1998
watershed area (square miles)	12,865	24,297	3,580	2,929	7,570
mean precipitation (inches/year)	19.5	25.6	46.6	47.2	47.8
mean precipitation (ac-ft/year)	13,372,409	33,128,908	8,899,780	7,377,989	19,282,844
mean evaporation (inches/year)	66.2	63.4	50.1	48.9	50.9
number of reservoirs	47	248	57	91	213
storage capacity (acre-feet)	879,824	3,780,342	718,699	877,938	6,262,314
mean storage (acre-feet)	610,254	3,369,963	624,481	753,868	6,114,799
mean storage (% of capacity)	69.36%	89.14%	86.89%	85.87%	97.64%
diversion target (acre-feet/year)	94,164	860,601	242,065	496,232	550,276
volume reliability (percent)	95.38%	97.25%	99.21%	77.96%	98.74%
naturalized flow (% of precip)	−	−	29.11%	22.71%	34.40%
regulated flow (% precipitation)	−	−	25.29%	19.96%	32.11%

WAM River System Volume Budget (acre-feet/year)

naturalized flows at outlet	217,548	10,093,274	2,590,678	1,675,698	6,633,087
regulated flows at outlet	128,393	9,116,350	2,250,450	1,472,695	6,191,736
water supply diversions	89,809	836,901	240,152	386,843	543,324
return flows	88,682	243,357	1,222	248,388	190,691
CI record constant inflows	1,715	7,900	217,250	1,754	107,644
net reservoir evaporation	62,269	328,422	55,808	42,312	216,206
(reservoir evaporation)	(90,564)	(948,381)	(224,763)	(170,409)	(1,056,656)
(reservoir precipitation)	(28,295)	(619,959)	(168,955)	(128,097)	(840,450)
net change in reservoir storage	0	1,948	0	-2.9	0
(beginning storage)	(429,055)	(3,200,513)	(628,635)	(783,458)	(6,013,477)
(ending storage)	(429,055)	(3,299,854)	(628,635)	(783,309)	(6,013,476)
channel loss credits	62,576	26,372	0	0	0
channel loss credit deductions	693	1,832	0	0	0
other gains or losses	-89,357	-85,450	-262,740	-23,993	19,844

Volume Budget Summary (acre-feet/year)

naturalized flows at outlet	217,548	10,093,274	2,590,678	1,675,698	6,633,087
return flows and other inflows	90,397	251,257	218,472	250,142	298,335
water supply diversions	89,809	836,901	240,152	386,843	543,324
net reservoir evaporation-precip	62,269	328,422	55,808	42,312	216,206
other gains and losses	-27,474	-62,858	-262,740	-23,990	19,844
regulated flows at outlet	128,393	9,116,350	2,250,450	1,472,695	6,191,736

Table 5.3 Continued

	Descriptive Informative for Each WAM Coastal Basin				
WAM coastal basin	San Antonio-Nueces	Lavaca-Guadalupe	Colorado-Lavaca	Trinity-San Jacinto	Neches-Trinity
simulation period for WAM	1940-1998	1940-1996	1940-1996	1940-1996	1940-1996
watershed area (square miles)	2,652	998	939	247	769
mean precipitation (inches/year)	35.1	39.6	40.0	48.1	49.6
mean precipitation (ac-ft/year)	4,958,103	2,108,064	2,005,438	633,847	2,032,559
mean evaporation (inches/year)	53.9	50.8	50.6	46.5	45.9
number of reservoirs	9	0	8	13	31
storage capacity (acre-feet)	1,481	0	7,227	4,876	57,986
mean storage (acre-feet)	1,139	0	5,967	3,194	19,827
mean storage (% of capacity)	76.91%	–	82.57%	65.50%	34.19%
diversion target (acre-feet/year)	481	230	36,103	10,094	208,845
volume reliability (percent)	89.40%	69.13%	65.13%	78.43%	67.39%
naturalized flow (% of precip)	11.40%	19.28%	19.76%	28.54%	56.72%
regulated flow (% precipitation)	11.40%	19.78%	19.19%	30.00%	51.82%
	WAM River System Volume Budget (acre-feet/year)				
naturalized flows at outlet	565,201	406,539	396,183	180,904	1,152,769
regulated flows at outlet	565,236	416,945	384,800	190,137	1,053,371
water supply diversions	430	159	23,514	7,917	140,746
return flows	209	24	3,263	338	0
CI record constant inflows	851	11,247	9,621	17,625	47,183
net reservoir evaporation	529	0	753	475	3,234
(reservoir evaporation)	(1,758)	(0)	(4,869)	(1,975)	(33,634)
(reservoir precipitation)	(1,229)	(0)	(4,116)	1,500	(30,400)
net change in reservoir storage	0	0	0	0	0
(beginning storage)	(1,365)	(0)	(6,635)	(3,016)	(19,357)
(ending storage)	(1,365)	(0)	(6,635)	(3,016)	(19,357)
channel loss credits	31	0	0	0	0
channel loss credit deductions	111	0	0	0	0
other gains or losses	14	-706	0	-338	-2,601
	Volume Budget Summary (acre-feet/year)				
naturalized flows at outlet	565,201	406,539	396,183	180,904	1,152,769
return flows and other inflows	1,060	11,271	12,884	17,963	47,183
water supply diversions	430	159	23,514	7,917	140,746
net reservoir evaporation-precip	529	0	753	475	3,234
other gains and losses	-66	-706	0	-338	-2,601
regulated flows at outlet	565,236	416,945	384,800	190,137	1,053,371

In evaluating the impact of long-term climate change and human activity on future water budgets in Texas, it is important to understand current water budgets in each of the river basins. As illustrated in Table 5.3, the Trinity, Sabine, Colorado, and Brazos river basins have reservoir storage capacities greater than 4,000,000 acre-feet. The reason for these high reservoir storage capacities is that these river basins have a large number of large reservoirs with an average surface area greater than 75,000 acres. Most basins with such large reservoir capacities are located in the upstream portion of major rivers, thus big reservoirs are necessary for these basins to meet their water supply demands. Additionally, basins with the smallest reservoir capacities such as Nueces-Rio Grande, San Antonio Nueces, Colorado Lavaca, Lavaca-Guadalupe and Trinity-San Jacinto river basins are located along the Gulf of Mexico. The average surface area of reservoirs in these basins is less than 800 acres. One reason for the lower average surface area of reservoirs is that these river basins are located at the most downstream portion of major rivers with less stress on water supplies.

Net evaporation-precipitation volumes are simulated by WRAP, while the reservoir evaporation and reservoir precipitation are computed by multiplying the reservoir net evaporation-precipitation rates provided from previous study. As seen in Table 5.3, the Brazos, Trinity, Sabine, Red, and Colorado River basins experience a great amount of net evaporation-precipitation for period of analysis. Reservoirs in these basins have large water surface areas, which contribute to high value for net reservoir evaporation, and cause large evaporation-precipitation volumes in these river basins. Some other river basins such as San Antonio Nueces, Colorado Lavaca, Lavaca-Guadalupe and Trinity San Jacinto river basins experience high precipitation rates, thus producing relatively low net evaporation-precipitation volumes.

Volume reliability is defined as the ratio of the actual diversion volume divided by the target diversion volume, and converted to a percentage. The volume reliabilities for Sulphur, Sabine, Red, Canadian, Guadalupe &San Antonio and Brazos river basins are the higher than 90%. These basins are located in the northeast region of the state where evaporation rates are low. Basins located in this general area typically have high volume reliabilities because of both ideal weather conditions for maintaining surface water supplies and more reservoirs for water supplies. In contrast, volume reliabilities in some basins are 70% or lower including the Lavaca-Guadalupe, Neches-Trinity, Nueces-Rio Grande, and Colorado-Lavaca river basins. Except for the Nueces-Rio Grande river basins, other basins' volume reliabilities are 60% or higher, meaning that the target diversion can be basically met. The diversion targets in each of these lower volume reliabilities basins are larger than reservoir storage capacities. In addition, a majority of these basins have a small number of reservoirs and are located in regions that experience high evaporation rates and low annual precipitation, leading to the difficulty of meeting water supply diversion targets.

The volume budgets reflects the relationship between input and output of water through a region. The inflows in our volume budgets are naturalized flows at outlet, return flows and other inflows, while the outflows are water supply diversions, net reservoir evaporation, and regulated flows. The value of other gains and losses are positive in some river basins such as the Colorado, Trinity, and Rio Grande, Nueces, Guadalupe &San Antonio, Sabine and Brazos River basins which means outflows are greater than inflows. However, the value of other gains and losses are negative in some river basins like the San Jacinto, Neches, Nueces-Rio Grande, Sulphur, Red, Canadian, Cypress San Antonio-Nueces, Lavaca-Guadalupe, Neches-Trinity, and the Trinity-San Jacinto, which means inflows always exceed outflows. In Colorado- Lavaca and Lavaca river basins other gains and losses are ideally nearly zero, which means the inflow is nearly equal with the outflow. The River basin volume budget summaries are provided in greater detail in Table 5.3. Terms in WAM river system volume budget table are explain in Table 5.4.

Table 5.4
Terms in WAM River System Volume Budget Table

Naturalized flows at outlet – Naturalized stream flows at one or more control points represents flows into the Gulf of Mexico. For the Canadian, Red, Sulphur, and Cypress Basins, outflows are the flows leaving Texas at the state border. Major rivers usually have a single outlet, and the coastal basins have multiple outlets representing multiple small streams flowing into the Gulf.

Regulated flows at outlet – Regulated flows tabulated for the same outlet control points adopted for the naturalized flows.

Water supply diversions – The total of all water right diversions in the WAM.

Return flows – Return flows in the WAM associated with the water right diversions.

CI record constant inflows – Flows entered on constant inflow CI records usually represent return flows from groundwater use but may also represent interbasin transfers or other inflows.

Net reservoir evaporation – Reservoir surface evaporation less precipitation falling on the reservoir surface adjusted for the portion of the precipitation that contributes to stream flow without the reservoir as reflected in the naturalized flows. The net reservoir evaporation computed in the WRAP/WAM simulation is split between evaporation and precipitation using results from a previous study.

Channel loss credits – Channel loss credits computed in the SIM simulation are associated with stream flow depletions for water supply diversions and filling reservoir storage. These credits represent a reduction in channel losses.

Channel loss credit deductions – Channel losses computed in the SIM simulation are associated with return flows and reservoir releases.

Other gains and losses – The quantity that completes the following volume balance.

naturalized flows – regulated flows – water supply diversions + return flows + CI record constant inflows – net reservoir evaporation – net reservoir storage change + channel loss credits – channel losses + other gains or losses = 0

Table 5.4 Continued

Volume Budget Summary

The Volume Budget Summary is developed from the preceding more detailed table as follows. Naturalized and regulated flows, water supply diversions, and net reservoir evaporation-precipitation volumes are the same as in the preceding tabulation.

Return flows and other inflows = return flows + CI record constant inflows other gains and losses = other gains and losses + channel losses credits – loss credit deductions

The computations are checked with the following volume balance equation.

naturalized flows at outlet + return flows and other inflows + other gains or losses – water supply diversions – net reservoir evaporation – regulated flows = zero

Table 5.5
Descriptive Information and Volume Budgets for Entire State of Texas

	WAM Total	Texas
Descriptive Information		
watershed area (square miles)	259,181	259,181
mean precipitation (inches/year)	–	29.94
mean precipitation (ac-ft/year)	391,285,647	391,285,647
mean evaporation (inches/year)	–	59.61
number of reservoirs	3,484	3,484
storage capacity (acre-feet)	38,412,599	35,053,265
mean storage (acre-feet)	31,300,013	27,964,230
mean storage (% of capacity)	81.48%	79.78%
diversion target (acre-feet/year)	17,373,920	17,373,920
volume reliability (percent)	86.55%	86.55%
naturalized flow (% of precip)	–	12.43%
regulated flow (% precipitation)	–	8.45%
Volume Budget Summary (acre-feet/year)		
naturalized flows at outlets	54,529,348	48,644,862
return flows and other inflows	8,513,236	8,513,236
water supply diversions	15,036,853	15,036,853
net reservoir evaporation-precip	2,540,087	2,441,708
other gains and losses	-464,949	26,635
regulated flows at outlets	45,000,695	39,706,172

Descriptive information and volume budgets for entire state of Texas are tabulated in Table 5.5. As shown in Table 5.5 the watershed area of Texas is 259,181 square miles, with the western half of the state having a semi-arid continental type climate, and the remainder areas having a humid sub-tropical climate. Mean precipitation in Texas is 29.94 inches/year and mean evaporation is 59.61 inches/year, which is nearly 2 times of evaporation. Mean storage in Texas is 35,053,265 ac-ft/year. Volume reliability is 79.78% in Texas and 81.48% for WAM which shows that in most time diversion targets will be satisfied. The net reservoir evaporation-precipitation from Total WAM is 2,540,087 acre-feet/year which is a little higher than 2,441,708 acre-feet/year in entire State of Texas. This is a relatively greater difference in value that other gains and losses, which are -464,949 ac-ft/year in the total WAM and 26,635 ac-ft/year for Texas. One reason is that the main inflow, naturalized flows at outlets for the total in WAM, is 5,884,486 ac-ft/year higher than the value in Texas. However the main outflow and regulated flows at outlets, is just 5,294,523 ac-ft/year higher.

5.3 Linear Trend Analysis of Reservoir Storage

To quantify the long-term changes in stream flows of river system water budgets attributable to water resources development and use, the simulation for reservoirs is necessary. Total reservoirs monthly storage volume in each 19 WAM river basins are simulated by WRAP-SIM. The SIM simulation results are tabulated as a standard set of time series tables by 2STO records. The time series are converted by TABLES to both two formats, one is tabulations in a columnar format, the other is records in a HEC-DSS file designed to be read by HEC-DSSVue. The simulated result for monthly reservoir storage volume are listed in Table 5.6.

The linear regression trend analysis is completed by the program HydStats, which is based on the Texas Water Development Board (TWDB) datasets in the files named Precipitation.PPP, Evaporation.EEE and results from WRAP simulation. The regression coefficients for simulated monthly reservoir storage contents are described in Table 5.7. WRAP also provides reservoir monthly stores in a DSS file, which is an input file for HEC-DSSVue's plotting and data manipulations.

Plots of simulated monthly reservoir storage volumes for 19 WAMs as discussed are can be found in Appendix D.

Table 5.6
Simulated Monthly Reservoir Storage Volume

Water Availability Model	Capacity (ac-ft)	Mean (ac-ft)	Stand Dev (ac-ft)	Minimum (ac-ft)	Maximum (ac-ft)
Brazos and San Jacinto-Brazos	4,015,865	3,332,798	366,301	1,941,981	3,861,882
Canadian River Basin	879,824	610,254	171,942	332,058	878,597
Colorado and Brazos-Colorado	4,709,829	3,497,778	291,605	2,356,907	4,330,434
Cypress Bayou Basin	877,938	753,868	44,350	605,165	812,735
Guadalupe and San Antonio	756,527	603,433	81,690	325,510	756,055
Lavaca River Basin	167,716	155,253	15,389	88,291	167,716
Neches River Basin	3,656,259	3,590,175	77,428	3,061,236	3,645,493
Nueces River Basin	959,827	508,744	264,848	4,813	952,669
Red River Basin	3,780,342	3,369,963	164,352	2,846,774	3,668,677
Rio Grande Basin	23,869,838	8,840,737	3,536,295	1,872,593	14,852,787
Sabine River Basin	6,262,314	6,114,800	171,985	5,138,603	6,258,565
San Jacinto River Basin	587,529	535,814	56,969	253,077	580,467
Sulphur River Basin	718,699	624,451	65,620	379,281	718,681
Trinity River Basin	7,356,200	5,819,605	854,458	2,527,518	7,295,806
Coastal Basins					
Colorado-Lavaca	7,227	5,967	755	4,112	7,072
Lavaca-Guadalupe	0	0	0	0	0
Neches-Trinity	57,986	19,826	2,544	13,231	28,996
Nueces-Rio Grande	113,092	39,059	4,772	27,470	52,188
San Antonio-Nueces	1,481	1,138	229	413	1,385
Trinity-San Jacinto	4,876	3,194	681	1,051	3,886

As indicated by the monthly reservoir storage volume summary table, reservoir storage capacities are cited in the water river basin water management. The mean reservoir storage volume varies from 1,138 ac-ft in the San Antonio-Nueces Coastal Basins to 8,840,737 ac-ft in the Rio Grande Basin. In some river basins, the mean value is larger than 75% of reservoir capacity reflecting that reservoir storage is always at high levels such as in the Brazos and San Jacinto-Brazos, Cypress Bayou, Guadalupe and San

Antonio, Lavaca, Neches, Red, Sabine, San Jacinto, Sulphur, Trinity, Colorado-Lavaca and San Antonio-Nueces River Basin. In contrast, other basins are less than 75%. The Standard Deviation value is increased with storage volume capacity, which means it is relatively high for river basins with a lot of reservoirs. Neches and Sabine River Basins' Standard Deviation are relatively lower than other river basins with large storage capacities.

The Minimum storage volumes are 4,813 ac-ft, 1,051 ac-ft and 1,872,593 ac-ft in the Nueces, Rio Grande Basin, and Trinity-San Jacinto River Basin. These represents only 1%, 8% and 22% of the reservoir's capacity respectively. However, in the Neches, Red, and Sabine River Basins Minimum storage volume are greater than 75% of the reservoirs capacity, which means the reservoirs in these river basins play an important role on water supplies availability. Maximum storage volume in the Nueces-Rio Grande, Neches-Trinity and Rio Grande River Basin is 52,188 ac-ft, 28,996 ac-ft, and 14,852,787 ac-ft. This represents 46%, 50% and 62% for the reservoirs capacity, while maximum storage volume for other river basins are near the total storage capacity.

Table 5.7
Regression Coefficients for Simulated Monthly Reservoir Storage Contents

Water Availability Model	Mean (ac-ft)	Intercept (ac-ft)	Slope (ac-ft)	Intercept (% Mean)	Slope (% Mean)
Brazos and San Jacinto-Brazos	3,332,800	3,063,283	615	91.9	0.0184
Canadian River Basin	610,254	830,128	-717	136	-0.118
Colorado and Brazos-Colorado	3,274,977	3,243,269	72.31	99.0	0.00221
Cypress Bayou Basin	753,868	748,098	18.8	99.2	0.00250
Guadalupe and San Antonio	756,527	602,442	2.09	99.8	0.00035
Lavaca River Basin	155,253	150,693	13.3	97.1	0.00857
Neches River Basin	3,590,175	3,599,930	-22.2	100	-0.00062
Nueces River Basin	508,744	596,049	-231	117	-0.0453
Red River Basin	3,369,965	3,282,500	285	97.4	0.00847
Rio Grande Basin	1,713,859	1,794,619	-220	105	-0.01286
Sabine River Basin	6,114,800	6,126,140	-25.9	100	-0.00042
San Jacinto River Basin	535,814	519,028	49.0	96.9	0.00915
Sulphur River Basin	624,451	625,488	-3.03	100	-0.00049
Trinity River Basin	5,819,603	5,200,339	1,412	89.4	0.02427
Coastal Basins					
Colorado-Lavaca	5,967	5,896	0.205	98.8	0.00344
Lavaca-Guadalupe	0	0	0	0	0
Neches-Trinity	19,827	19,840	-0.0383	100	-0.00019
Nueces-Rio Grande	39,059	37,880	3.85	97.0	0.00985
San Antonio-Nueces	1,139	1060	0.26	93.1	0.0226
Trinity-San Jacinto	3,194	3,133	0.177	98.1	0.00555

According to Table 5.7, there is great diversity between regression coefficients for simulated monthly reservoir storage for each of the 23 Texas river basins modeled by the 21 datasets. The simulation for all the reservoir storages in this thesis set beginning-of-simulation storage contents equal to the end-of-simulation storage contents by BES routine used in SIM input and output.

The regression slopes for monthly reservoir storage are relatively high in river basins with large storage capacities, thus slope as a percentage of the mean reflects long-term changes more accurately. There are 12 river basins that have positive values for slopes as a percentage of the mean, while 7 river basins have negative values for slopes. However, all of the slopes are near zero and intercepts are approximate to the mean reservoir storage, thus indicating there is no long-term linear trend in simulated reservoir storage.

Results in Table 5.7 shows that the Canadian River Basin has the lowest regression slope, which is -0.118% for the mean monthly reservoir storage, reflecting this river basin may experience a the declining trend over the period. Analyzing annual precipitation and evaporation amounts will clearly explain this reservoir storage value decrease because evaporation rates in this river basin are much higher than the average annual precipitation amounts.

Exceedance frequency is an expression for the percentage of time that particular storage amounts can be expected to occur. Equivalently, the exceedance frequency represents the likelihood or probability of a certain amount of water being available (Wurbs 2011). Frequency tables are created with TABLES 2FRE records. Reservoir storage frequency tables show what percentages of the maximum reservoir storage capacity are equal or exceed 100, 99, 98, 95, 90, 80, 70, 60, 50, 40, 30, 20, 10, 5, 2, 1 and 0.5% of the simulation sequence time.

Exceedance frequencies are determined from the results of a SIM simulation based on counting the relative frequency in which various quantities are equaled or exceeded. The mean storage volume, SD (standard deviation) maximum and minimum storage volume are at the top and bottom respectively with each column in units of acre-feet. The exceedance frequencies are listed in the first column.

The relative frequency equation is expressed by Eq. 5.1. In this equation, n is the number of months during the simulation that a particular flow or storage amount is equaled or exceeded, and N is the total number of months considered (Wurbs 2011). Reservoir storage frequency metrics in acre-feet for 20 WMA river basins are listed in Table 5.8.

$$\text{Exceedance Frequency} = \frac{n}{N}(100\%) \tag{5.1}$$

According to Table 5.8, the Lavaca River Basin has the largest exceedance frequency for full storage volume. The total reservoirs in this basin are nearly full at 100 percent capacity in 25 percent of the months for the 876 months of simulation. One possible reason is that only 21 reservoirs with 8 primary control points are in this river basin, thus the reservoirs are nearly full 25% for simulation time. Another reasonable factor is that climate in this basin is slightly wet with low evaporation and high precipitation rates.

Table 5.8
Reservoir Storage Frequency Metrics in acre-feet

	Colorado	Brazos	San Jacinto	Trinity	Neches
Mean	3,274,978	3,332,798	535,814	5,819,604	3,590,175
SD	434,369	366,301	56,969	854,458	77,428
Min	1,703,109	1,941,981	253,077	2,527,518	3,061,236
99.5%	1,943,192	2,101,658	279,338	2,642,273	3,243,630
99%	2,065,189	2,146,023	327,304	3,045,641	3,308,954
98%	2,263,165	2,297,065	386,944	3,364,477	3,371,322
95%	2,454,602	2,599,524	415,450	4,246,650	3,423,859
90%	2,673,102	2,844,695	452,510	4,785,074	3,484,408
85%	2,813,601	3,012,033	485,580	5,133,439	3,524,542
80%	2,922,046	3,080,316	501,486	5,315,968	3,552,808
75%	3,026,422	3,133,384	512,108	5,417,545	3,570,501
70%	3,108,938	3,203,081	523,719	5,512,516	3,589,987
60%	3,241,059	3,288,125	544,291	5,715,956	3,612,185
50%	3,330,371	3,428,300	561,332	5,931,644	3,623,266
40%	3,402,275	3,514,518	570,123	6,094,204	3,631,042
30%	3,488,144	3,576,961	574,893	6,248,728	3,636,754
25%	3,555,350	3,618,770	577,042	6,380,957	3,638,729
20%	3,672,154	3,652,525	578,193	6,519,455	3,640,652
15%	3,744,935	3,685,262	578,956	6,628,969	3,641,926
10%	3,818,686	3,706,213	579,430	6,804,933	3,643,083
5%	3,902,309	3,758,571	580,110	7,100,001	3,644,772
2%	4,003,559	3,800,552	580,354	7,261,623	3,645,230
1%	4,059,010	3,828,657	580,409	7,273,592	3,645,328
0.5%	4,109,053	3,840,319	580,438	7,291,789	3,645,384
Max	4,133,082	3,861,882	580,467	7,295,806	3,645,493

Table 5.8 Continued

	Canadian	Red	Sulphur	Cypress	Sabine
Mean	610,254	3,369,963	624,451	753,868	6,114,800
SD	171,942	164,352	65,620	44,350	171,985
Min	332,058	2,846,774	379,281	605,165	5,138,603
99.5%	340,403	2,890,551	397,378	614,070	5,249,399
99%	341,913	2,907,920	433,698	618,828	5,395,487
98%	344,855	2,972,759	466,342	635,168	5,646,705
95%	353,143	3,042,846	503,895	662,179	5,780,343
90%	367,195	3,111,638	538,457	689,688	5,903,030
85%	398,887	3,197,816	557,207	707,454	5,965,109
80%	422,412	3,239,806	573,477	717,662	6,014,913
75%	439,231	3,274,452	588,893	731,344	6,044,374
70%	477,418	3,302,715	602,561	738,954	6,077,161
60%	549,521	3,361,189	619,924	755,031	6,127,765
50%	639,546	3,403,304	629,973	767,632	6,169,118
40%	685,745	3,438,492	636,538	775,246	6,206,933
30%	738,107	3,471,458	662,211	783,933	6,235,053
25%	754,551	3,486,422	676,156	788,447	6,245,369
20%	777,207	3,509,374	689,848	792,865	6,248,876
15%	812,676	3,531,653	696,756	796,167	6,252,497
10%	845,210	3,554,812	714,741	799,302	6,254,827
5%	870,696	3,604,061	718,336	803,050	6,256,493
2%	876,792	3,616,589	718,650	807,254	6,258,001
1%	878,289	3,633,843	718,679	810,218	6,258,422
0.5%	878,452	3,649,513	718,680	811,850	6,258,516
Max	878,597	3,668,677	718,681	812,735	6,258,565

Table 5.8 Continued

	San Antonio-Nueces	Lavaca-Guadalupe	Colorado-Lavaca	Trinity-San Jacinto	Neches-Trinity
Mean	1,139	0	5,967	3,194	19,827
SD	229	0	755	681	2,544
Min	413	0	4,112	1,051	13,231
99.5%	488	0	4,174	1,143	14,394
99%	526	0	4,236	1,293	14,924
98%	611	0	4,367	1,537	15,252
95%	693	0	4,578	1,875	15,990
90%	752	0	4,817	2,202	17,081
85%	854	0	4,966	2,518	17,845
80%	938	0	5,149	2,584	18,156
75%	990	0	5,408	2,614	18,404
70%	1,046	0	5,660	2,775	18,585
60%	1,147	0	6,014	3,207	19,021
50%	1,214	0	6,062	3,379	19,354
40%	1,272	0	6,251	3,641	19,815
30%	1,315	0	6,411	3,802	20,366
25%	1,330	0	6,569	3,816	20,695
20%	1,344	0	6,680	3,825	21,342
15%	1,365	0	6,807	3,833	22,318
10%	1,368	0	6,947	3,843	23,614
5%	1,378	0	6,962	3,852	25,394
2%	1,382	0	6,976	3,867	26,623
1%	1,383	0	6,994	3,878	27,255
0.5%	1,384	0	7,031	3,884	27,679
Max	1,385	0	7,072	3,886	28,996

Table 5.8 Continued

	Rio Grande	Nueces-Rio Grande	Nueces	Guadalupe and San Antonio	Lavaca
Mean	1,713,860	39,059	508,744	603,433	155,253
SD	999,347	4,772	264,848	81,691	15,389
Min	222,827	27,470	4,814	325,501	88,291
99.5%	287,636	28,363	5,208	333,810	93,687
99%	303,787	28,668	5,885	375,109	100,808
98%	327,357	29,277	7,389	425,032	112,764
95%	352,302	30,740	39,477	473,224	126,293
90%	387,840	32,348	125,603	501,422	132,784
85%	438,122	33,667	176,153	513,571	138,093
80%	539,589	34,661	247,620	528,311	143,682
75%	666,864	35,456	304,904	542,790	147,560
70%	903,770	36,508	356,647	558,889	150,925
60%	1,375,231	37,968	450,449	585,752	156,660
50%	1,715,720	39,308	546,301	612,419	160,837
40%	2,096,475	40,877	611,164	636,834	165,037
30%	2,425,137	41,984	677,416	650,708	167,684
25%	2,564,534	42,904	716,155	662,066	167,714
20%	2,764,003	43,401	760,545	678,031	167,714
15%	2,939,645	43,956	814,263	688,781	167,716
10%	3,116,707	44,927	856,561	706,997	167,716
5%	3,233,823	46,041	911,147	725,313	167,716
2%	3,319,648	47,720	944,674	749,527	167,716
1%	3,405,030	49,698	949,561	754,474	167,716
0.5%	3,495,433	50,824	951,819	755,521	167,716
Max	3,498,063	52,188	952,669	756,055	167,716

Table 5.8 also shows, during 75 percent of the simulation period, the total storage volume equals or exceeds147, 560 acre-feet, which represents 88% of the reservoirs capacity and 95% of mean storage volume. The storage volume equals or exceeds 126,293 acre-feet, during 95 percent of months from 1940-2012, which is 75.3% of

capacity and 81.3 of the mean. Although, the reservoirs are full nearly one fourth of the month, the minimum volume is 88,291ac-ft, thus the SD value is 15,389.

The Brazos River Basin, contains over 700 reservoirs cited in water right permits, is one of the basins with a large number of reservoirs. Forty-three of these permitted reservoirs have conservation storage capacities of 5,000 acre-feet or greater (Wurbs, 2012). As seen from Table 5.8, the maximum storage volume in the Brazos is 3,861,882 ac-ft which is 96.1% of the storage capacity. The total reservoir storage volume in this basin is 3,133,384 ac-ft at 78 percent capacity in 75 percent of the months for the 876 month simulation. During 95 percent of the simulation period, the total storage volume equals or exceeds 2,599,524 acre-feet, which represents 64.7% of the reservoirs capacity. Most of the total reservoir storage capacity in the Brazos River Basin is contained in a relatively few large reservoirs even if numerous smaller reservoirs in this basin.

Appendix D is HEC-DSSVue plots for 19 of the monthly reservoirs storage volumes during a simulation period. According to Appendix D, dramatic spatial variations occur over the different river basins and adjoining coastal basins. One of the reason is that climate, hydrology, and geography vary from river basin to river basin. In most cases, the increase storage volume would be expected as larger reservoir storage is able to supply a greater amount of water to meet the targeted diversions. The decreasing reservoir volumes is reasonable to expect because several hydrologic changes can occur on a basin level basis. It is logical to expect that reservoir storage levels would decrease because more climate changes such as high temperatures lead to more evaporation from the surface or human supply using more water from the reservoir to meet the demand. In addition, reservoir storage capacity is diminished over time due to accumulation of sediment. Total storage volume for all reservoirs in the Rio Grande River Basin has great variability in storage volume during the time 1940-2000. The Amistad, Falcon and Red Bluff are three major reservoirs in the Rio Grande. Red Bluff reservoir on the Pecos River is the only reservoir of these three that is totally located in the United States, while the other two reservoirs' storage capacity are nearly 50% in Mexico. The minimum storage volume is 222,827ac-ft in July1956, which is 6.37% of storage capacity in the United States. The mean storage volume is 1,713,859 ac-ft, which is 50% of storage capacity in United States. The Maximum volume is 3,498,063ac-ft in Dec1942, which is 99.97% of storage capacity. From the plots of storage, volumes is shown high in 1942 and in 1943 and then decreases from 1944 to 1956. The lower storage volumes in 1956, 1971, 1960 and 2000 may match well with the drought which happened in Texas during 1956, 1980, and 2012.

The Colorado River Basin with 489 reservoirs is another river basin with relatively large changes in storage volume from 1940 to 2012. Austin is one of the largest cities in Texas and the largest in the Colorado River Basin. The Colorado River flows through Austin and thus serves as the primary water supply source for the city (Wurbs, 2013). The minimum storage volume is 1,703,109 ac-ft in July1952, which is 36.2% of the total storage capacity. The maximum volume is 4,133,082ac-ft in Jan 1958 and is 87.7% for storage capacity. As seen in Appendix D, the storage volume is relatively large in autumn than in summer. One reason is that demand of domestic water in summer is larger than winter. The drought occurred in Texas during 1956, 1980, and 2012 which also contributed to the low reservoirs storage volume in Colorado River Basin.

Additionally, reservoir storage volumes for most river basins, which near the outlet of the Gulf of Mexico, show no great variability in storage volume during the simulation period. It is attributed to several factors. One factor contributing to less variability is that water supplies in eastern river basins are relatively easily satisfied which causes reservoir volumes to remain with high levels during the course of the year. Another contributing factor is that the number of reservoirs in eastern Texas is lower than northern Texas.

5.4 Frequency Metrics for Naturalized versus Regulated Stream Flows

In order to understand current river basin conditions, frequency analyses for naturalized and regulated stream flows are performed by using the WRAP-SIM. Naturalized stream flows are flows that would have occurred naturally without specified water uses, reservoirs, or any other human impact. Regulated flows are computed by the WRAP simulation model by a series of water management scenario. Regulated flows at basin outlets are computed flows reflecting the water management scenario incorporated in the river basin.

Frequency analyses are performed for the simulated naturalized and regulated flows at basin outlets to determine the flows that are equaled or exceeded in 0.5%, 1%, 2%, 5%, 10%, 25%, 50%, 75%, 90%, 95%, and 100% of the months of the hydrologic period-of-analysis. Mean and maximum flows will also be determined.

Table 5.9

Frequency Metrics in acre-feet/month for Naturalized and Regulated Flows at Basin Outlets

	Colorado		Brazos		San Jacinto		Trinity		Neches	
	Nat	Reg	Nat	Reg	Nat	Reg	Nat	Reg	Nat	Reg
Mean	259,899	158,991	603,864	508,343	189,174	201,247	552,523	402,395	518,629	464,311
SD	325,784	280,161	786,811	765,166	254,331	244,428	679,163	598,593	584,119	591,800
Min	7,909	0	4	6,981	2,791	40,591	749	407	4,994	0
99.5%	10,553	0	13,372	7,869	5,428	41,213	2,232	1,505	10,923	0
99%	14,479	0	17,611	8,646	6,196	41,773	3,408	5,725	12,712	0
98%	20,898	0	25,190	9,391	7,717	42,710	5,993	9,530	15,567	0
95%	34,149	1,223	38,338	11,121	10,905	45,860	11,908	10,611	24,953	0
90%	45,931	3,188	59,028	14,528	14,583	48,451	30,487	14,099	43,258	1,691
85%	54,576	9,417	82,255	24,918	19,987	51,014	48,113	17,199	59,447	4,060
80%	66,073	16,651	108,003	42,557	25,461	55,809	68,064	19,766	79,925	14,592
75%	75,635	20,685	131,538	62,325	32,393	59,495	100,678	22,783	98,825	29,465
70%	84,755	22,468	161,341	82,164	40,138	62,802	141,863	27,232	125,075	54,883
60%	109,193	33,784	226,102	131,086	60,857	76,668	211,016	71,463	205,239	130,108
50%	142,149	48,514	306,959	196,625	86,984	99,991	285,135	136,368	287,667	223,969
40%	191,547	76,896	409,074	295,867	126,001	135,882	422,850	248,579	426,012	366,105
30%	265,618	145,931	600,253	470,179	203,779	191,444	607,035	395,816	630,880	553,972
25%	322,934	186,456	735,958	628,899	248,301	237,967	750,025	540,770	761,127	701,327
20%	377,934	237,732	940,576	821,493	314,771	305,465	942,151	702,955	908,150	846,565
15%	461,371	315,901	1,254,435	1,124,451	388,272	384,418	1,153,102	887,741	1,068,342	1,036,418
10%	602,881	413,935	1,559,164	1,432,321	524,462	517,392	1,436,856	1,180,682	1,326,510	1,278,601
5%	843,832	643,383	2,261,526	2,026,017	701,710	710,395	2,007,756	1,653,765	1,744,840	1,704,955
2%	1,368,840	1,094,956	3,033,807	2,917,662	942,826	930,232	2,741,290	2,423,908	2,236,289	2,213,305
1%	1,724,149	1,503,652	3,769,842	3,730,842	1,126,219	1,142,190	3,149,243	2,805,262	2,564,708	2,572,751
0.5%	2,043,951	1,695,060	4,183,200	4,040,264	1,472,855	1,479,899	3,765,780	3,371,059	2,854,361	2,854,859
Max	2,947,059	2,867,877	7,573,162	7,375,430	2,264,852	2,238,260	4,629,959	3,847,882	3,942,327	3,865,810

Table 5.9 Continued

	Rio Grande		Nueces-Rio Grande		Nueces		Guadalupe and San Antonio		Lavaca	
	Nat	Reg	Nat	Reg	Nat	Reg	Nat	Reg	Nat	Reg
Mean	91,633	6,264	25,026	26,500	53,994	36,701	185,011	171,918	71,700	67,195
SD	84,373	35,923	82,274	81,514	126,476	90,170	236,167	233,266	123,746	121,105
Min	12,898	4.94	0	1,506	92	534	1,352	0	0	178
99.5%	23,714	9.58	0	1,539	175	1,206	3,530	838	0.38	413
99%	25,440	13.3	0	1,557	280	1,785	4,607	1,074	66	468
98%	27,651	28.3	0	1,569	377	8,697	6,868	1,597	389	610
95%	34,019	68.2	0	1,633	698	8,819	11,794	6,367	1,700	1,256
90%	40,058	131	0	1,776	1,445	9,520	26,744	20,058	2,798	2,785
85%	44,204	193	0	1,820	2,031	9,724	38,598	26,996	4,997	4,383
80%	47,540	256	0	1,909	3,170	9,880	48,135	38,255	6,631	5,954
75%	50,846	337	0	2,032	4,085	10,432	57,883	45,776	8,184	7,438
70%	53,592	392	0	2,088	5,355	10,694	66,784	55,611	10,391	9,323
60%	60,018	545	0	2,145	8,193	11,479	85,253	70,586	15,550	12,328
50%	67,964	690	8.69	2,194	12,400	13,226	104,962	91,999	22,239	18,120
40%	76,965	895	663	2,557	21,930	14,126	133,967	121,790	35,268	29,065
30%	91,964	1,224	3,824	5,326	35,215	21,980	187,250	170,597	61,205	50,636
25%	103,636	1,460	7,959	9,264	47,780	24,554	222,115	206,069	75,036	68,999
20%	112,705	1,993	15,658	16,761	69,568	33,497	275,412	257,721	107,172	98,702
15%	136,980	2,925	28,410	28,854	100,619	45,990	332,823	316,342	139,881	134,821
10%	158,731	4,789	66,134	65,598	142,052	69,213	435,713	424,763	208,550	202,336
5%	212,498	14,546	152,482	151,985	229,647	135,572	558,313	540,738	310,262	302,682
2%	321,721	72,700	263,741	262,910	416,438	295,849	991,366	959,690	476,902	470,762
1%	562,280	147,053	432,098	431,541	593,797	419,235	1,226,298	1,195,312	639,956	613,460
0.5%	683,349	236,509	632,501	627,111	798,457	736,631	1,419,013	1,418,177	818,156	805,978
Max	938,629	663,763	884,553	886,800	1,775,739	1,300,862	2,485,789	2,462,770	1,147,303	1,123,271

Table 5.9 Continued

	Canadian		Red		Sulphur		Cypress		Sabine	
	Nat	Reg	Nat	Reg	Nat	Reg	Nat	Reg	Nat	Reg
Mean	18,129	10,699	841,106	759,696	215,890	209,162	139,642	122,725	552,757	515,978
SD	39,454	29,604	909,792	884,994	295,309	281,126	178,930	174,578	564,470	572,702
Min	0	18.5	10,988	8,249	1	9,907	0	0	4,190	3,303
99.5%	0	22	35,594	22,725	41.7	9,907	0	0	13,298	9,027
99%	11.5	28	43,374	29,140	69	9,907	0	0	16,947	11,185
98%	98.7	81.8	59,408	45,270	118	9,907	1.48	0.69	22,188	13,360
95%	417	203	93,625	65,017	808	13,229	297	10.7	37,220	19,270
90%	664	315	126,644	88,958	2,048	15,094	1,519	107	58,792	31,391
85%	850	407	159,415	111,335	5,223	16,184	3,566	119	78,191	45,446
80%	1,122	544	189,766	132,373	9,547	17,256	8,892	128	99,199	60,087
75%	1,596	735	239,388	172,435	12,997	20,978	14,315	140	130,133	80,585
70%	2,073	944	289,111	210,174	20,088	27,811	20,331	140	162,333	114,812
60%	3,136	1,535	382,079	306,647	42,253	44,741	37,312	14,875	235,498	184,482
50%	5,201	2,894	527,208	448,777	91,751	87,935	64,737	41,501	349,501	297,513
40%	8,838	5,049	723,617	614,502	162,359	147,491	108,998	91,111	505,222	454,203
30%	14,433	7,016	963,235	883,137	255,347	241,061	167,690	147,014	684,841	647,757
25%	17,631	8,615	1,158,713	1,094,913	307,025	284,912	203,078	185,087	823,795	797,532
20%	23,560	11,011	1,342,618	1,238,228	380,647	356,242	243,178	226,921	990,837	957,570
15%	30,780	15,097	1,607,078	1,507,619	457,778	440,138	299,747	279,812	1,139,717	1,108,683
10%	42,627	21,345	1,875,588	1,752,718	608,303	585,394	388,209	373,940	1,336,891	1,321,293
5%	75,848	42,152	2,657,580	2,570,737	864,124	834,620	515,721	500,022	1,628,330	1,634,512
2%	145,050	102,467	3,678,647	3,459,597	1,138,103	1,072,663	695,768	647,140	2,055,026	2,046,774
1%	228,077	142,093	4,350,456	3,973,142	1,341,679	1,316,299	831,095	801,007	2,446,408	2,375,020
0.5%	289,275	218,011	5,205,627	5,131,623	1,586,838	1,506,763	904,173	873,950	3,021,878	3,053,333
Max	431,251	388,692	7,930,258	7,674,306	1,925,586	1,813,977	1,166,637	1,055,123	4,224,389	4,239,640

Table 5.9 Continued

	San Antonio-Nueces		Lavaca-Guadalupe		Colorado-Lavaca		Trinity-San Jacinto		Neches-Trinity	
	Nat	Reg	Nat	Reg	Nat	Reg	Nat	Reg	Nat	Reg
Mean	47,100	47,103	33,878	34,745	32,700	31,752	15,075	15,845	96,064	87,781
SD	155,369	155,391	70,436	70,426	53,668	53,094	23,482	23,370	117,721	113,379
Min	1	69.7	0	520	0	31	0	1,393	129	1,482
99.5%	50.2	104	0	546	0	102	0	1,486	150	1,687
99%	96.4	140	0	562	0	178	131	1,515	165	2,212
98%	187	207	0	605	0	389	369	1,634	550	2,479
95%	350	382	43.6	747	174	856	558	1,775	1,089	3,584
90%	556	565	403	1,219	858	1,443	829	1,941	4,561	5,136
85%	834	838	748	1,636	1,556	2,209	1,058	2,175	9,571	7,482
80%	1,042	1,030	1,159	2,100	2,049	2,694	1,426	2,439	15,232	11,441
75%	1,193	1,195	1,595	2,551	3,261	3,498	1,915	2,848	20,275	16,055
70%	1,469	1,474	2,227	3,130	4,208	4,226	2,588	3,481	25,693	20,106
60%	2,252	2,238	4,097	4,959	6,352	6,292	4,006	4,580	39,031	32,713
50%	3,808	3,816	7,446	8,403	12,636	10,448	5,643	6,241	57,302	49,486
40%	7,743	7,761	12,401	13,334	19,600	18,004	8,441	8,861	81,833	71,434
30%	17,423	17,367	20,966	21,890	30,226	28,222	14,346	14,931	113,585	100,631
25%	24,313	24,151	30,978	31,695	36,554	34,355	18,420	18,606	131,646	117,388
20%	36,626	36,704	43,429	44,122	46,621	44,890	23,955	24,456	151,466	138,726
15%	65,028	65,129	65,110	65,960	68,635	67,754	32,049	32,205	179,679	165,768
10%	103,882	103,922	99,668	100,488	93,810	92,359	41,302	42,197	219,223	204,249
5%	251,606	251,735	163,155	163,987	131,978	129,152	59,345	60,324	319,685	306,101
2%	536,597	536,771	277,267	277,987	189,995	189,058	85,577	86,418	465,176	442,608
1%	597,850	598,025	383,610	384,299	290,822	290,312	133,641	132,868	620,661	601,403
0.5%	666,612	666,607	464,636	465,237	378,539	378,787	159,854	160,366	739,043	716,614
Max	2,591,183	2,591,572	619,624	620,274	431,306	429,875	197,802	198,678	1,006,057	986,885

Frequency metrics in acre-feet/month for naturalized and regulated flows at 20 WAM basin outlets are provided in Table 5.9. According to Table 5.9, both naturalized and regulated flows in each of the river basins outlets varies in amount, corresponding period of analysis. The basins with larger naturalized flows also have larger regulated flows. Some of the larger river basins including, the Sabine, Red, Brazos, Trinity and Neches river basin have naturalized flows larger than 400,000 acre-feet/month, while naturalized flows in other river basins such as Trinity-San Jacinto, Colorado-Lavaca, Lavaca-Guadalupe, are less than 40,000 acre-feet/month.

The index, expresses the altered mean regulated flow as a percentage of the original mean natural flow. The Rio Grande, Canadian and Colorado River Basins are the three river basins with the lowest index, which is 6.83%, 59.0%, and 61.2% respectively. The index for the other river basins are all higher than 65 percent.

As illustrated in Table 5.9, most of river basins' naturalized flows are greater than regulated flow at the basin outlet, such as the Colorado, Brazos, Trinity, Neches, Guadalupe, San Antonio, Rio Grande, Nueces, Lavaca, Canadian, Red, Sulphur, Cypress, Sabine, Colorado-Lavaca and Neches-Trinity River Basins. As the naturalized flows are the total stream flow without human activities, it is expected to be greater than the regulated flows. Compared with most coastal basins, the river basins in the western part of Texas such as Brazos, Colorado and Trinity have larger regulated flows. These basins have relatively larger reservoir storage capacities, and thus it is expected that regulated flows should be larger.

CHAPTER VI

COMPARATIVE ANALYSIS OF OBSERVED, NATURALIZED, AND REGULATED FLOWS

Long-term trends for both observed gauged flows from USGS records at selected sites and the corresponding computed naturalized, regulated flows from the WAM System datasets are analyzed. Statistical trend analyses of naturalized flows will contribute to differentiating between various factors that caused flow changes. The statistical analyses of gauged flows represent a traditional approach that can be compared with the analyses of WRAP/WAM system simulation results to quantifying long-term changes on river systems in this chapter.

6.1 Selected WAM Control Point at 35 Gauge Sites

In order to synthesize and analyze the relative effects of climate change, water resources development, and other factors on river flow, there are 31 control points gauges selected from the 35 gauge sites discussed in chapter 4. Both observed gauged flows from USGS records at these selected sites and the corresponding computed naturalized, regulated flows from the WAM System datasets are compared for each of this 31 gauges. For lack of WAM system dataset for gauges on the Rio Grande River at EI Paso, the Rio Grande River at Brownsville, and the Red River near the cities of Terrel and Red River Arthur these four gauges are taken off from 35 gauge sites. A variety of river basin information for selected stream flow on gauging stations including period of analysis, Fig 4.3 ID, gauge ID, Location (River and Nearest city), WAM CP ID, and watershed area are listed in Table 6.1. The WRAP will be executed with the WAM System dataset for a particular river basin with sequences of naturalized and regulated flows output for selected gauges locations.

The observed flows show the volume of runoff from 31 selected USGS measured gauge sites. The naturalized flows in the WAM System datasets were computed by adjusting gauged flows to remove all the effects of constructing and operating dams, reservoirs, other facilities, water supply diversions, and return flows from surface and ground water use. Regulated flows are physical flows at a control point that reflects the local water management scenario which is incorporated in the simulation model. The 2-Month Minimum and 2-Month Maximum Flows are minimum or maximum flow volumes in two consecutive months, which are calculated respectively using monthly flow-rate data series. They are used to indicate the range of two month change.

Table 6.1
Selected Control Points at Stream Flow Gauging Stations

Fig. 4.3 ID	Gauge ID	Location River and Nearest City	WAM CP ID	Analysis Period	Watershed Area Total (square miles)	Watershed Area Contributing (square miles)
3	08412500	Pecos River at Orla	GT3000	1940-2000	25,070	21,229
4	08210000	Nueces River at Three Rivers	CP29	1934-1996	15,427	–
5	08211000	Nueces River at Mathis	CP30	1934-1996	16,503	–
6	08183500	San Antonio River Falls City	CP32	1940-2012	2,113	–
7	08188500	San Antonio River at Goliad	CP37	1940-2012	3,921	–
8	08167500	Guadalupe River at Spring Branch	CP02	1940-2012	1,315	–
9	08176500	Guadalupe River at Victoria	CP15	1940-2012	5,198	–
10	08164000	Lavaca River near Edna	GS300	1940-1996	817	–
11	08147000	Colorado River near San Saba	F10000	1940-2012	31,217	19,819
12	08158000	Colorado River at Austin	I10000	1940-2012	39,009	27,606
13	08161000	Colorado River at Columbus	J10000	1940-2012	41,640	30,237
14	08162500	Colorado River near Bay City	K10000	1940-2012	42,240	30,837
15	08082500	Brazos River at Seymour	BRSE11	1940-2012	15,538	5,972
16	08096500	Brazos River at Waco	BRWA41	1940-2012	29,559	19,993
17	08106500	Little River at Cameron	LRCA58	1940-2012	7,065	–
18	08110500	Navasota River at Easterly	NAEA66	1940-2012	968	–
19	08114000	Brazos River at Richmond	BRRI70	1940-2012	45,107	35,541
20	08074000	Buffalo Bayou in Houston	BBHO	1940-1996	336	–
21	08068000	West Fork San Jacinto near Conroe	WSCN	1940-1996	828	–
22	08048000	West Fork Trinity at Fort Worth	8WTFW	1940-2012	2,615	–
23	08057000	Trinity River at Dallas	8TRDA	1940-2012	6,106	–
24	08062500	Trinity River near Rosser	8TRRS	1940-2012	8,146	–
25	08065000	Trinity River near Oakwood	8TROA	1940-2012	12,833	–
26	08066500	Trinity River at Romayor	8TRRO	1940-2012	17,186	–
27	08033500	Neches River near Rockland	NERO	1940-2012	3,636	–
28	08041000	Neches River near Evansdale	NEEV	1940-2012	7,951	–
29	8022040	Sabine River near Beckville	SRBE	1940-2012	3,589	–
30	8030500	Sabine River near Ruliff	SRRL	1940-2012	9,329	–
31	07346000	Big Cypress Bayou at Jefferson	B10000	1940-1998	850	–
34	07227500	Canadian River near Amarillo	A10000	1948-1998	19,445	15,376
35	07228000	Canadian River near Canadian	B10000	1948-1998	22,866	18,178

Some large basins, such as Trinity, Colorado, and Brazos river basins vary in shape, climate, geology, and topography, therefore, more control gauges are chosen for these basins. According to Table 6.1, there is great diversity between the 31 selected stream flow gauges stations. Analysis period in most control gauges are from 1940 to 2012, but for some gauges stations in Nueces, Buffalo Bayou, West Fork San Jacinto, and the Lavaca River are only updated to 1996. Similarly, selected gauges in Big Cypress Bayou and the Canadian River are updated to 1998. The Gauge ID are number ID for these gauges recorded in the U. S. Geological Survey, while WAM CP ID is the number ID used in WRAP program.

The Total watershed area is equal to the contributing watershed area in most selected gauges stations. However, in some gauges sites such as on the Pecos River at Orla, Brazos River at Seymour, Brazos River at Waco, Brazos River at Richmond Canadian River near Amarillo, Canadian River near Canadian and four gauges at the Colorado River, contributing watershed area is less than the total watershed area. The calculated mean annual flow, averaged over a simulation period of the 31 gauges stations are shown in Table 6.2. The means value of annual 2-month minimum and 2-month maximum flows in the gauging stations are listed in Table 6.3.

Table 6.2
Mean Annual Flows

Fig. 4.3		Mean Annual Flow (acre-feet/year)		
ID	Location (River, Nearest City)	Observed	Naturalized	Regulated
3	Pecos River, Orla	99,293	124,378	77,003
4	Nueces, Three Rivers	544,744	575,466	598,812
5	Nueces, Mathis	533,083	585,993	492,724
6	San Antonio, Falls City	388,601	328,547	357,568
7	San Antonio, Goliad	589,033	528,485	556,432
8	Guadalupe, Spring Branch	284,370	257,372	250,323
9	Guadalupe, Victoria	1,412,554	1,329,654	1,267,790
10	Lavaca, Edna	249,702	250,968	250,591
11	Colorado, San Saba	575,496	819,503	525,213
12	Colorado, Austin	1,320,592	1,749,807	1,024,126
13	Colorado, Columbus	2,002,189	2,459,684	1,764,293
14	Colorado, Bay City	1,486,548	2,767,169	1,516,501
15	Brazos, Seymour	223,943	238,820	230,604
16	Brazos, Waco	1,622,980	1,882,353	1,520,040
17	Little River, Cameron	1,268,964	1,351,437	1,129,312
18	Navasota, Easterly	303,359	325,370	259,276
19	Brazos, Richmond	13,094,677	5,822,300	5,103,043
20	Buffalo Bayou, Houston	331,338	224,032	248,821
21	WF San Jacinto, Conroe	362,369	379,319	318,392
22	WF Trinity, Fort Worth	291,285	440,922	224,582
23	Trinity, Dallas	1,383,755	1,612,520	1,062,185
24	Trinity, Rosser	2,334,780	2,487,750	1,843,320
25	Trinity, Oakwood	3,949,702	4,149,320	3,146,506
26	Trinity, Romayor	5,824,135	6,077,828	4,983,771
27	Neches, Rockland	1,752,373	1,746,876	1,693,894
28	Neches, Evansdale	4,468,493	4,532,595	4,158,388
29	Sabine, Beckville	1,837,156	2,007,905	1,694,619
30	Sabine, Ruliff	5,979,583	6,271,324	5,854,440
31	Big Cypress, Jefferson	297,780	500,164	373,063
34	Canadian, Amarillo	152,878	153,760	153,547
35	Canadian, Canadian	130,457	189,221	97,582

Other relative variable information of the selected stream flows gauging stations include Fig 4.3 ID, Location (River and Nearest City), and mean annual flow for observed, naturalized, and regulated are described in Table 6.2. Units for mean observed annual USGS gauged flow are daily average cubic feet per second. These observed annual flows are converted into acre-feet per year to correspond to WRAP-SIM results naturalized and regulated flow.

According to Table 6.2, annual regulated flows are in proportion to annual observed and naturalized flows. Regulated flows in some gauge sites such as the Brazos River at Richmond, Trinity River near Oakwood, Trinity River at Romayor, Neches River near Evansdale and Sabine River near Ruliff are greater than 3,000,000 acre-feet. High volume is expected for the regulated flows in these gauge sites because they have high volume of both observed and naturalized flows. In addition, these gauges are located in the downstream portion of some main rivers or along the Gulf of Mexico, thus stream flow volumes are relatively large in these gauges. Gauge sites with the smaller regulated flow are located in the upstream portion of some major rivers, including the gauges on the Pecos River at Orla, Big Cypress Bayou at Jefferson, Colorado River near San Saba, Brazos River at Seymour, Navasota River at Easterly, West Fork Trinity at Fort Worth and Canadian River near Canadian. The volume of regulated flows in these gauges sites is less than 400,000 acre-feet.

The maximum value of observed, naturalized and regulated flows is 13,094,677 acre-feet, 5,822,300 acre-feet and 5,103,043 acre-feet detected in the Brazos River at the Richmond gauge site. A possible reason for this large stream flow is that the total watershed area is 45,107 square miles and the contributing watershed area is 35,541 square miles, both of which are the largest among all the gauge sites. Another reason may be that the number of reservoirs and average sizes of the reservoirs are very large in this watershed area. The minimum value for annual observed, naturalized and regulated flows are 99,293acre-feet, 124,378 acre-feet and 77,003acre-feet which has taken place in the Pecos River at Orla. The total watershed area is 25,070 square miles and contributing watershed area is 21,229 square miles. Though none of them is the smallest watershed area, this gauge is located in portions of the state that has a relatively high evaporation rate, which leads to such small volumes.

At most gauge sites, the mean annual naturalized flows are larger than the mean annual observed flows, which attributes to the fact that observed flows are influenced by water supply. Thus naturalized flows, or flows without human activity impacts, are reasonable to have higher volumes of flows than the flows impacted by water delivery. However, in some gauges such as selected ones in the San Antonio River, Guadalupe River and Neches River near Rockland, the mean annual naturalized flows are less than the mean annual observed flows. The relatively smaller volume of naturalized flows may result from the insufficient water supply of existing surface water supplies, and therefore the possibility of a future increase in surface water supplies is very slim. (TWDB 2012).

Table 6.3
Means of Annual 2-Month Minimum and 2-Month Maximum Flows

	Location	2-Month Minimum (acre-feet)			2-Month Maximum (acre-feet)		
	River, Nearest City	Observed	Natural	Regulated	Observed	Natural	Regulated
3	Pecos River, Orla	2,002	5,782	857	40,829	54,217	33,153
4	Nueces, Three Rivers	6,352	7,227	20,430	318,014	337,537	303,623
5	Nueces, Mathis	10,560	6,413	32,771	312,841	345,454	223,278
6	San Antonio, Falls City	26,455	14,745	22,817	143,749	139,626	139,044
7	San Antonio, Goliad	33,333	20,113	28,171	241,730	237,673	236,481
8	Guadalupe,SpringBranch	11,785	9,834	9,008	125,221	111,918	110,370
9	Guadalupe, Victoria	79,335	62,429	56,001	543,697	551,387	539,552
10	Lavaca, Edna	4,524	4,300	4,267	130,623	131,702	131,612
11	Colorado, San Saba	13,589	29,415	16,749	308,926	410,542	278,642
12	Colorado, Austin	51,957	83,449	26,833	521,552	769,199	478,627
13	Colorado, Columbus	100,181	113,973	71,375	759,916	1,027,331	747,226
14	Colorado, Bay City	57,747	129,424	17,170	634,909	1,126,143	740,021
15	Brazos, Seymour	2,318	2,564	2,506	131,872	142,277	137,808
16	Brazos, Waco	50,357	35,893	16,828	813,948	941,290	842,464
17	Little River, Cameron	25,597	25,631	18,177	555,770	664,722	583,781
18	Navasota, Easterly	1,853	1,374	500	170,591	178,897	155,139
19	Brazos, Richmond	329,852	170,782	129,274	5,357,842	2,520,559	2,326,046
20	Buffalo Bayou, Houston	7,591	7,127	11,327	121,665	92,445	96,544
21	WF San Jacinto, Conroe	5,297	4,539	4,288	172,780	179,495	155,782
22	WF Trinity, Fort Worth	5,573	4,537	927	182,127	264,162	160,861
23	Trinity, Dallas	47,796	20,957	43,978	660,926	879,891	565,301
24	Trinity, Rosser	86,396	34,983	78,834	1,069,880	1,309,667	941,155
25	Trinity, Oakwood	110,312	61,313	88,441	1,878,444	2,075,970	1,625,333
26	Trinity, Romayor	161,127	116,710	142,659	2,571,135	2,708,987	2,283,471
27	Neches, Rockland	34,153	27,962	24,334	771,425	774,980	769,180
28	Neches, Evansdale	211,669	87,610	50,544	1,683,207	1,923,570	1,872,013
29	Sabine, Beckville	30,582	35,037	23,993	856,086	912,283	830,215
30	Sabine, Ruliff	241,493	174,384	129,298	2,298,889	2,499,285	2,447,682
31	Big Cypress, Jefferson	3,793	4,622	840	135,109	234,779	197,117
34	Canadian, Amarillo	1,752	1,757	1,817	84,429	84,745	84,579
35	Canadian, Canadian	1,913	2,275	1,015	74,185	102,188	55,618

In order to get an integrated description of annual stream flow, means of annual 2-Month Minimum and 2-Month Maximum flows are an indices on severity. They are calculated using a daily flow-rate data series. As seen in Table 6.3, the lowest value for

2-Month Minimum observed flows is 1,752 acre-feet, while 1,757 acre-feet and 1,817 acre-feet for natural and regulated respectively in the gauge on the Canadian River near Amarillo. The second lowest value for 2-Month Minimum observed flows is 1,853 acre-feet, natural flow being 1,374 acre-feet and regulated flow being 500 acre-feet which occurred in the Navasota River at Easterly. The third lowest observed value for 2-Month Minimum flows been gauged on the Canadian River near Canadian.

According to Table 6.3, the highest value for 2-Month Maximum observed flows is 5,357,842acre-feet, while 2,520,559acre-feet and 2,326,046acre-feet are for natural and regulated flow respectively in this gauge on the Brazos River at Richmond. The second highest value for 2-Month Maximum observed flow is 2,571,135 acre-feet, read at the gauge on the Trinity River at Romayor. Natural and regulated flow are 2,708,987 acre-feet and 2,283,471 acre-feet in those gauges. The third highest value for 2-Month Maximum flow is in the Sabine River near Ruliff.

6.2 Linear Trend Analyses

The linear trend analyses of gauged flows and WRAP/WAM system simulation natural and regulated flows represent a traditional statistical approach for quantifying long-term changes in stream flows. Linear trend regression analyses operated by the program HydStats, which is similar to the routines in the WRAP program HYD that are based on the Texas Water Development Board (TWDB) datasets in the files Precipitation.PPP and Evaporation.EEE. The input file for program HydStats is a file named HSF, with data sequences included in the HSF file. The HydStats may read data sequences from the input files Precipitation.PPP, and Evaporation.EEE as an alternative.

The HydStats program first reads sequences of monthly data and develops sequences of annual data from the monthly data. Then the program computes basic statistics values such as mean, and maximum and minimum flow. Finally, it performs linear trend regression analyses and stores the time series data, computes metrics in a text file, and stores the time series data in a DSS file. Output files with filename extensions MSS and OUT are automatically created, and DSS output files being optionally created in this simulation are accessed with HEC-DSSvue for plotting.

The parameter OUTFILE in HS record field 7 controls the OUT file. When the OUTFILE option 3 is used, the regression coefficient table will be created in the OUT file. Regression analyses are performed for the data series defined by SERIES which consists of all of aggregated annual quantities, annual minima of two-month forward moving averages and annual maxima of two-month forward moving averages, with value equaling 2, 3, 4 in SERIES. The results of linear trend regression coefficients about mean annual observed, naturalized and regulated flows in the selected 31 gauges are listed in the Table 6.4 for comparison.

Table 6.4
Linear Trend Regression Coefficients for Mean Annual Flow

		Slope (percent of mean)			Intercept (percent of mean)		
	River, Nearest City	Observed	Natural	Regulated	Observed	Natural	Regulated
3	Pecos River, Orla	-3.455	-2.825	-3.348	207.1	187.6	203.8
4	Nueces, Three Rivers	-1.086	-0.770	-0.582	131.5	122.3	116.9
5	Nueces, Mathis	-1.400	-0.948	-0.880	140.6	127.5	125.5
6	San Antonio, Falls City	1.253	0.619	0.643	53.6	75.2	74.3
7	San Antonio, Goliad	0.892	0.430	0.451	67.0	82.8	81.9
8	Guadalupe,SpringBranch	1.021	0.462	0.471	62.2	81.5	81.2
9	Guadalupe, Victoria	0.561	0.160	0.175	79.2	93.6	93.0
10	Lavaca, Edna	0.823	0.852	0.853	76.1	75.3	75.3
11	Colorado, San Saba	-1.364	-0.534	-0.615	150.5	119.8	122.8
12	Colorado, Austin	-0.474	-0.0234	0.212	117.5	100.9	92.1
13	Colorado, Columbus	-0.327	-0.0490	0.0776	112.1	101.8	97.1
14	Colorado, Bay City	0.818	0.0953	0.345	69.7	96.5	87.2
15	Brazos, Seymour	-1.108	-0.701	-0.714	141.0	125.9	126.4
16	Brazos, Waco	-0.345	-0.073	-0.038	112.8	102.7	101.4
17	Little River, Cameron	0.057	0.238	0.306	97.9	91.2	88.7
18	Navasota, Easterly	0.013	0.235	0.271	99.5	91.3	90.0
19	Brazos, Richmond	-0.362	0.070	0.099	113.4	97.4	96.3
20	Buffalo Bayou, Houston	3.246	0.568	0.510	5.88	83.5	85.2
21	WF San Jacinto, Conroe	-0.087	0.109	0.073	102.5	96.8	97.9
22	WF Trinity, Fort Worth	-0.288	0.038	0.215	110.6	98.6	92.1
23	Trinity, Dallas	0.529	0.360	0.555	80.4	86.7	79.5
24	Trinity, Rosser	0.626	0.422	0.597	76.8	84.4	77.9
25	Trinity, Oakwood	0.248	0.110	0.190	90.8	95.9	93.0
26	Trinity, Romayor	0.143	0.073	0.105	94.7	97.3	96.1
27	Neches, Rockland	-0.059	-0.112	-0.144	102.2	104.1	105.3
28	Neches, Evansdale	-0.083	-0.072	-0.102	103.1	102.7	103.8
29	Sabine, Beckville	-0.231	-0.074	-0.095	108.5	102.7	103.5
30	Sabine, Ruliff	-0.439	-0.294	-0.372	116.3	110.9	113.8
31	Big Cypress, Jefferson	0.802	0.416	0.525	79.2	89.2	86.3
34	Canadian, Amarillo	-1.696	-1.700	-1.698	144.1	144.2	144.1
35	Canadian, Canadian	-4.496	-2.104	-2.973	216.9	154.7	177.3

The regression provides an indication of long-term trends in changes in observed, natural, and regulated flows. A slope of zero and intercept equal to the mean indicates that there is no long-term linear trend. The linear trend regression coefficients shown in Table 6.4 are the slope and intercept expressed as a percentage of the mean annual flow. Observing from Table 6.4, in most selected gauges both the long-term increase and decrease trend of observed flow are consistent with the trend in natural and regulated annual flow.

There is a decrease trend on mean annual of observed flow on gauges in the Pecos River at Orla, Nueces River at Three Rivers, Nueces River at Mathis, Colorado River near San Saba, Brazos River at Seymour, Brazos River at Waco, Neches River near Rockland, Neches River near Evansdale, Sabine River near Beckville, Sabine River near Ruliff, Canadian River near Amarillo, Colorado River at Austin, Brazos River at Richmond, West Fork San Jacinto near Conroe, West Fork Trinity at Fort Worth, Colorado River at Columbus and Canadian River near Canadian, while in other gauges show a modest increase for long-term trend. The decrease trend on mean annual observed flow is the greatest in the gauges in the Canadian River near Canadian. The regression slope is -4.496%, and the regression intercept is 216.9% for the mean annual observed flow respectively. A series of factors may contribute to the decrease in the observed flow. One reasonable factor is that most gauges with large decrease trend are located in the portions of the state that experience high evaporation rates and low precipitation rates. In addition, growth rate of population in these areas are higher than in previous projections, thus human activity also plays an important role in this decrease (TWDB, 2012).

The greatest increase trend of observed flow is in the gauge on Buffalo Bayou in Houston, which has a regression slope of 3.246%, and the regression intercept is 5.88% for the mean annual observed flow respectively. This increase trend occurred could due to both relatively wet climate and human activity, such as a dredged channel, water reused, and reservoir releases.

The value of slope and intercept as a percentage of the annual mean value for both naturalized and regulated flows are less than the observed flows. Naturalized and regulated flows would be expected to have less changes because they are simulation flows computed by the WRAP program. However, in some cases decreases in the amount of annual regulated flow can occur due to the loss of reservoir capacity to sedimentation. The linear trend regression coefficients for annual 2-month minimum flow on 31 selected gauges are described in the Table 6.5

Table 6.5
Linear Trend Regression Coefficients for Annual 2-Month Minimum Flow

	River, Nearest City	Slope (% mean) Observed	Natural	Regulated	Intercept (% mean) Observed	Natural	Regulated
3	Pecos River, Orla	-3.611	-1.883	-4.458	211.9	158.4	238.2
4	Nueces, Three Rivers	1.666	0.508	0.409	51.7	85.3	88.1
5	Nueces, Mathis	1.935	2.013	-0.109	43.9	41.6	103.1
6	San Antonio, Falls City	0.637	-0.776	-0.232	76.4	131.0	109.3
7	San Antonio, Goliad	0.763	-1.078	-0.612	71.8	143.1	124.5
8	Guadalupe,SpringBranch	0.551	-0.358	-0.310	79.6	114.3	112.4
9	Guadalupe, Victoria	0.238	-1.301	-1.275	91.2	152.1	151.0
10	Lavaca, Edna	-0.684	-0.769	-0.773	119.8	122.3	122.4
11	Colorado, San Saba	-1.598	-0.107	-0.248	159.1	103.9	109.2
12	Colorado, Austin	-2.318	0.0405	0.577	185.8	98.5	78.6
13	Colorado, Columbus	-1.304	-0.137	0.0830	148.3	105.1	96.9
14	Colorado, Bay City	0.483	-0.178	-0.0898	82.1	106.6	103.3
15	Brazos, Seymour	0.845	0.797	0.762	68.7	70.5	71.8
16	Brazos, Waco	-0.308	-0.438	0.546	111.4	116.2	79.8
17	Little River, Cameron	-0.148	-0.605	-0.276	105.5	122.4	110.2
18	Navasota, Easterly	-0.208	-2.465	-3.154	107.7	191.2	216.7
19	Brazos, Richmond	-0.358	0.797	-0.433	113.3	121.0	116.0
20	Buffalo Bayou, Houston	2.782	1.749	1.075	19.3	49.3	68.8
21	WF San Jacinto, Conroe	0.078	-1.080	-0.751	97.7	131.3	121.8
22	WF Trinity, Fort Worth	-2.356	-1.713	0.179	187.2	163.4	93.4
23	Trinity, Dallas	1.581	0.371	0.072	41.5	86.3	97.3
24	Trinity, Rosser	1.736	-0.255	-0.117	35.8	109.4	104.3
25	Trinity, Oakwood	1.131	-0.460	0.022	58.2	117.0	99.2
26	Trinity, Romayor	0.473	-0.815	-0.216	82.5	130.1	108.0
27	Neches, Rockland	0.041	-0.829	-0.756	98.5	130.7	128.0
28	Neches, Evansdale	1.565	-1.364	-1.295	42.1	150.5	147.9
29	Sabine, Beckville	-0.629	-0.533	-0.569	123.3	119.7	121.1
30	Sabine, Ruliff	0.471	-0.862	-1.067	82.6	131.9	139.5
31	Big Cypress, Jefferson	0.343	-2.431	-0.696	91.1	163.2	118.1
34	Canadian, Amarillo	0.140	-0.015	0.000	96.4	100.4	100.0
35	Canadian, Canadian	1.154	0.947	1.111	70.0	75.4	71.1

According to Table 6.5, the annual 2-month minimum observed flow on the gauge site in Pecos River at Orla has the greatest decrease trend, with the regression slope of -3.611%, and the regression intercept of 211.9% for the mean annual 2-month minimum observed flow respectively; in contrast, the greatest increase trend happened in the gauge on the Buffalo Bayou in Houston, with regression slope of 2.782% and the intercept of 19.3% for the mean annual 2-month minimum observed flow.

Longer records suggest that there is a decrease trend showing in the following areas: gauges on the Pecos River at Orla, Lavaca River near Edna, Colorado River near San Saba, Colorado River at Austin, Colorado River at Columbus, Brazos River at Waco, Little River at Cameron, Navasota River at Easterly, Brazos River at Richmond, West Fork Trinity at Fort Worth and Sabine River near Beckville, while the other 64.5% of the total selected gauges have an increase long-term trend. The linear trend regression coefficients for annual 2-month maximum flows on 31 selected gauges are listed in Table 6.6.

Table 6.6
Linear Trend Regression Coefficients for Annual 2-Month Maximum Flow

		Slope (% mean)			Intercept (% mean)		
	River, Nearest City	Observed	Natural	Regulated	Observed	Natural	Regulated
3	Pecos River, Orla	-3.650	-2.446	-3.837	213.1	175.8	219.0
4	Nueces, Three Rivers	-1.159	-0.697	-0.569	133.6	120.2	116.5
5	Nueces, Mathis	-1.643	-0.960	-1.208	147.7	127.8	135.0
6	San Antonio, Falls City	1.456	1.024	1.041	46.1	59.1	58.3
7	San Antonio, Goliad	0.865	0.634	0.626	68.0	74.6	75.0
8	Guadalupe,SpringBranch	1.262	0.573	0.584	53.3	77.1	76.7
9	Guadalupe, Victoria	0.844	0.615	0.634	68.8	75.4	74.7
10	Lavaca, Edna	1.250	1.274	1.275	63.8	63.1	63.0
11	Colorado, San Saba	-1.258	-0.537	-0.664	146.5	119.9	124.6
12	Colorado, Austin	0.063	-0.047	0.290	97.7	101.7	89.3
13	Colorado, Columbus	0.109	0.067	0.277	96.0	97.5	89.7
14	Colorado, Bay City	1.201	0.232	0.589	55.5	91.4	78.2
15	Brazos, Seymour	-1.275	-0.743	-0.750	147.2	127.5	127.7
16	Brazos, Waco	-0.221	-0.066	-0.083	108.2	102.4	103.1
17	Little River, Cameron	0.009	0.527	0.645	99.7	80.5	76.1
18	Navasota, Easterly	0.061	0.258	0.304	97.7	90.5	88.8
19	Brazos, Richmond	-0.209	0.157	0.178	107.7	94.2	93.4
20	BuffaloBayou, Houston	2.509	0.299	0.287	27.2	91.3	91.7
21	WF San Jacinto, Conroe	-0.216	-0.021	0.009	106.3	100.6	99.7
22	WF Trinity, Fort Worth	0.102	0.280	0.332	96.2	89.6	87.7
23	Trinity, Dallas	0.266	0.370	0.525	90.1	86.3	80.6
24	Trinity, Rosser	0.332	0.499	0.721	87.7	81.5	73.3
25	Trinity, Oakwood	0.113	0.125	0.107	95.8	95.4	96.0
26	Trinity, Romayor	0.080	0.073	0.012	97.0	97.3	99.6
27	Neches, Rockland	-0.015	0.014	-0.008	100.6	99.5	100.3
28	Neches, Evansdale	-0.441	0.085	0.080	116.3	96.9	97.0
29	Sabine, Beckville	-0.303	-0.167	-0.206	111.2	106.2	107.6
30	Sabine, Ruliff	-0.566	-0.177	-0.226	120.9	106.5	108.4
31	Big Cypress, Jefferson	0.753	0.019	0.132	80.4	99.5	96.6
34	Canadian, Amarillo	-2.029	-2.030	-2.028	152.8	152.8	152.7
35	Canadian, Canadian	-5.480	-2.867	-3.896	242.5	174.5	201.3

As seen form Table 6.6, annual 2-month maximum flow has obviously increased since the 1940s in gauges on the Buffalo Bayou in Houston. The regression slope is 2.509 % and the regression intercept is 27.2 as a percent for the mean annual 2-month maximum observed flow; however, a pronounced decrease has occurred in the gauge on the Canadian River near Canadian with the regression slope of -5.480 % and the intercept of 242.5 as a percent for the mean annual 2-month maximum observed flow. Compared with the annual 2-month minimum flow, the long-term trend for 2-month maximum flow are steeper.

There are decreases of annual 2-month maximum trends in 45% of 31 gauges, such as in the gauge on Pecos River at Orla, Nueces River at Three Rivers, Nueces River at Mathis, Colorado River near San Saba, Brazos River at Seymour, Brazos River at Waco, Brazos River at Richmond, West Fork San Jacinto near Conroe, Neches River near Rockland, Neches River near Evansdale, Sabine River near Beckville, Sabine River near Ruliff, Canadian River near Amarillo and Canadian River near Canadian.

Conversely, the trends are generally increasing at gauge sites on the San Antonio River at Falls City, San Antonio River at Goliad, Guadalupe River at Spring Branch, Guadalupe River at Victoria, Lavaca River near Edna, Colorado River at Austin, Colorado River at Columbus, Colorado River near Bay City, Little River at Cameron, Navasota River at Easterly, Buffalo Bayou in Houston, West Fork Trinity at Fort Worth, Trinity River at Dallas, Trinity River near Rosser, Trinity River near Oakwood, Trinity River at Romayor and Big Cypress Bayou at Jefferson.

6.3 Flow Comparison

Comparing statistically annual, 2-month minima and annual 2-month maxima long-term trends on observed, naturalized and regulated flow, will contribute to current understanding of the role of climate change in variability, and the necessity of adaptation. In order to be better compared, the simulation period for linear trend analyses are the same in all observed, naturalized, and regulated flows. The plots of monthly naturalized flows at 31 control points and plots of annual flows are in Appendix E. Besides, the annual, 2-month minima, and 2-month maxima comparing observed, naturalized, and regulated flows discussed in chapter 6 can also be found in Appendix E. The results shown in Appendix E are both naturalized and regulated flow compiled with WRAP-SIM and observed flow from USGS records computed to annual flow by HydStats. The annual, 2-month minima and annual 2-month maxima naturalized, regulated and observed flow are plots as a solid blue line, dashed red line and black dotted line respectively for 31 gauges sites.

There is an eastern-western divide with trends toward increasing of observed flows in several regions in the eastern quarter of the state, notably in the gauges the Buffalo Bayou in Houston, on the San Antonio River in Falls City, on the Guadalupe River at Spring Branch, as well as in San Antonio River at Goliad. Contrary to the east, there is a relative severity decrease trend happening in most of the arid west and around the Mediterranean parts of Texas, especially in the Canadian River near Canadian, Pecos River at Orla and Canadian River near Amarillo.

Obviously, from Appendix E, we can see that all of annual, 2-month minima and annual 2-month maxima naturalized flows are larger than regulated and observed flow. In most cases, the annual regulated flow is less than observed flows, but in some cases, especially in some drought periods the annual regulated flows are larger than annual observed flows. Although, annual observed flows in most gauges show decreasing trends, there are no strong or consistent evidences for decreases in naturalized flows or modest decreases in regulated flows. No evidence for pronounced changes in naturalized and regulated should be expected, from the current simulation flows from the WRAP program. Therefore, even though the demands and management of water in the real world has changed over time since 1940, the demands in the model are simulated as constants for the entire period of analysis based on their permitted diversion targets specified in water right permits. In fact, the demands that are simulated over the 1940-2012 period of analysis did not necessarily occur historically. The purpose for simulation is to provide information about the expected reliability for a permit given the historical from year 1940 to 2012 hydrology period and the effects of all the other permits.

CHAPTER VII

SUMMARY AND CONCLUSIONS

The goal of this research is focused on evaluating the impact of climate change, water resources development and other factors on change to the long-term water budgets, flow-frequency, and storage-frequency characteristics of the different river systems in the state of Texas. This included developing a literature review based on quantifying the impacts of urbanization, agricultural practices, dams and reservoirs, human water use, and climate change on stream flow. The TCEQ WAM System was used to develop river system water budgets and reservoir flow-frequency tables. Simulations performed in the HydStats Program helped provide a better understanding of long-term trends in flows in Texas using regression analyses. The analyses noted above will be analyzed and synthesized to develop conclusions regarding the relative impacts of various factors on long-term changes in river flows, reservoir storage, evaporation volumes, water use, and other components of river system water budgets in the different regions of Texas.

7.1 Literature Review Assessment

Texas has a large land area 685,000 km2 with a population of 21 million. Therefore, climate, geography, and water management vary dramatically across the state from the arid west to humid east, from sparsely populated rural regions to metropolitan areas. The 15 major river basins and eight coastal basins in Texas, are represented in 21 WRAP input datasets which contain over 10,000 modeled water rights corresponding to almost 8,000 water right permits. Mean annual precipitation varies from 16 inches in the

Rio Grande River Basin to 50 inches in the Neches-Trinity River Basin, while mean annual evaporation changes from 47 inches in the Trinity-San Jacinto River Basin to 66 inches in the Canadian River Basin. The 21 WRAP input datasets contain 3,365 reservoirs, but over 90 percent of the total conservation storage capacity of the 3,365 reservoirs is contained in the 211largest reservoirs, which is mostly located in the eastern part of the state. Large reservoirs are defined as those with conservation storage capacities exceeding 5,000 acre-feet. Generally, water supplies are less stressed in the eastern part of the state than in the western part of Texas due to high annual precipitation rates and low annual evaporation rates in the eastern part of Texas.

The literature review provides a great deal of information regarding quantification of the impacts of urbanization, agricultural practices, dams, reservoirs, human water use, and climate change on stream flow. Statistical trend analyses of gauged stream flow data such as linear regression or the Mann-Kendall test and watershed precipitation-runoff simulation models like the SWAT watershed model and WRAP water management model are the major methods used to investigate changes in steam flow. The results vary depending on the study area, methods, and simulation period. Analysis within and near Oklahoma showed an upward trend in stream flow at 14 stations and a downward trend at 4 stations. On the contrary, declines in flows over several decades were observed in the Republican River of Kansas, Nebraska, and Colorado. Additionally, some investigations found that flows at low to median flow percentiles have increased across broad sections of the U.S. but decreased in some areas, with a less significant pattern of increases and decreases in annual maximum daily flows. In spite of the different methods and study areas, essentially all of the investigations agreed that effects of human activities played a more important role than climate change on impacting stream flow. Agricultural activities, construction of reservoirs, and increased population density have significantly reduced the flows in rivers.

7.2 Statistical Trend Analyses and Simulation Findings

Until now, the scientific hypothesis that climate change could impact hydrological circulation has remained an unproven idea. Statistical trend analysis is a traditional and direct approach to quantifying the long-term effects of climate change and human activity on river system water budgets. Monthly precipitation and reservoir evaporation rates in the TWDB datasets for each of the 92 one-degree quadrangles encompassing Texas during 1940-2012 were used to show climate variability. The effects of human activity were quantified by comparing observed flows with naturalized and regulated flows computed from WAM simulations reflecting current conditions of river basin development.

The programs HydStats and HEC-DSSVue were used to quantify and plot the long-term changes in precipitation and reservoir surface evaporation. The results indicate that the mean precipitation is higher in east Texas, while mean surface evaporation is higher in the western part of Texas. For Texas as a whole, the regression intercepts were 99.959% and 95.048%; the slopes were are 0.00112% and 0.165% for the mean annual precipitation and evaporation respectively. Therefore, even though precipitation and reservoir evaporation rates vary geographically and seasonally, the long-term overall trends in Texas are minimal.

The stream flow data in this thesis are based on 33 U.S. Geological Survey (USGS) stream gauges, and the data for the 2 gauges on the Rio Grande River from the International Boundary and Water Commission (IBWC). The plotting and data manipulations from HEC-DSSVue show the mean annual observed flow for each of the 35 gauges vary geographically from 0.083 inches/year at the Pecos River at Orla to 19.56 inches/year at Buffalo Bayou near Houston. The mean observed flows are lower for most control points located in west Texas compared to gauges along the Gulf of Mexico. Analysis for monthly observed stream flows at the 35 gauging stations showed an upward trend in stream flows at 15 stations and a downward trend at 10 stations for the full period of record at each gauge.

The WAM simulation model was used for developing river system water budget summaries and flow frequency statistics for undeveloped natural flows as well as regulated flows reflecting present conditions of river basin development and management. Additionally, the HydStats and WRAP programs were applied to analyze the linear trend and frequency statistics for reservoir storage. According to the WRAP simulation results, the volume reliabilities for river basins located in the northeast region of the state such as the Sulphur, Sabine, Red, Canadian, Guadalupe &San Antonio and Brazos river basins are higher compared with other area in Teaxs. The value of other gains and losses are negative in some river basins such as the San Jacinto, Neches, Nueces-Rio Grande, Sulphur, Red, Canadian, Cypress San Antonio-Nueces, Lavaca-

Guadalupe, Neches-Trinity, and Trinity-San Jacinto river basins, which means inflows always exceeded outflows. The linear trend regression coefficients for reservoir storage detected no significant changes.

Long-term trends for both observed flows from USGS records and the simulated naturalized, regulated flows from the WAM System datasets were compared. Analysis for observed annual, 2-month minima and annual 2-month maxima stream flow on the 31 gauging stations shows that the gauges 17, 14 and 12 for annual, 2-month minima and annual 2-month maxima separately give decrease trends while the other 13, 17and 19 gauges show increase trend on annual, 2-month minima and annual 2-month maxima respectively. There is an eastern-western divide in the trends, including an increasing trend in observed flows in several regions in the eastern quarter of the state, notably at the gauge on the Buffalo Bayou in Houston. In contrast, there is a relatively severe decreasing trend in observed flows in west and central Texas, especially in the Canadian River near Canadian. No significant trends have been expected for naturalized and regulated flows, because both of them are simulated flows from the WRAP program, in which demands in the model are simulated as constants for the entire period of analysis based on their permitted diversion targets specified in water right permits. Long-term trends or changes in naturalized flows represent climate change (expected precipitation and surface evaporation), watershed land use change, groundwater pumping or other factors not incorporated in the flow naturalization process. Decreases in regulated flows may occur due to reservoir sedimentation.

7.3 Conclusions and Recommendations

Long-term changes in river system water budgets is a significant factor for managing future water supplies. Therefore, quantifying long-term changes will contribute to understanding how climate change and human activity impact river systems.

The USGS has a dense network of river flow monitoring sites which provides a strong foundation for detecting long-term changes in flow. The annual observed flows in arid west and central Texas shows a decreasing trend. In contrast, observed flows show an increasing trend in several regions in the eastern quarter of the state. According to statistical trend analyses results for precipitation and reservoir surface evaporation, there was no evidence for pronounced changes in these two components of the water budget. Thus, compared with climate change, human activity plays a major role on changes in the water budget.

Recommendations for future studies are as follows. It is clear that different study periods will lead to different observed trends in flow. Besides performing statistical trend analysis for annual flow, statistical trend analyses could be performed for the 12 individual months of the year to investigate seasonal characteristics of flow changes. Secondly, the variability of hydrological phenomena is naturally very high. For example if a very high flow during a flood occurred at the beginning of a simulation period, an artificial decreasing trend could be observed. Thus, minima and maxima values can mask the true trends. Additional analyses for these periods are suggested. Thirdly, artificial trends may be created due to metrological errors in the hydrometric data. For instance, the evaporation values are lower when computed using an updated method compared to the method used prior to 1954. In order to avoid artificial trends, evaluation of the accuracy of hydrometric data is necessary in future research.

REFERENCES

Allison, I., N.L. Bindoff, R.A. Bindschadler, P.M. Cox, N. de Noblet, M.H. England, J.A. Francis, N. Gruber,A.M. Haywood, D.J. Karoly, G. Kaser, C. Le Quéré, T.M. Lenton, M.E. Mann, B.I. McNeil, A.J. Pitman, S. Rahmstorf, E. Rignot, H.J. Schellnhuber, S.H. Schneider, S.C. Sherwood, R.C.J. Somerville, K. Steffen, E.J. Steig, M. Visbeck, and A.J. Weaver, 2009. The Copenhagen diagnosis, 2009: Updating the world on the latest climate science, 60 pp. University of New South Wales Climate Change Research Centre (CCRC).

Brumbelow, K., and Georgakakos, A. (2001). "An assessment of irrigation needs and crop yield for the United States under potential climate changes." Journal of Geophysical Research-Atmospheres, 106(27), 383-406.

Cleveland, W.S. (1979). "Robust locally weighted regression and smoothing scatterplots." Journal of American Statistical Association, 74(368), 829-836.

Cleveland, W.S., and Devlin, S.J. (1988). "Locally-weighted regression: an approach to regression analysis by local fitting." Journal of American Statistical Association, 83(403), 596-610.

Dewalle, D.R., Swistock, B.R., Johnson, T.E. and McGuire K.J. (2000). "Potential effects of climate change and urbanization on mean annual stream flow in the United States." Journal of Water Resources Research, American Geophysical Union, 36(9), 2655-2664.

EPA, Climate Change Indicators in the United States, 2012, 2nd edition http://www.epa.gov/climatechange/pdfs

Flato, G.M., Boer, G.J., Lee, W.G., McFarlane, N.A., Ramsden, D., Reader, M.C., and Weaver, A.J. (2000). "The Canadian Centre for climate modeling and analysis global coupled model and its climate." Journal of Climate Dynamics, 16(6), 451-467.

Frederick, K.D., Major, D.C., and Stakhiv, E.Z., Editors. (1997). Climate change and water resources planning criteria. Kluwer Academic Publishers, Norwell, Massachusetts.

Gleick, P.H. (2000). Water: the potential consequences of climate variability and change for the water resources of the United States. U.S. Global Change Program, Pacific Institute for Studies in Development, Environment, and Security, Oakland, California. http://www.gcrio.org

Hansen, J.E., R. Ruedy, M. Sato, and K. Lo, 2010. NASA GISS surface temperature (GISTEMP) analysis, in trends: A compendium of data on global change. Carbon Dioxide Information Analysis Center, U.S. Department of Energy, Oak Ridge, U.S.A. http://pubs.giss.nasa.gov/abs/ha00510u.html

Helsel, D. R., and Hirsch, R. M. (1992). Statistical methods in water resources. Elsevier, New York, NY.

Hubert, P., Carbonnel, J.P., and Chaouche, A. (1989). "Hydrometeorological time series segmentation - application to West African rainfall and discharge series." Journal of Hydrology, 110(3-4), 349-367.

Inter-governmental Panel on Climate Change (2001). Climate change 2001: impacts, adaptations, and vulnerability, Cambridge University Press. http://www.grida.no/publications/other/ipcc_tar/

IPCC, (2007). Summary for policymakers, in S. Solomon, et al. (eds.), Climate change 2007: the physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom, and New York, USA. Texas Water Development Board, Historical water use summary for Texas (Last visited December 18, 2007.)

Jones, P.D., D.H. Lister, T.J. Osborn, C. Harpham, M. Salmon, and C.P. Morice, (2012). “Hemispheric and large-scale land-surface air temperature variations.” Journal of Geophysical Research. An extensive revision and an update to 2010. J. Geophys. Res., 117(D5), D05127.

Langland, M.J., S.W. Phillips, J.P. Raffensperger, D.L. Moyer (2004). Changes in streamflow and water quality in selected nontidal sites in the Chesapeake Bay Basin 1985-2003. Scientific Investigations Report 2004-5259, U.S. Geological Survey, Denver, Colorado.

Lenz, B.N. (2004). Analysis of stream flow and water-quality data at two long-term monitoring sites on the St. Croix River. Wisconsin and Minnesota, USGS Water Resources Investigations Report 03–4334. http://pubs.usgs.gov/wri/wri034334/

Lettenmaier, D.P., E.F. Wood, and J.R. Wallis (1994). “Hydro-climatological trends in the continental United States 1948-1988.” Journal of Climatology, 7(4), 586-607.

Lettenmaier, D.P., Wood, A.W., Palmer, R.N., Wood, E.F., and Stakhiv, E.Z. (1999). "Water resources implications of global warming: a U.S. regional perspective." Journal of Climate Change, 43(3), 537-579.

Lins, H.F., and J.R. Slack (1999). "Stream flow trends in the United States." Journal of Geophysical Research Letters, American Geophysical Union, 26(2), 227-230.

Matheussen, B., Kirschbaum, R.L., O’Donnell, G.M., and Lettenmaier, D.P. (2000). "Effects of land cover change on stream flow in the interior Columbia River Basin (USA and Canada)." Journal of Hydrological Processes, 14(5), 867-885.

Matondo, J.I., and Msibi, K.M. (2001). "Estimation of the impact of climate change on hydrology and water resources in Swaziland." Journal of Water International, 26(3), 425-433.

McCabe G.J, and D.M.Wolock (2002). "A step increase in stream flow in the conterminous United States." Journal of Geophysical Research Letters, American Geophysical Union, 29(24), 93-98.

McCuen, R.H. (2003). Modeling hydrologic change: statistical methods. Lewis Publishers, Boca Raton, Florida.

Meehl, G.A., C. Tebaldi, G. Walton, D. Easterling, and L. McDaniel, (2009). “Relative increase of record high maximum temperatures compared to record low minimum temperatures in the U.S.” Journal of Geophysical Research Letters, 36(23), 1-5.

Miller, J.R., and Russell, G.L. (1992). "The impacts of global warming on river runoff." Journal of Geophysical Research, 97(D3), 2757-2764.

National Assessment Synthesis Team (2000). Climate change impacts on the United States: the potential consequences of climate variability and change, U.S. Global Change Research Program, Cambridge University Press.

National Research Council (2005). The science of in stream flows: a review of the Texas in stream flow program. National Academies Press, Washington, D.C.

NOAA NCDC, (2011). State of the climate: Global analysis for annual 2011. NOAA National Climatic Data Center http://www.ncdc.noaa.gov/sotc/global/2011/13.

Peters, D.L., and Prowse, T.D. (2001). "Regulation effects on the lower Peace River, Canada." Journal of Hydrological Processes, 15(16), 3181-3194.

Piao, S., Ciais, P., Huang, Y., Shen, Z., Peng, S., Li, J., Zhou, L., Liu, H., Ma, Y., Ding, Y., Friedlingstein, P., Liu, C., Tan, T., Yu, Y., Zhang, T., and Fang, J. (2010). “The impacts of climate change on water resources and agriculture in China.” Journal of Nature, 467(7311), 43-51.

Smith, S.J., and K.L. Wahl (2003). “Changes in streamflow and summary of major-ion chemistry and loads in the North Fork Red River Basin upstream from Lake

Alyus, Northwestern Texas and Western Oklahoma water resources investigations.” Report 03-4086, U.S. Geological Survey.

Stankowski, S.J. (1972). Population density as an indirect indicator of urban and suburban land-surface modifications. Geophysical Survey Research, Chapter B, pp.B219-B224.

Stednick, J.D. (1996). "Monitoring the effects of timber harvest on annual water yield." Journal of Hydrology, 176(1-4), 79-95.

Sumioka, S.S. (2004). Trends in streamflow and comparisons with instream flows in the Lower Puyallup River Basin. Washington, Scientific Investigations Report 2004-5016, U.S. Geological Survey.

Szilagyi, J. (2001). "Identifying cause of declining flows in the Republican River." Journal of Water Resources Planning and Management, American Society of Civil Engineers, 127(4), 244-253.

Texas Water Development Board (2007). Water for Texas – 2007, Austin, Texas. http:www.twdb.state.tx.us

Texas Water Development Board. (2012). Water for Texas – 2012. Austin, Texas. www.twdb.state.tx.us,

Trimble, S.W. and Weirich, F.H. (1978). “Reforestation reduces stream flow in the southeastern United States.” Journal of Soil and Water Conservation, 42(4), 274-276.

Van Dam, J.C., Editor, (1999). Impacts of climate change and climate variability on Hydrologic Regimes. Cambridge University Press.

Wanga, J., Ishidairaa, H., Xub, Z.X. (2012). “Effects of climate change and human activities on inflow into the Hoabinh Reservoir in the Red River Basin.” Journal of Procedia Environmental Sciences, 13(162), 1688-1698

Wurbs, R.A. (2005). "Texas water availability modeling system." Journal of Water Resources Planning and Management, American Society of Civil Engineers, 131(4), 270-279.

Wurbs, R.A. (2006a). Chapter 24, Water rights analysis package (WRAP) modeling system. Watershed Models (V.P. Singh and D.K. Frevert, Editors), CRC Press, Boca Raton, Florida.

Wurbs, R.A. (2006b). "Methods for developing naturalized monthly flows at gaged and ungagged sites." Journal of Hydrologic Engineering, American Society of Civil Engineers, 11(1), 55-64.

Wurbs, R.A. (2011). Water rights analysis package (WRAP) modeling system reference manual. Technical Report -255, Eighth Edition, Texas Water Resources Institute, College Station, Texas.

Wurbs, R.A., Richard J. Hoffpauir, and Spencer T. Schnier (2012). Application of expanded WRAP modeling capabilities to the Brazos WAM TR-389, Second Edition, Texas Commission on Environmental Quality, Austin, Texas

Wurbs, R.A. (2013a). Water rights analysis package (WRAP) modeling system reference manual. TR-255, 10th Edition, Texas Water Resources Institute, College Station, Texas.

Wurbs, R.A. (2013b). Water rights analysis package (WRAP) modeling system users manual. TR-256, 10th Edition, Texas Water Resources Institute, College Station, Texas.

Wurbs, R.A. (2013c). Fundamentals of water availability modeling with WRAP, TR-283, 7th Edition, Texas Water Resource Institute, College Station, Texas.

Wurbs, R.A. (2013d). WRAP river system hydrology, TR-431, Texas Water Resource Institute, 2nd Ed, College Station, Texas.

Wurbs, R.A., Hoffpauir, R.J. (2013a). Water rights analysis package daily modeling system, TR-430, Texas Water Resource Institute, 2nd Ed, College Station, Texas.

Wurbs, R.A., Hoffpauir, R.J. (2013b). Environmental flows in water availability modeling, TR-440, Texas Water Resource Institute, College Station, Texas

Wurbs, R.A., Richard J. Hoffpauir, and Spencer T. Schnier (2013). Application of expanded WRAP modeling capabilities to the Colorado WAM TR-389, Second Edition, Texas Commission on Environmental Quality, Austin, Texas

Wurbs, R.A., and Sisson, E.D. (1999). Comparative evaluation of methods for distributing naturalized stream flows from gaged to ungagged sites. TR-179, Texas Water Resources Institute, College Station, Texas. http://twri.tamu.edu/reports.php

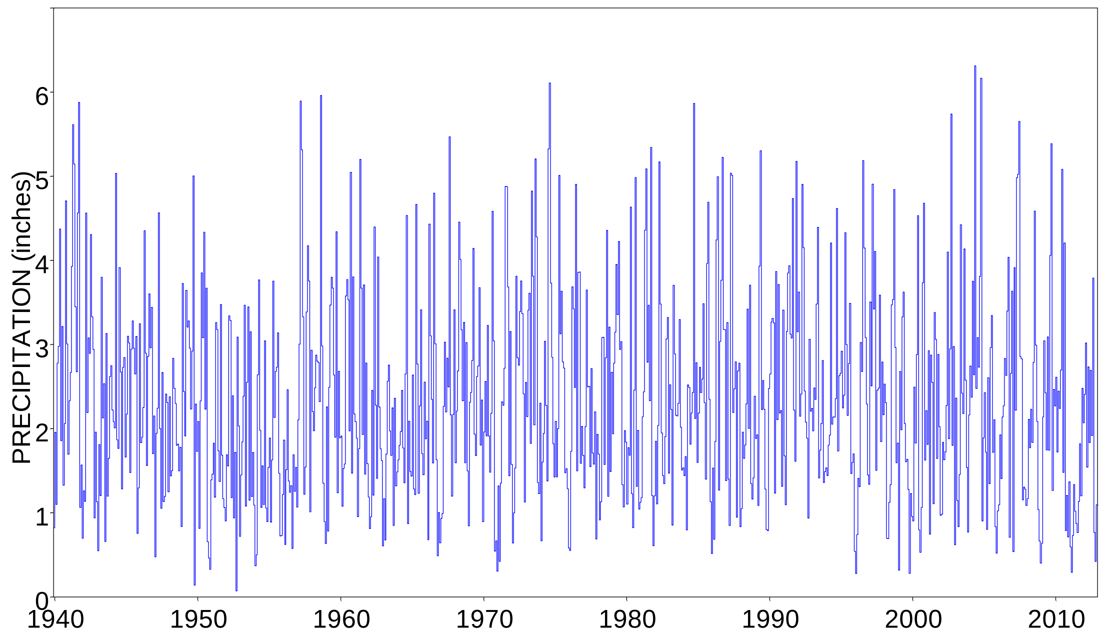
Wurbs, R.A., R.J. Hoffpauir, H.E. Olmos, A.A. Salazar (2009). Conditional reliability, sub-monthly time step, flood control, and salinity features of WRAP. TR-284, Texas Water Resource Institute, College Station, Texas. http://twri.tamu.edu/reports.php

Wurbs, R.A., R.S. Muttiah, and F. Felden (2005). "Incorporation of climate change in water availability modeling." Journal of Hydrologic Engineering, American Society of Civil Engineers, 10(5), 375-385.

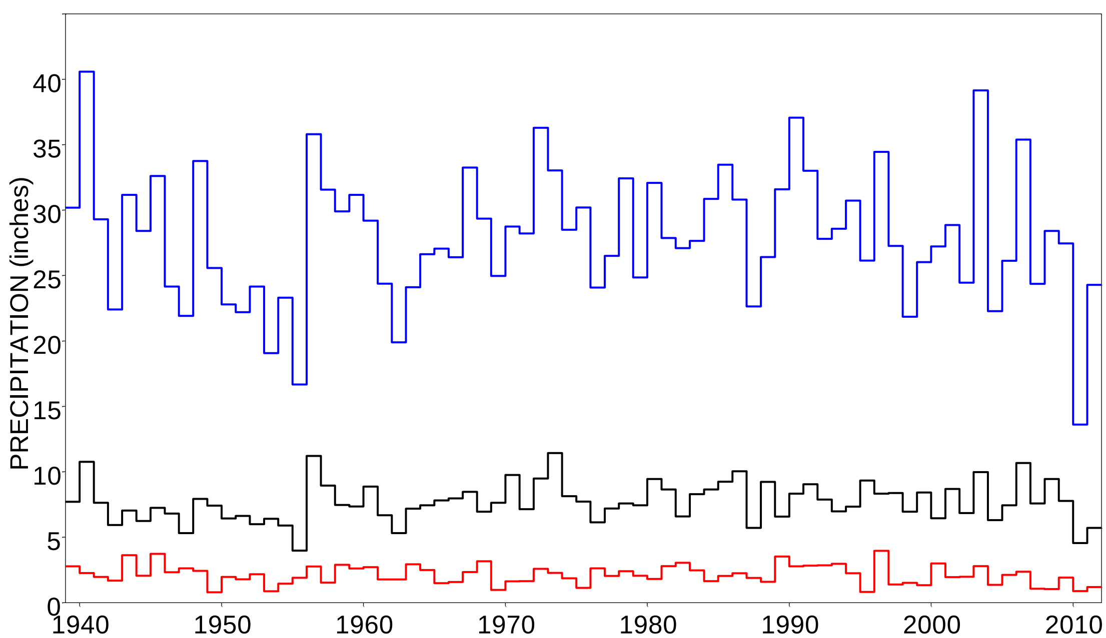
Ye, B., D. Yang, and D.L. Kane (2003). "Changes in Lena River stream flow hydrology: human impacts versus natural variations." Journal of Water Resources Research, 39(7), 8.1-8.14.

APPENDIX A

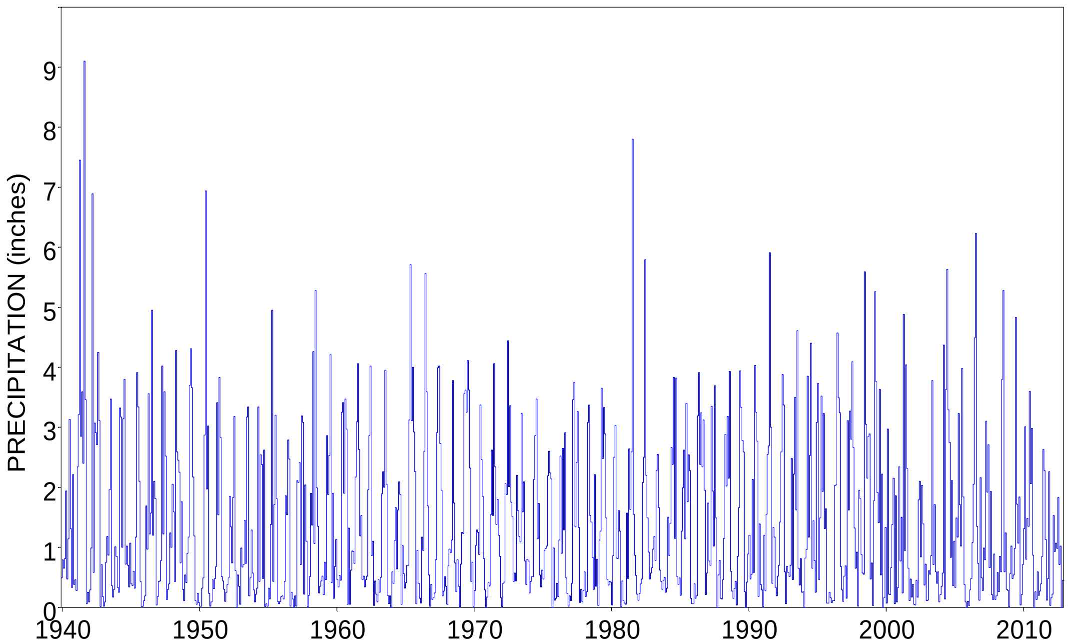
PLOTS OF MONTHLY PRECIPITATION FOR 92 QUADRANGLES



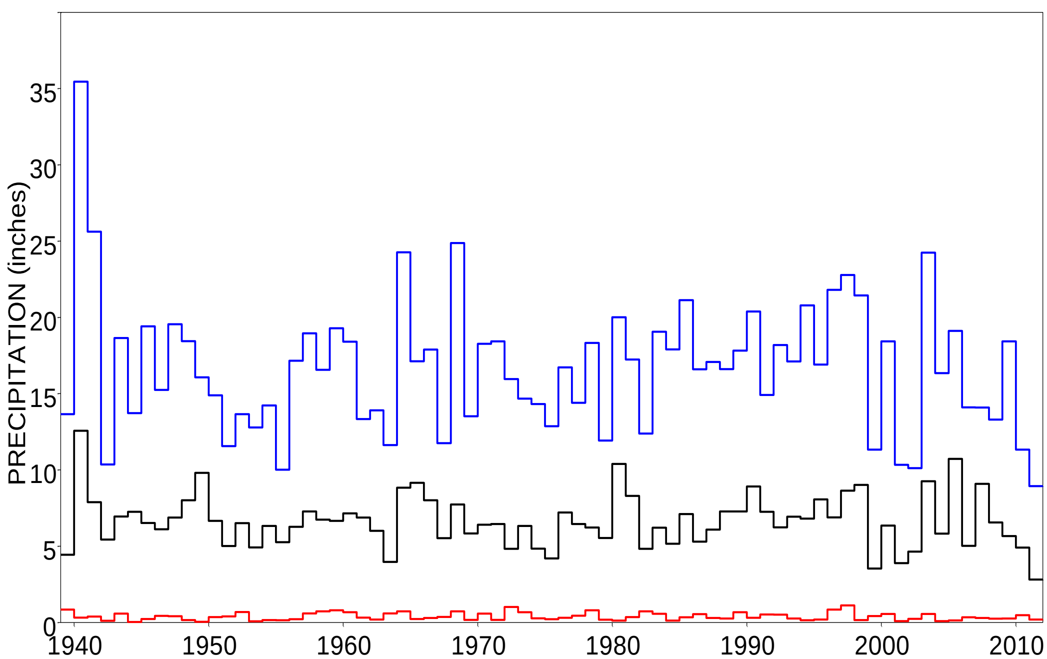
Monthly Precipitation for the 92 Quadrangles



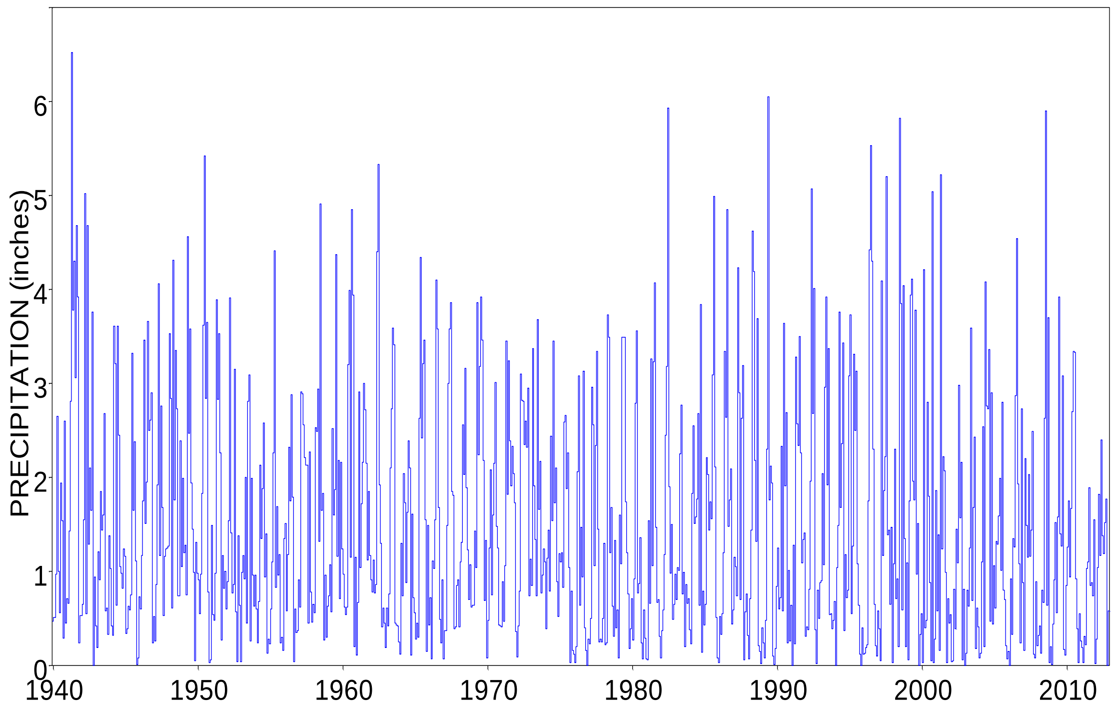
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for the 92 Quadrangles



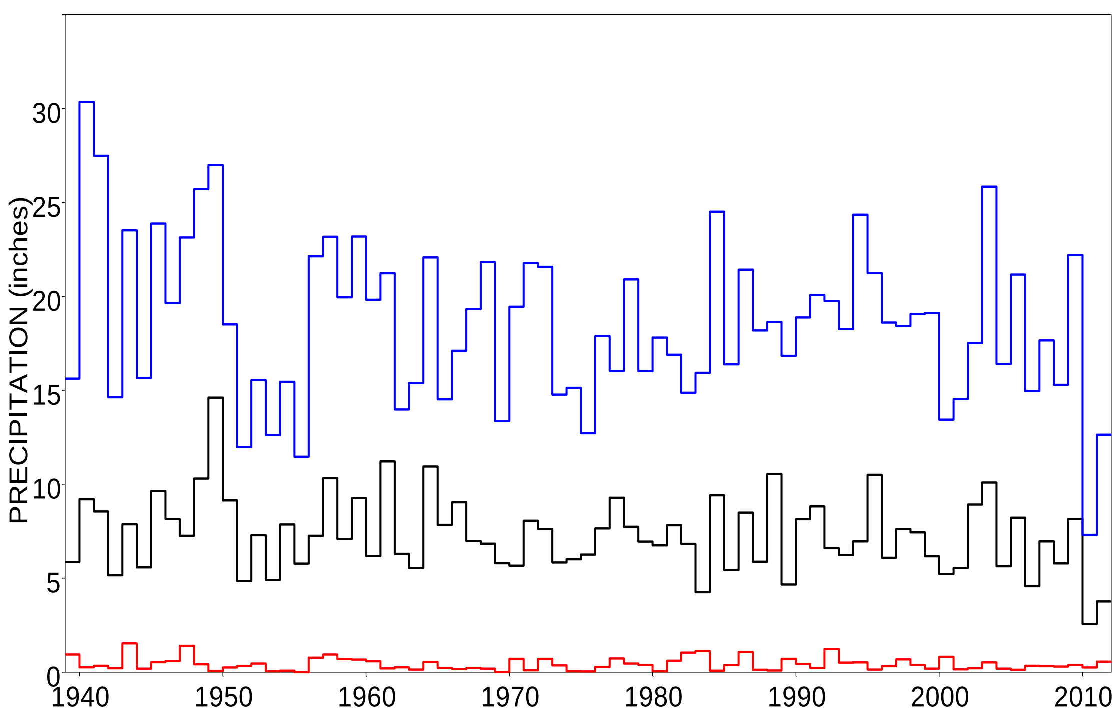
Monthly Precipitation for Quadrangle 104



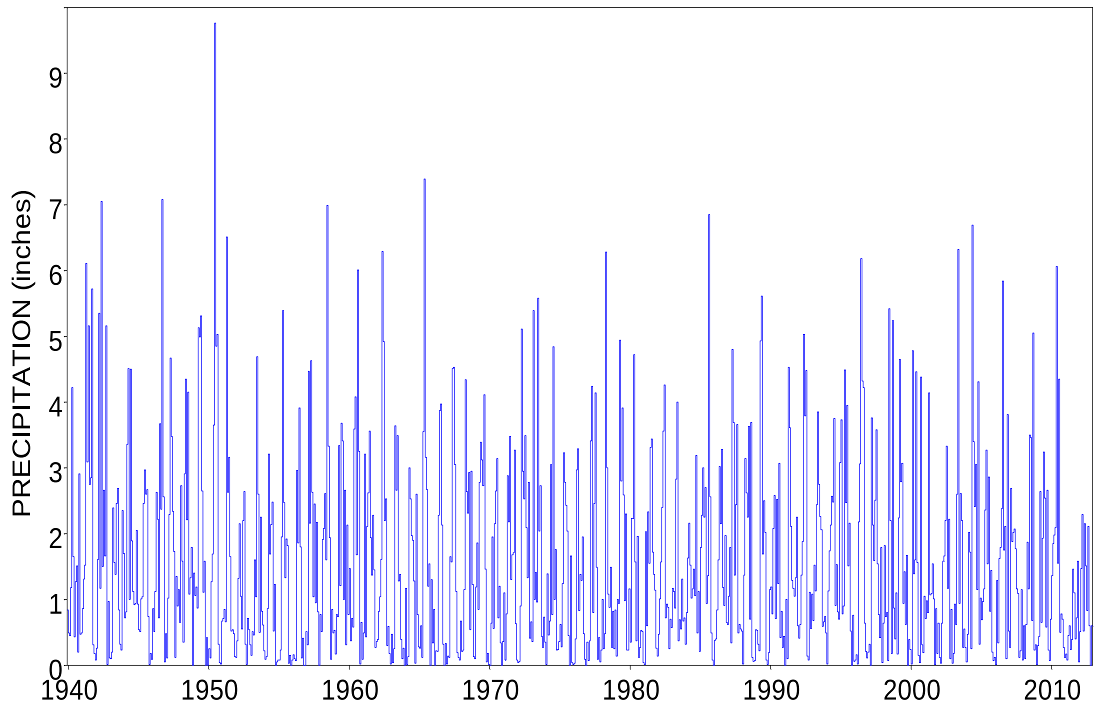
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 104



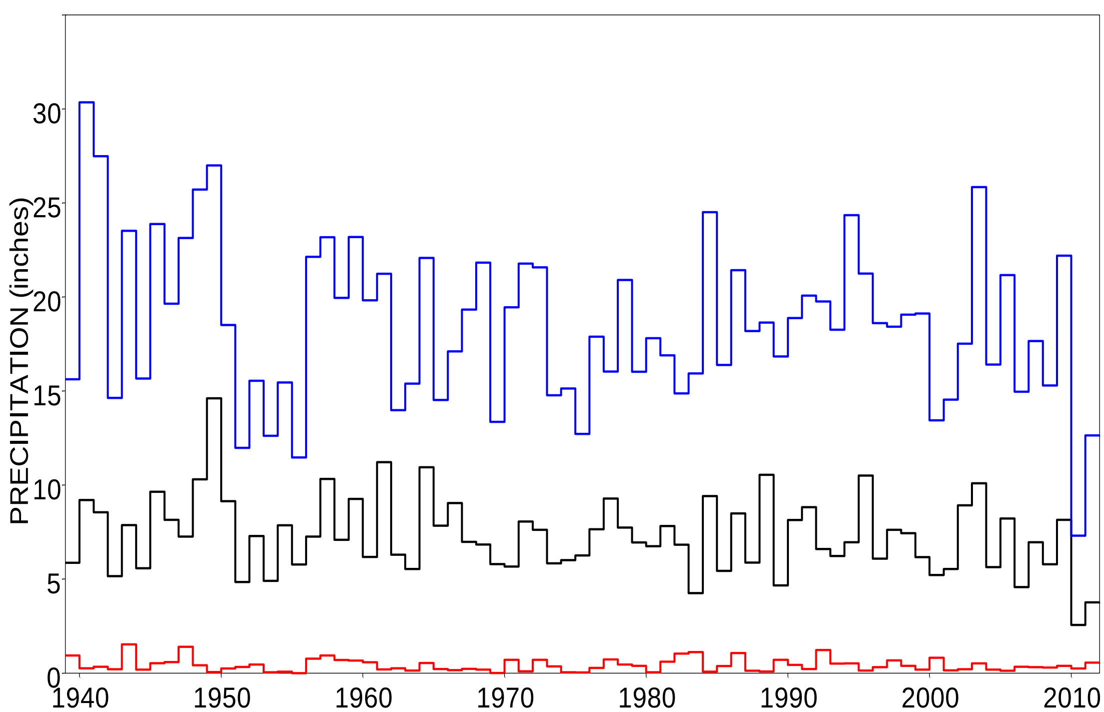
Monthly Precipitation for Quadrangle 105



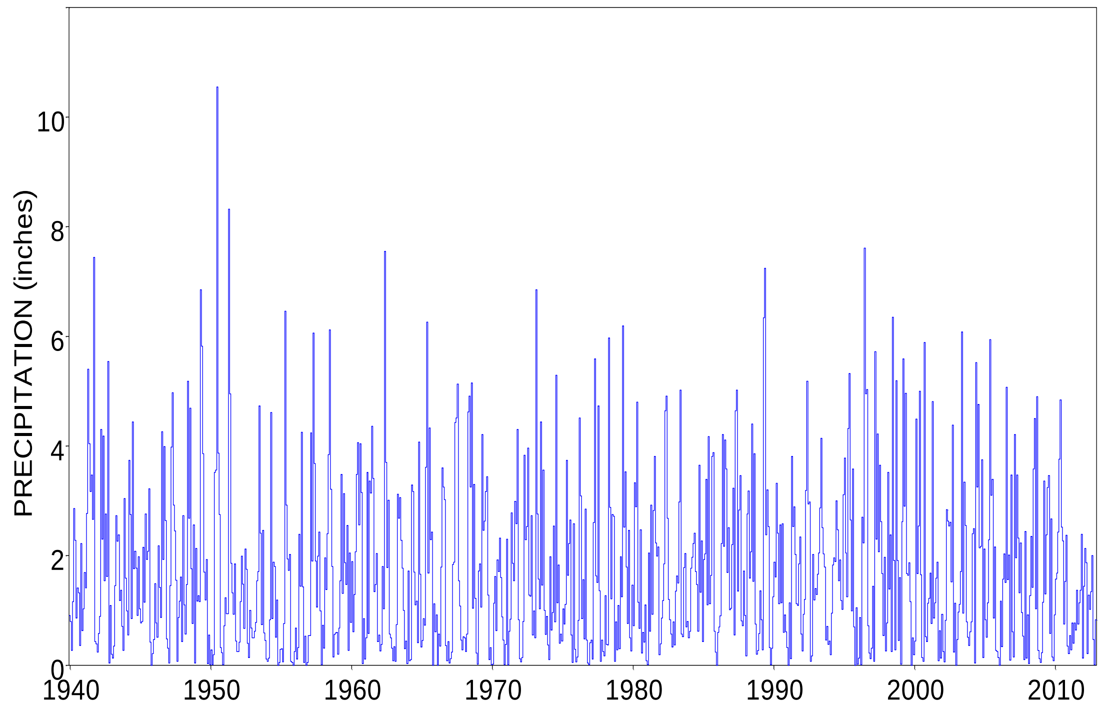
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 105



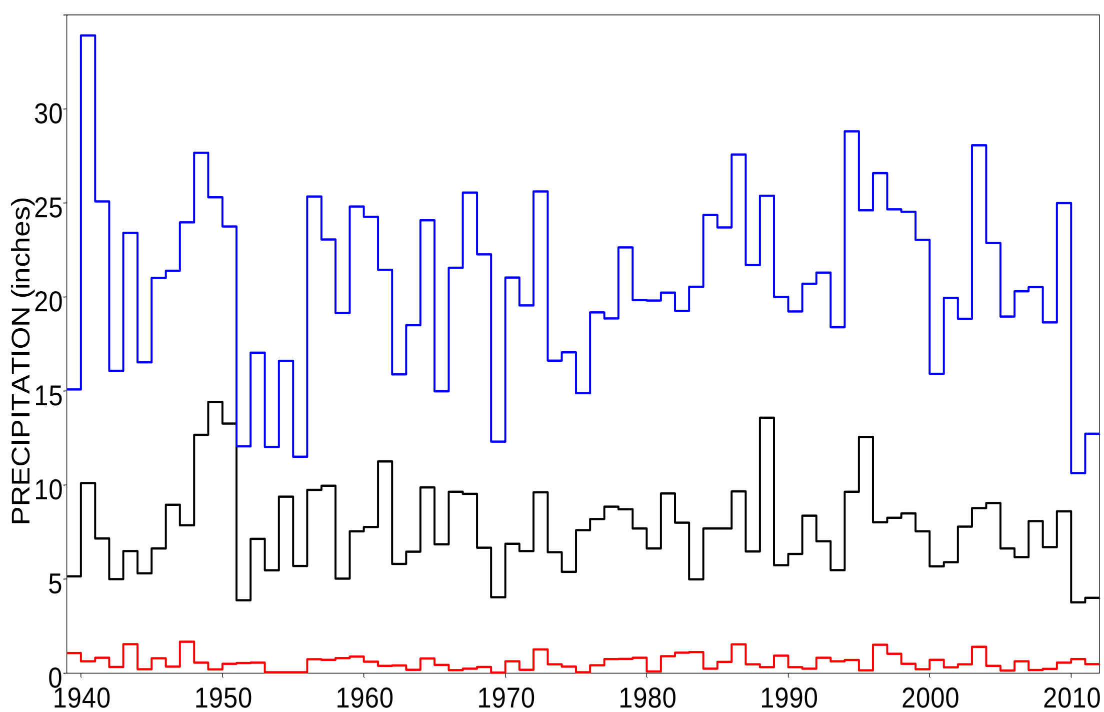
Monthly Precipitation for Quadrangle 106



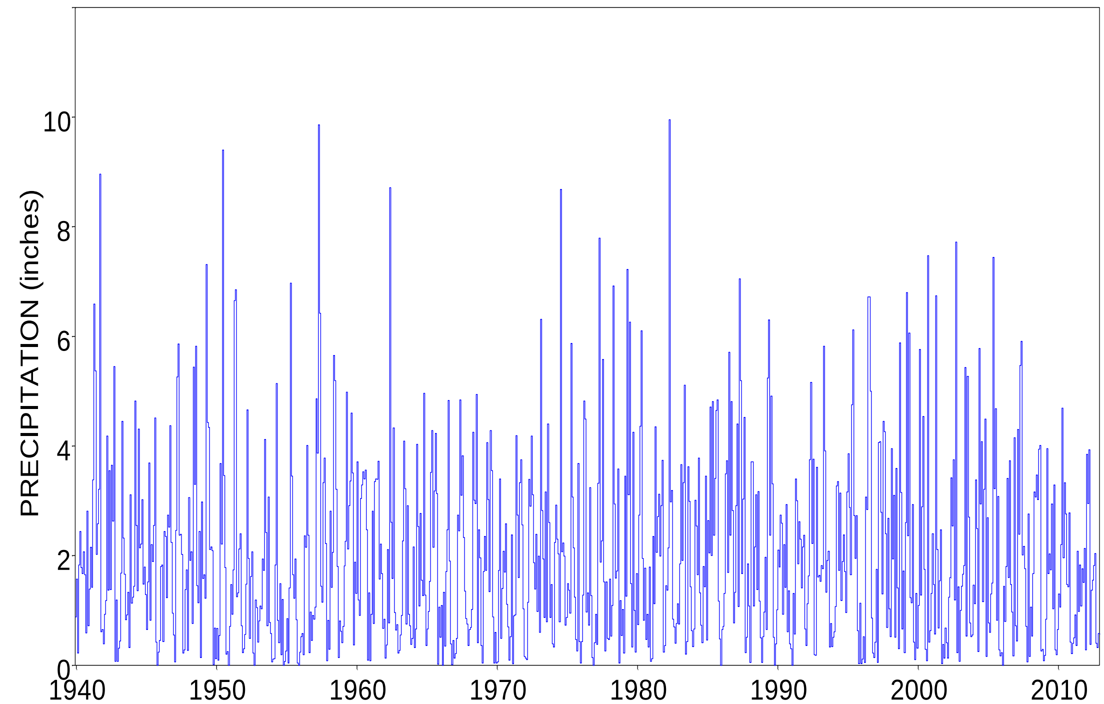
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 106



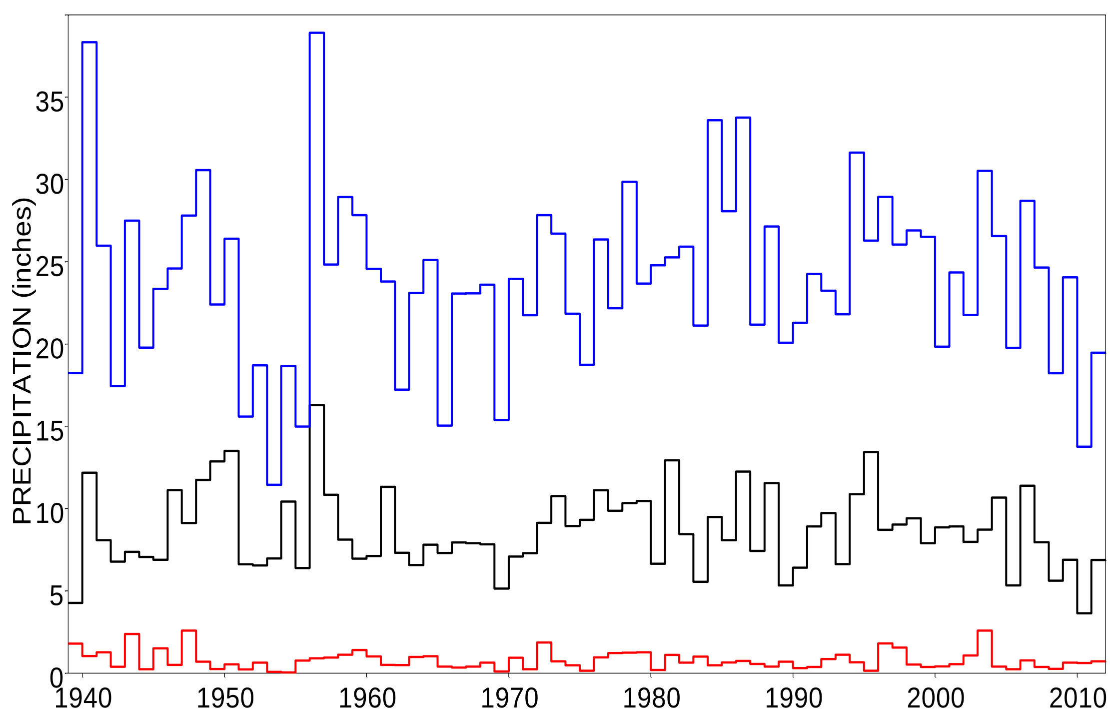
Monthly Precipitation for Quadrangle 107



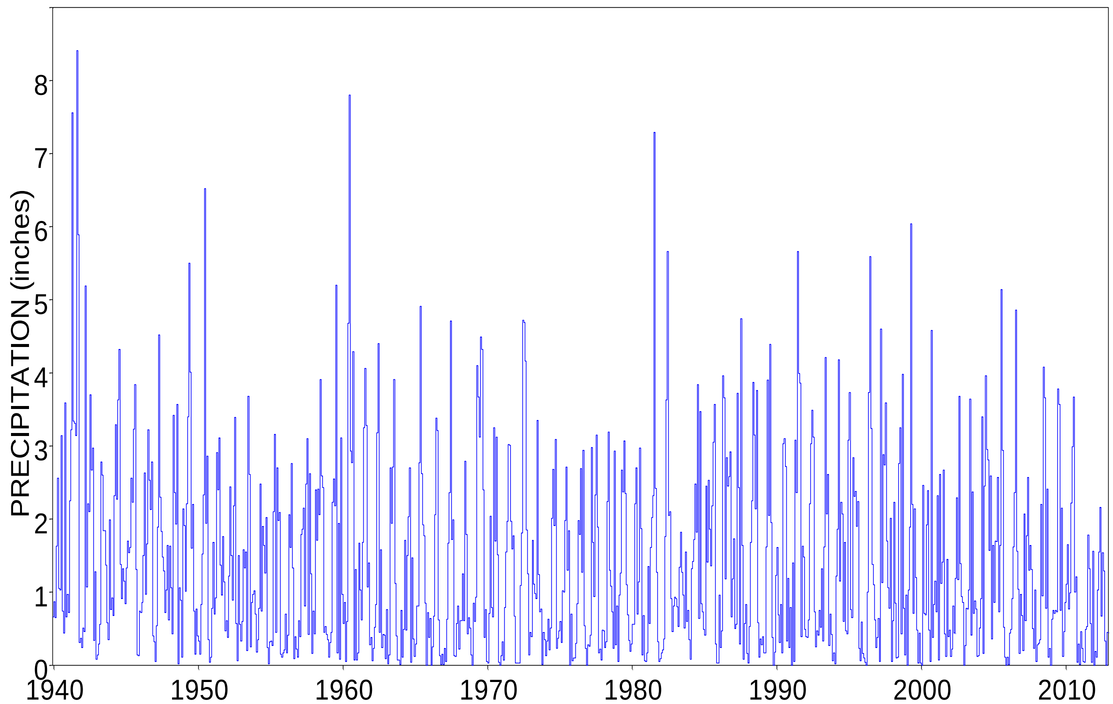
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 107



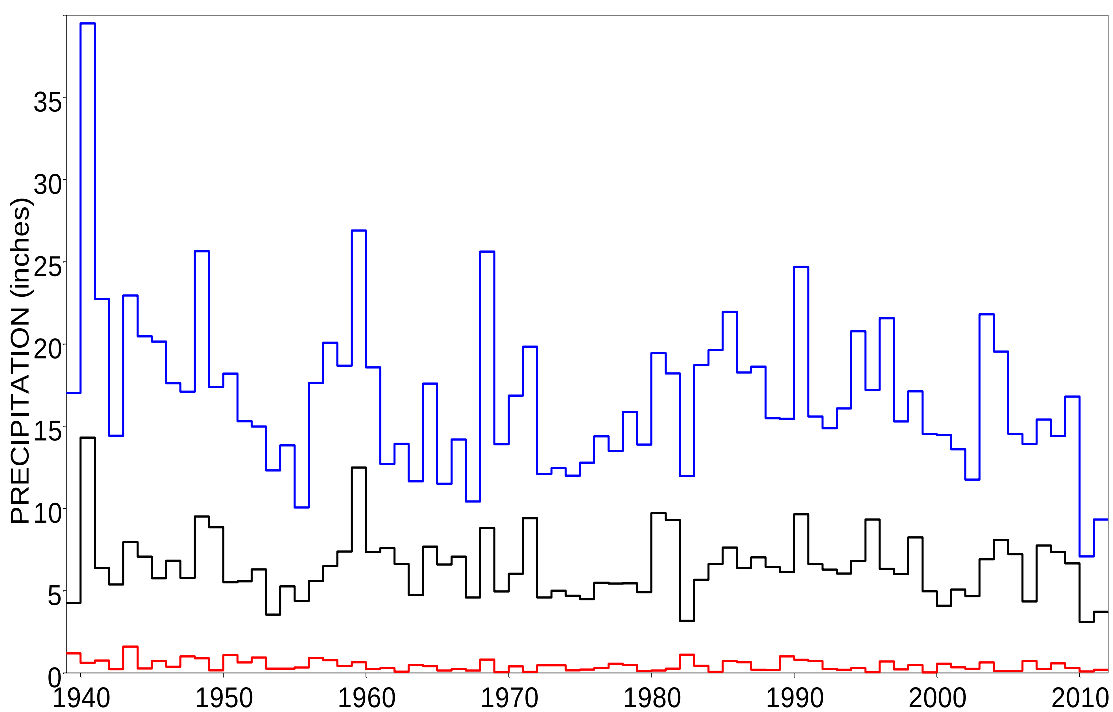
Monthly Precipitation for Quadrangle 108



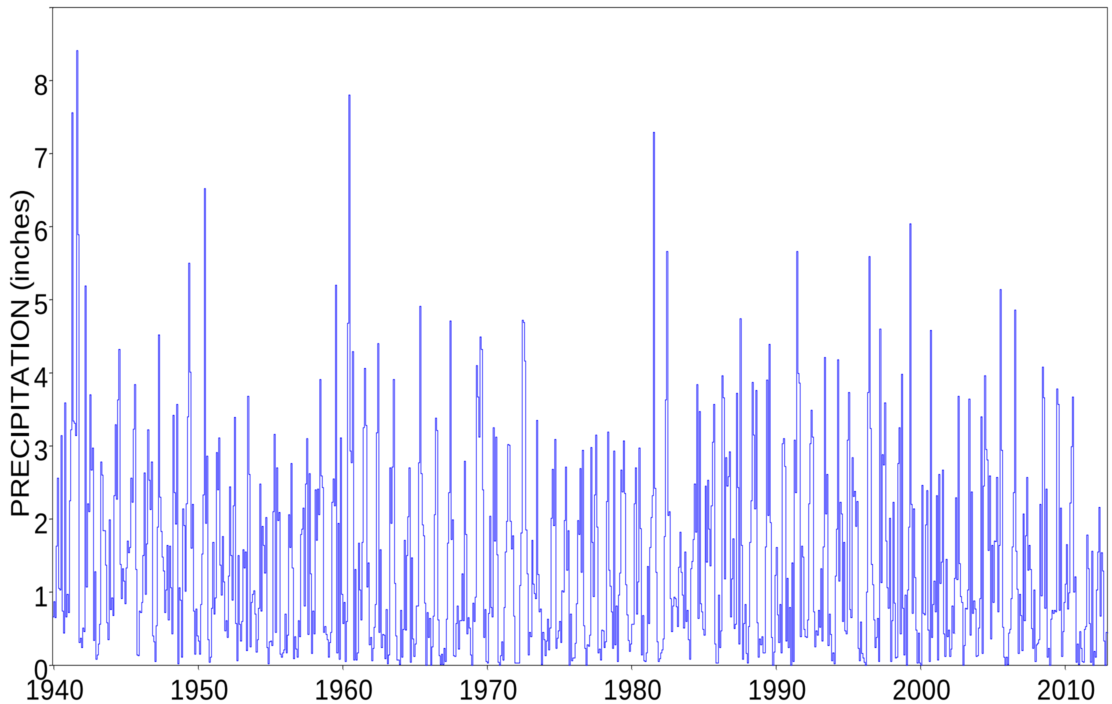
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 108



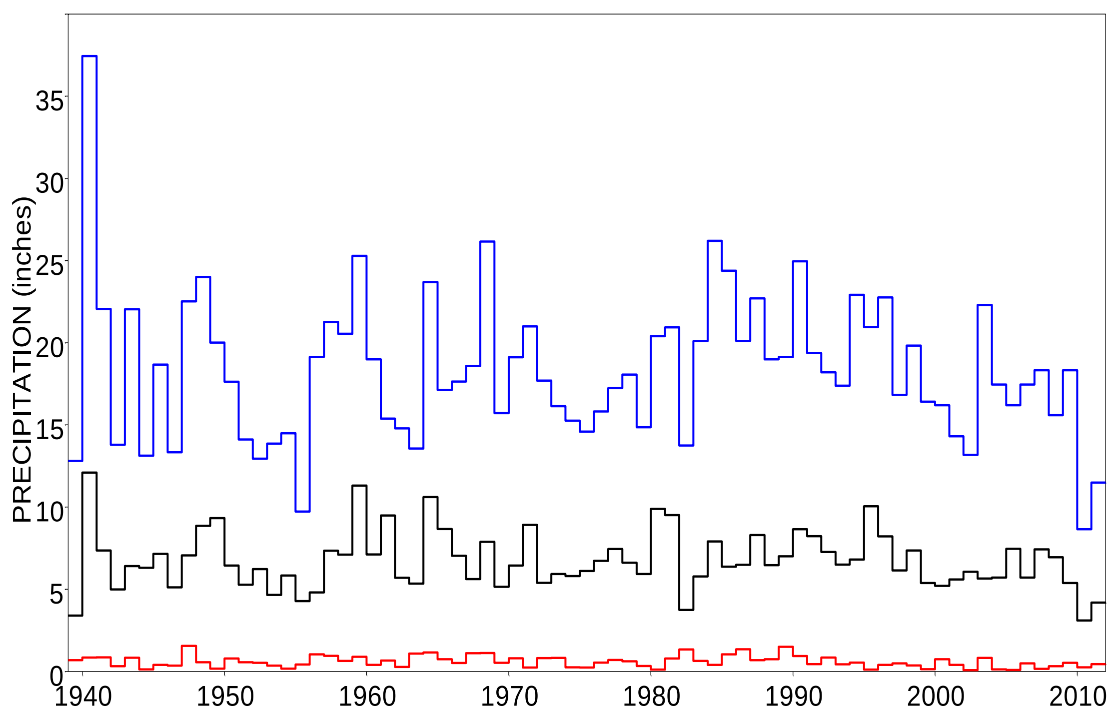
Monthly Precipitation for Quadrangle 204



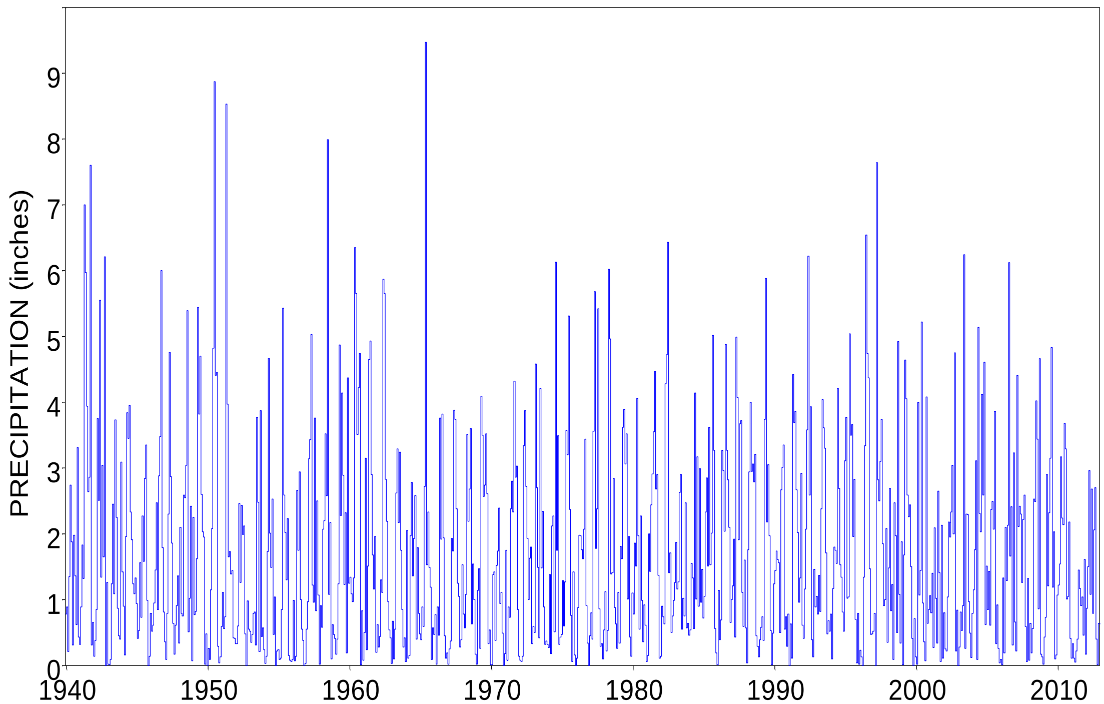
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 204



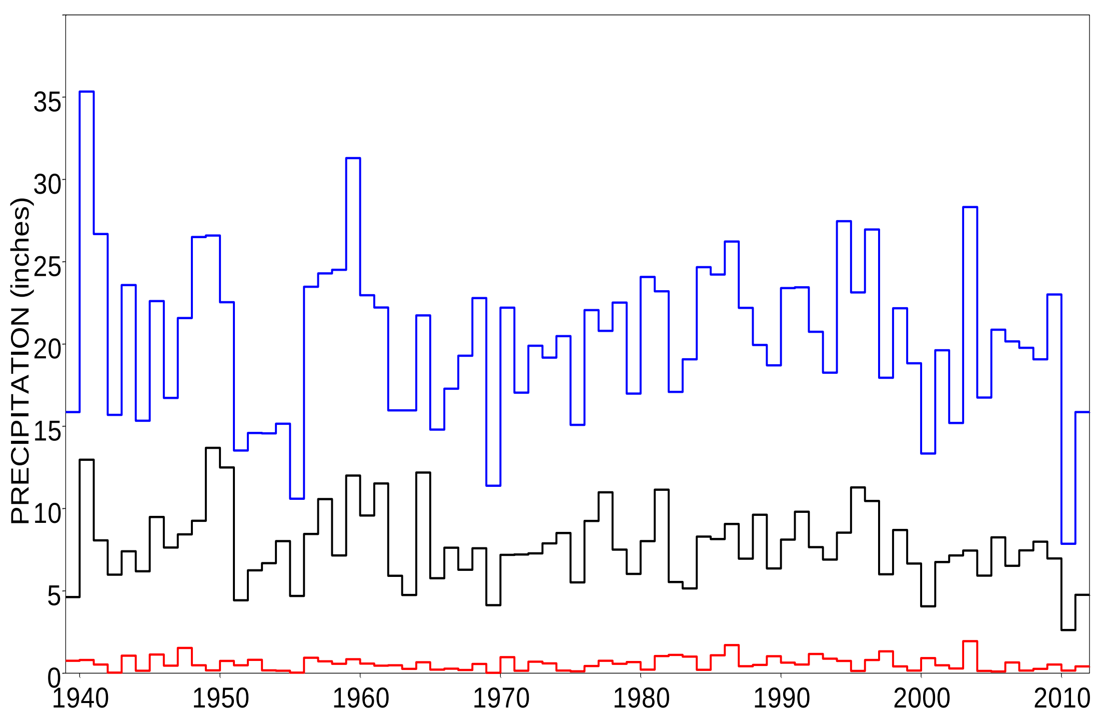
Monthly Precipitation for Quadrangle 205



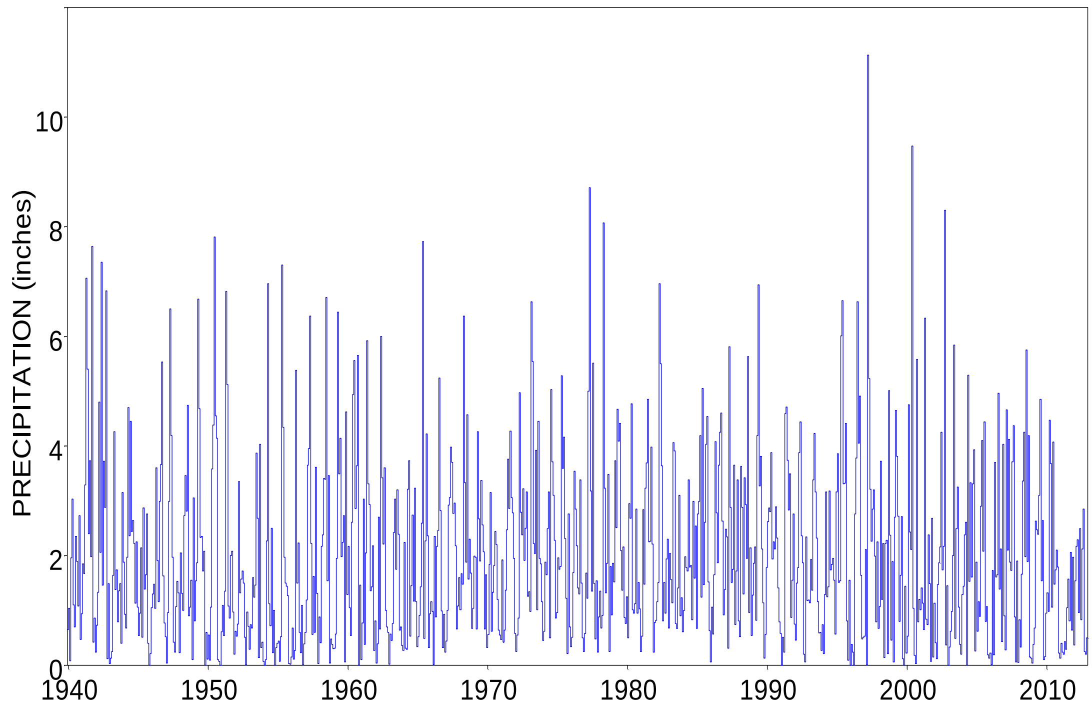
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 205



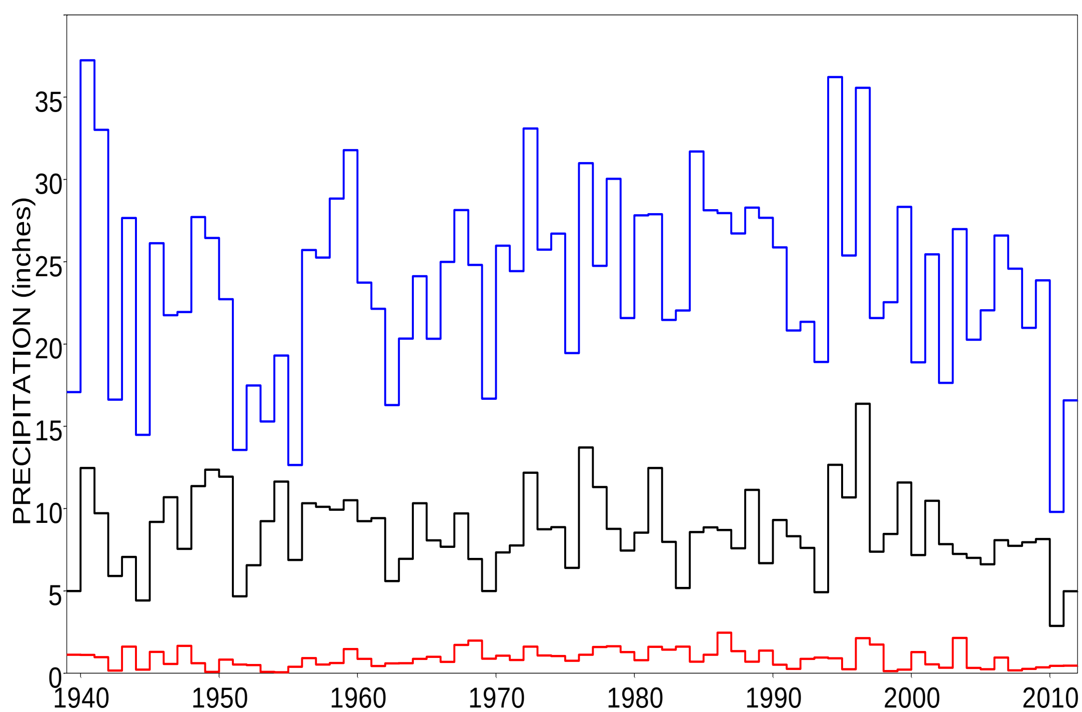
Monthly Precipitation for Quadrangle 206



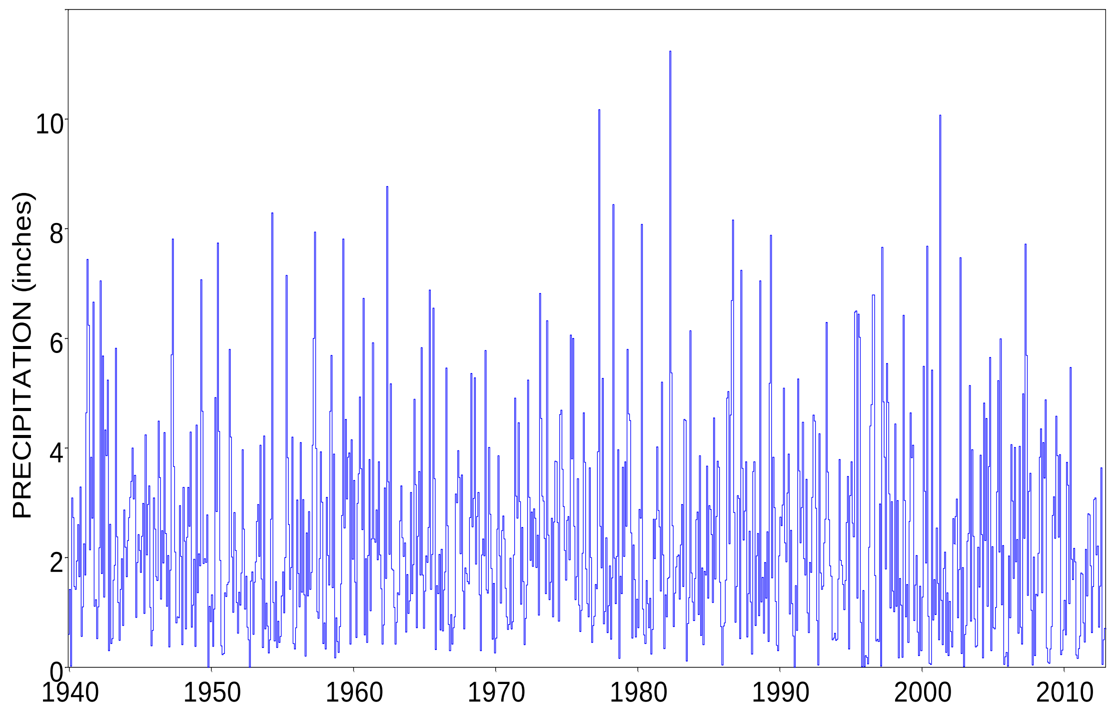
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 206



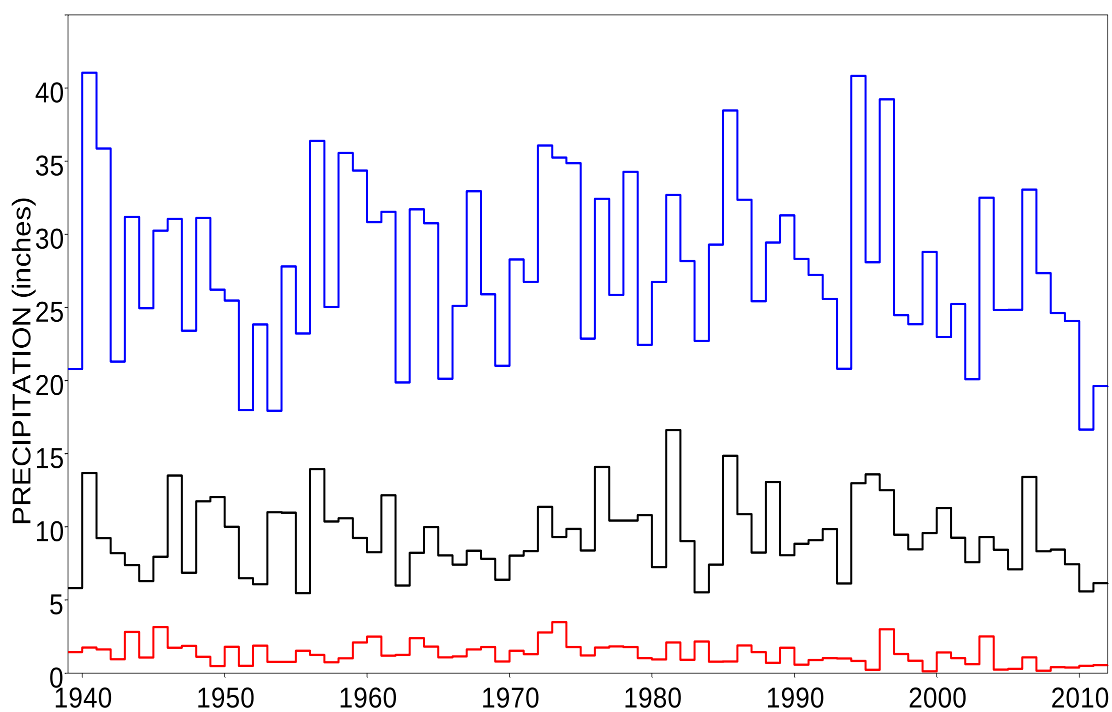
Monthly Precipitation for Quadrangle 207



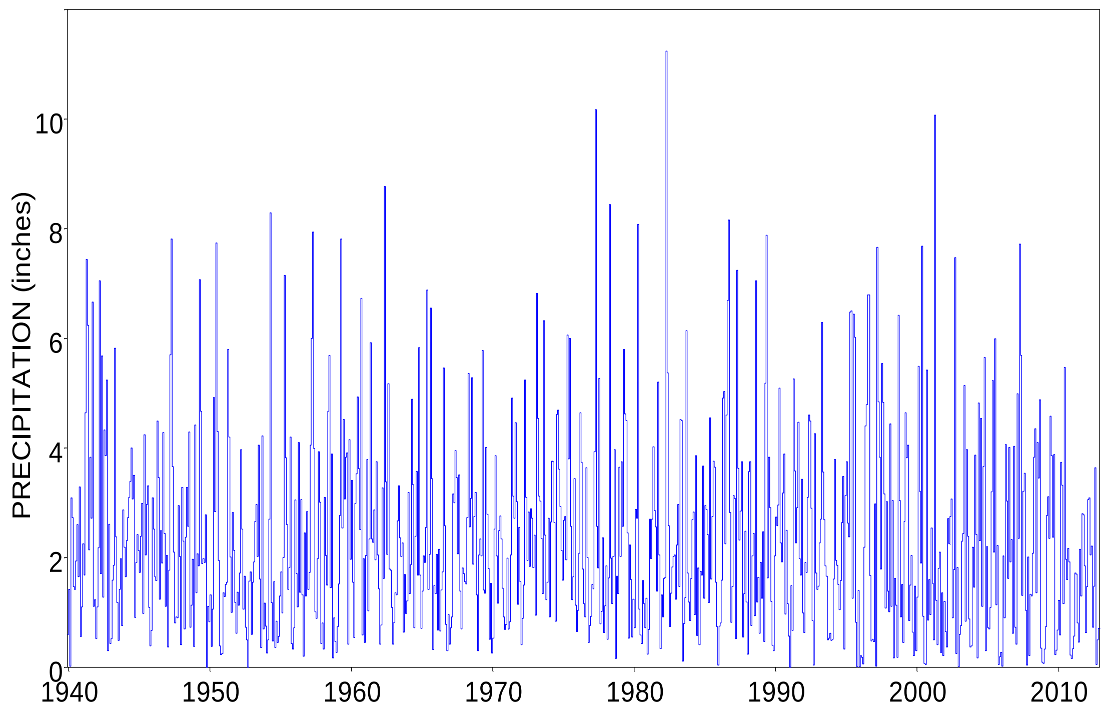
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 207



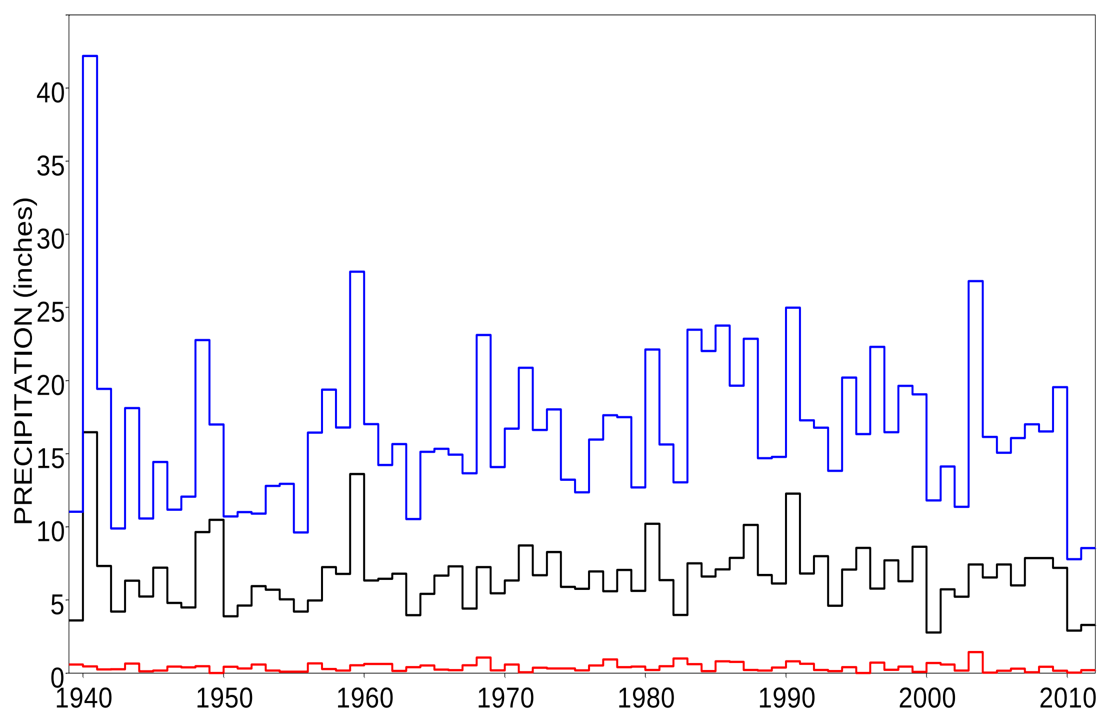
Monthly Precipitation for Quadrangle 207



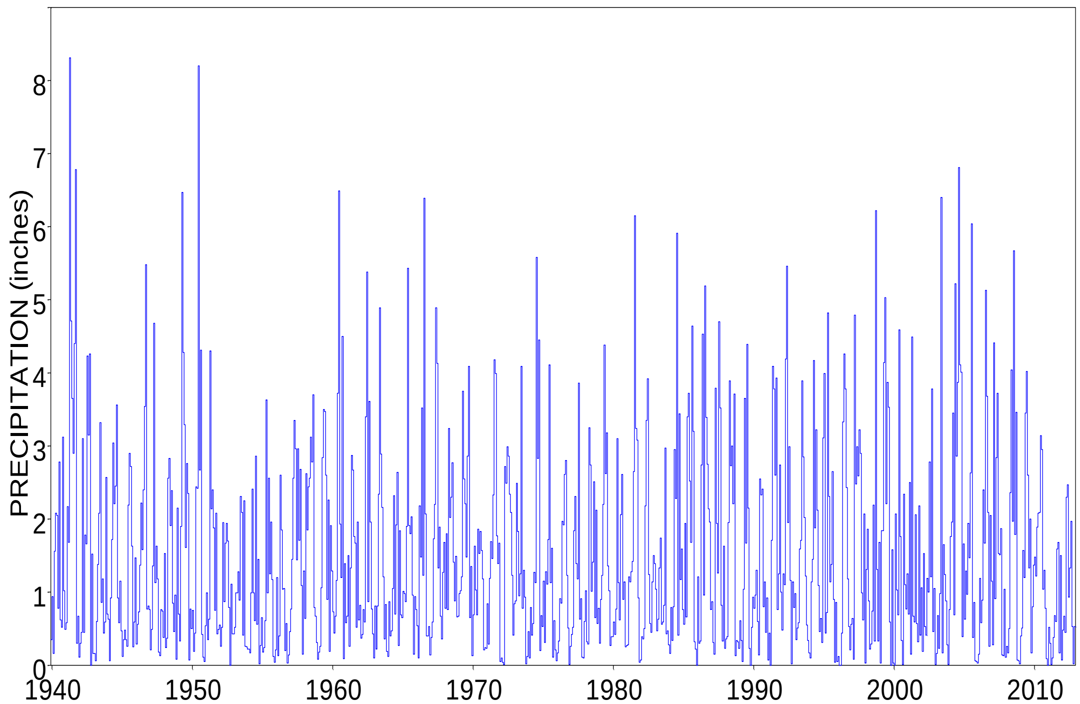
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 207



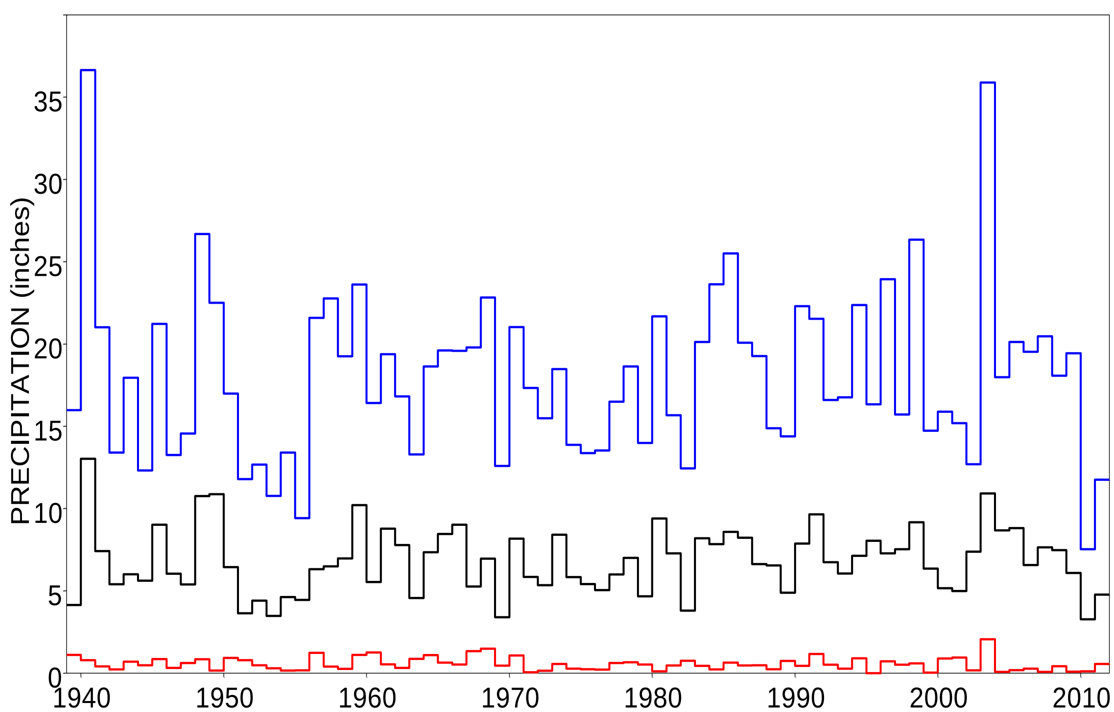
Monthly Precipitation for Quadrangle 304



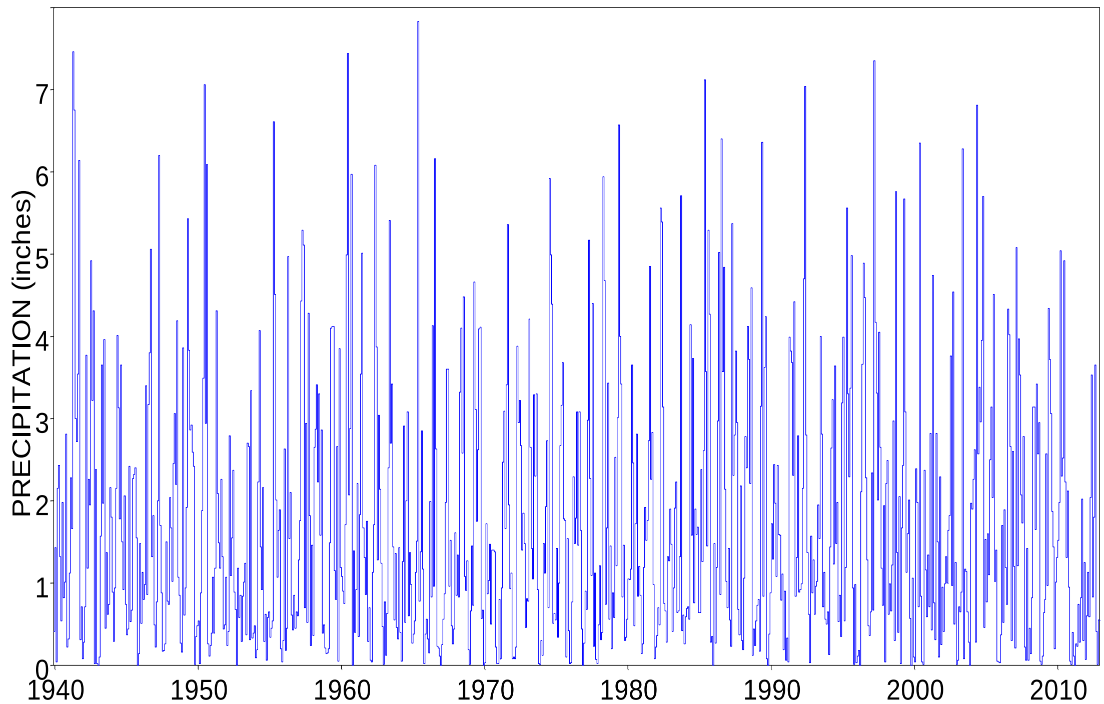
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 304



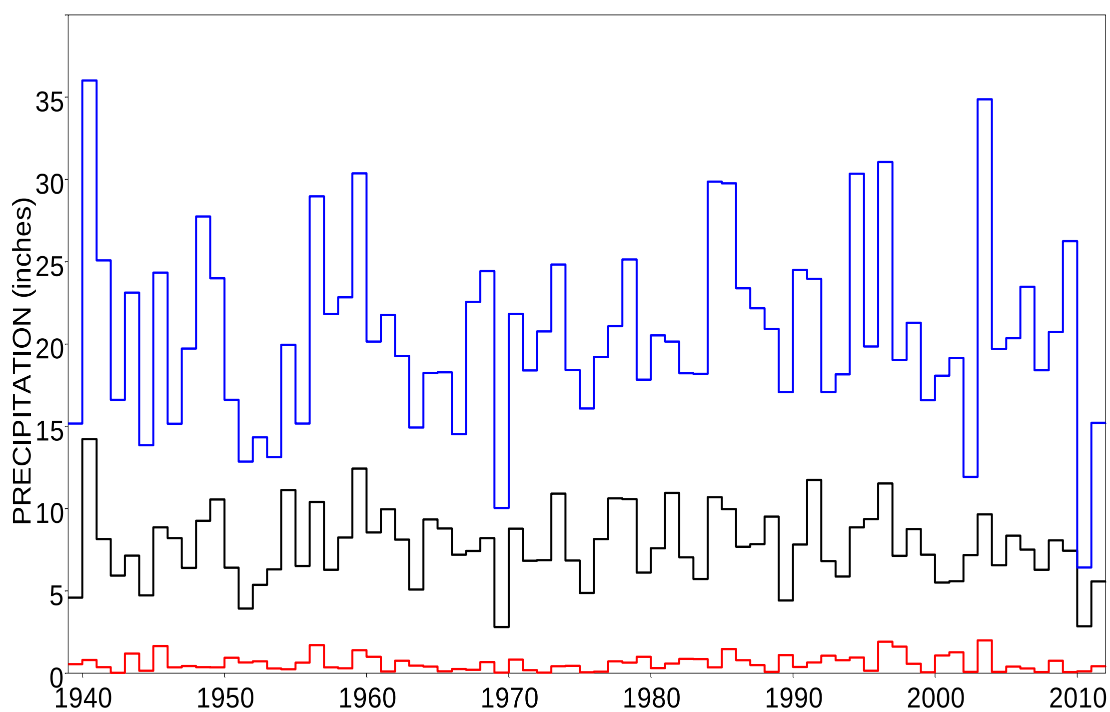
Monthly Precipitation for Quadrangle 305



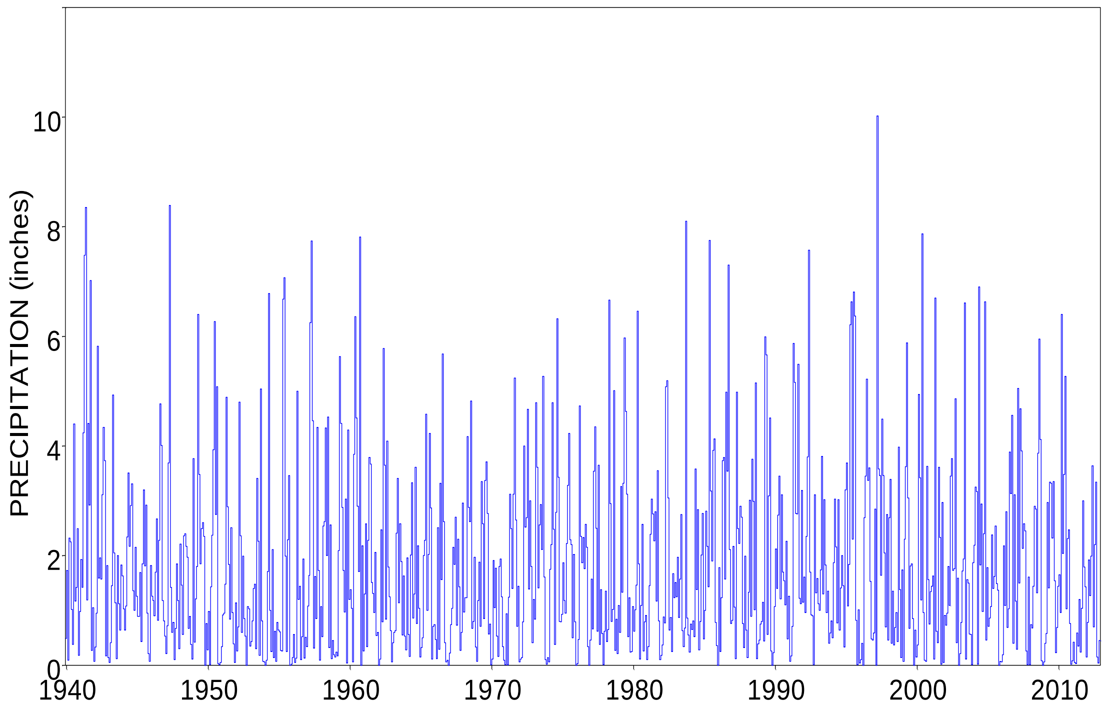
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 305



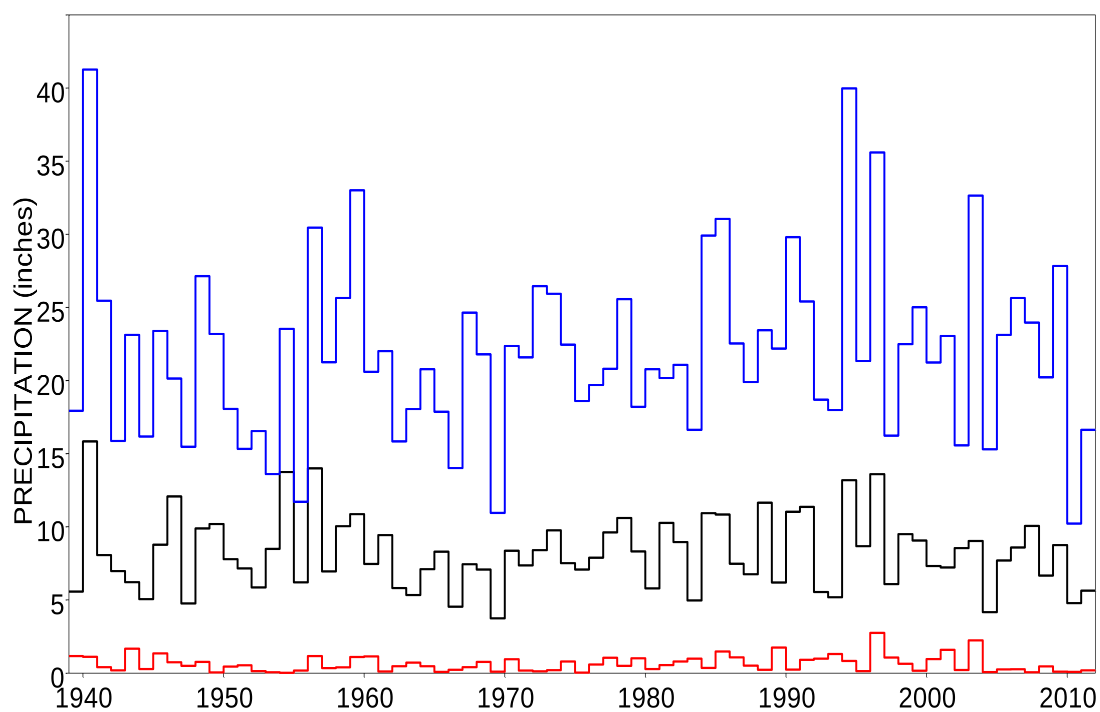
Monthly Precipitation for Quadrangle 306



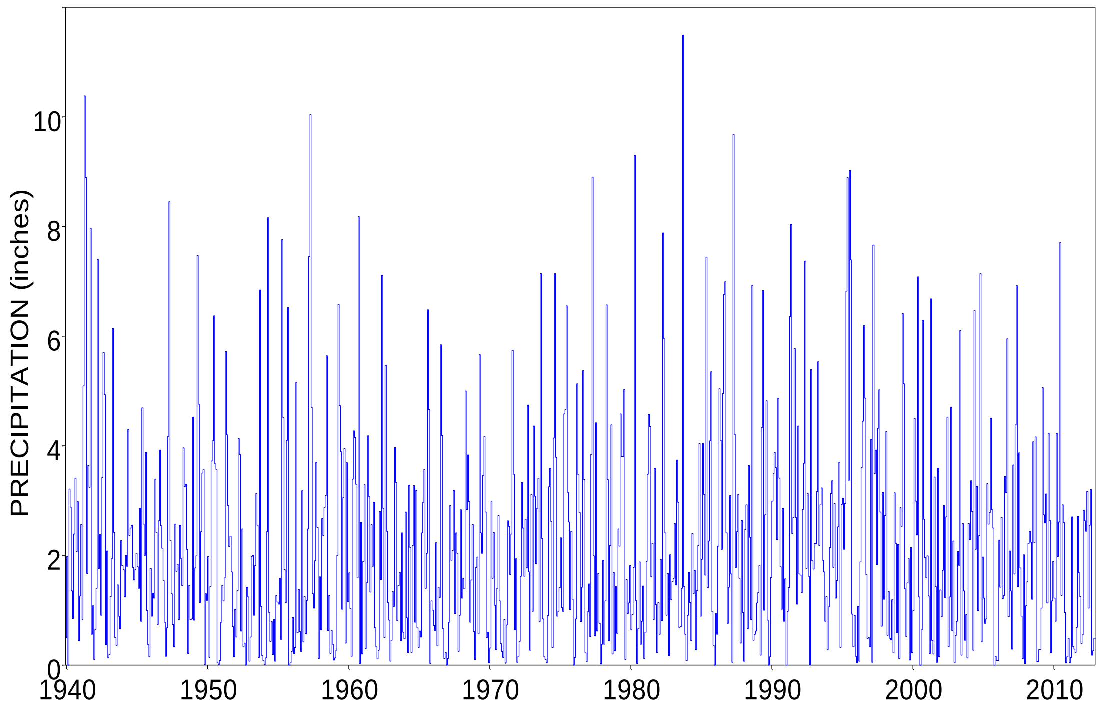
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 306



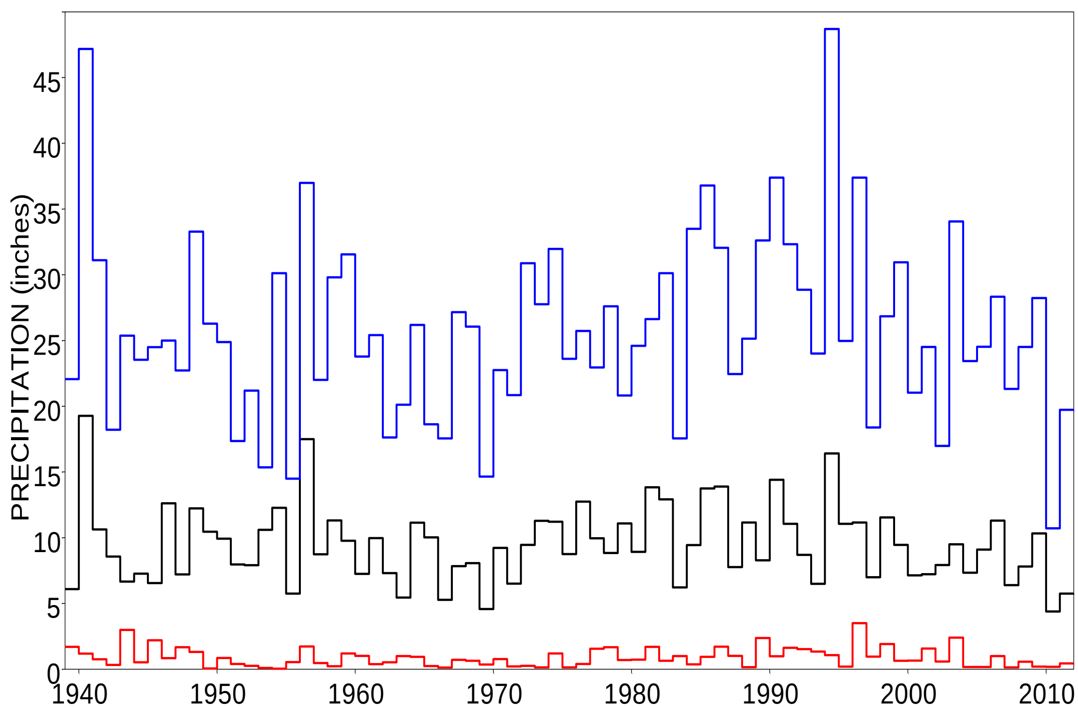
Monthly Precipitation for Quadrangle 307



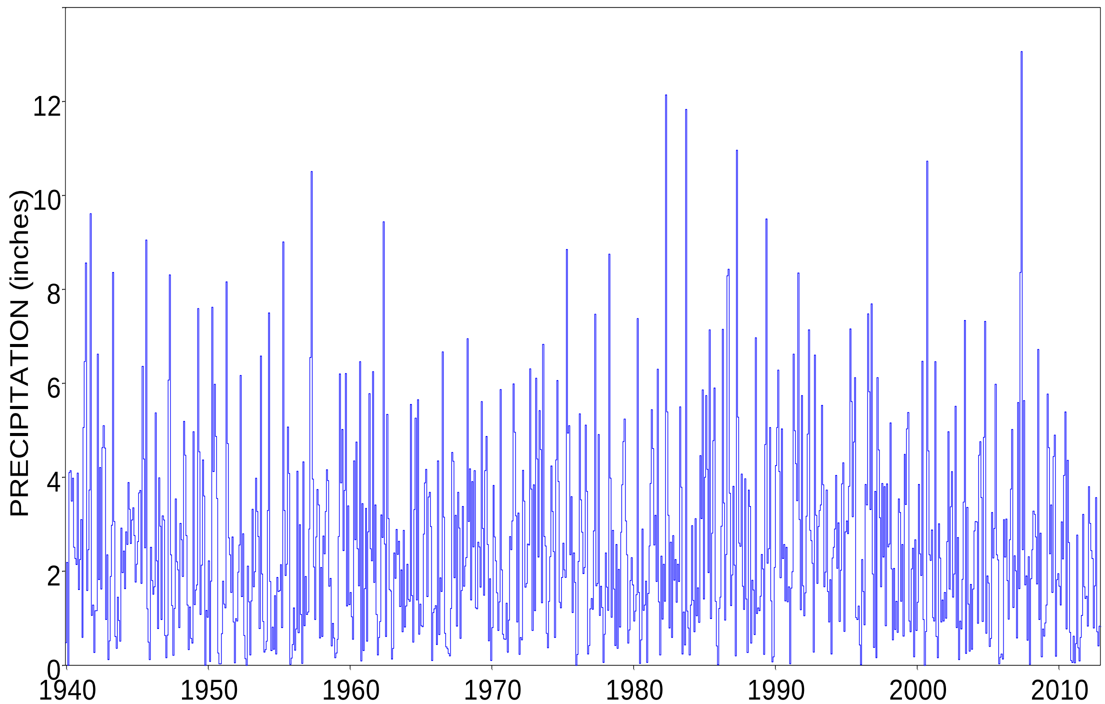
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 307



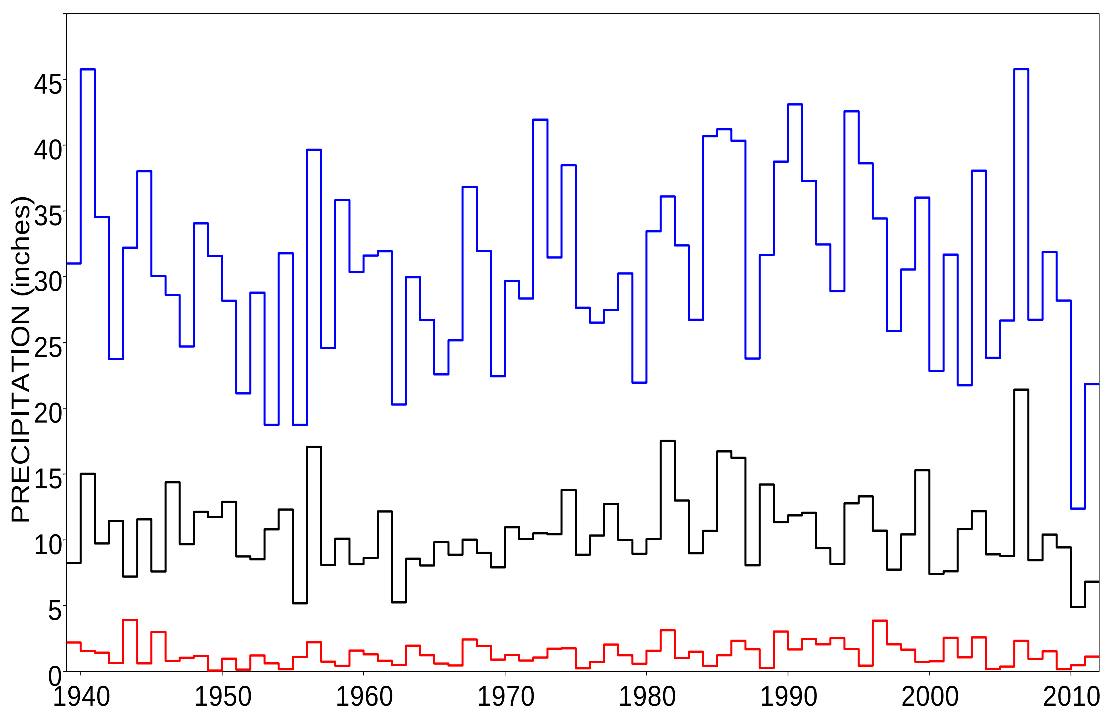
Monthly Precipitation for Quadrangle 308



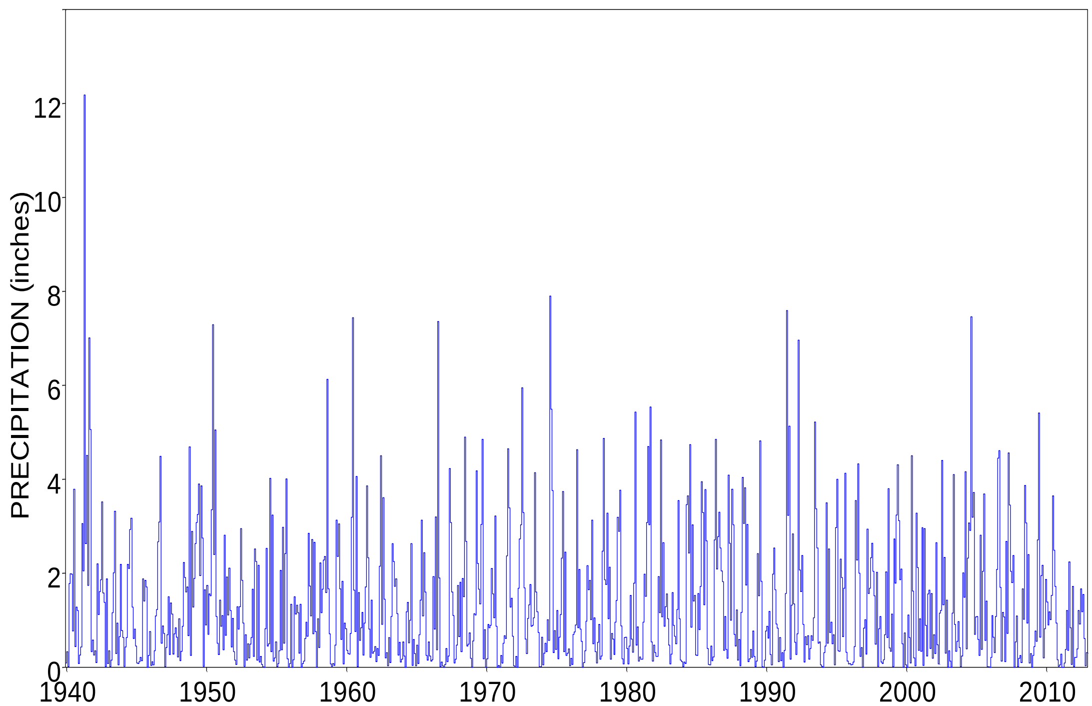
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 308



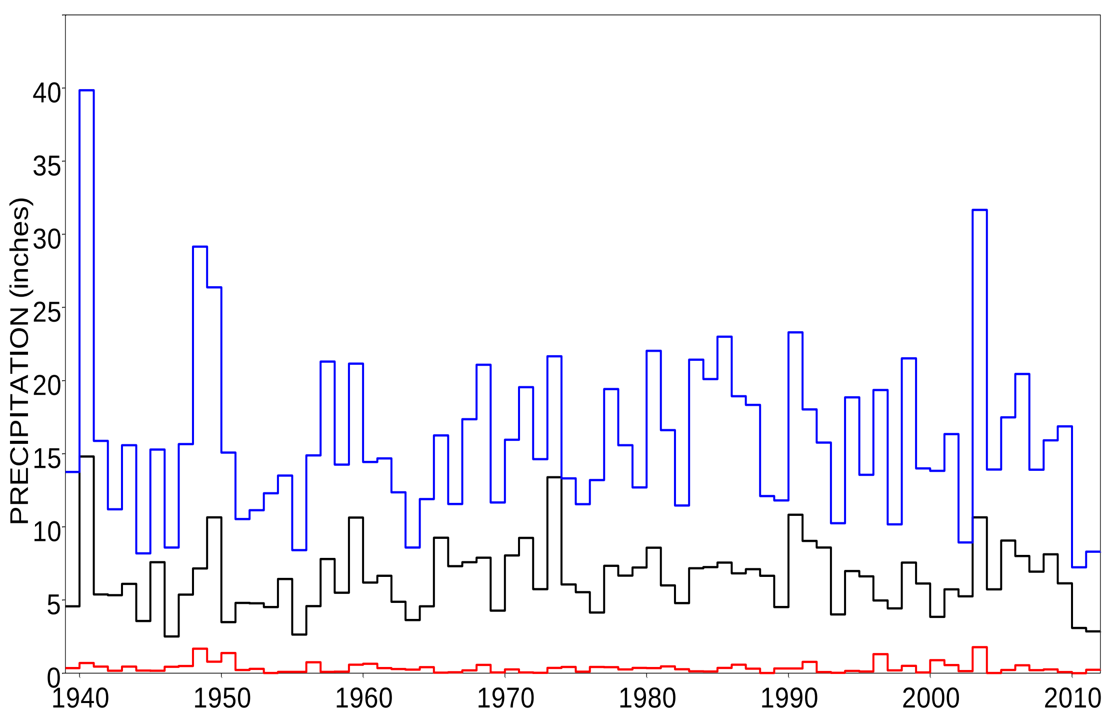
Monthly Precipitation for Quadrangle 309



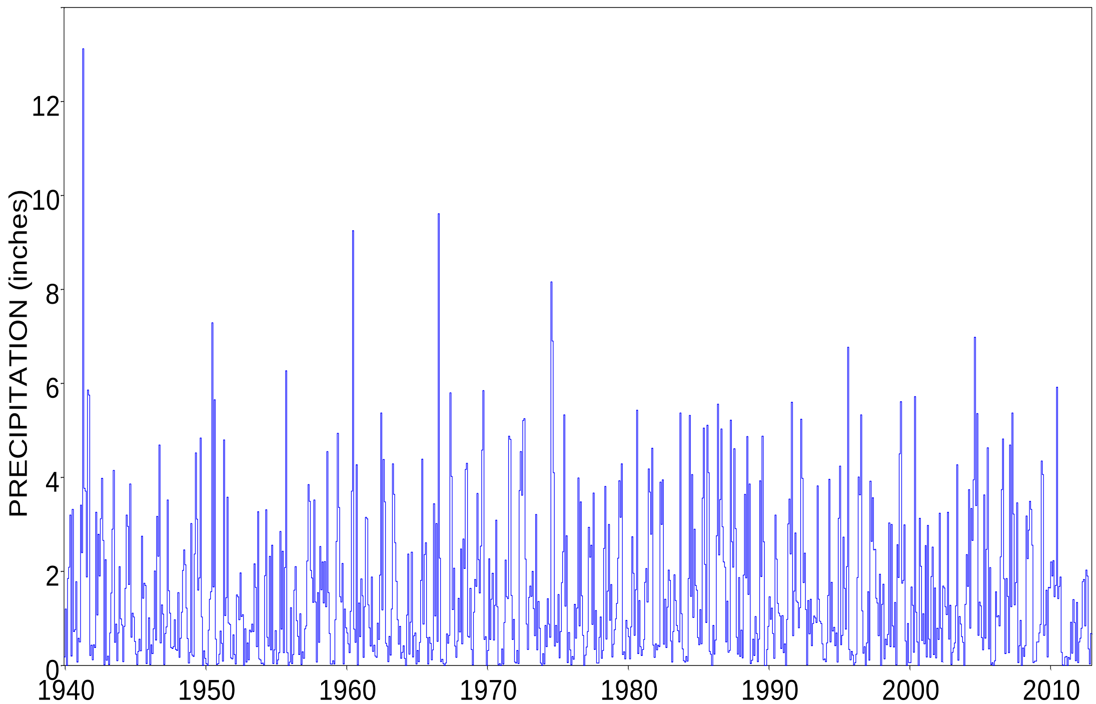
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 309



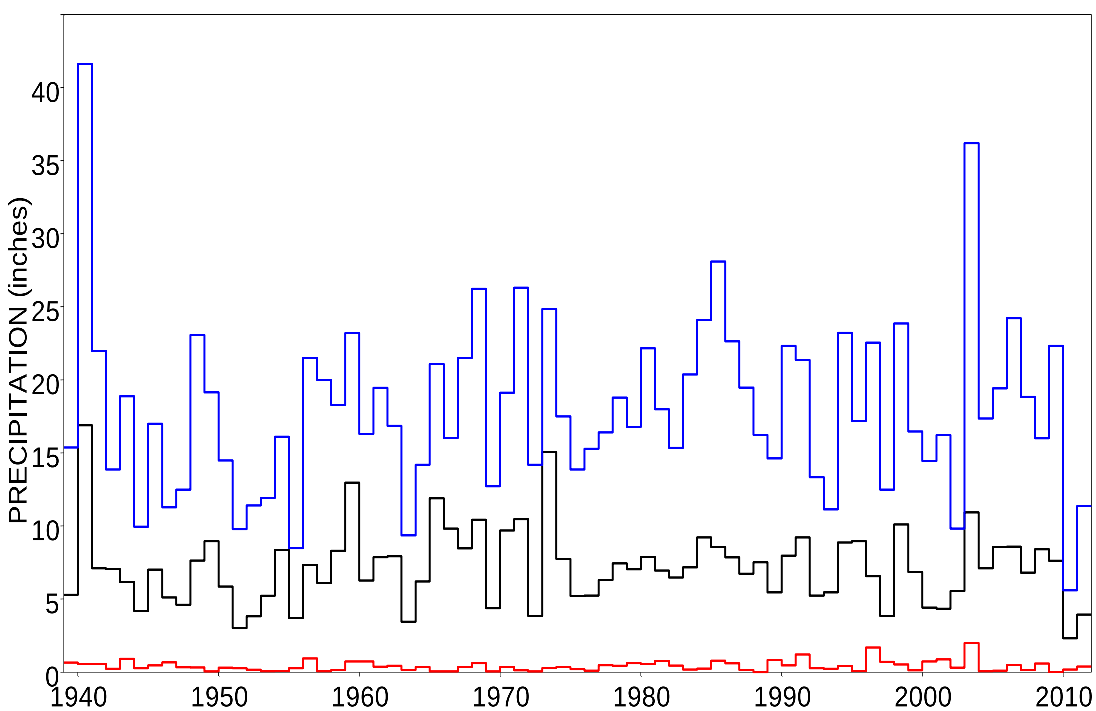
Monthly Precipitation for Quadrangle 404



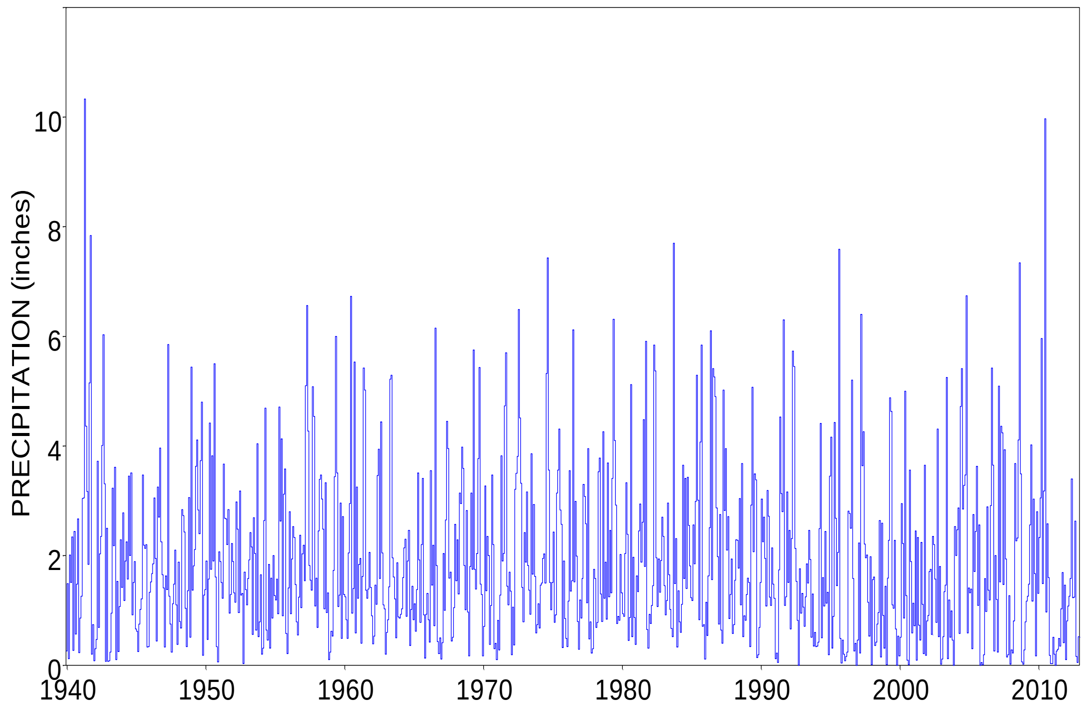
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 404



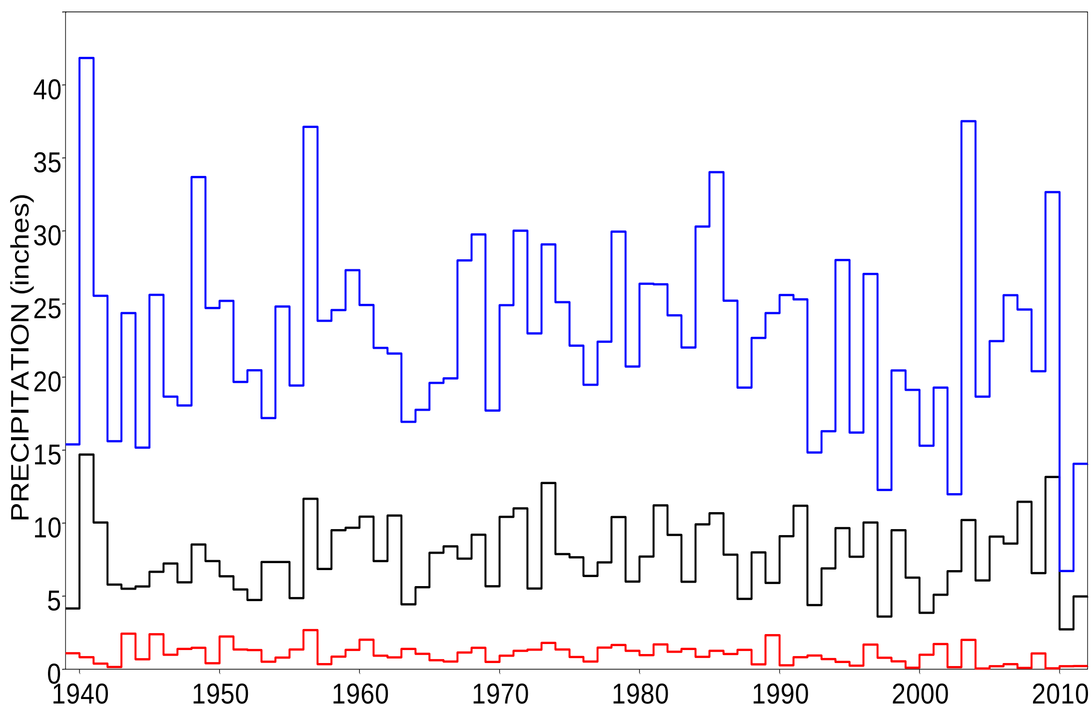
Monthly Precipitation for Quadrangle 405



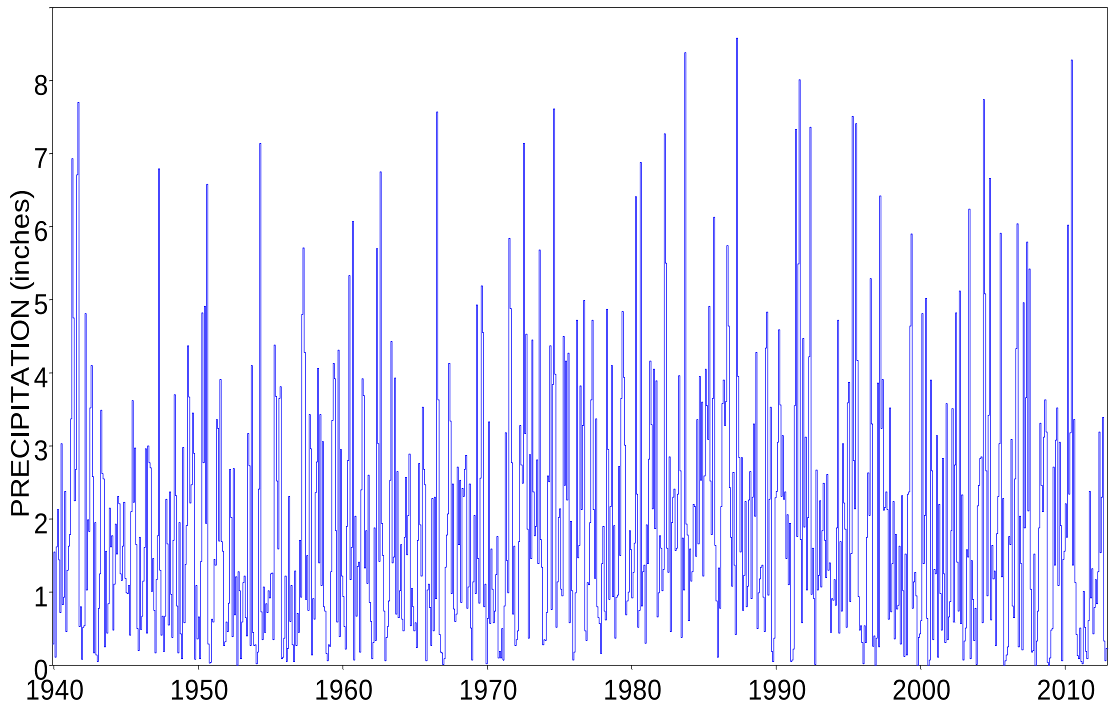
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 405



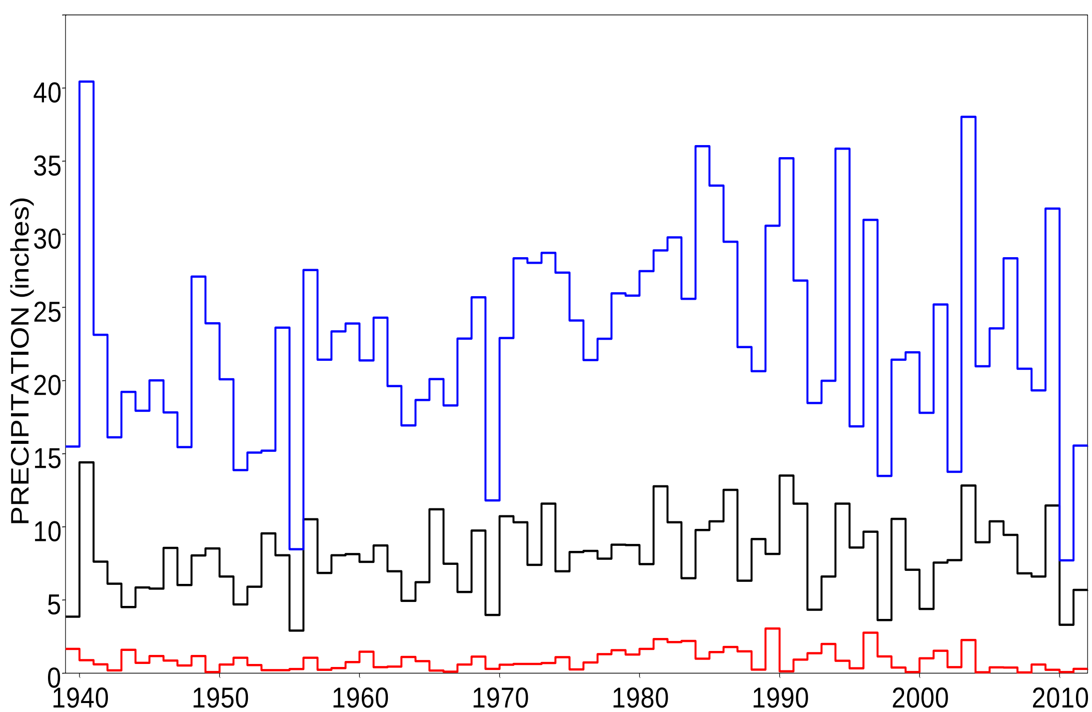
Monthly Precipitation for Quadrangle 406



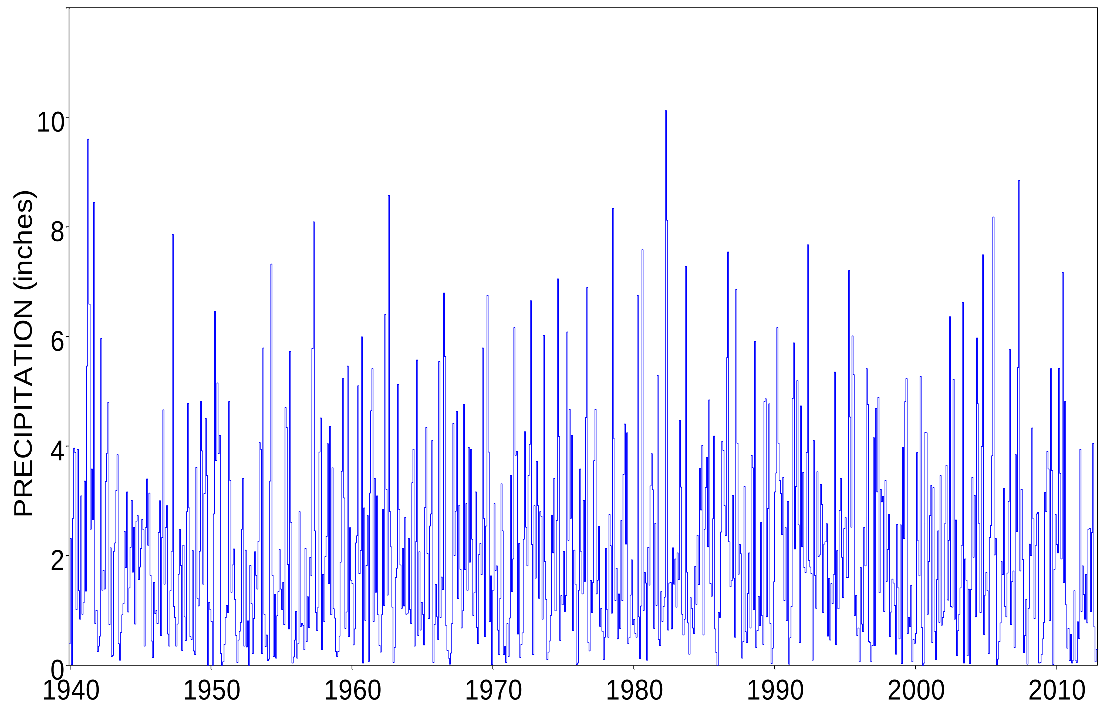
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 406



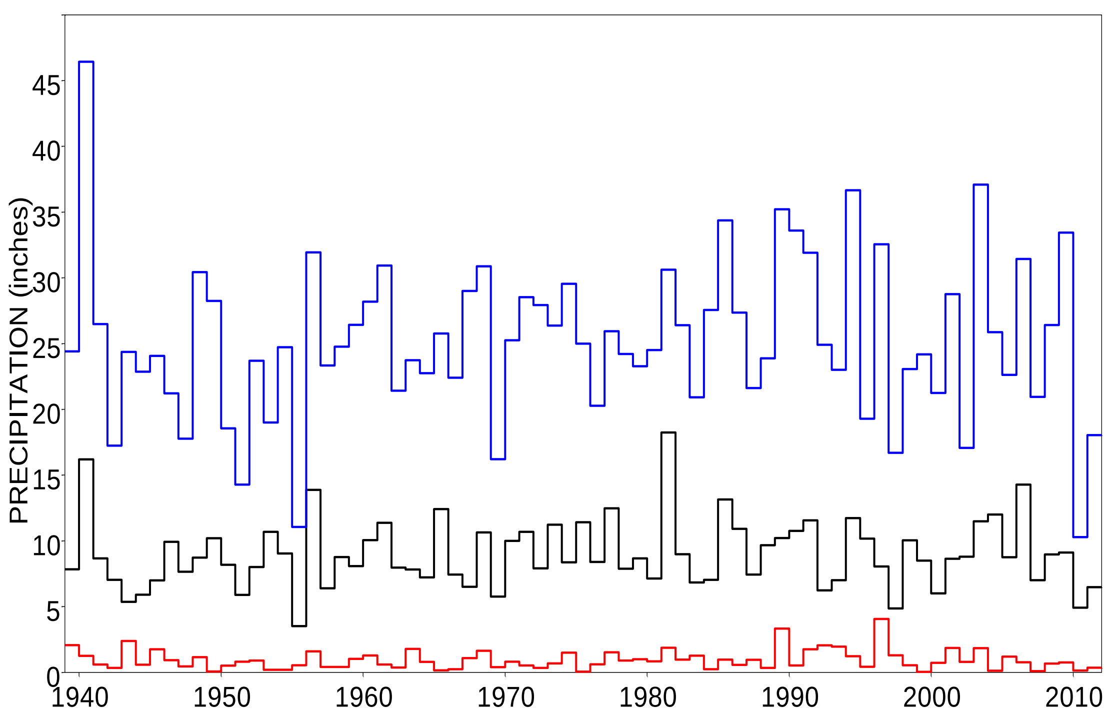
Monthly Precipitation for Quadrangle 407



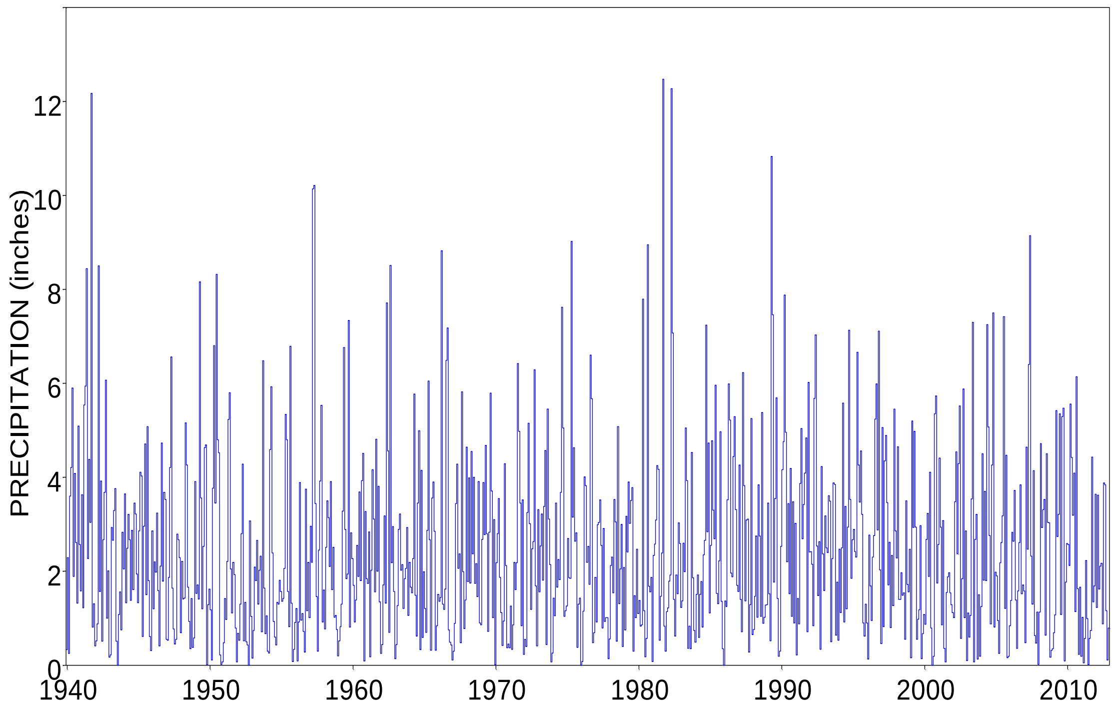
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 407



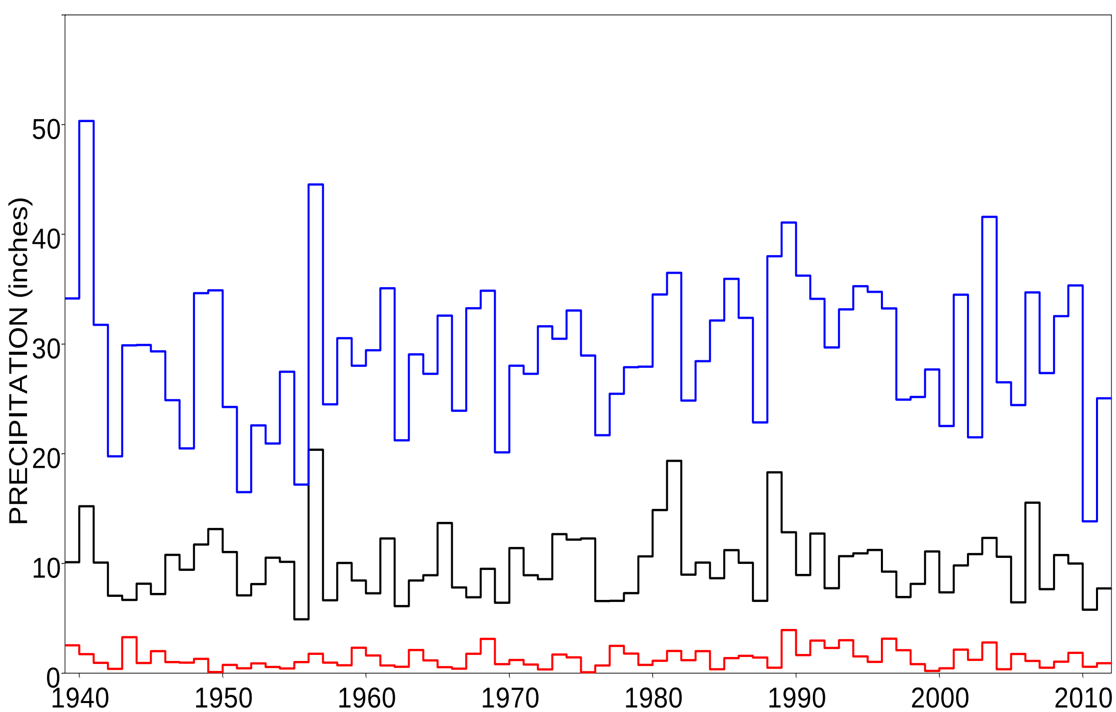
Monthly Precipitation for Quadrangle 408



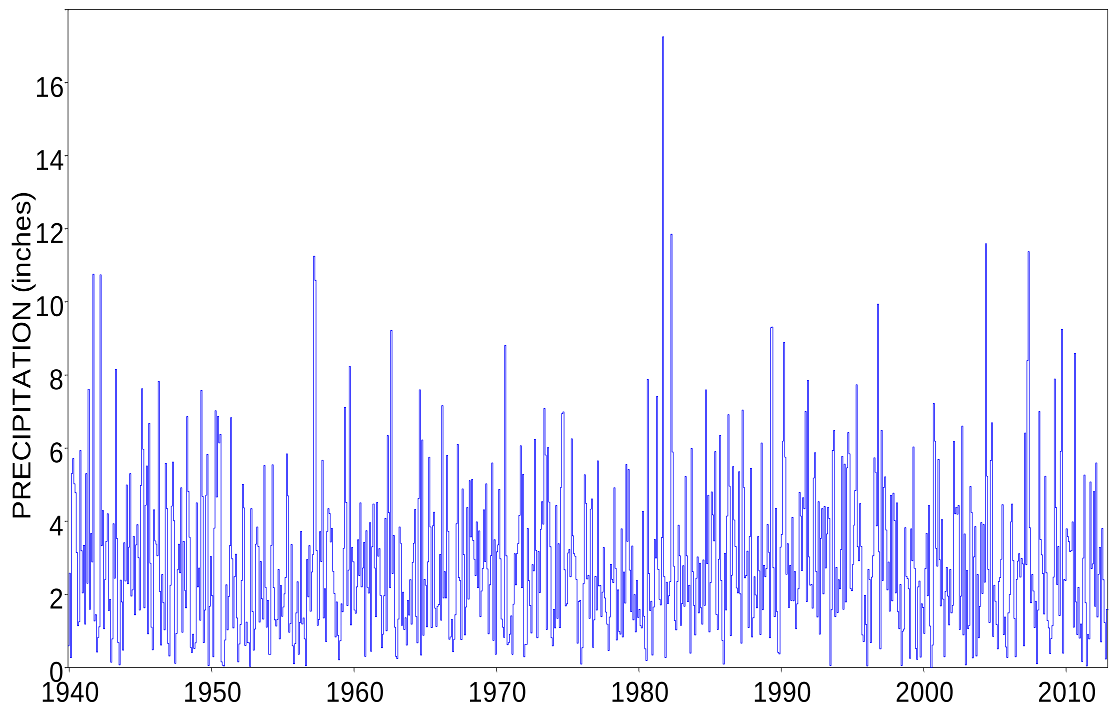
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 408



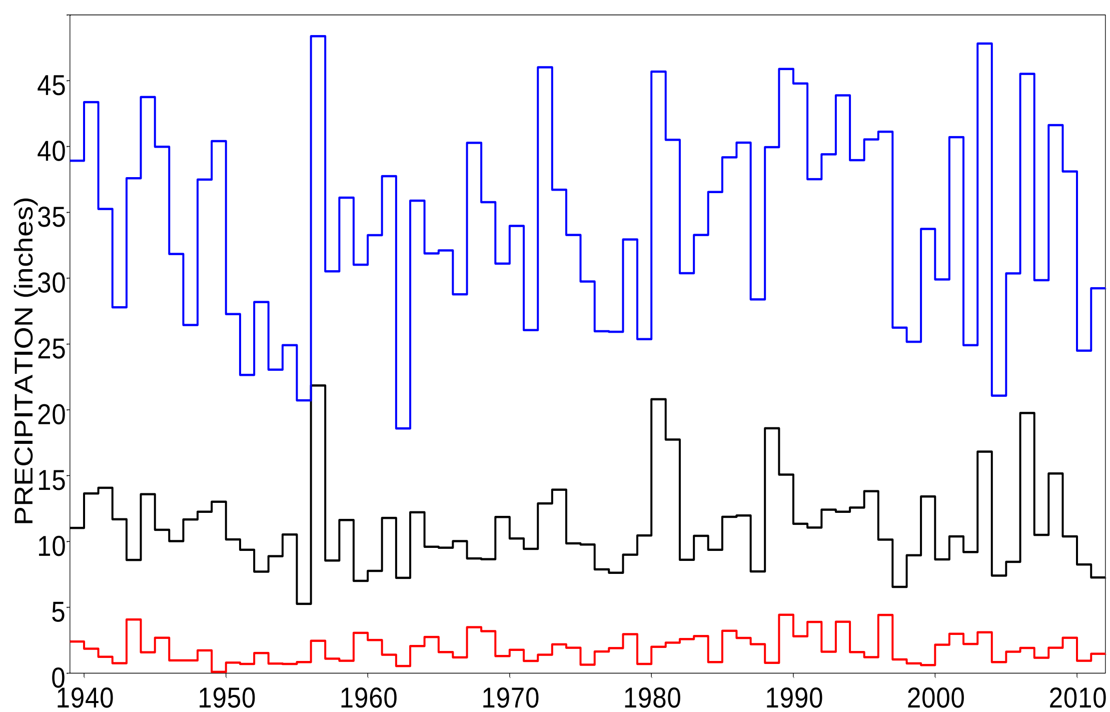
Monthly Precipitation for Quadrangle 409



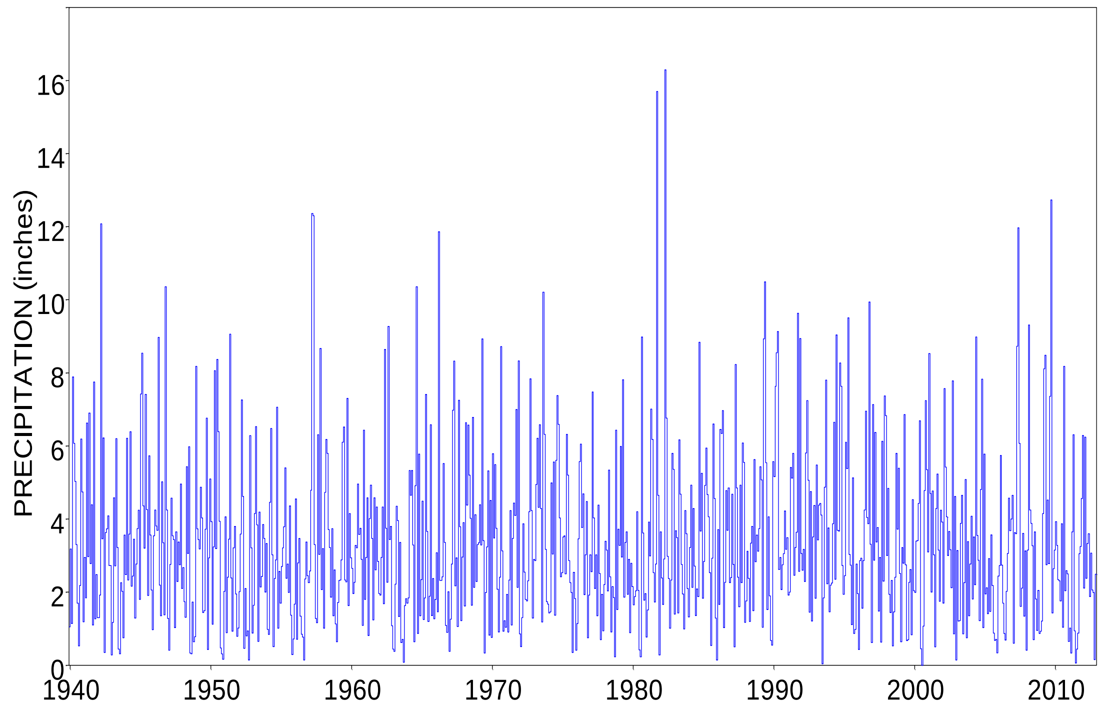
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 409



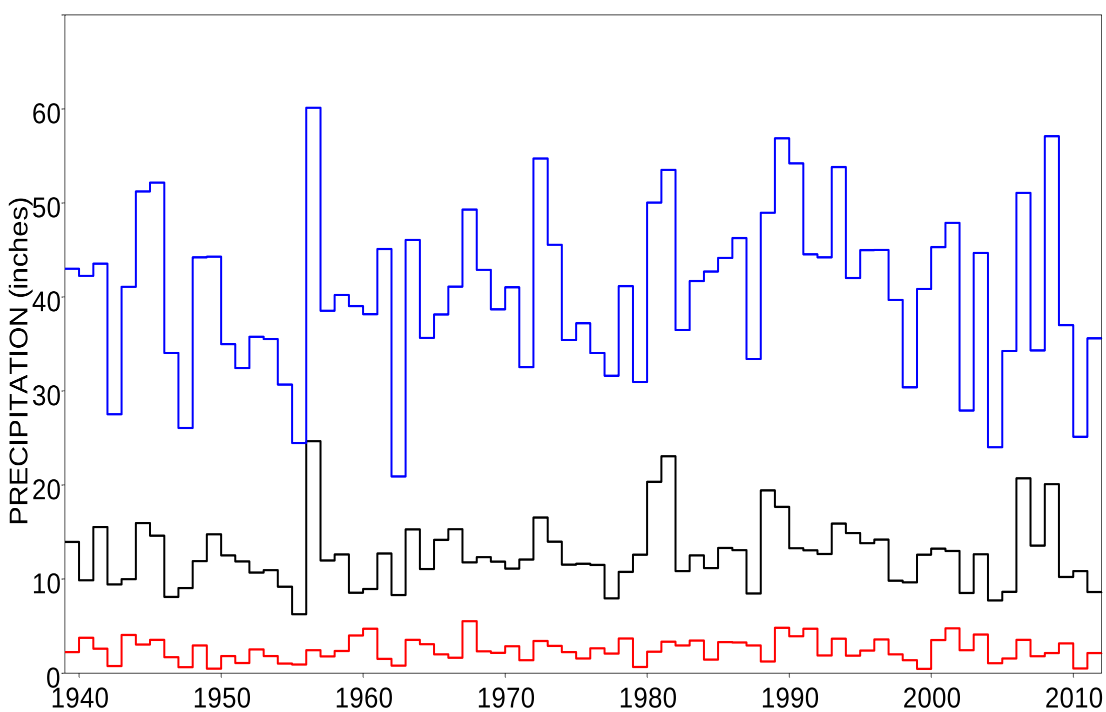
Monthly Precipitation for Quadrangle 410



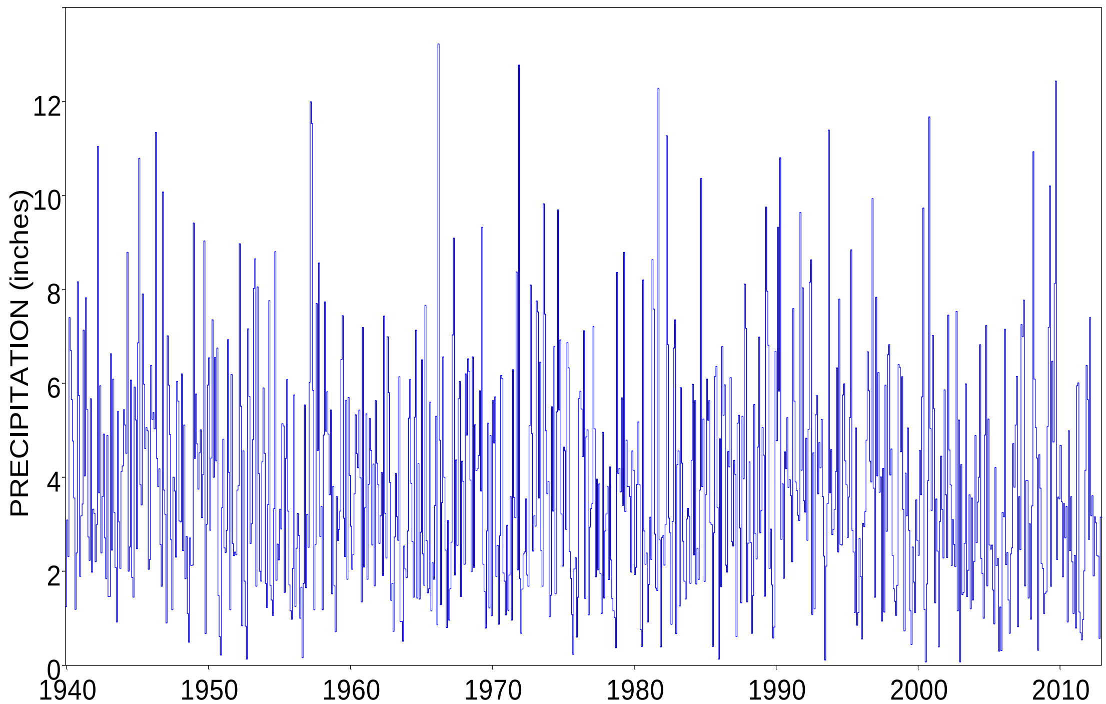
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 410



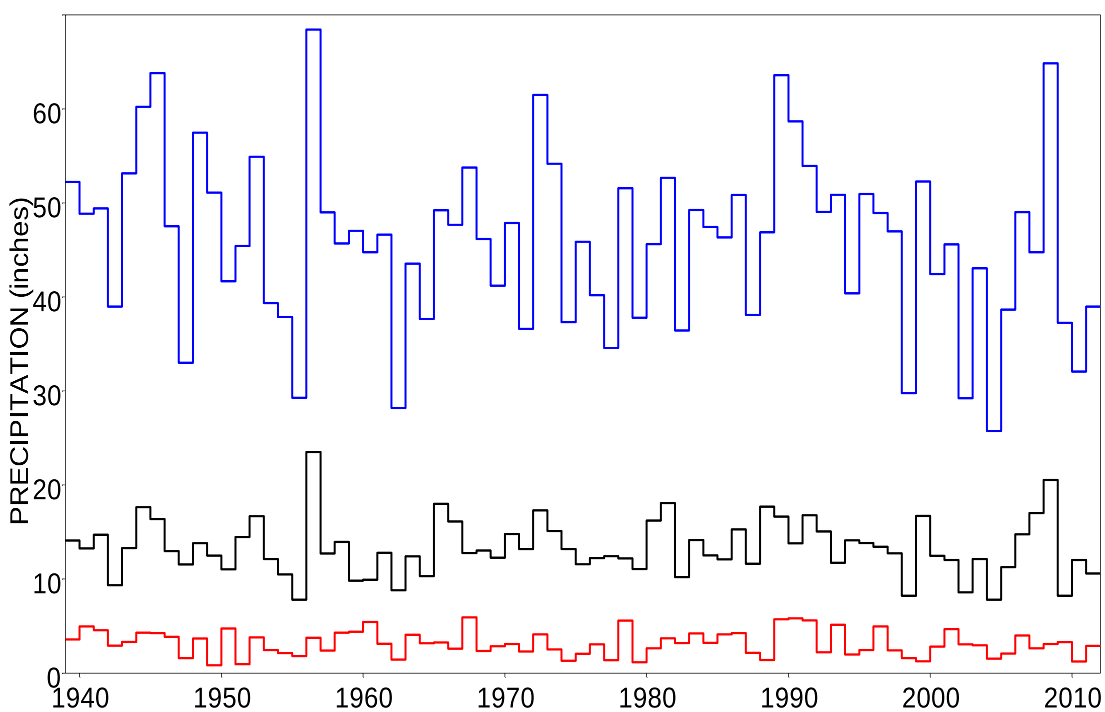
Monthly Precipitation for Quadrangle 411



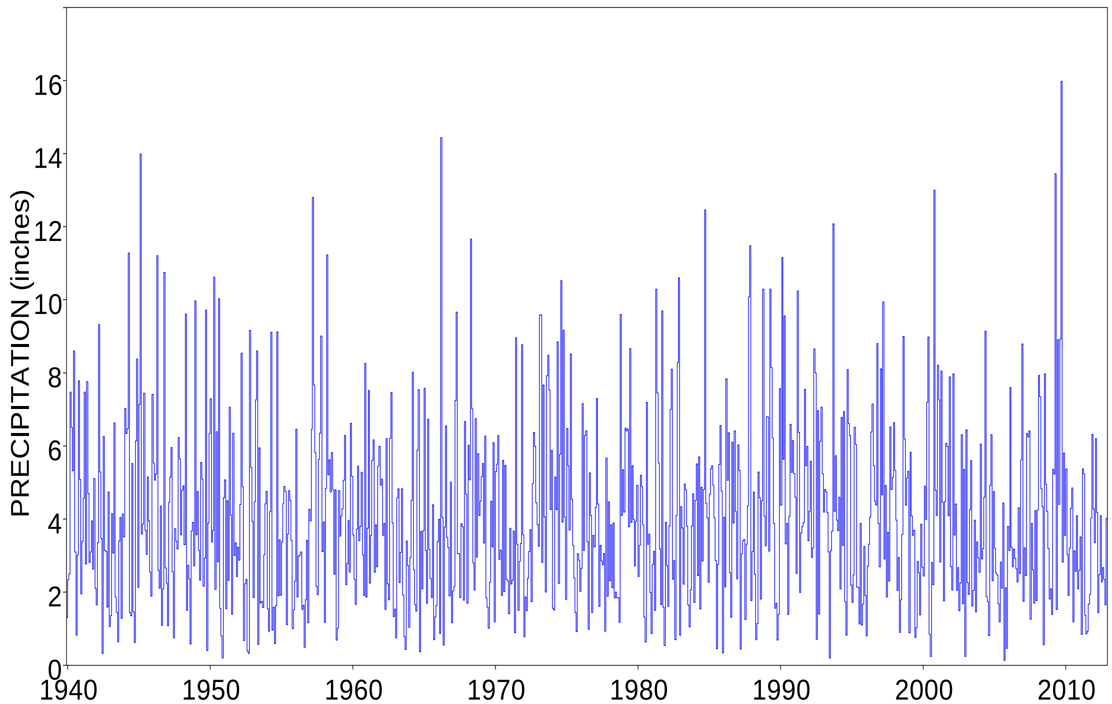
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 411



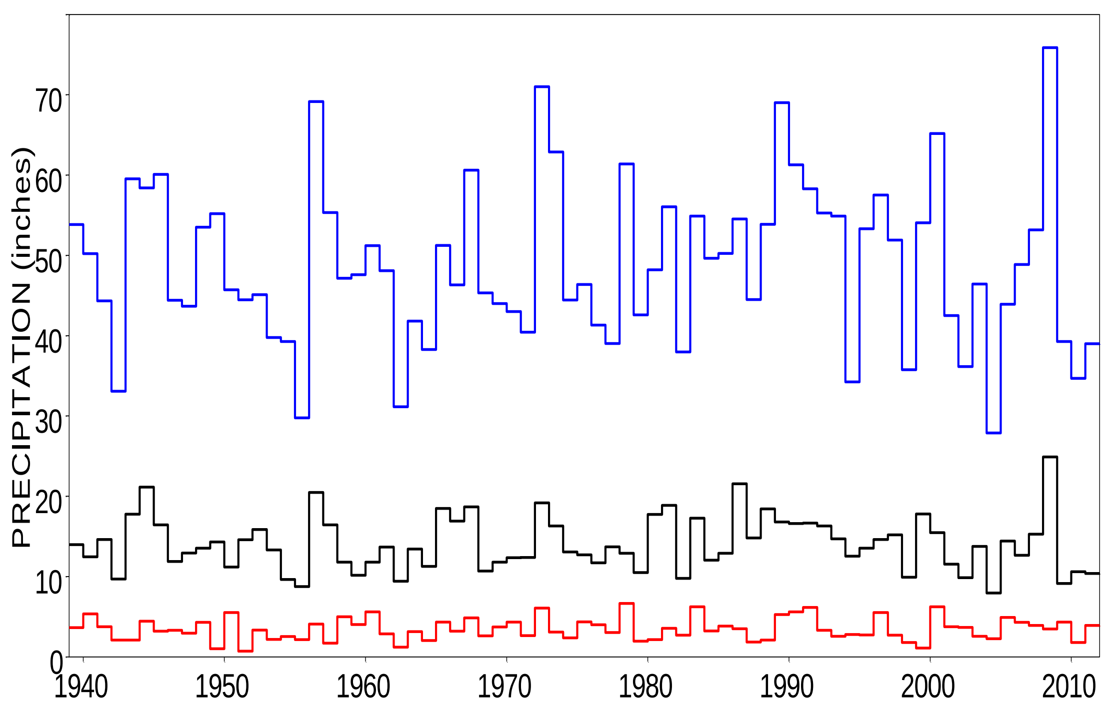
Monthly Precipitation for Quadrangle 412



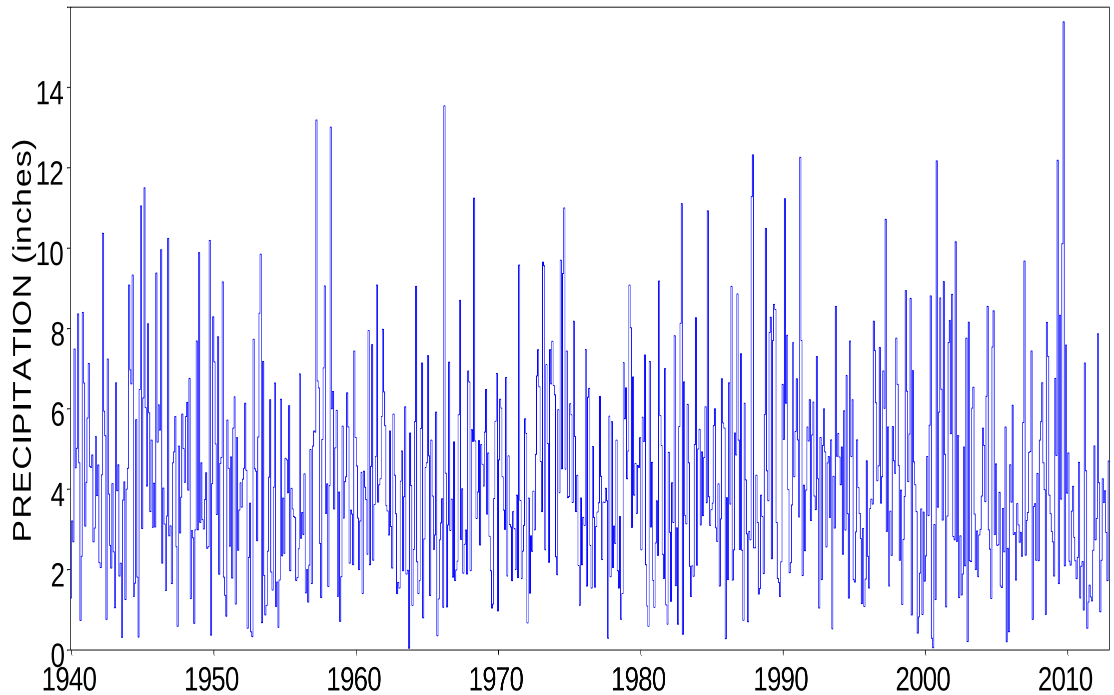
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 412



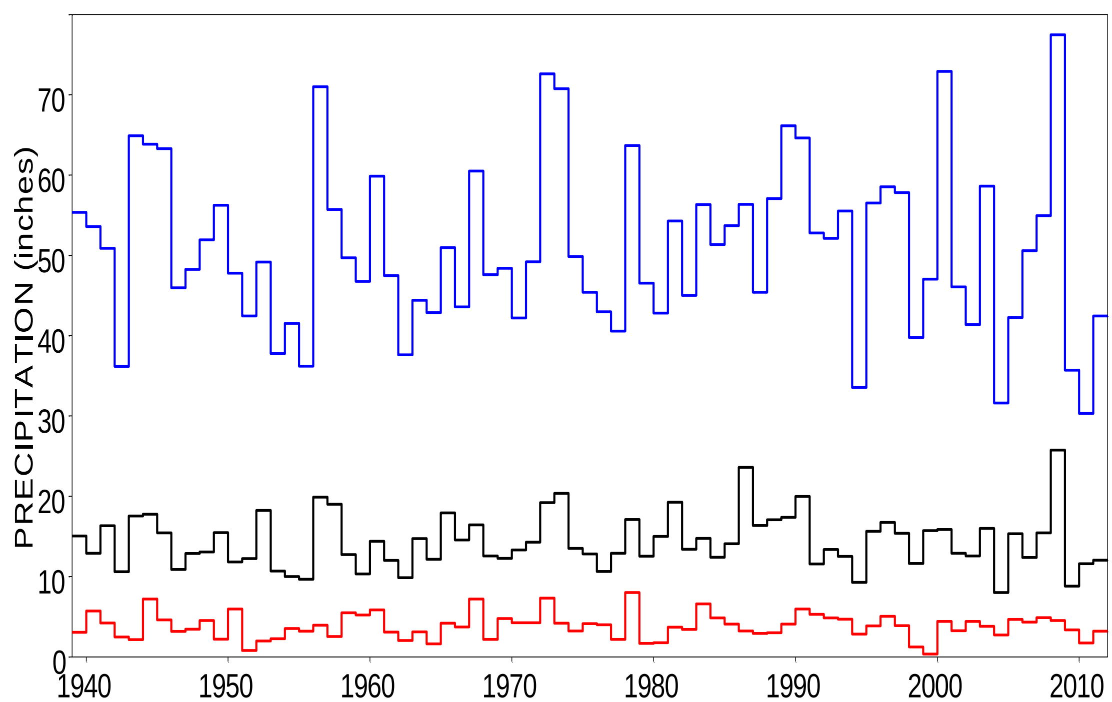
Monthly Precipitation for Quadrangle 413



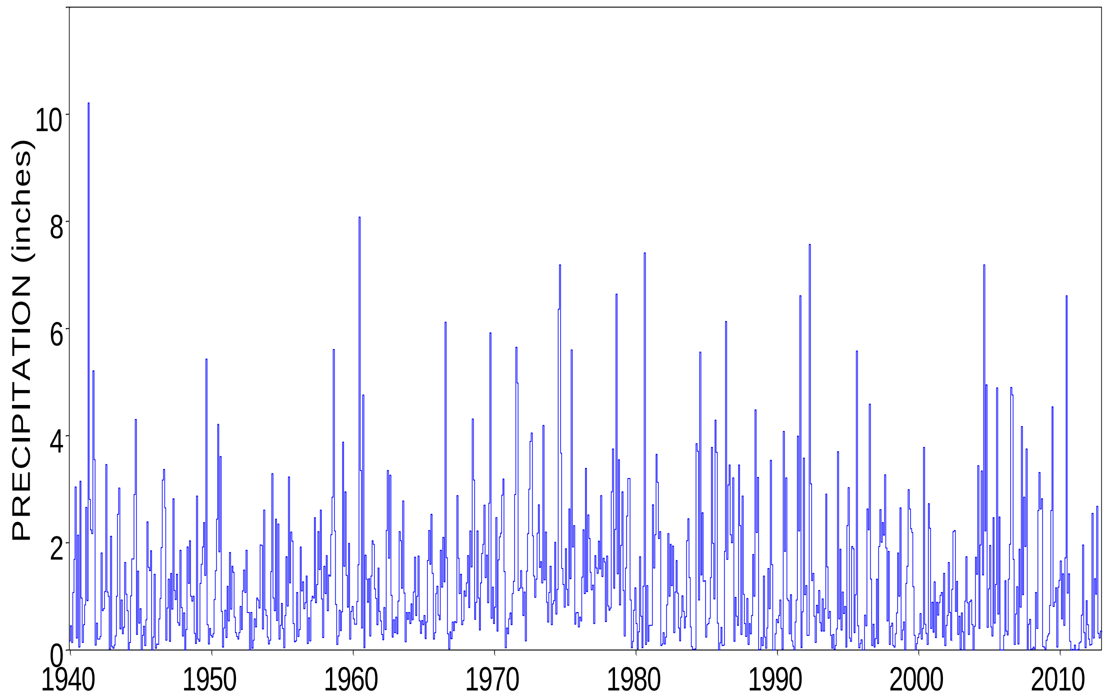
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 413



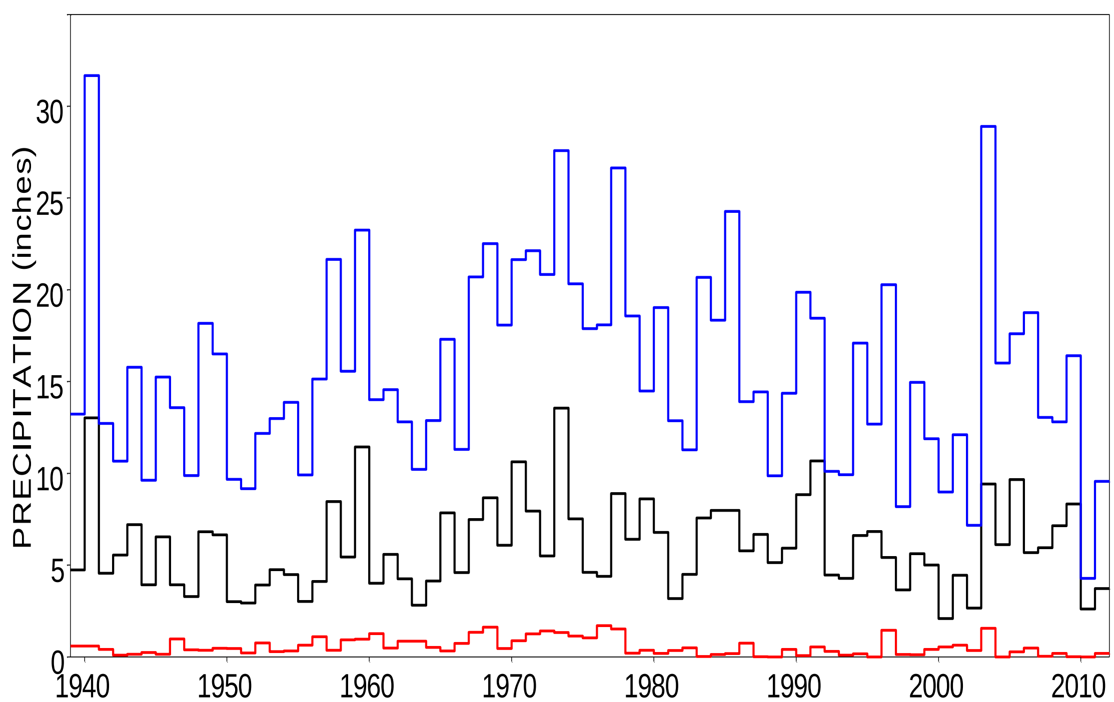
Monthly Precipitation for Quadrangle 414



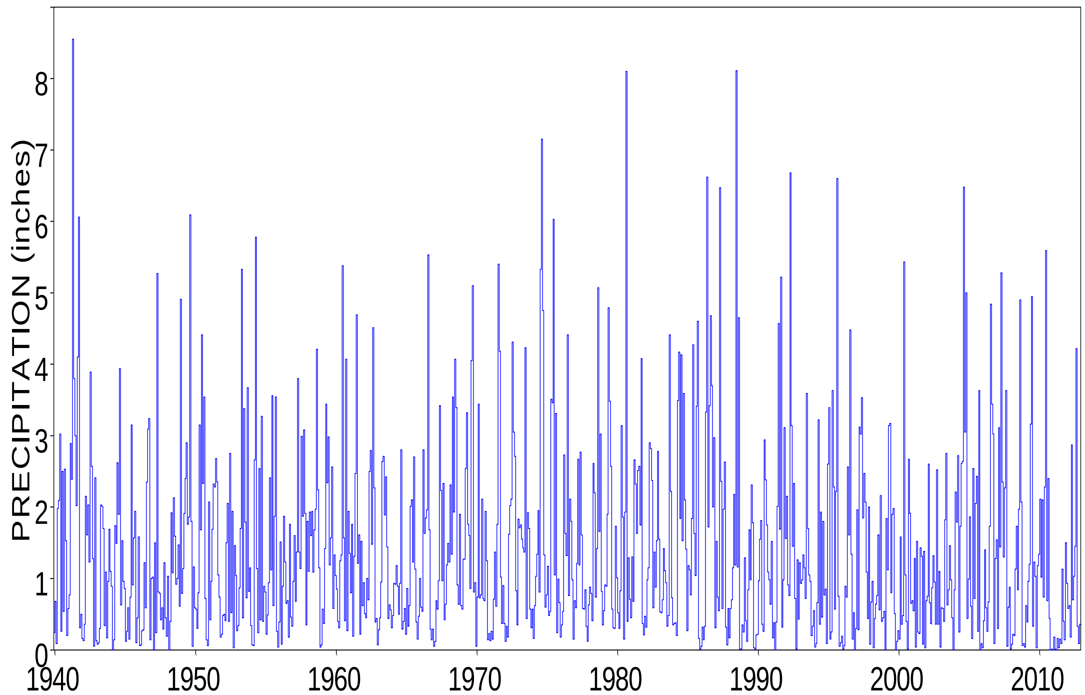
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 414



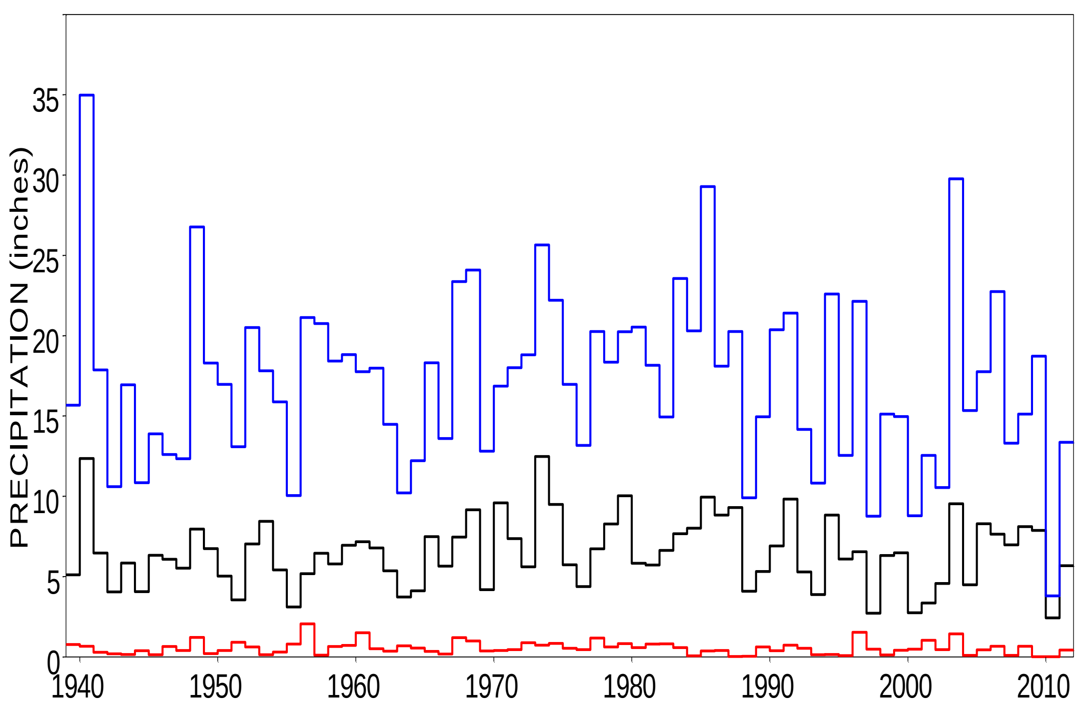
Monthly Precipitation for Quadrangle 504



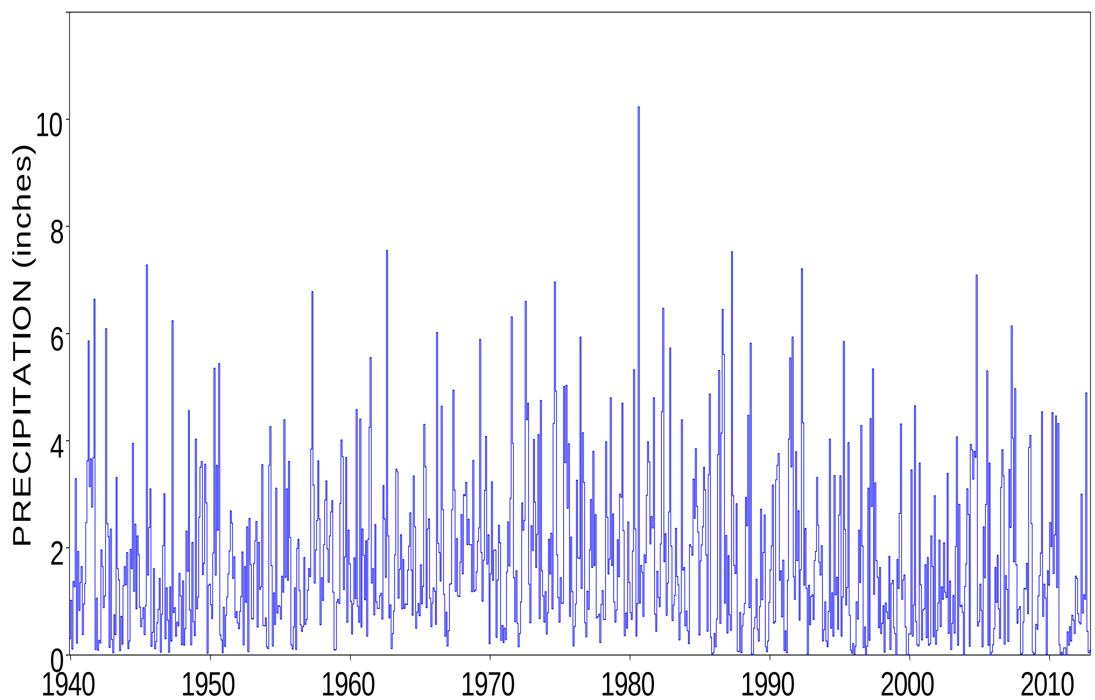
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 504



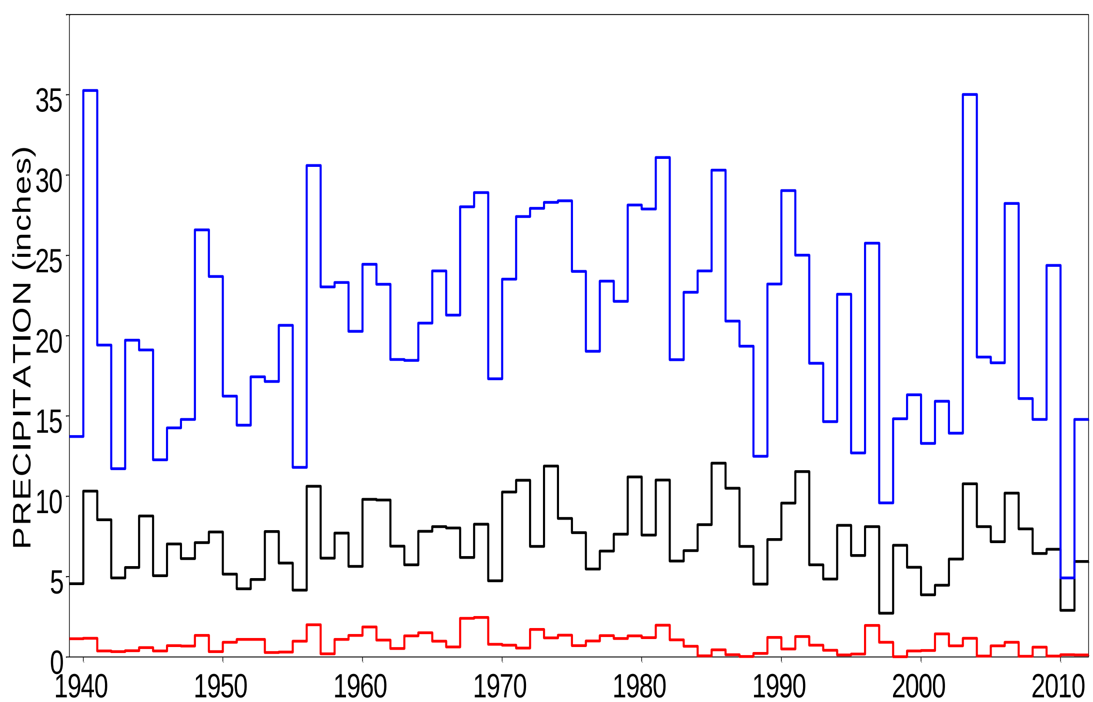
Monthly Precipitation for Quadrangle 505



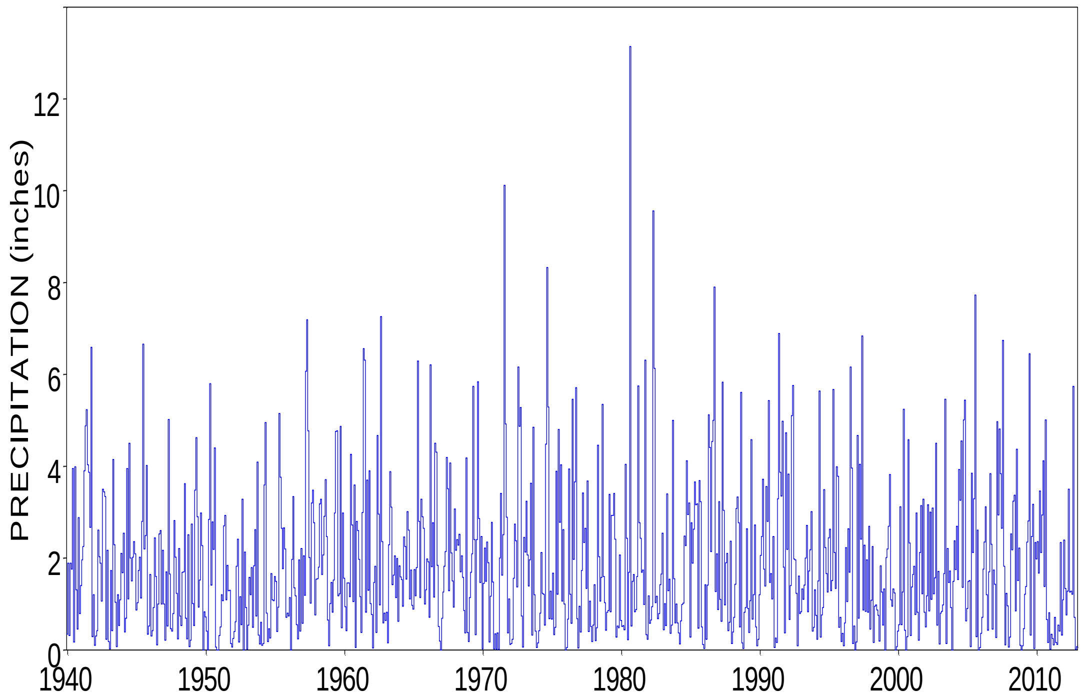
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 505



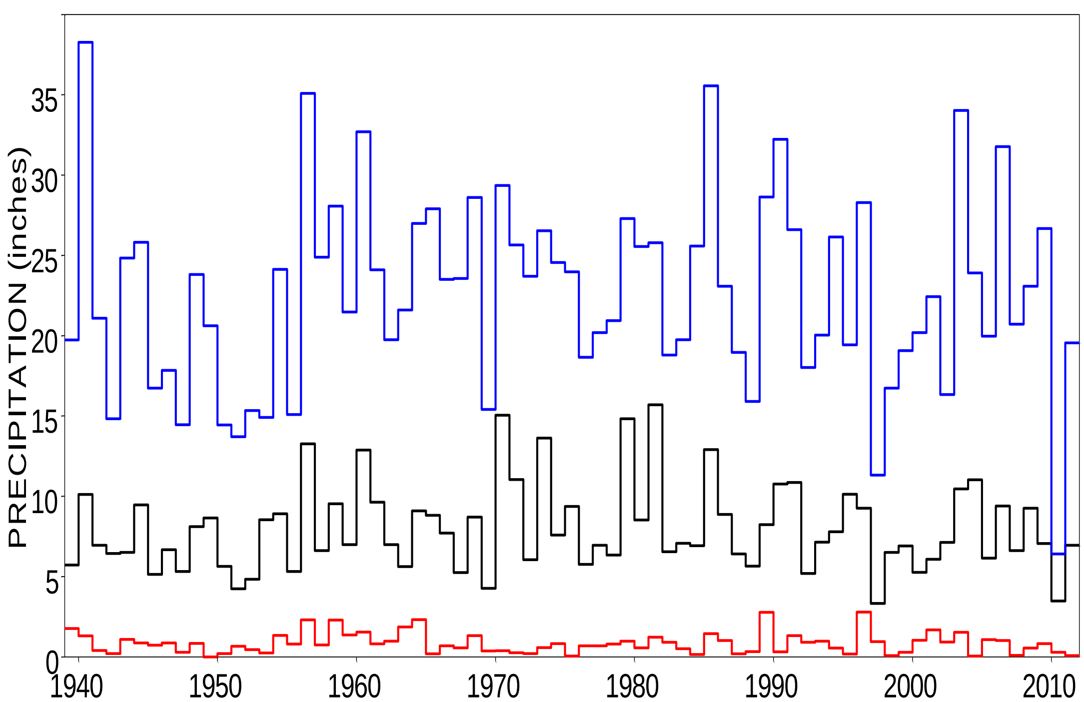
Monthly Precipitation for Quadrangle 506



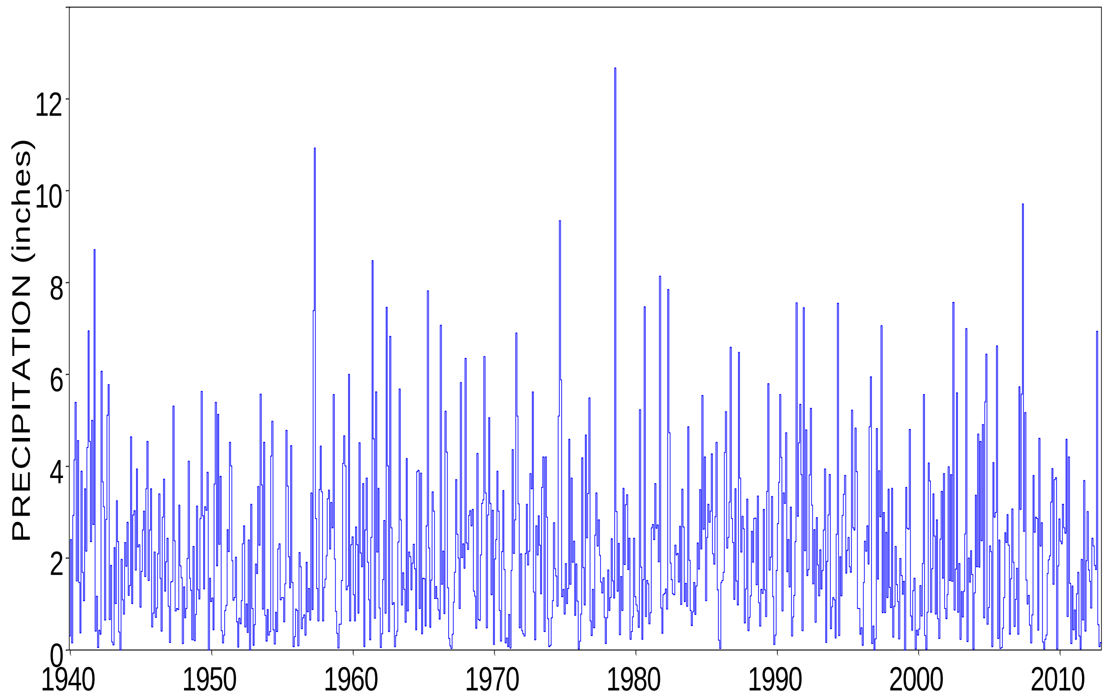
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 506



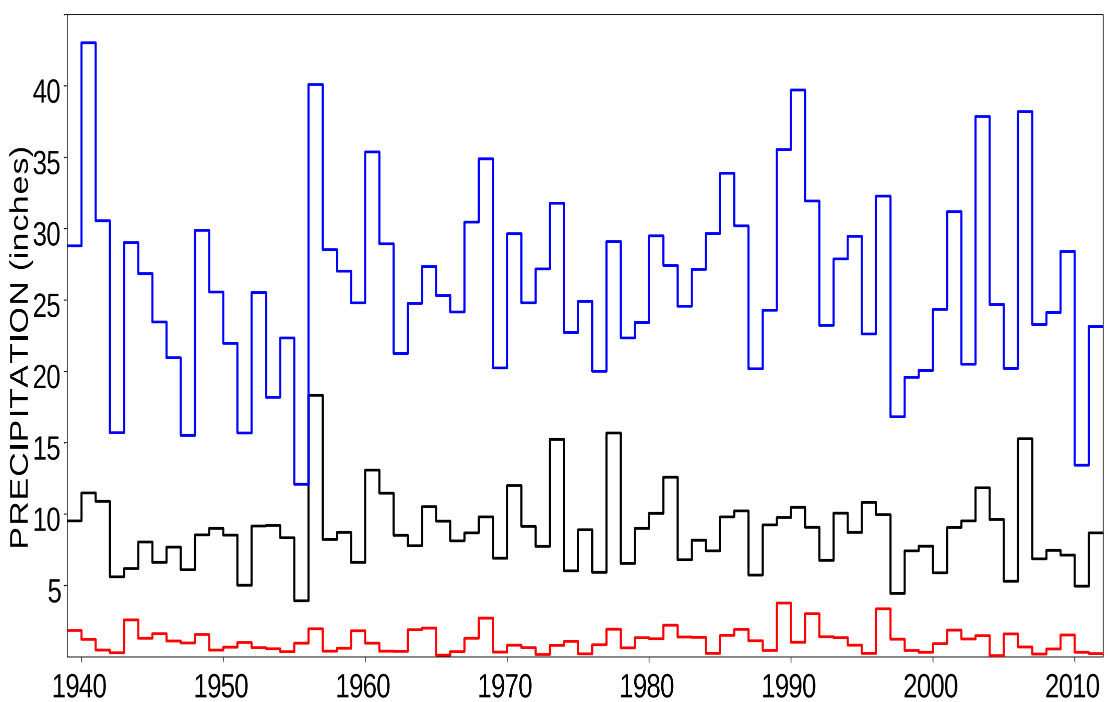
Monthly Precipitation for Quadrangle 507



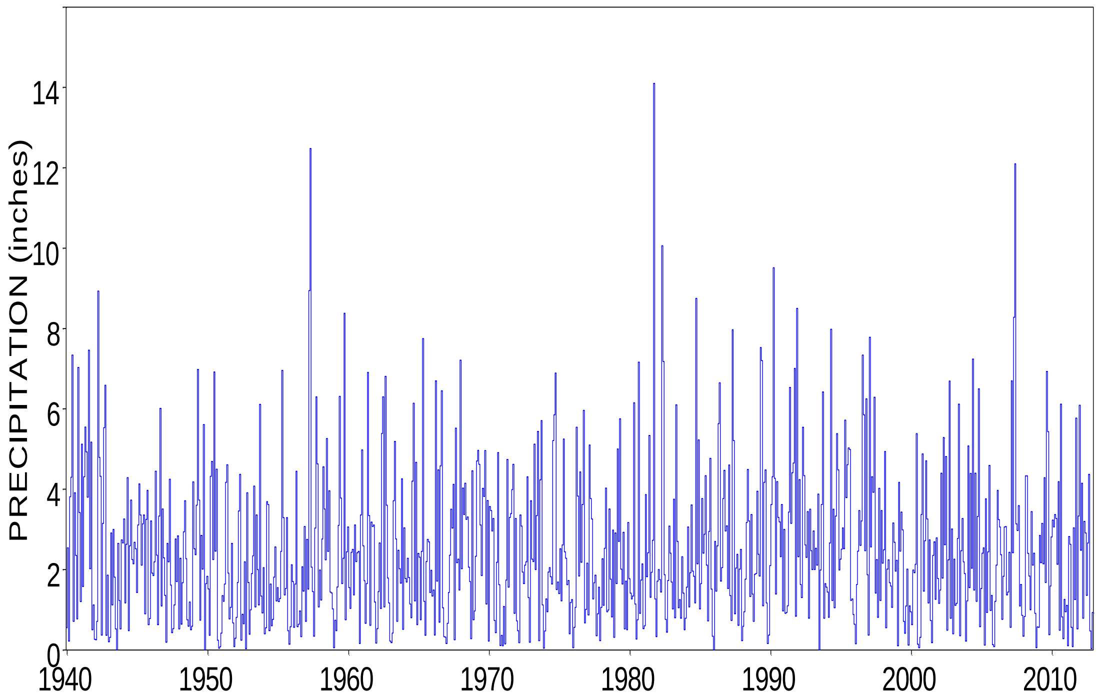
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 507



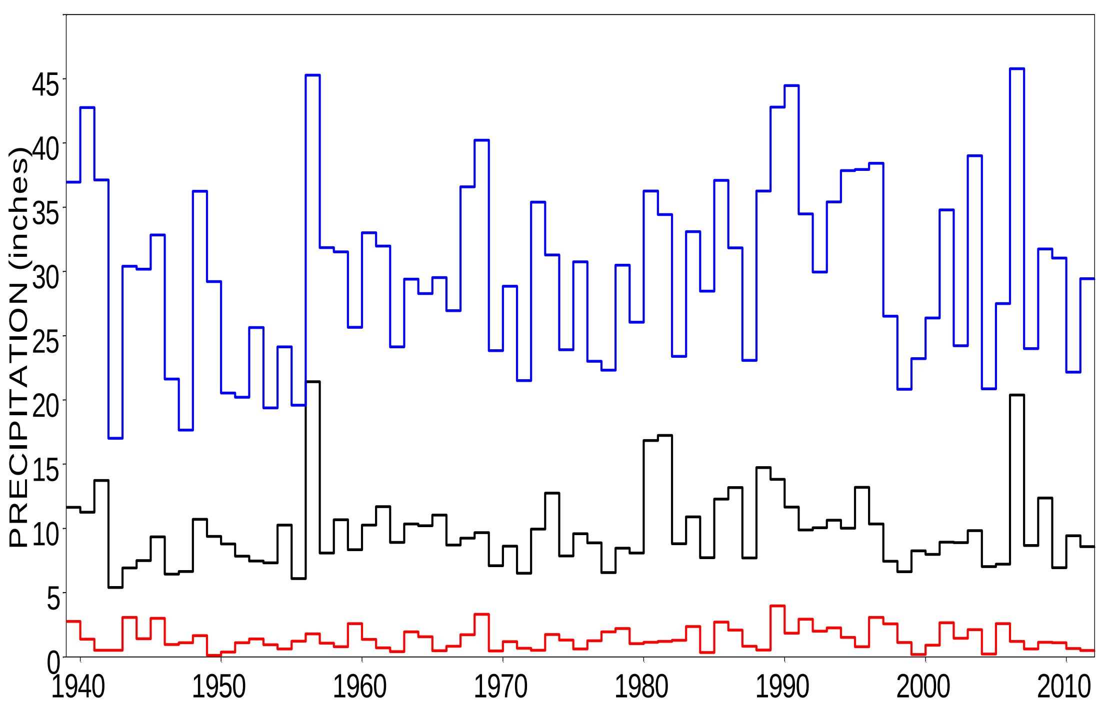
Monthly Precipitation for Quadrangle 508



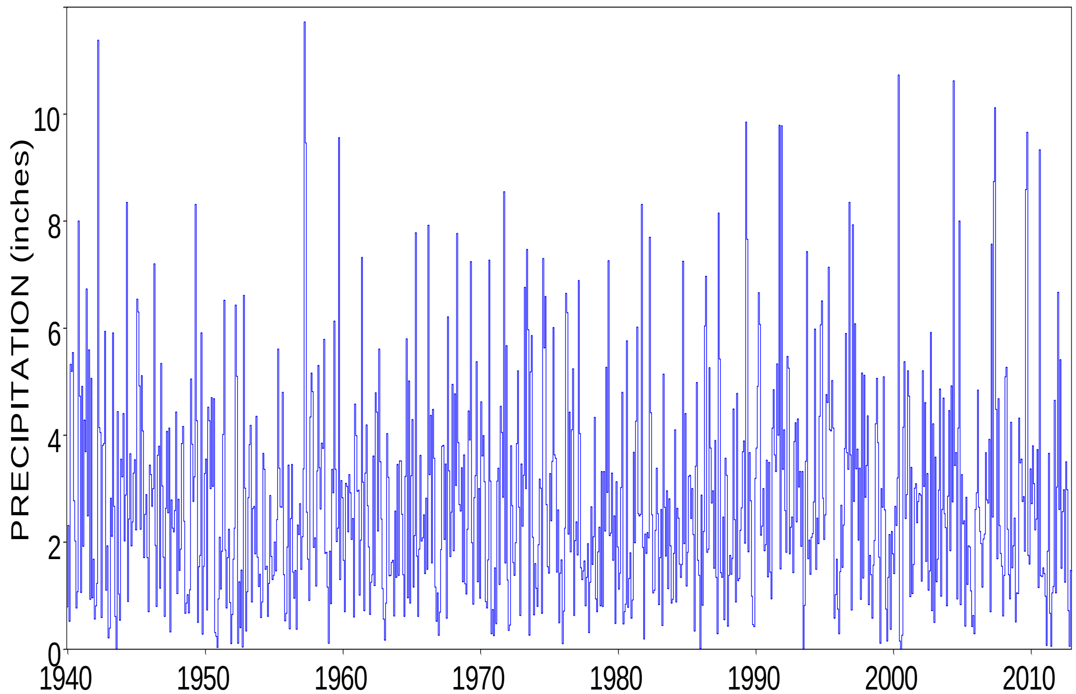
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 508



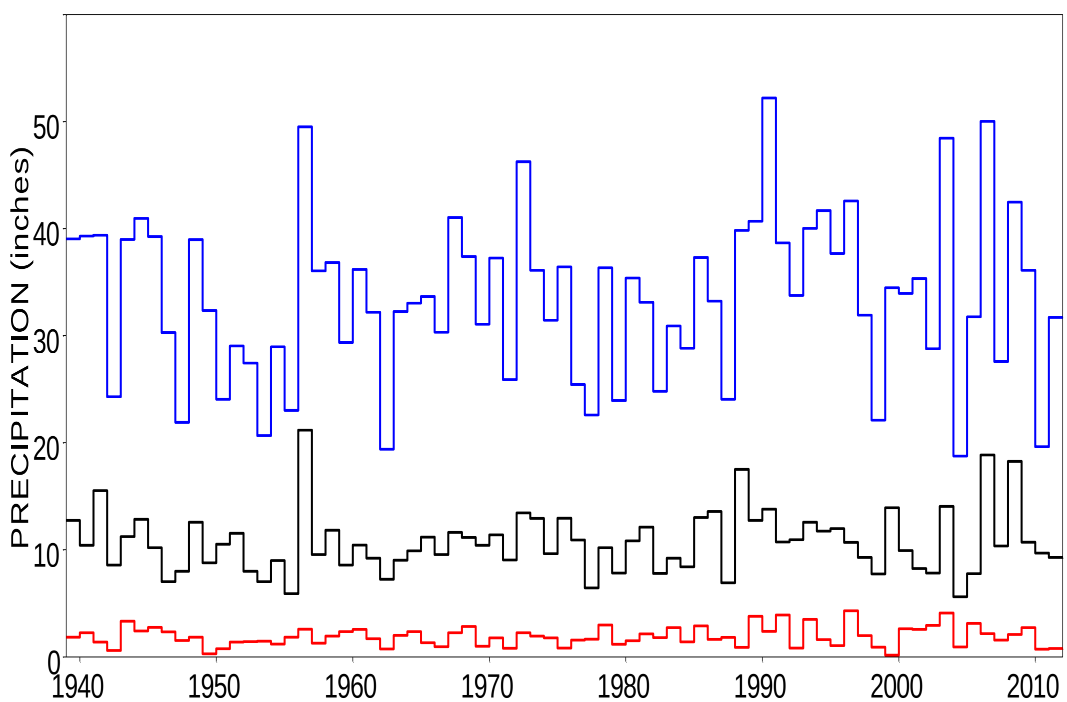
Monthly Precipitation for Quadrangle 509



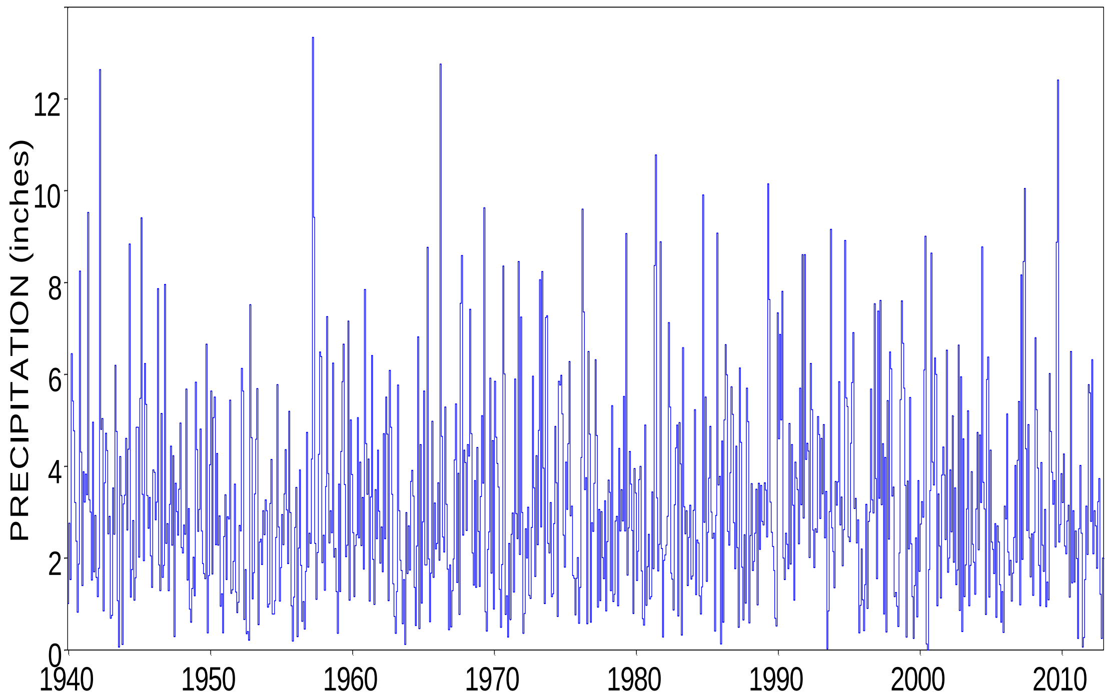
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 509



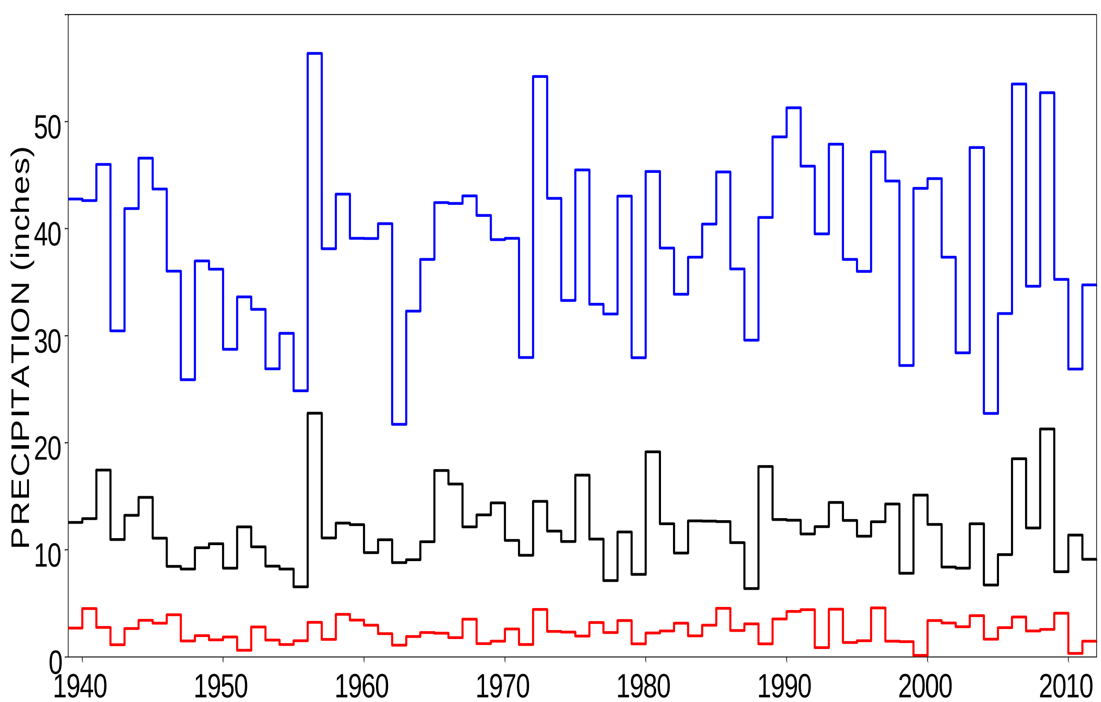
Monthly Precipitation for Quadrangle 510



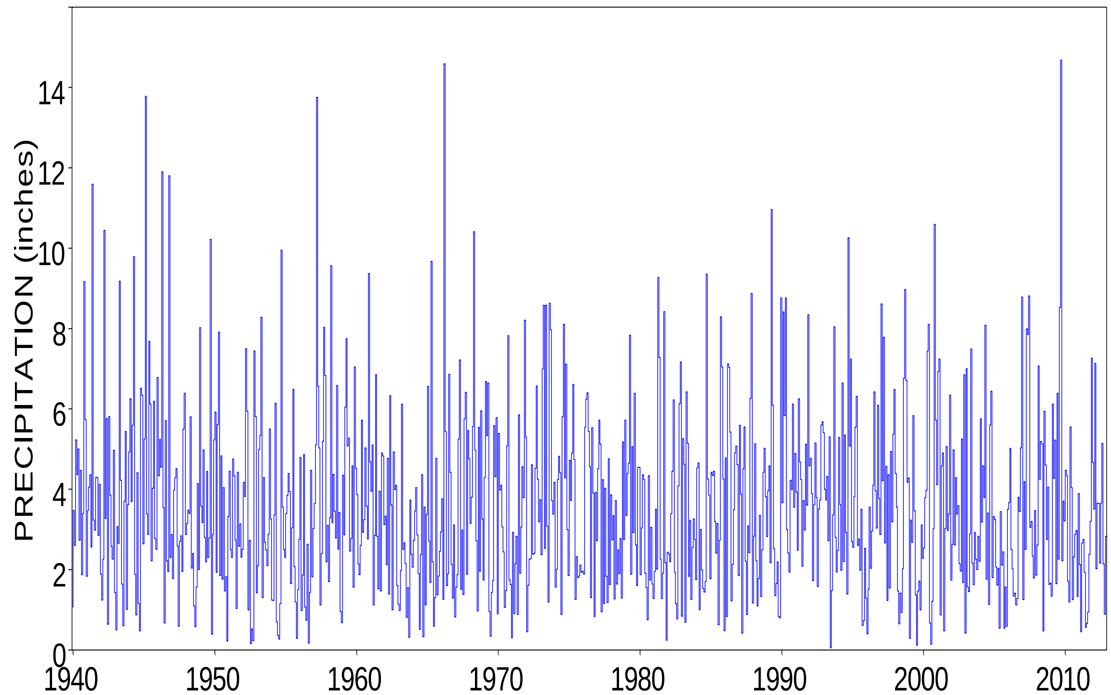
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 510



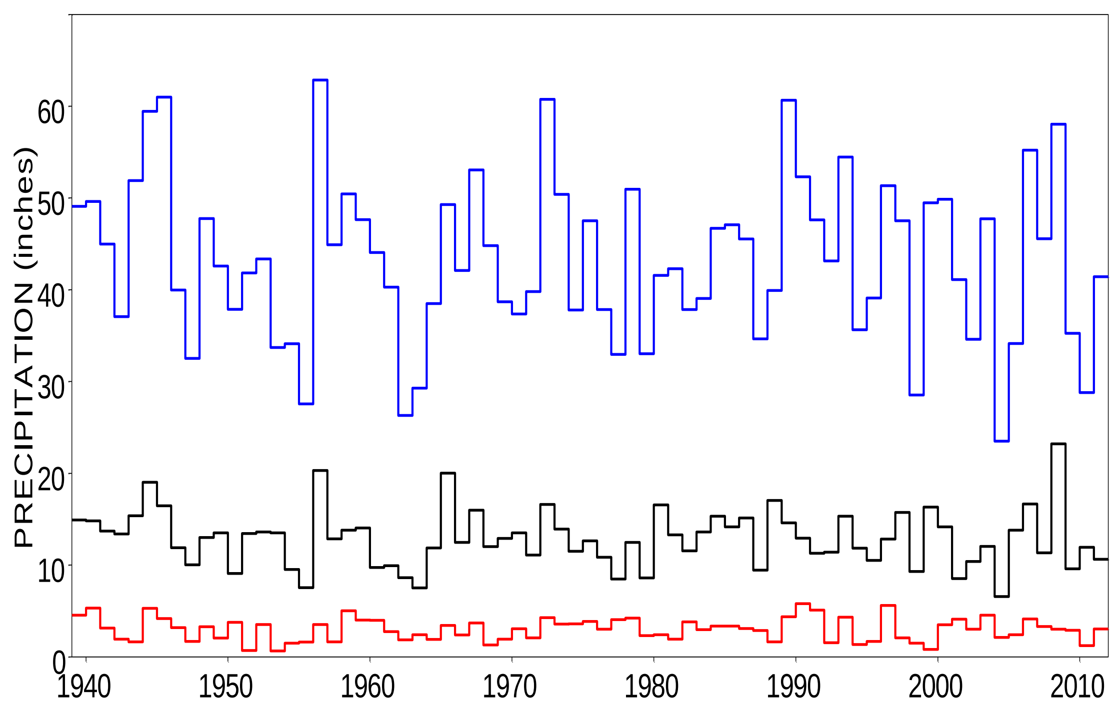
Monthly Precipitation for Quadrangle 511



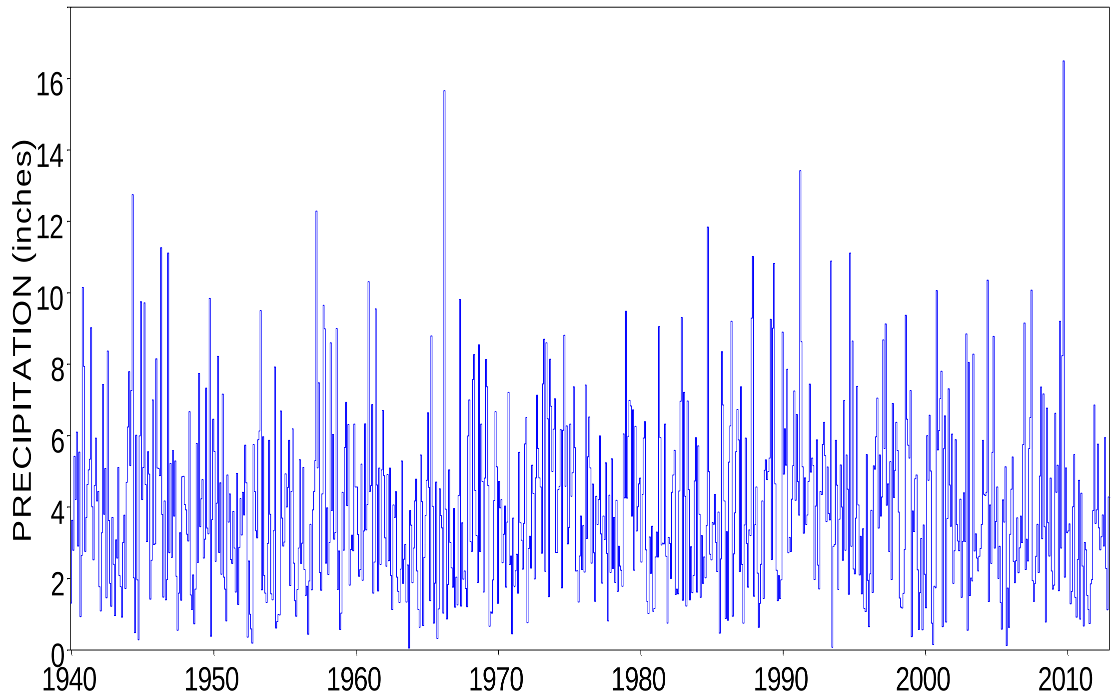
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 511



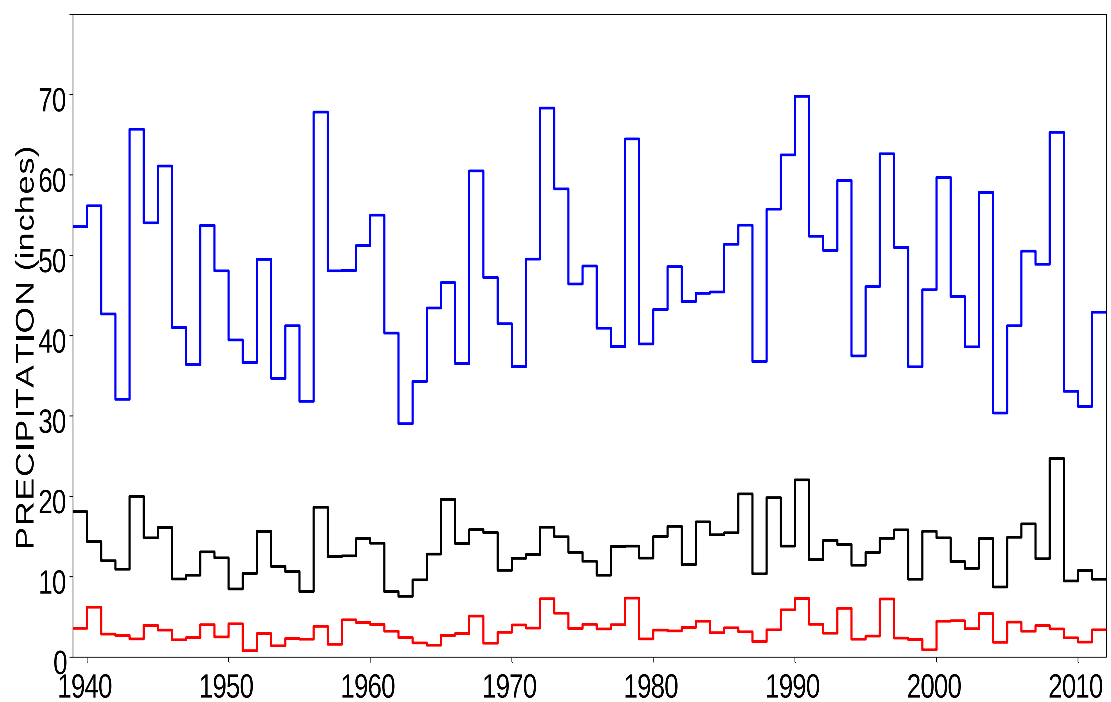
Monthly Precipitation for Quadrangle 512



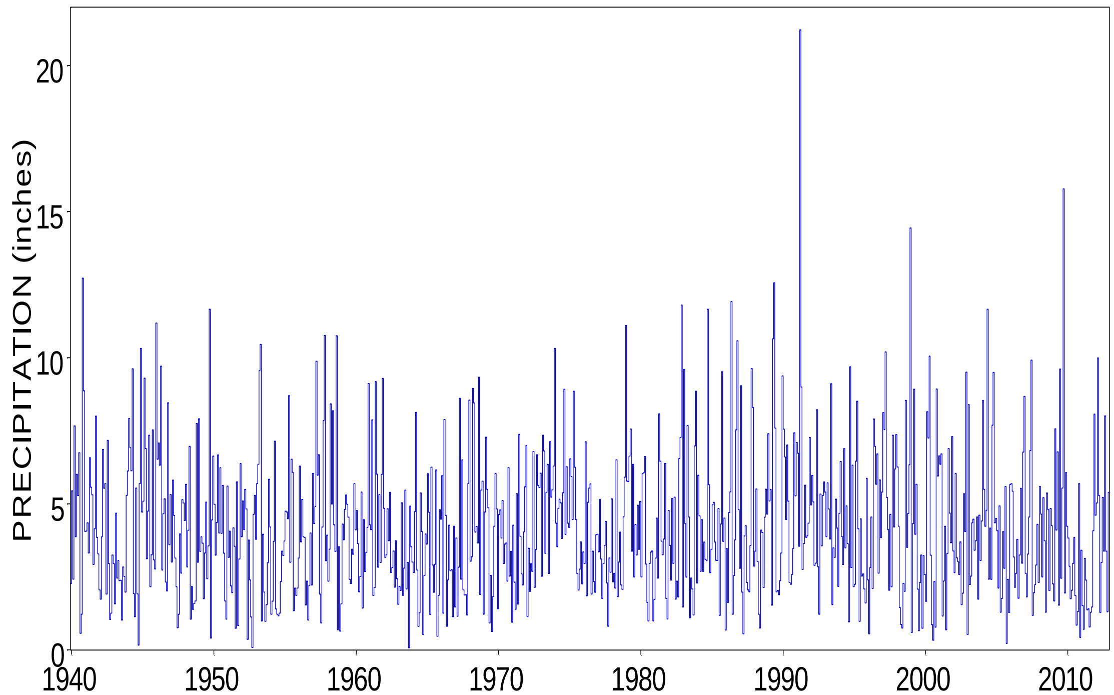
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 512



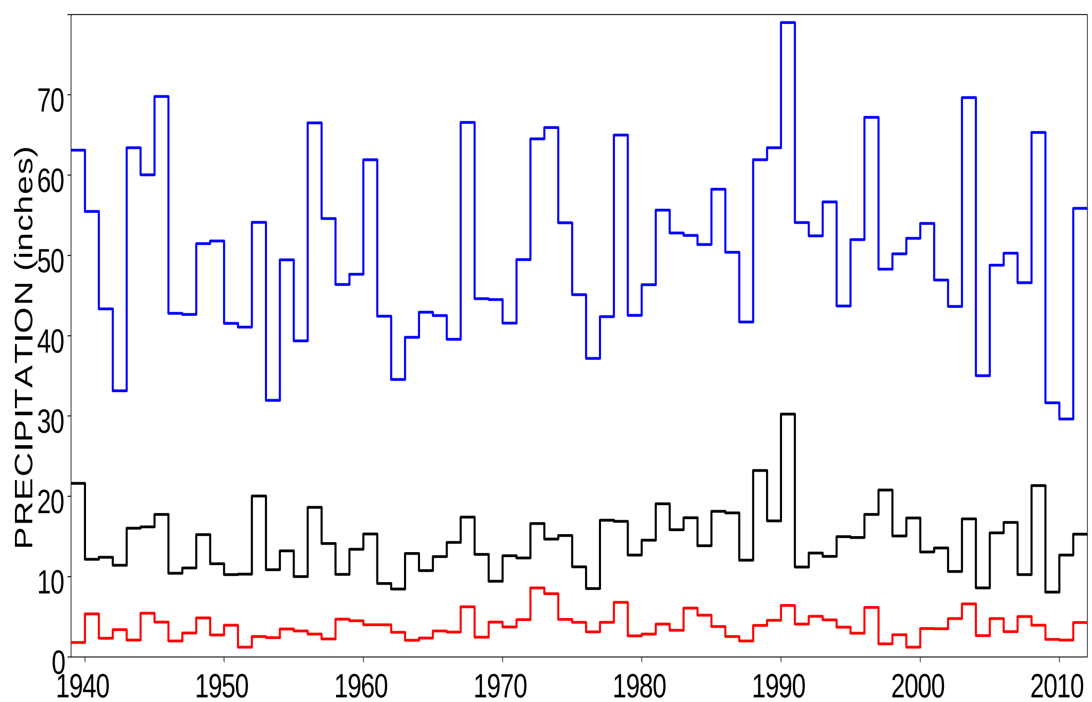
Monthly Precipitation for Quadrangle 513



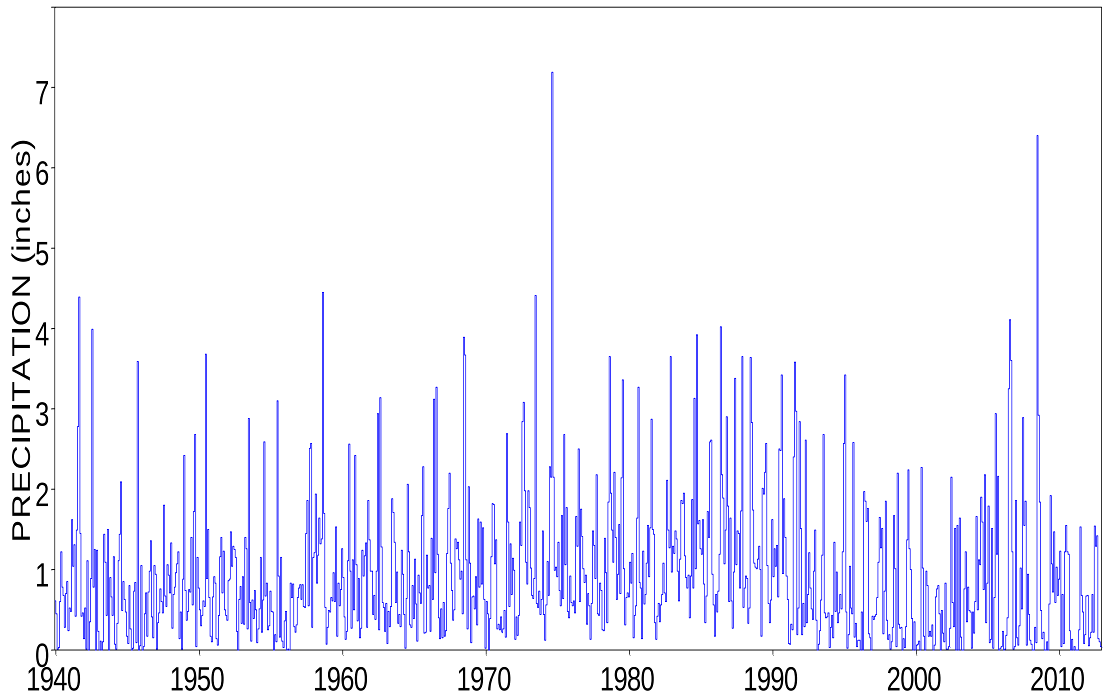
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 513



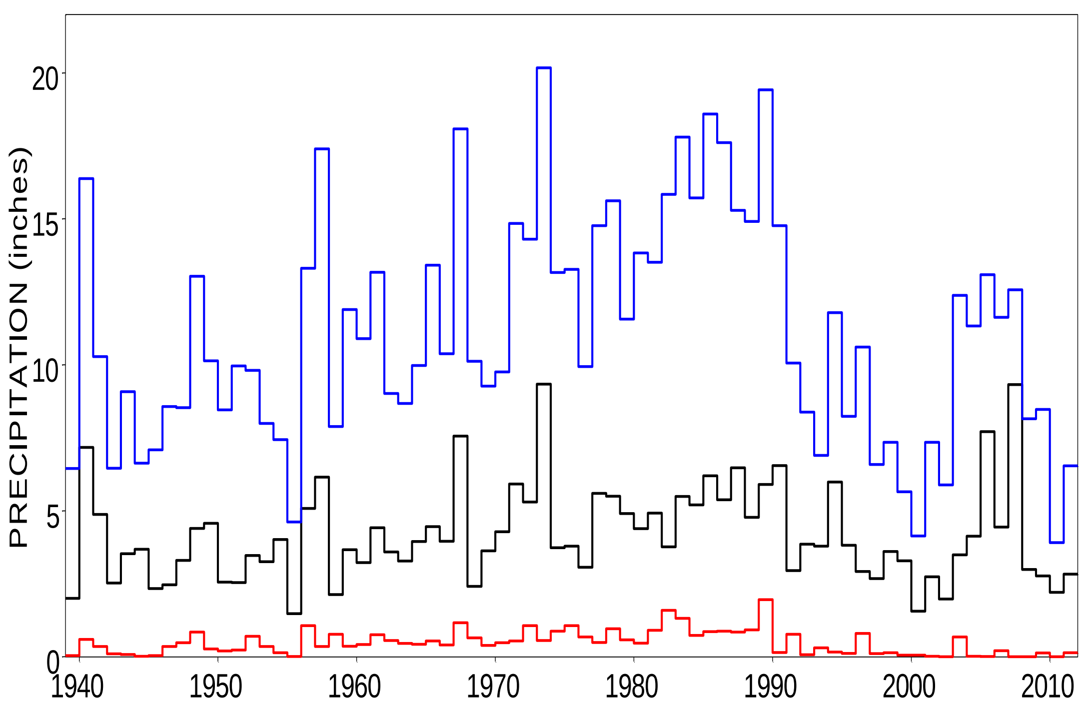
Monthly Precipitation for Quadrangle 514



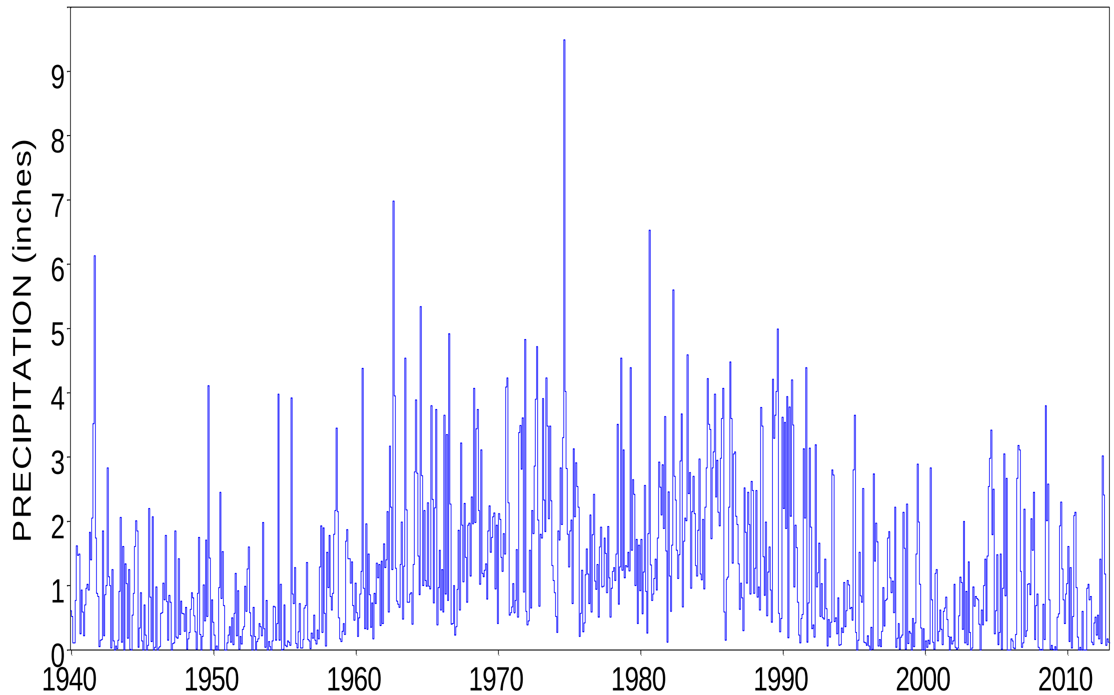
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 514



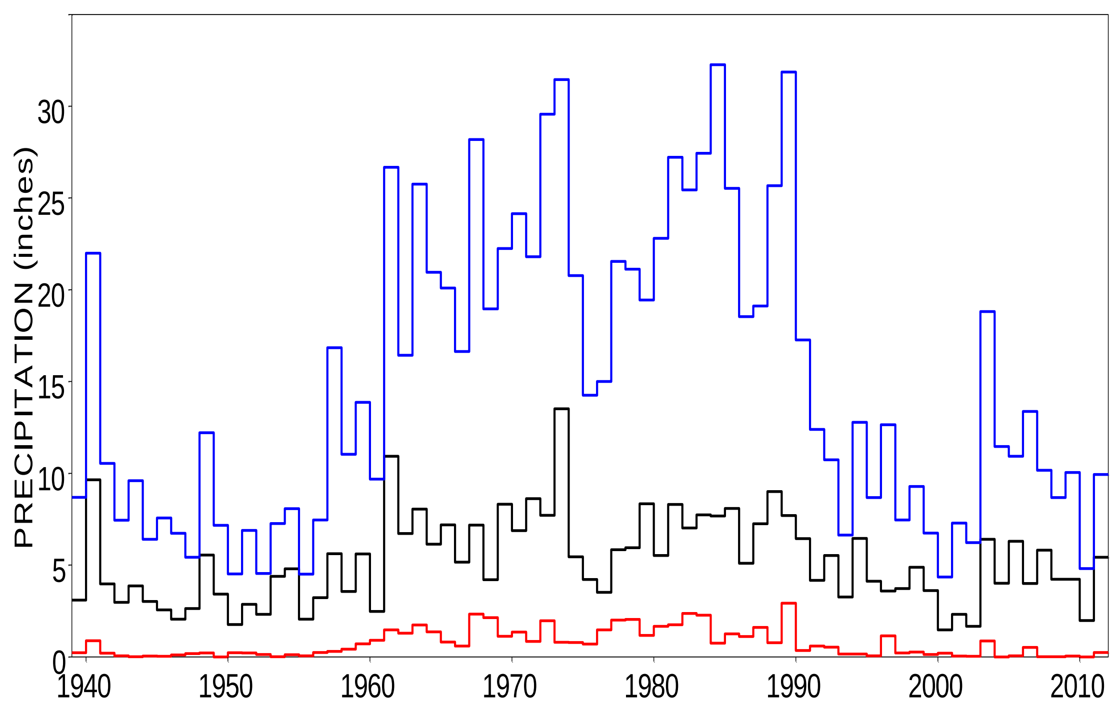
Monthly Precipitation for Quadrangle 601



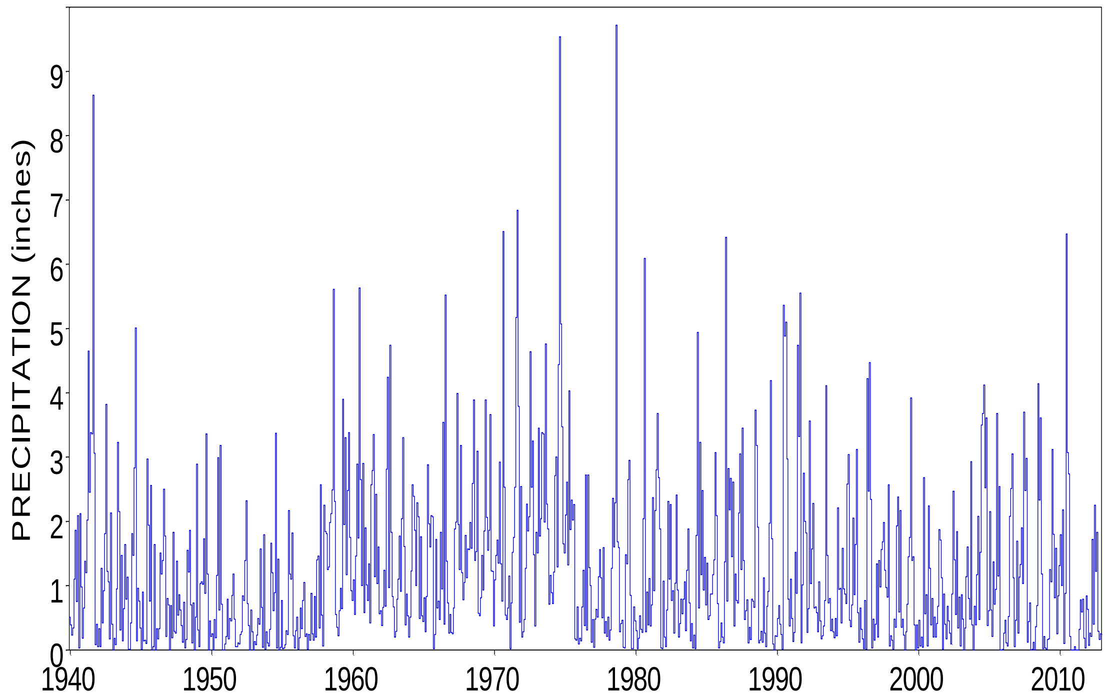
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 601



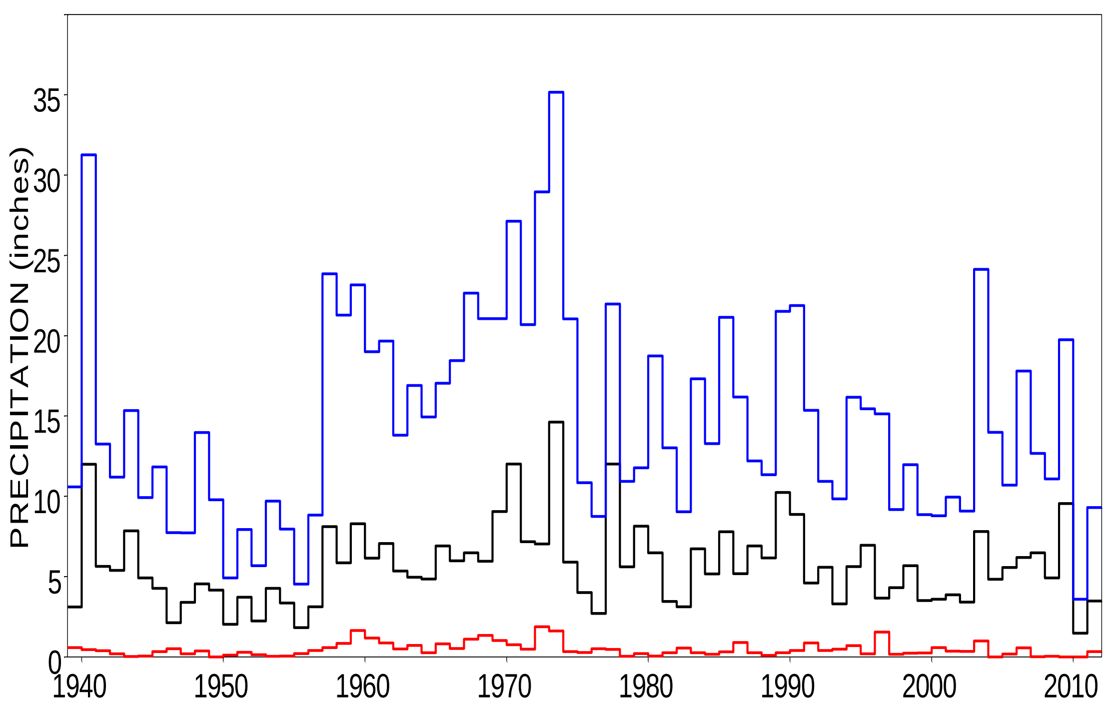
Monthly Precipitation for Quadrangle 602



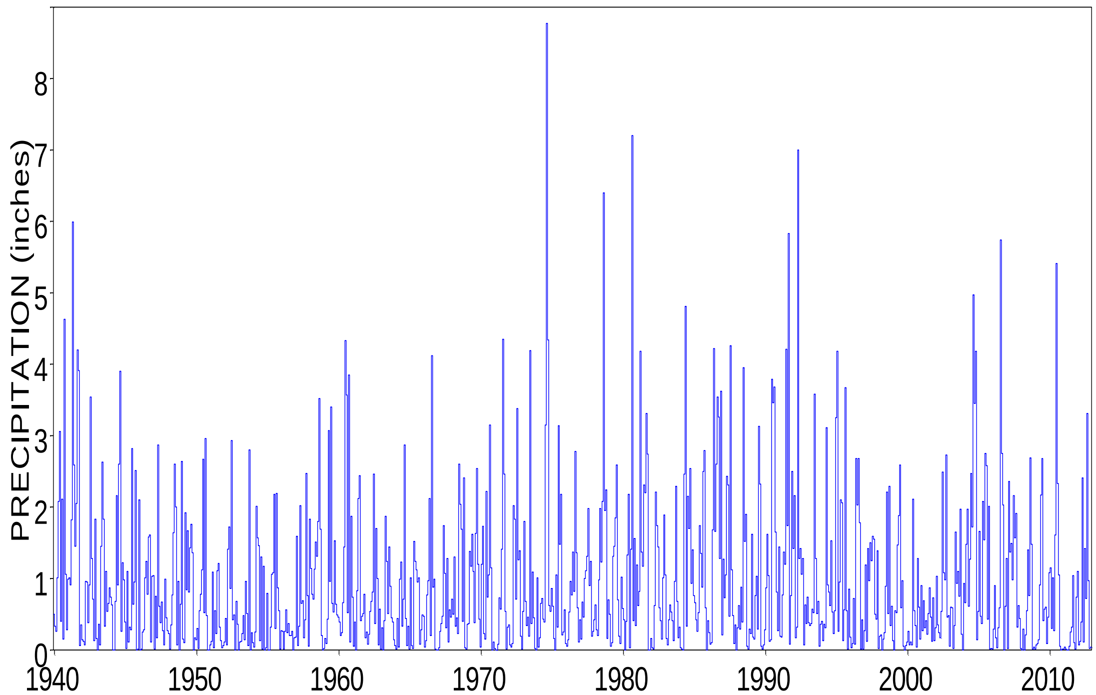
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 602



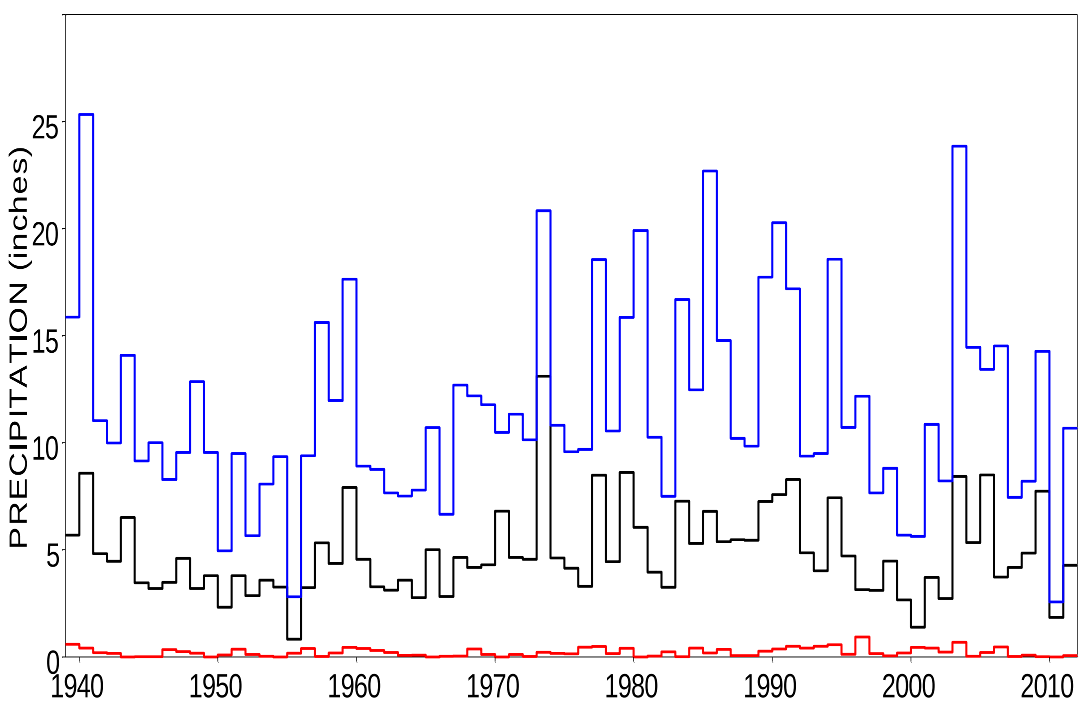
Monthly Precipitation for Quadrangle 603



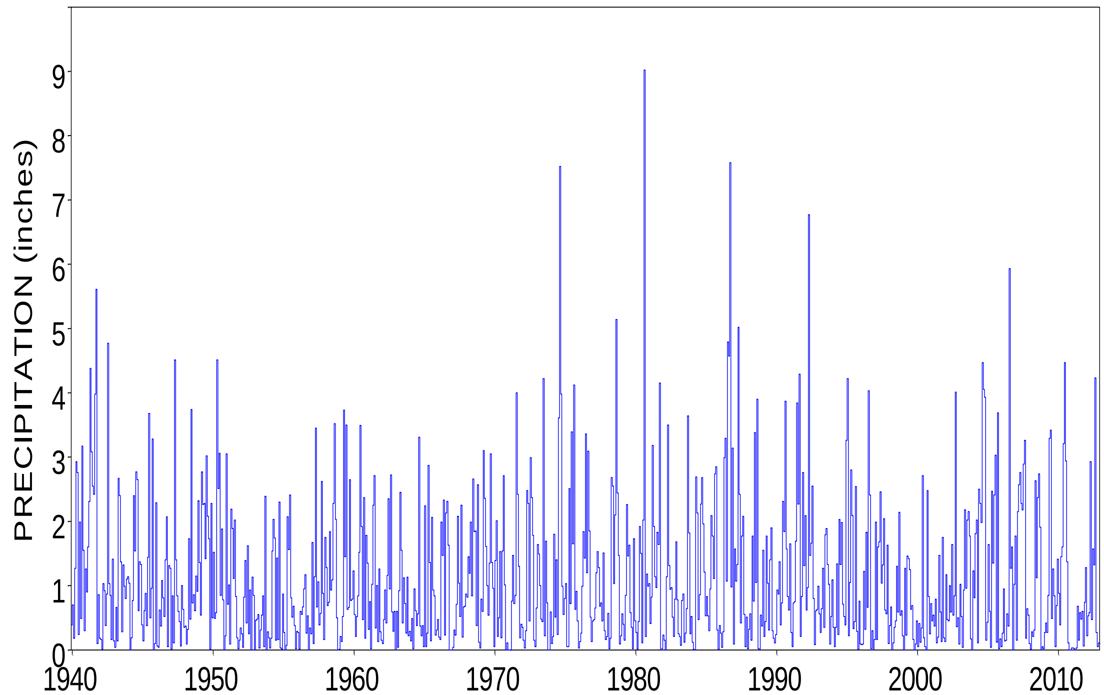
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 603



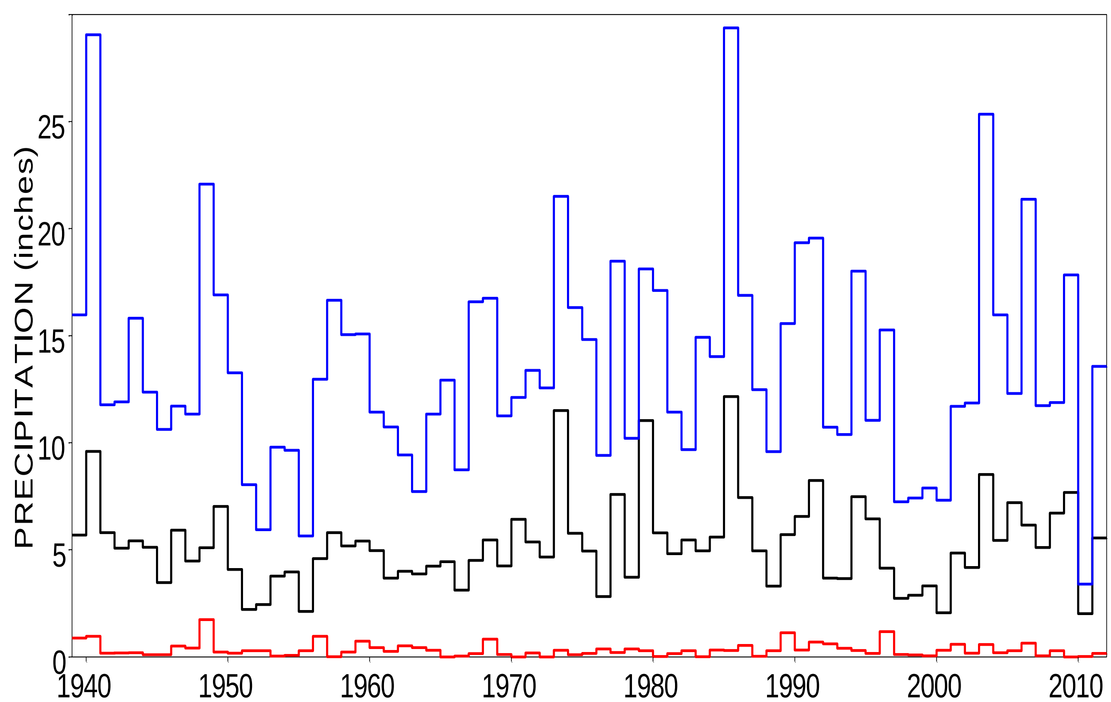
Monthly Precipitation for Quadrangle 604



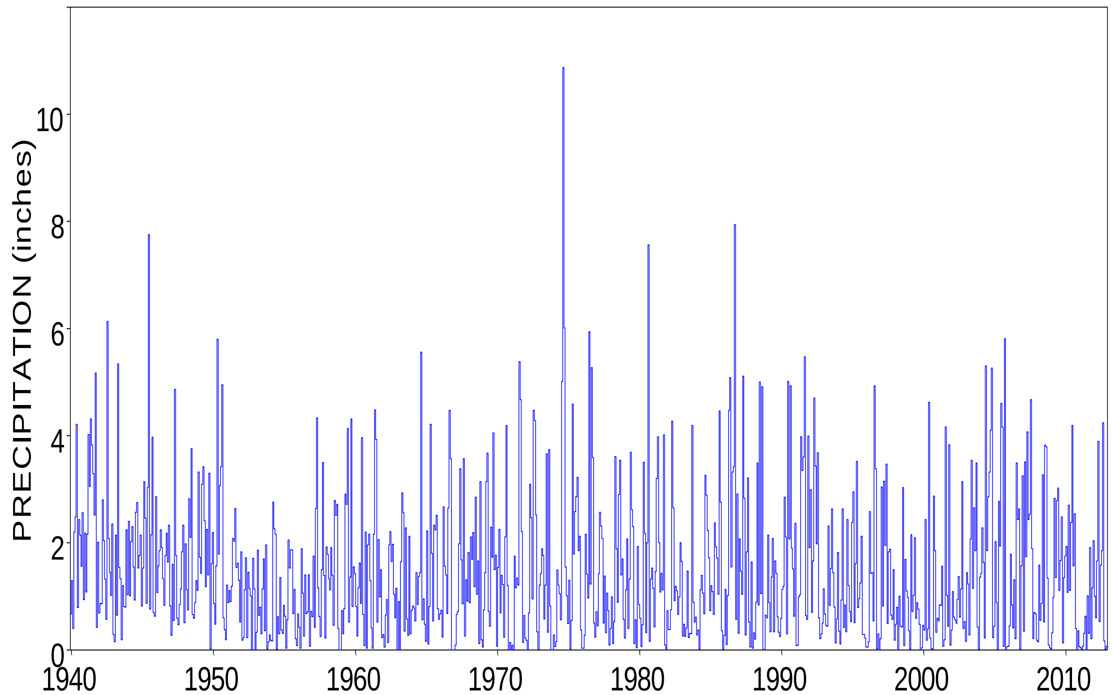
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 604



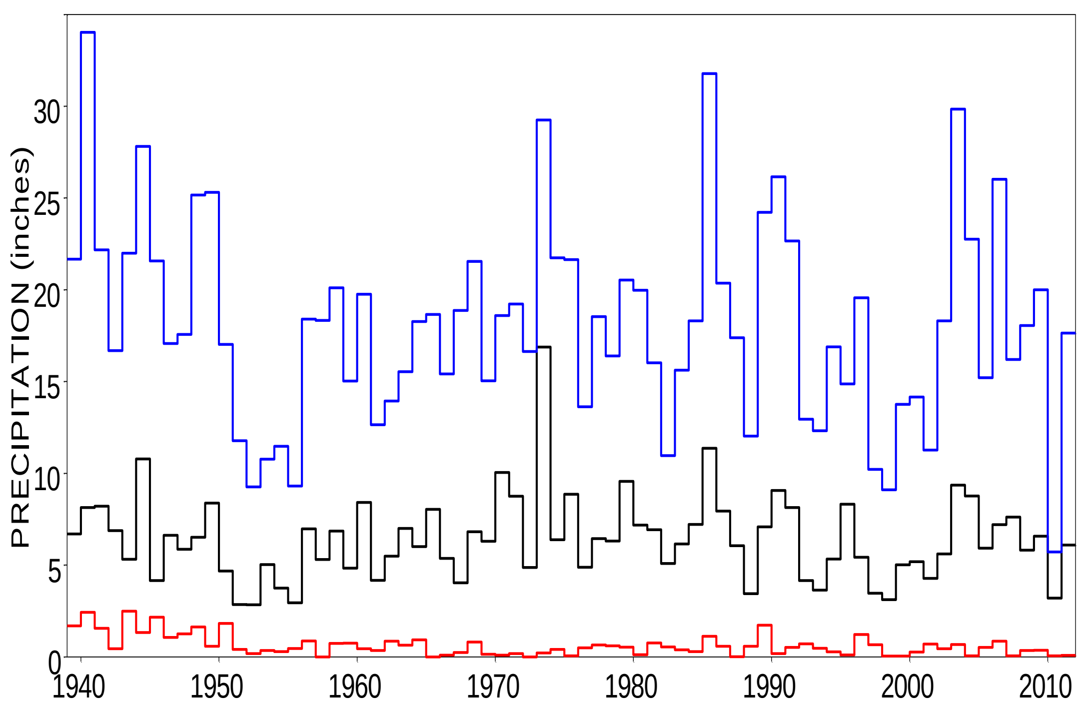
Monthly Precipitation for Quadrangle 605



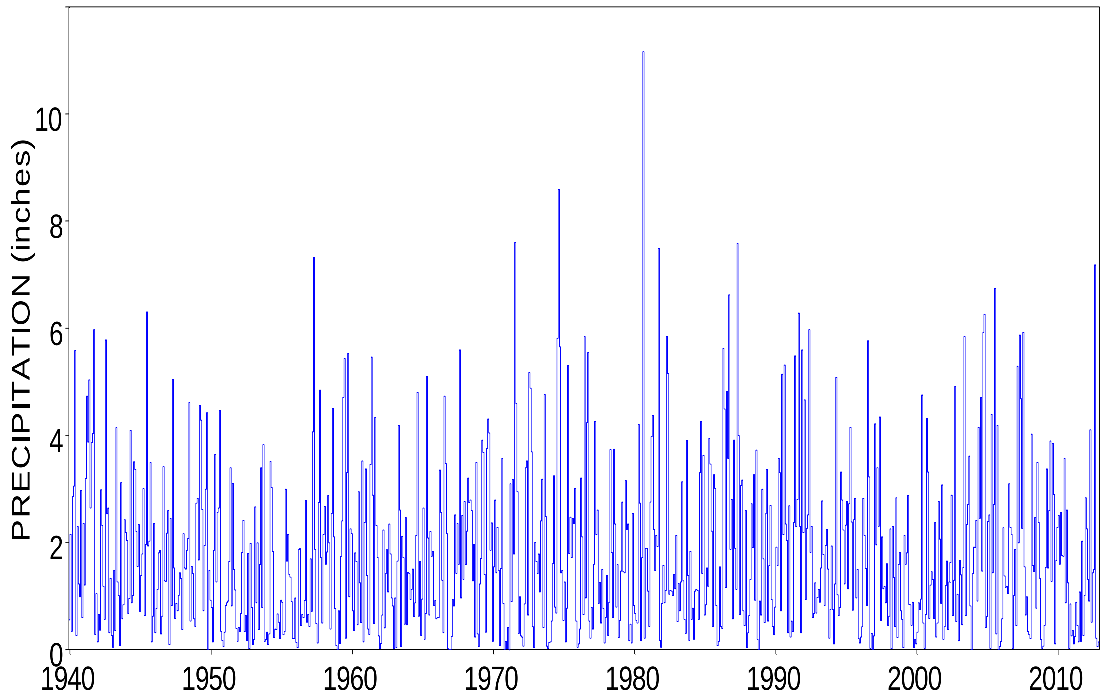
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 605



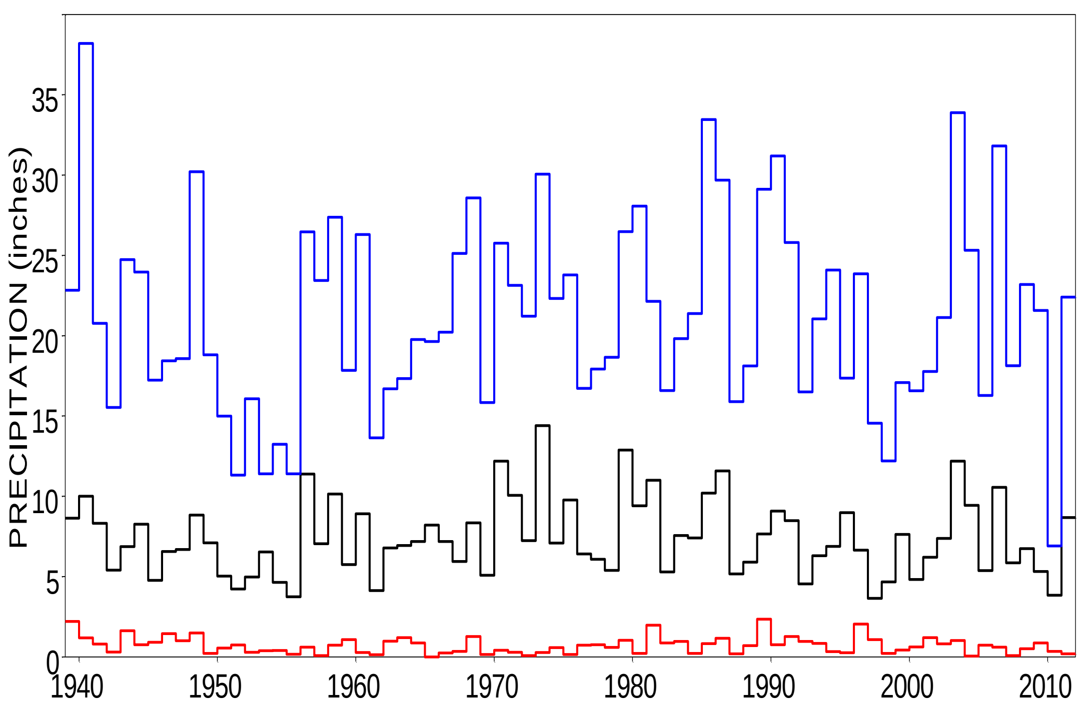
Monthly Precipitation for Quadrangle 606



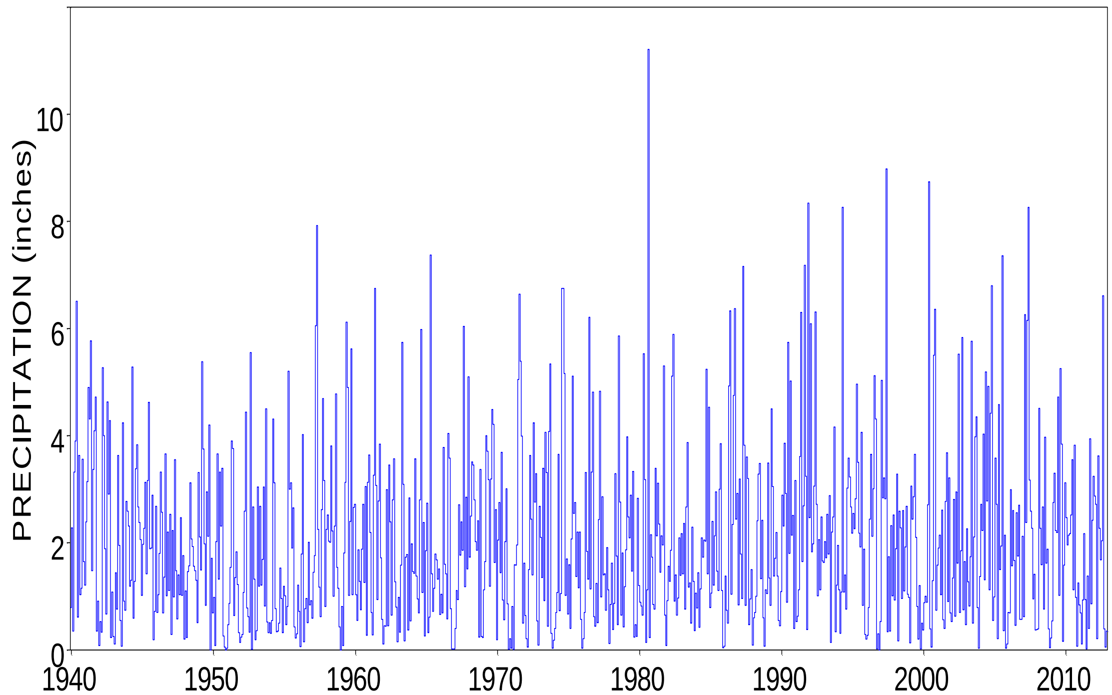
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 606



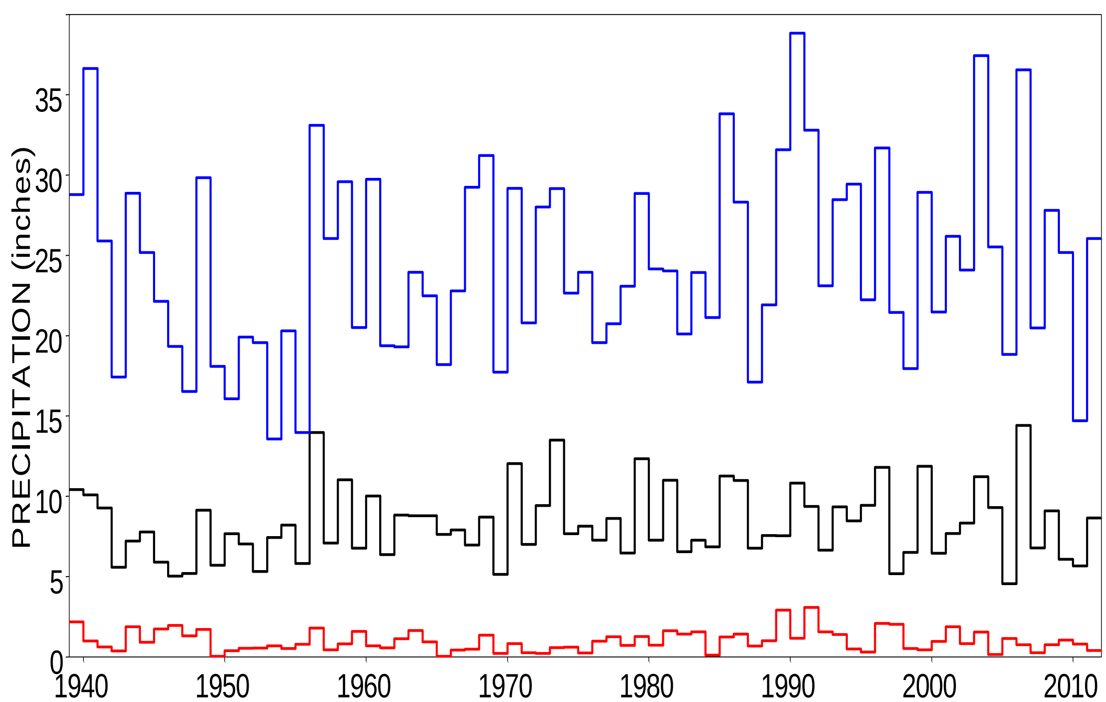
Monthly Precipitation for Quadrangle 607



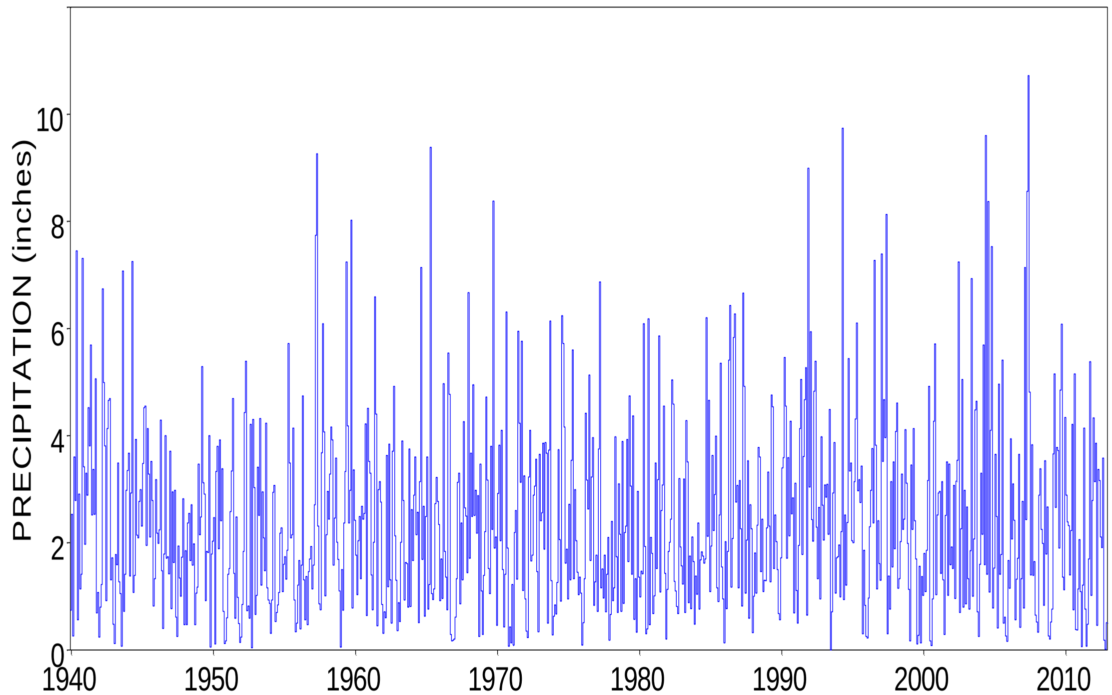
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 607



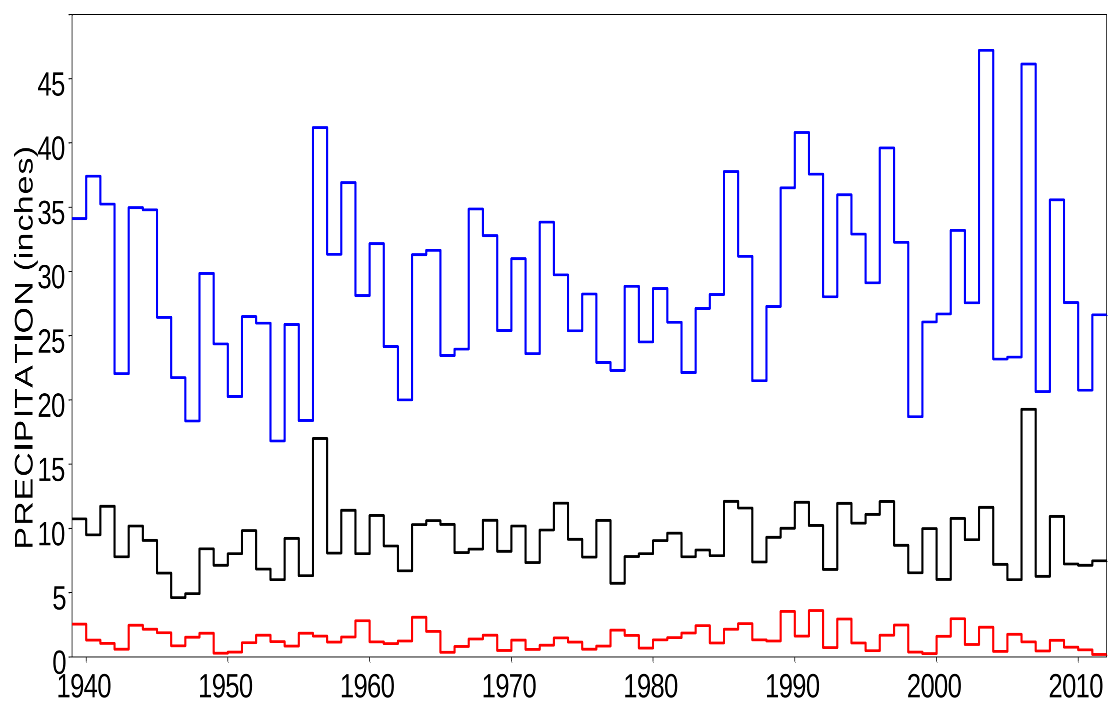
Monthly Precipitation for Quadrangle 608



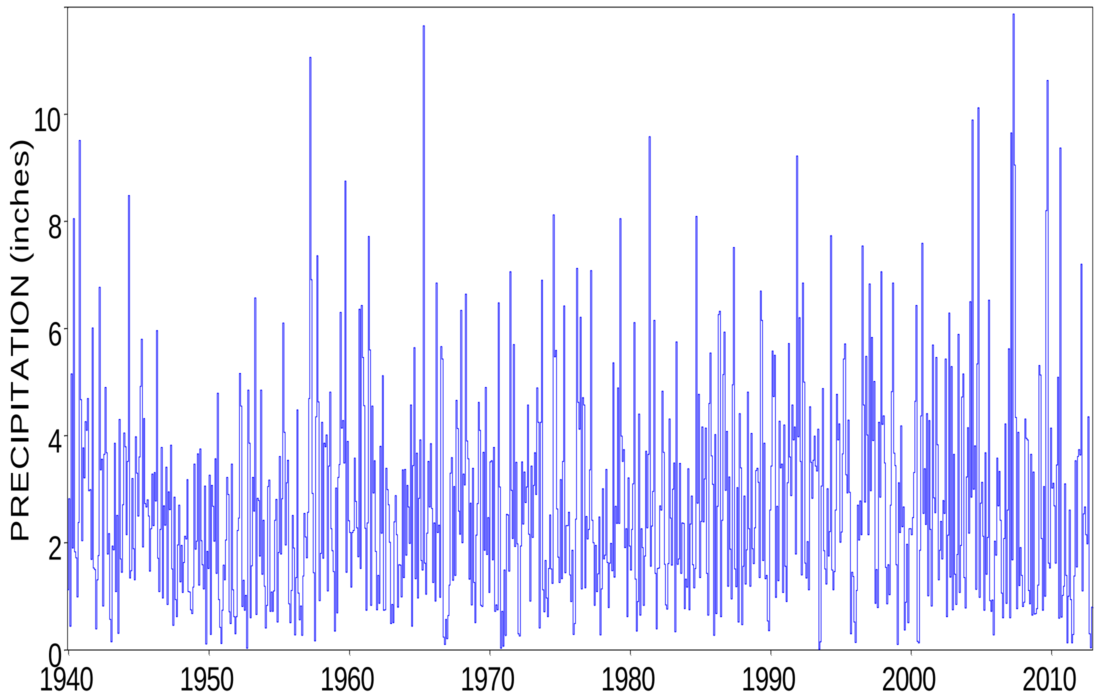
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 608



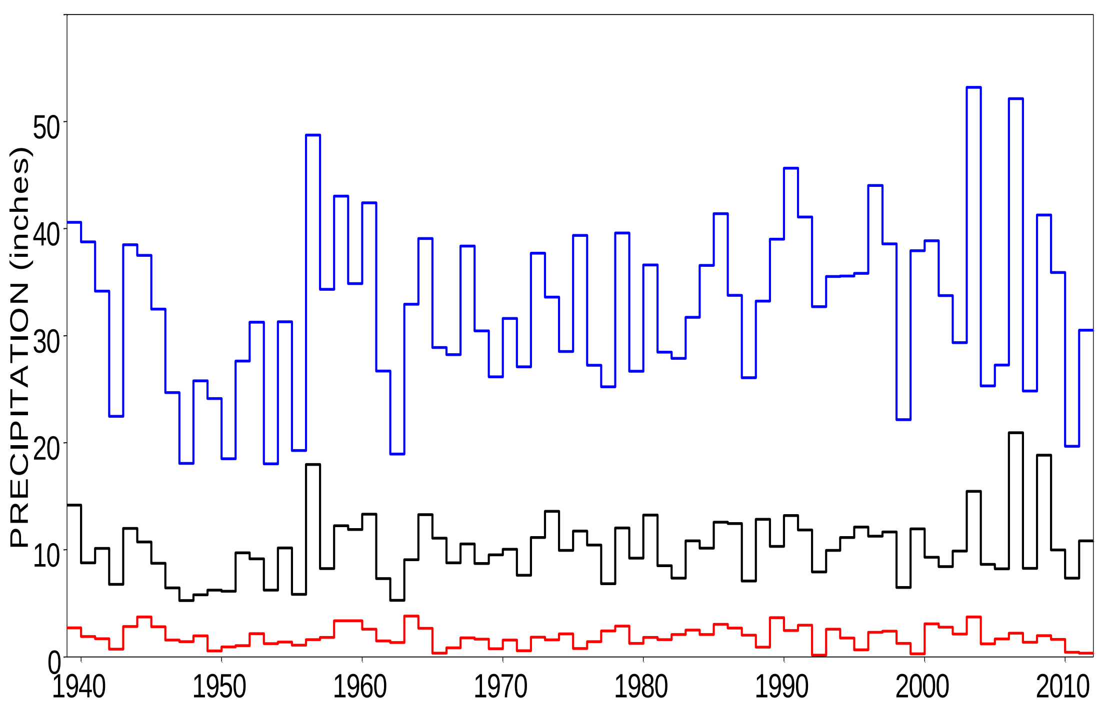
Monthly Precipitation for Quadrangle 609



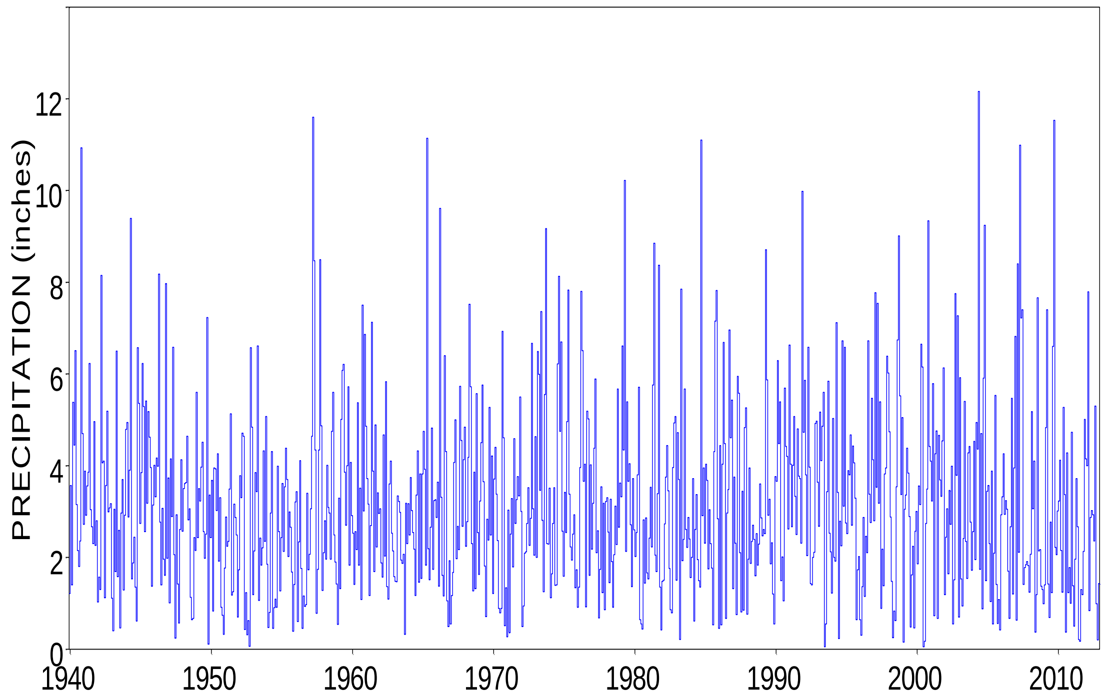
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 609



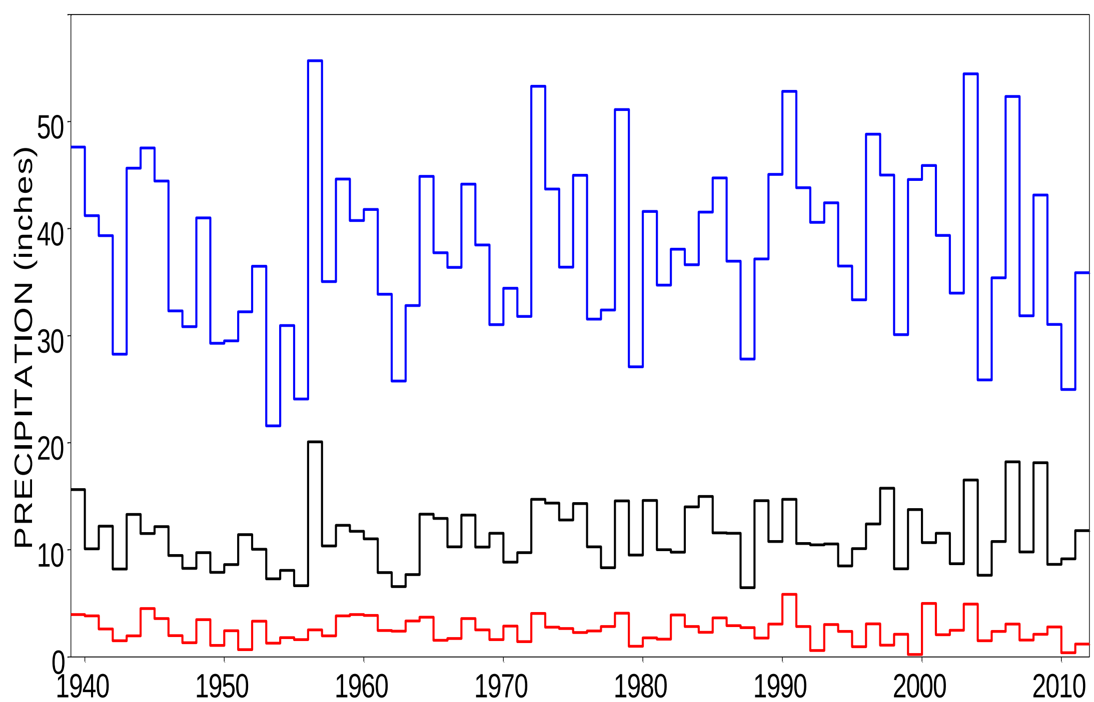
Monthly Precipitation for Quadrangle 610



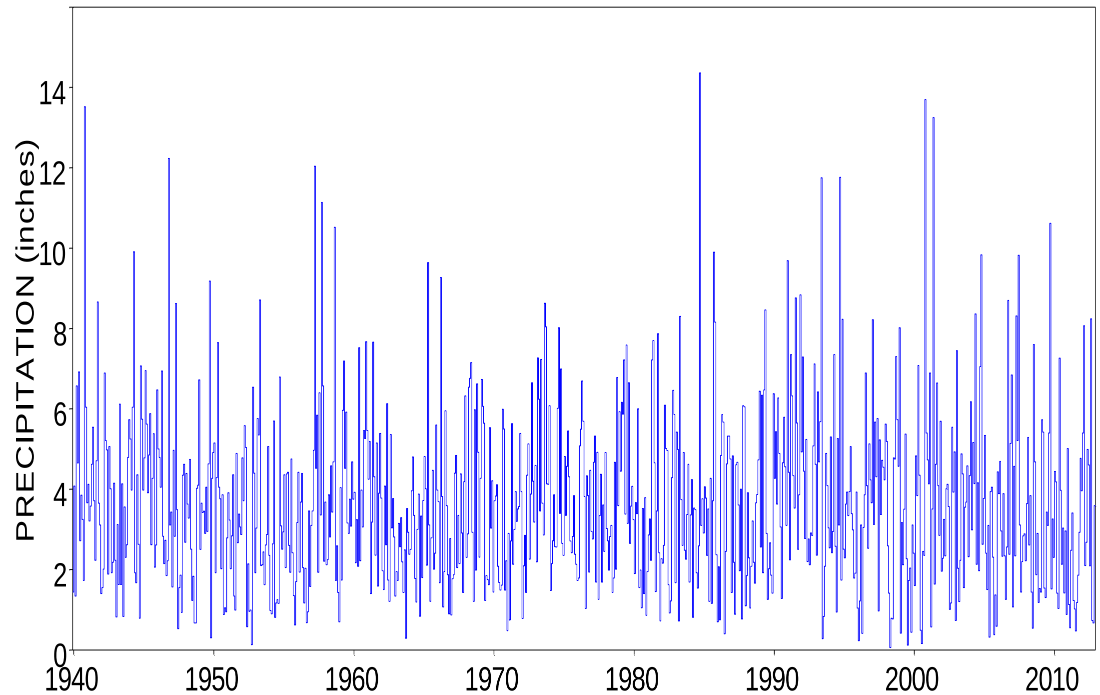
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 610



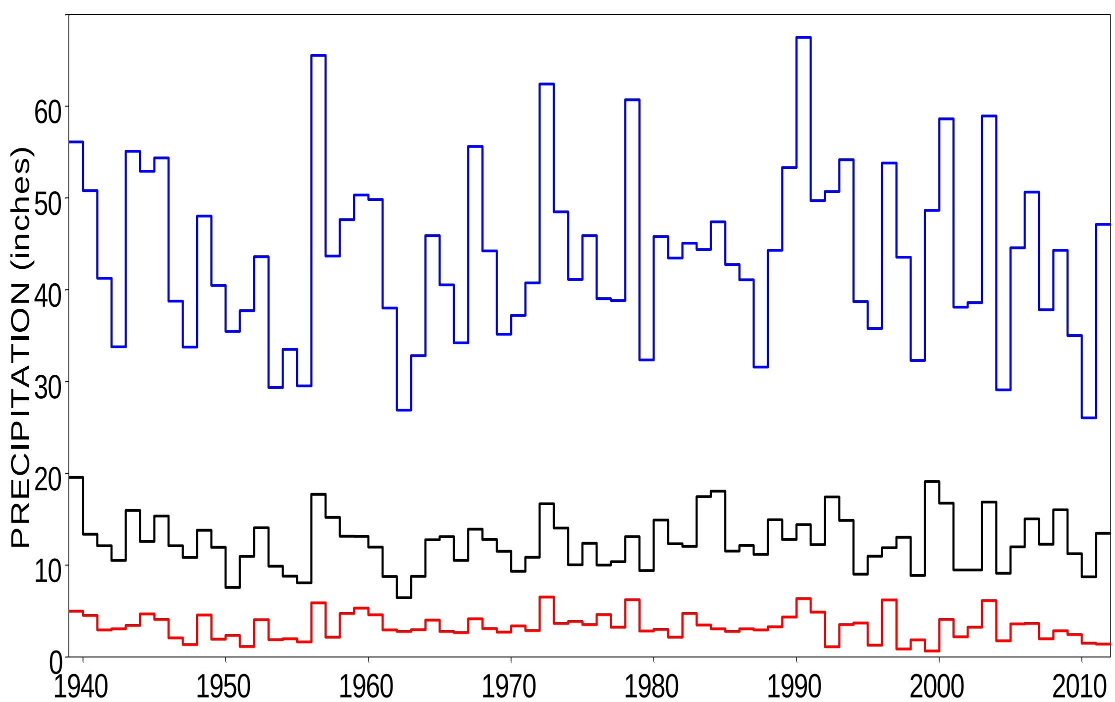
Monthly Precipitation for Quadrangle 611



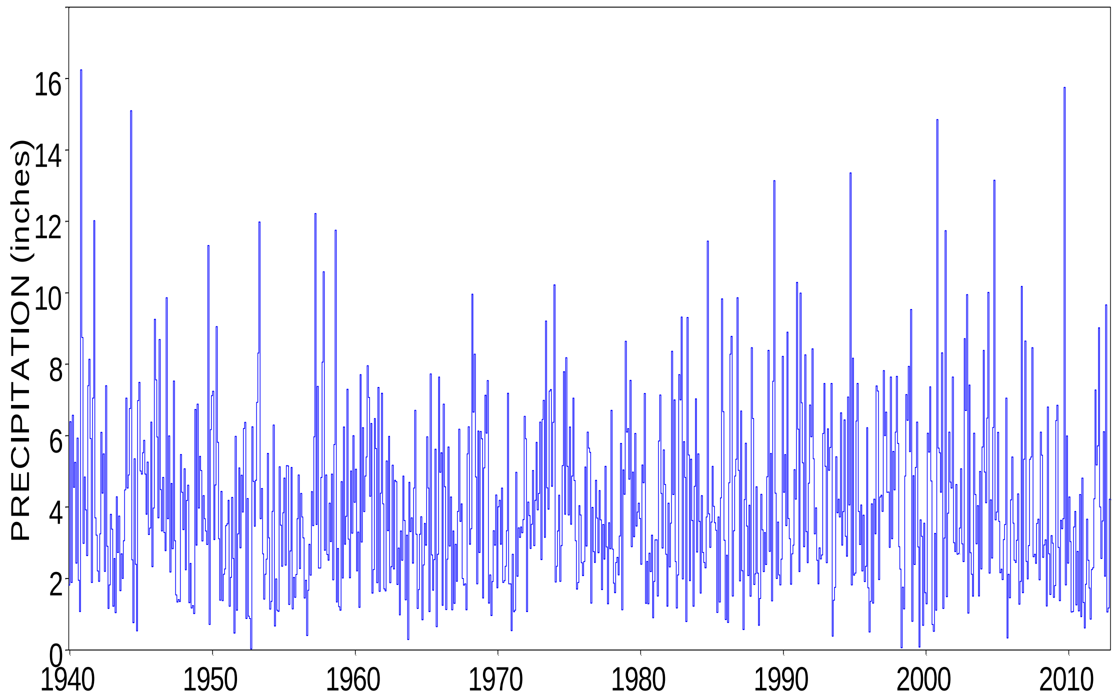
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 611



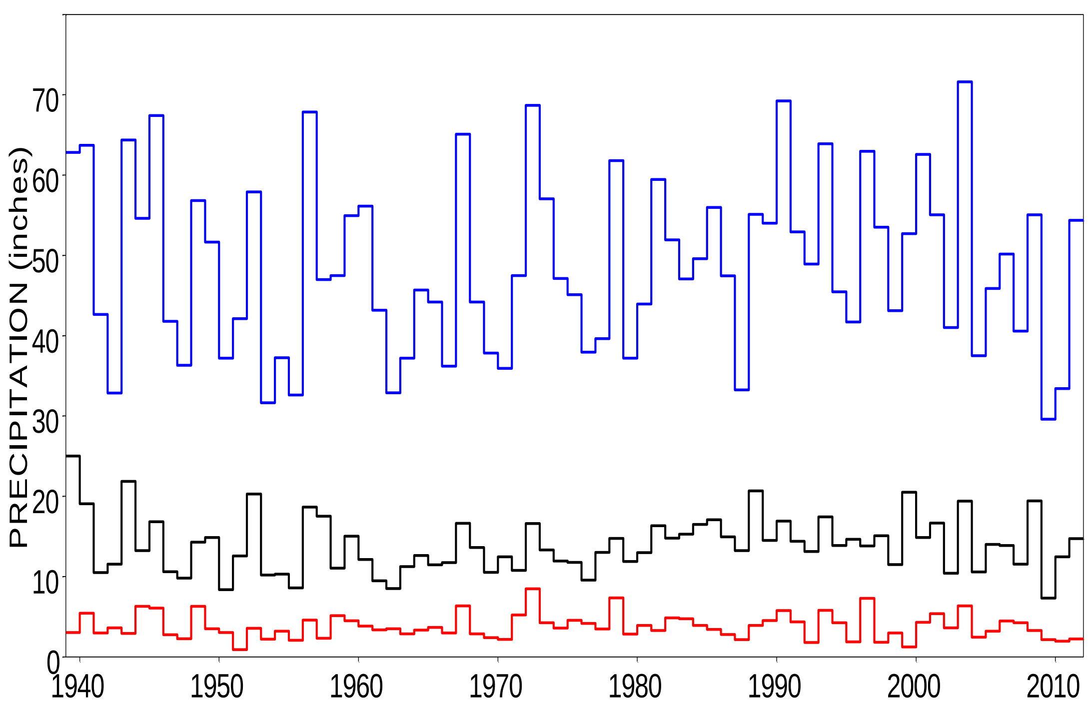
Monthly Precipitation for Quadrangle 612



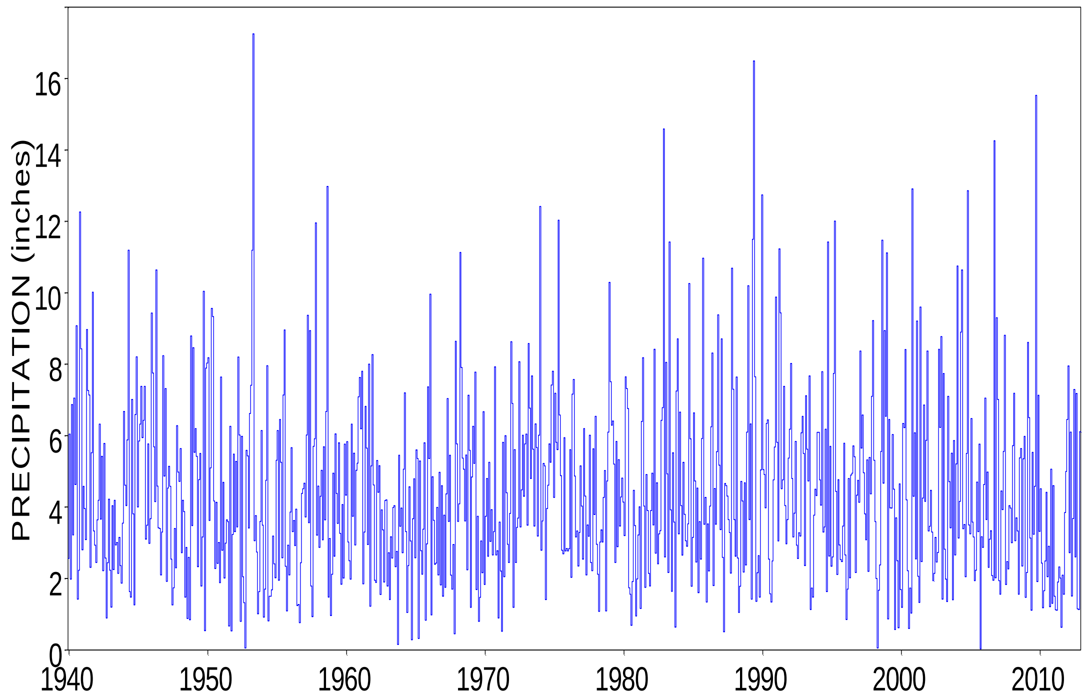
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 612



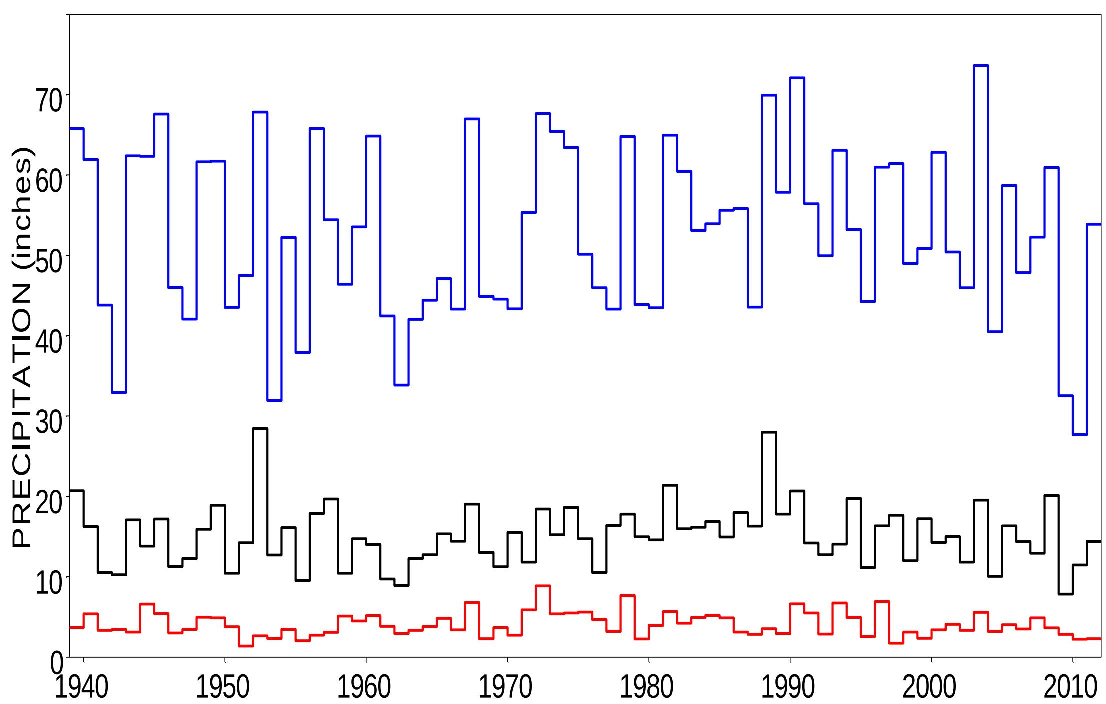
Monthly Precipitation for Quadrangle 613



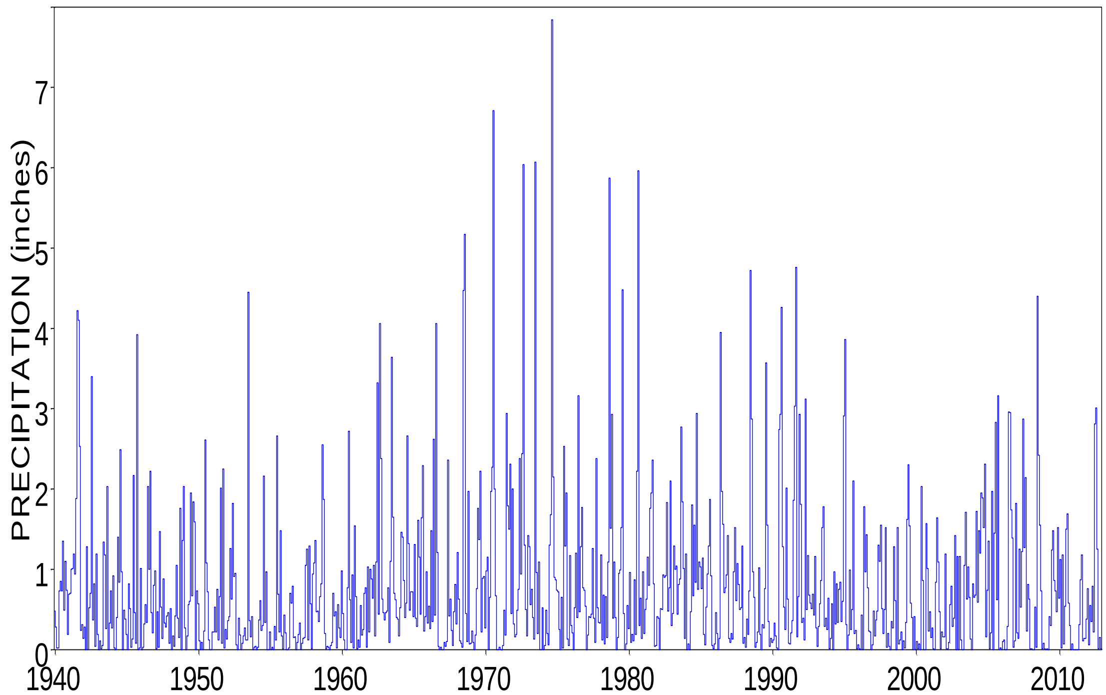
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 613



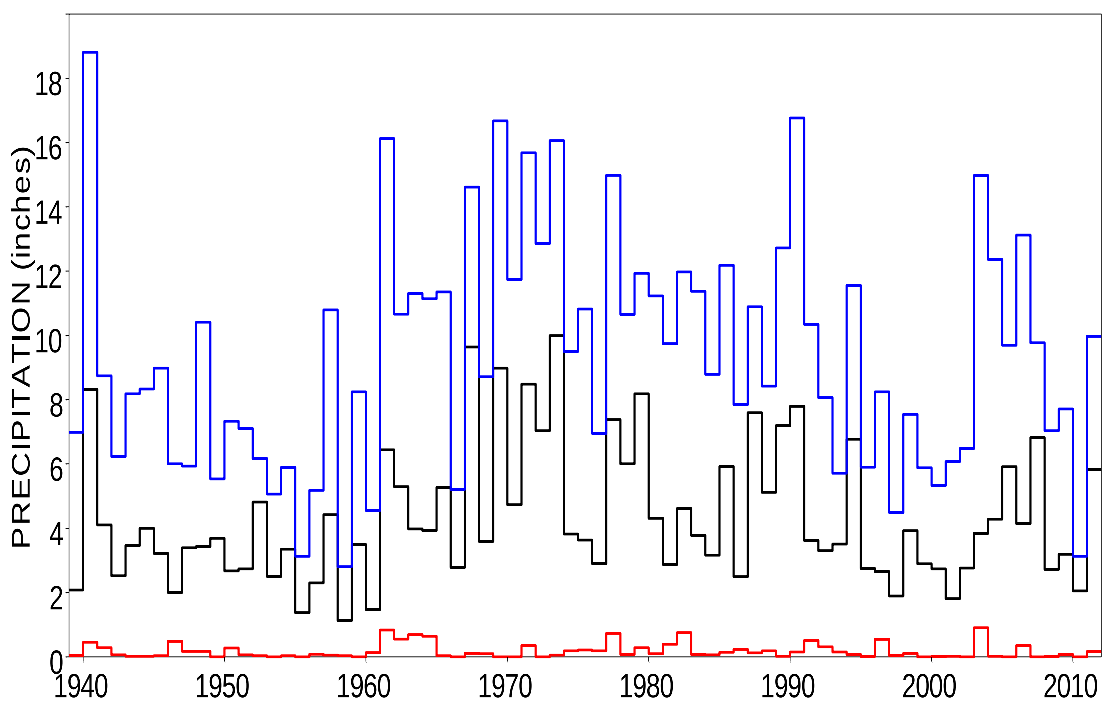
Monthly Precipitation for Quadrangle 614



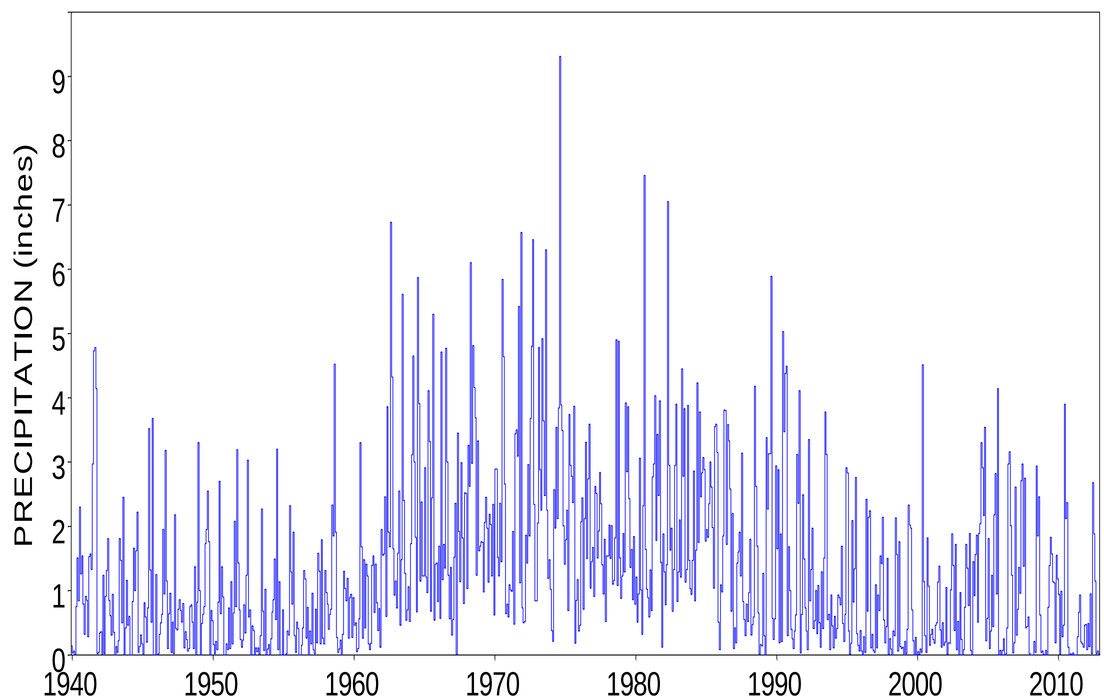
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 614



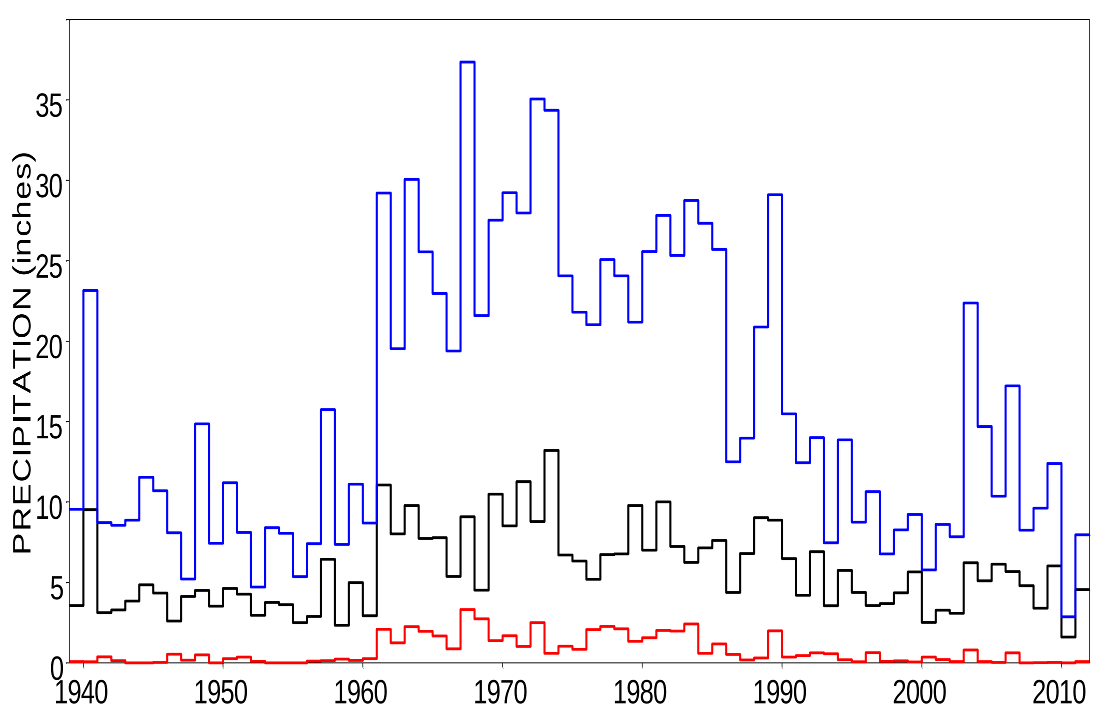
Monthly Precipitation for Quadrangle 701



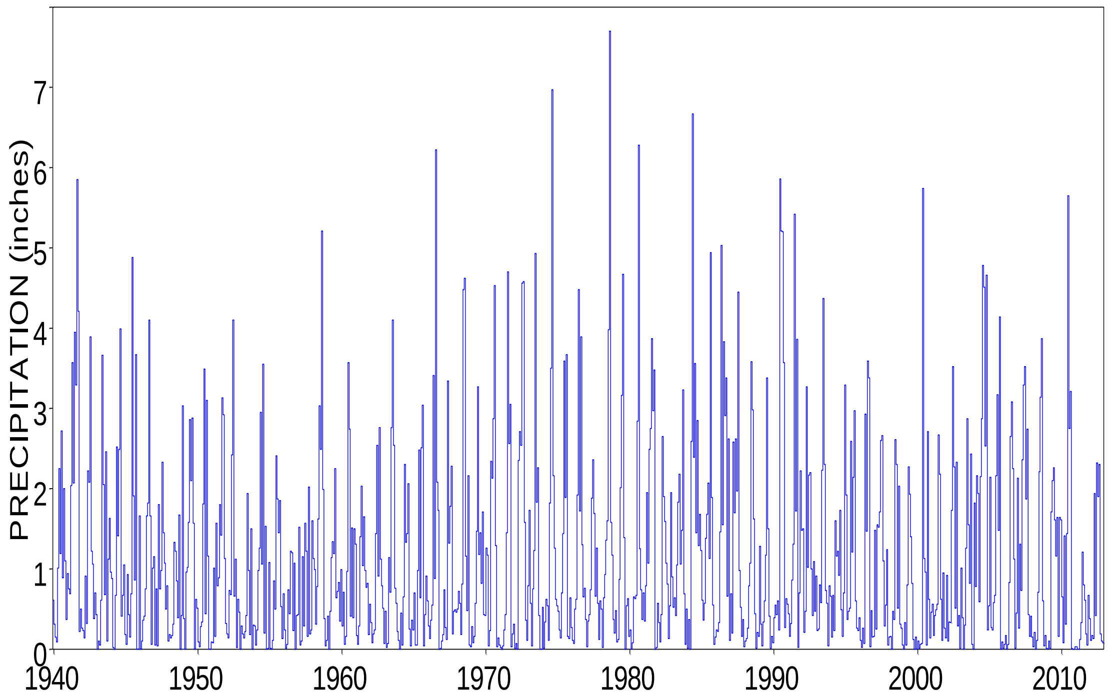
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 701



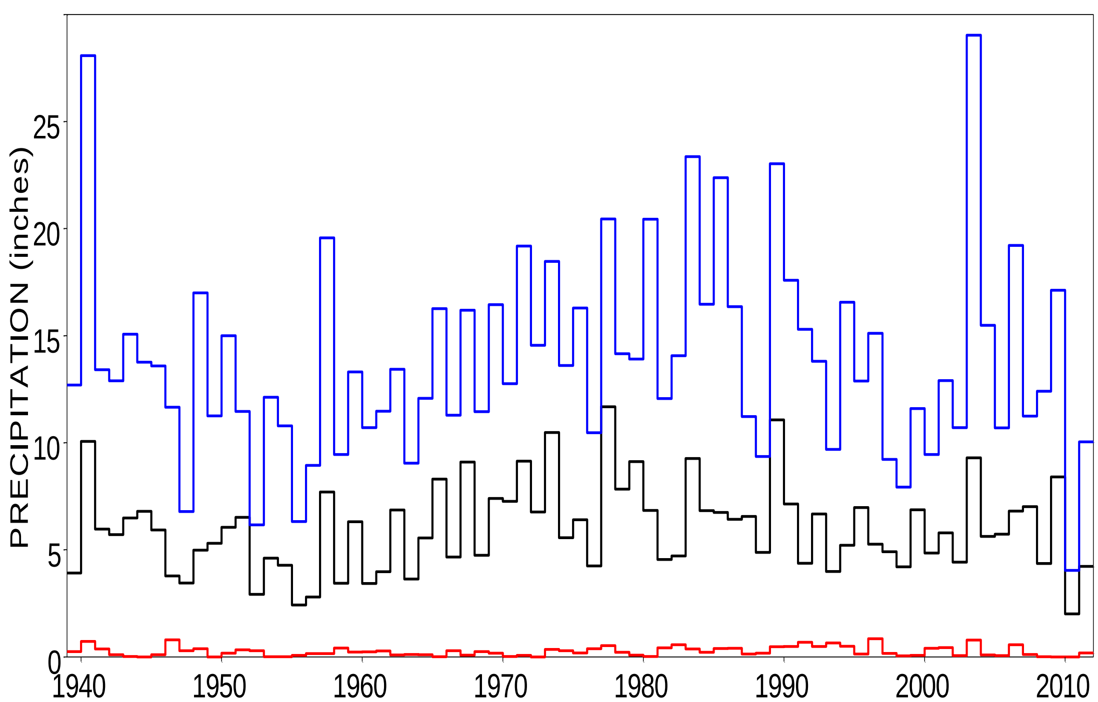
Monthly Precipitation for Quadrangle 702



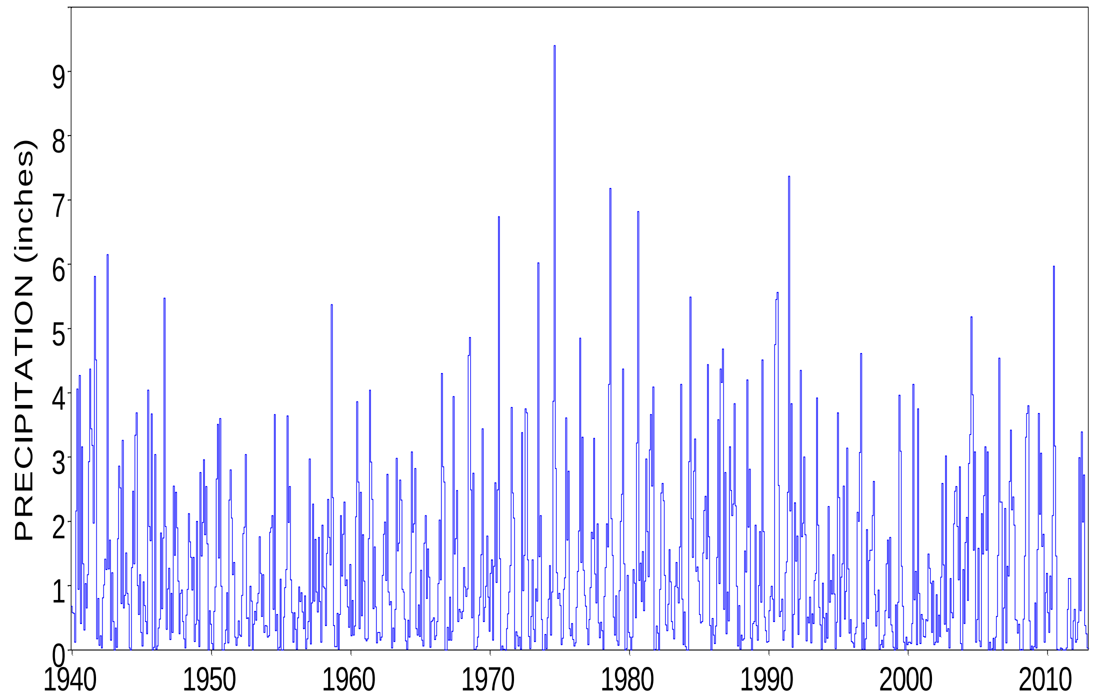
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 702



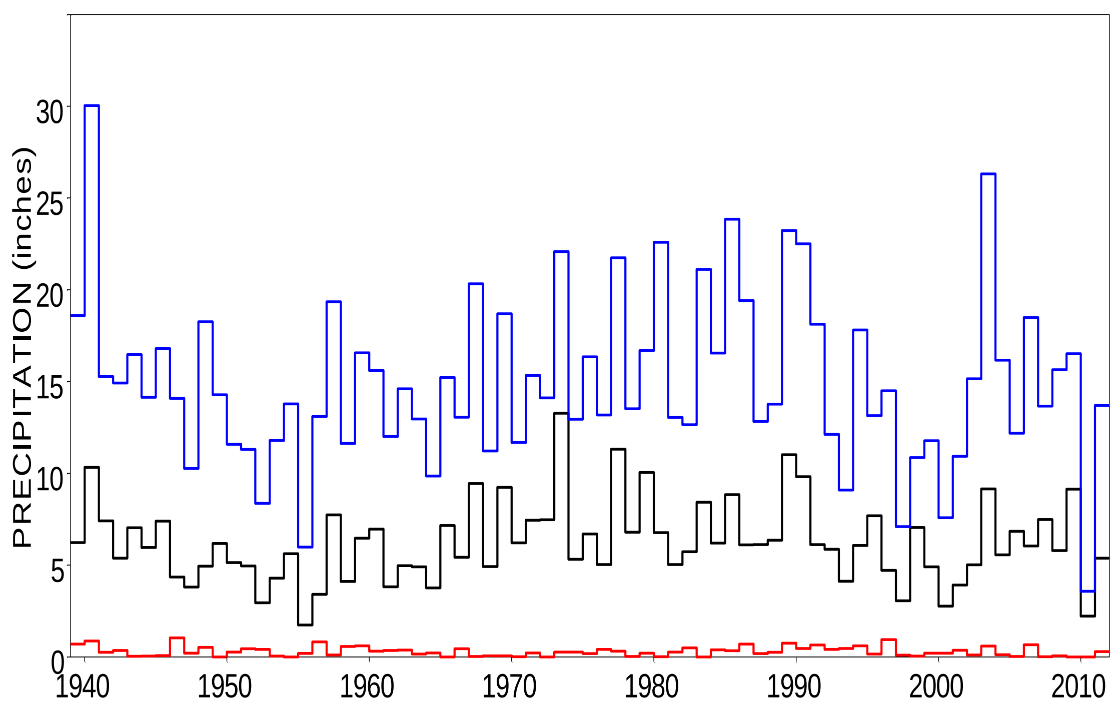
Monthly Precipitation for Quadrangle 703



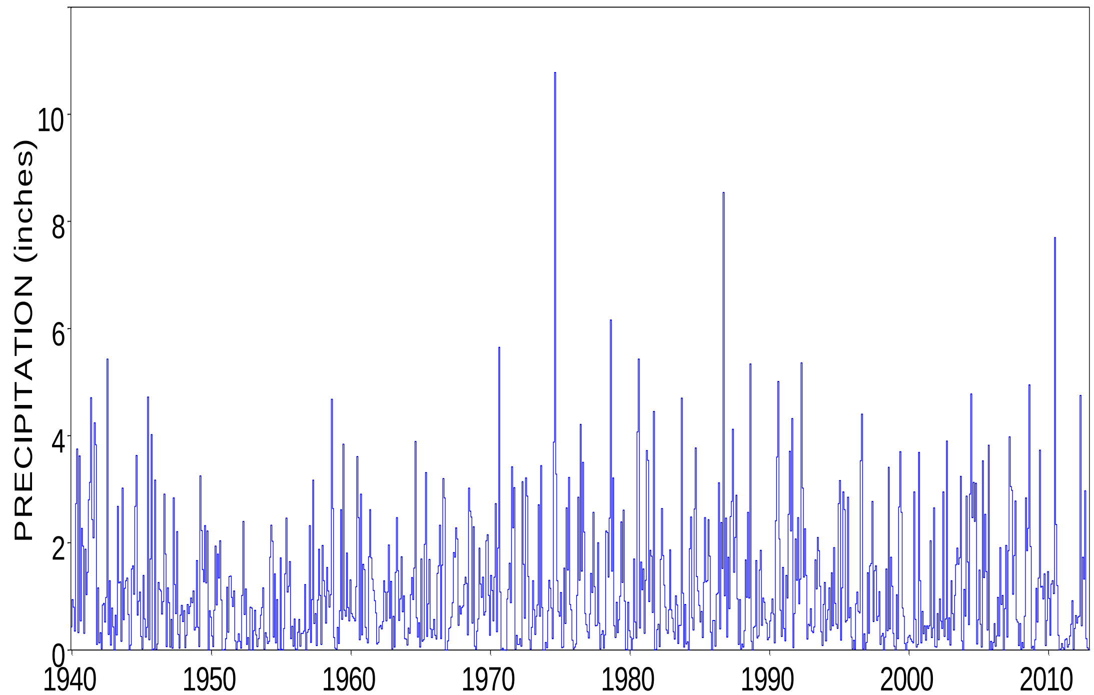
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 703



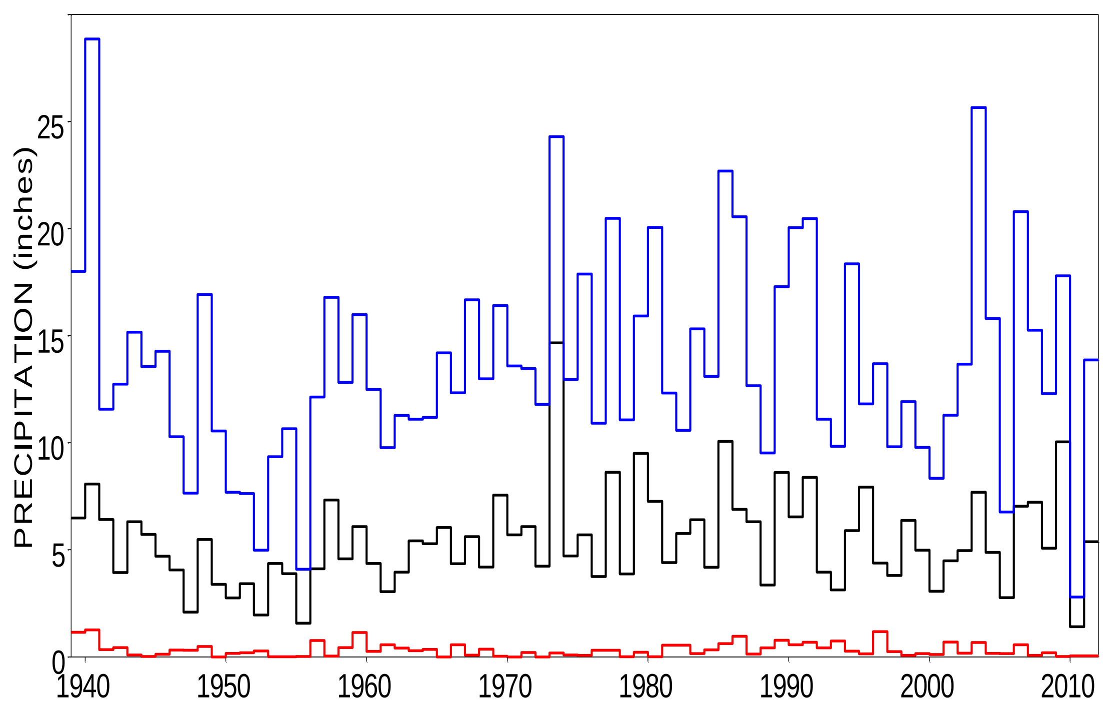
Monthly Precipitation for Quadrangle 704



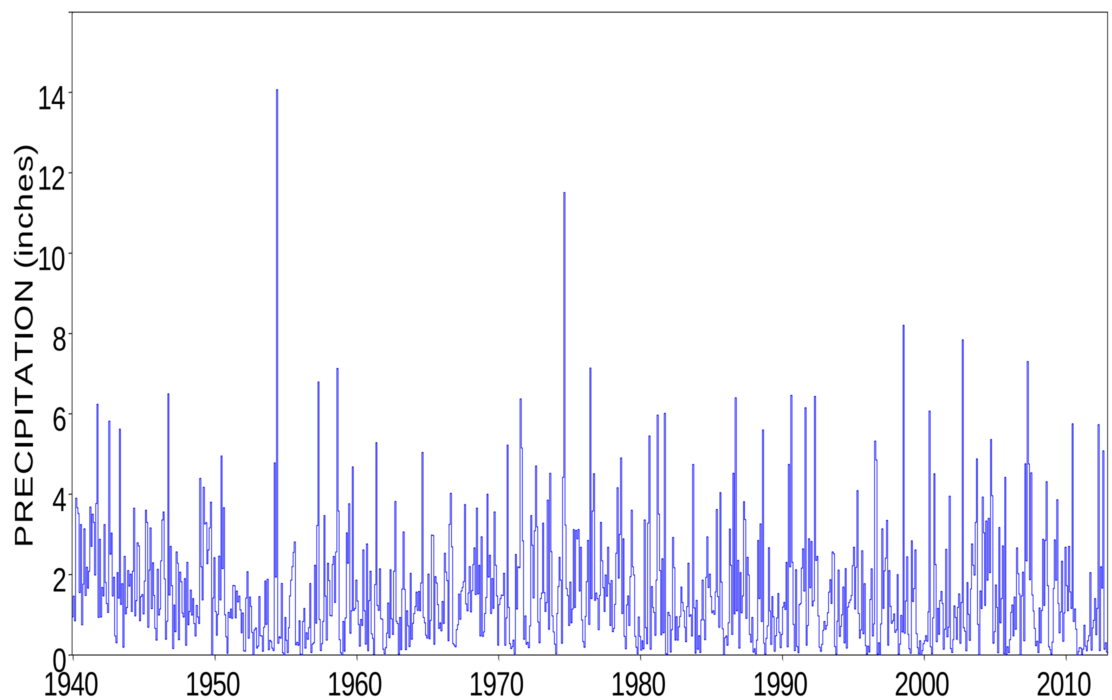
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 704



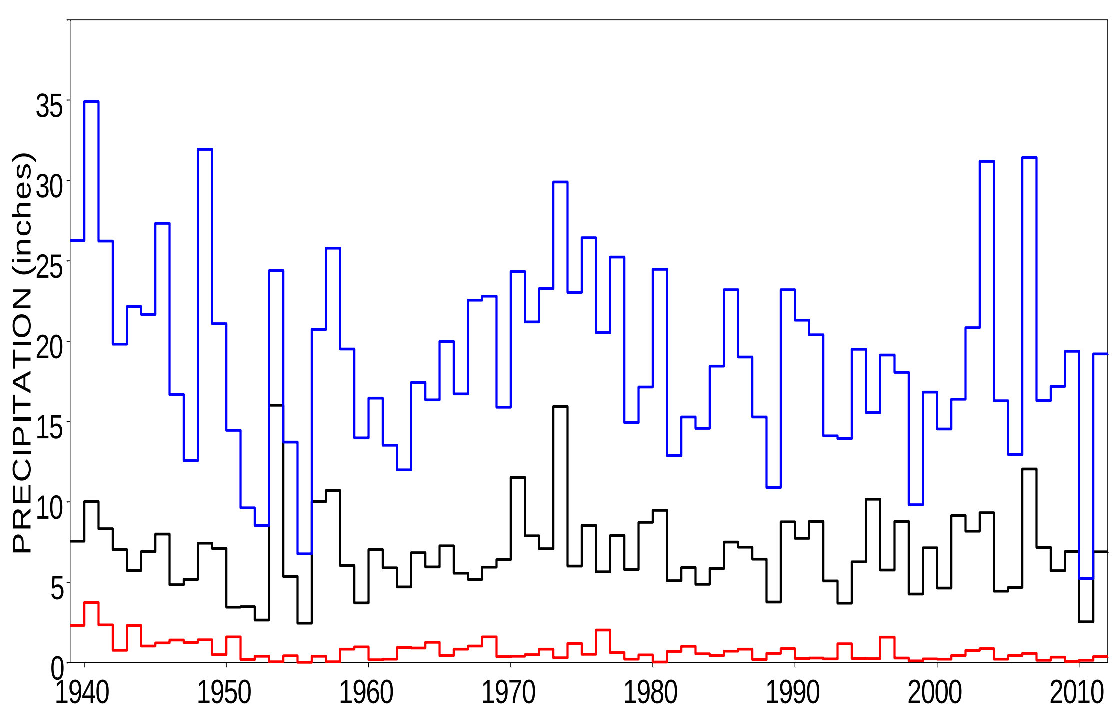
Monthly Precipitation for Quadrangle 705



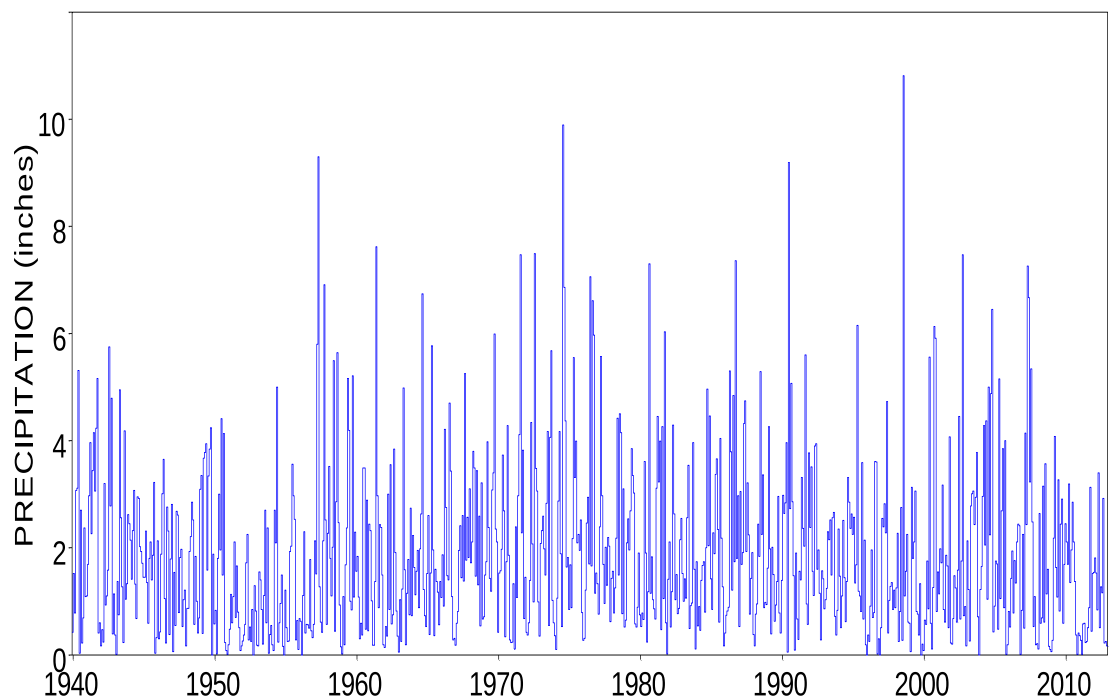
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 705



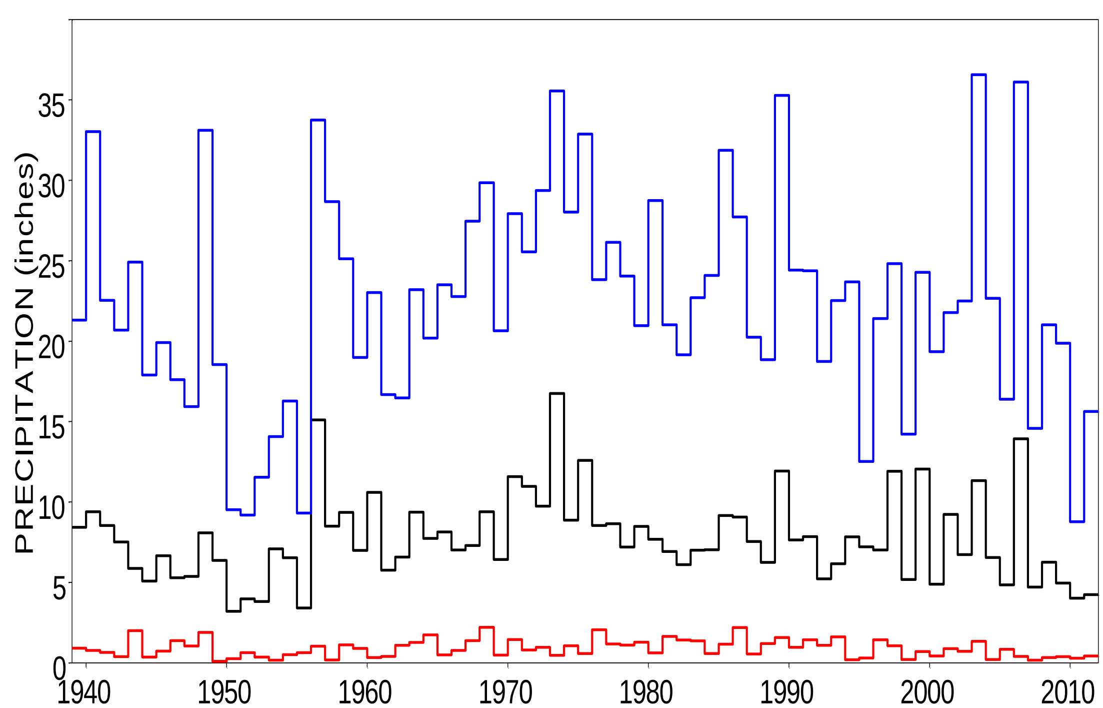
Monthly Precipitation for Quadrangle 706



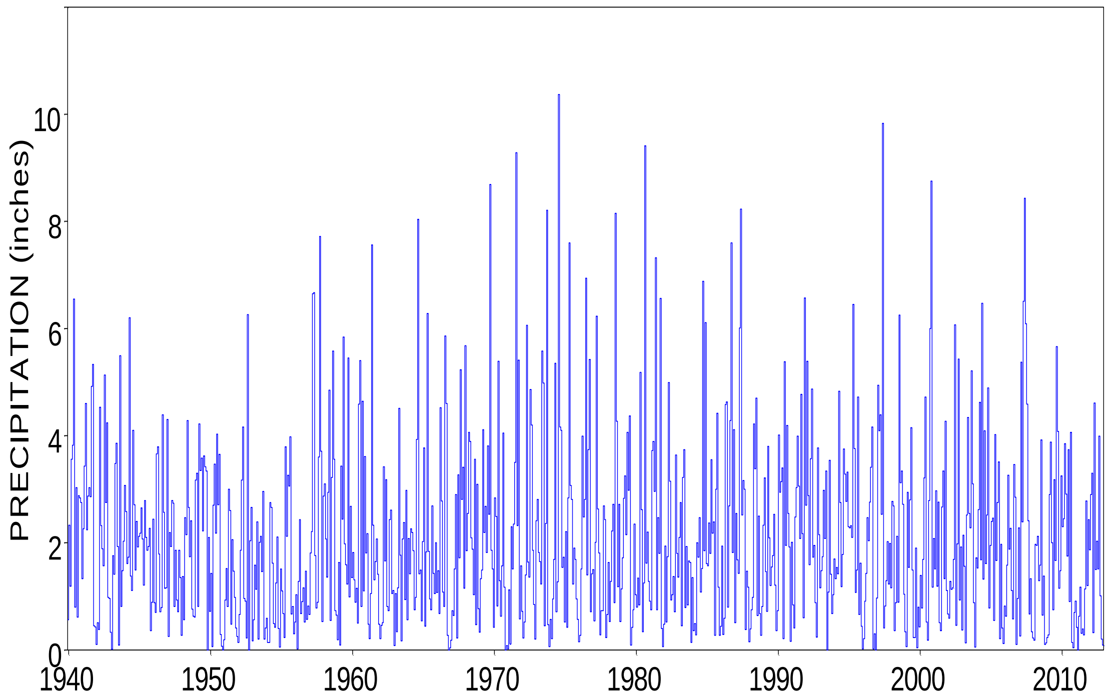
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 706



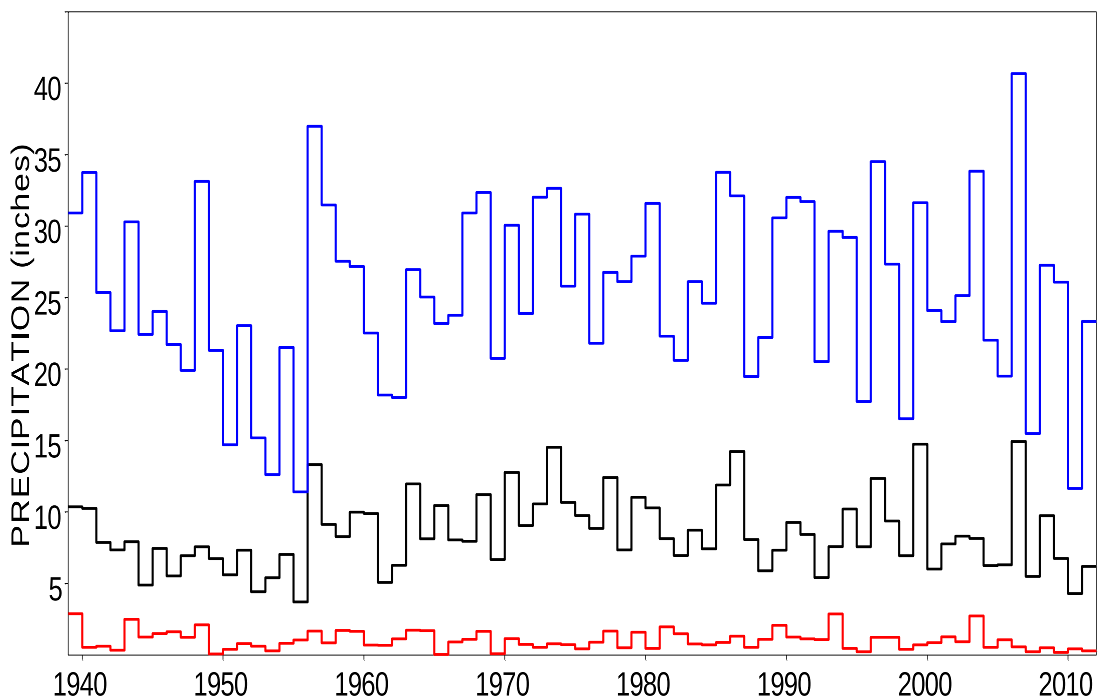
Monthly Precipitation for Quadrangle 707



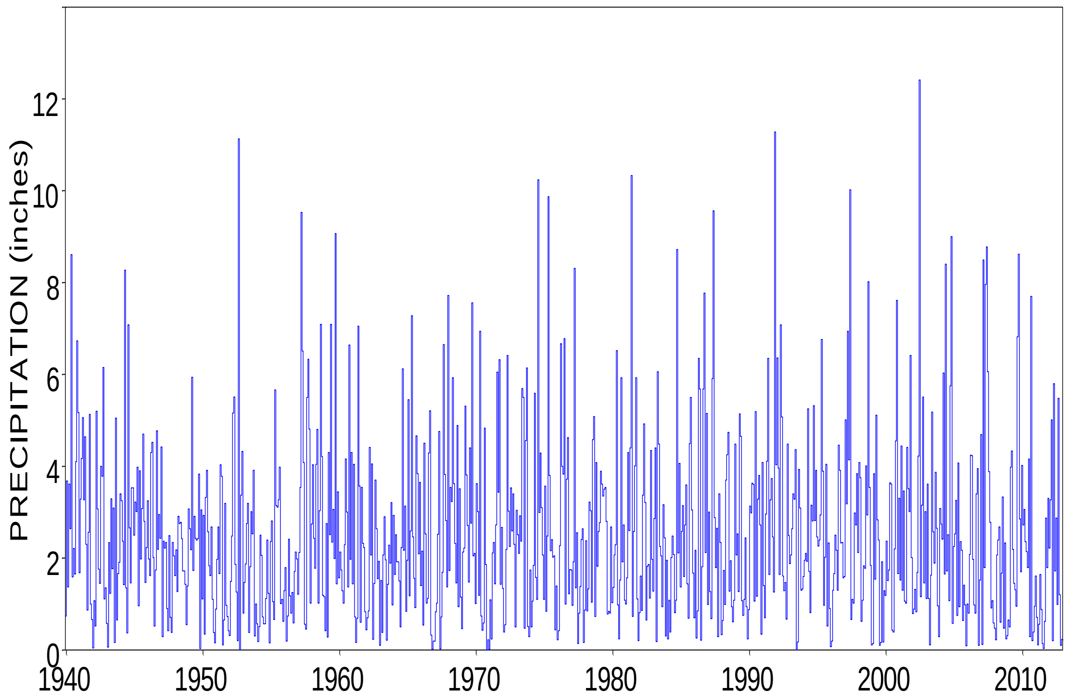
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 707



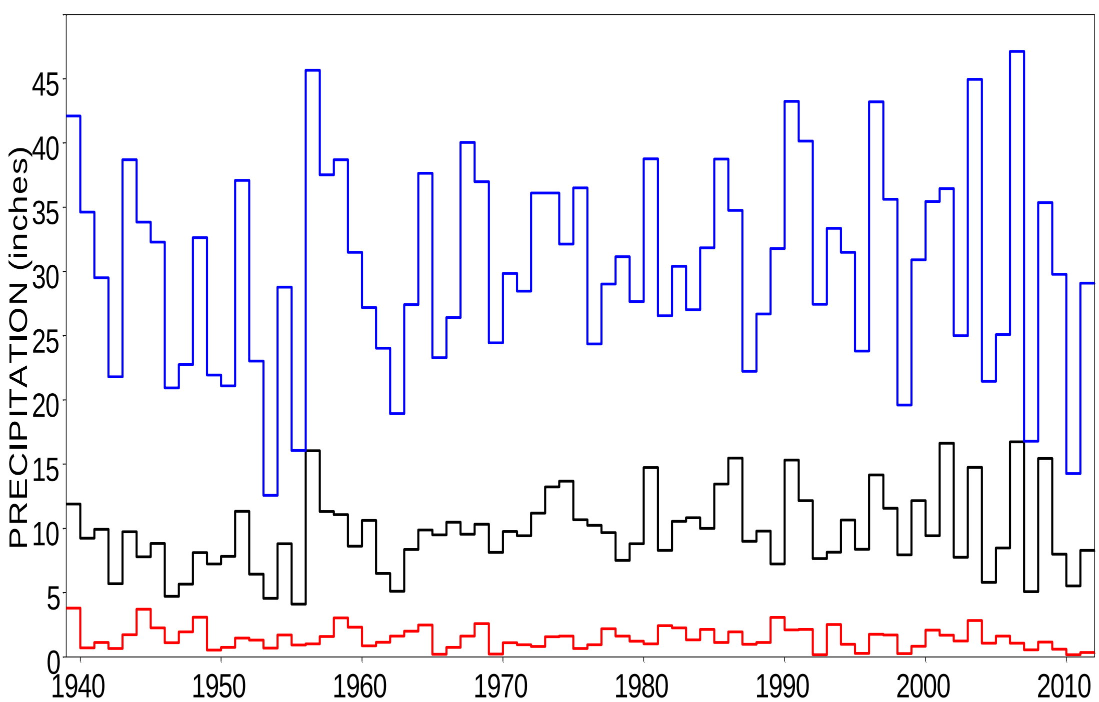
Monthly Precipitation for Quadrangle 708



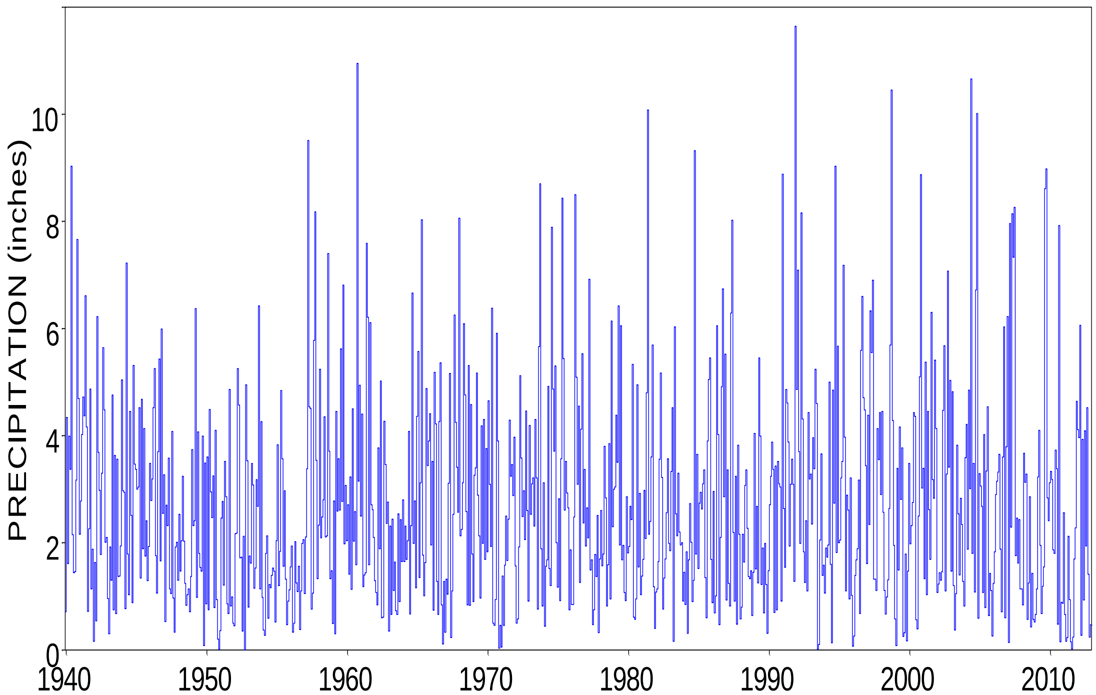
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 708



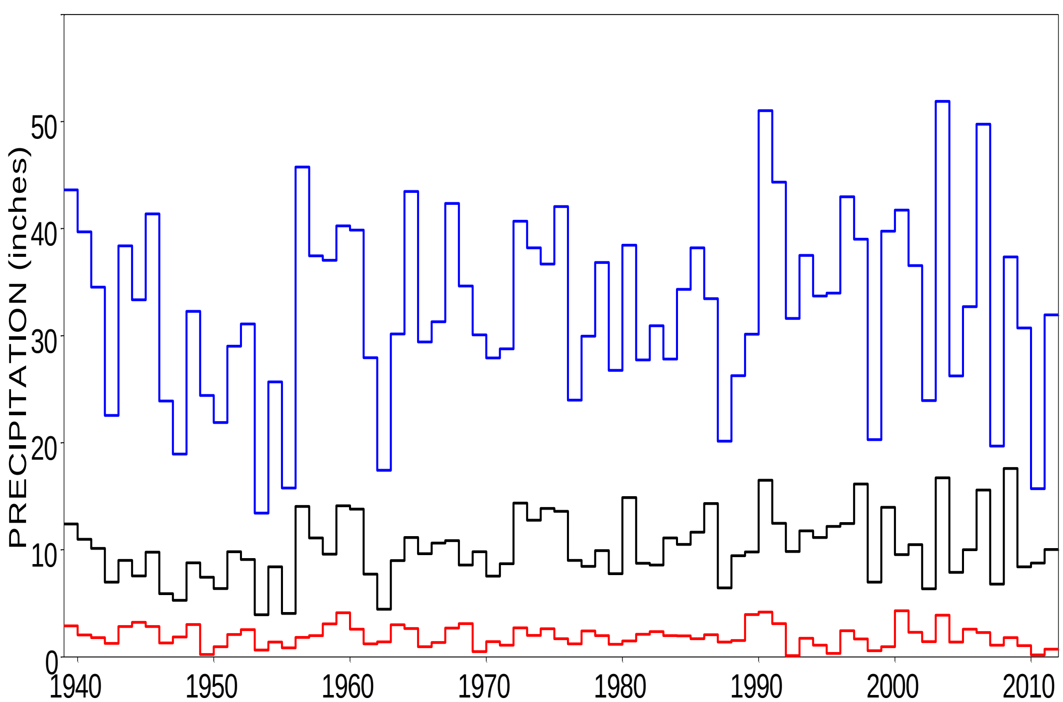
Monthly Precipitation for Quadrangle 709



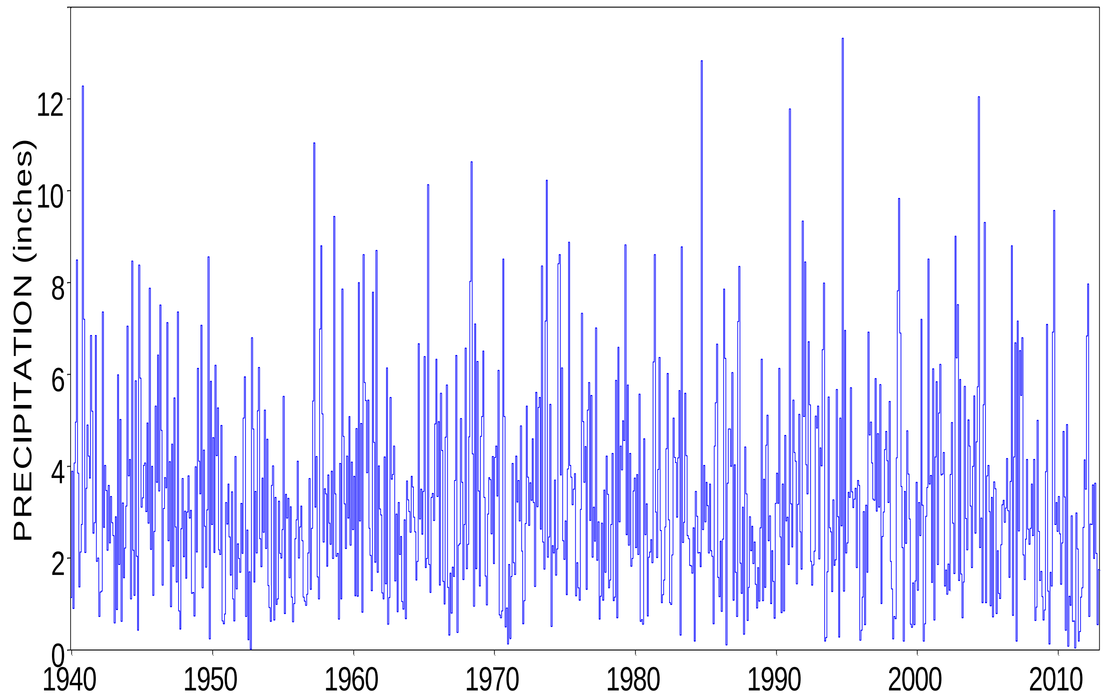
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 709



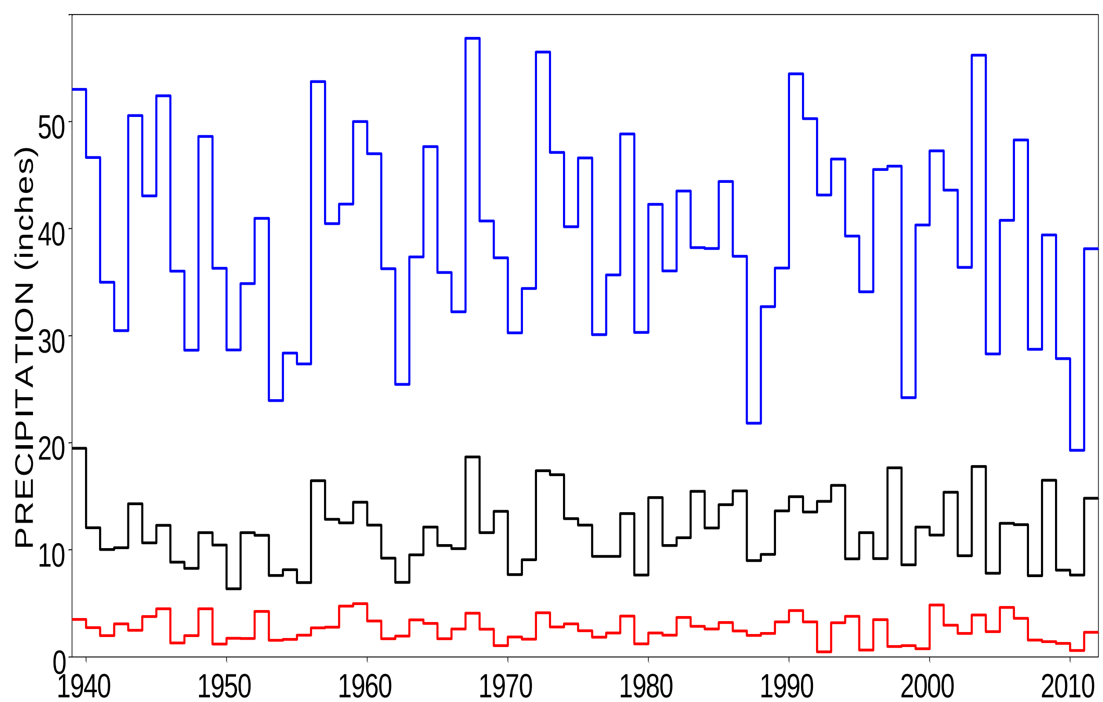
Monthly Precipitation for Quadrangle 710



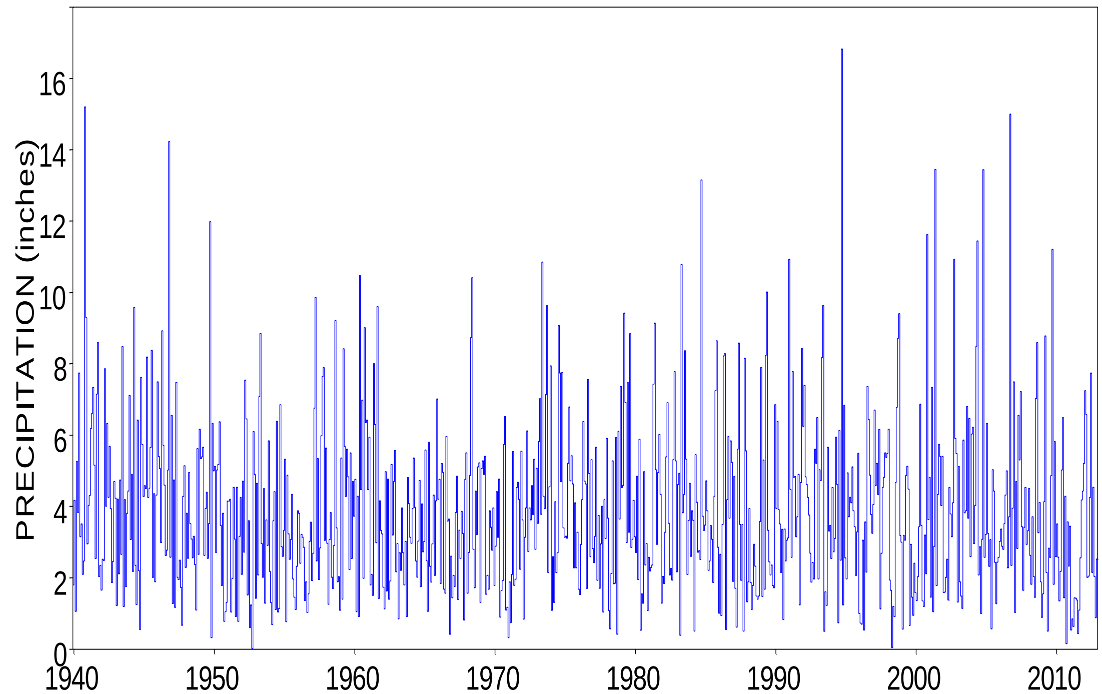
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 710



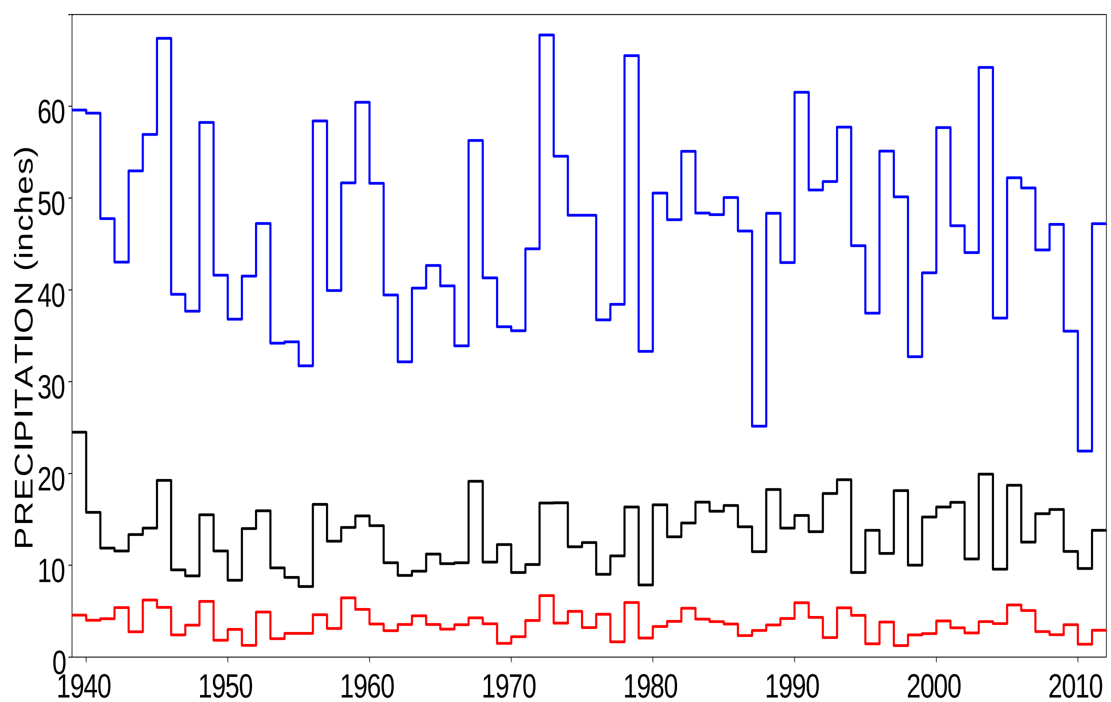
Monthly Precipitation for Quadrangle 711



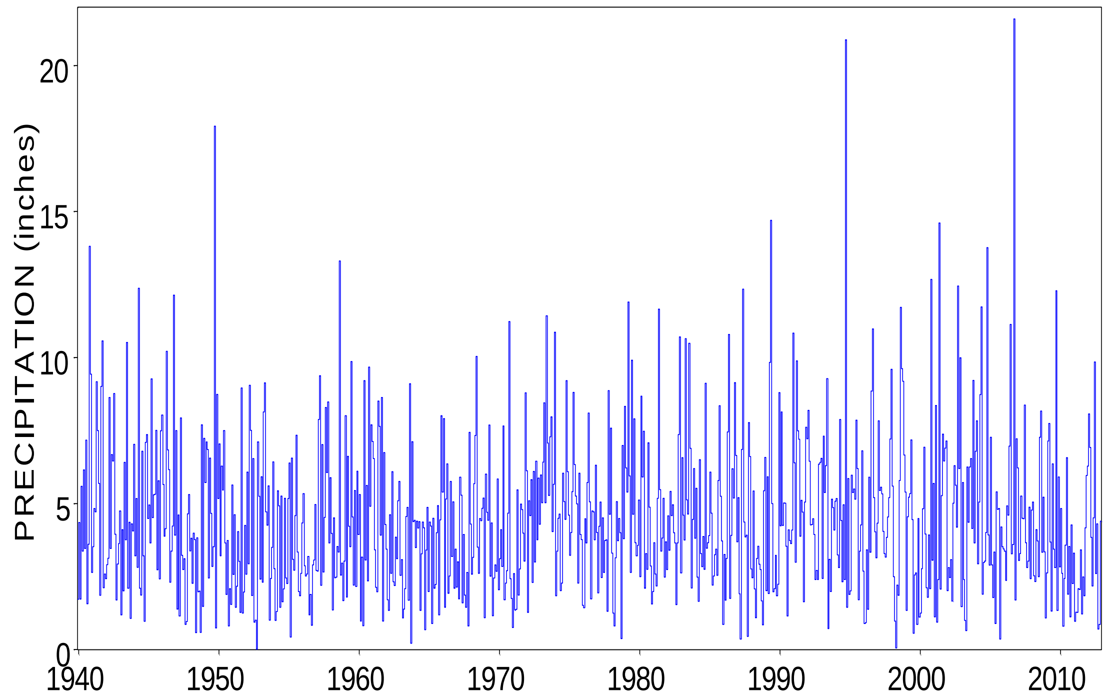
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 711



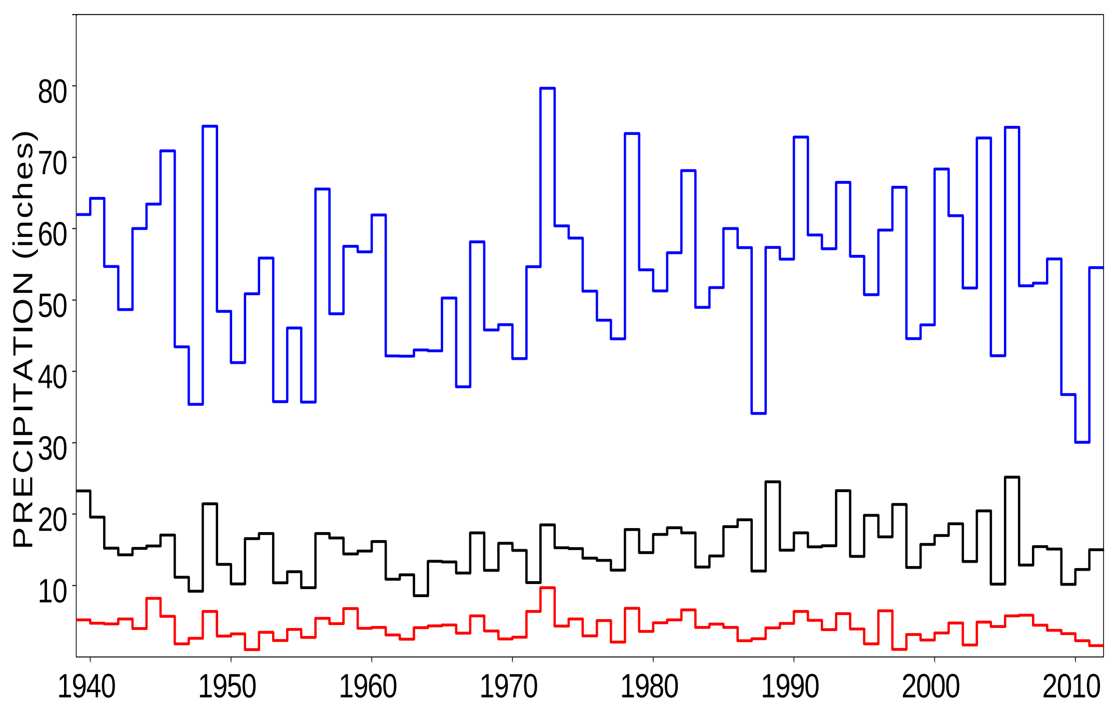
Monthly Precipitation for Quadrangle 712



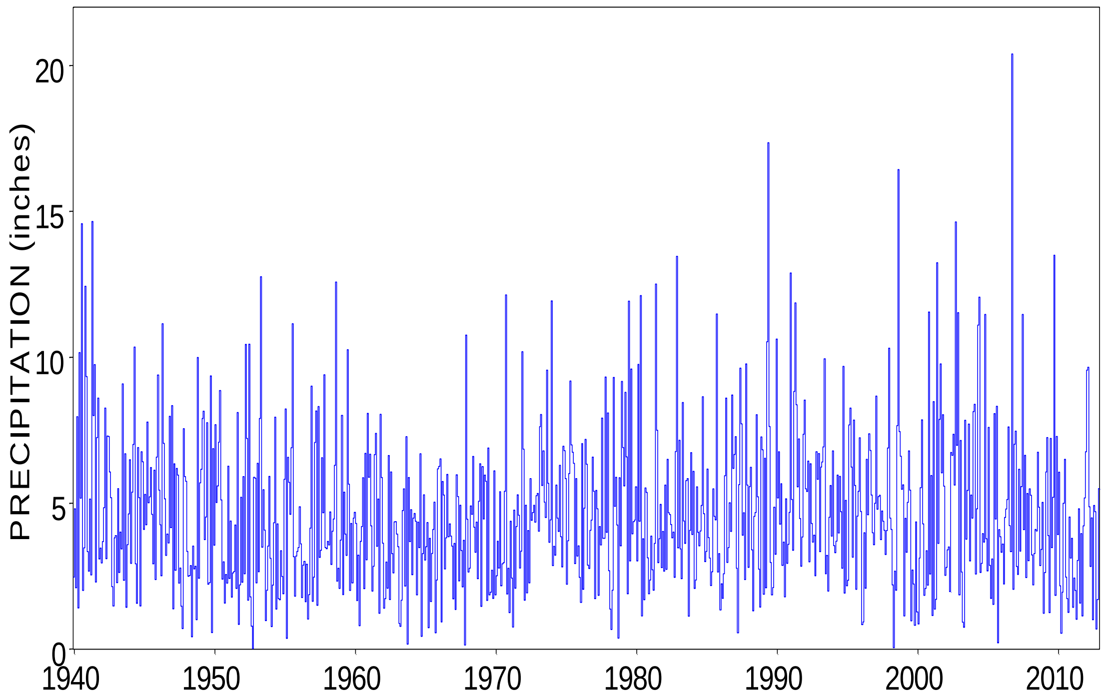
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 712



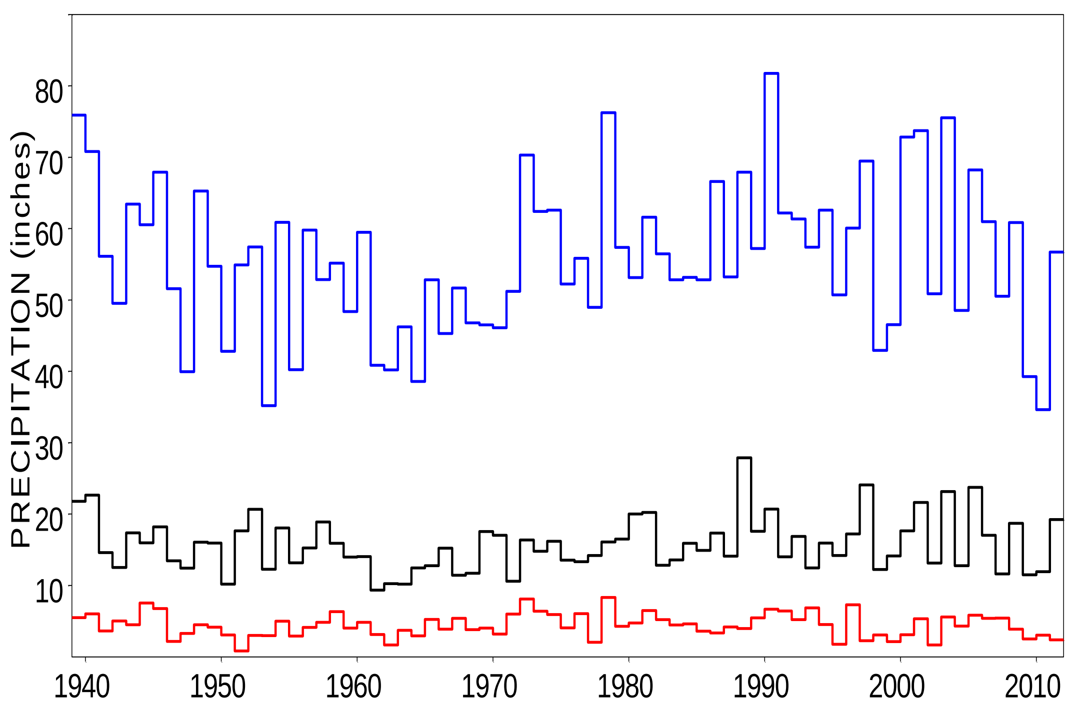
Monthly Precipitation for Quadrangle 713



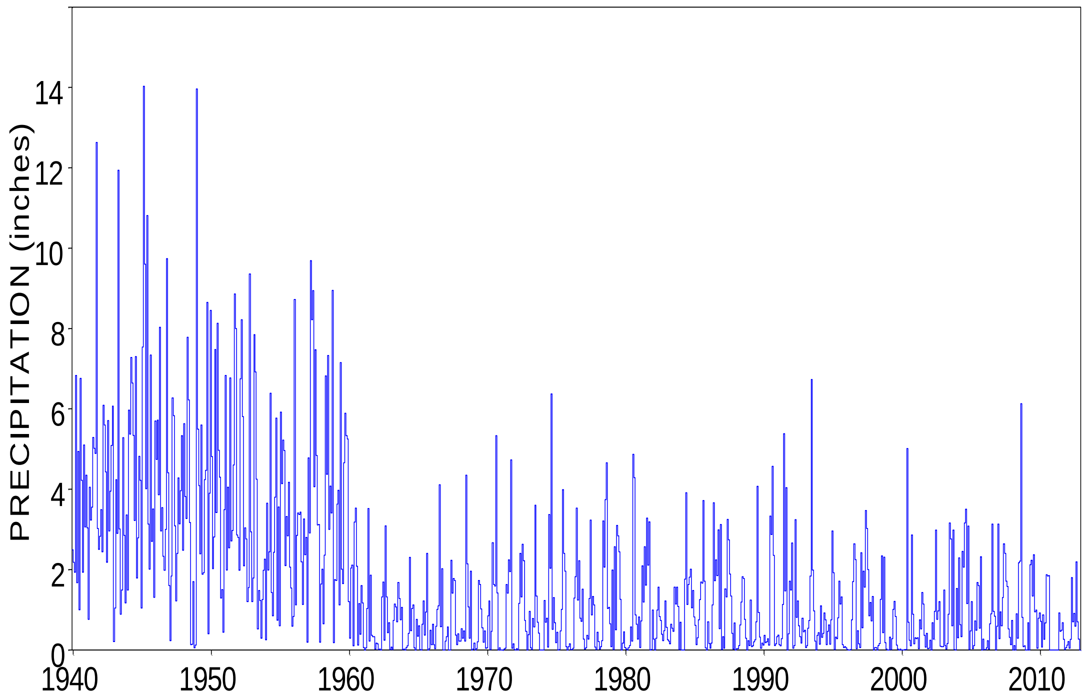
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 713



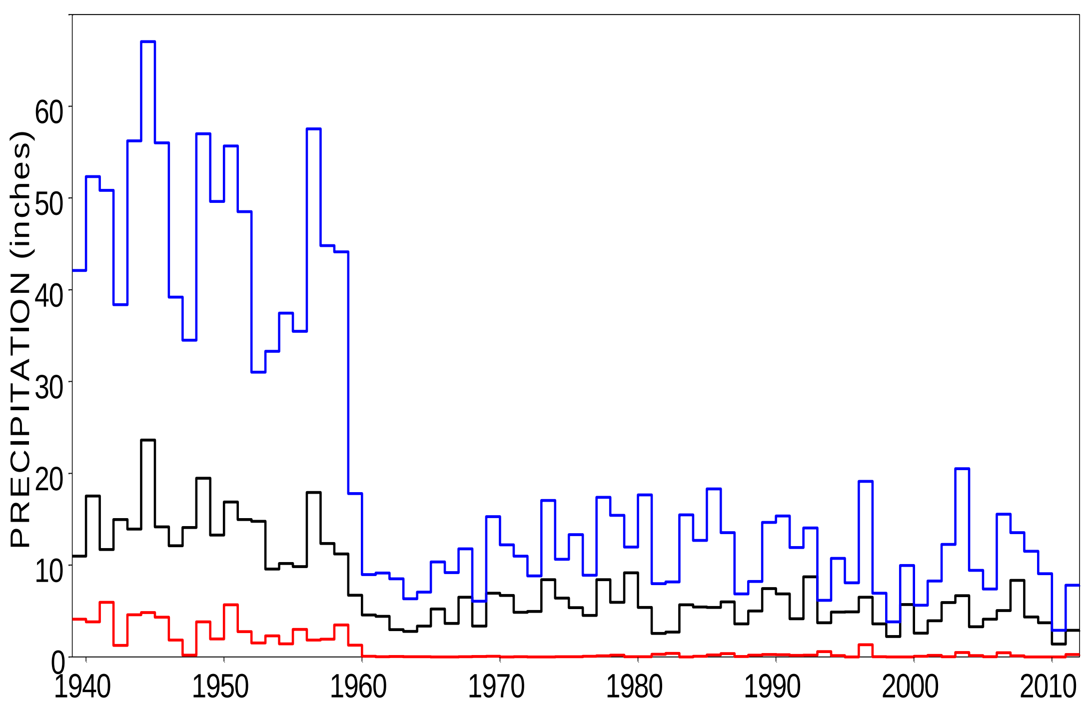
Monthly Precipitation for Quadrangle 714



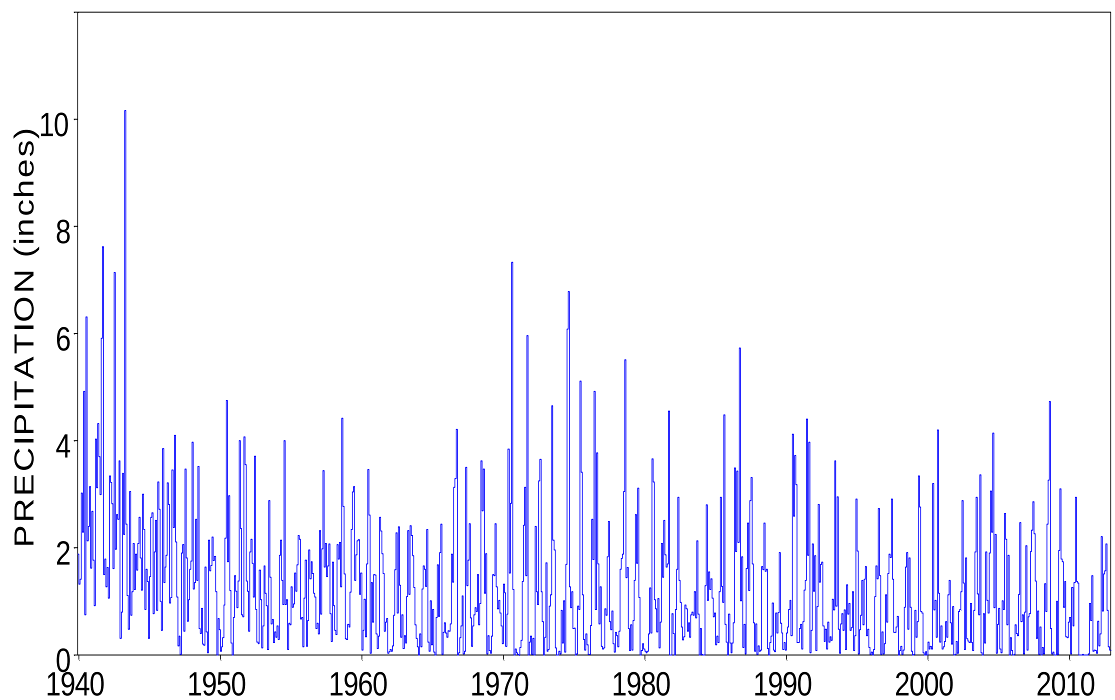
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 714



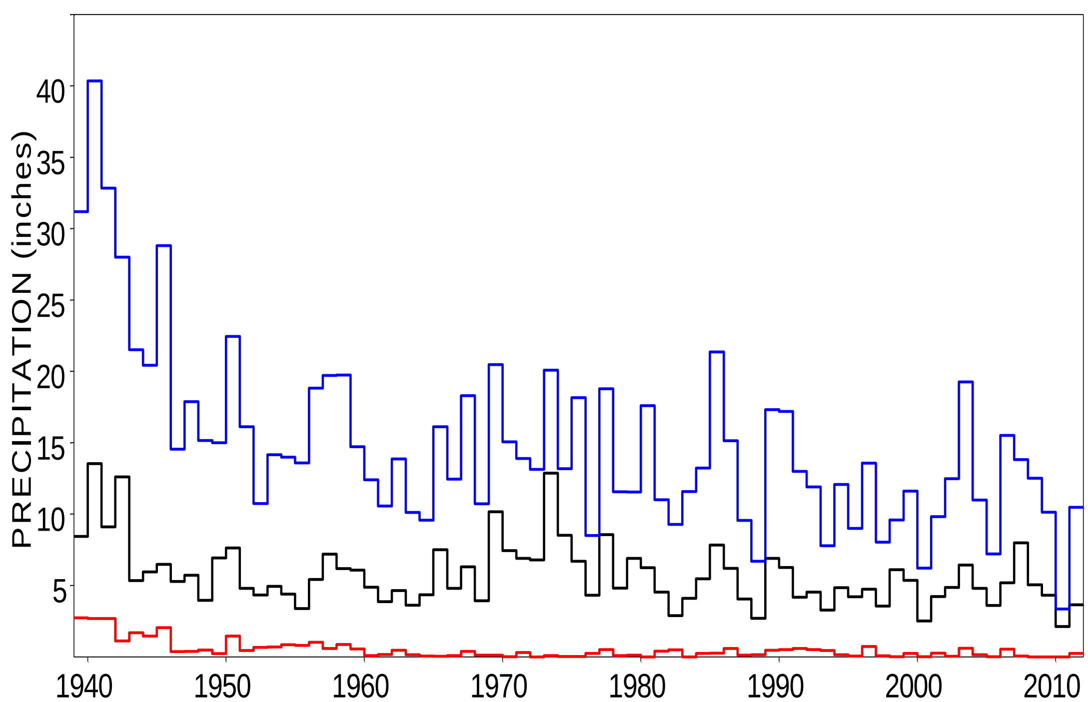
Monthly Precipitation for Quadrangle 803



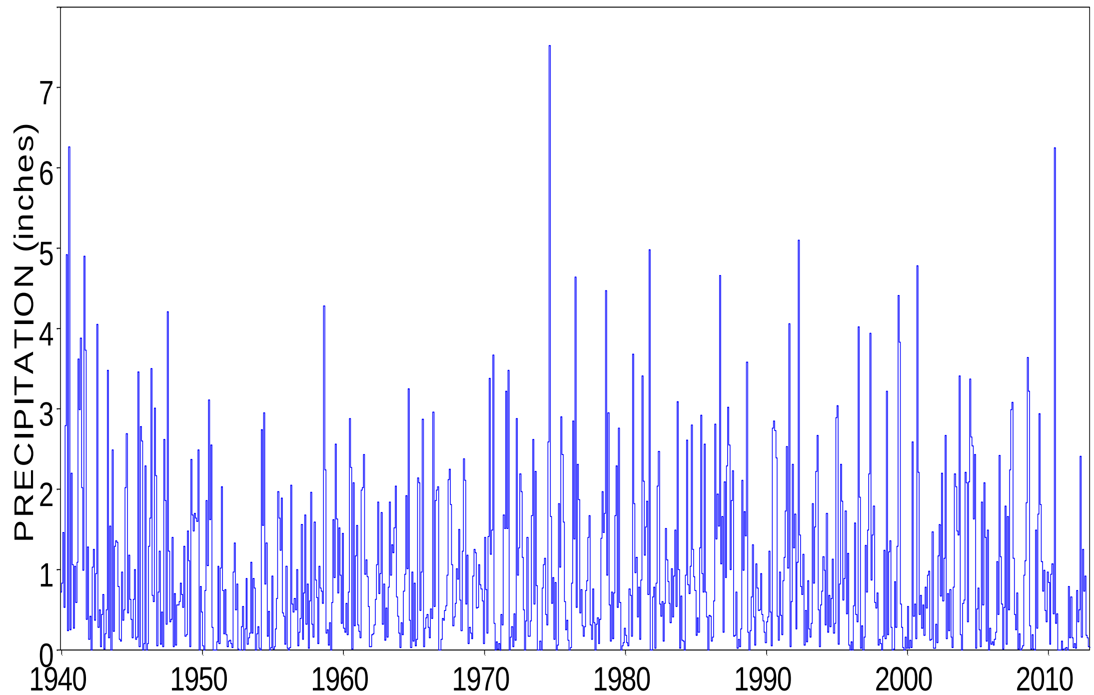
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 803



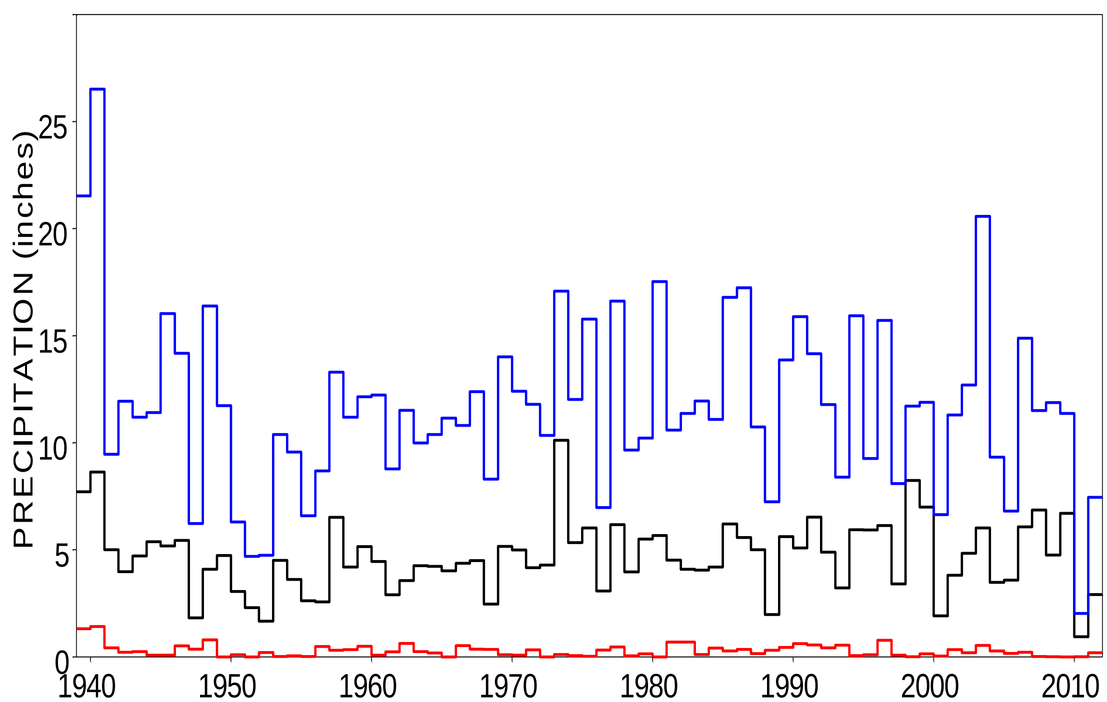
Monthly Precipitation for Quadrangle 804



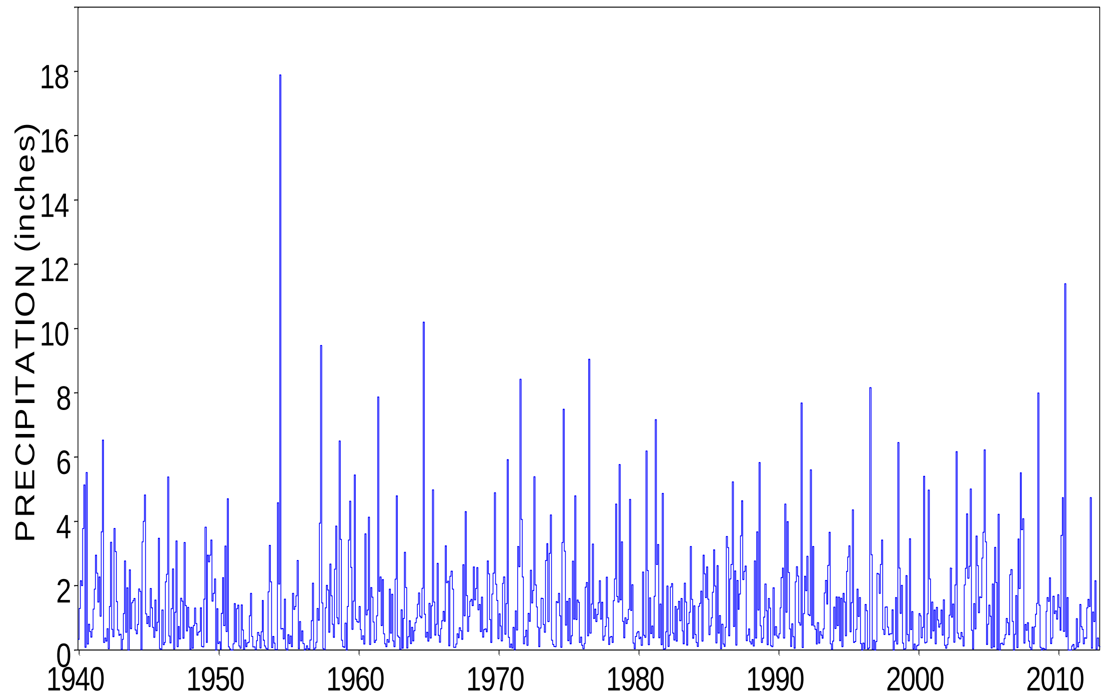
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 804



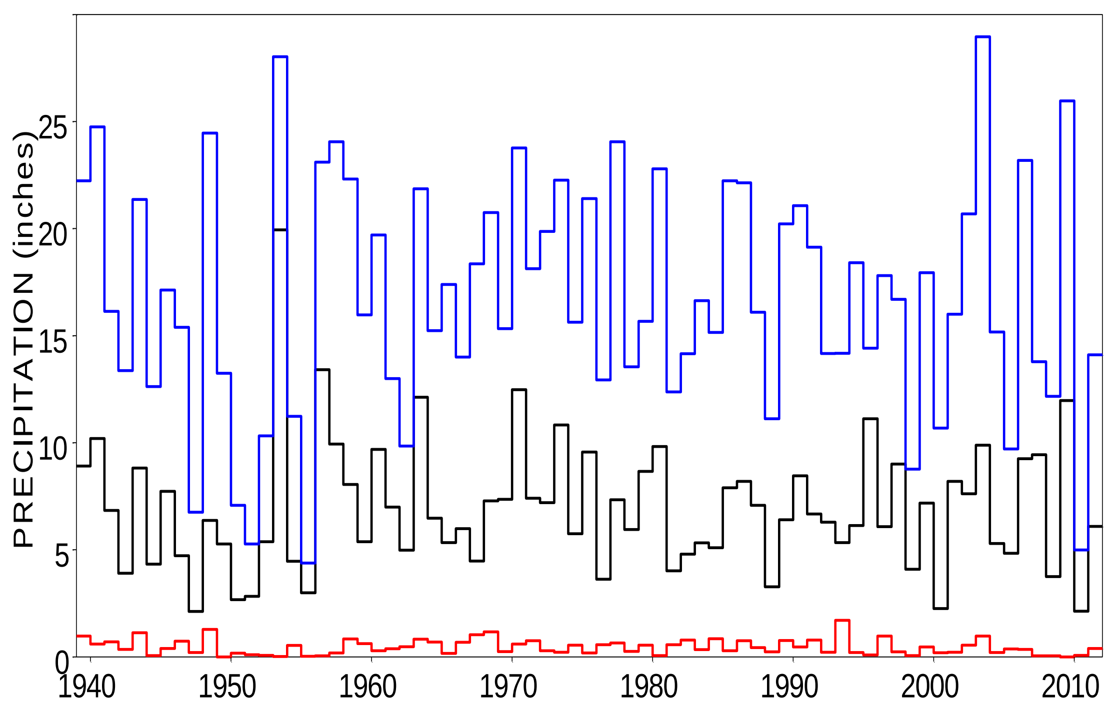
Monthly Precipitation for Quadrangle 805



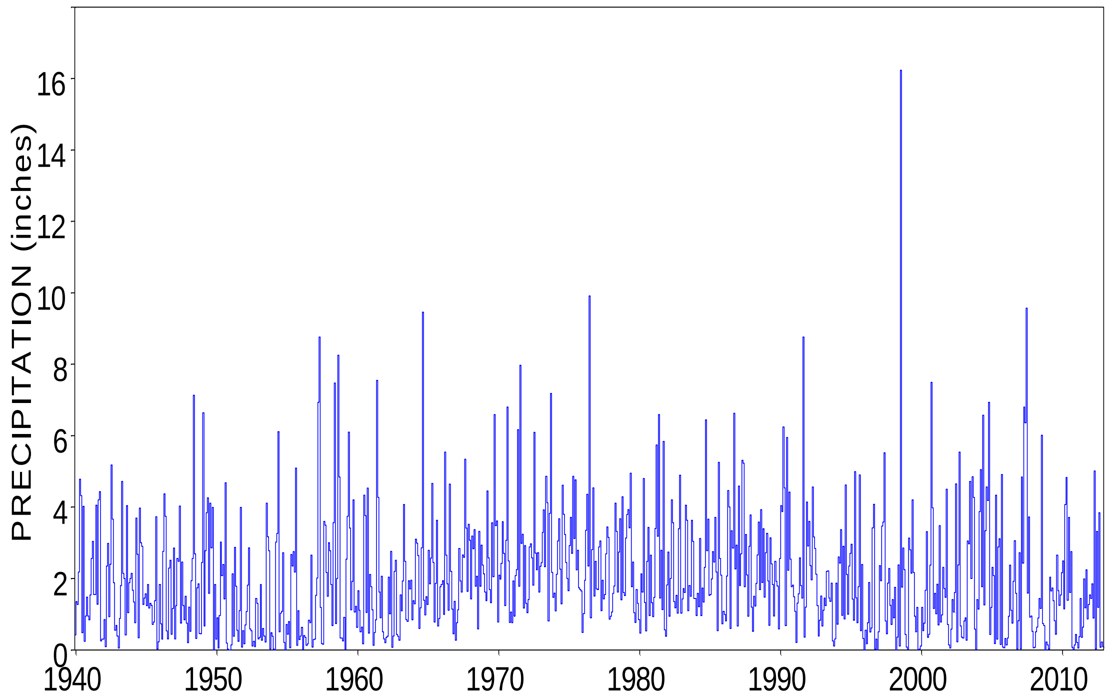
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 805



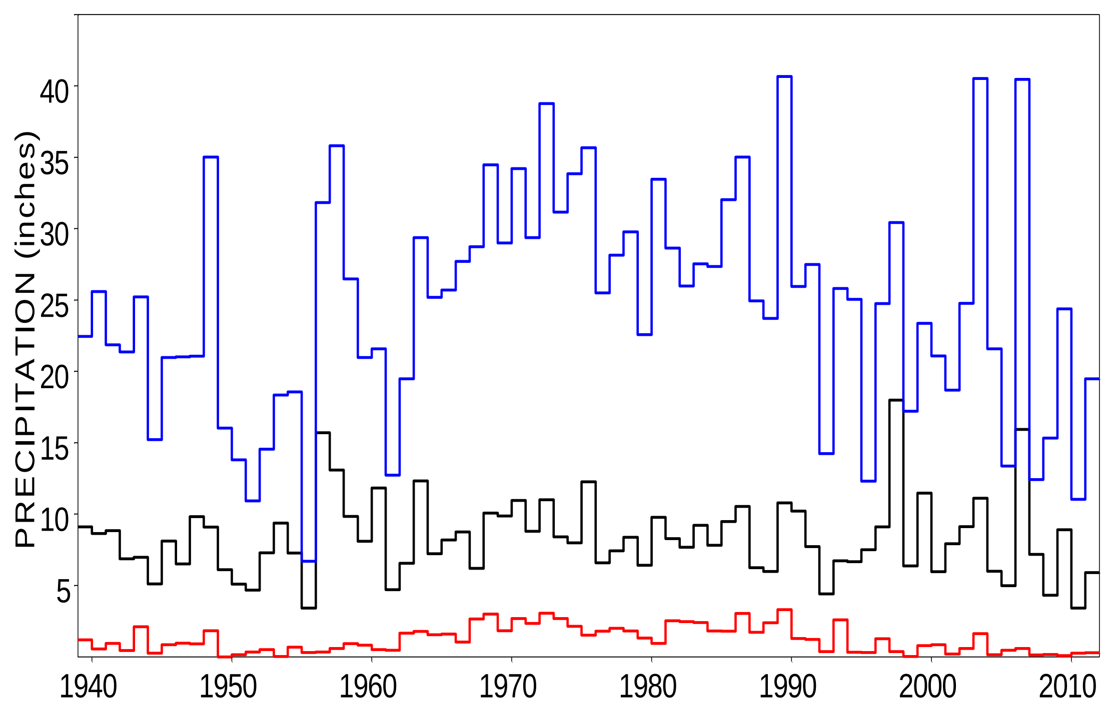
Monthly Precipitation for Quadrangle 806



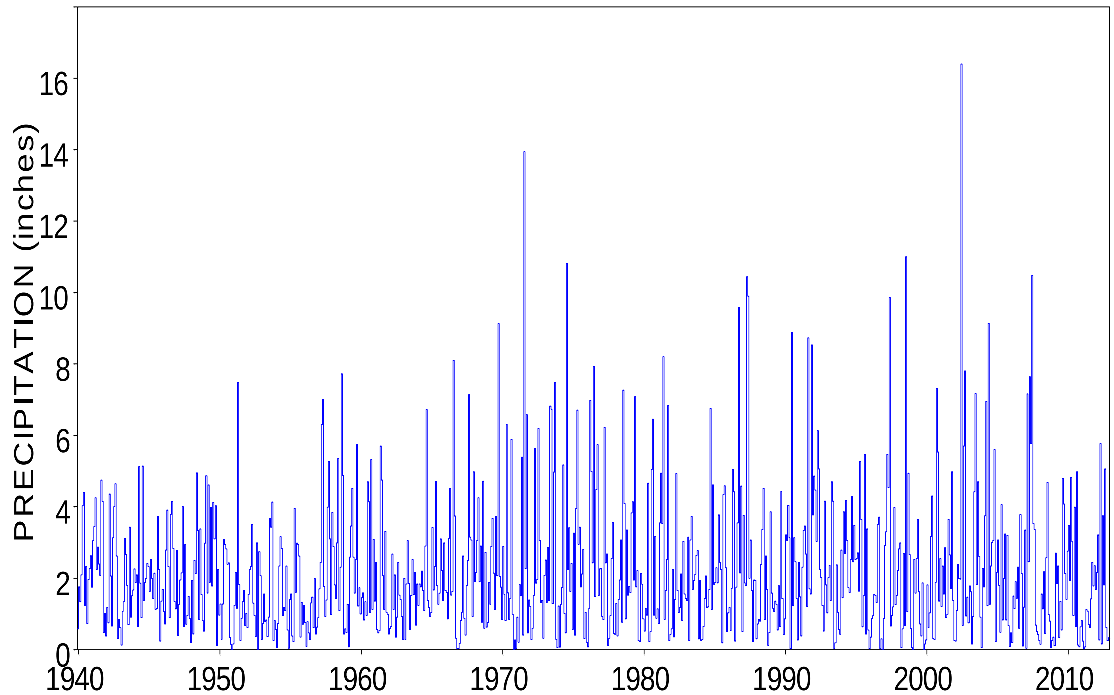
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 806



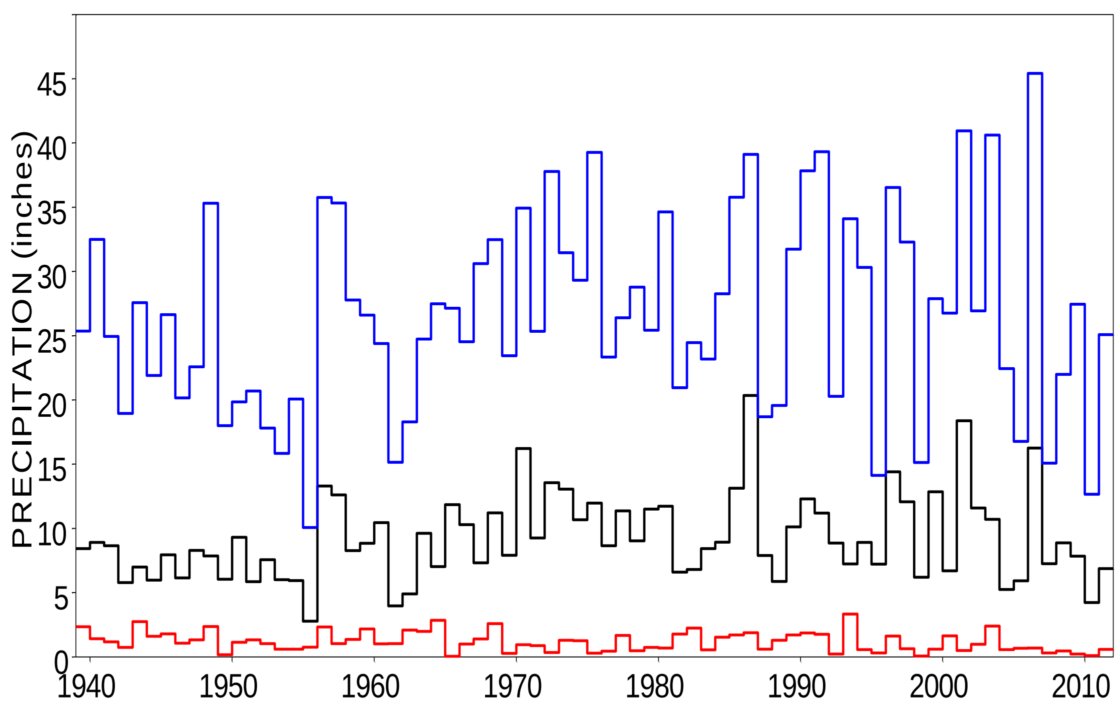
Monthly Precipitation for Quadrangle 807



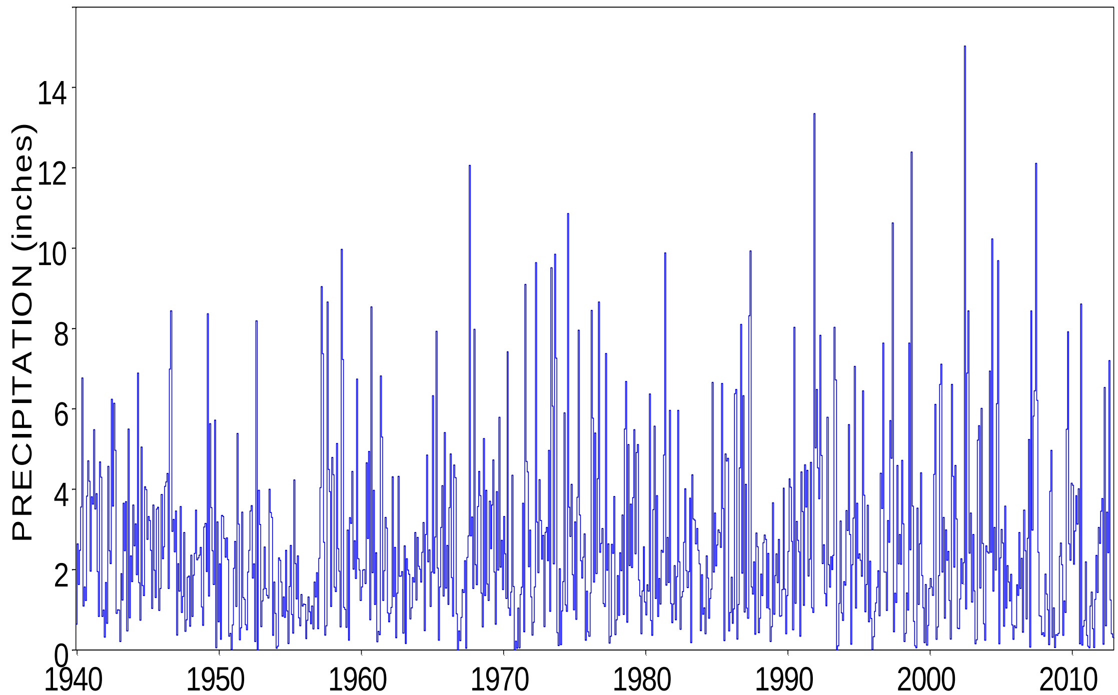
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 807



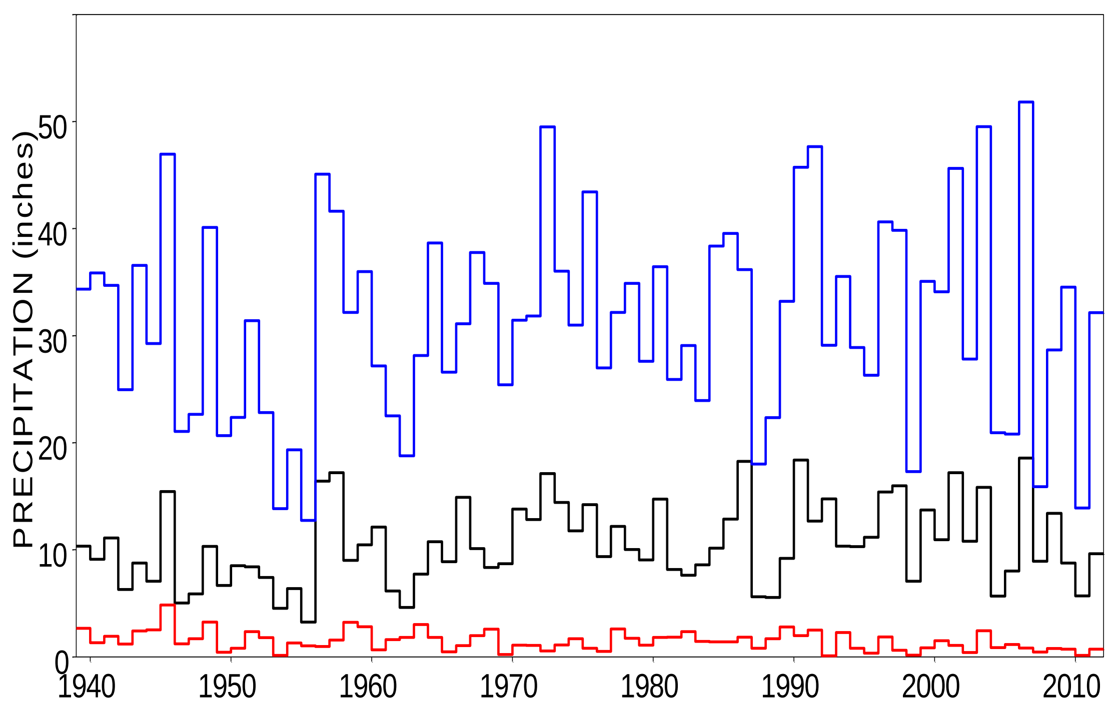
Monthly Precipitation for Quadrangle 808



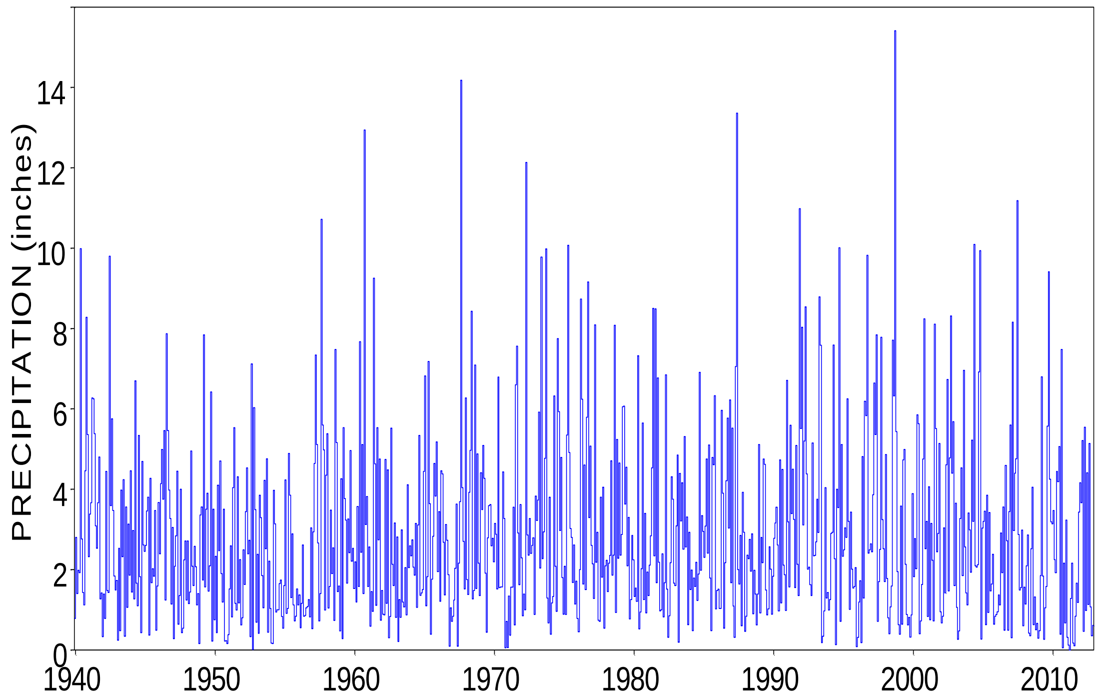
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 808



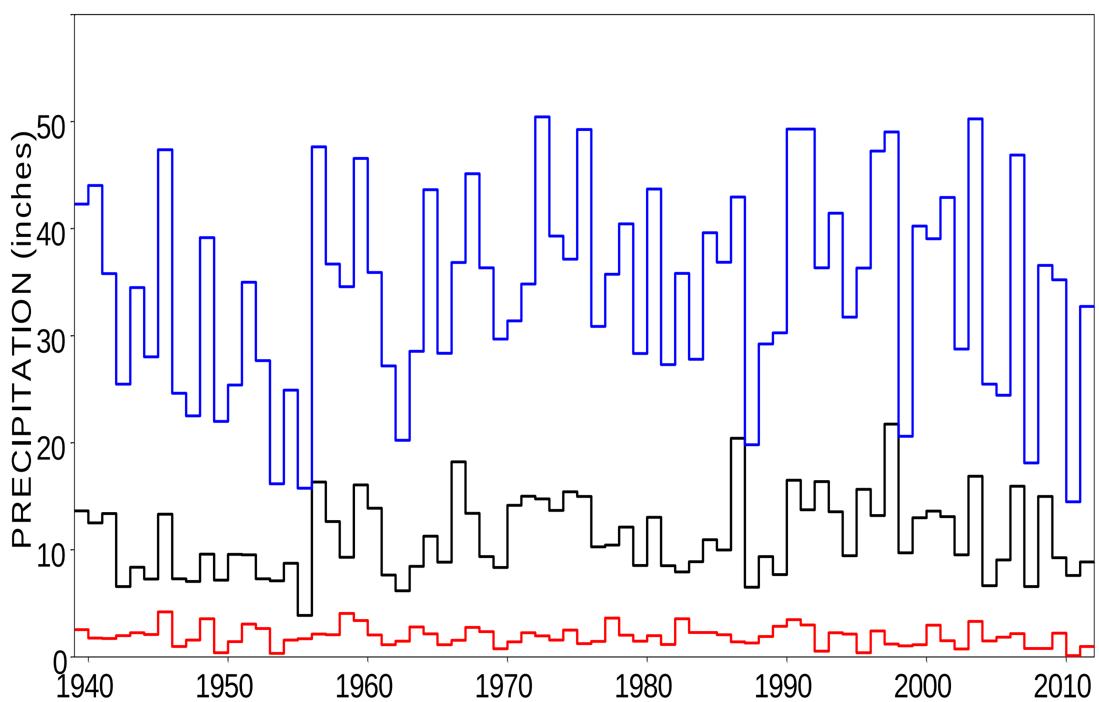
Monthly Precipitation for Quadrangle 809



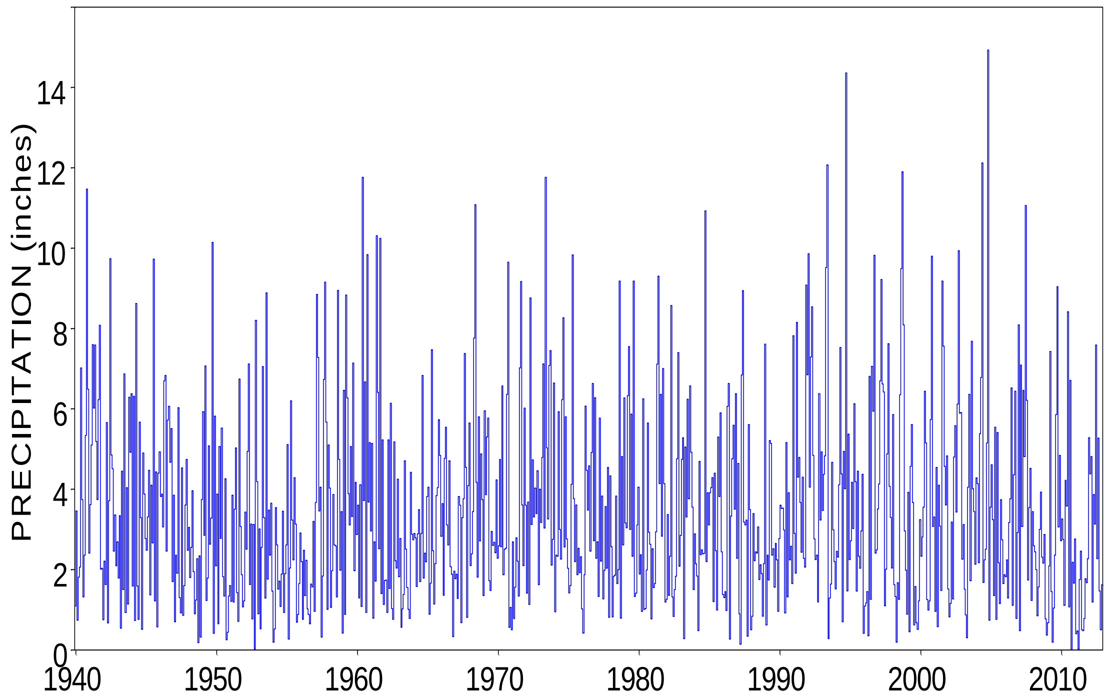
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 809



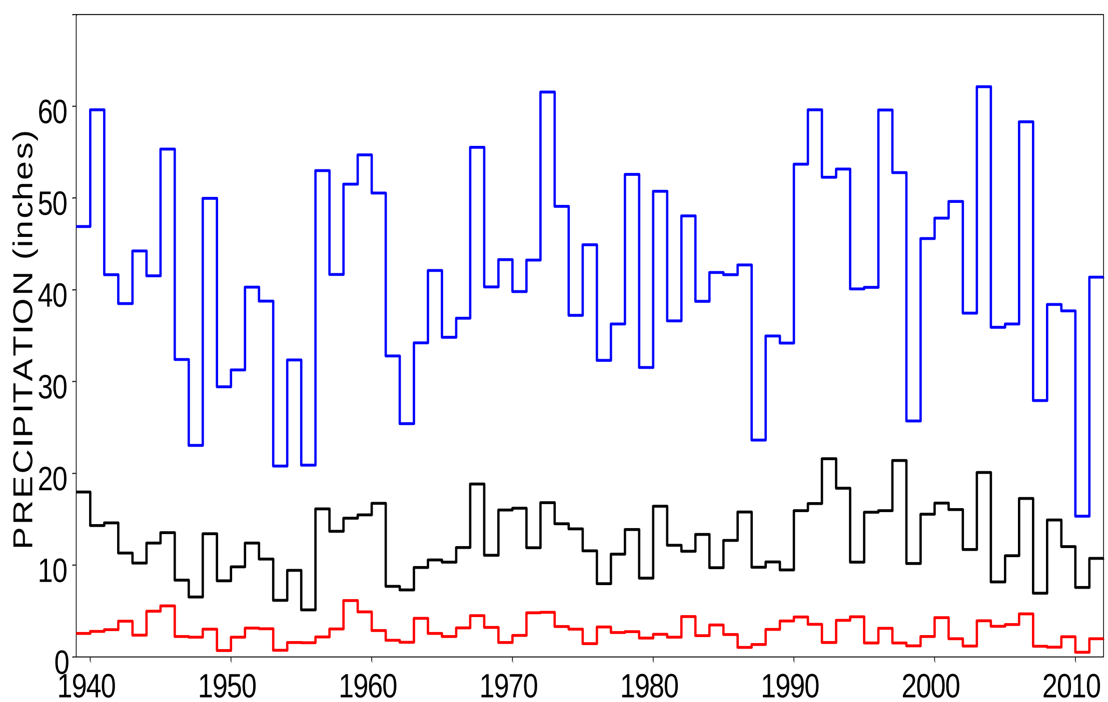
Monthly Precipitation for Quadrangle 810



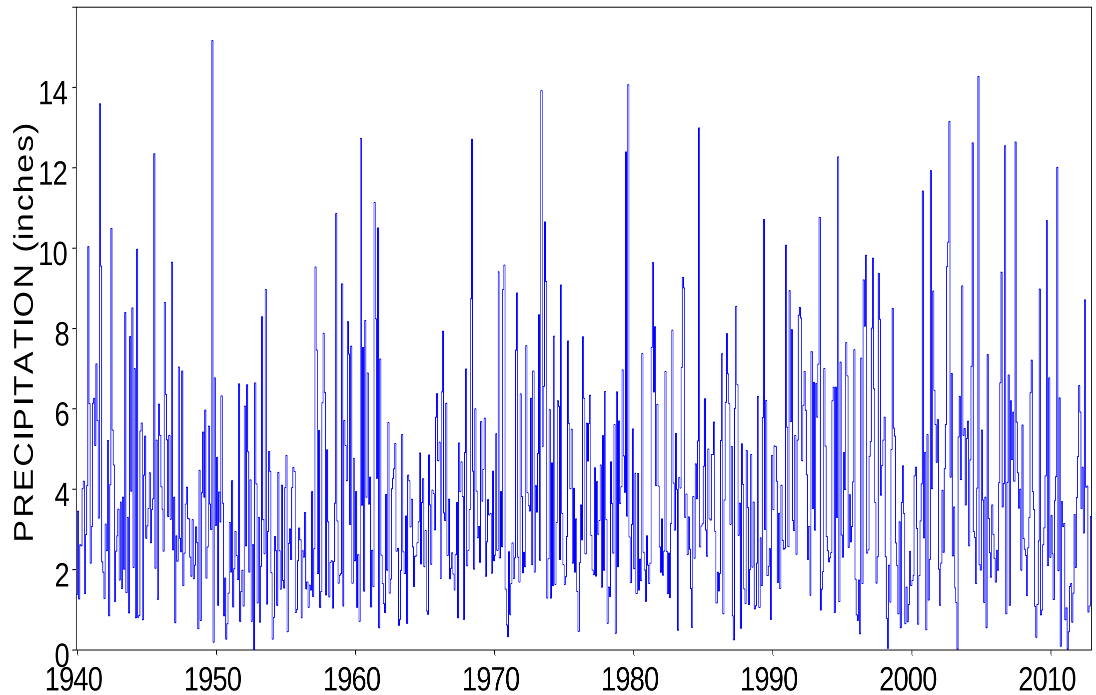
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 810



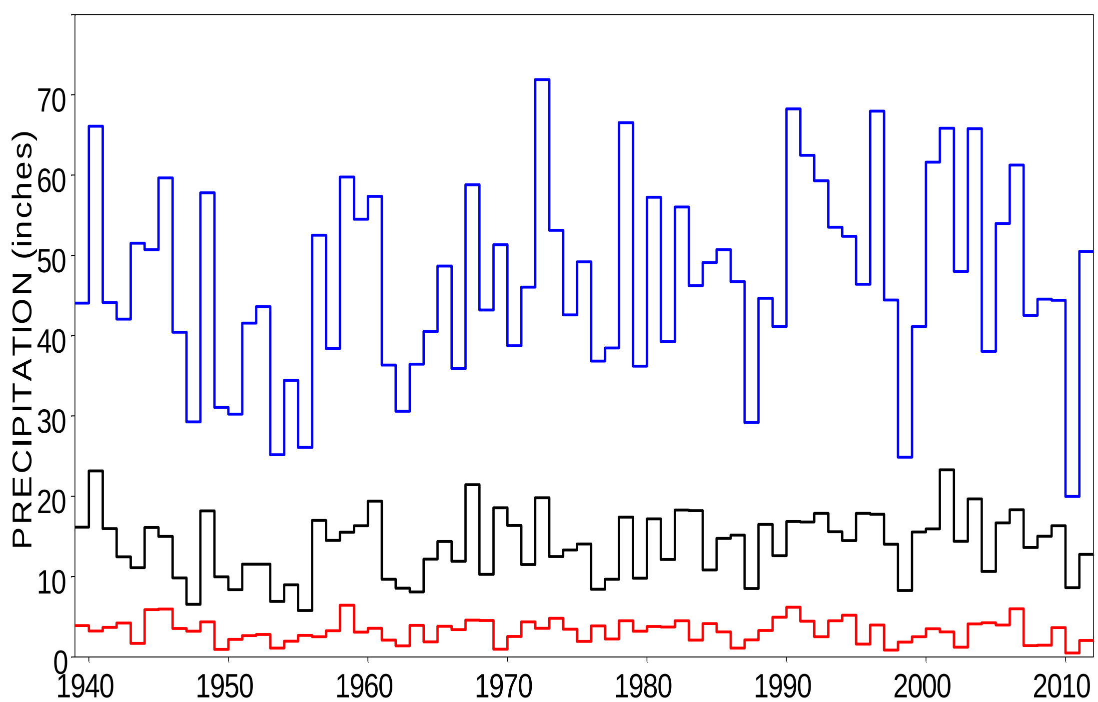
Monthly Precipitation for Quadrangle 811



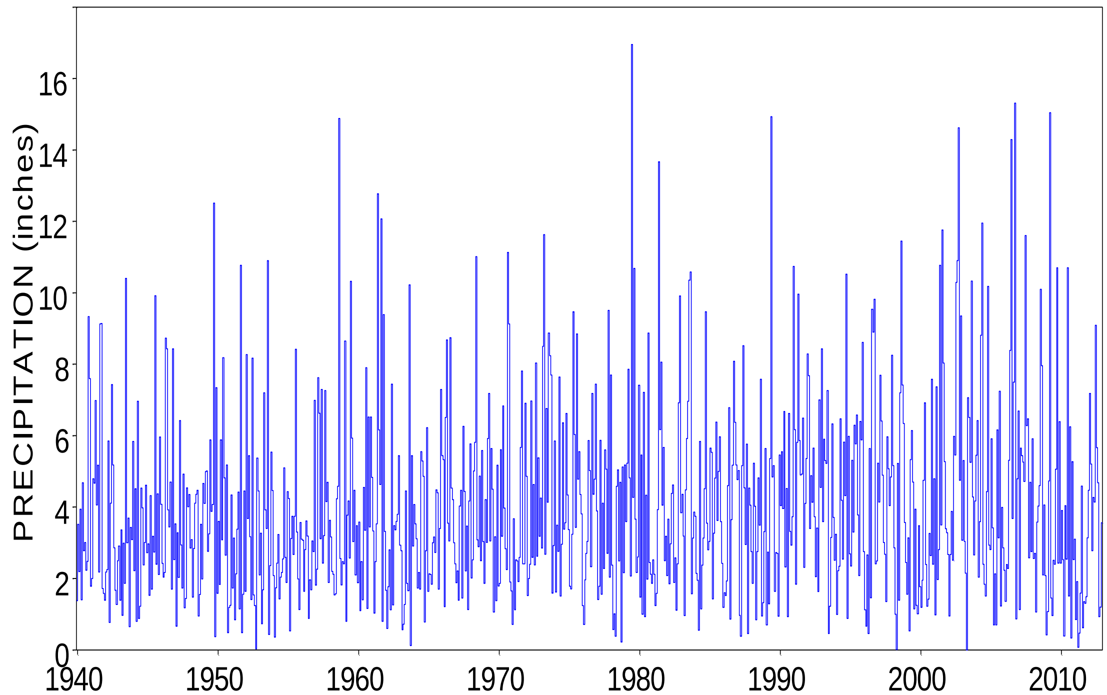
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 811



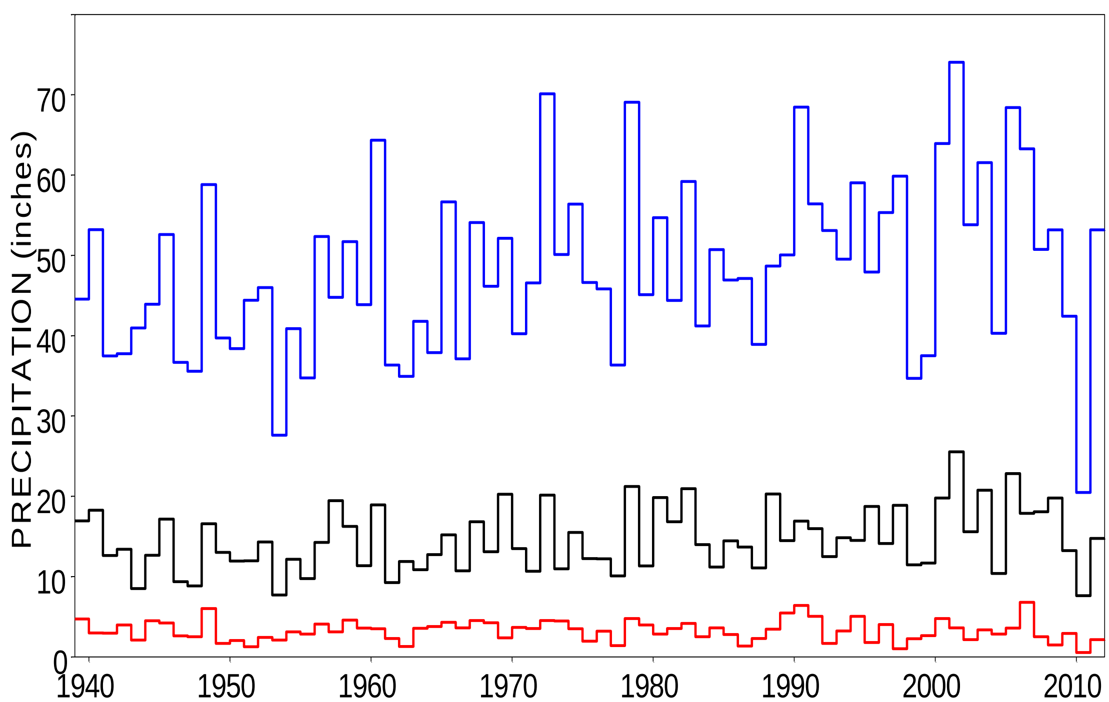
Monthly Precipitation for Quadrangle 812



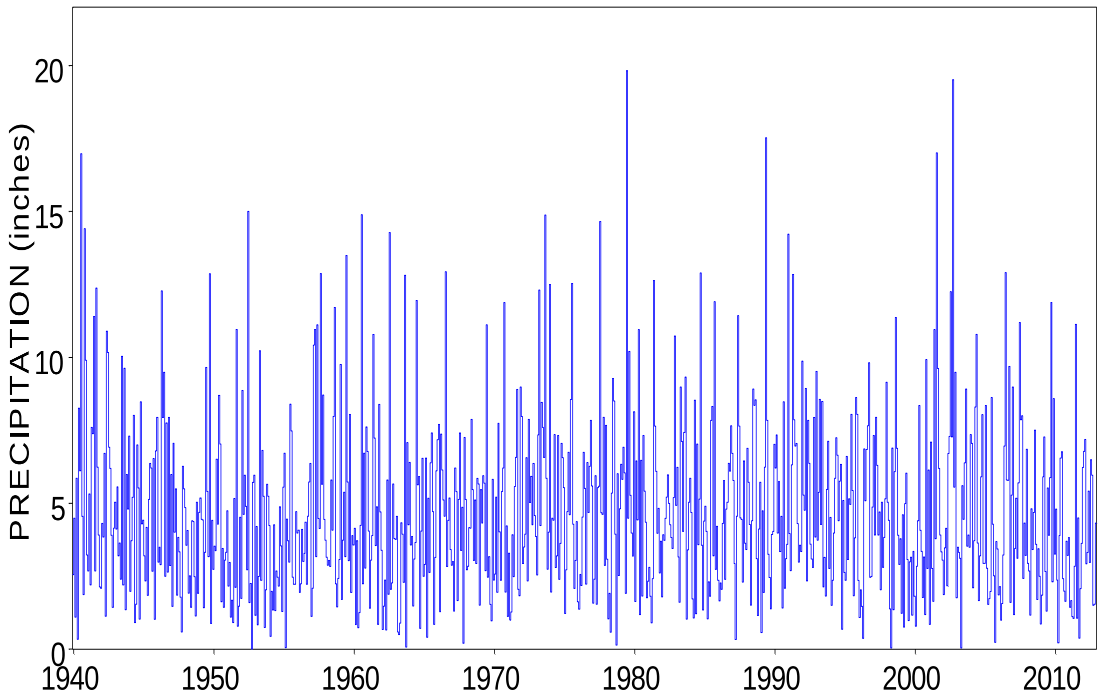
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 812



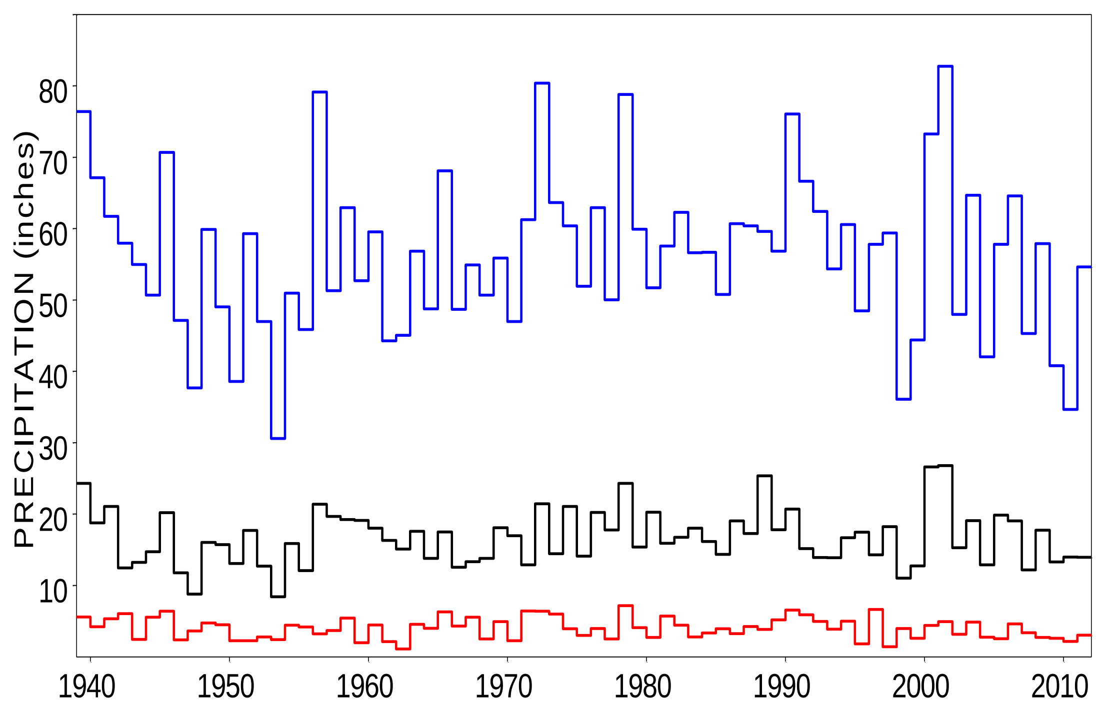
Monthly Precipitation for Quadrangle 813



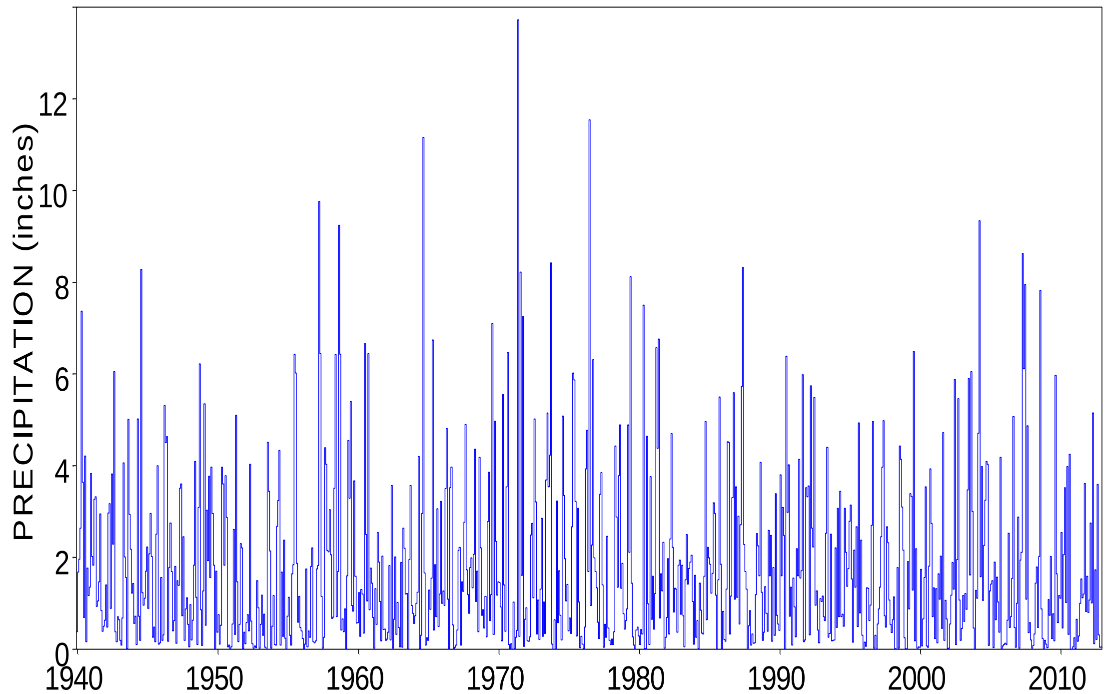
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 813



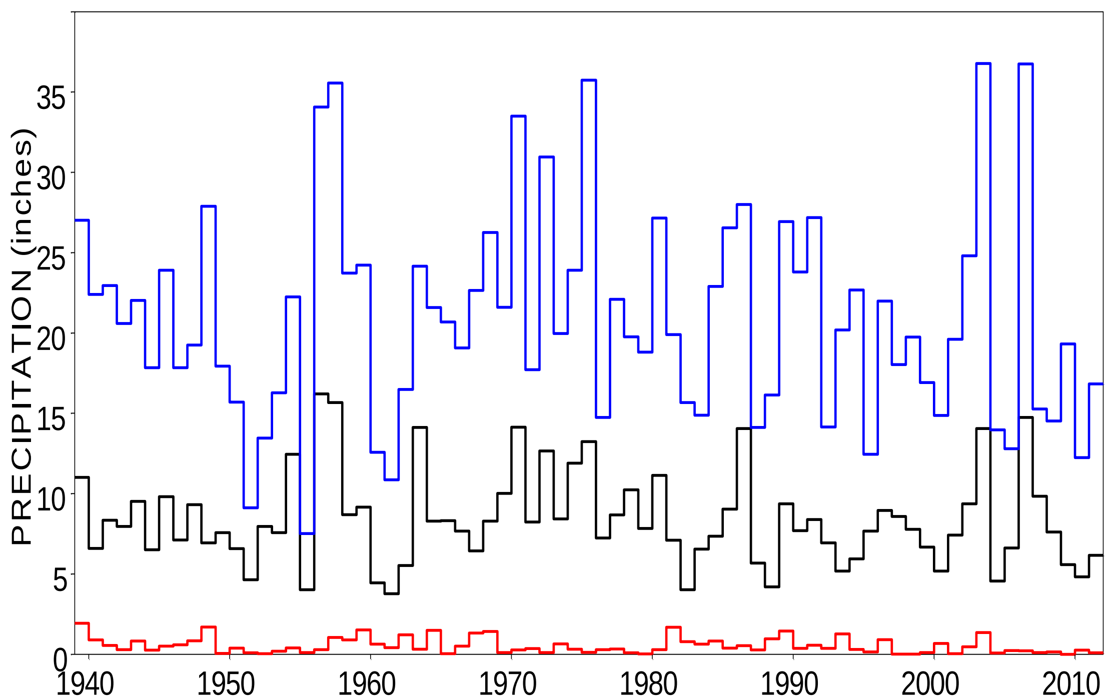
Monthly Precipitation for Quadrangle 814



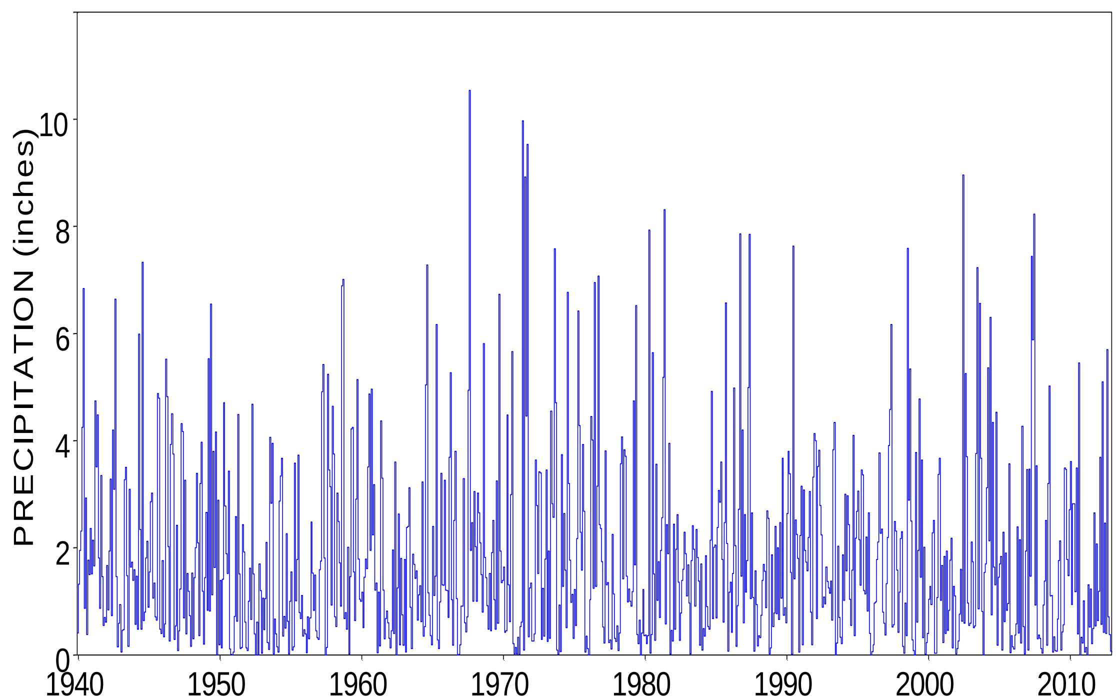
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 814



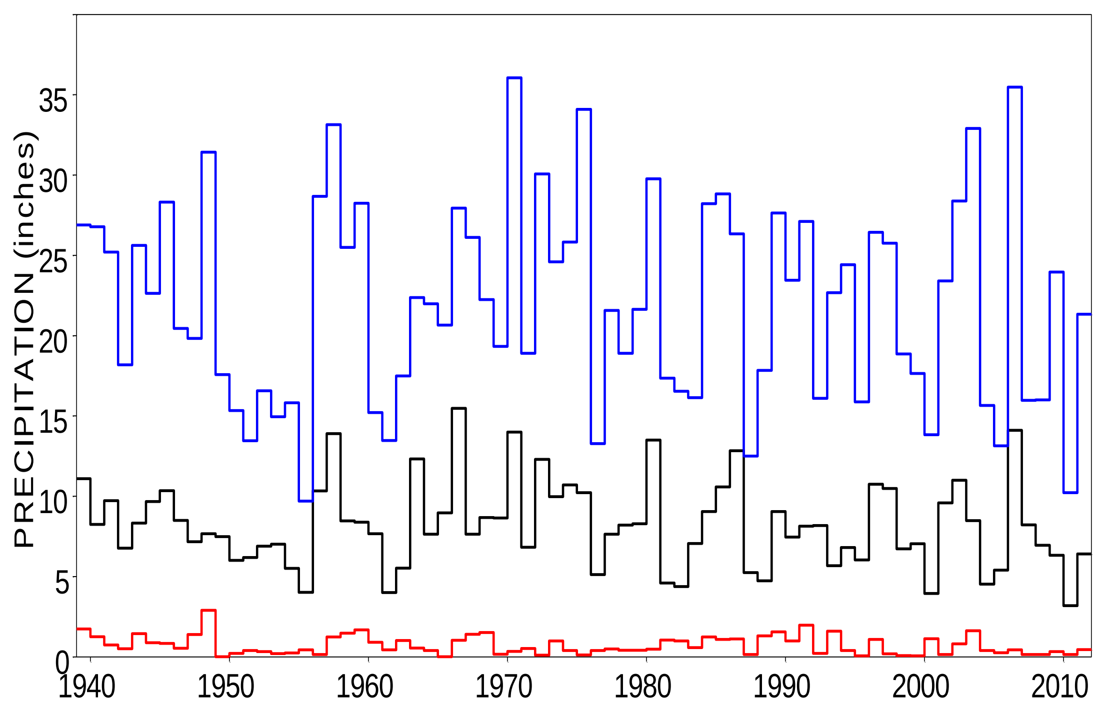
Monthly Precipitation for Quadrangle 907



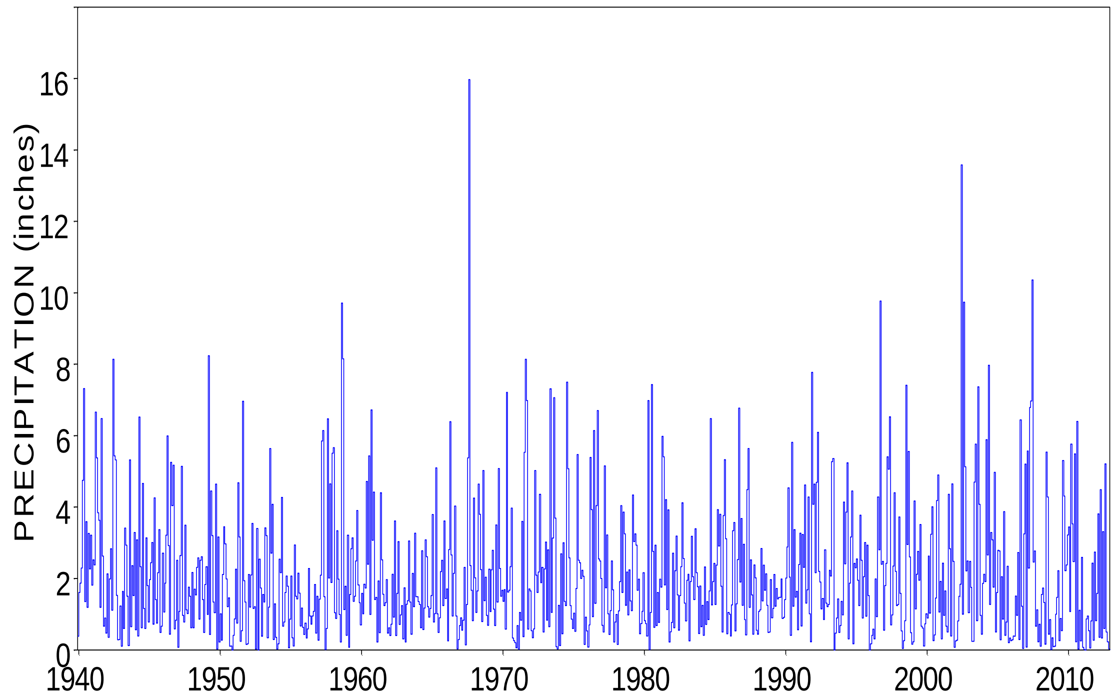
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 907



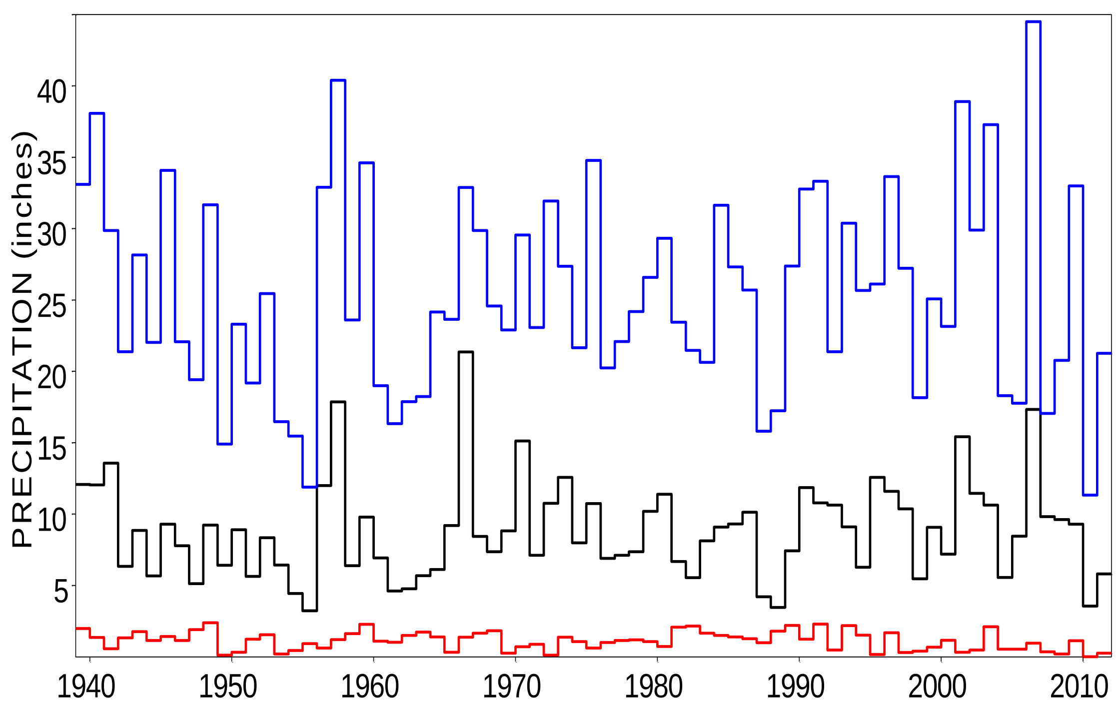
Monthly Precipitation for Quadrangle 908



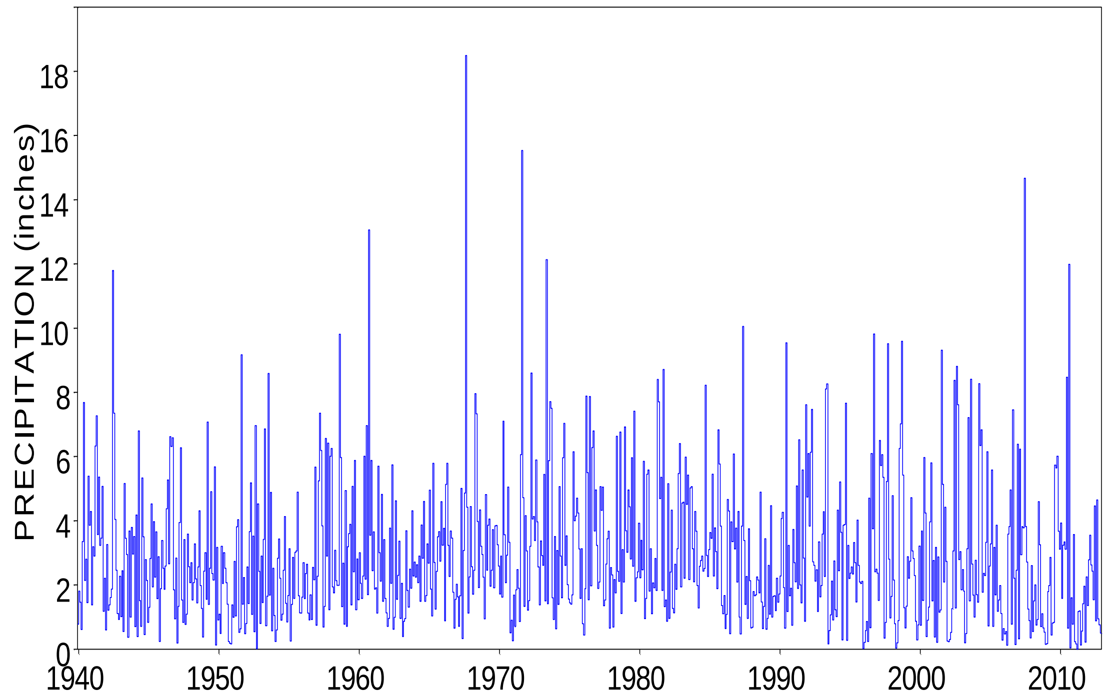
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 908



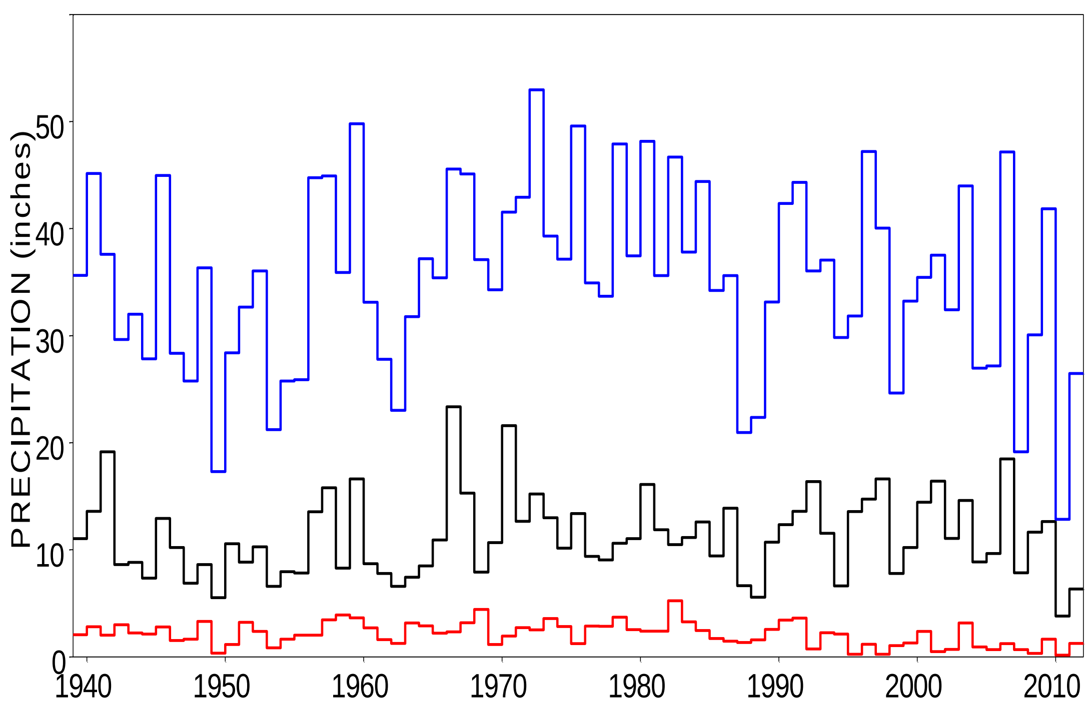
Monthly Precipitation for Quadrangle 909



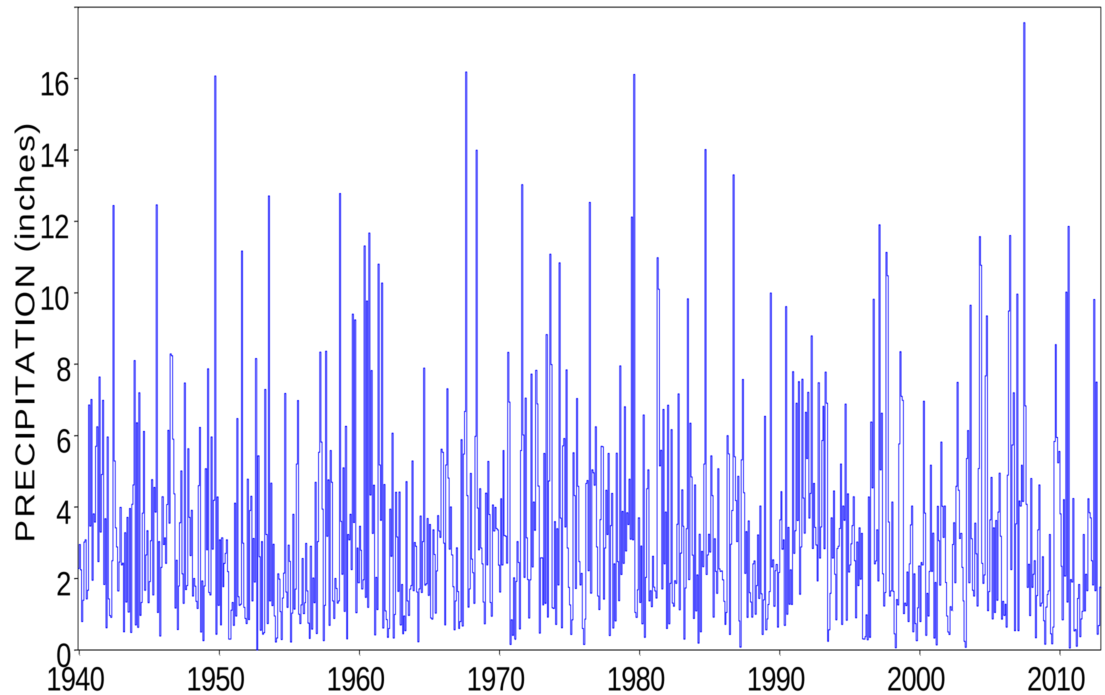
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 909



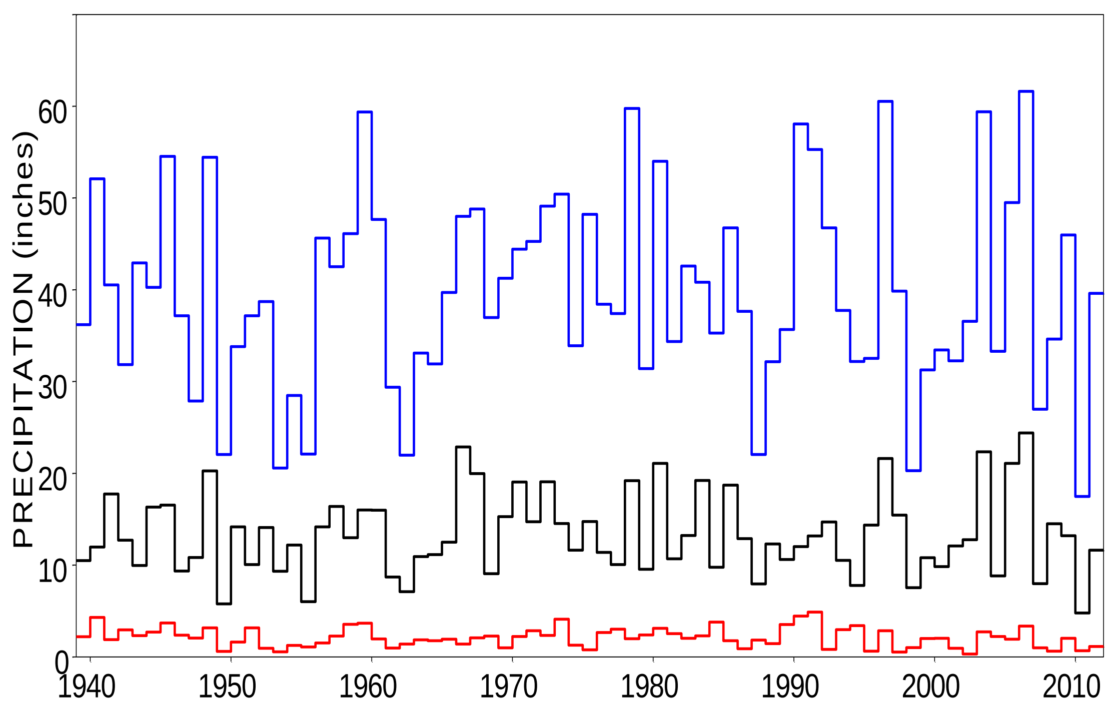
Monthly Precipitation for Quadrangle 910



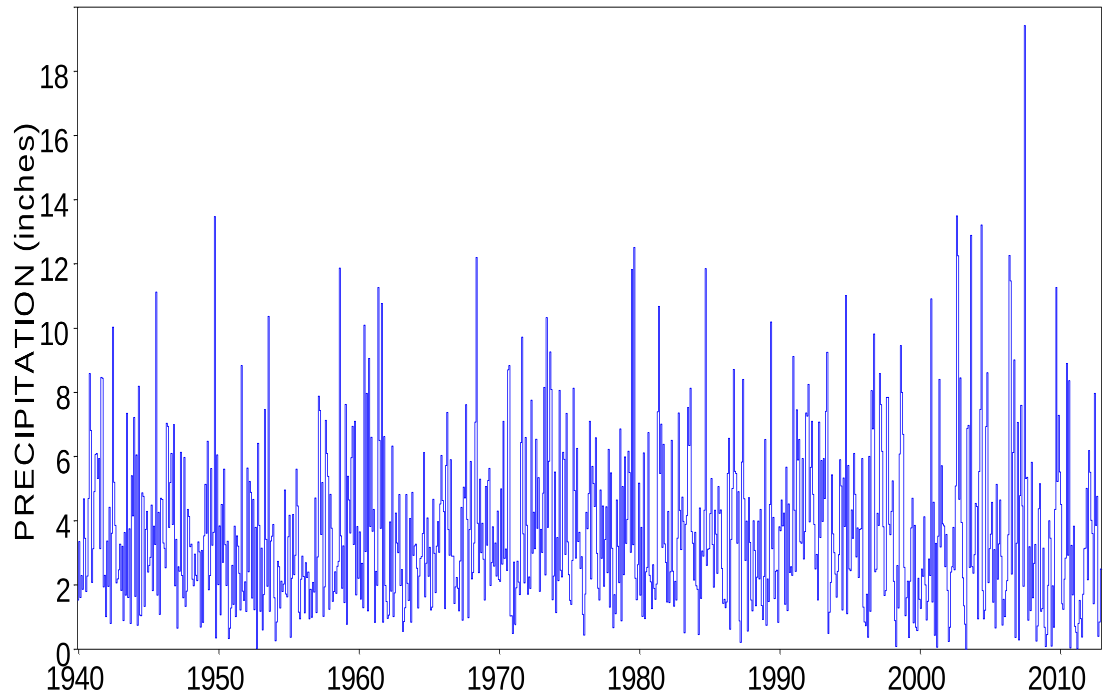
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 910



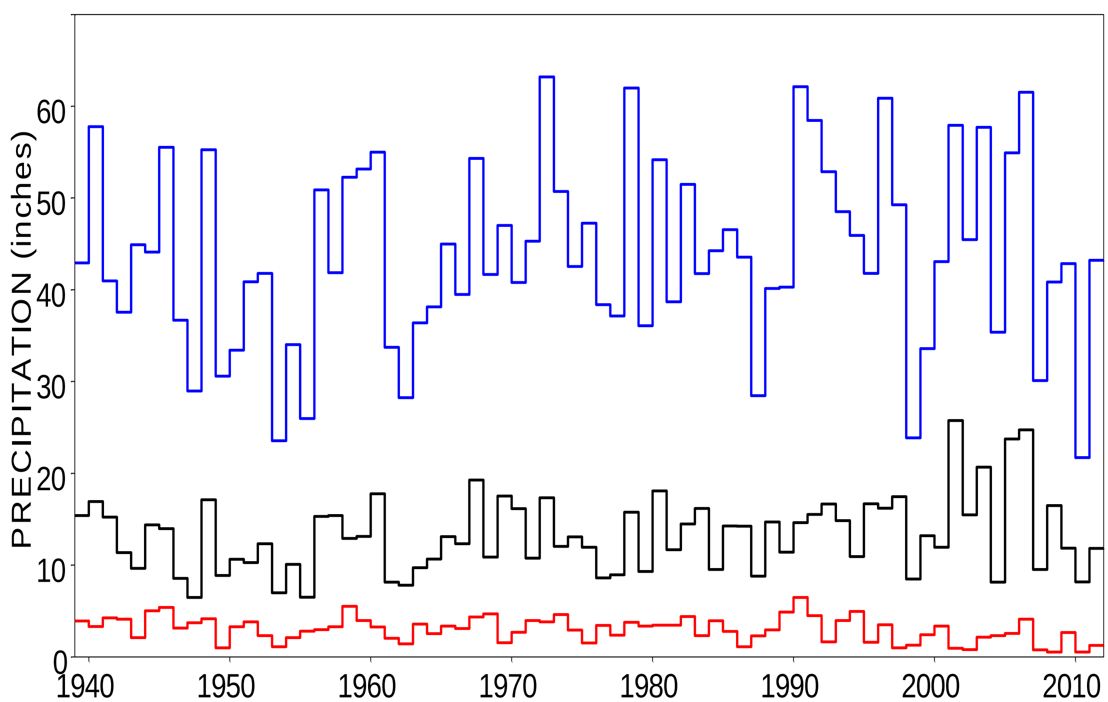
Monthly Precipitation for Quadrangle 911



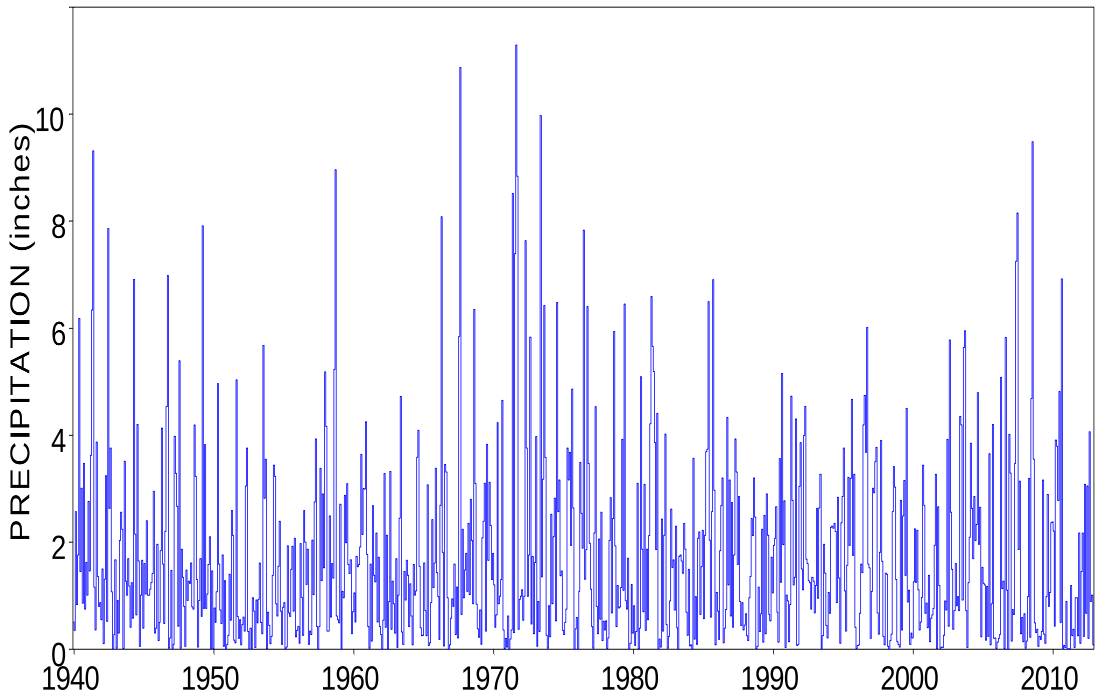
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 911



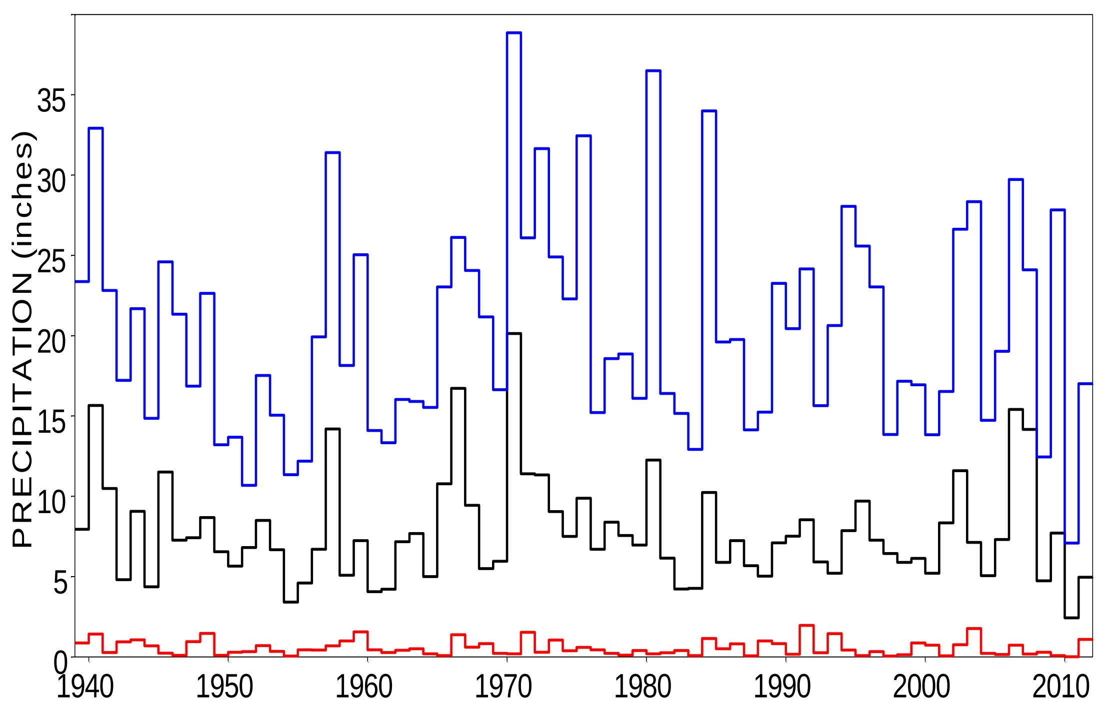
Monthly Precipitation for Quadrangle 912



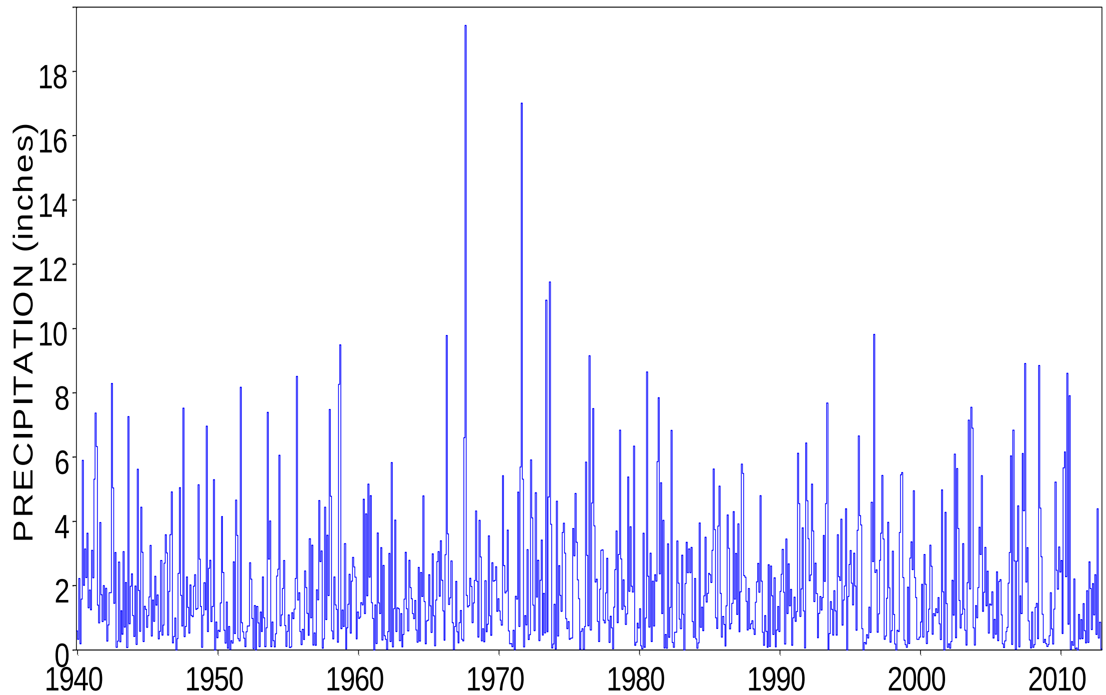
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 912



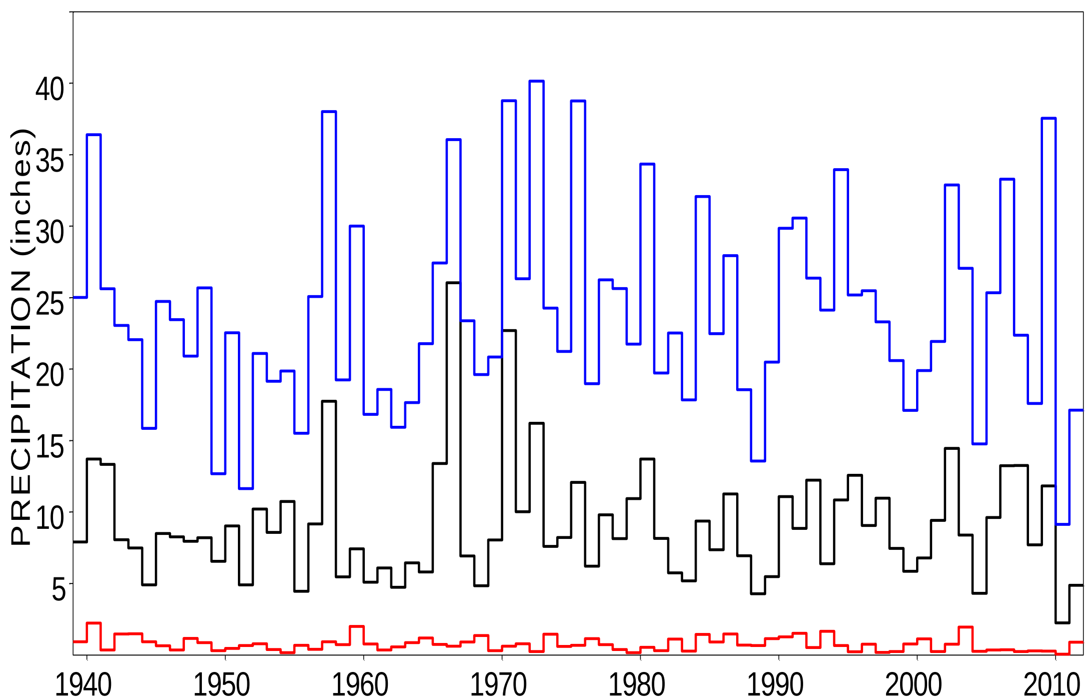
Monthly Precipitation for Quadrangle 1008



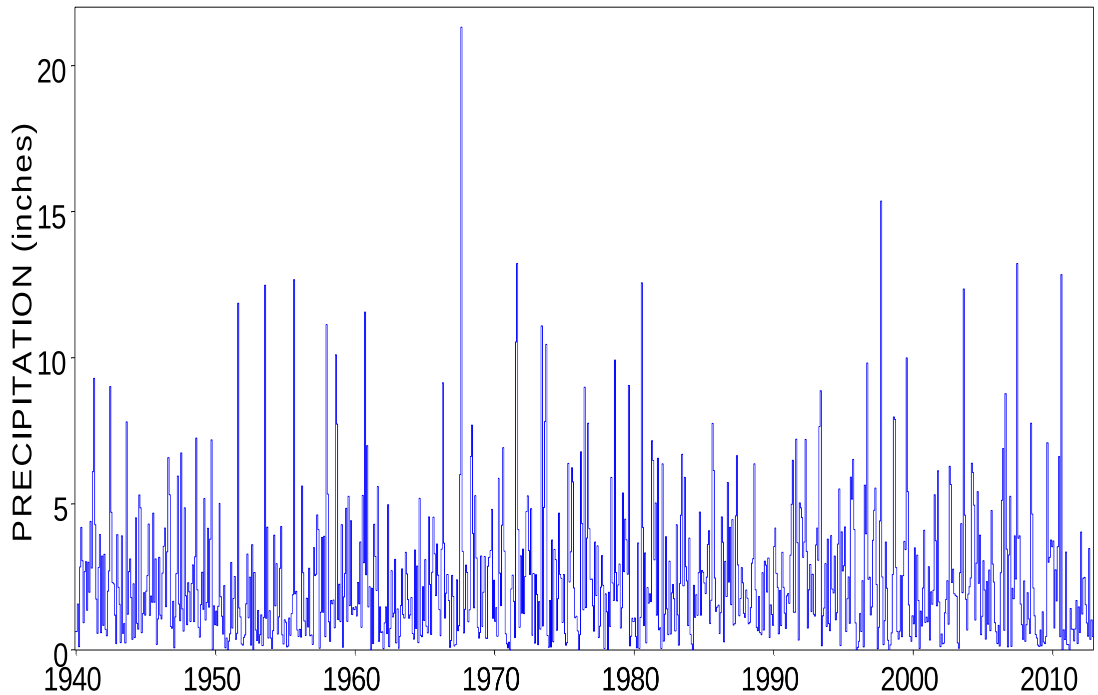
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 1008



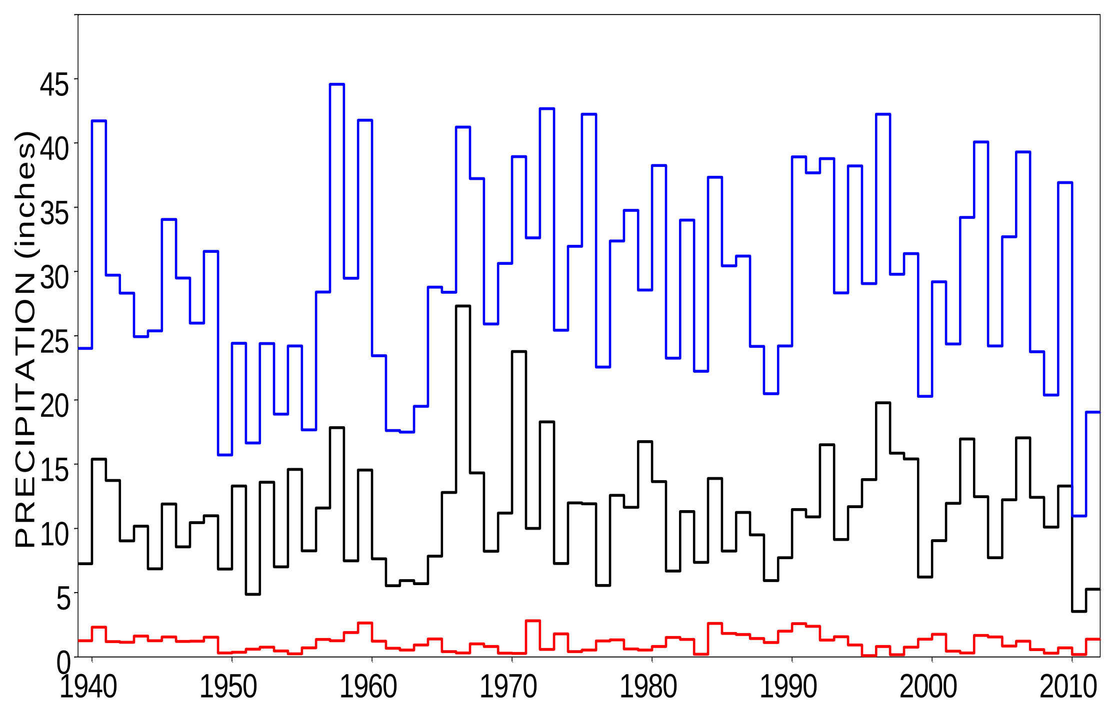
Monthly Precipitation for Quadrangle 1009



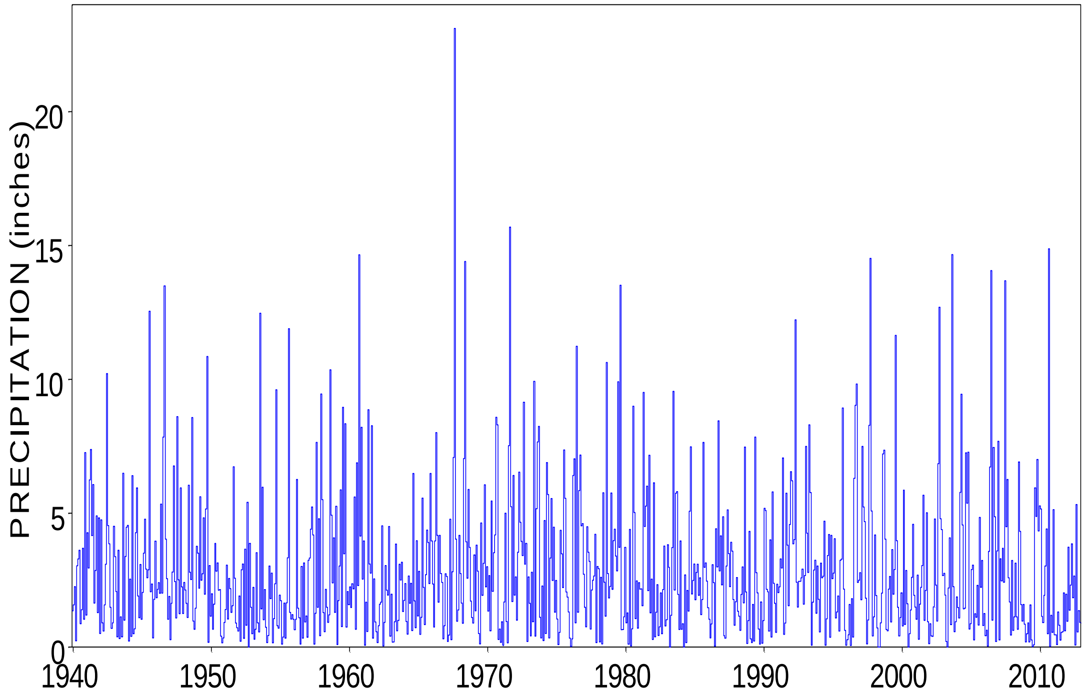
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 1009



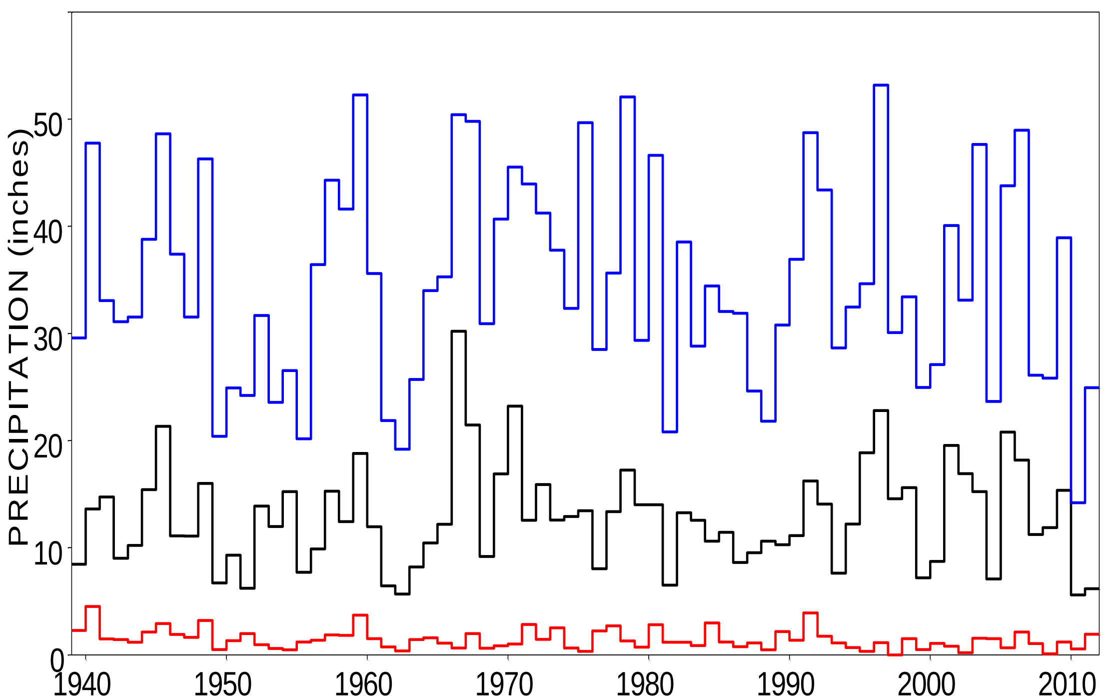
Monthly Precipitation for Quadrangle 1010



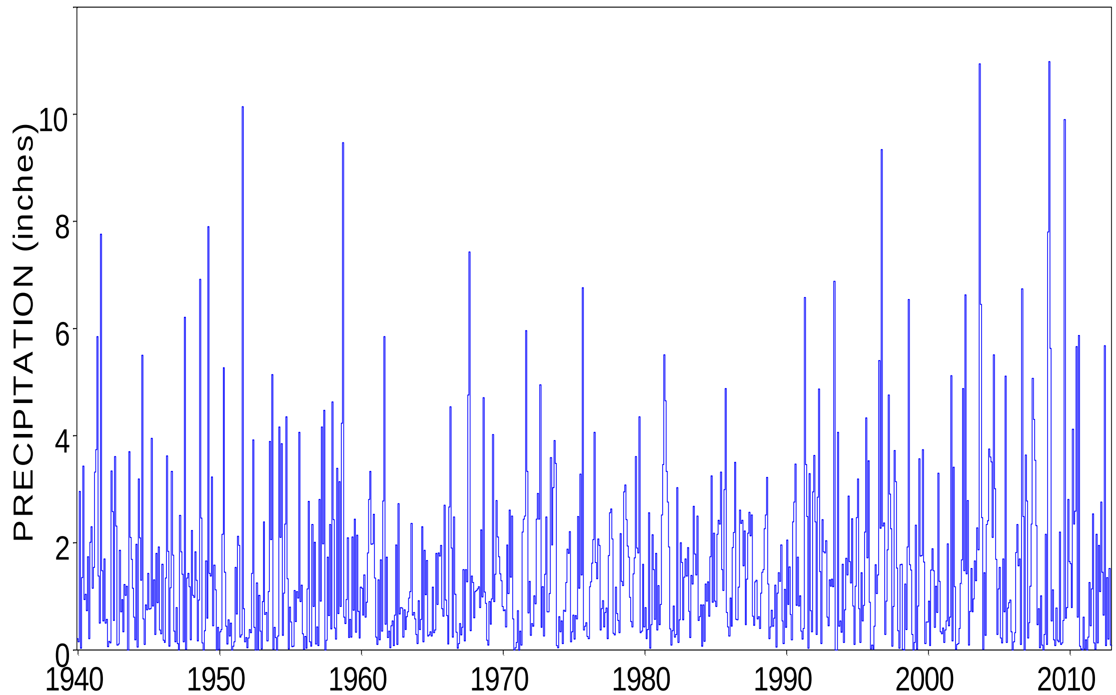
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 1010



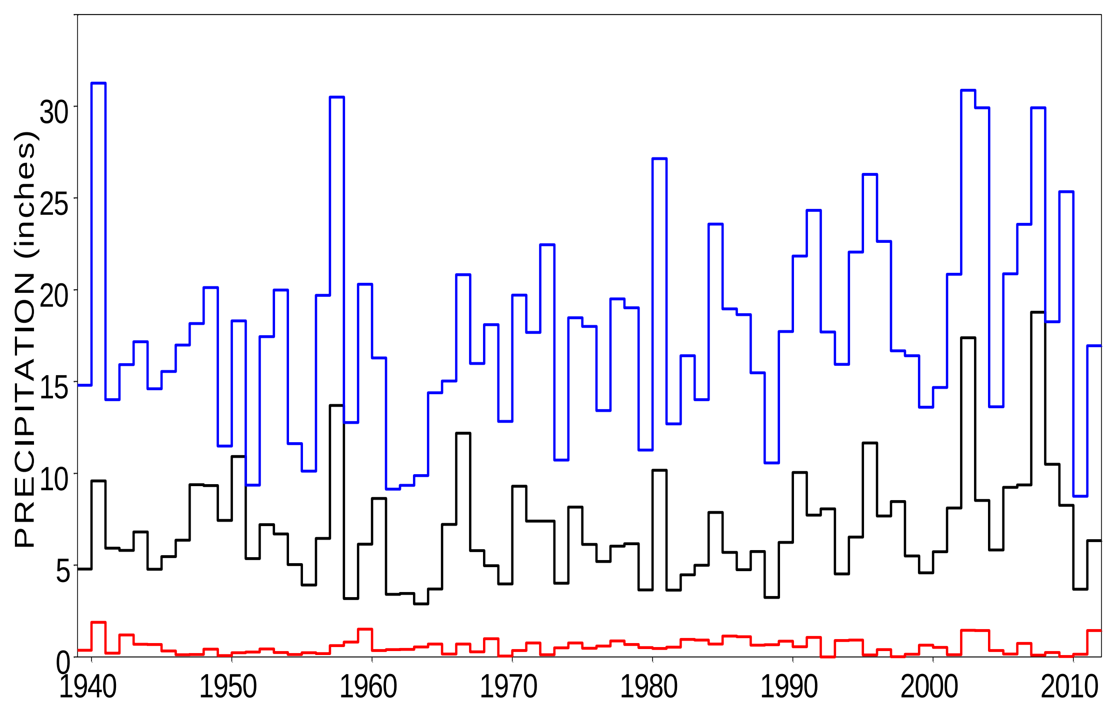
Monthly Precipitation for Quadrangle 1011



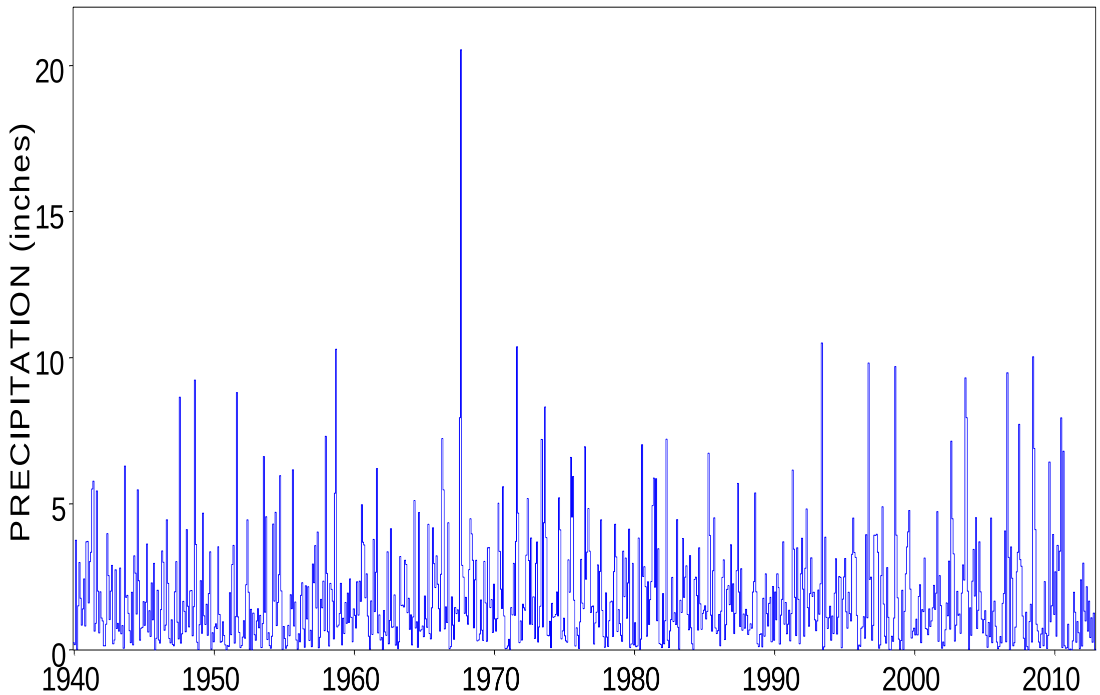
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 1011



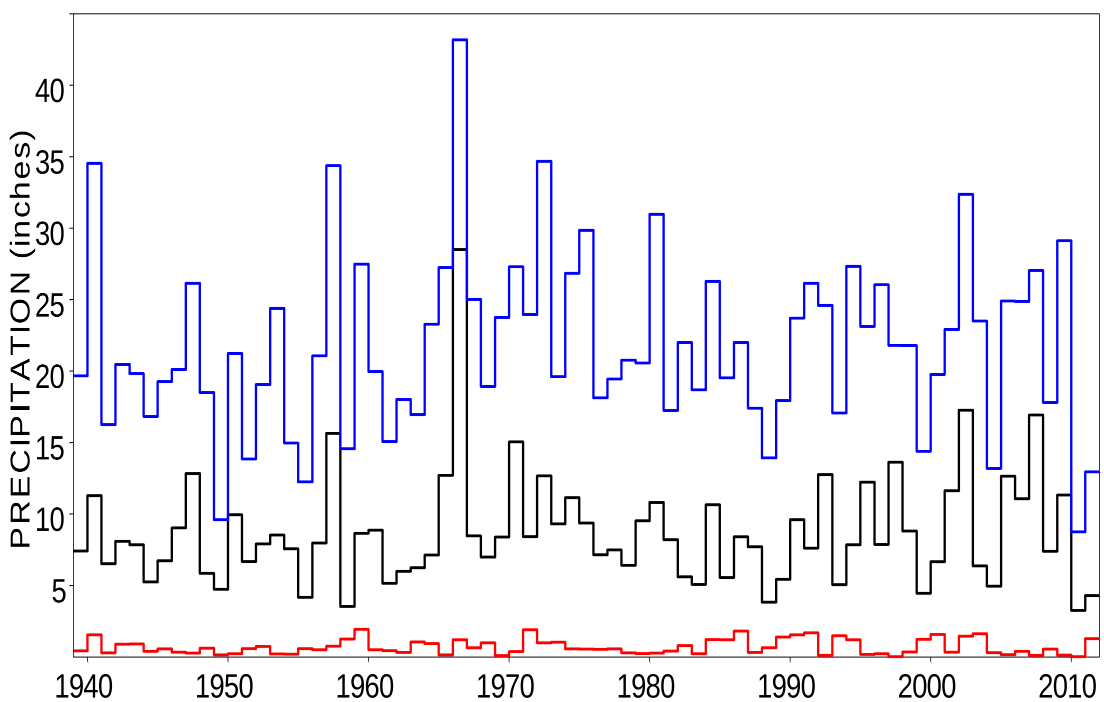
Monthly Precipitation for Quadrangle 1108



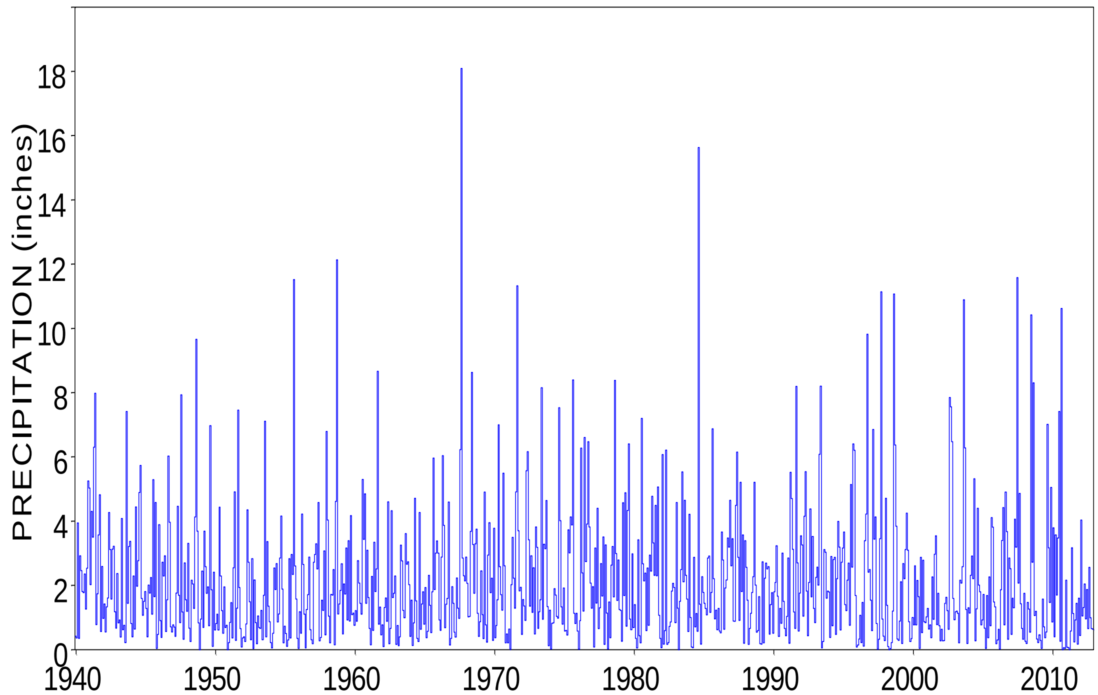
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 1108



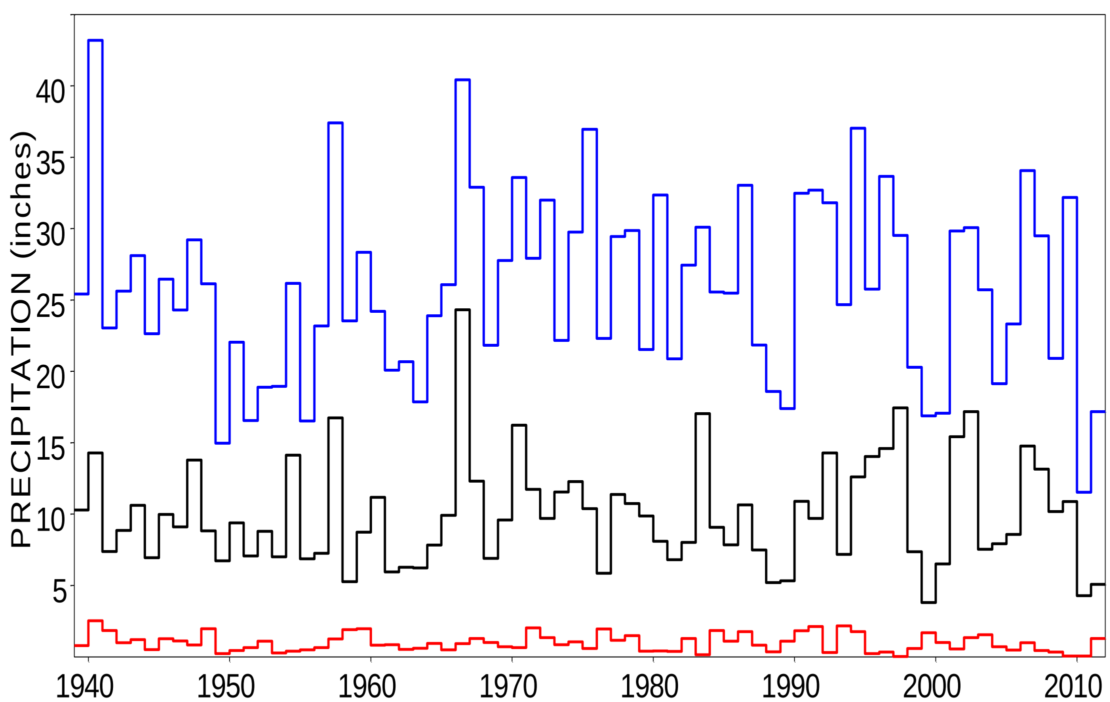
Monthly Precipitation for Quadrangle 1109



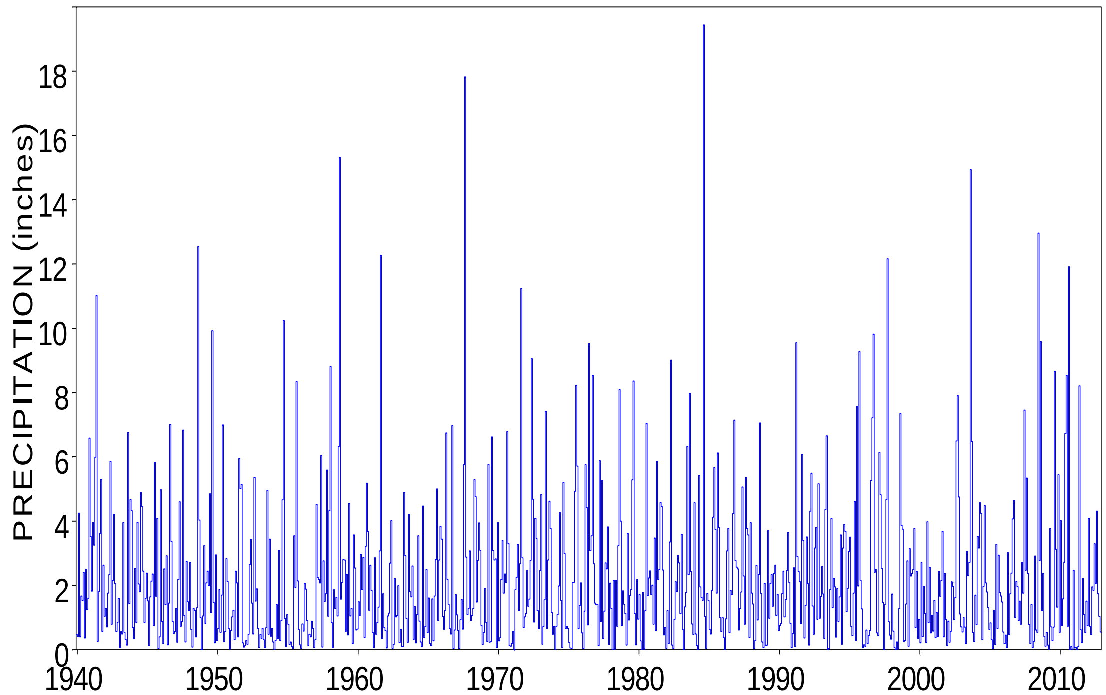
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 1109



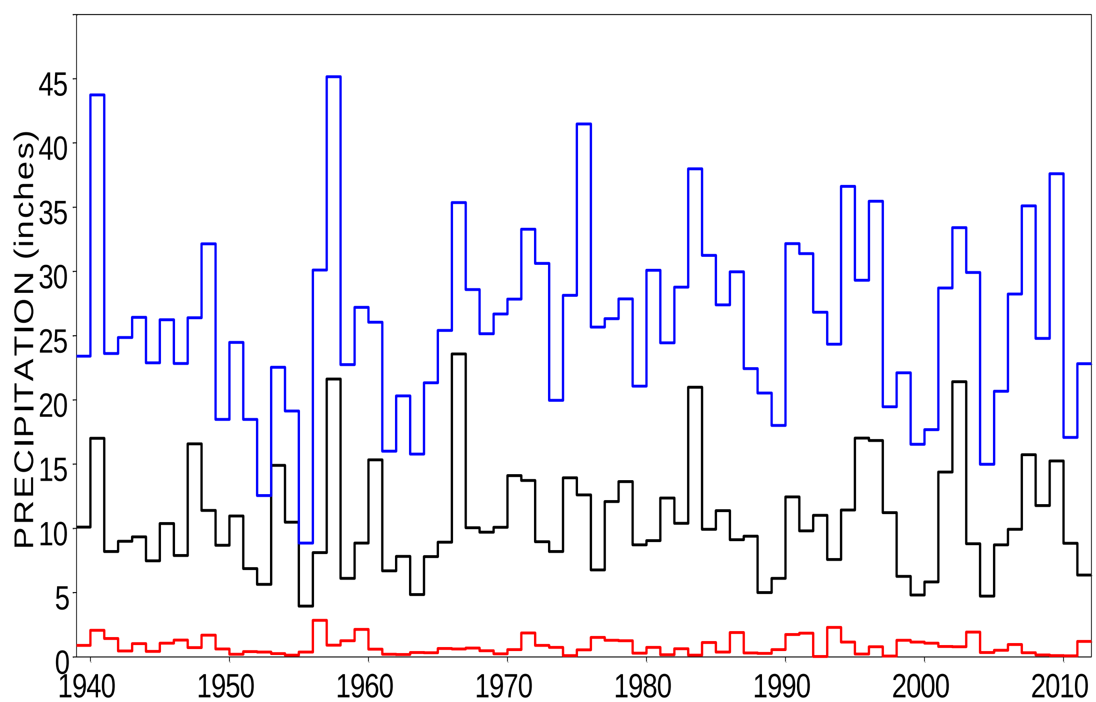
Monthly Precipitation for Quadrangle 1110



Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 1110



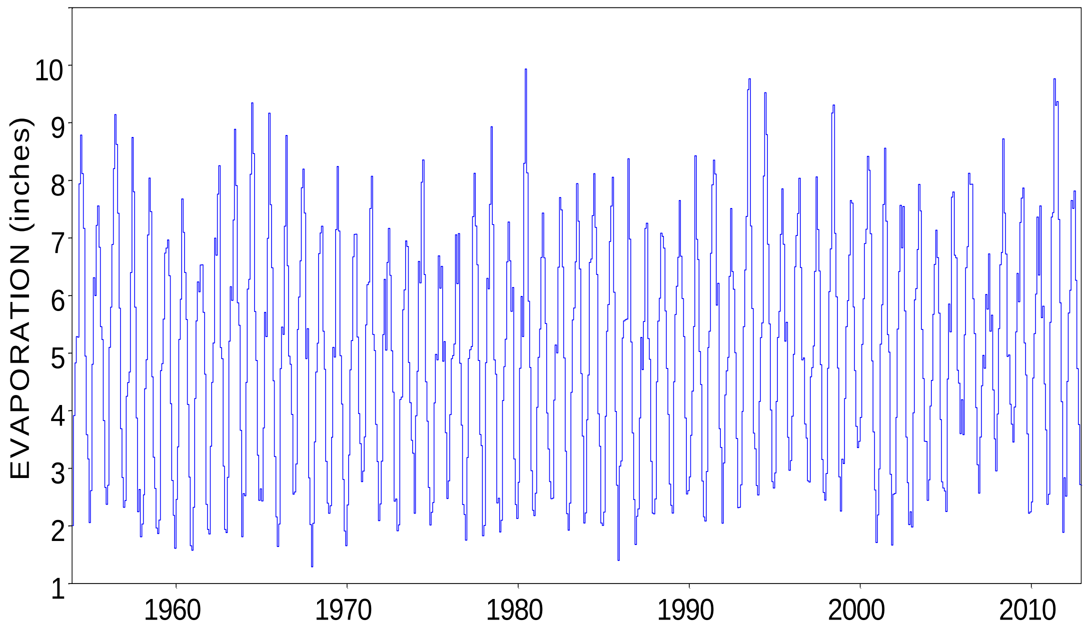
Monthly Precipitation for Quadrangle 1210



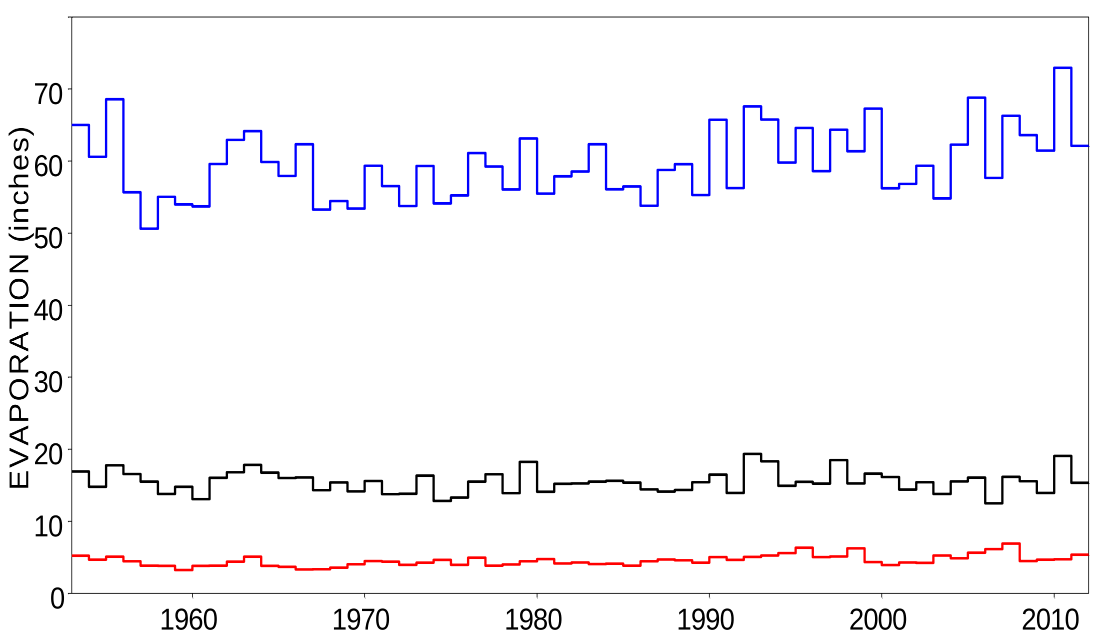
Annual Total, 2-Month Maximum, and 2-Month Minimum Precipitation for Quadrangle 1210

APPENDIX B

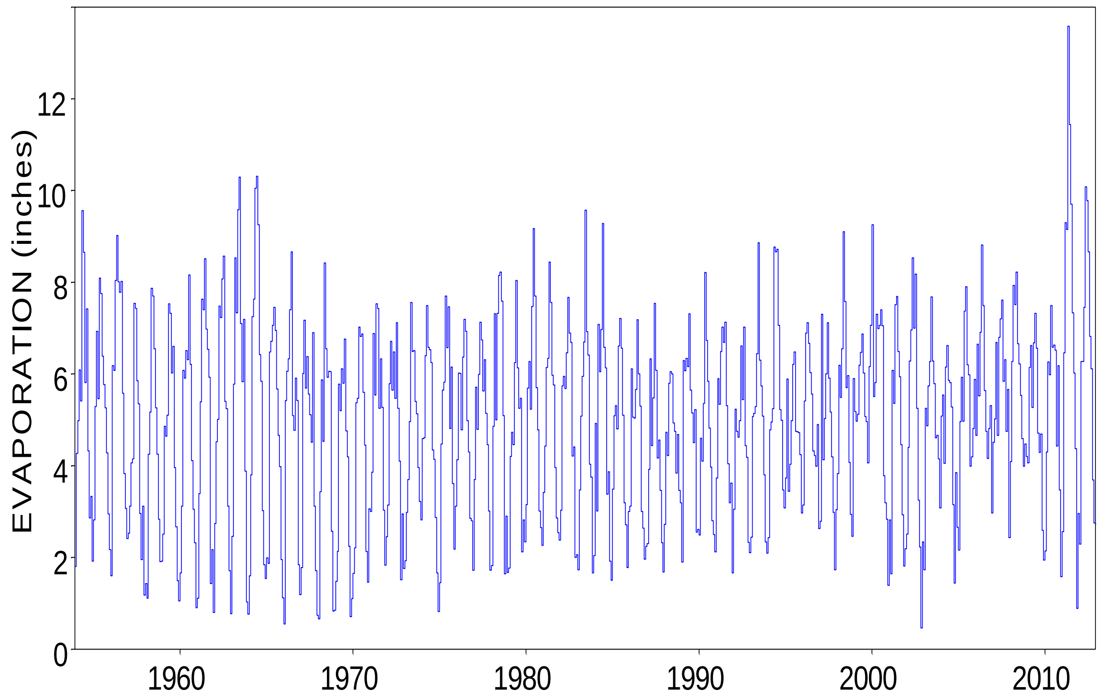
PLOTS OF RESERVOIR EVAPORATION RATES FOR 92 QUADRANGLES



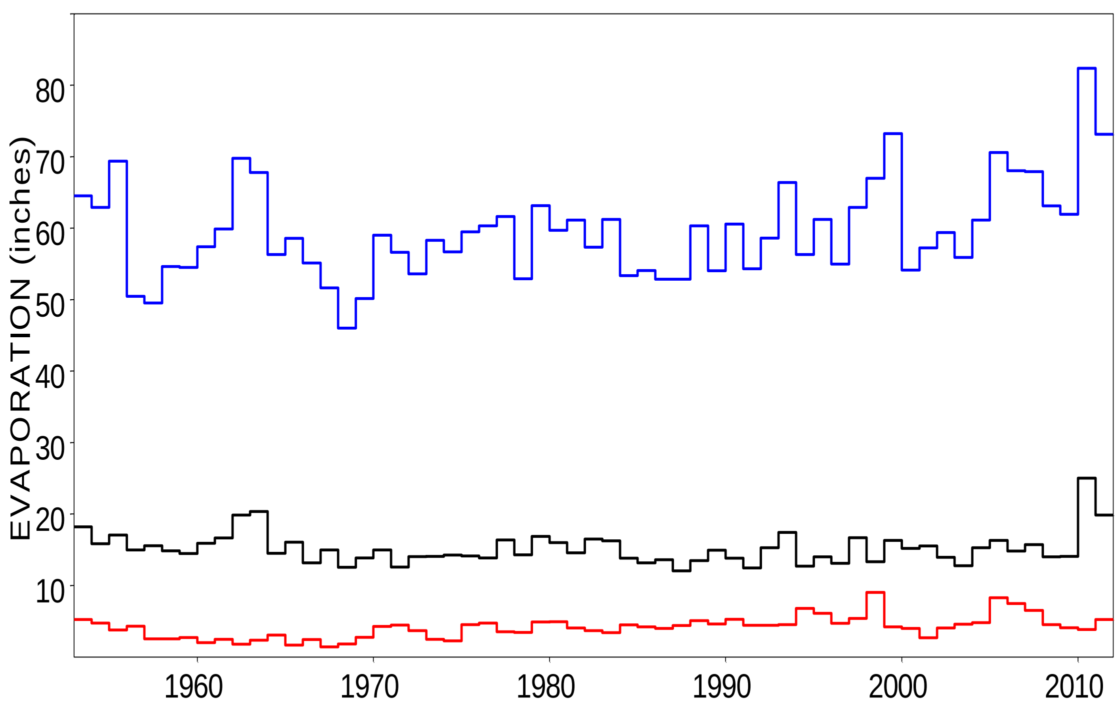
Monthly Evaporation for Quadrangle Total



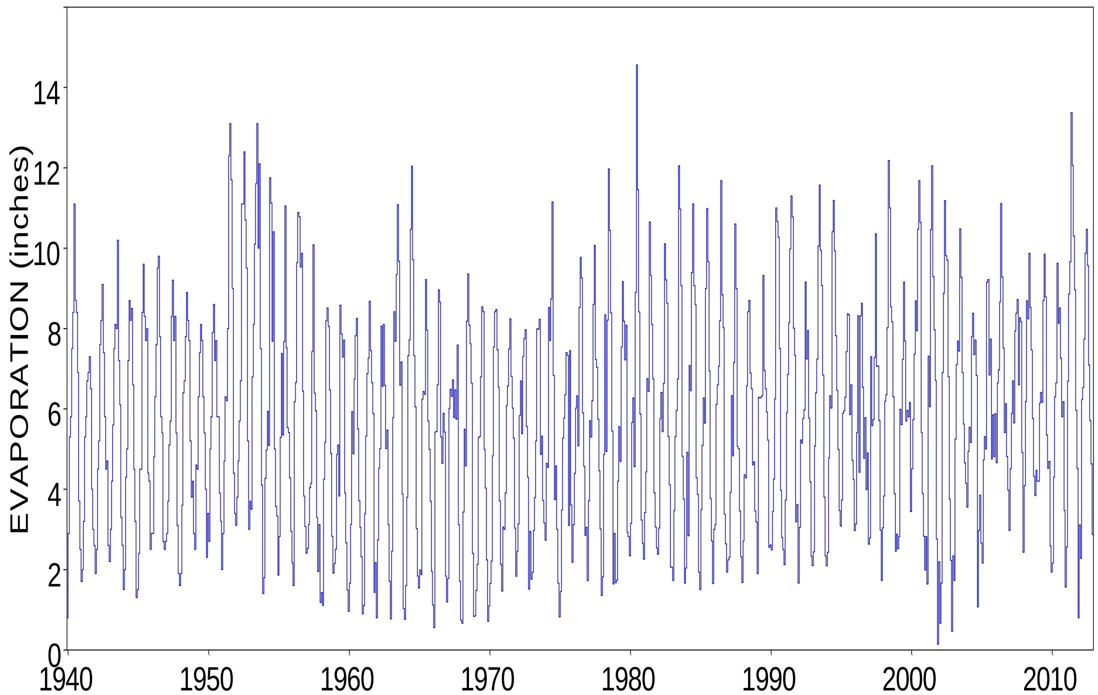
Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles Total



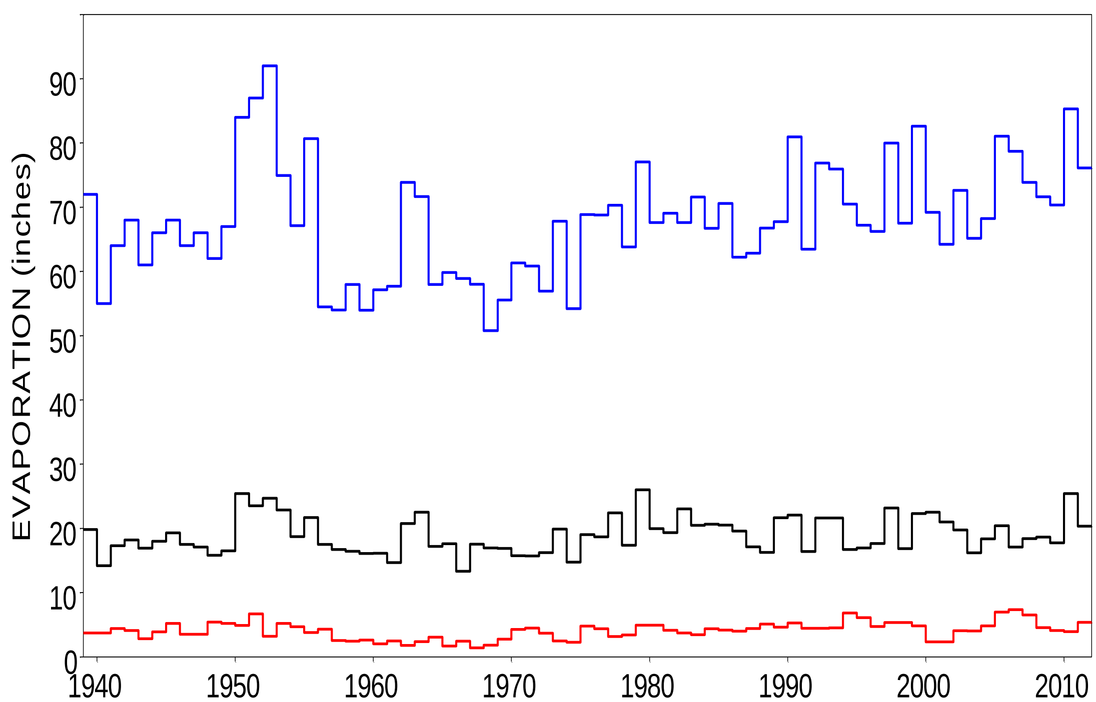
Monthly Evaporation for Quadrangle 104



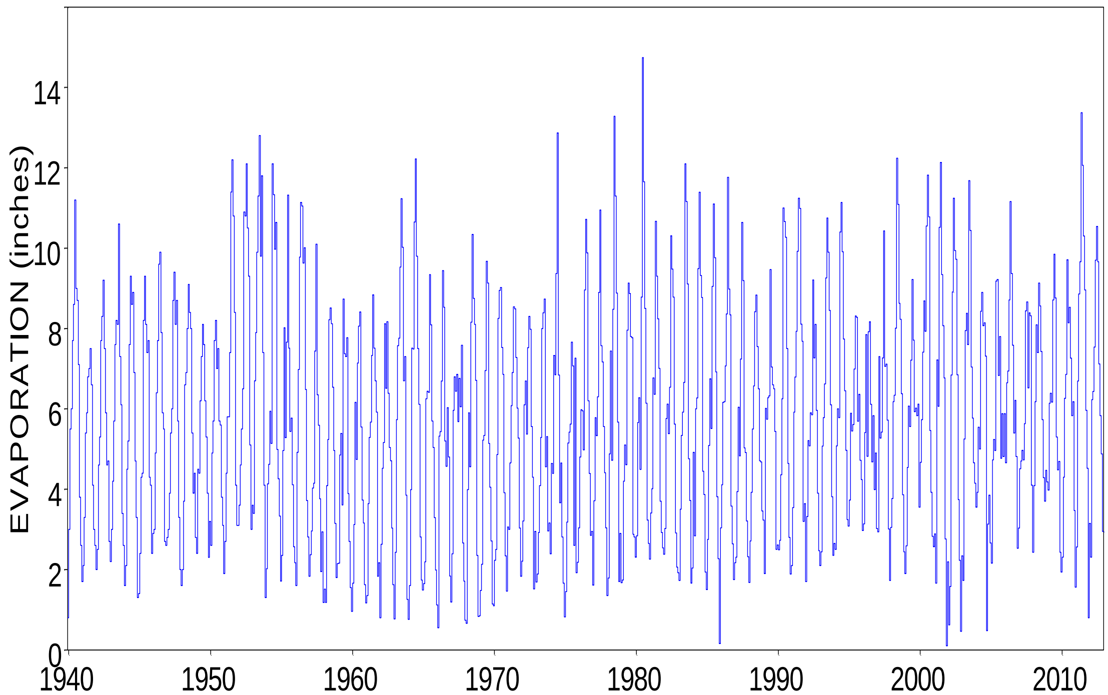
Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles 104



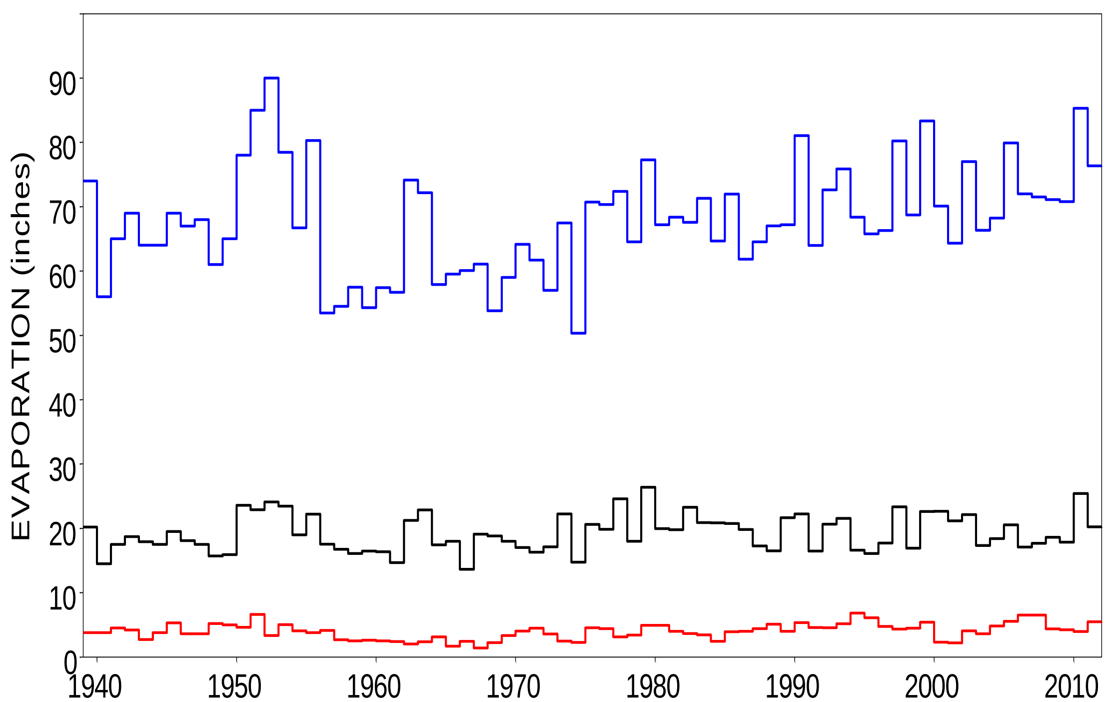
Monthly Evaporation for Quadrangle 105



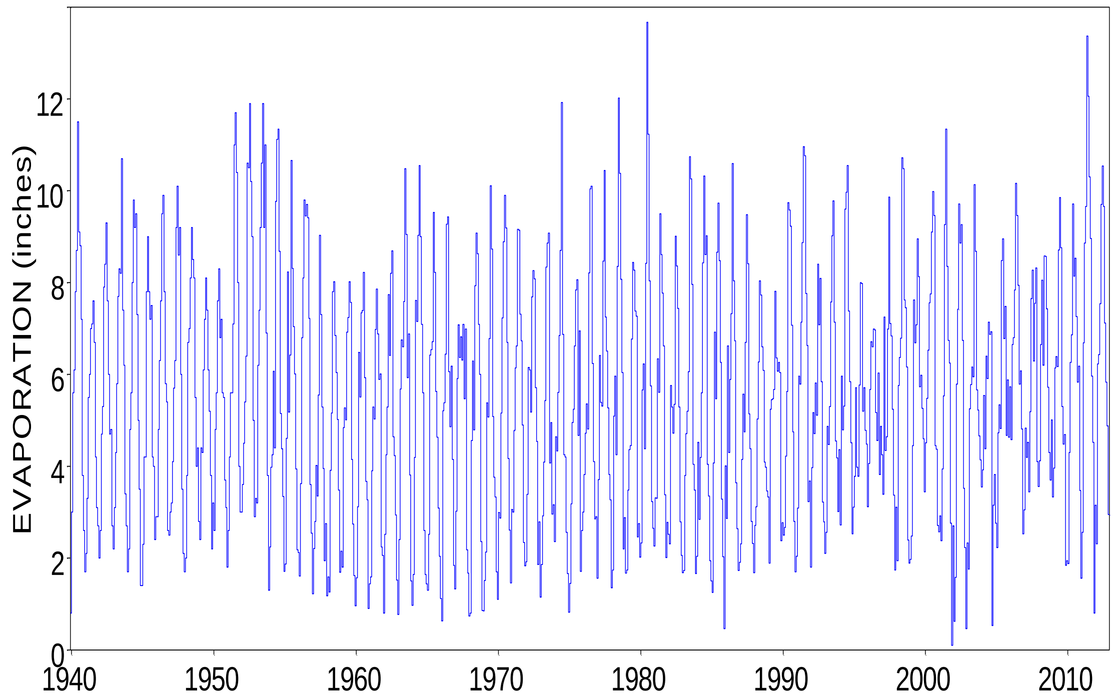
Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles 105



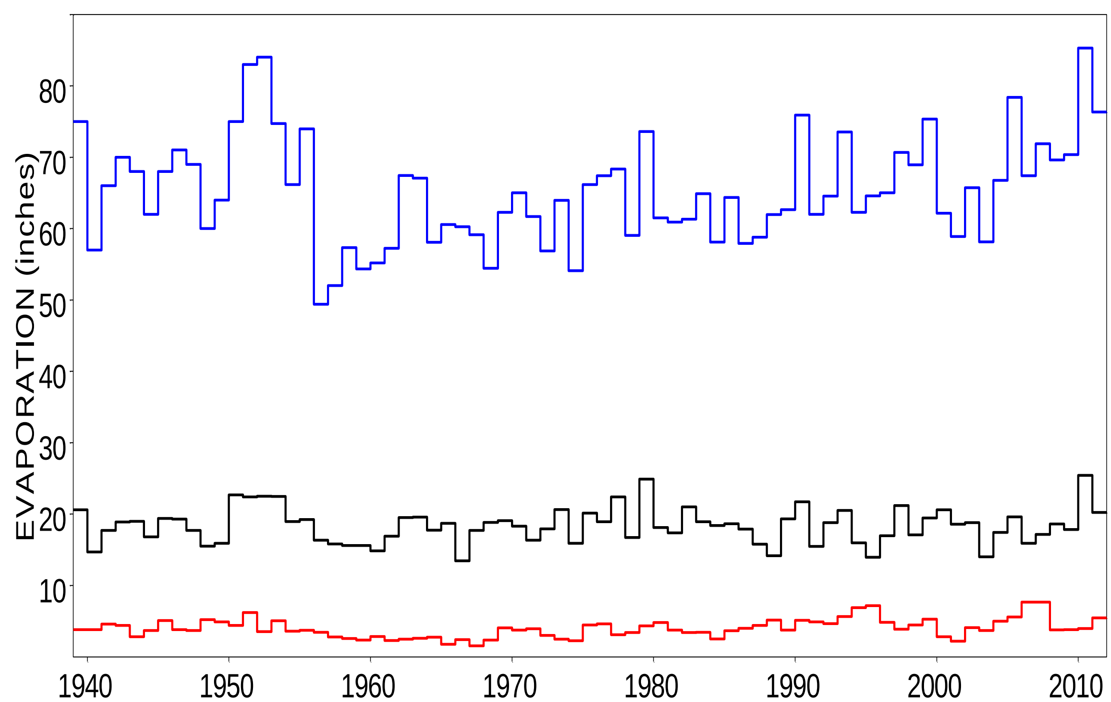
Monthly Evaporation for Quadrangle 106



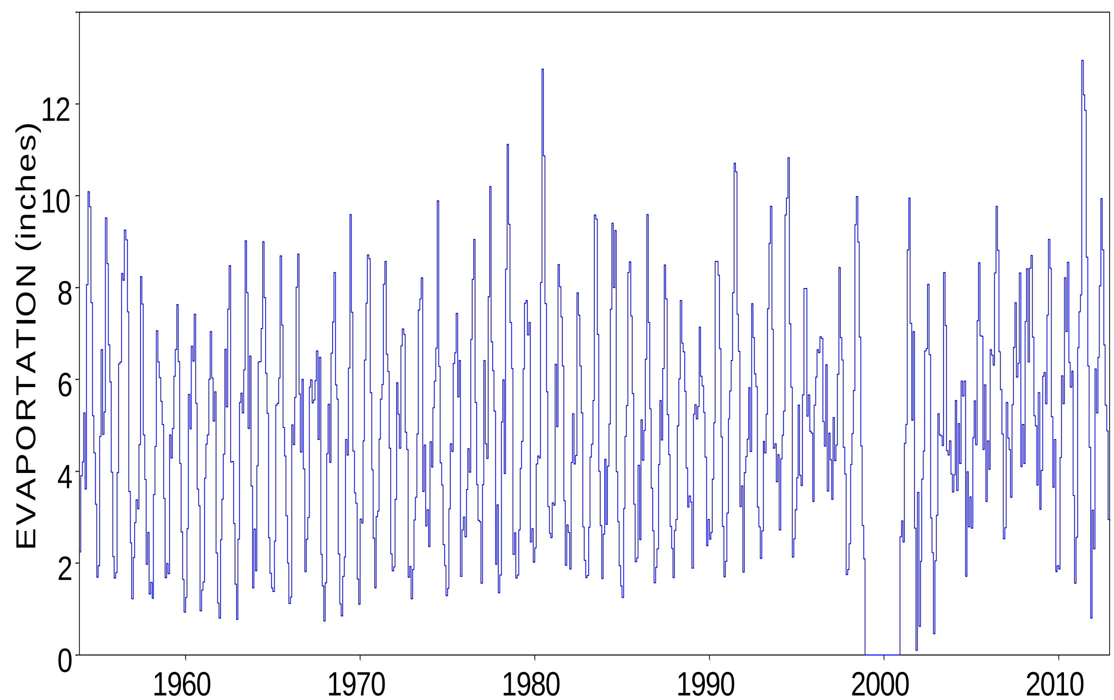
Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles 106



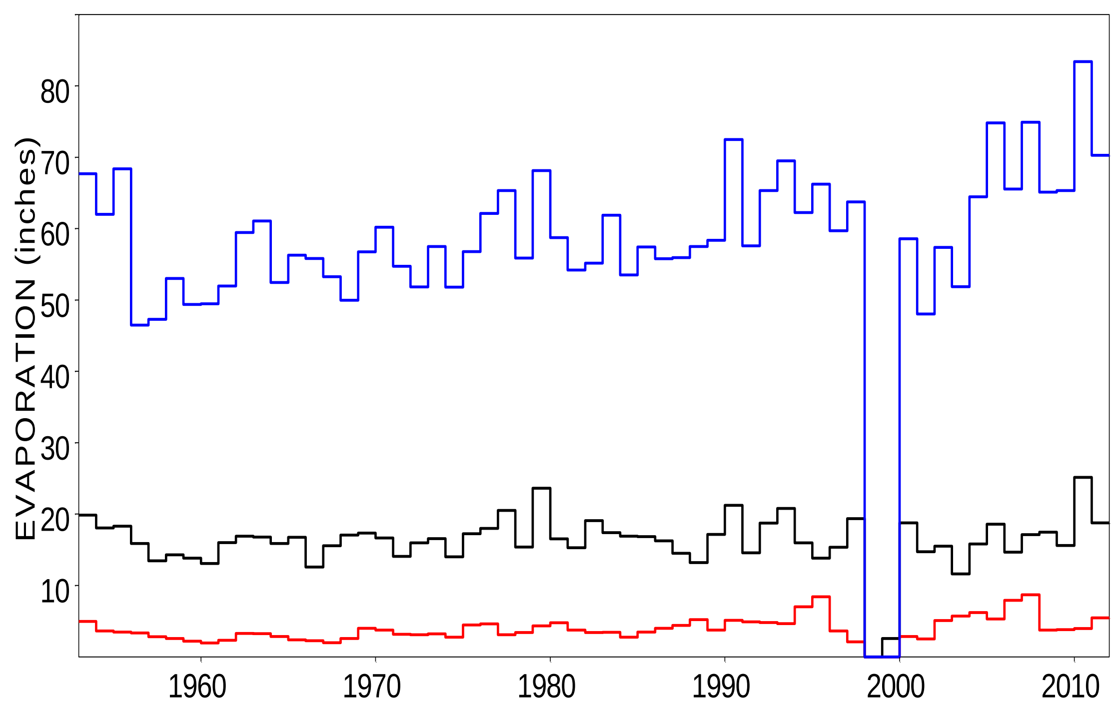
Monthly Evaporation for Quadrangle 107



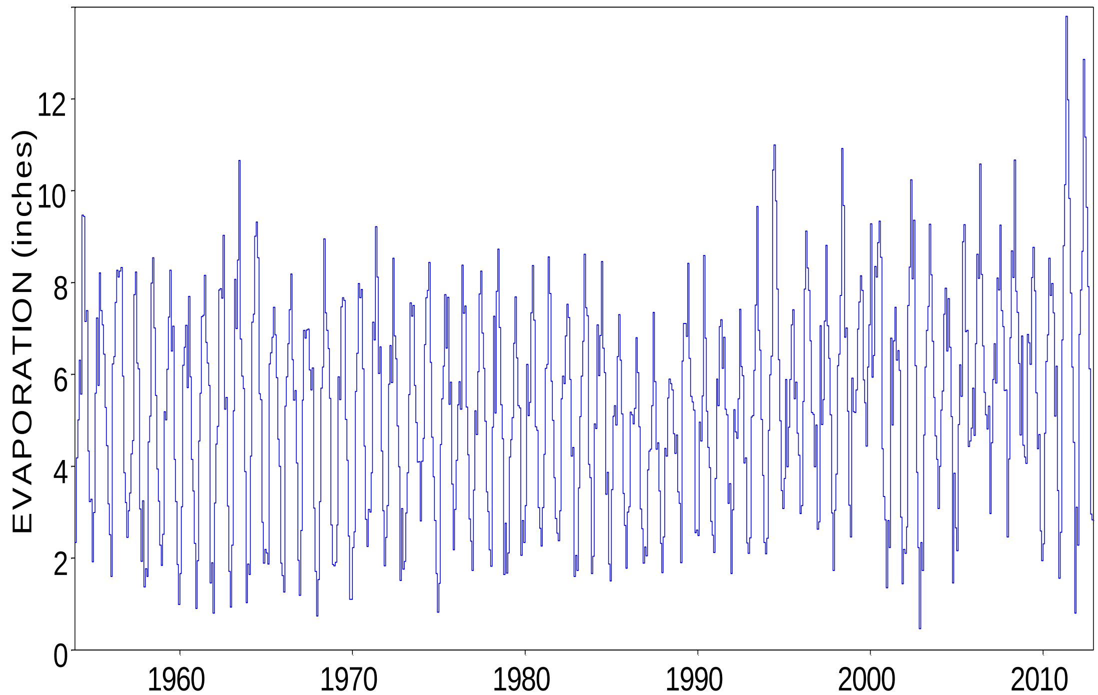
Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles 107



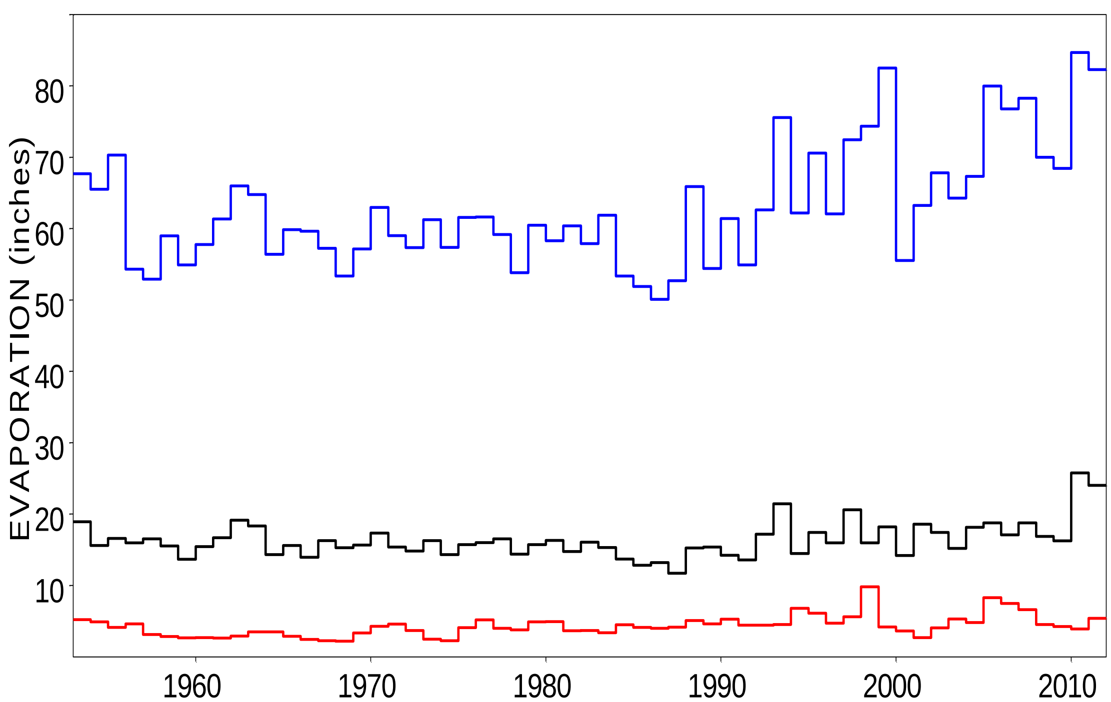
Monthly Evaporation for Quadrangle 108 (missing date form 1999-2000)



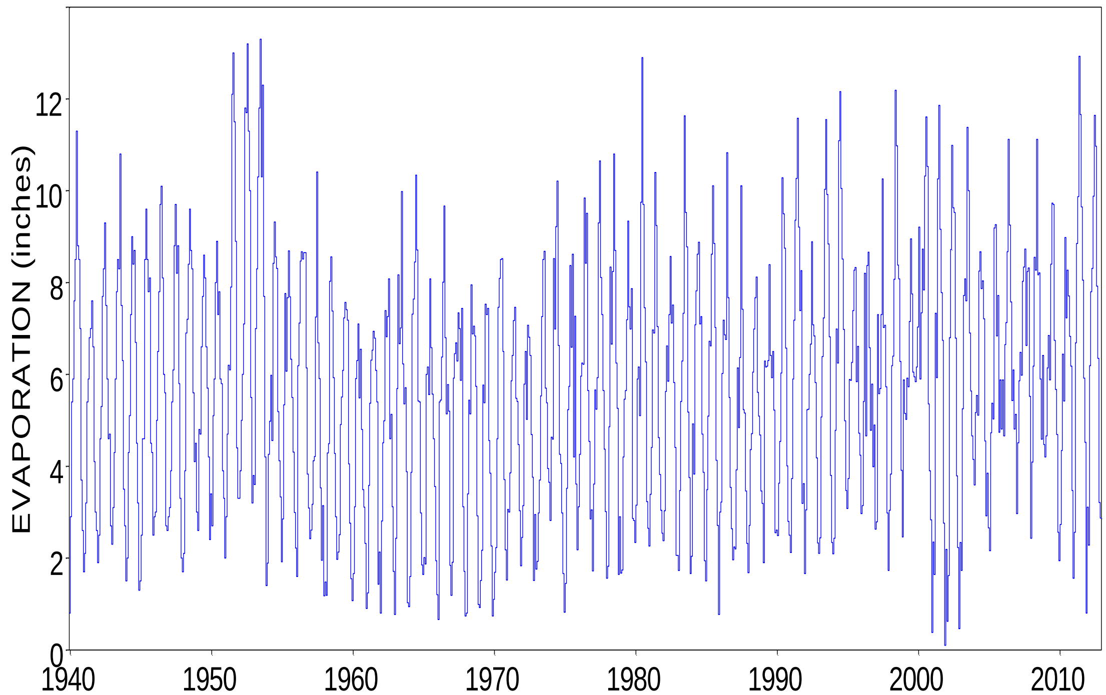
Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles 108 (missing date form 1999-2000)



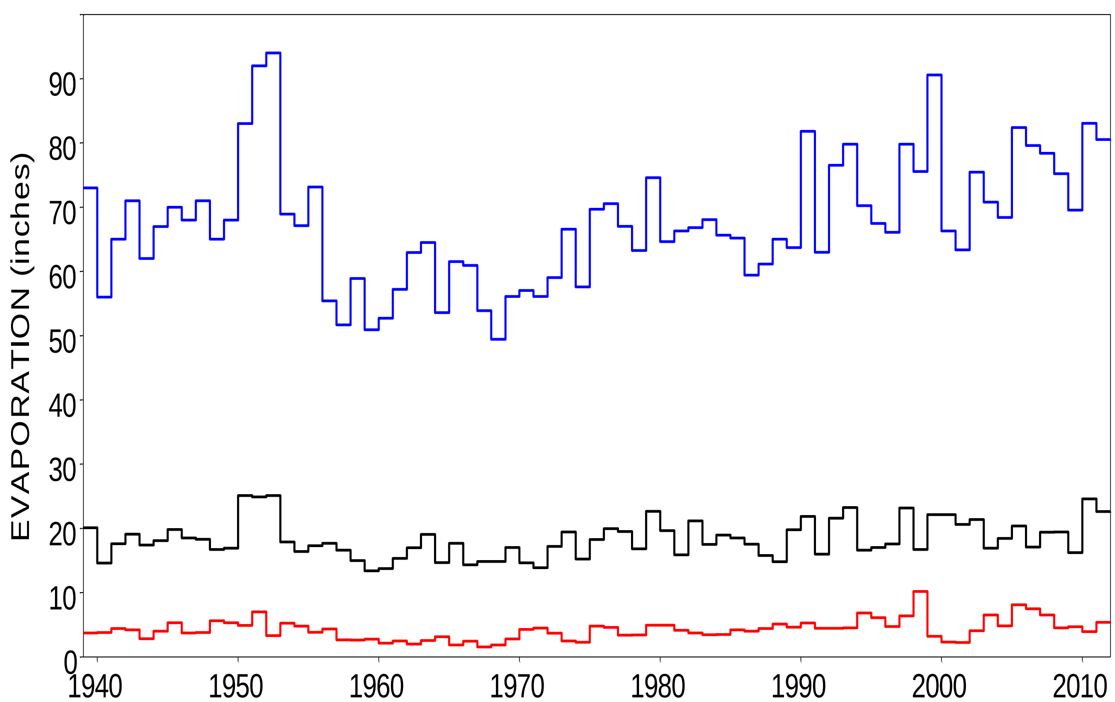
Monthly Evaporation for Quadrangle 204



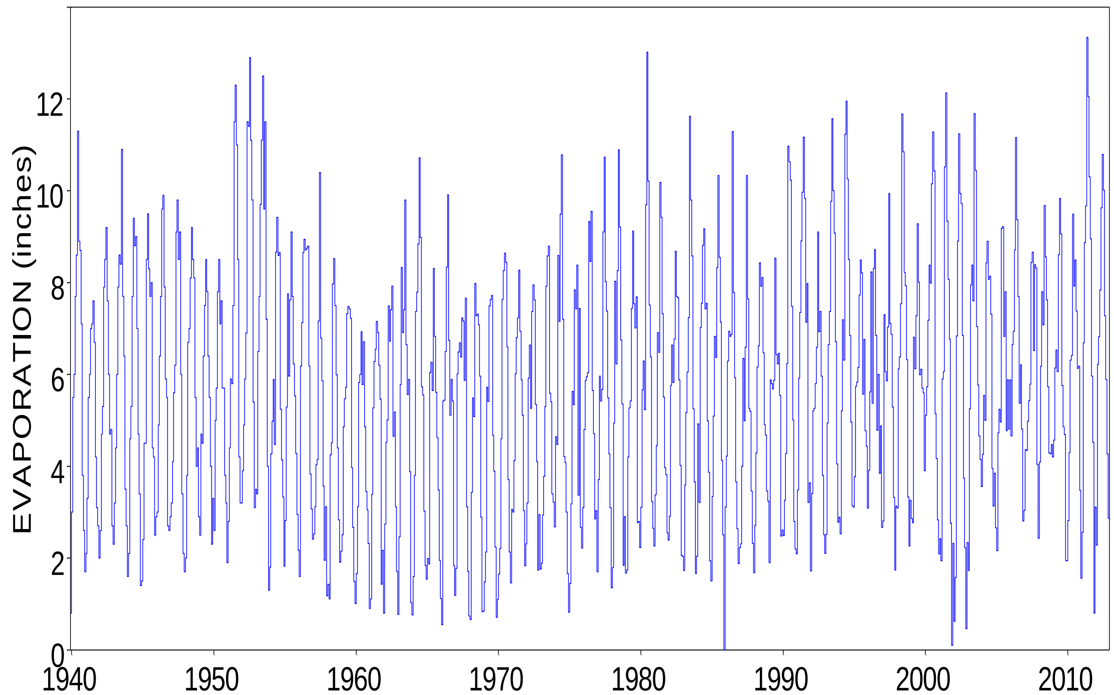
Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles 204



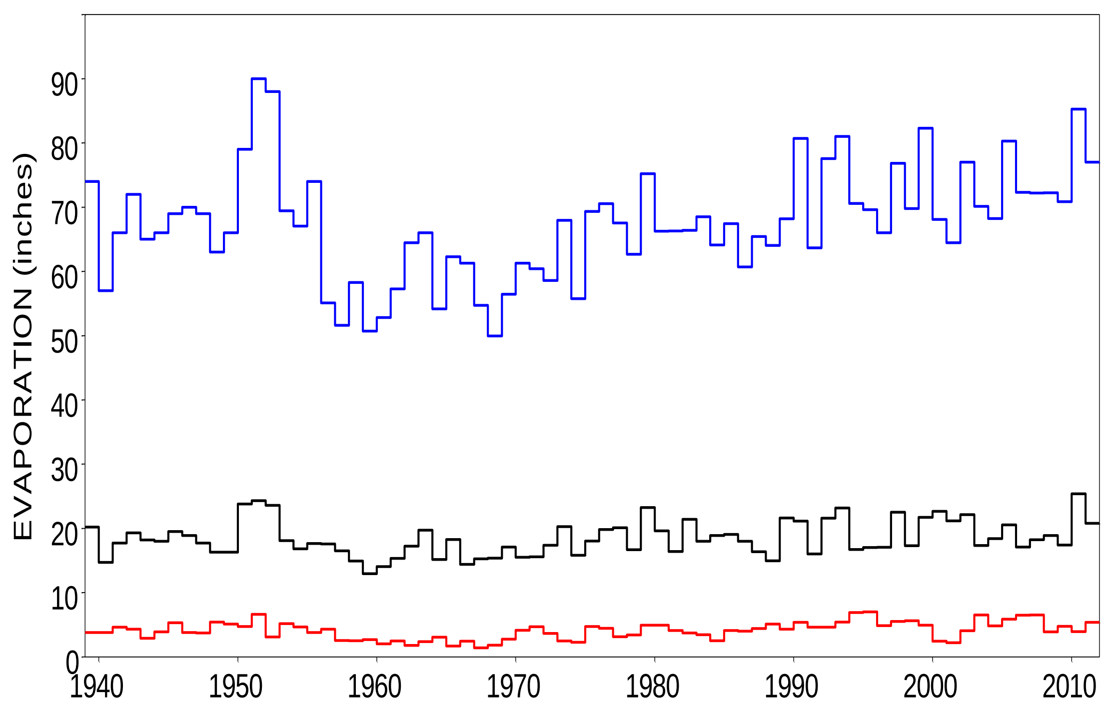
Monthly Evaporation for Quadrangle 205



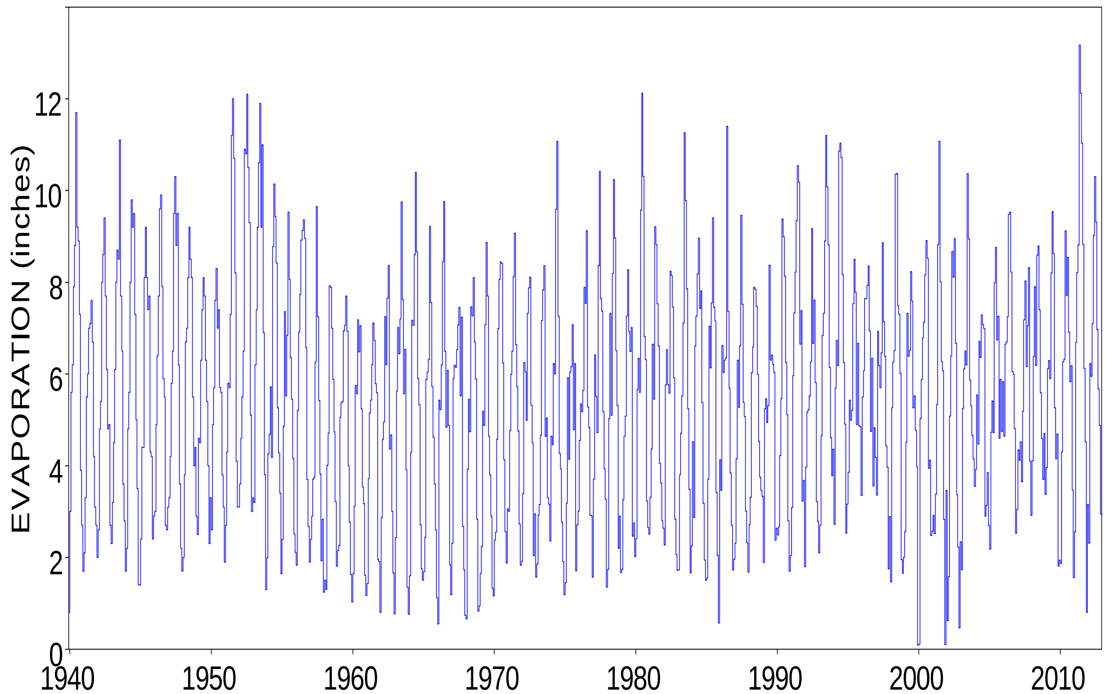
Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles 205



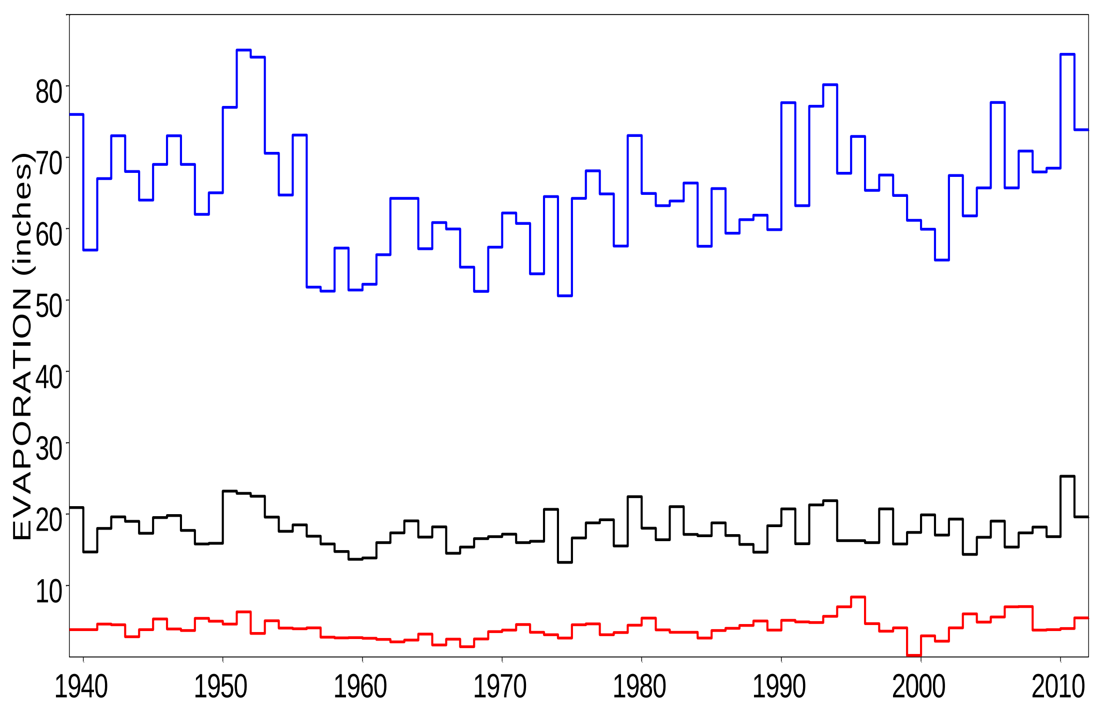
Monthly Evaporation for Quadrangle 206



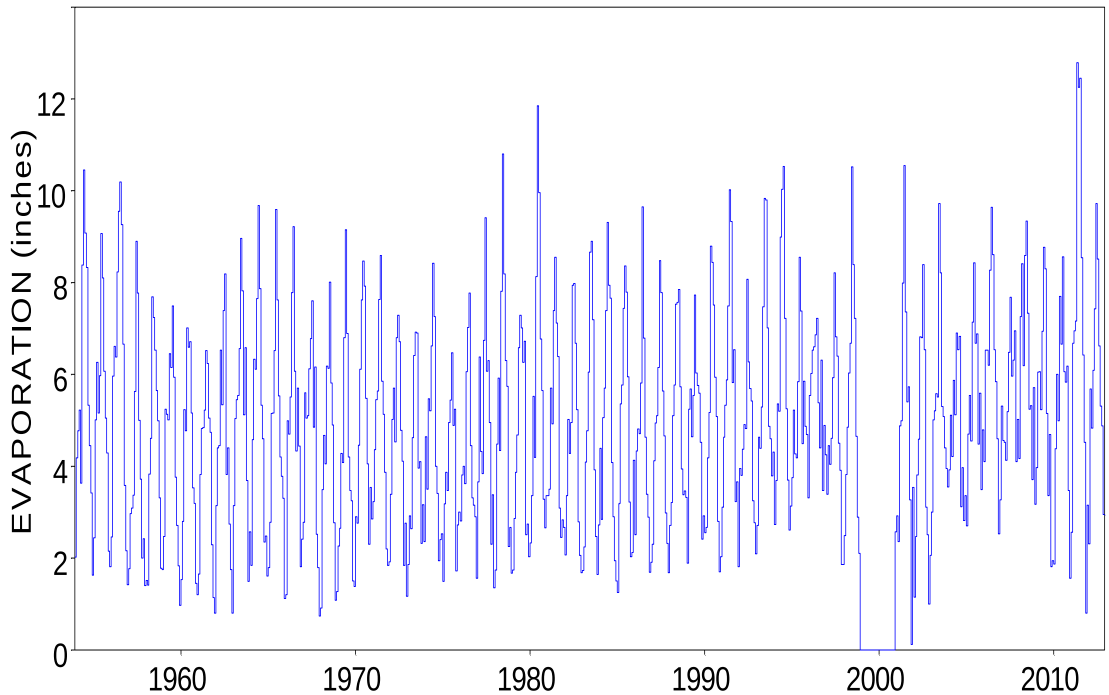
Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles 206



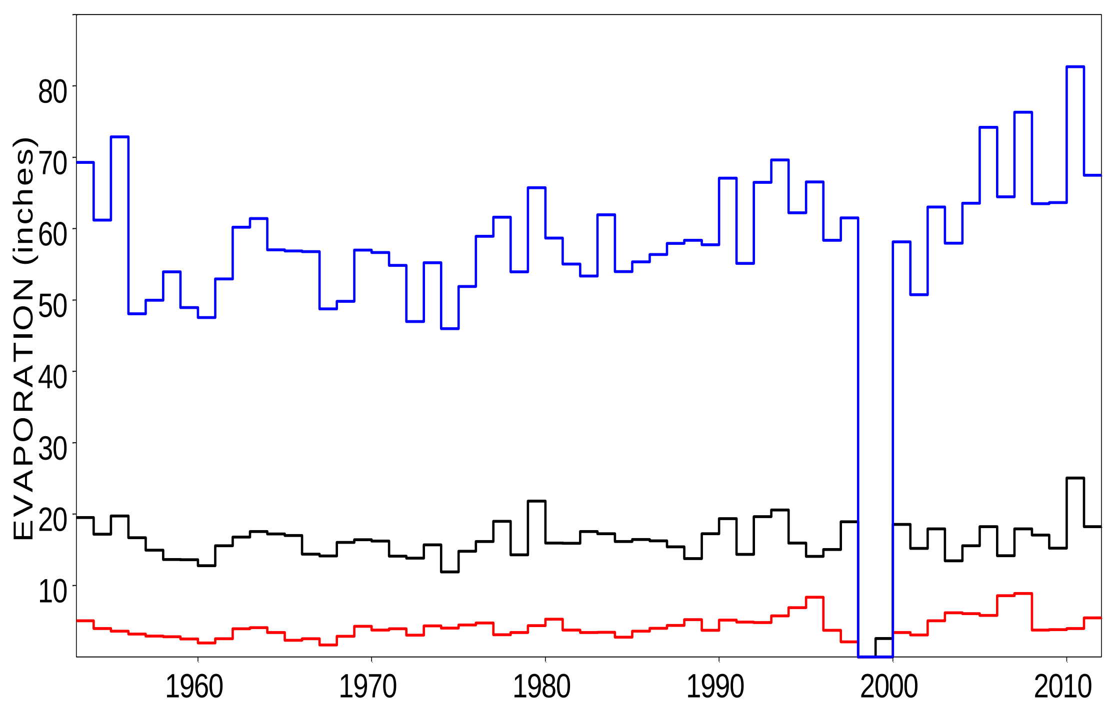
Monthly Evaporation for Quadrangle 207



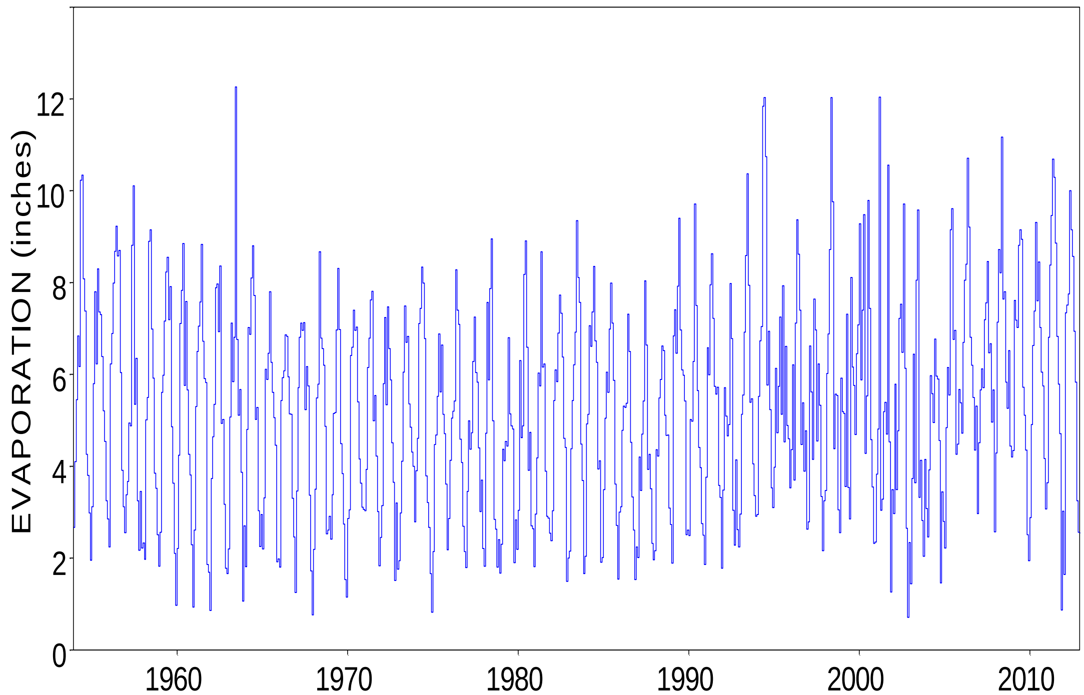
Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles 207



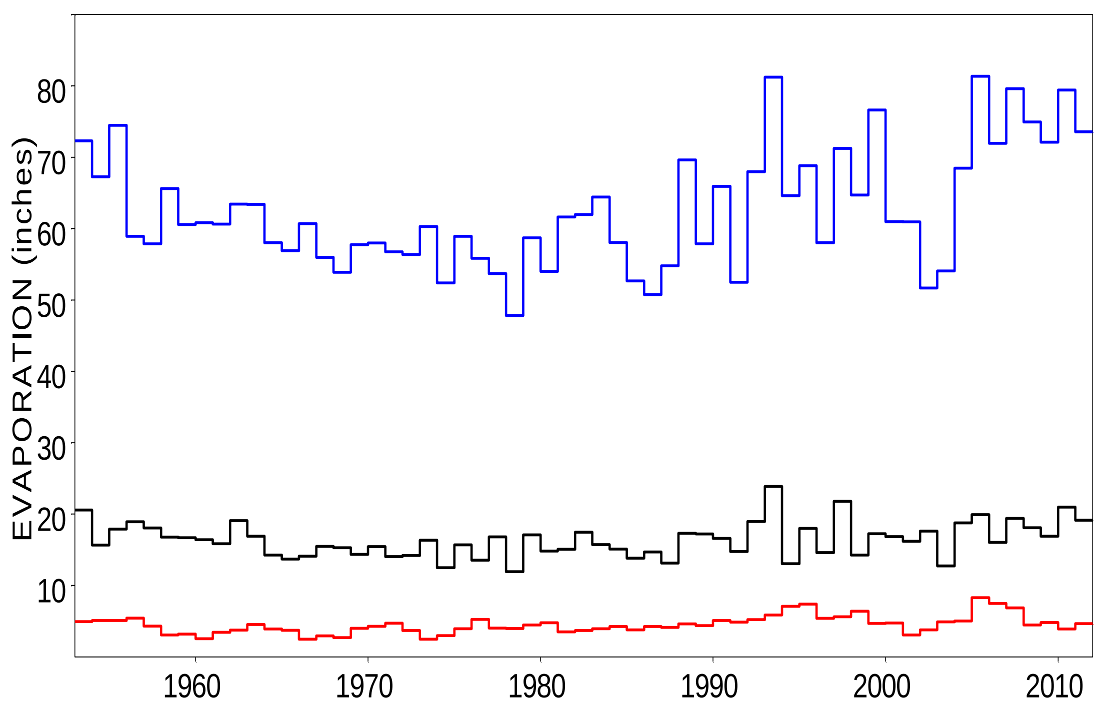
Monthly Evaporation for Quadrangle 208(missing date form 1999-2000)



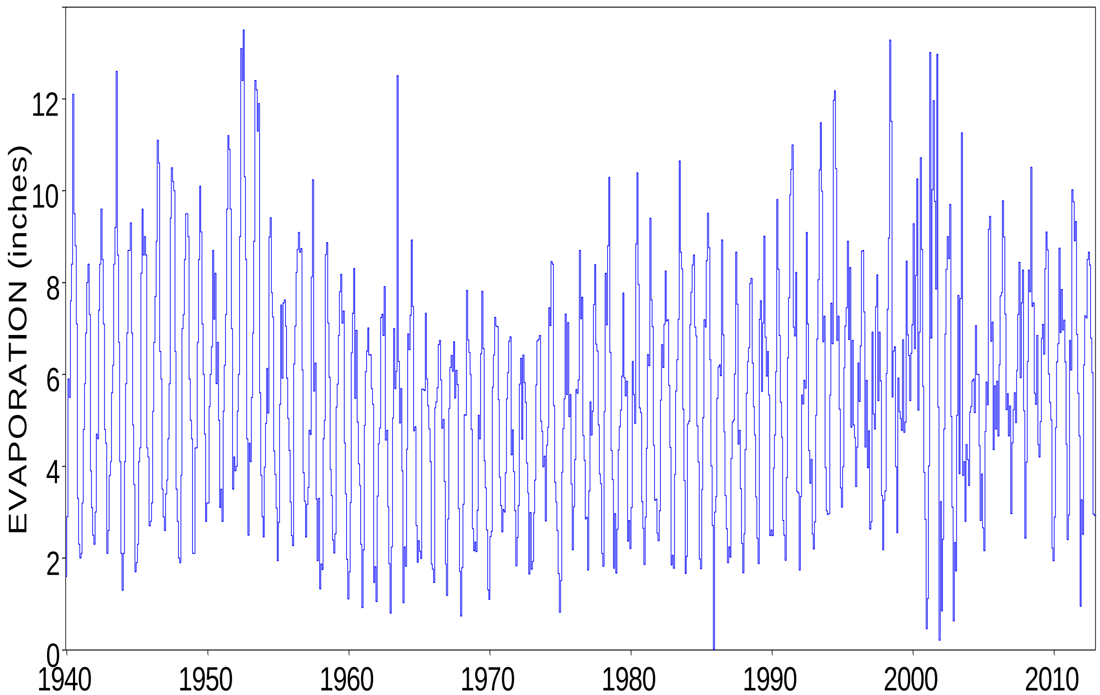
Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles 208
(missing date form 1999-2000)



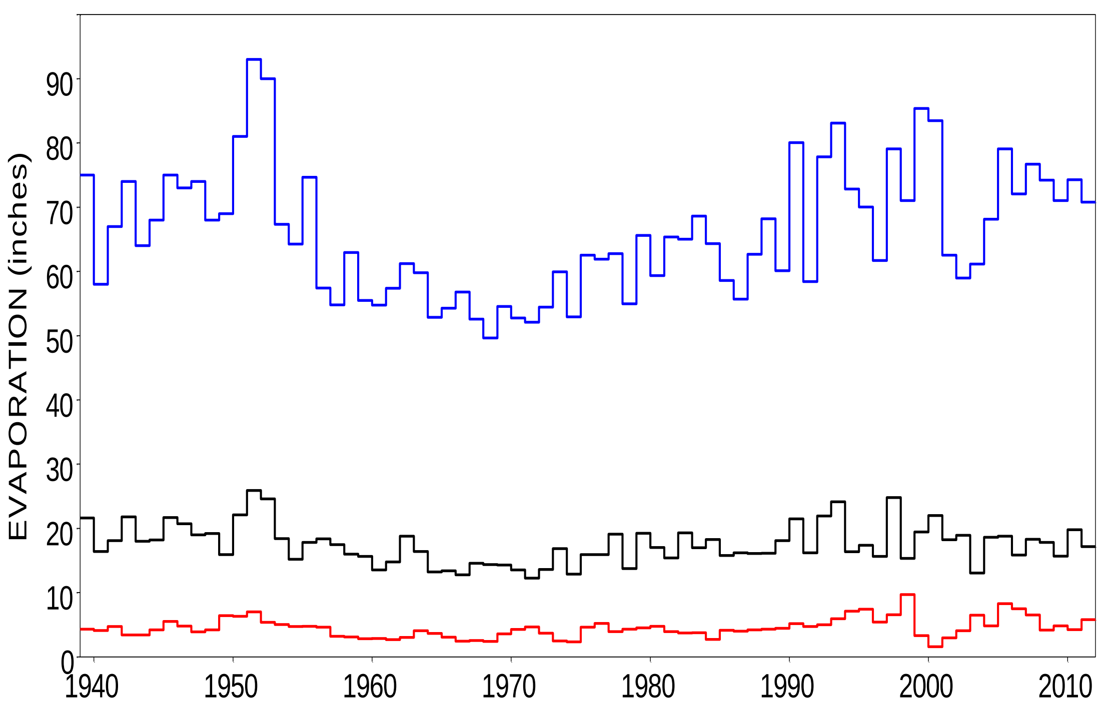
Monthly Evaporation for Quadrangle 304



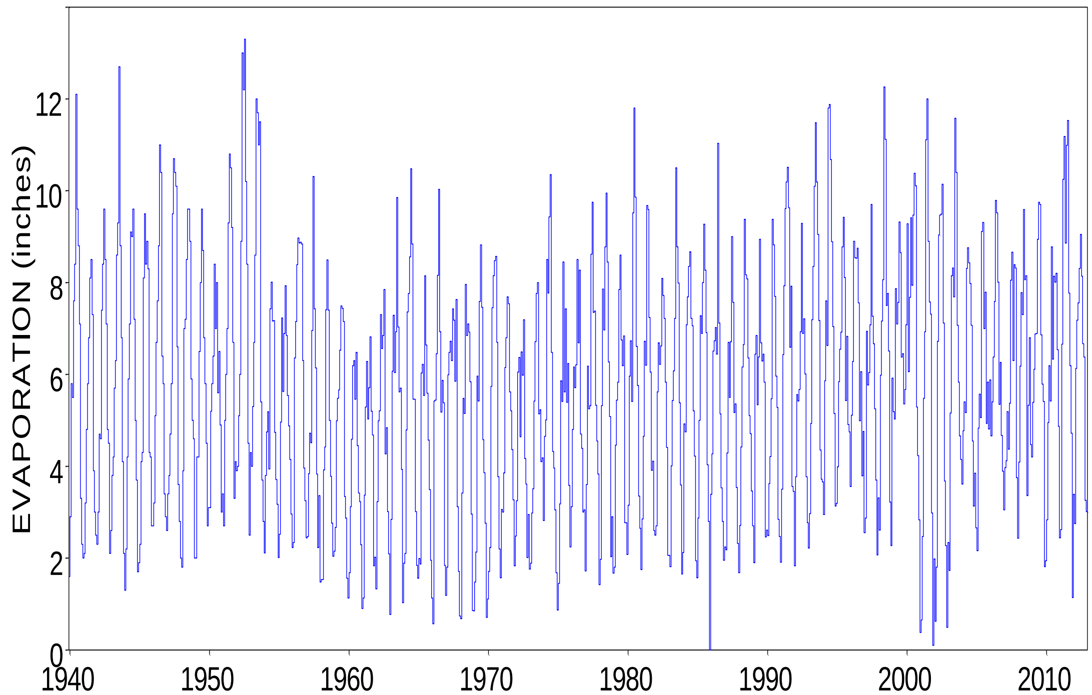
Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles 304



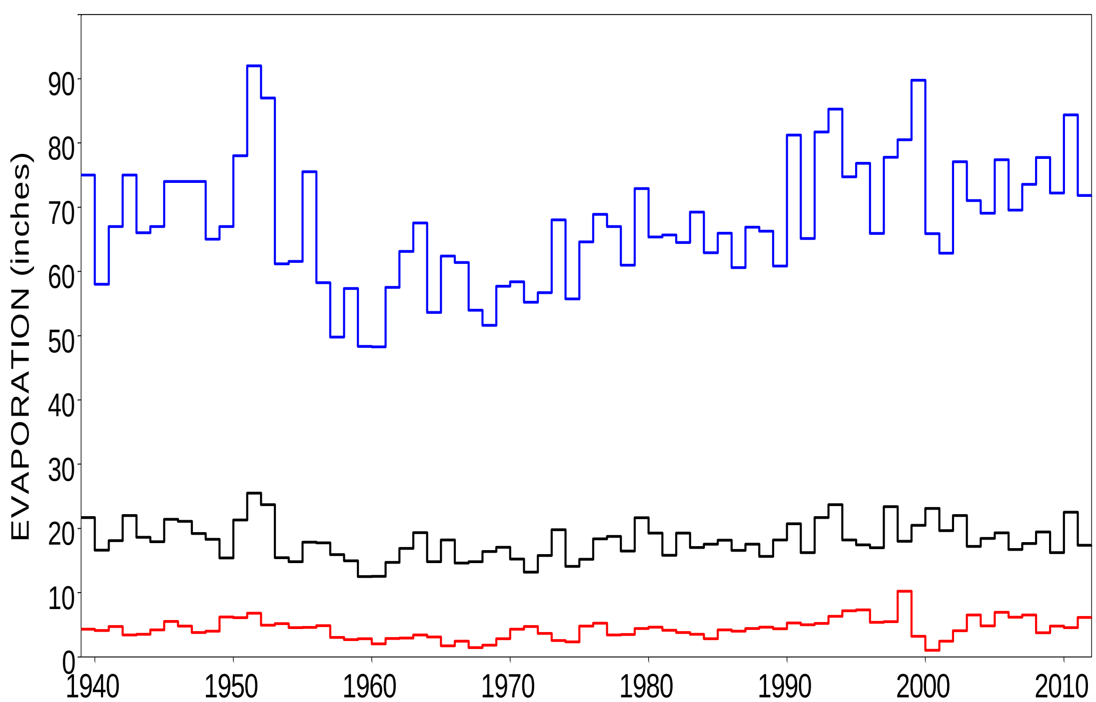
Monthly Evaporation for Quadrangle 305



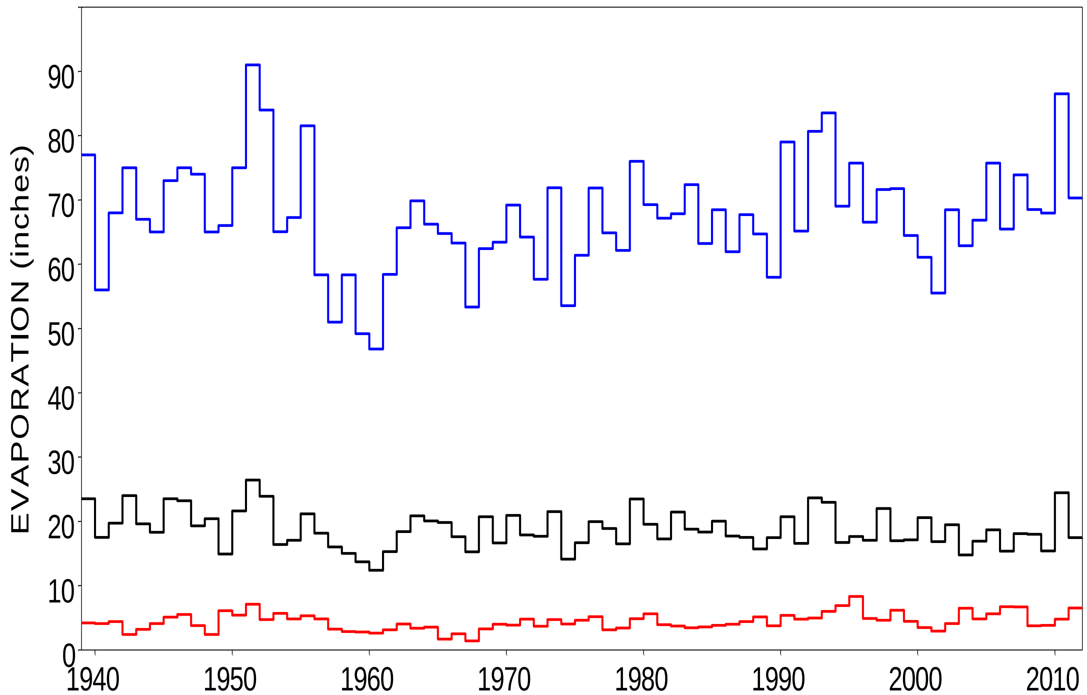
Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles 305



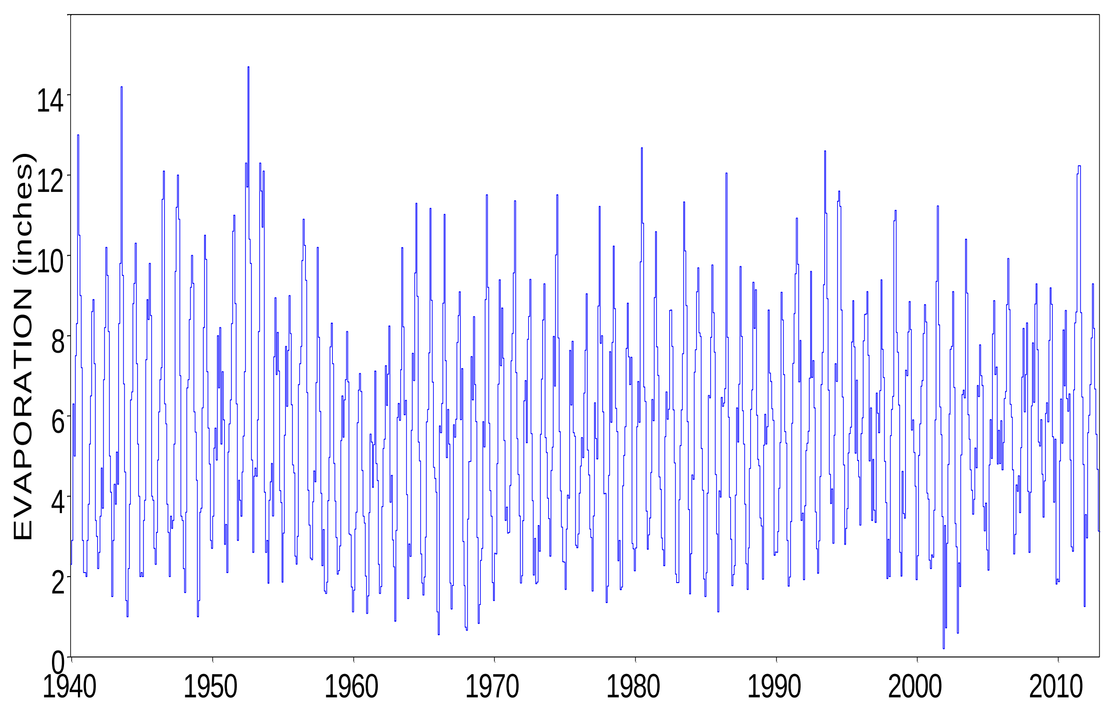
Monthly Evaporation for Quadrangle 306



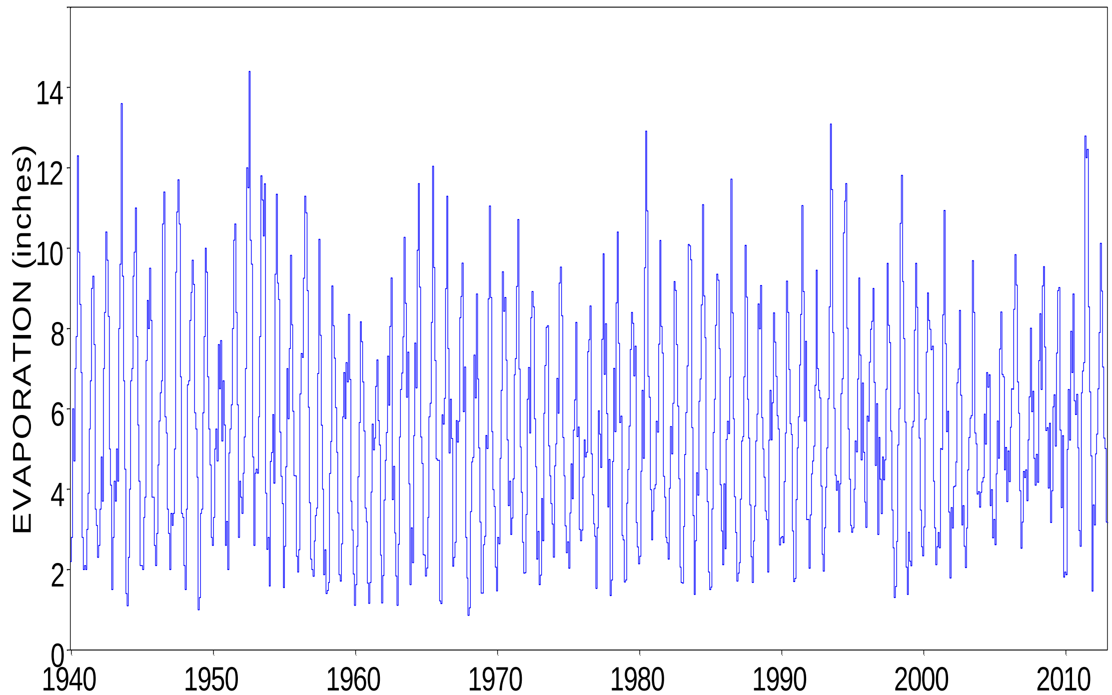
Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles 306



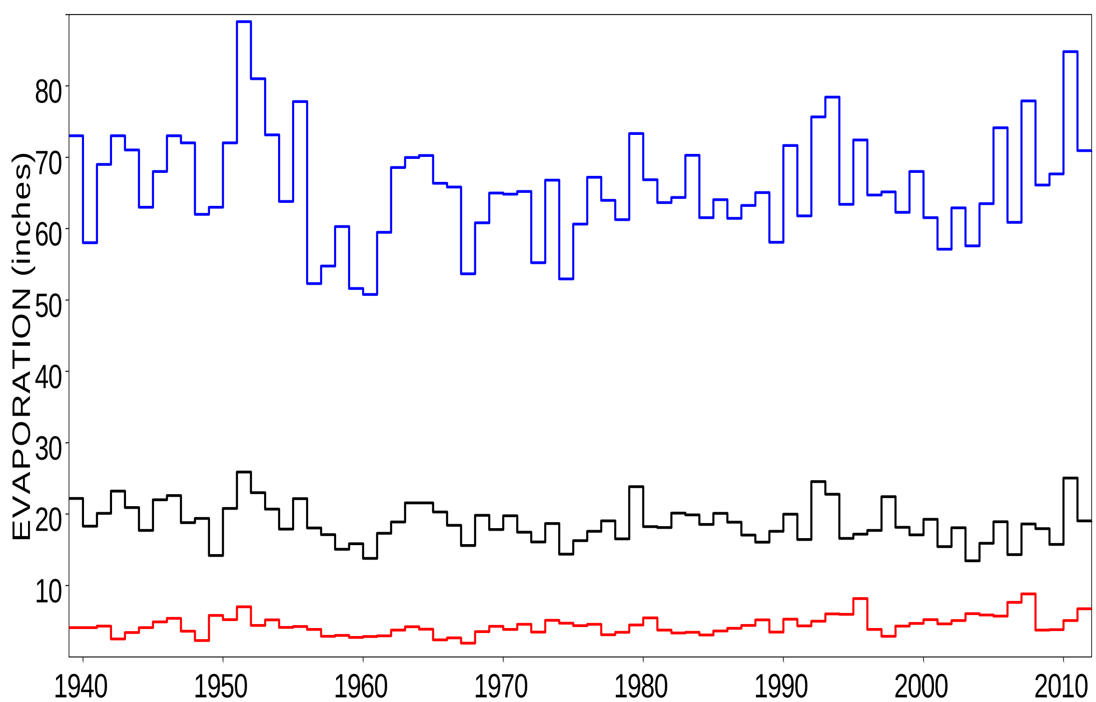
Monthly Evaporation for Evaporation 307



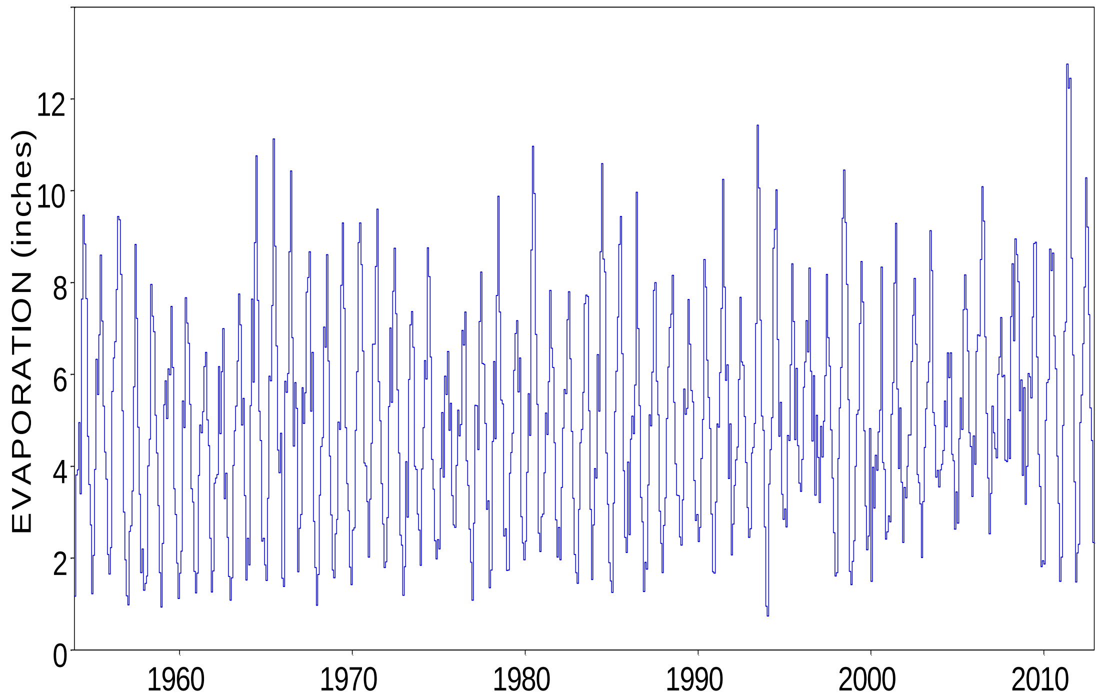
Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles 307



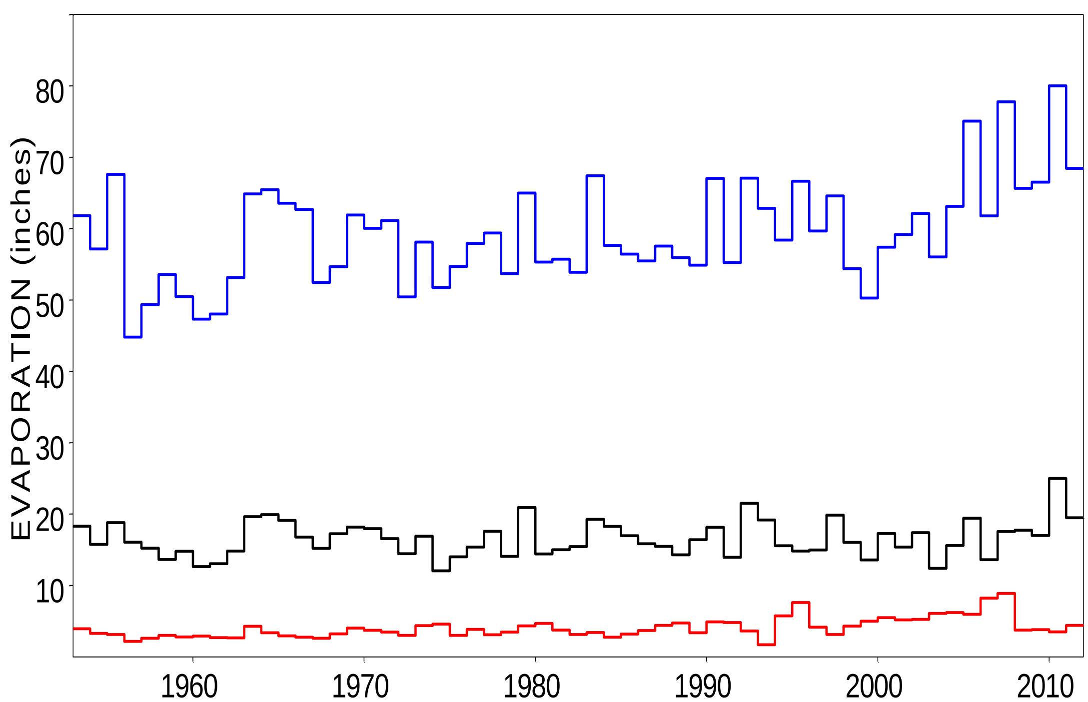
Monthly Evaporation for Quadrangle 308



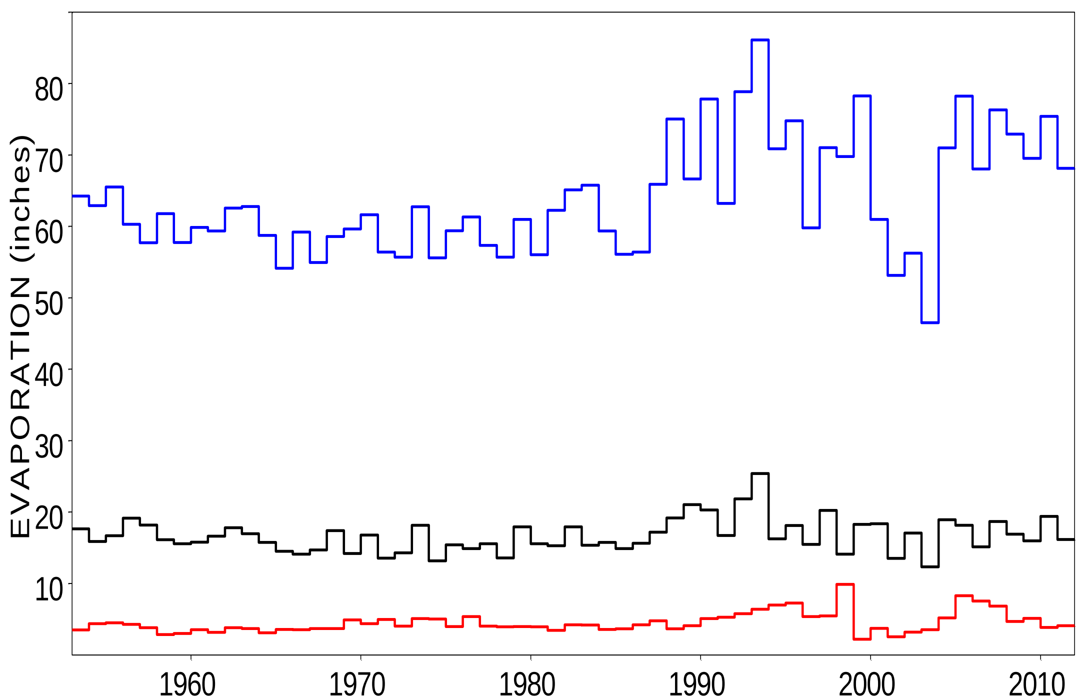
Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles 308



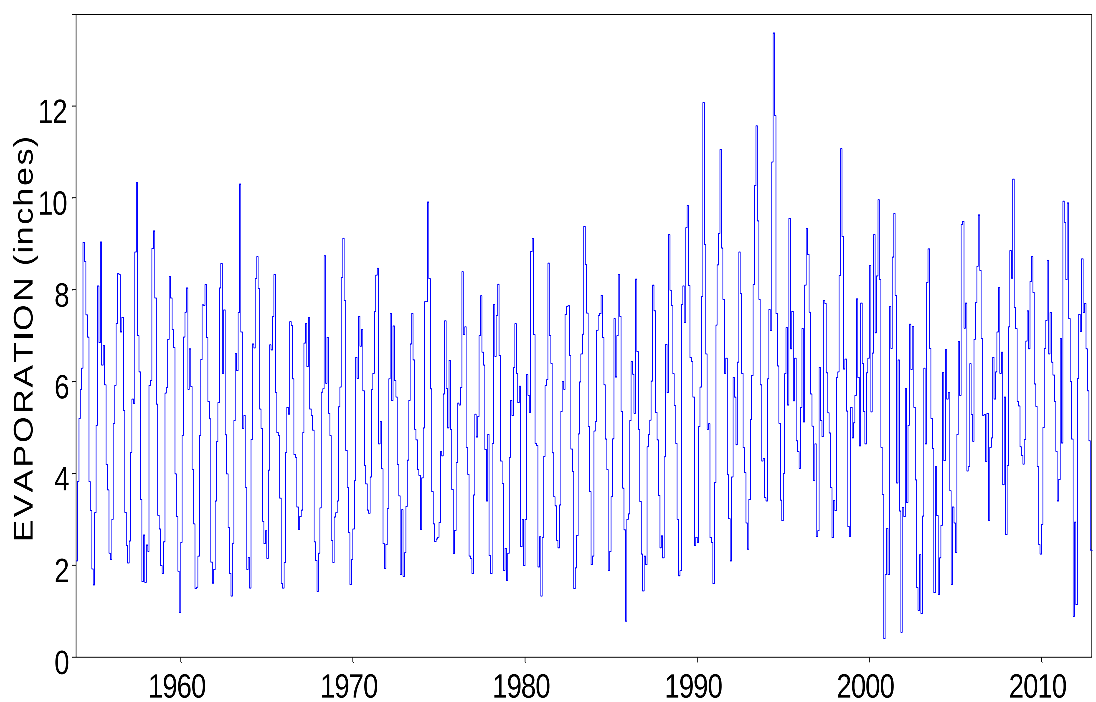
Monthly Evaporation for Quadrangle 309



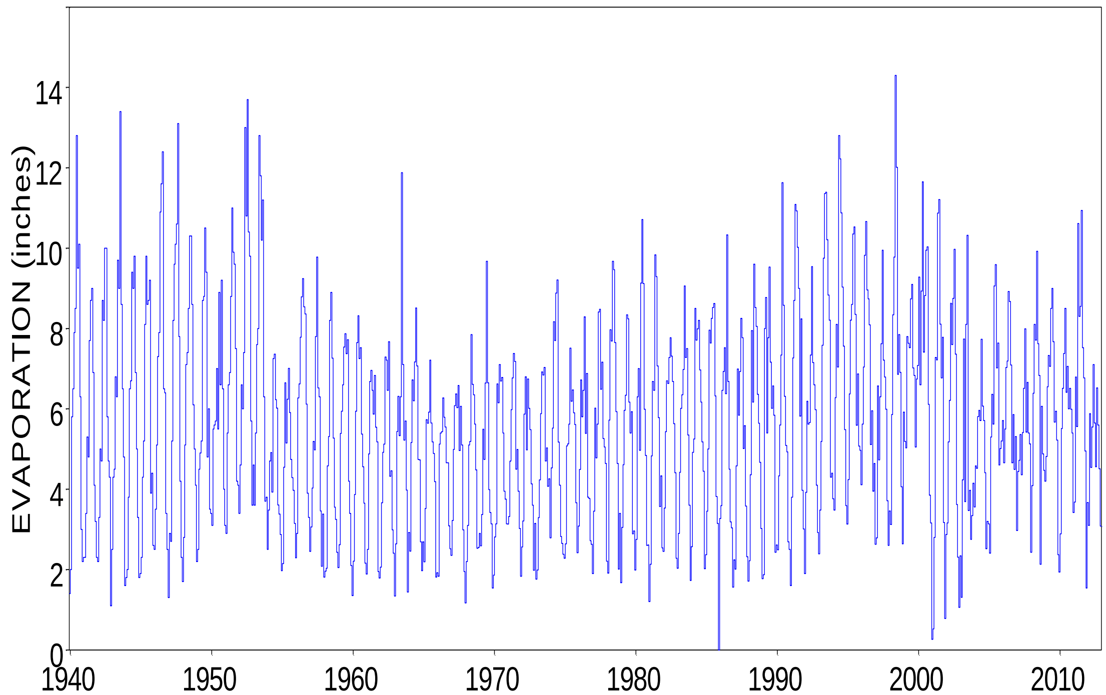
Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles 309



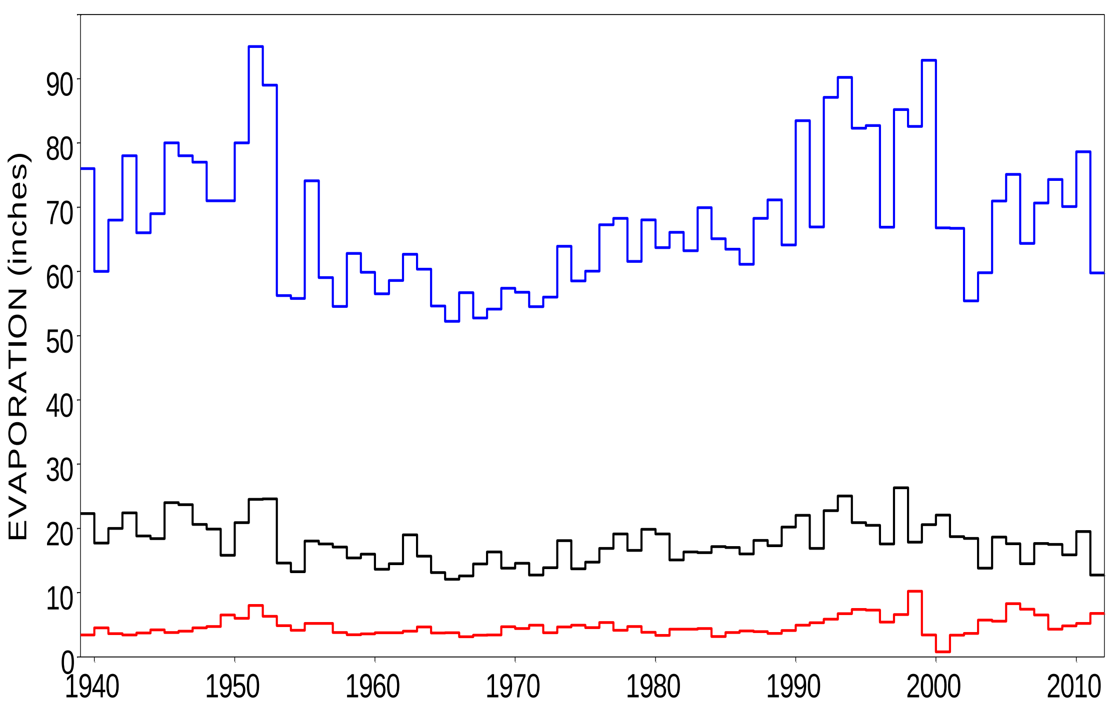
Monthly Evaporation for Quadrangle 404



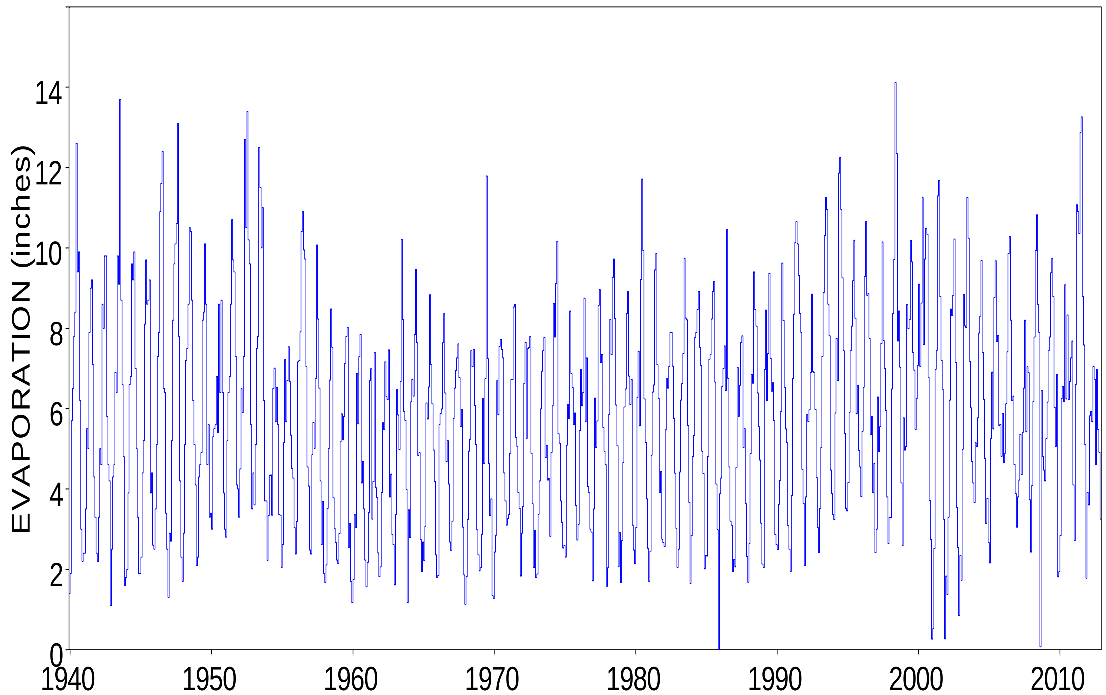
Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles 404



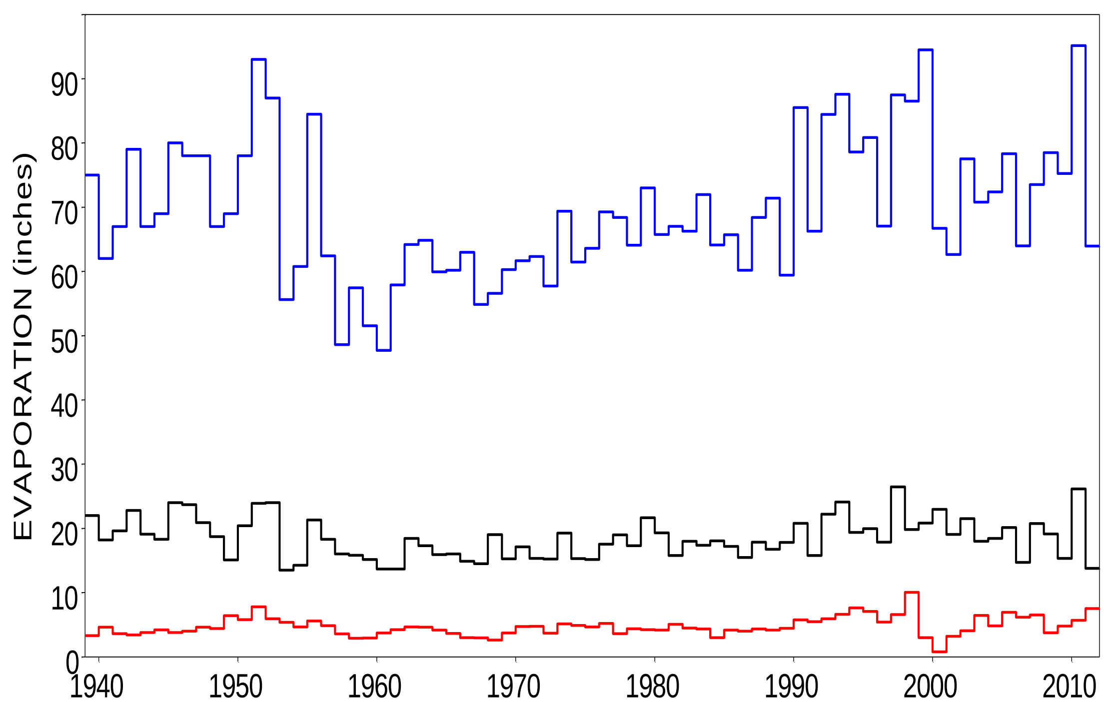
Monthly Evaporation for Quadrangle 405



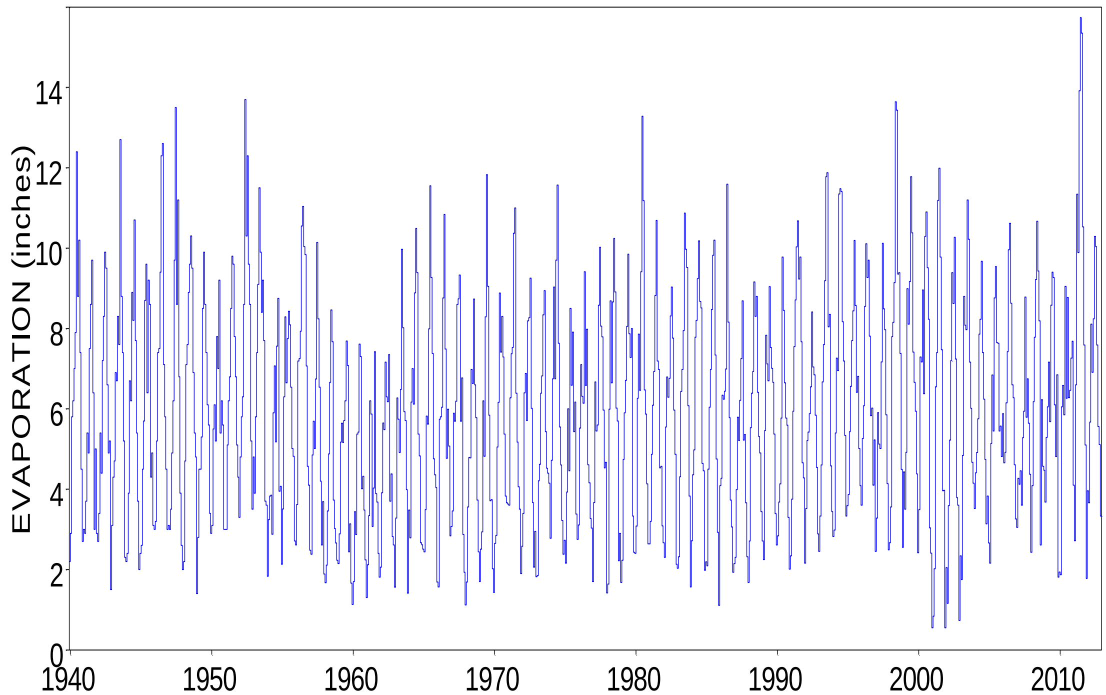
Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles 405



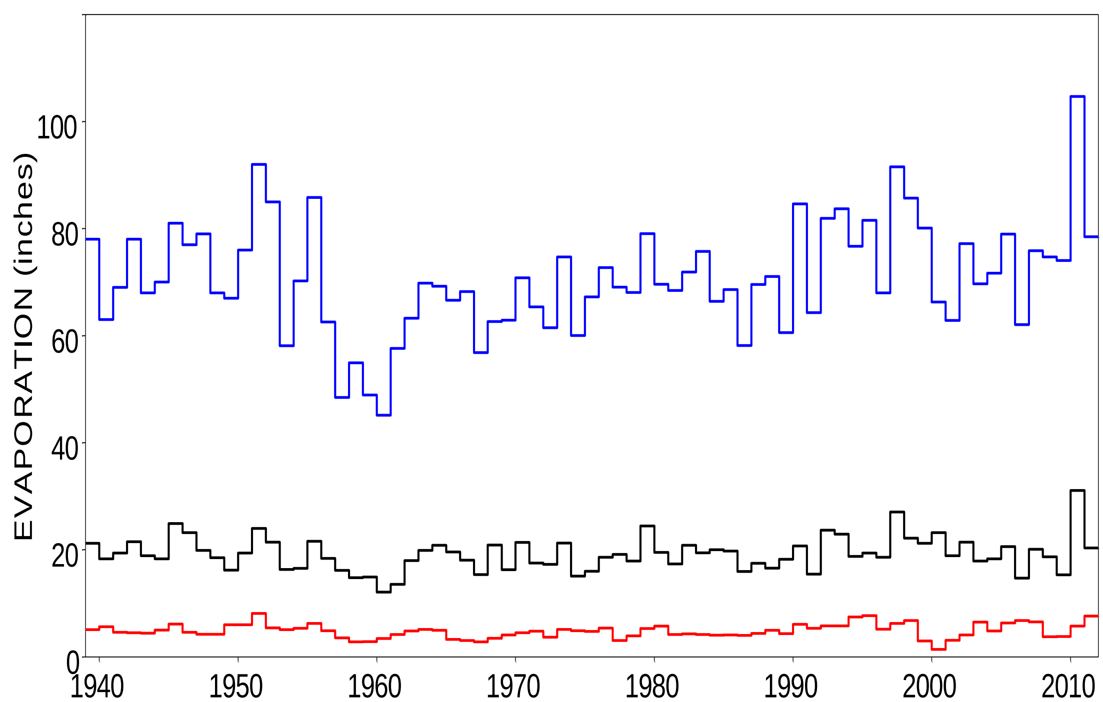
Monthly Evaporation for Quadrangle 406



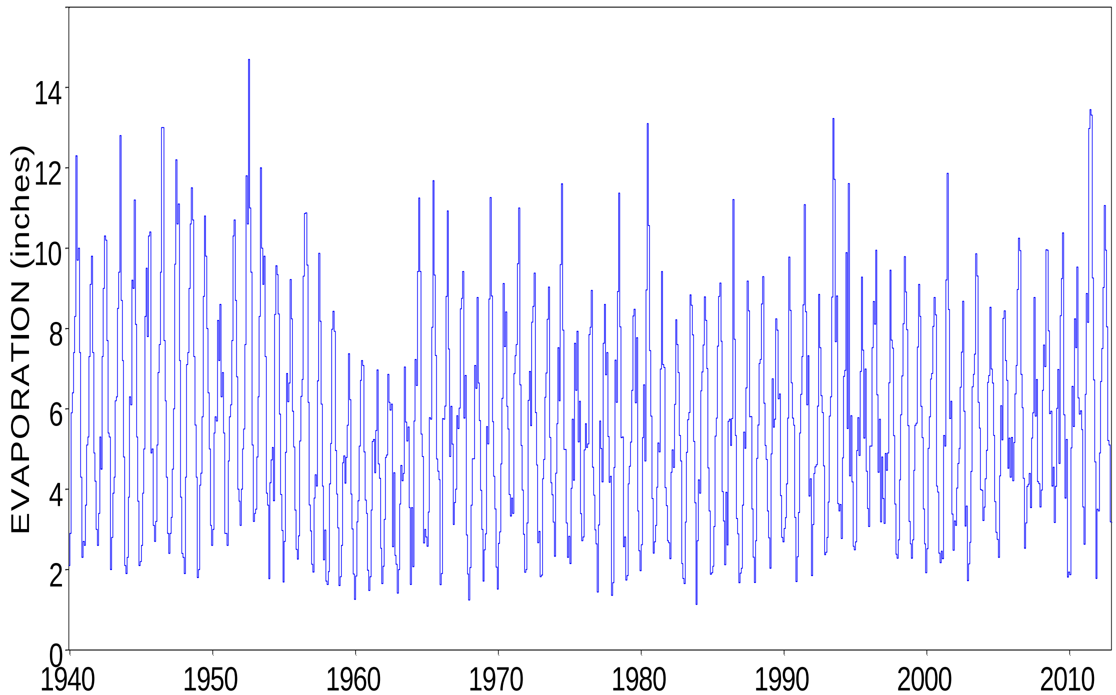
Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles 406



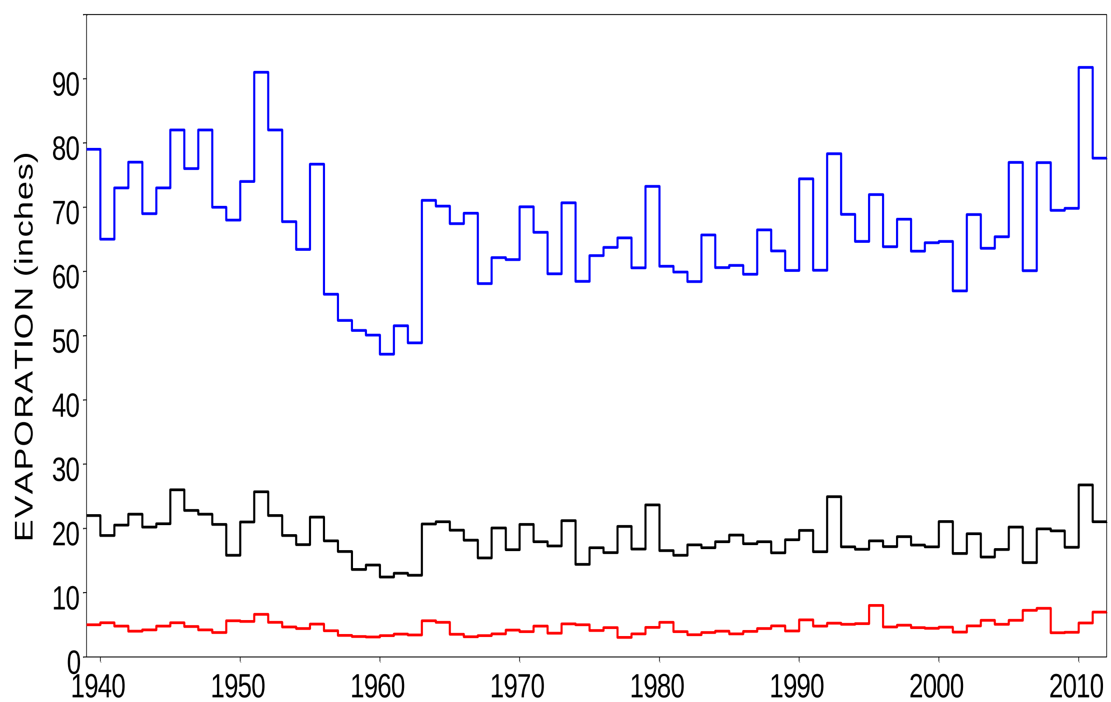
Monthly Evaporation for Quadrangle 407



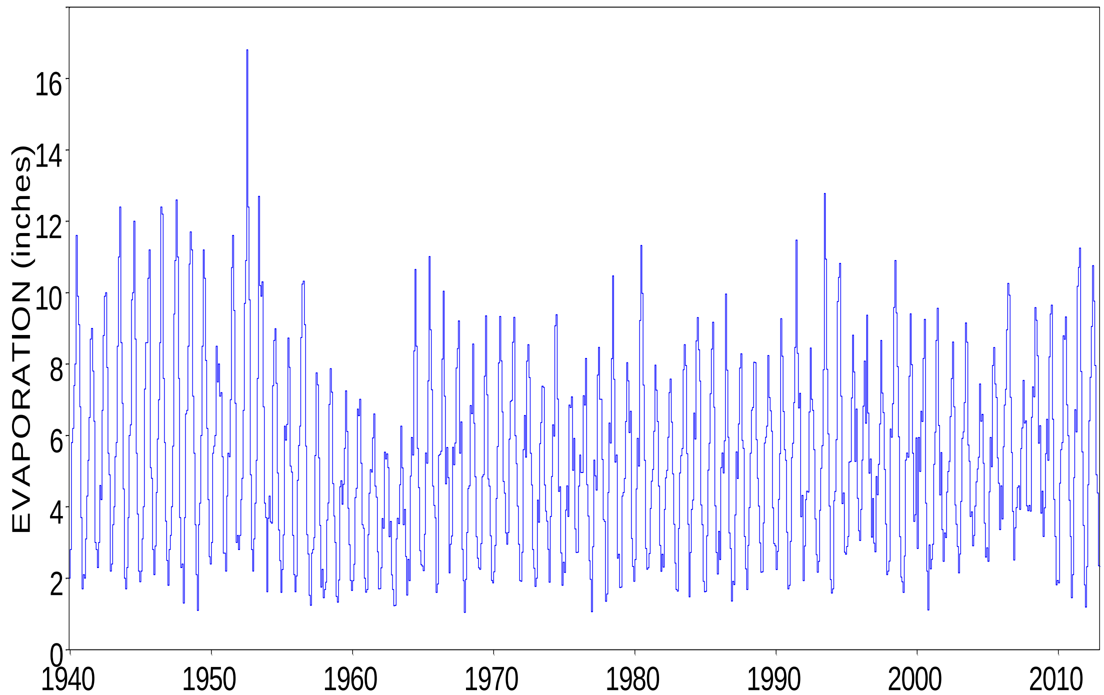
Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles 407



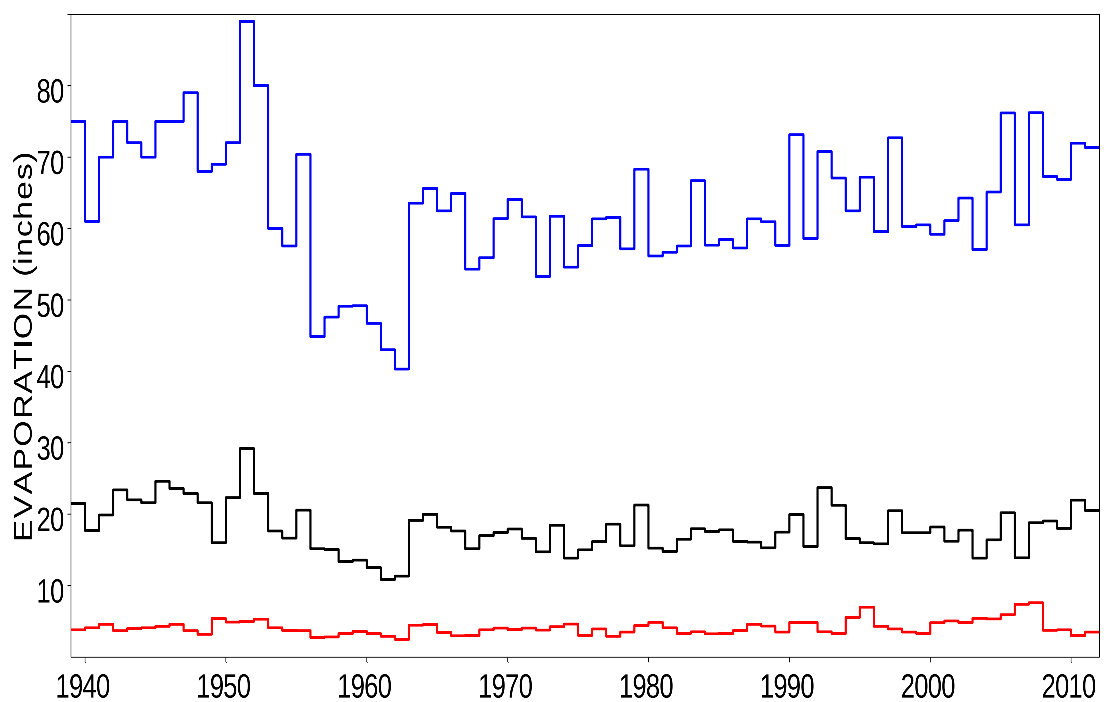
Monthly Evaporation for Quadrangle 408



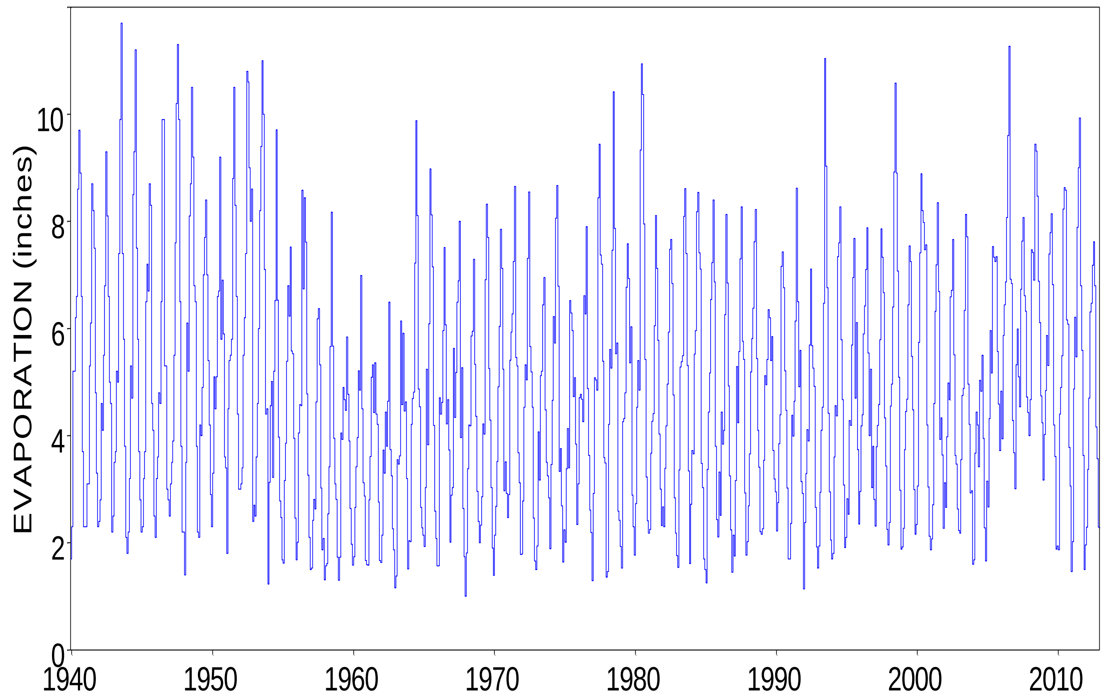
Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles 408



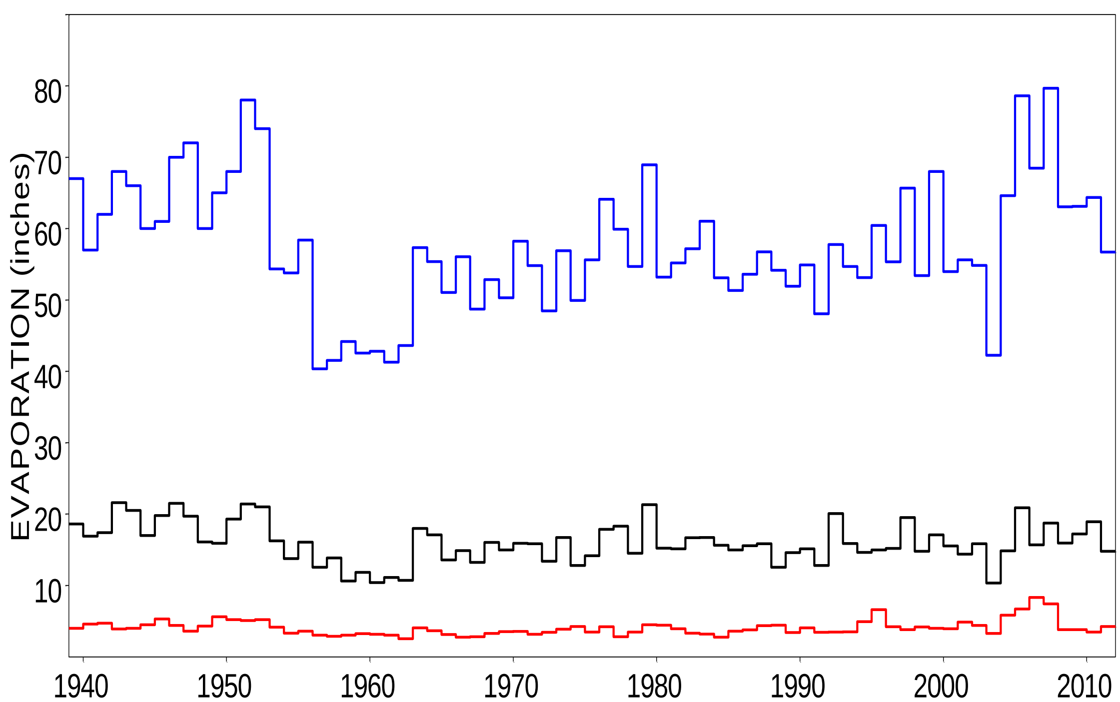
Monthly Evaporation for Quadrangle 409



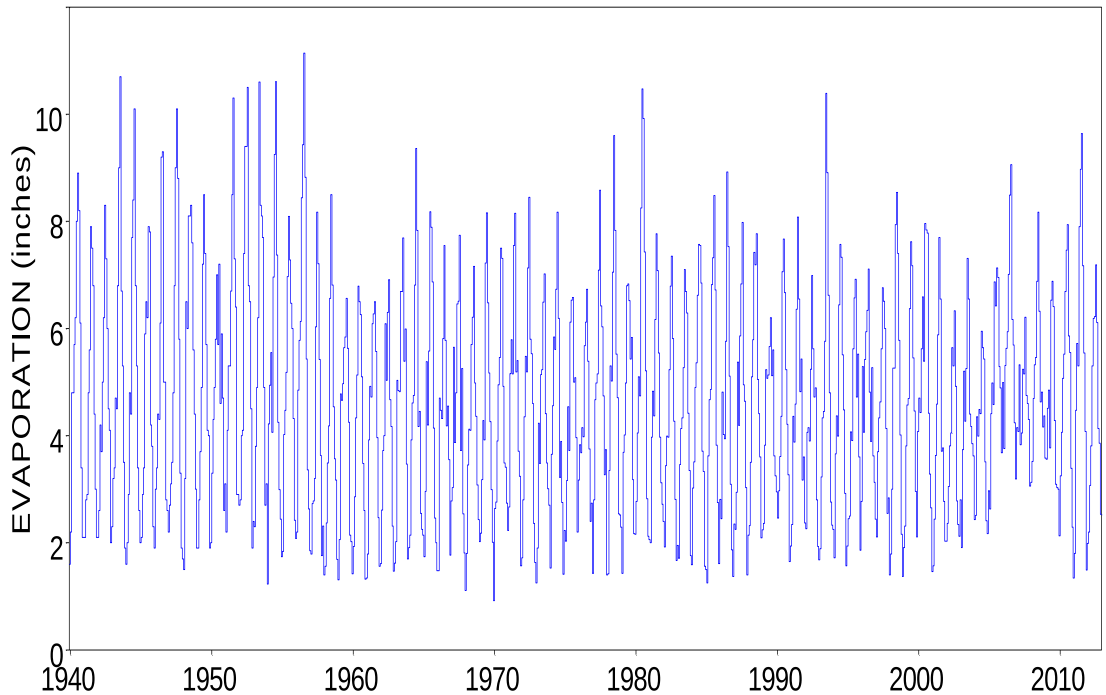
Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles 409



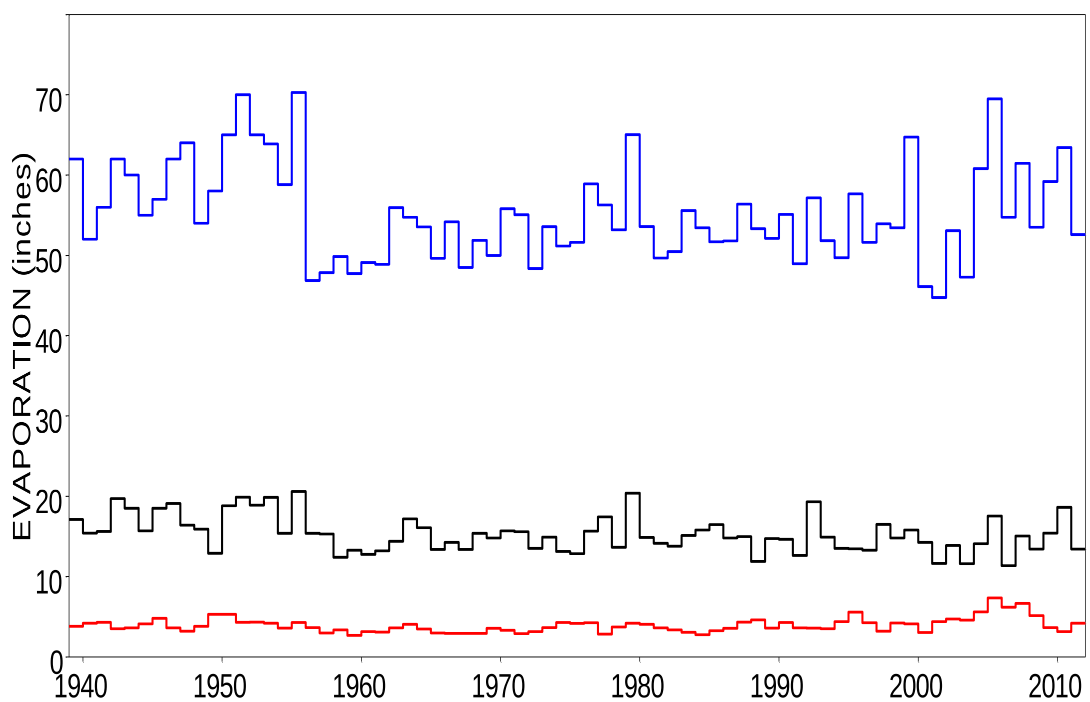
Monthly Evaporation for Quadrangle 410



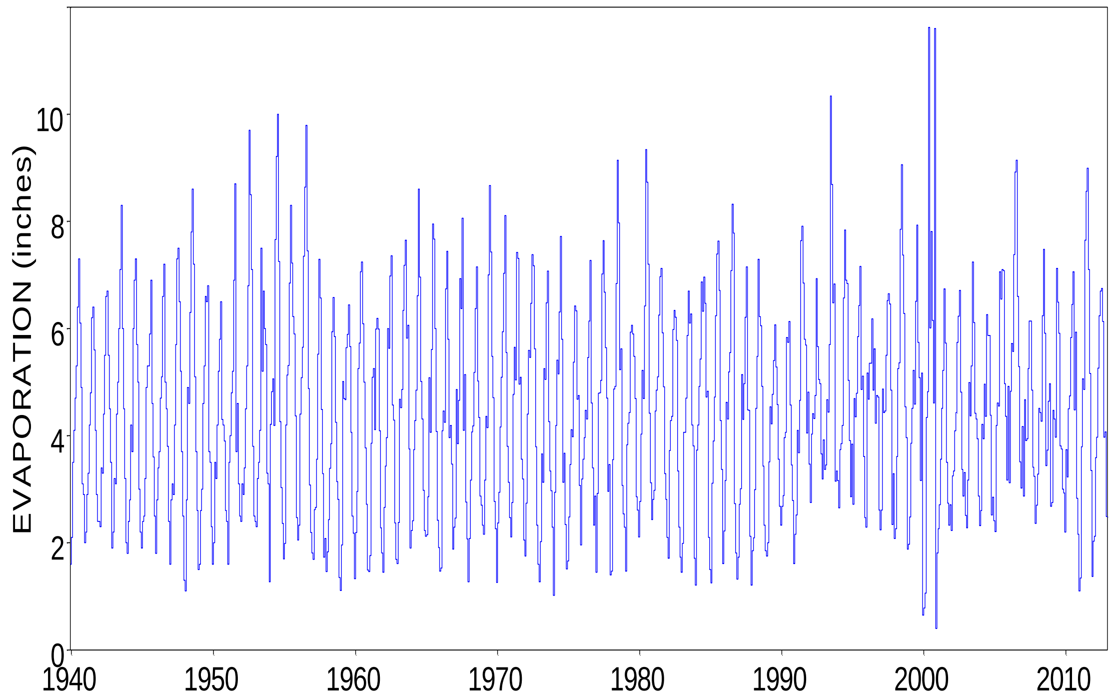
Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles 410



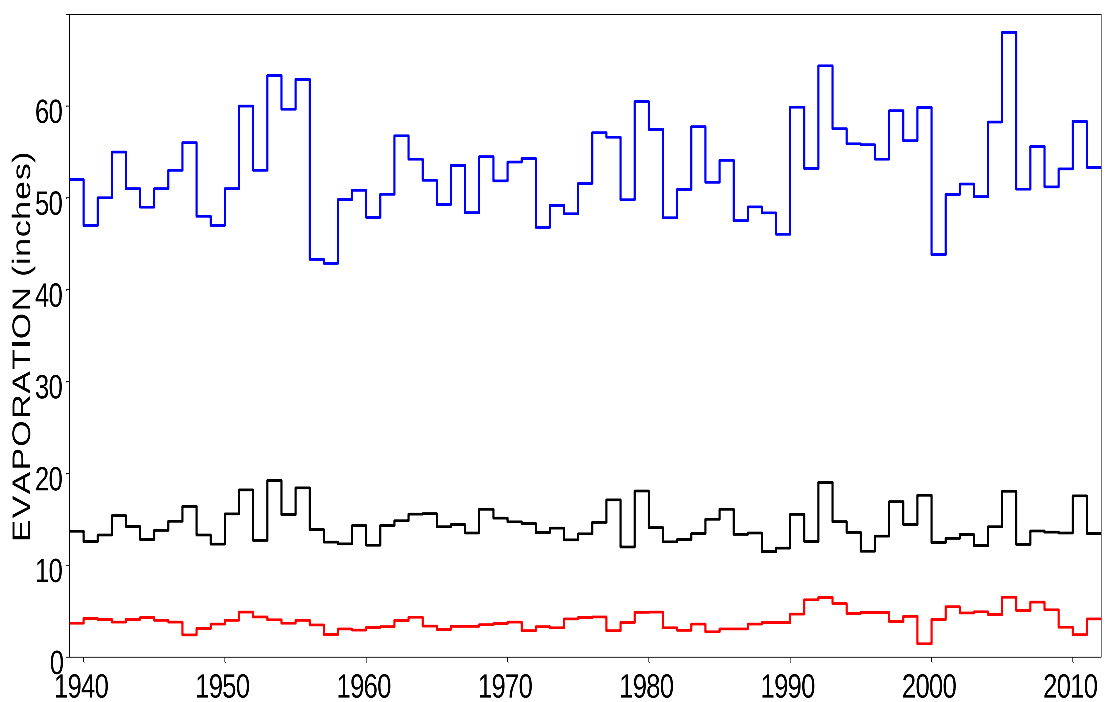
Monthly Evaporation for Quadrangle 411



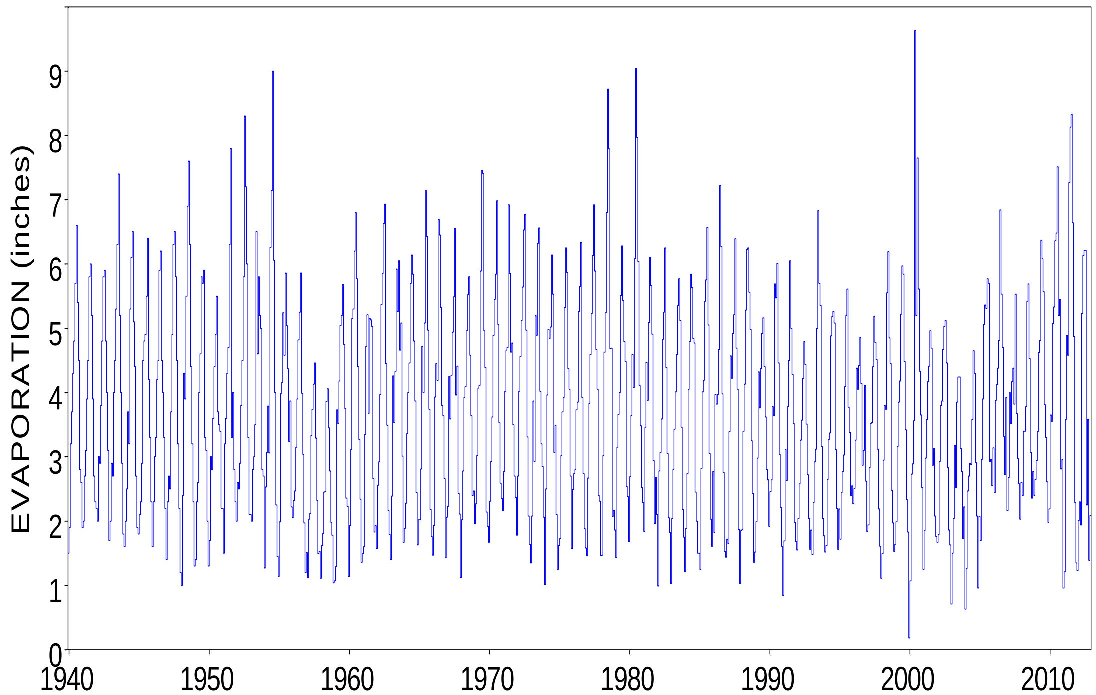
Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles 411



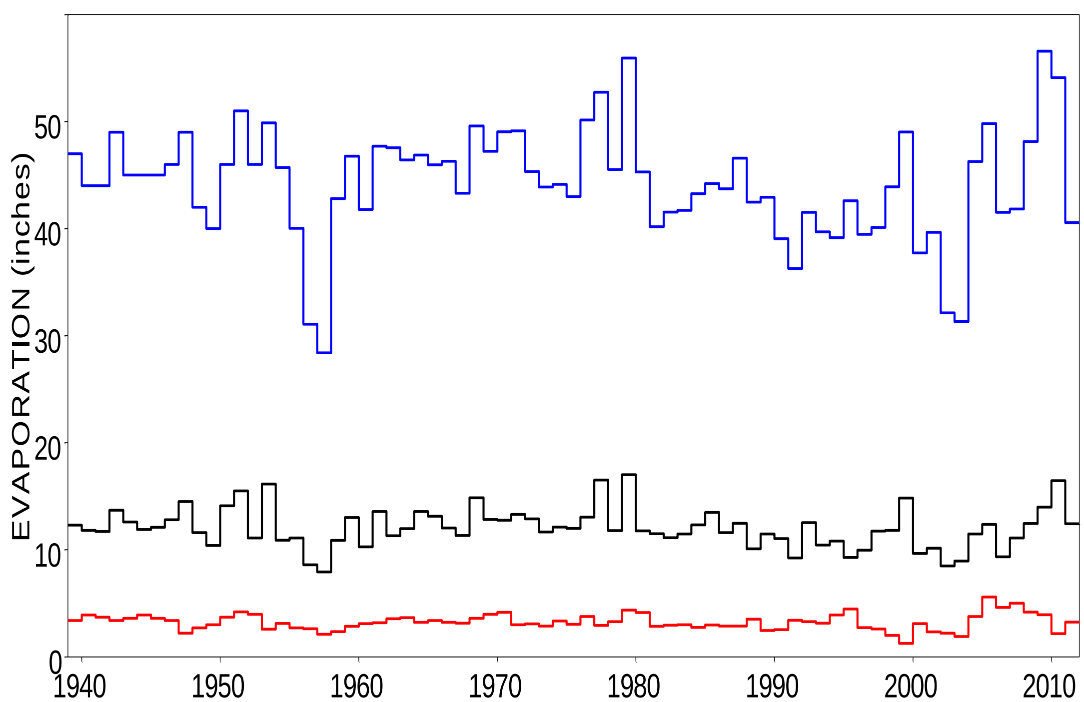
Monthly Evaporation for Quadrangle 412



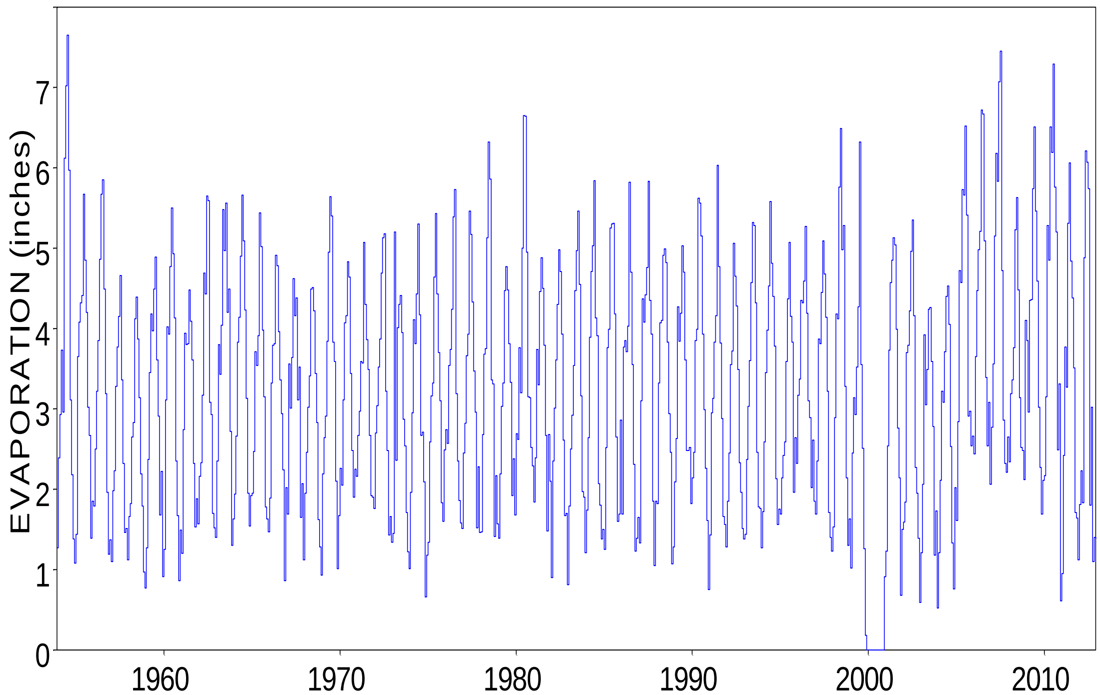
Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles 412



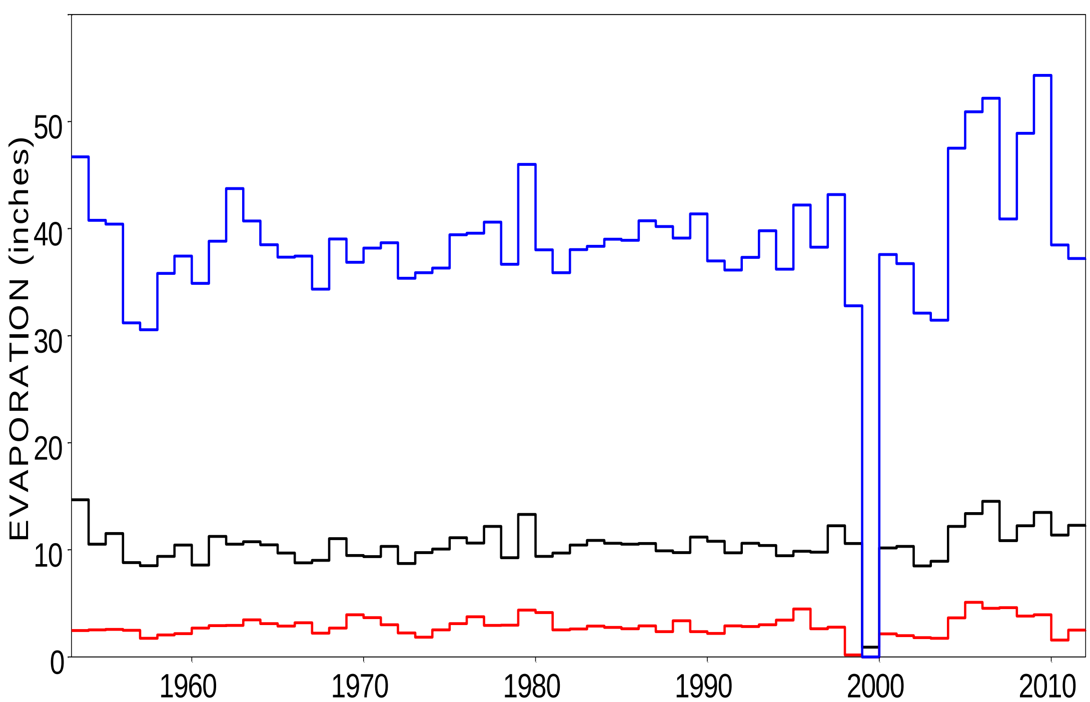
Monthly Evaporation for Quadrangle 413



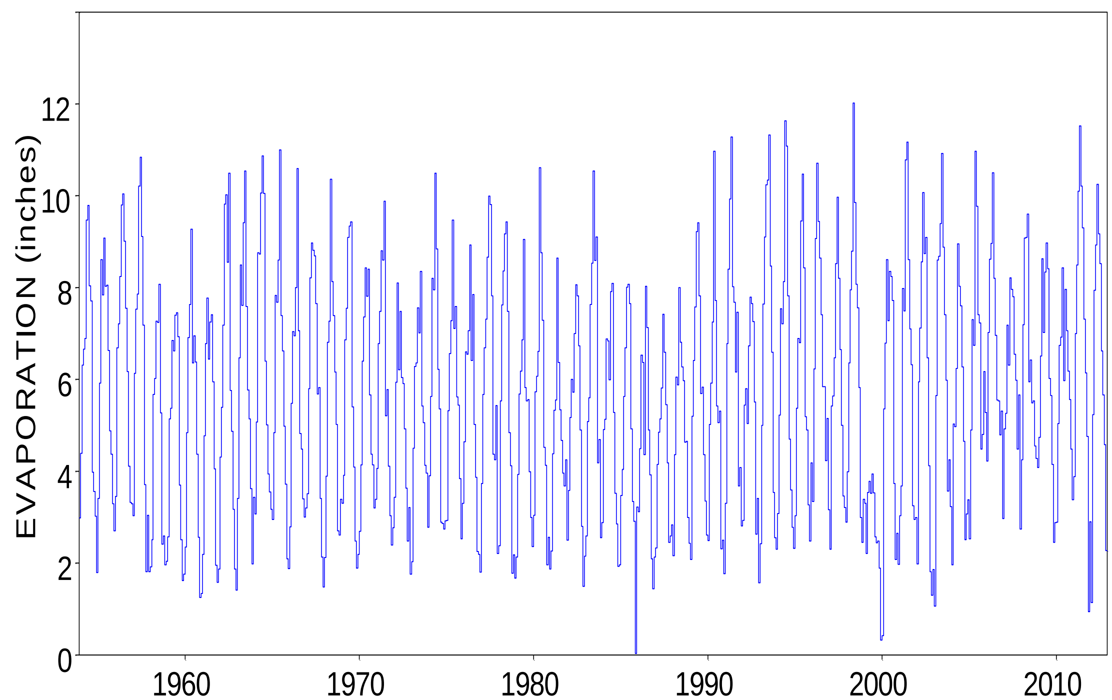
Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles 413



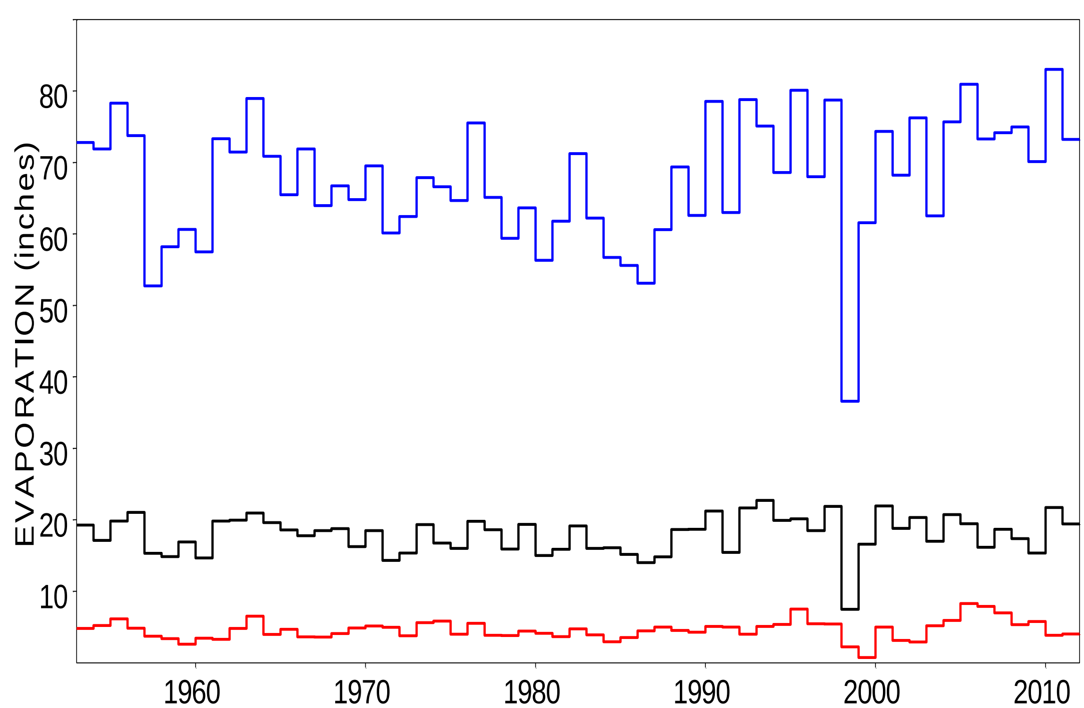
Monthly Evaporation for Quadrangle 414(missing date in 2000)



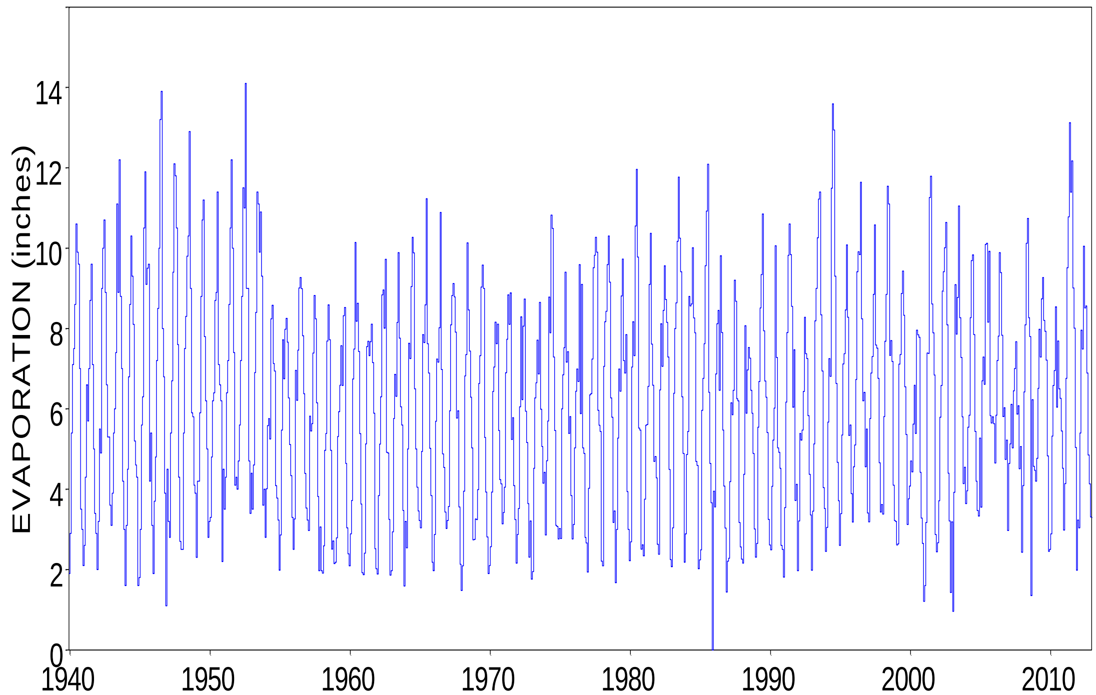
Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles 414
(missing date in 2000)



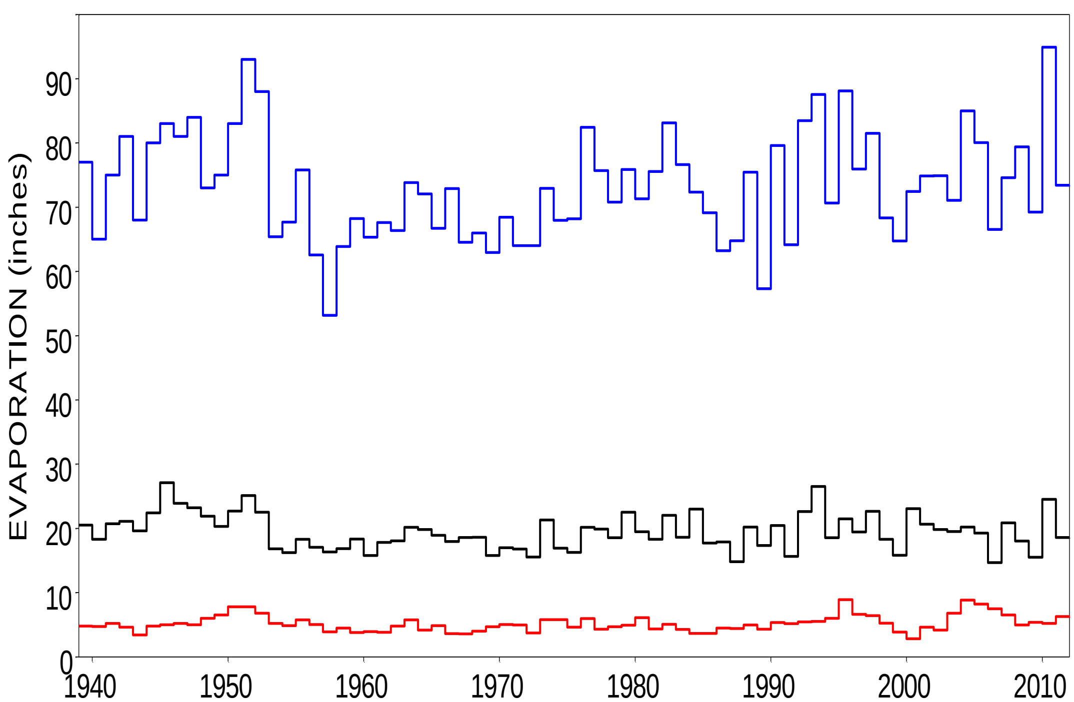
Monthly Evaporation for Quadrangle 504



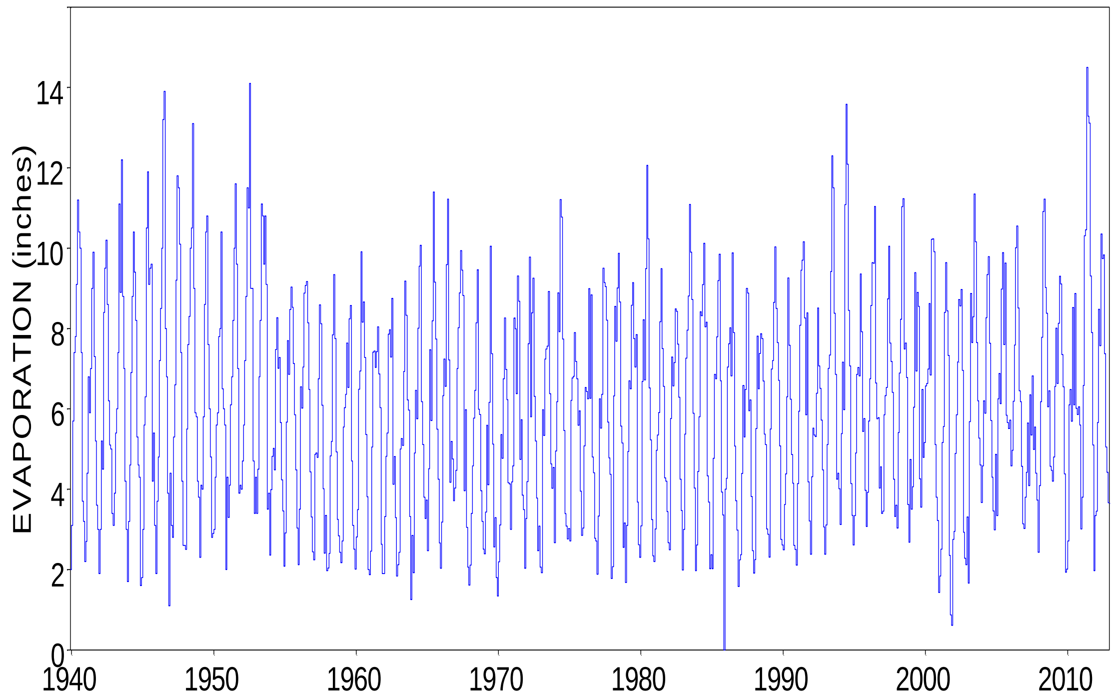
Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles 504



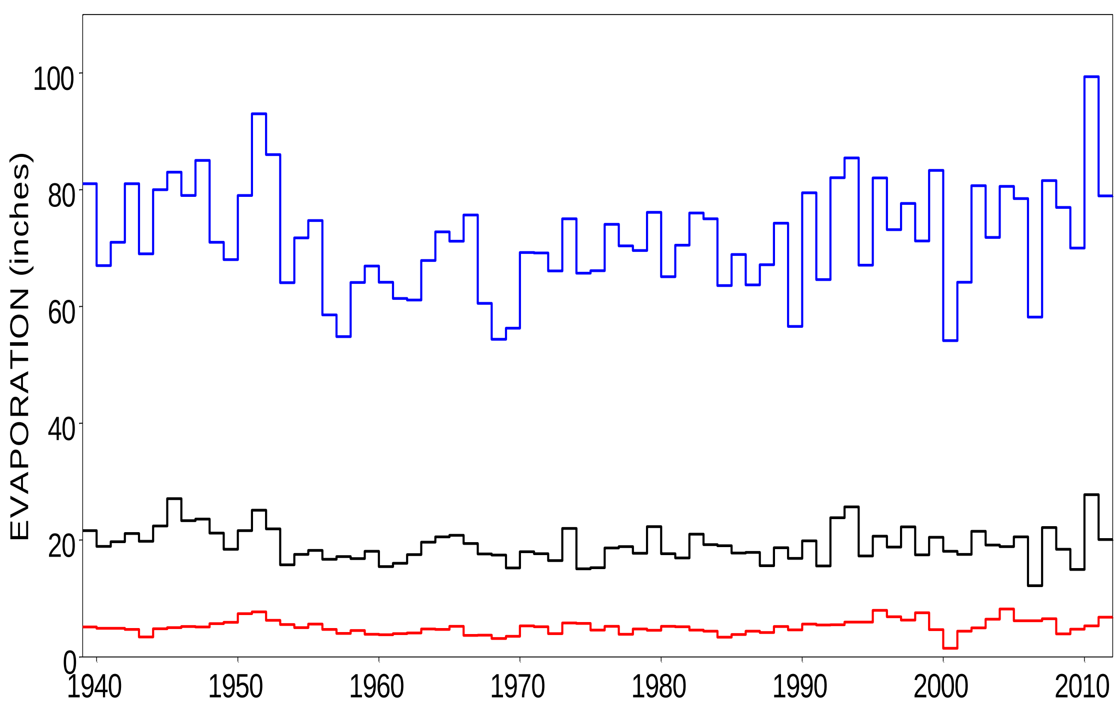
Monthly Evaporation for Quadrangle 505



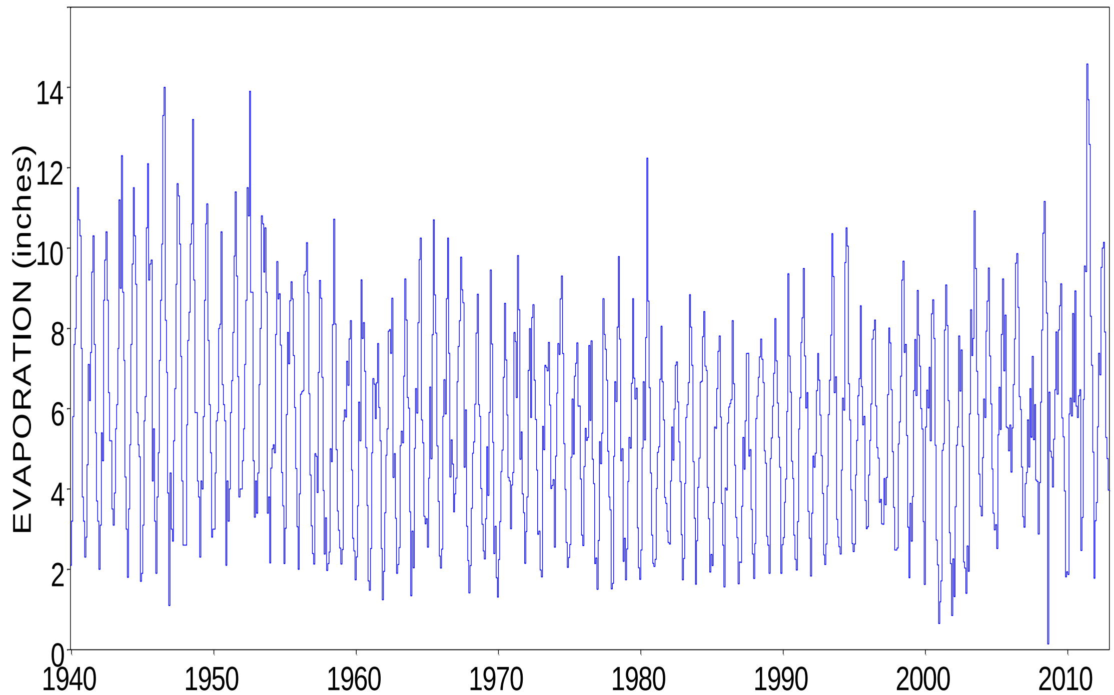
Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles 505



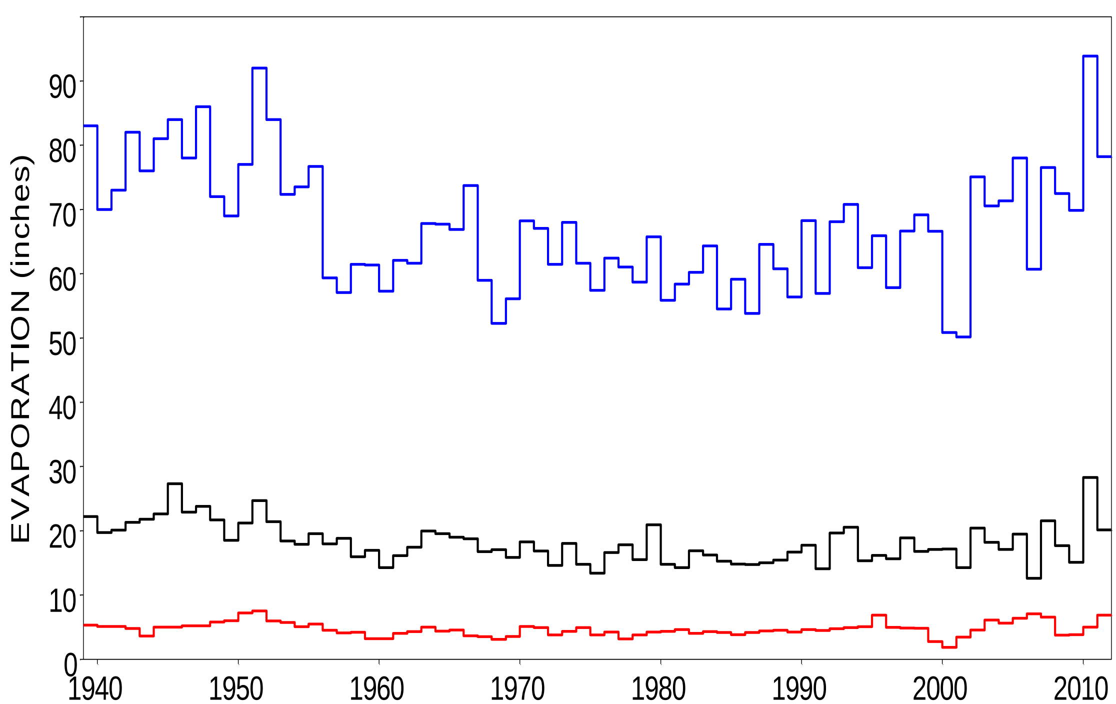
Monthly Evaporation for Quadrangle 506



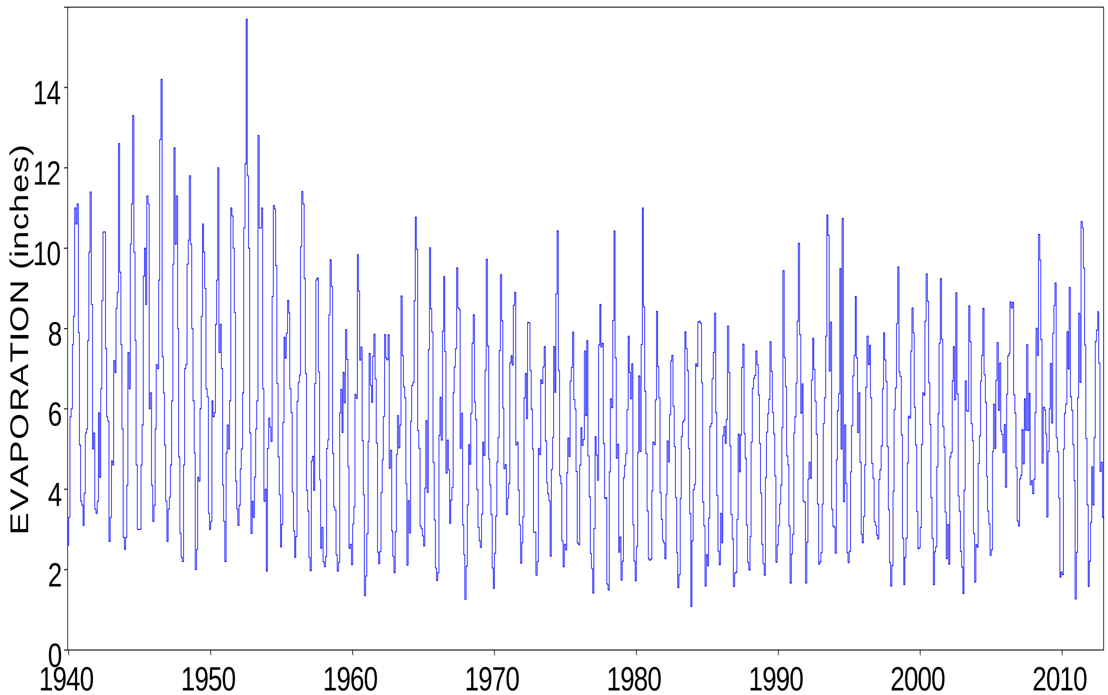
Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles 506



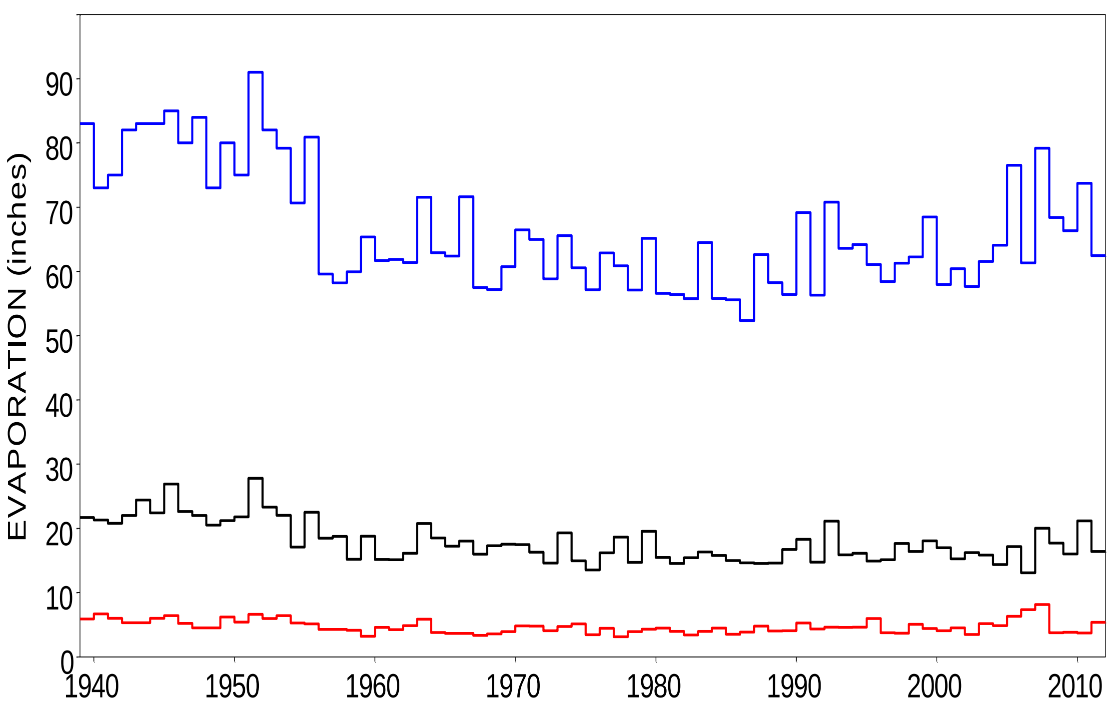
Monthly Evaporation for Quadrangle 507



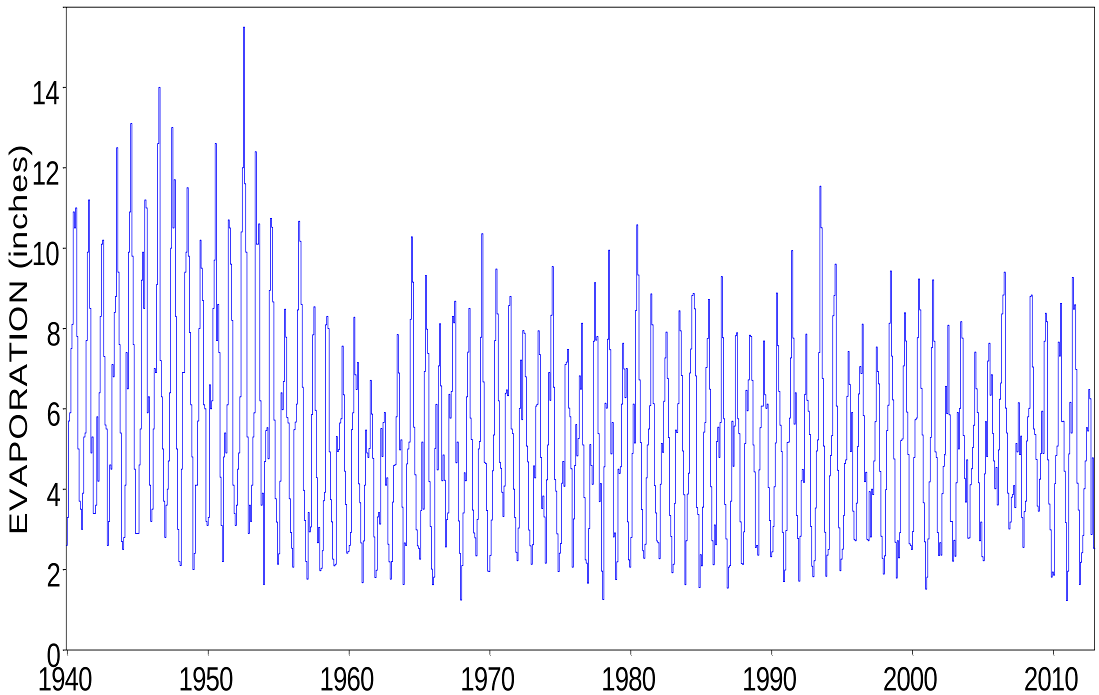
Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles 507



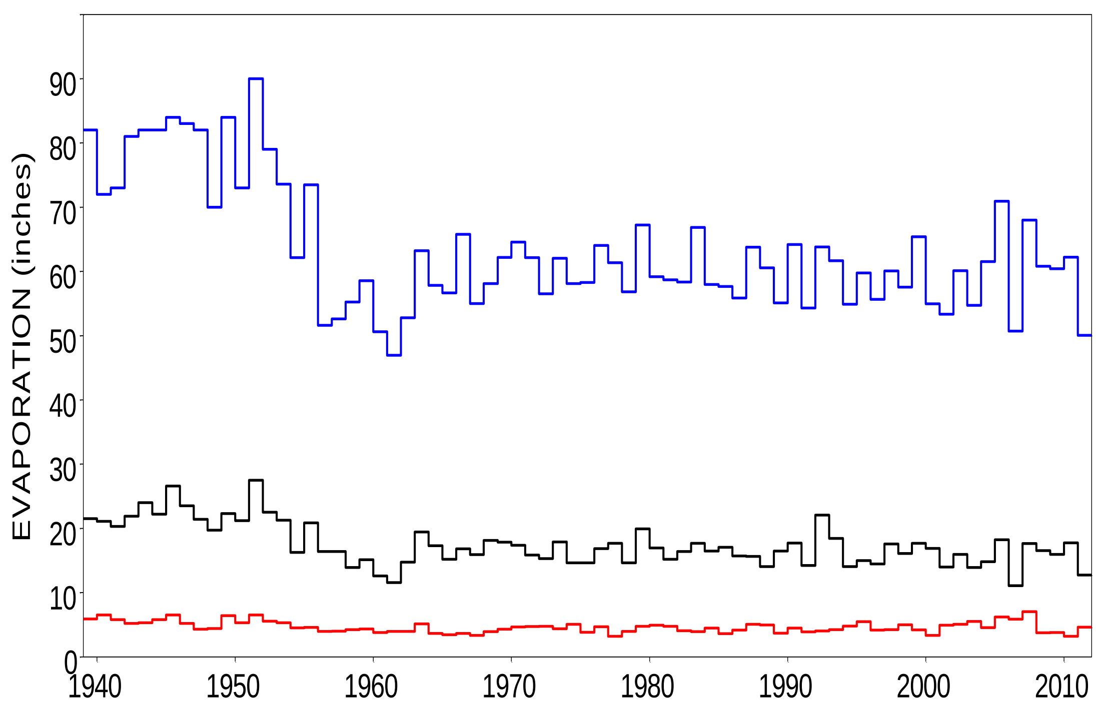
Monthly Evaporation for Quadrangle 508



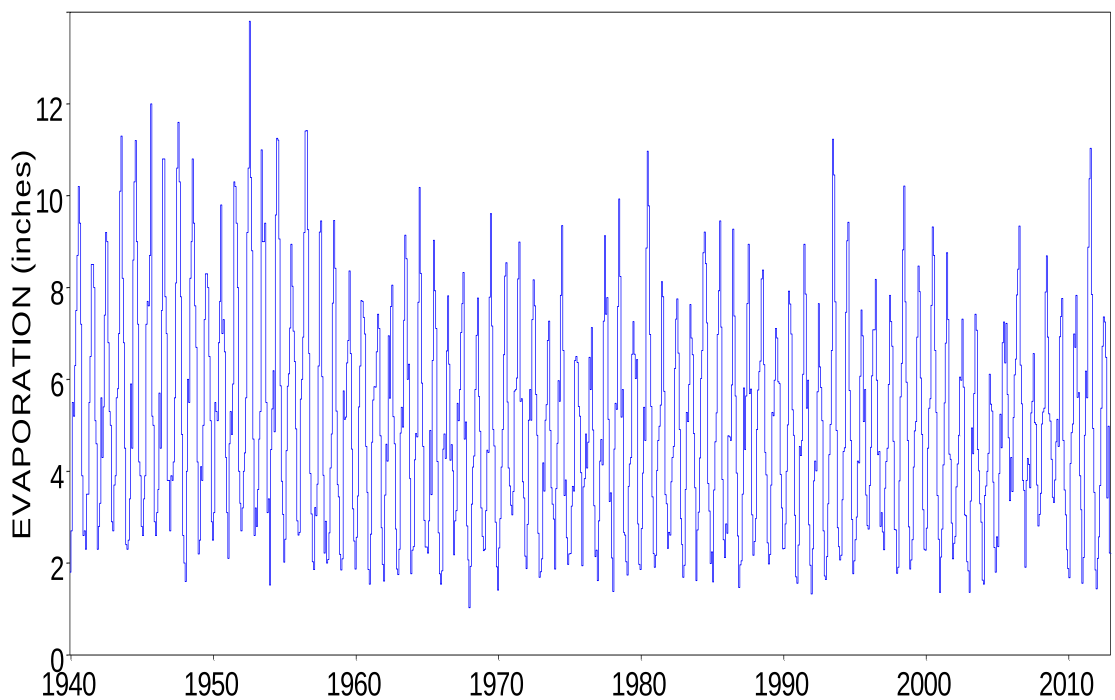
Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles 508



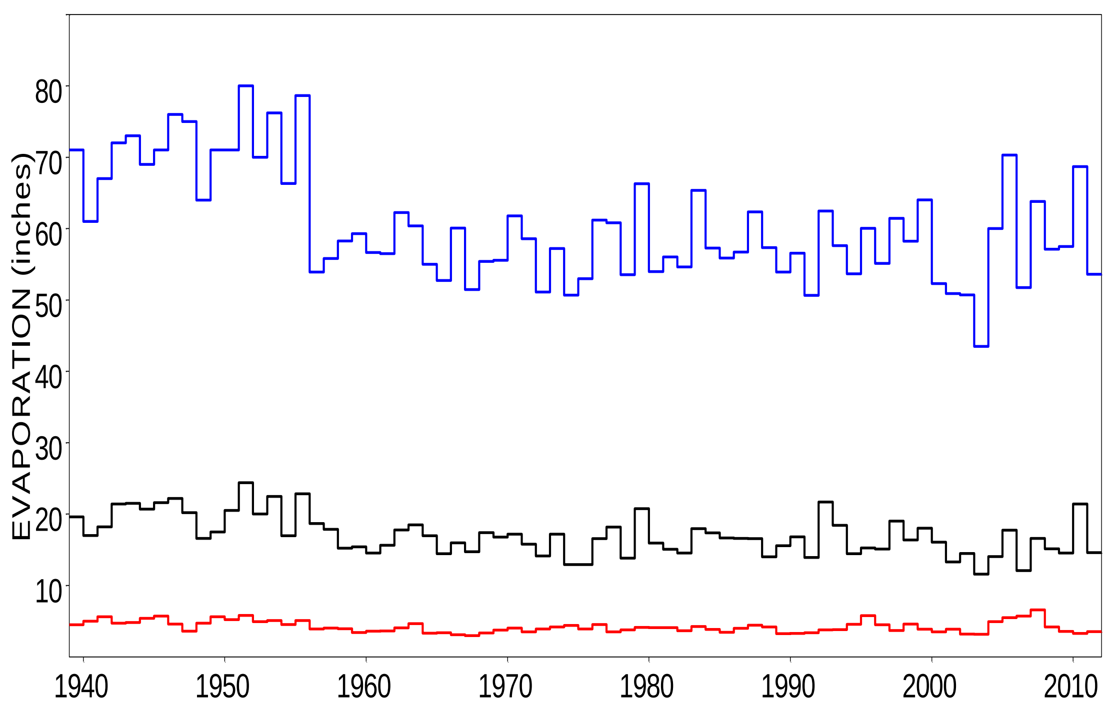
Monthly Evaporation for Quadrangle 509



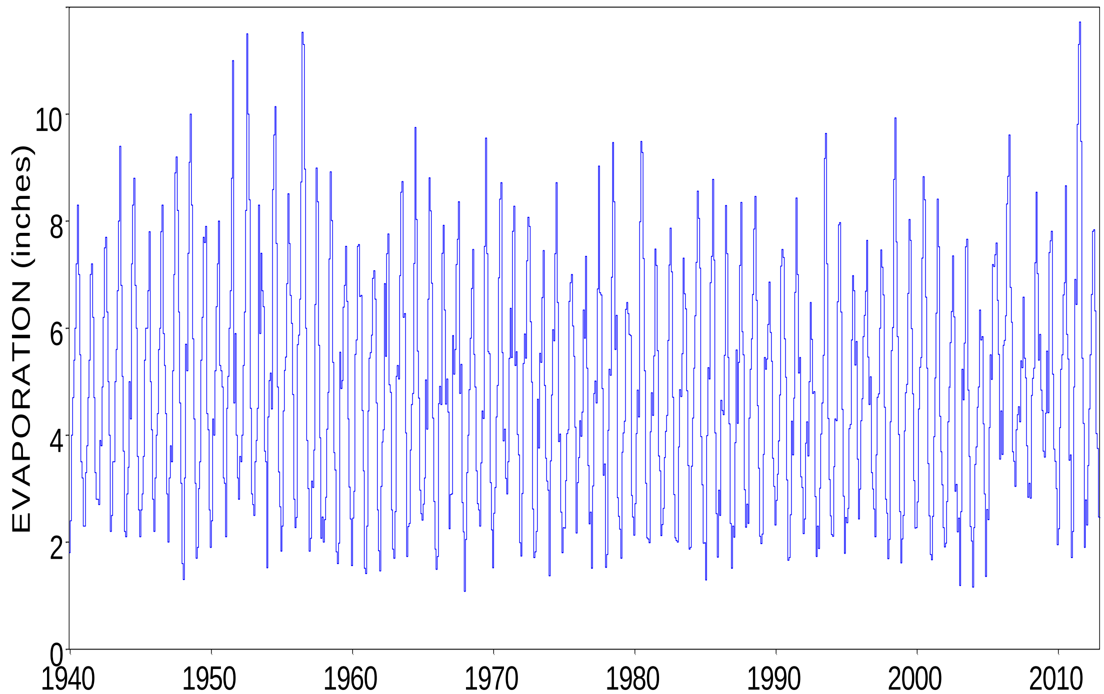
Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles 509



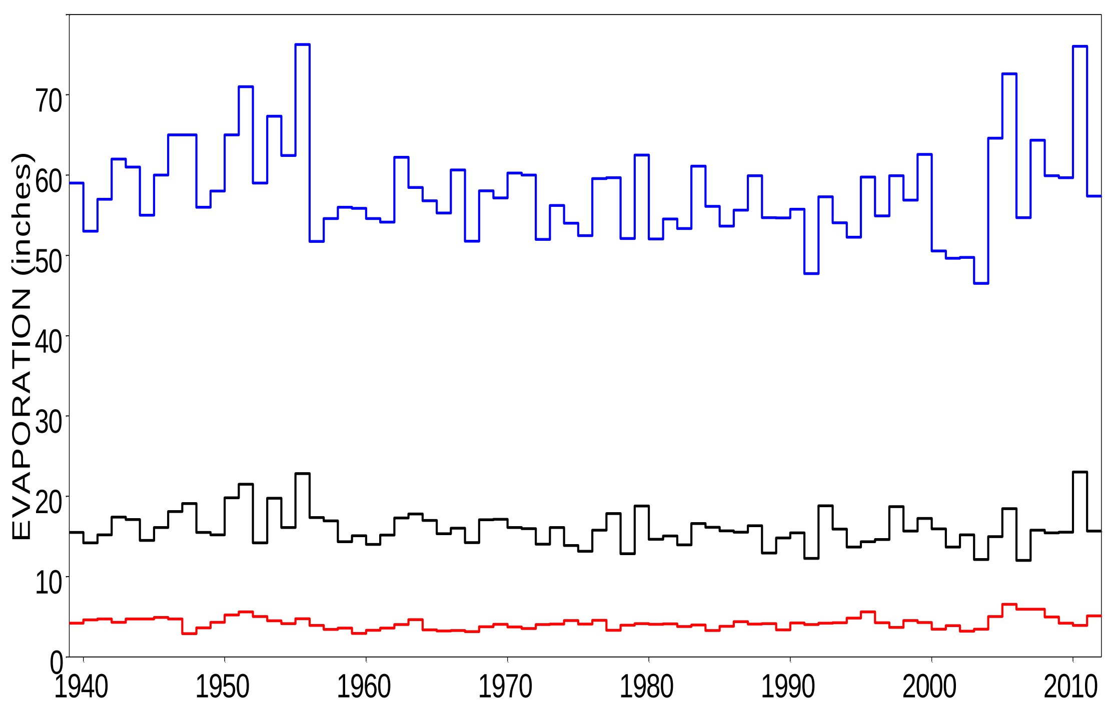
Monthly Evaporation for Quadrangle 510



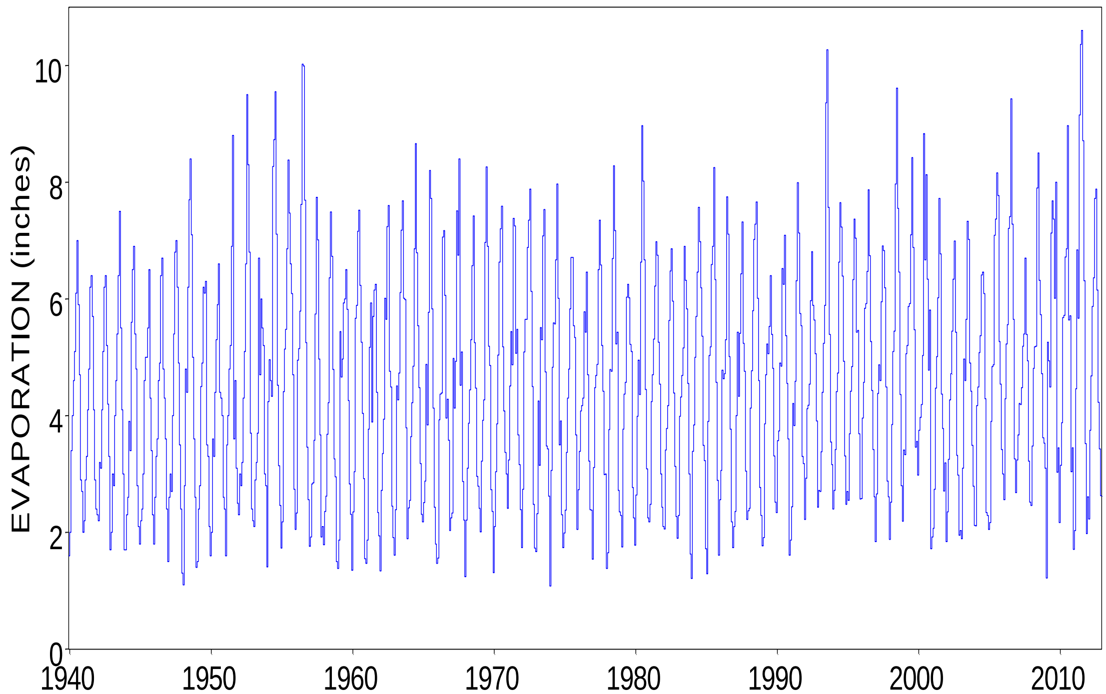
Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles 510



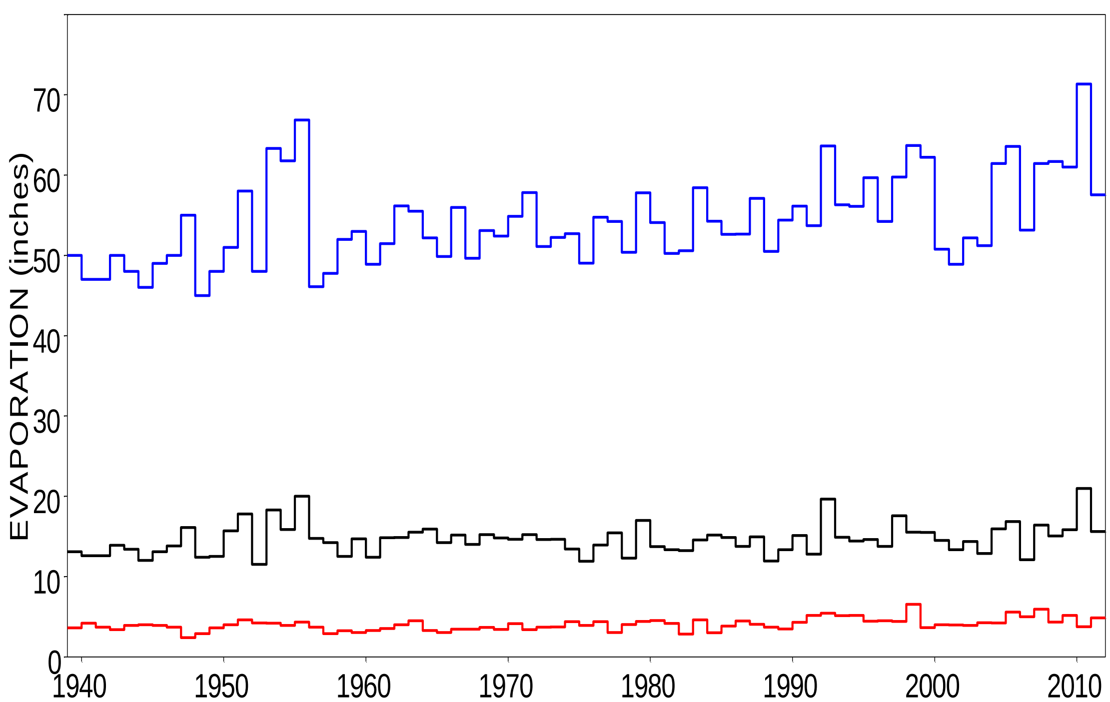
Monthly Evaporation for Quadrangle 511



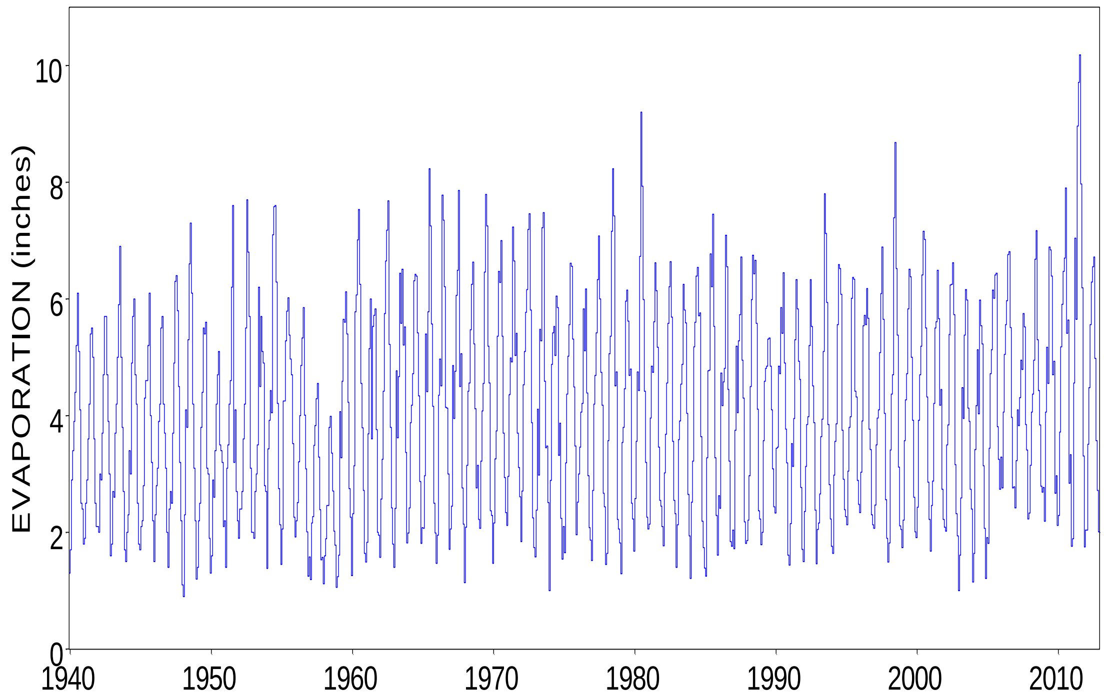
Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles 511



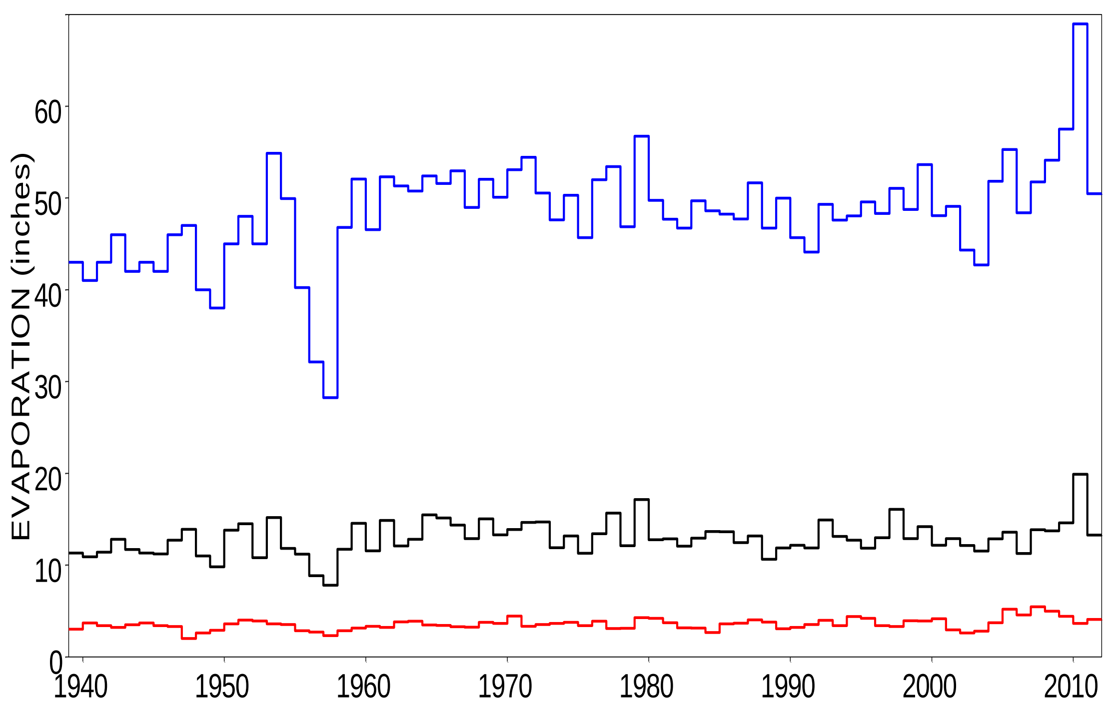
Monthly Evaporation for Quadrangle 512



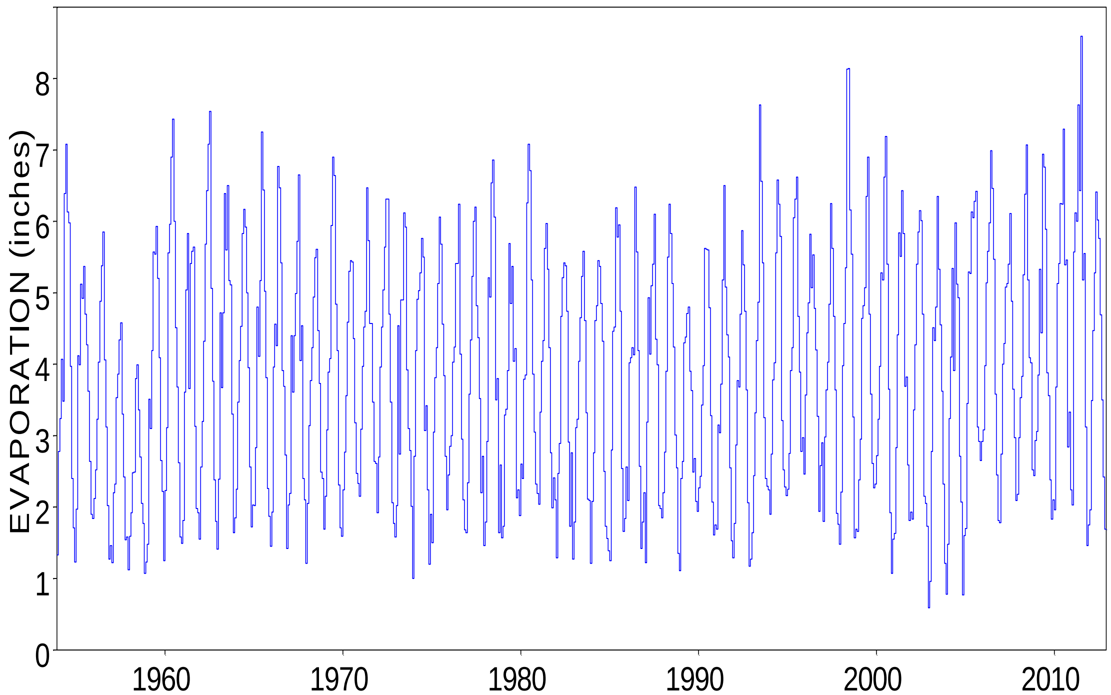
Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles 512



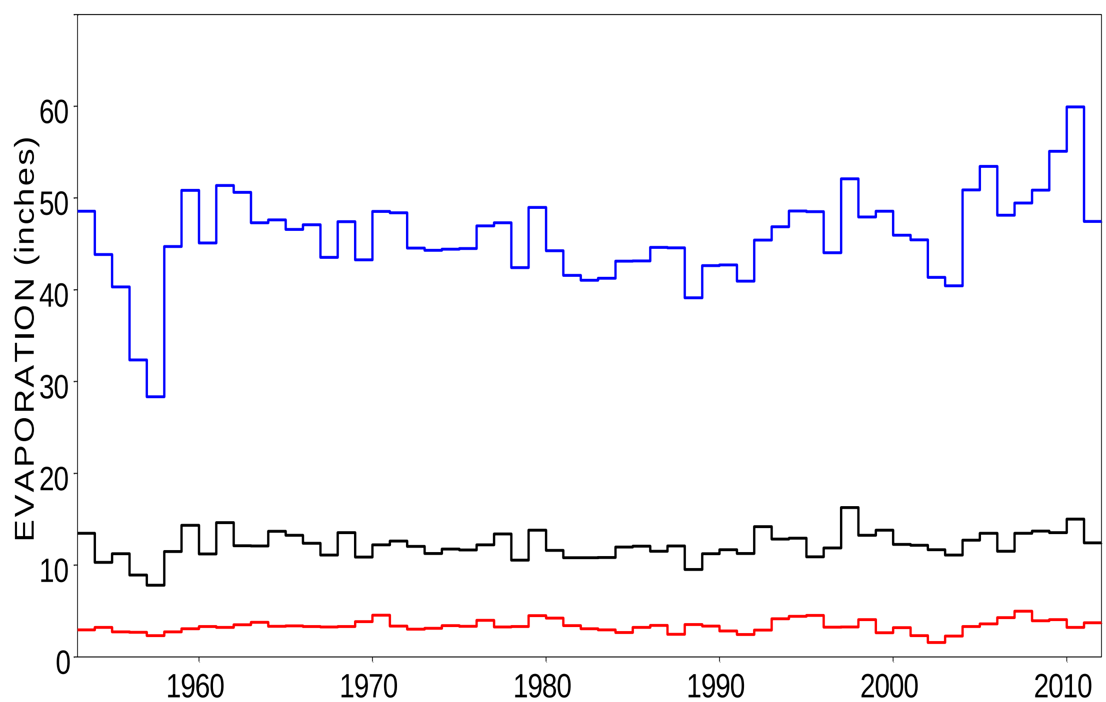
Monthly Evaporation for Quadrangle 513



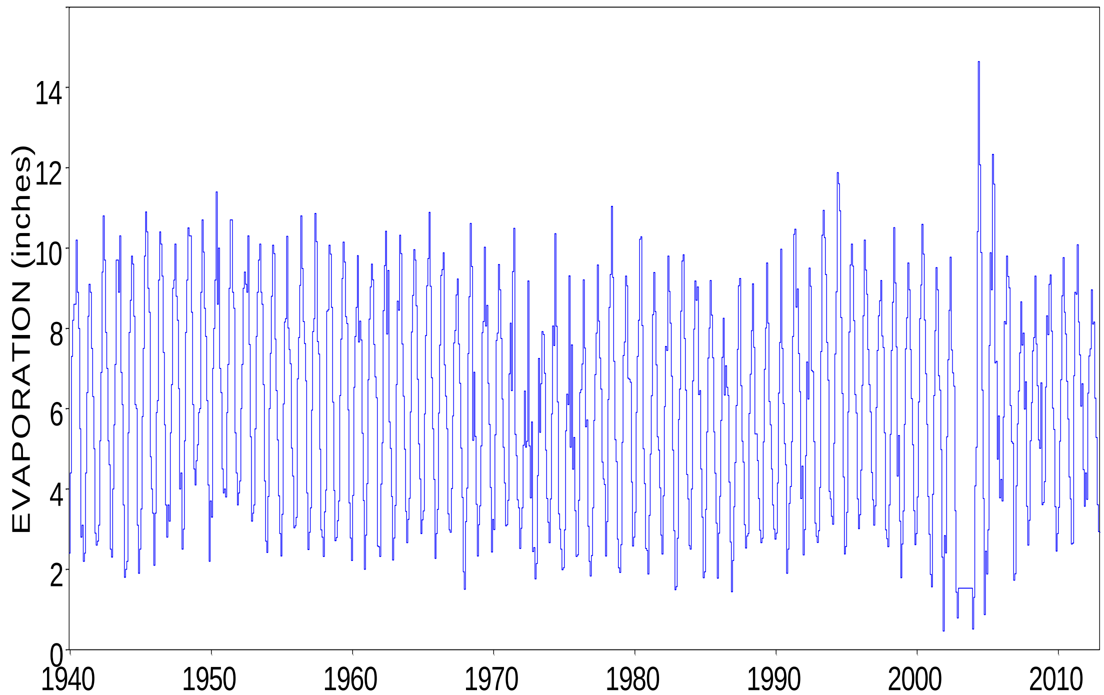
Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles 513



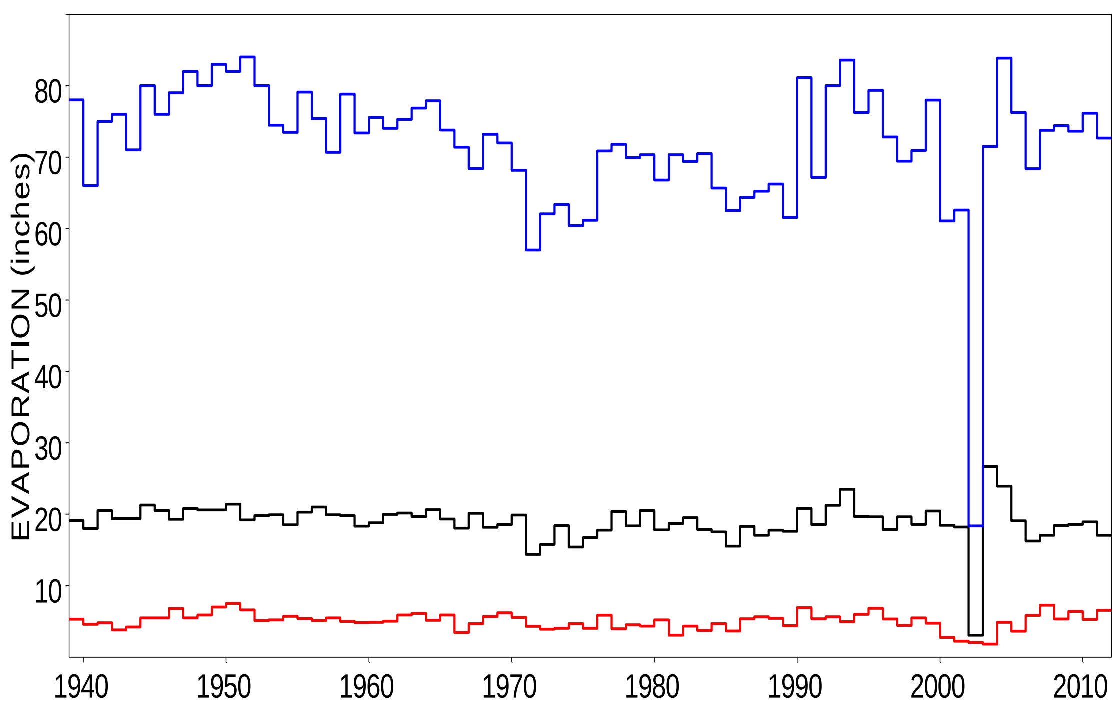
Monthly Evaporation for Quadrangle 514



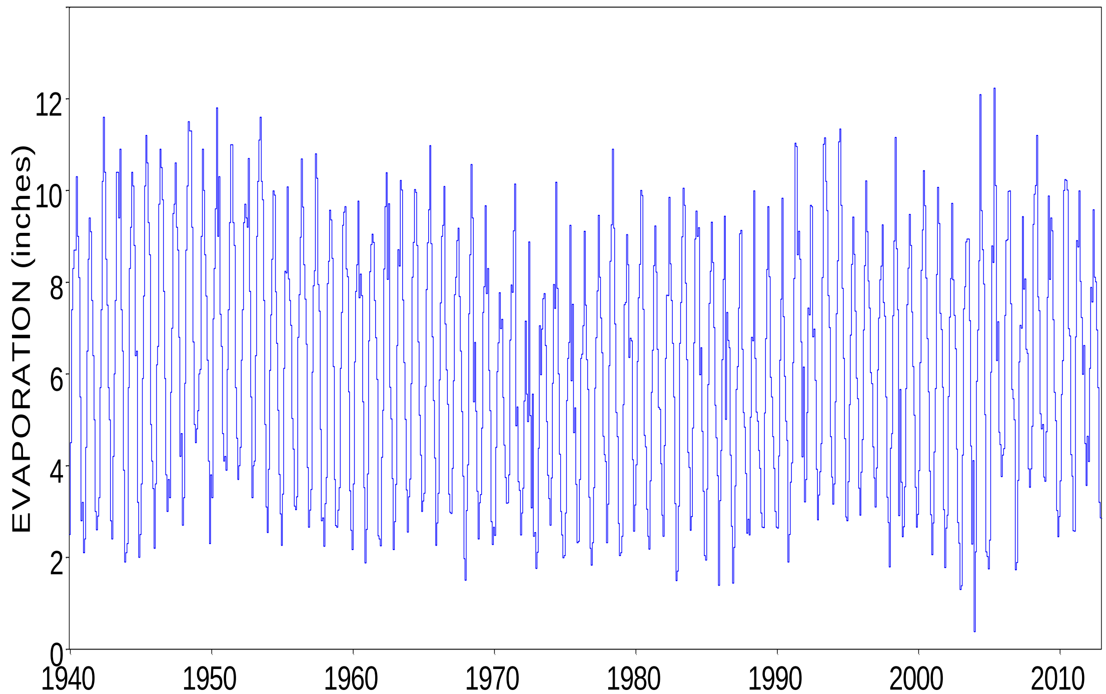
Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles 514



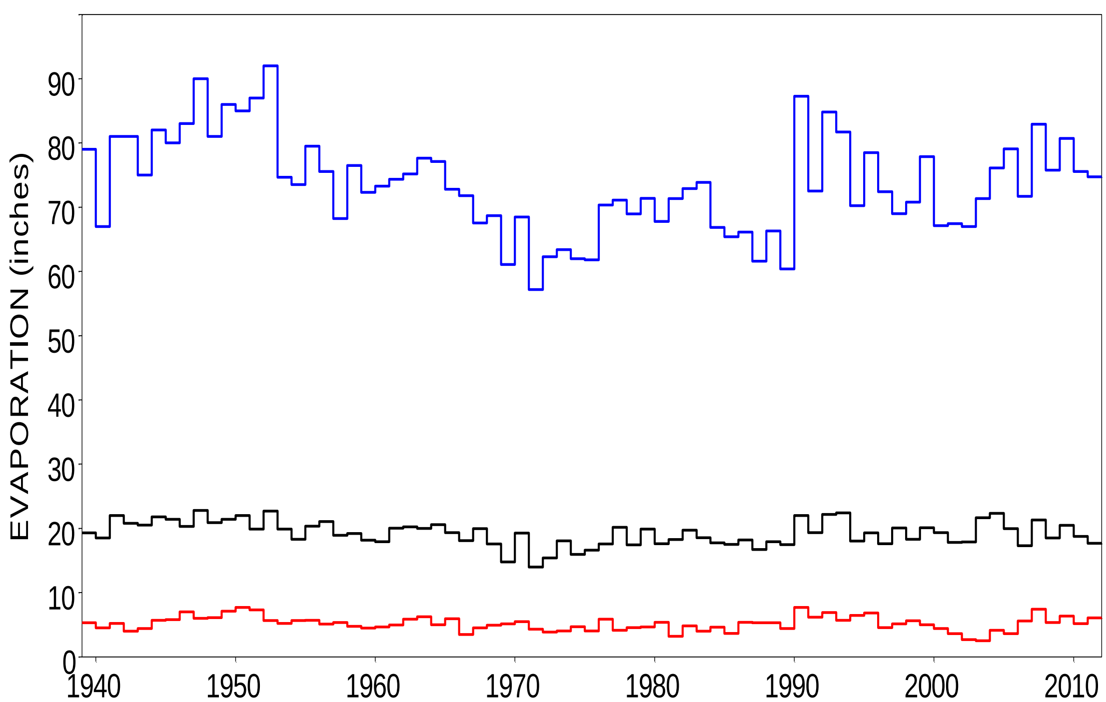
Monthly Evaporation for Quadrangle 601



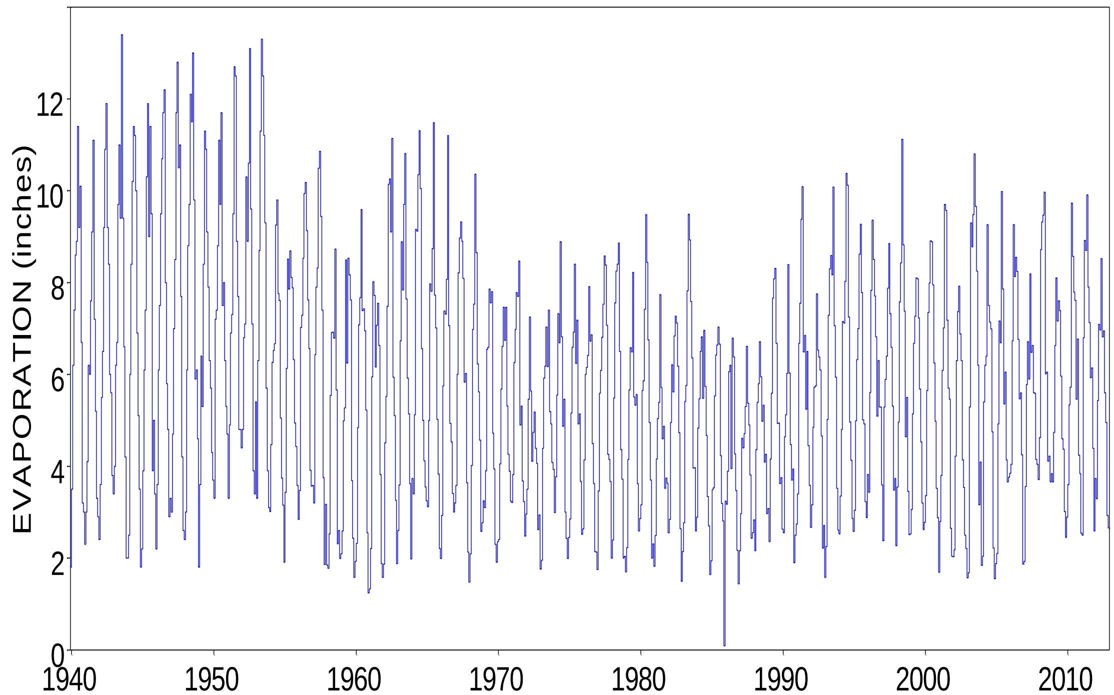
Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles 601



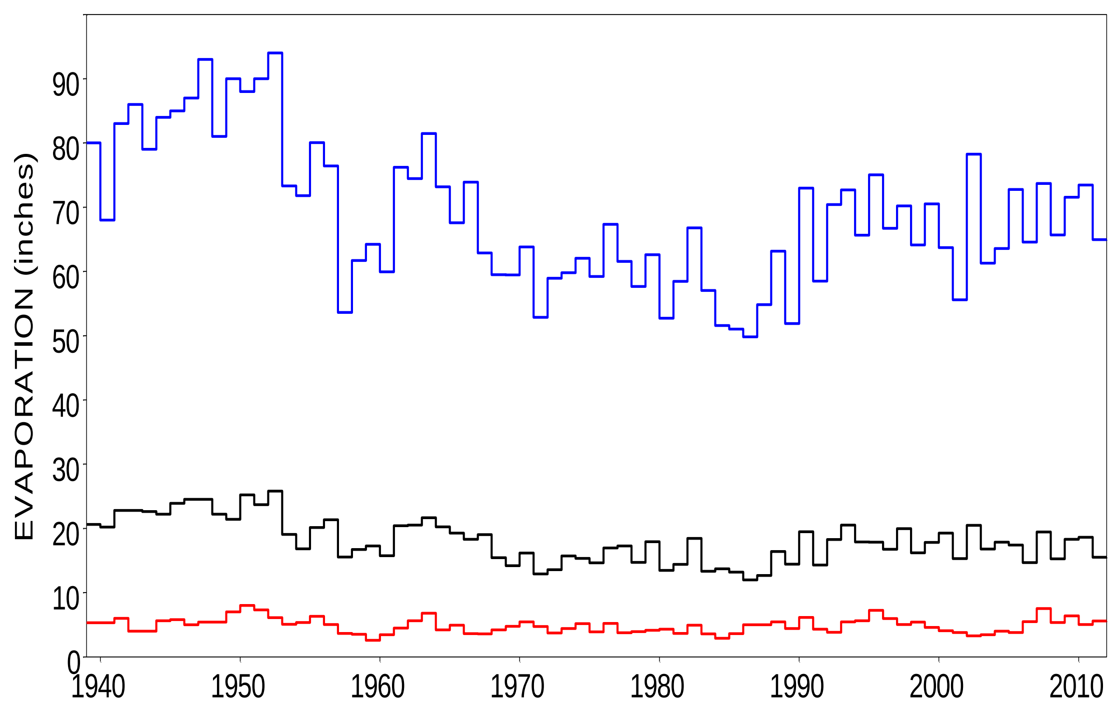
Monthly Evaporation for Quadrangle 602



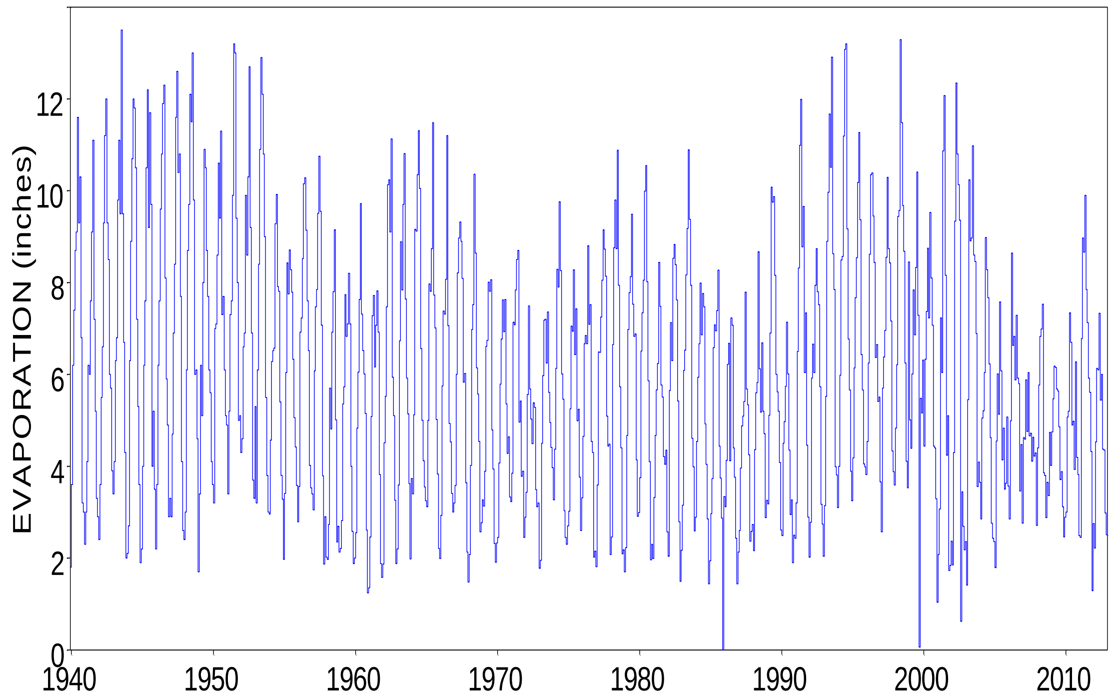
Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles 602



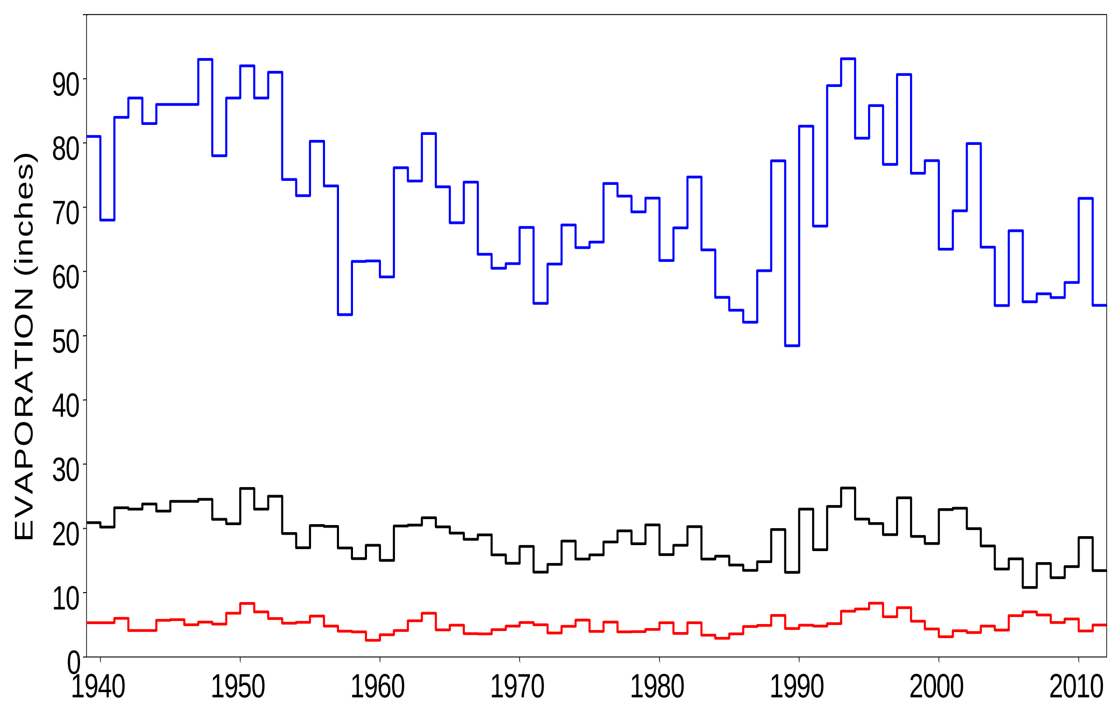
Monthly Evaporation for Quadrangle 603



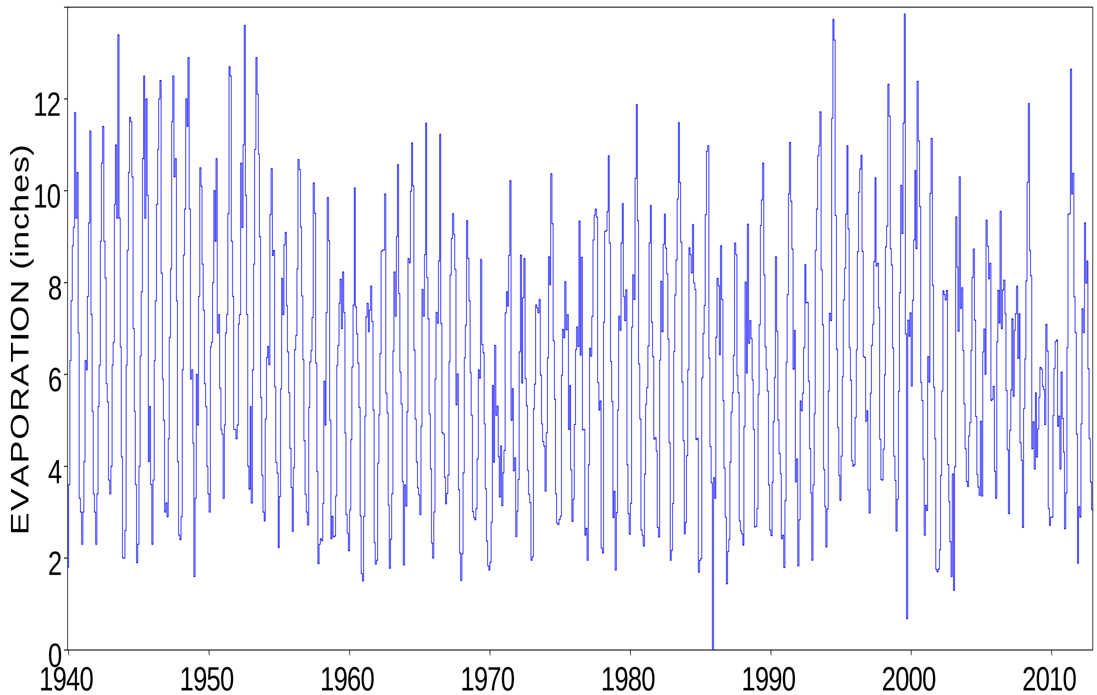
Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles 603



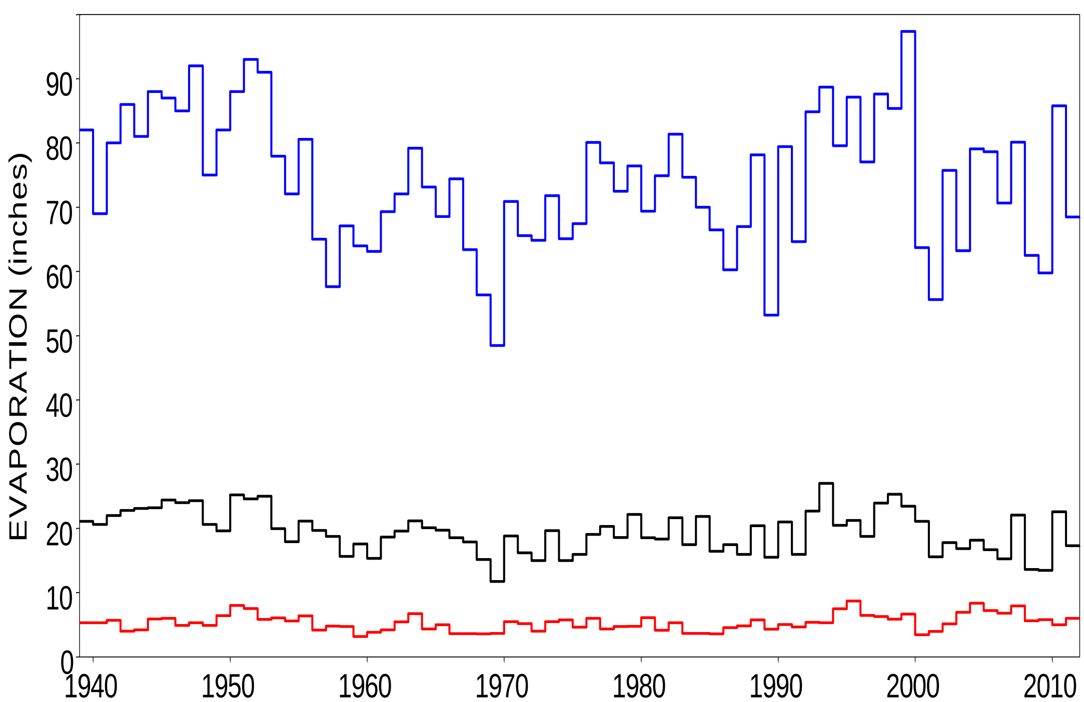
Monthly Evaporation for Quadrangle 604



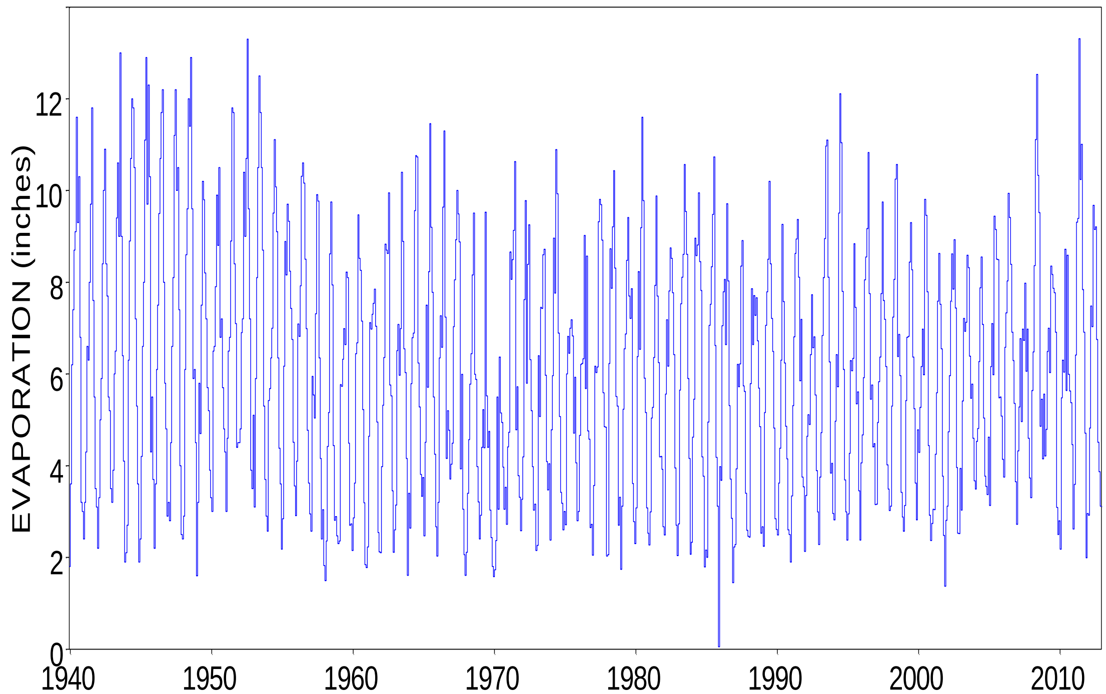
Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles 604



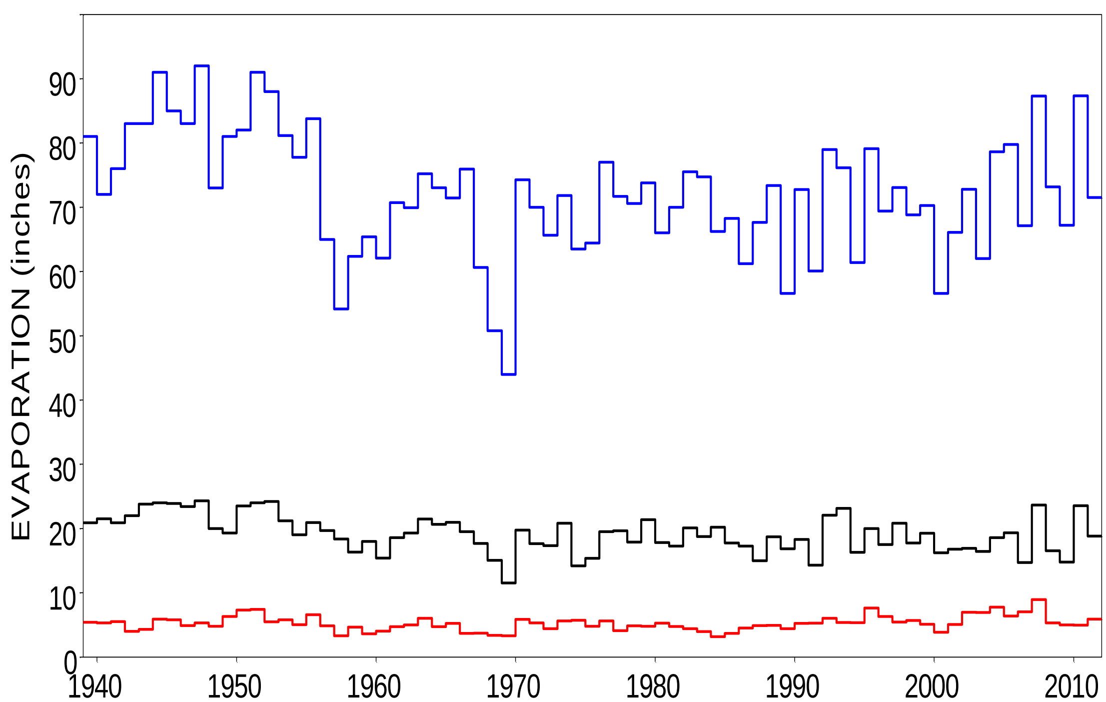
Monthly Evaporation for Quadrangle 605



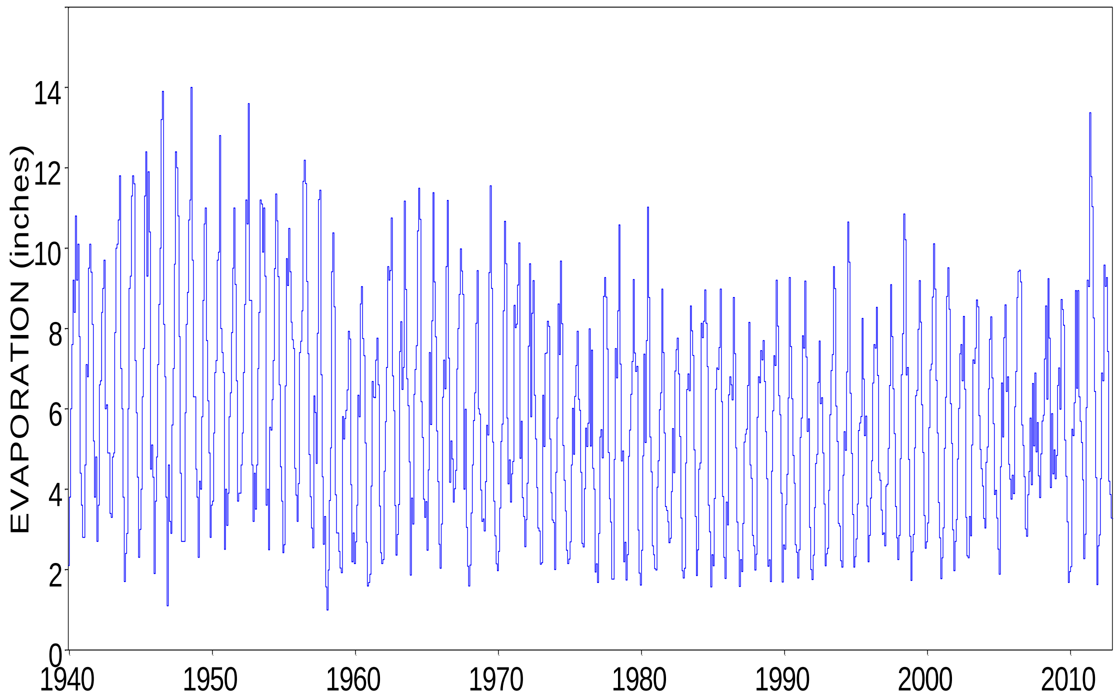
Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles 605



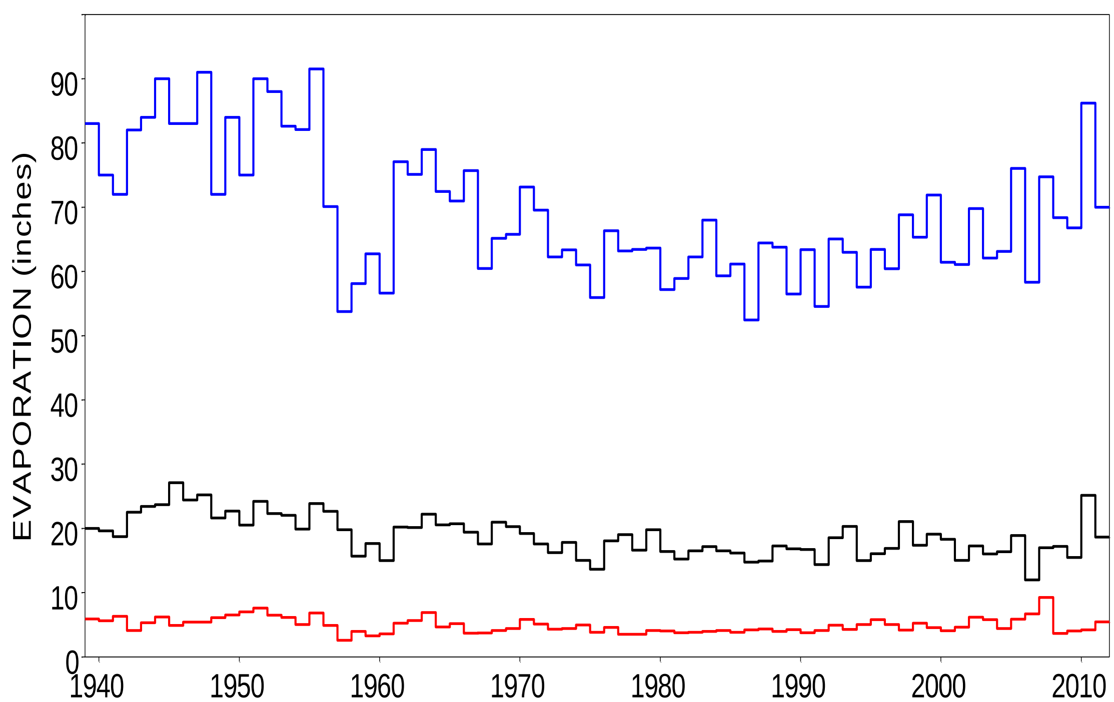
Monthly Evaporation for Quadrangle 606



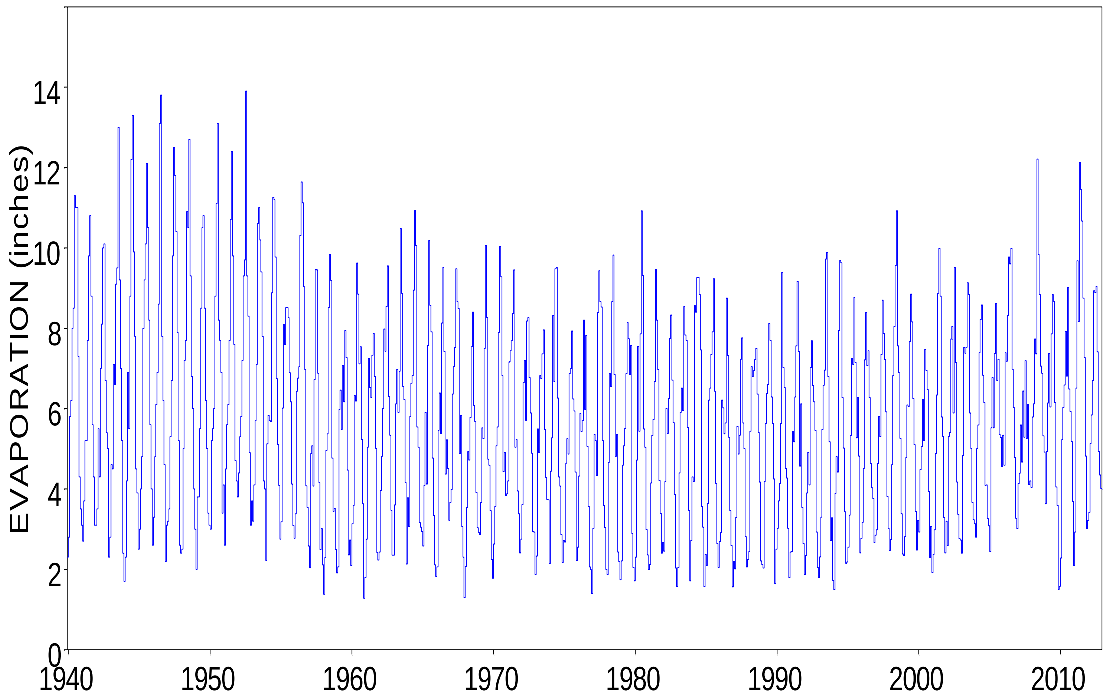
Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles 606



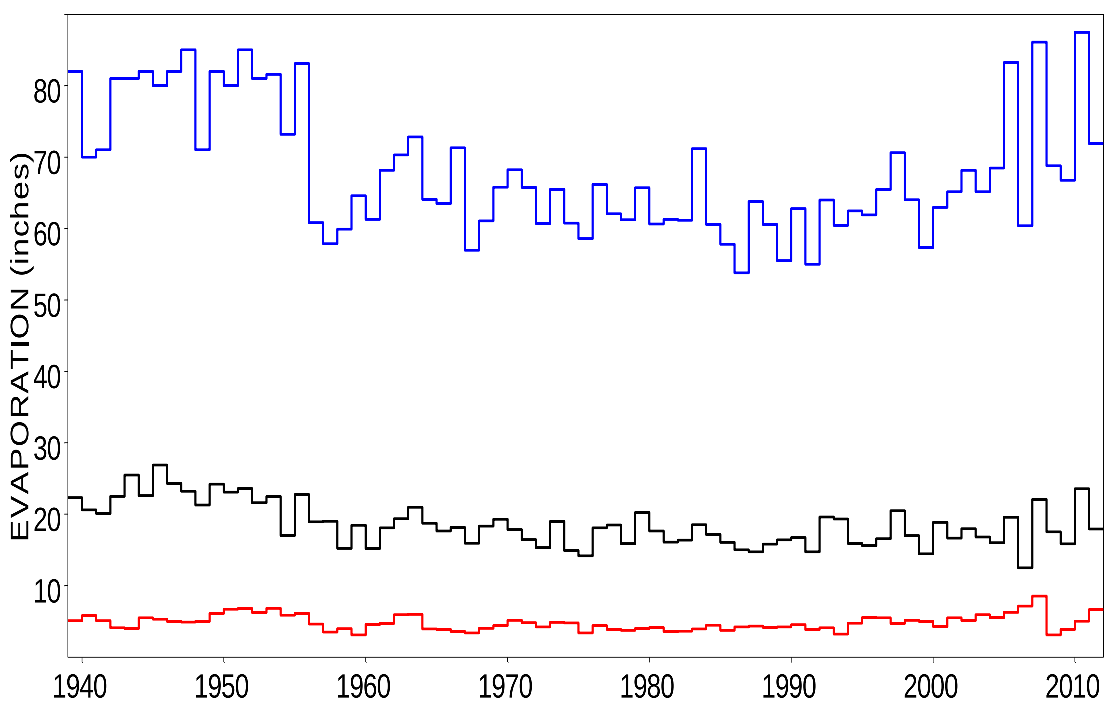
Monthly Evaporation for Quadrangle 607



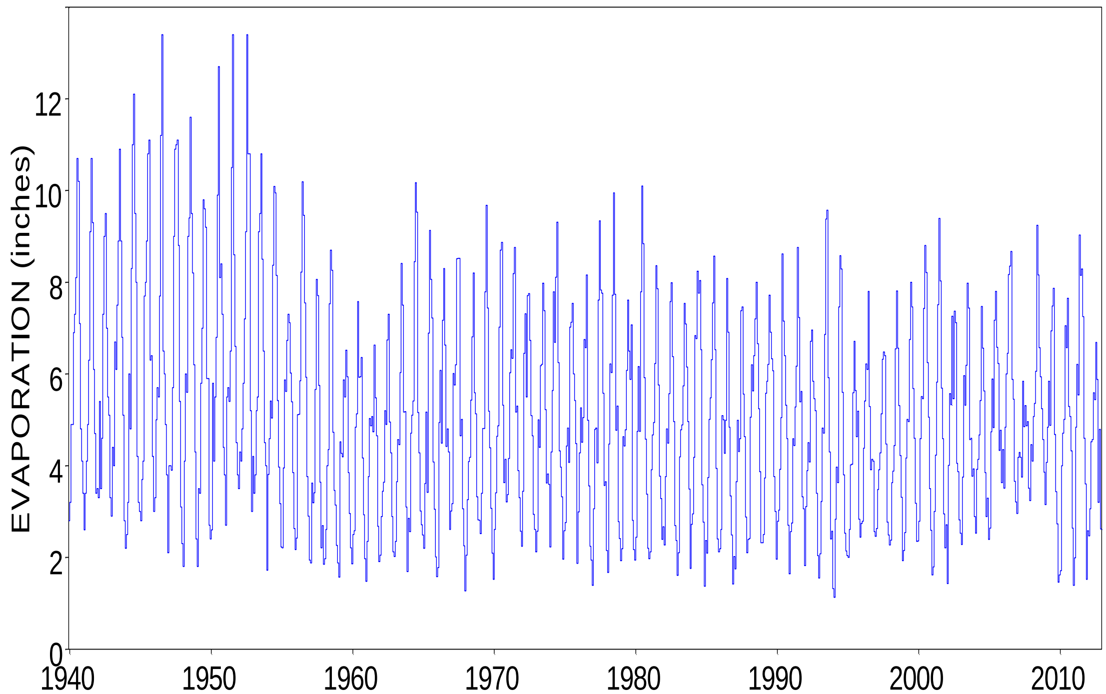
Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles 607



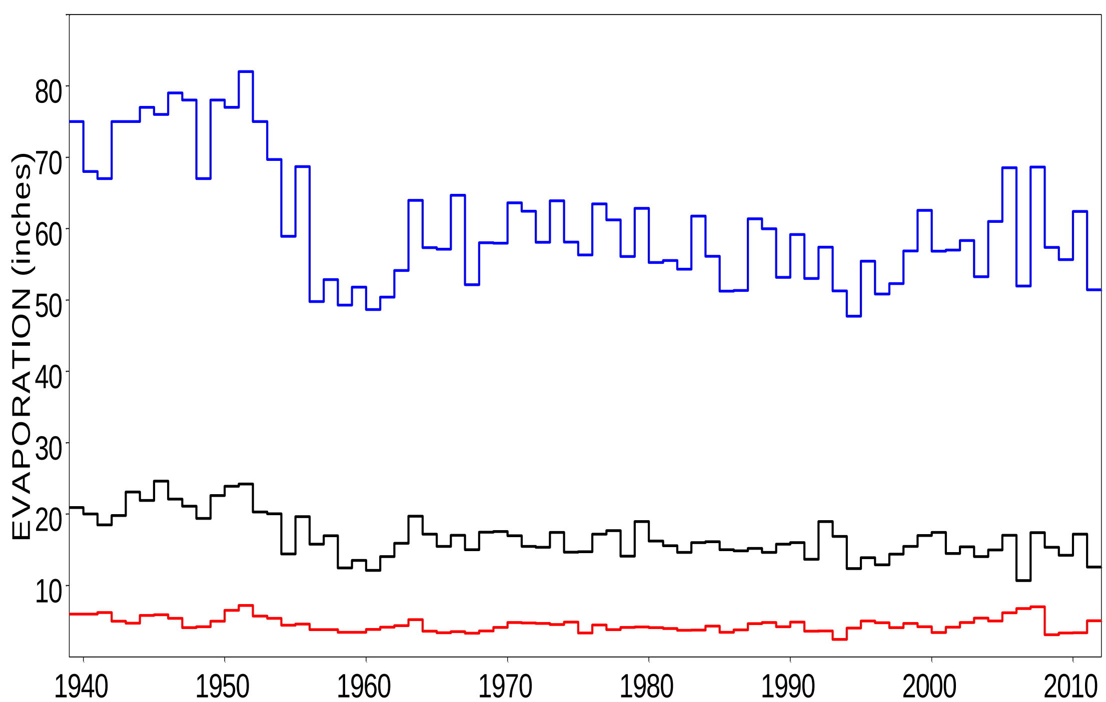
Monthly Evaporation for Quadrangle 608



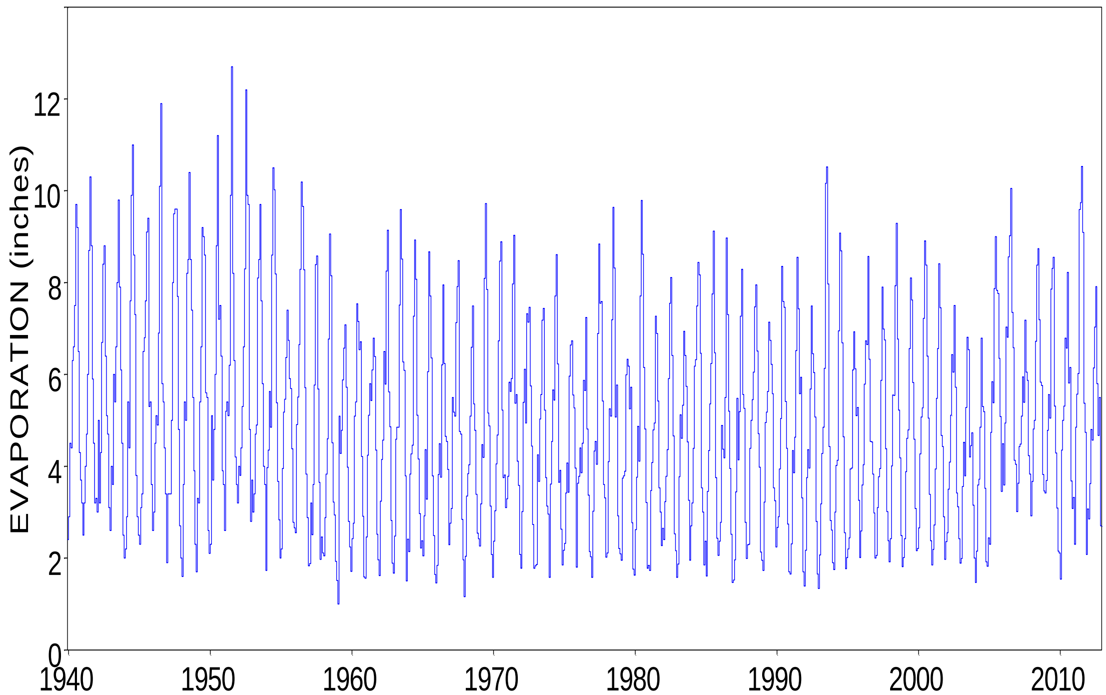
Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles 608



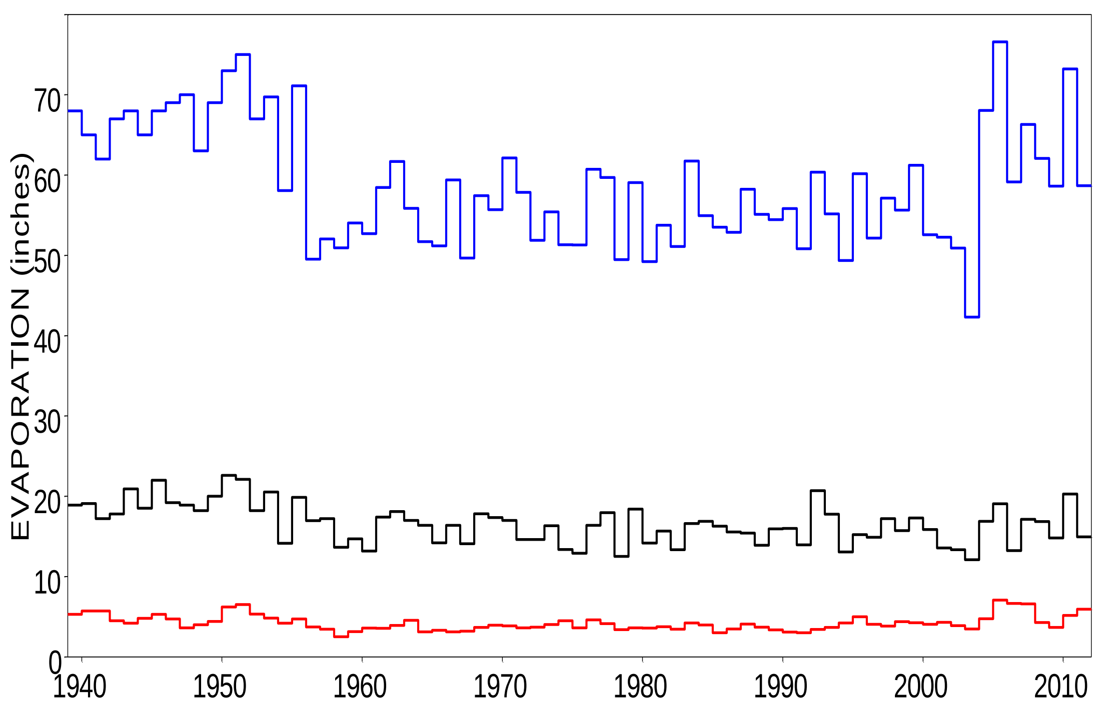
Monthly Evaporation for Quadrangle 609



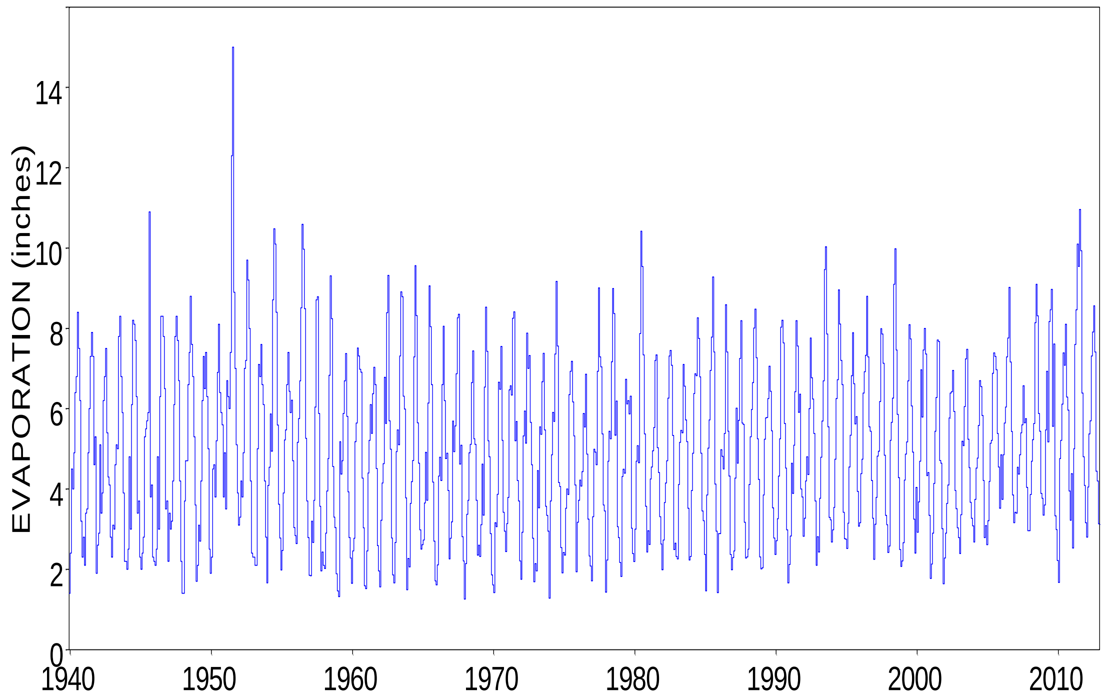
Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles 609



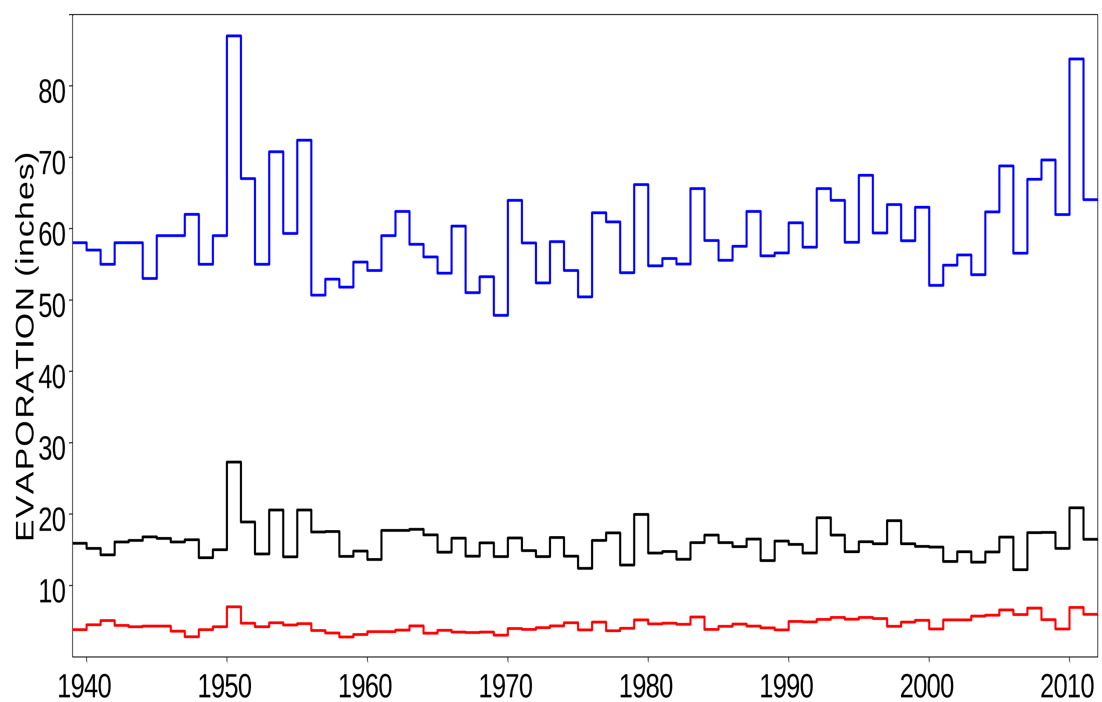
Monthly Evaporation for Quadrangle 610



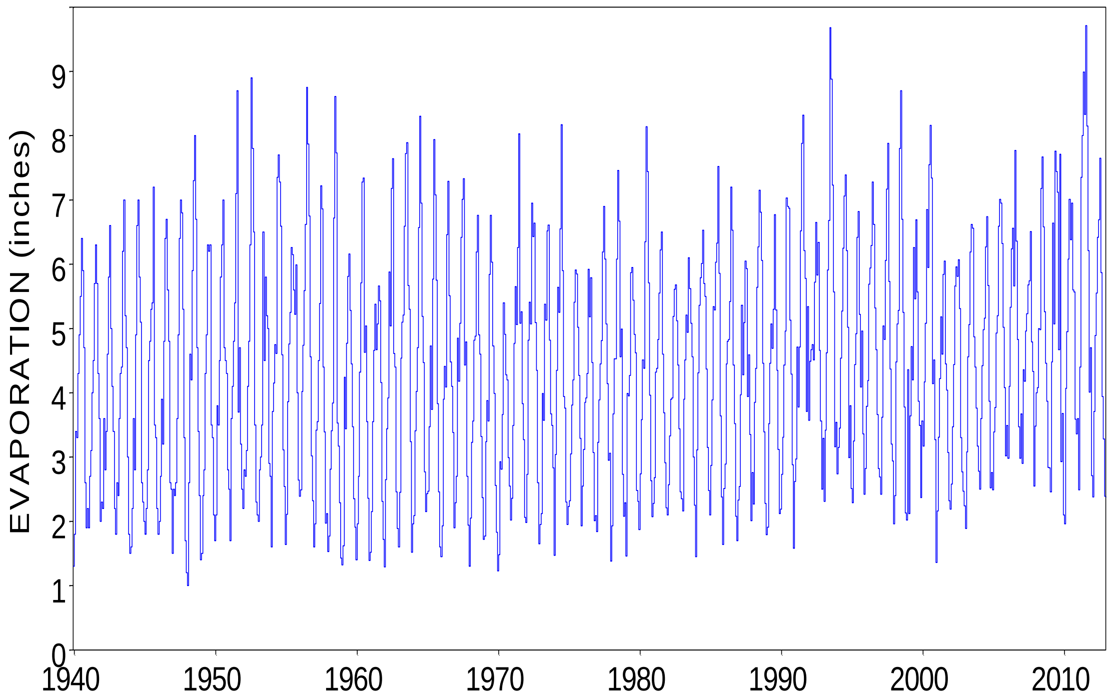
Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles 610



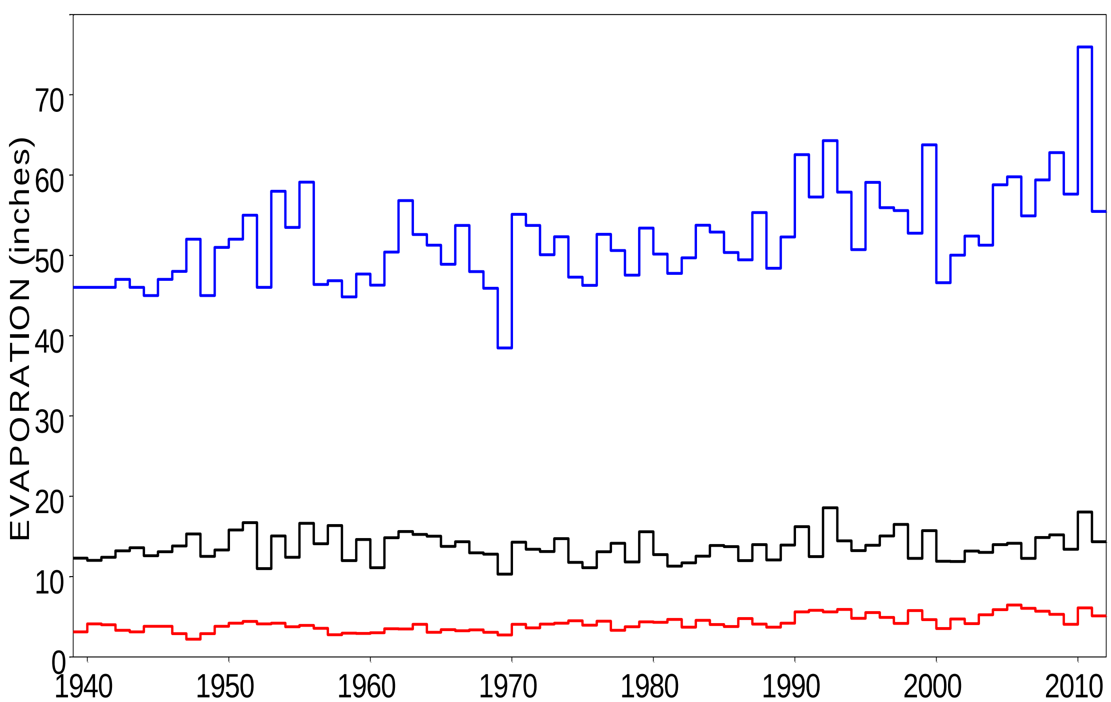
Monthly Evaporation for Quadrangle 611



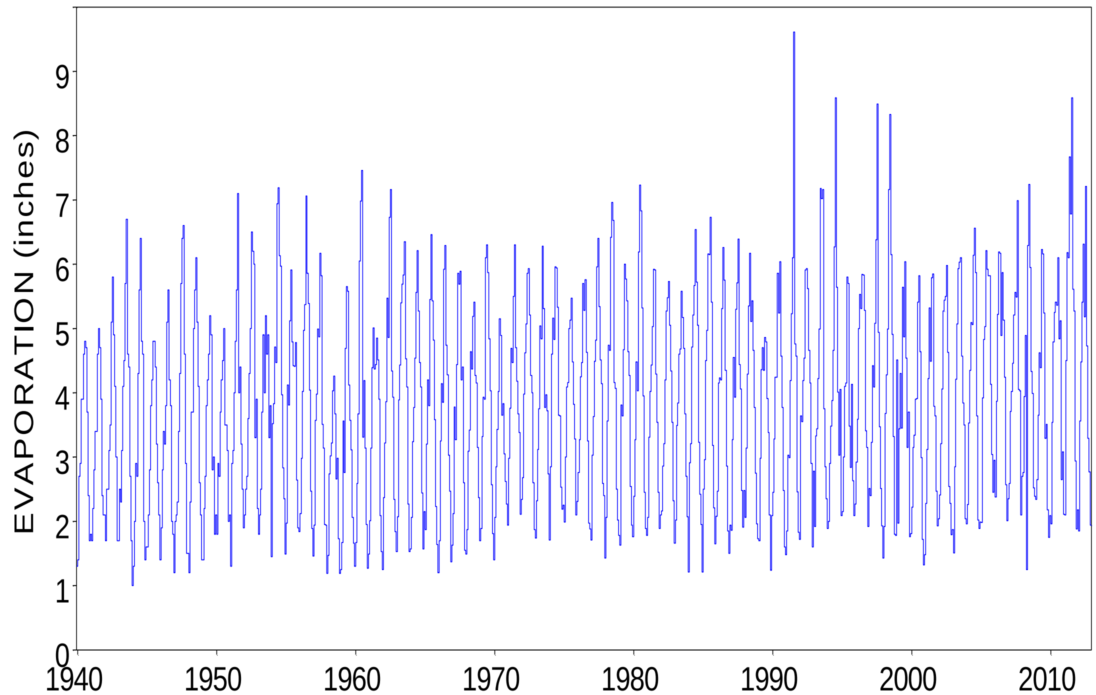
Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles 611



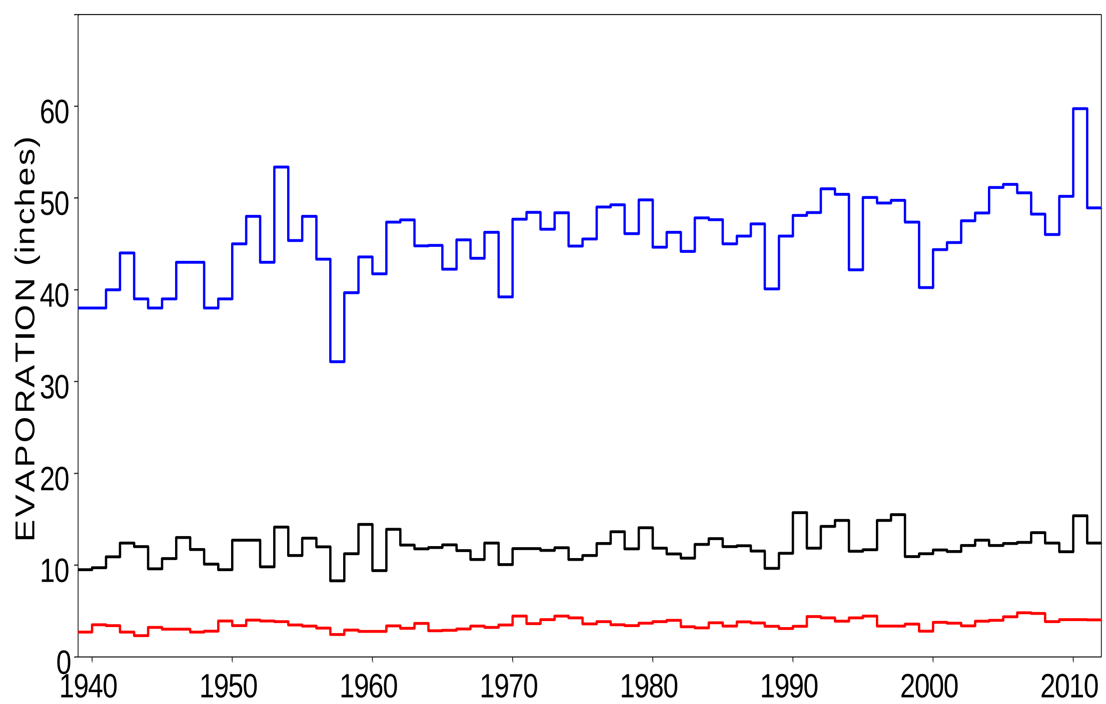
Monthly Evaporation for Quadrangle 612



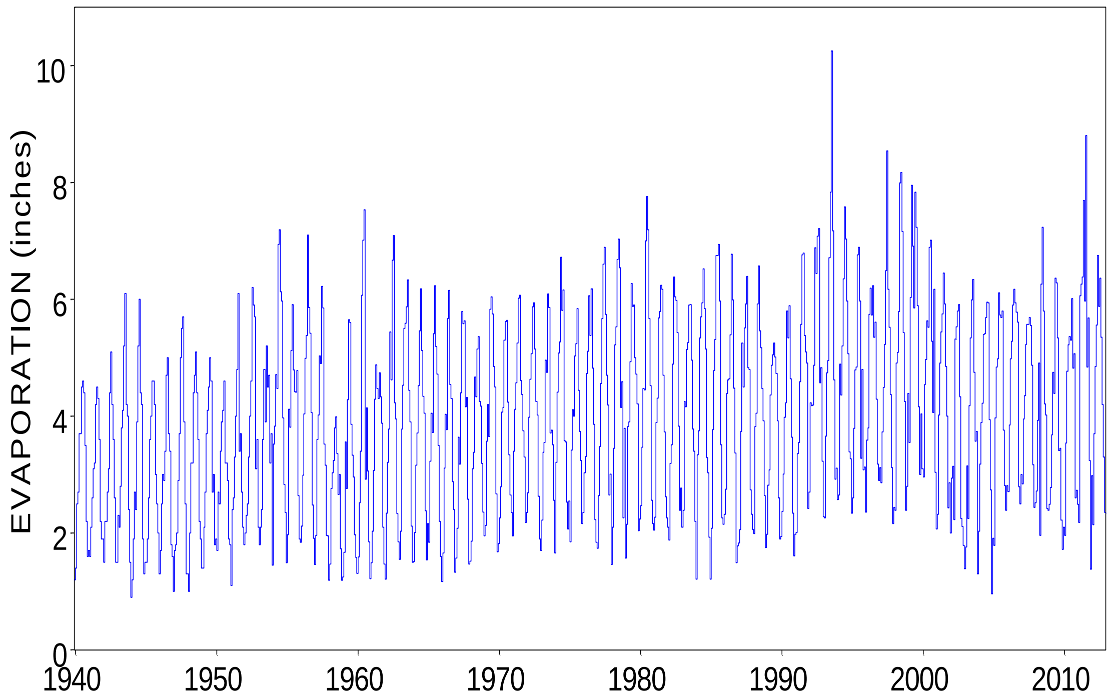
Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles 612



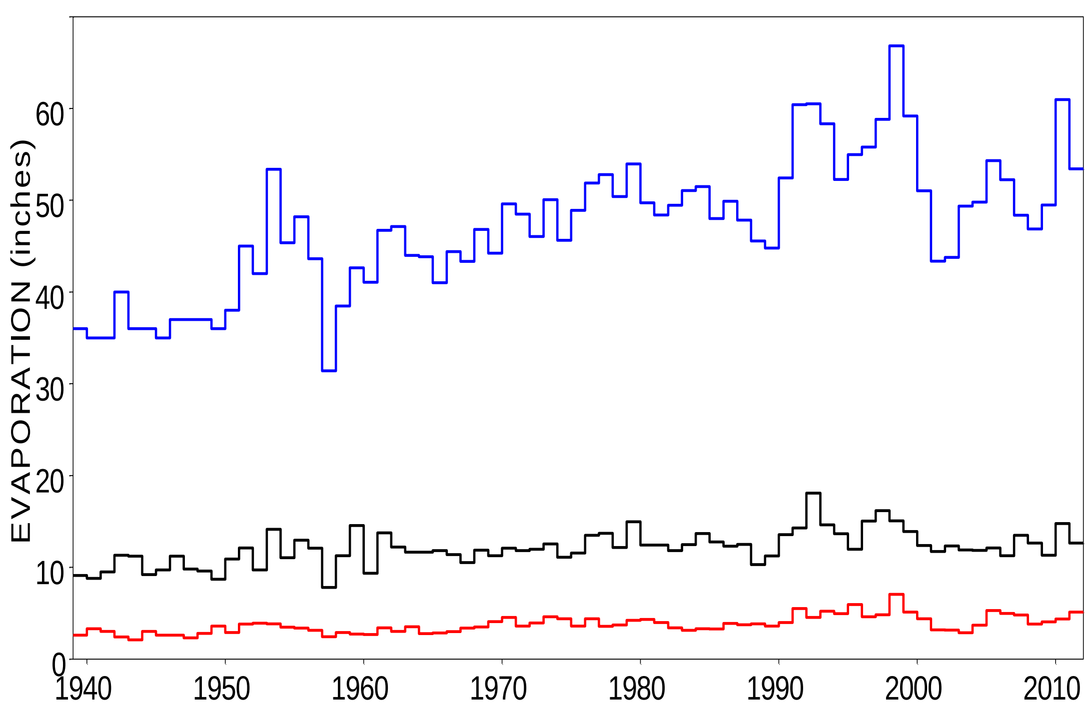
Monthly Evaporation for Quadrangle 613



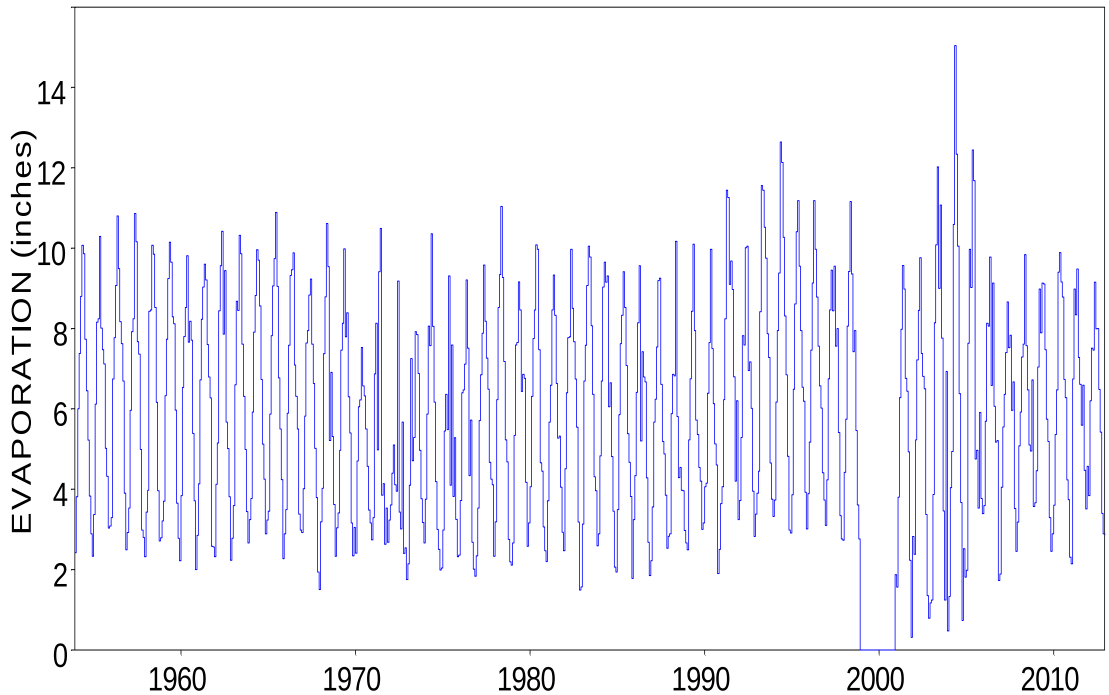
Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles 613



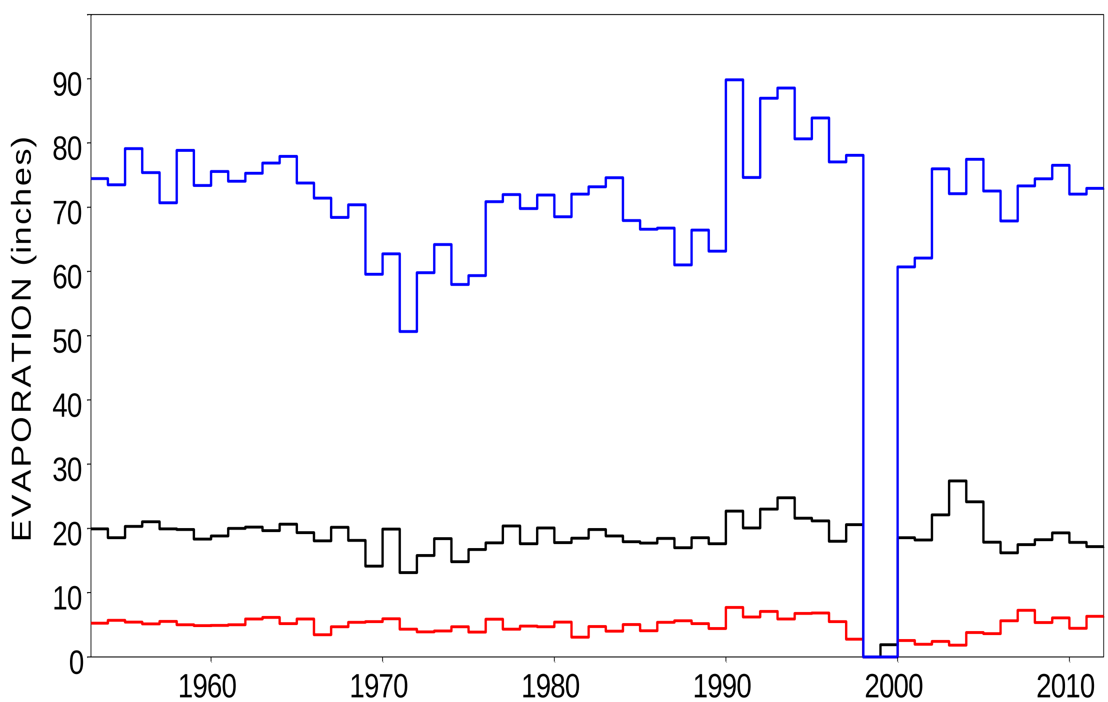
Monthly Evaporation for Quadrangle 614



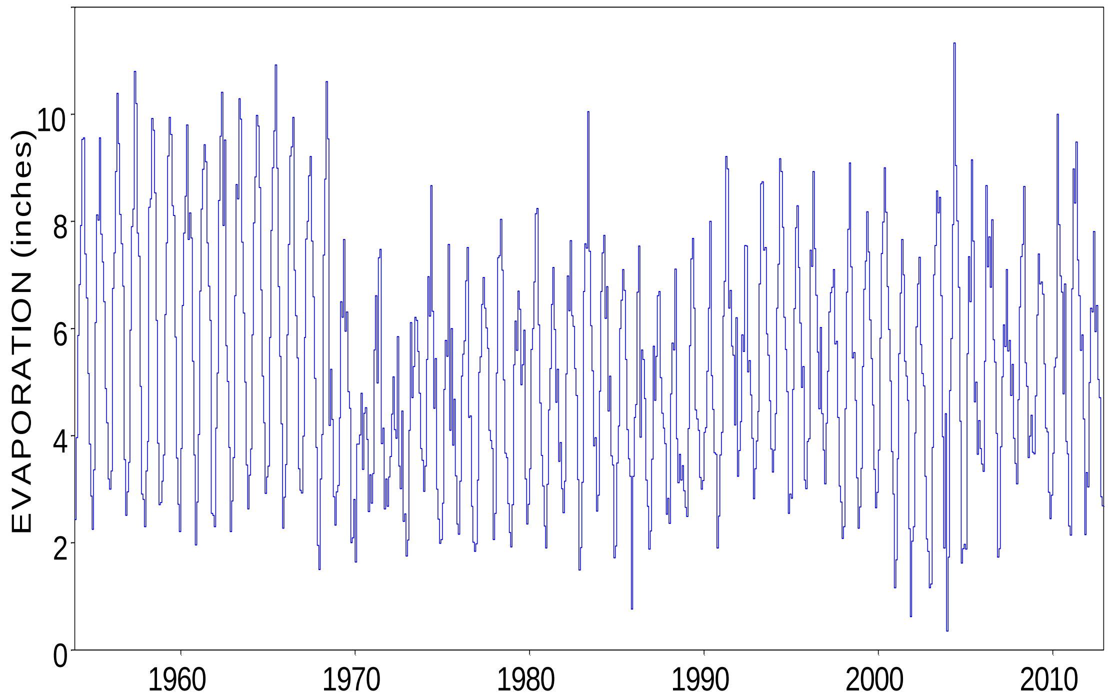
Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles 614



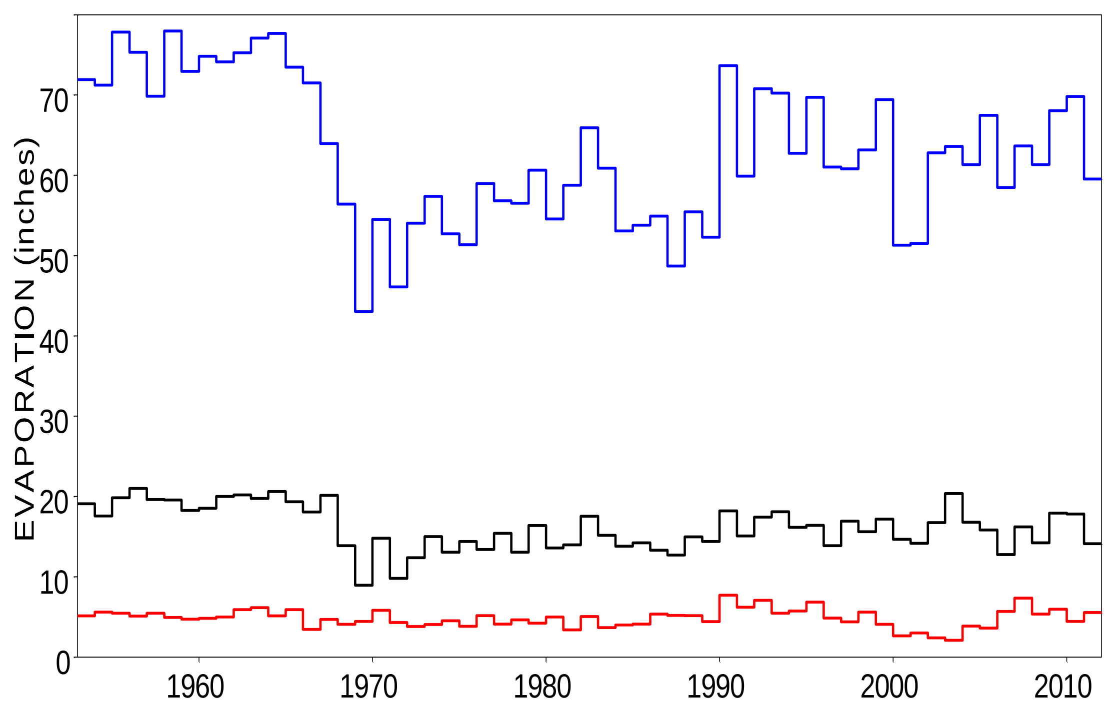
Monthly Evaporation for Quadrangle 701(missing date form 1999-2000)



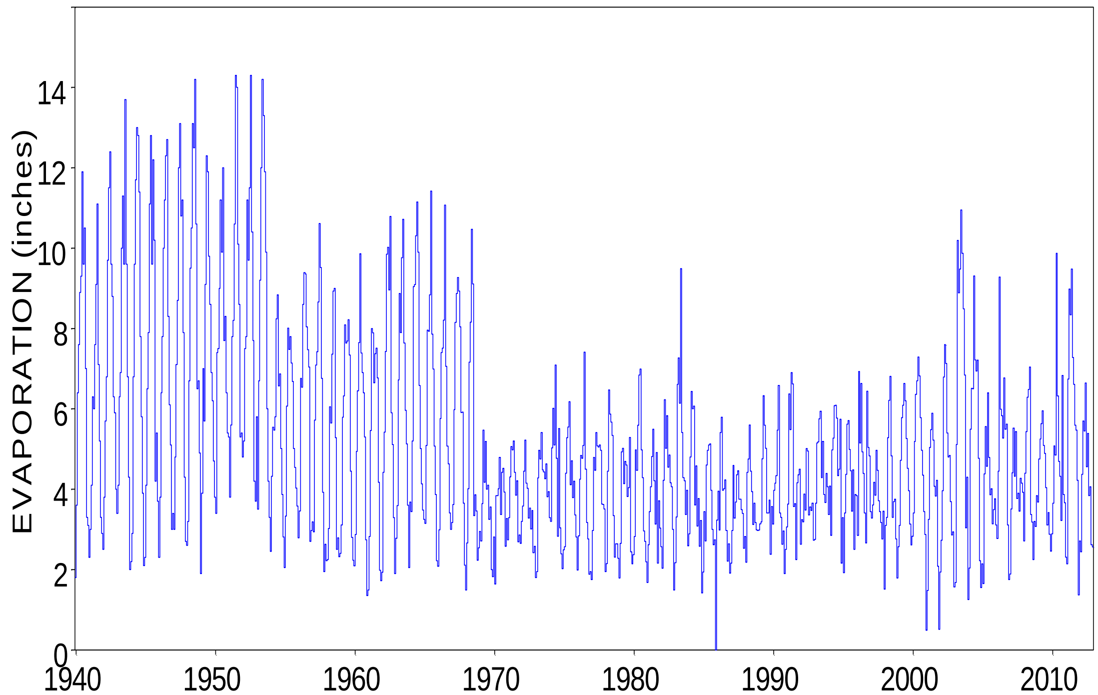
Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles 701
(missing date form 1999-2000)



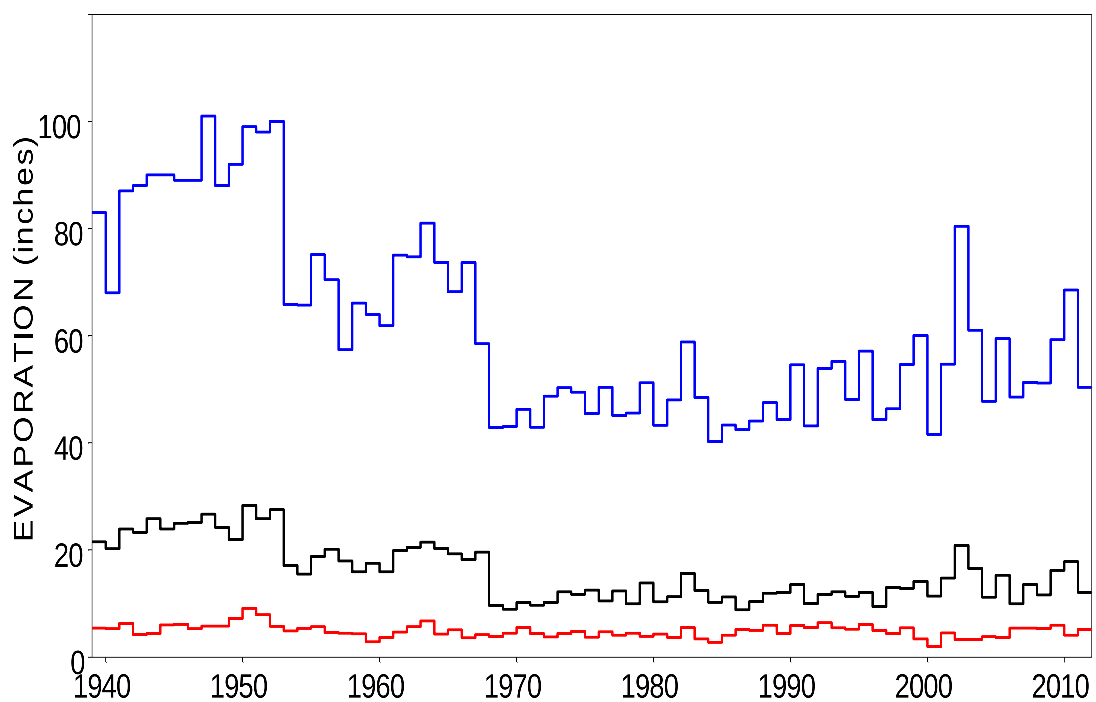
Monthly Evaporation for Quadrangle 702



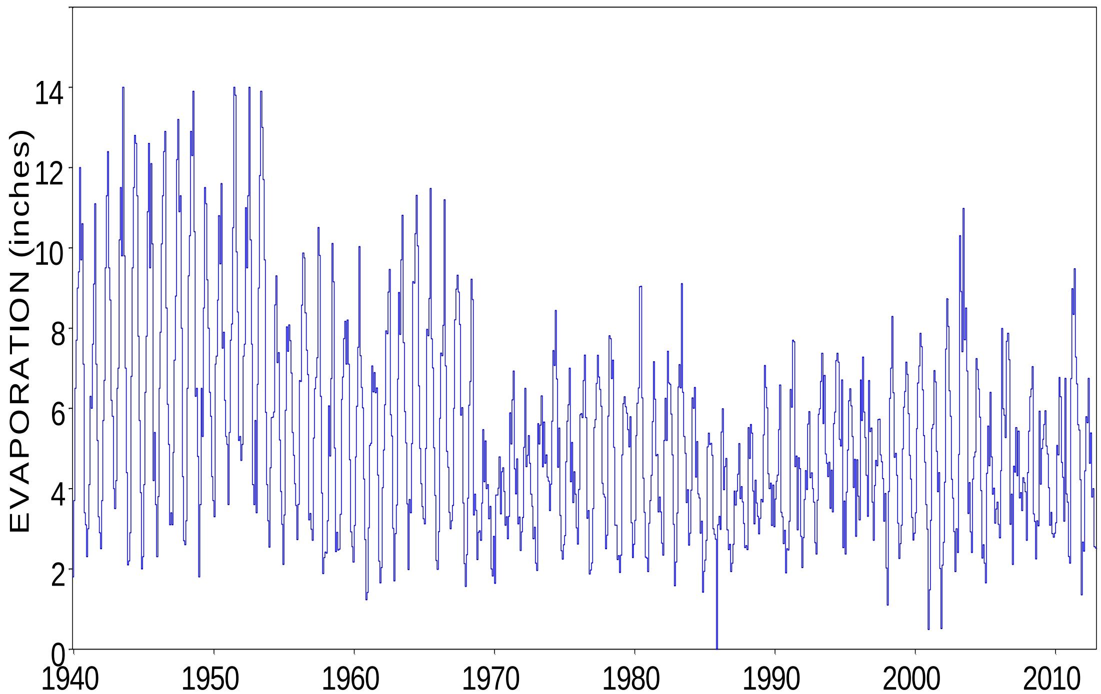
Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles 702



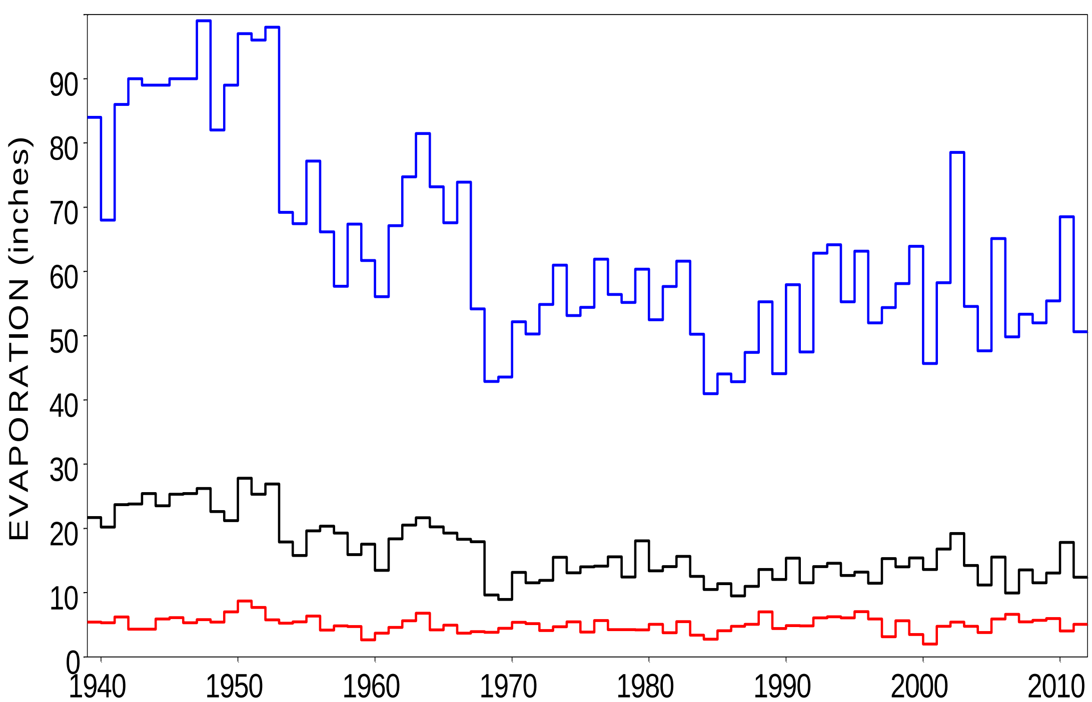
Monthly Evaporation for Quadrangle 703



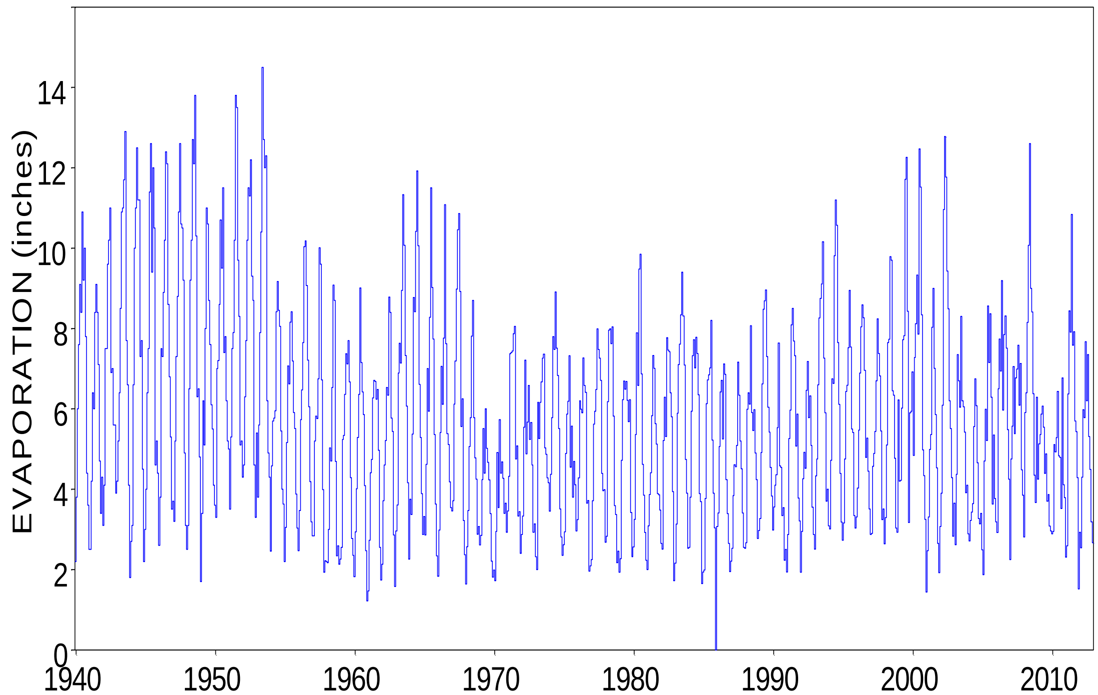
Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles 703



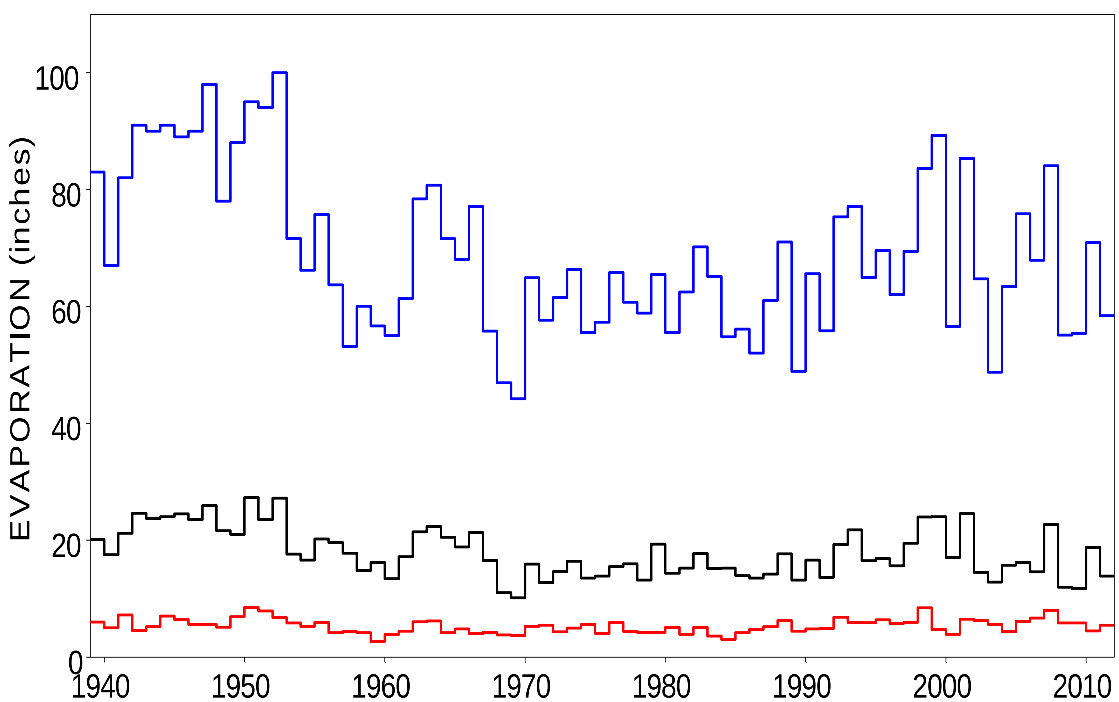
Monthly Evaporation for Quadrangle 704



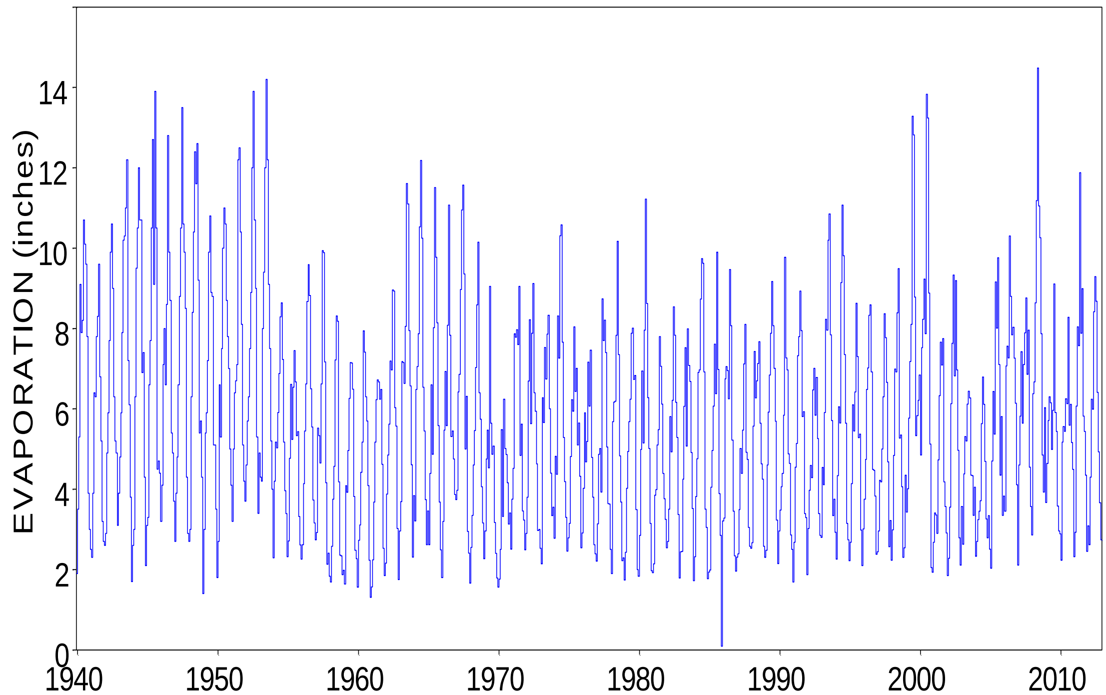
Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles 704



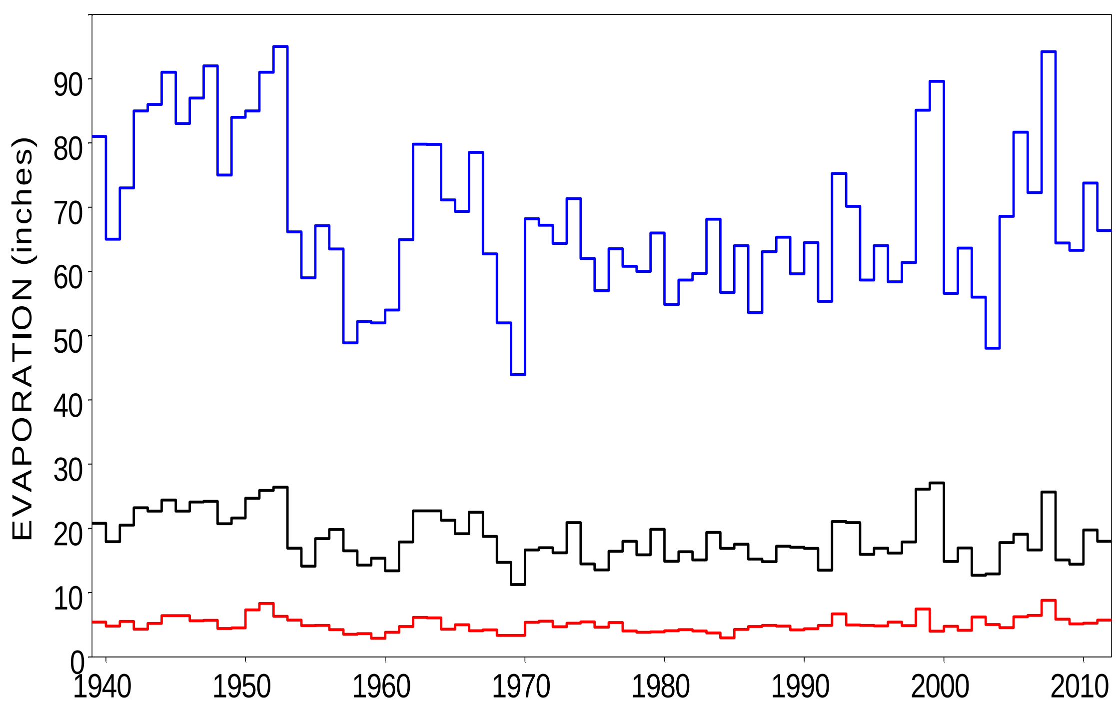
Monthly Evaporation for Quadrangle 705



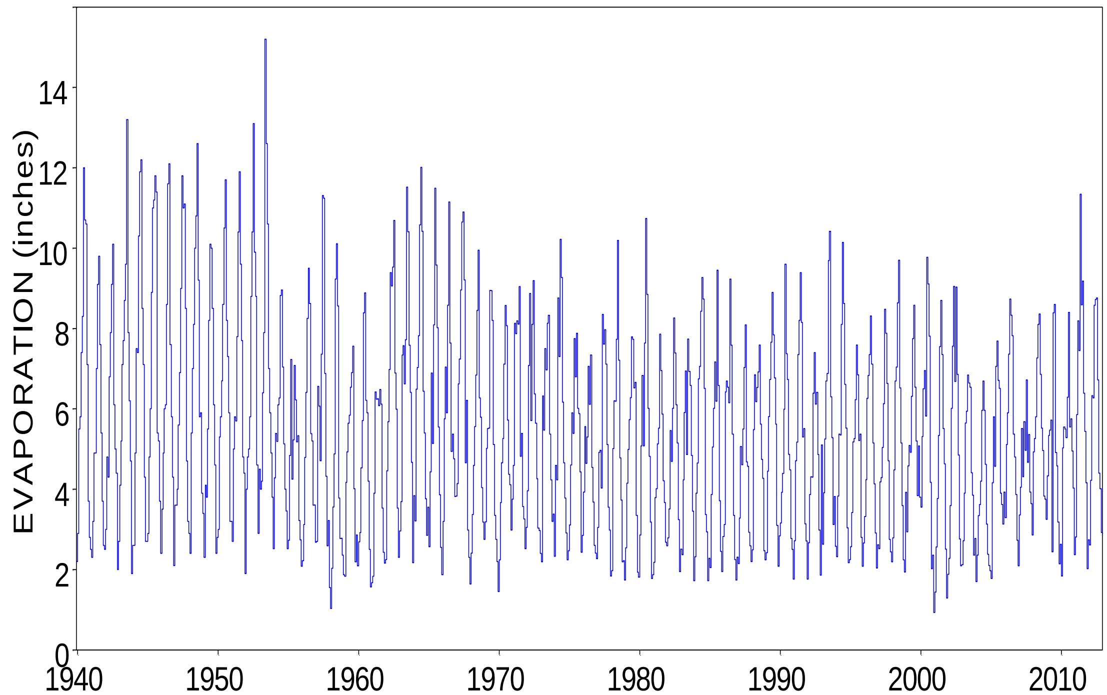
Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles 705



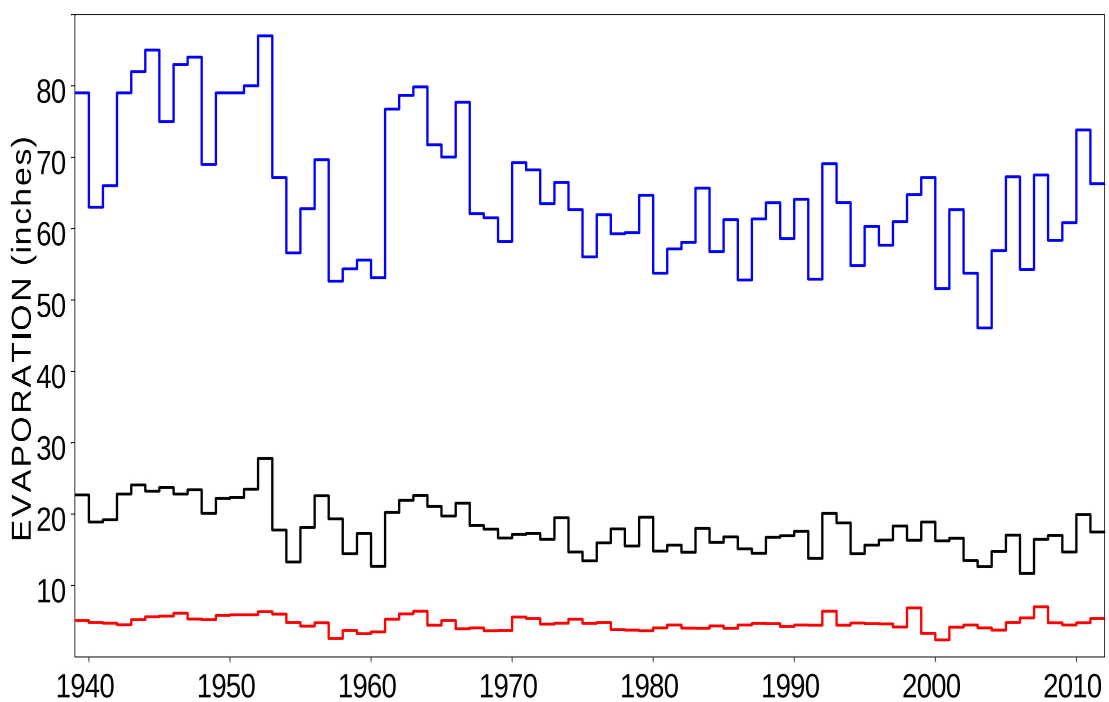
Monthly Evaporation for Quadrangle 706



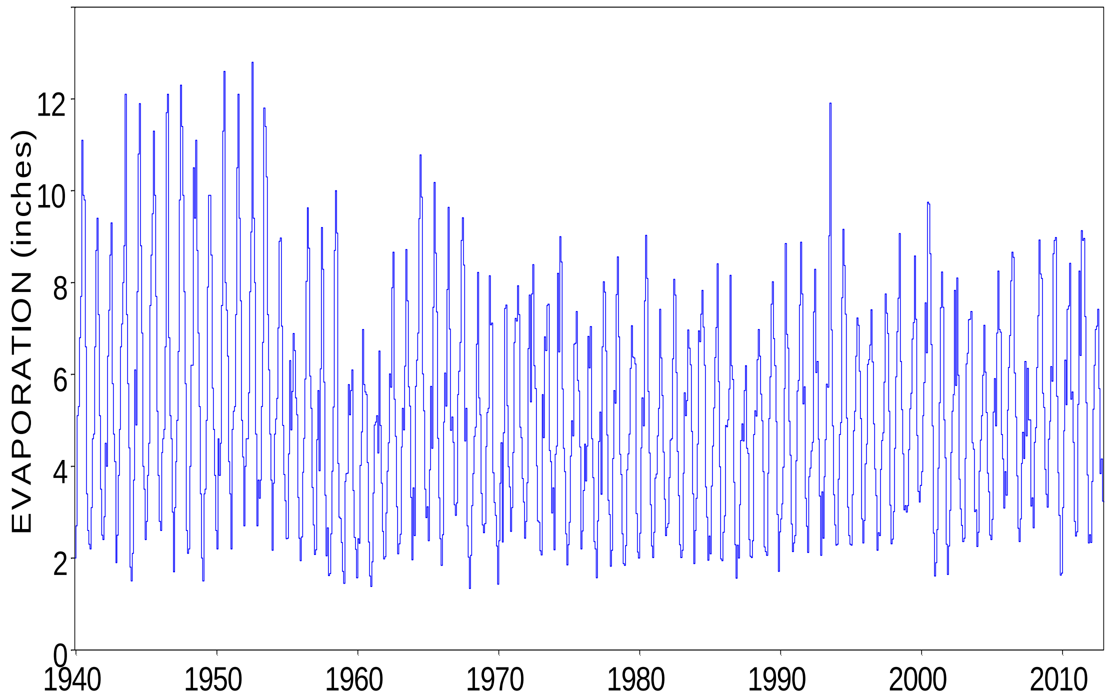
Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles 706



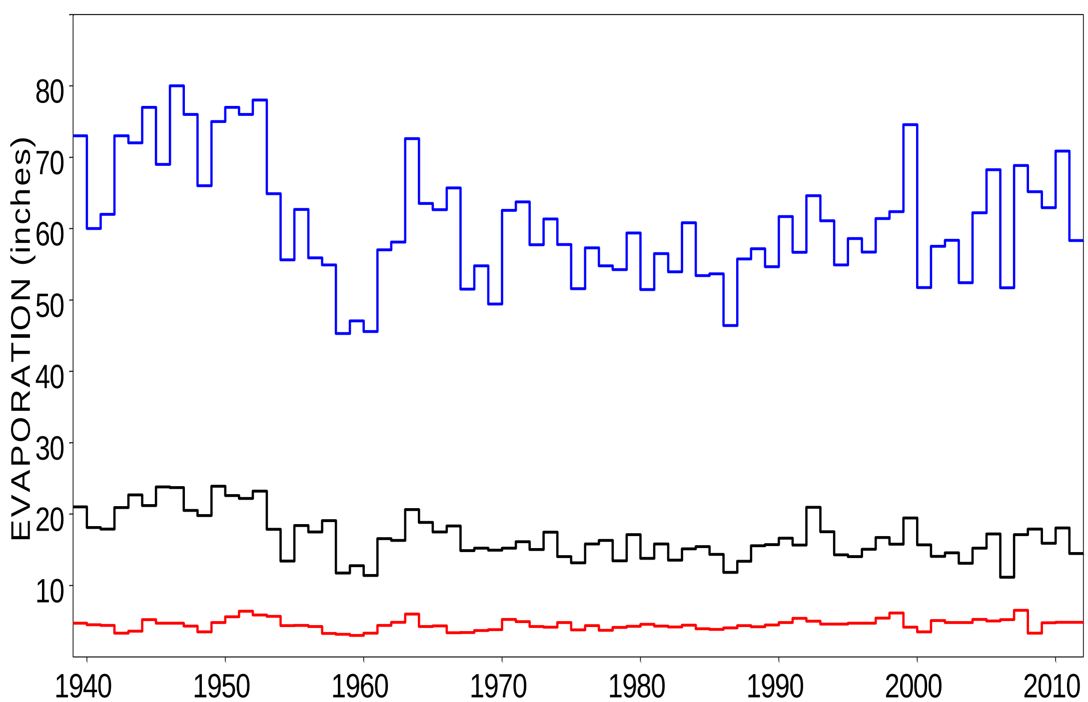
Monthly Evaporation for Quadrangle 707



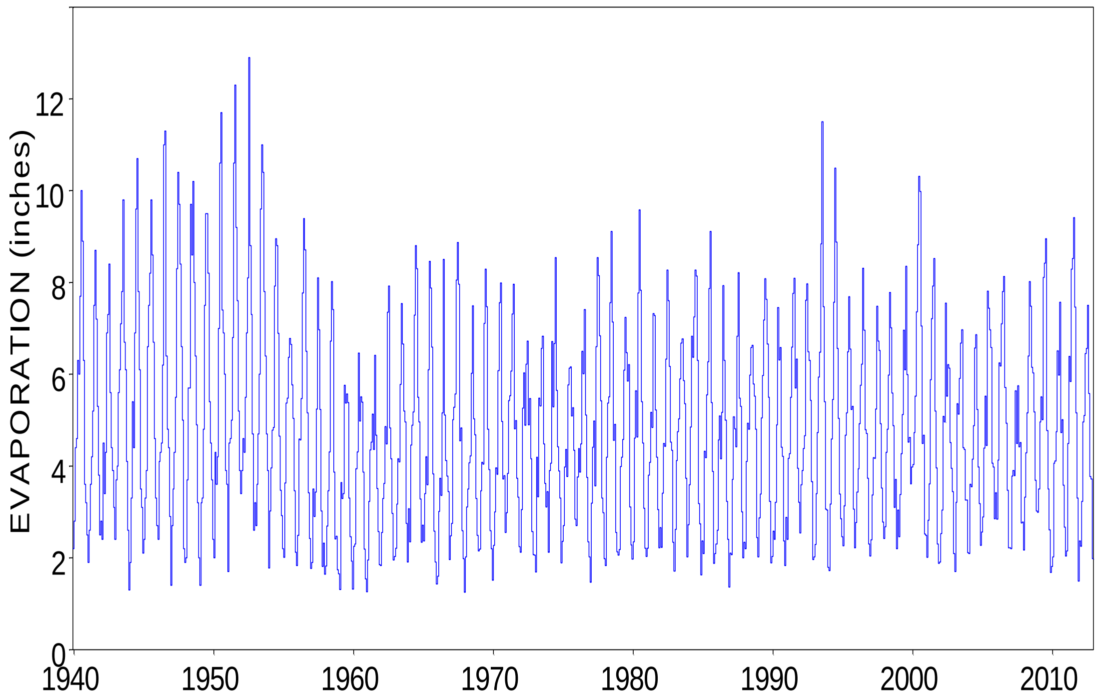
Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles 707



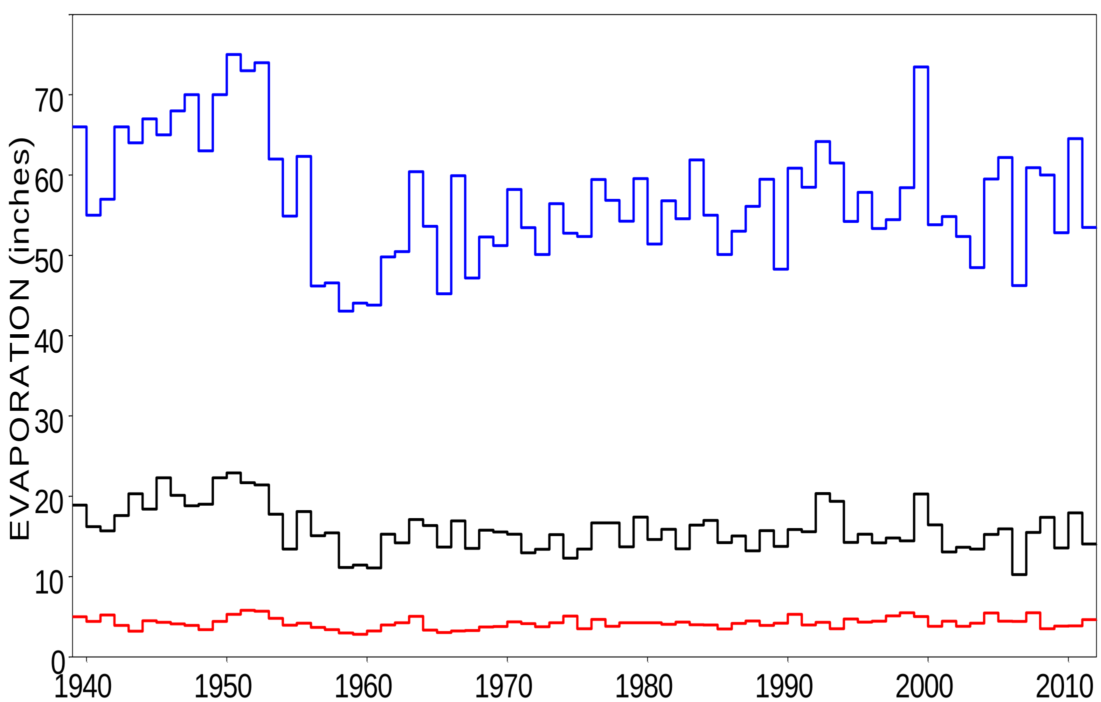
Monthly Evaporation for Quadrangle 707



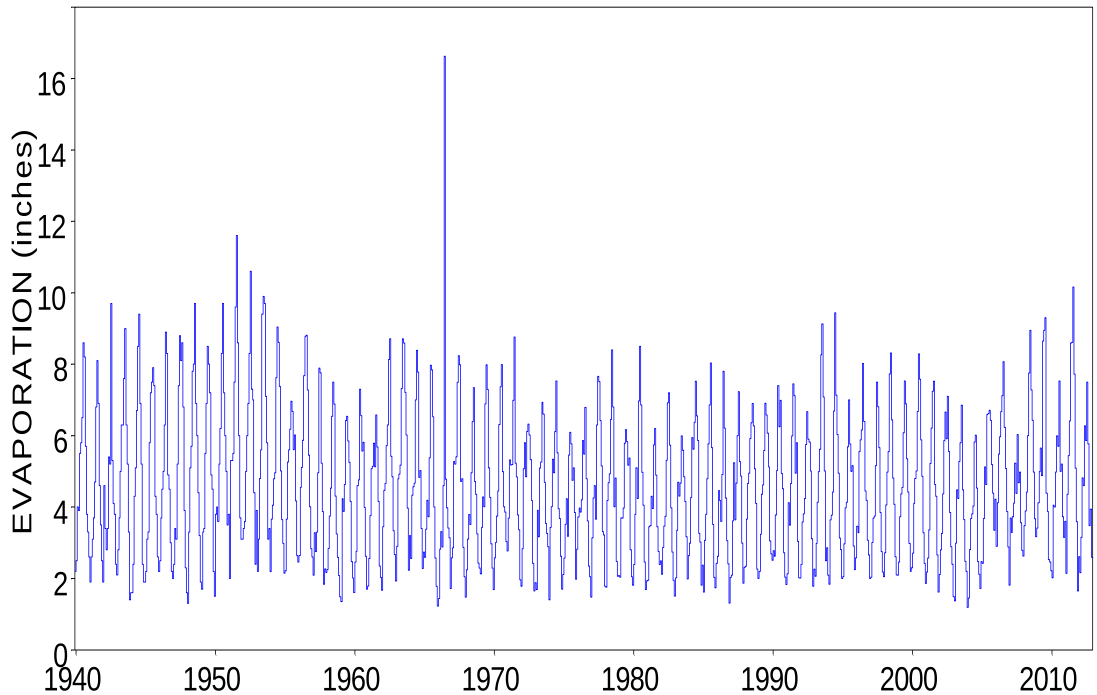
Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles 708



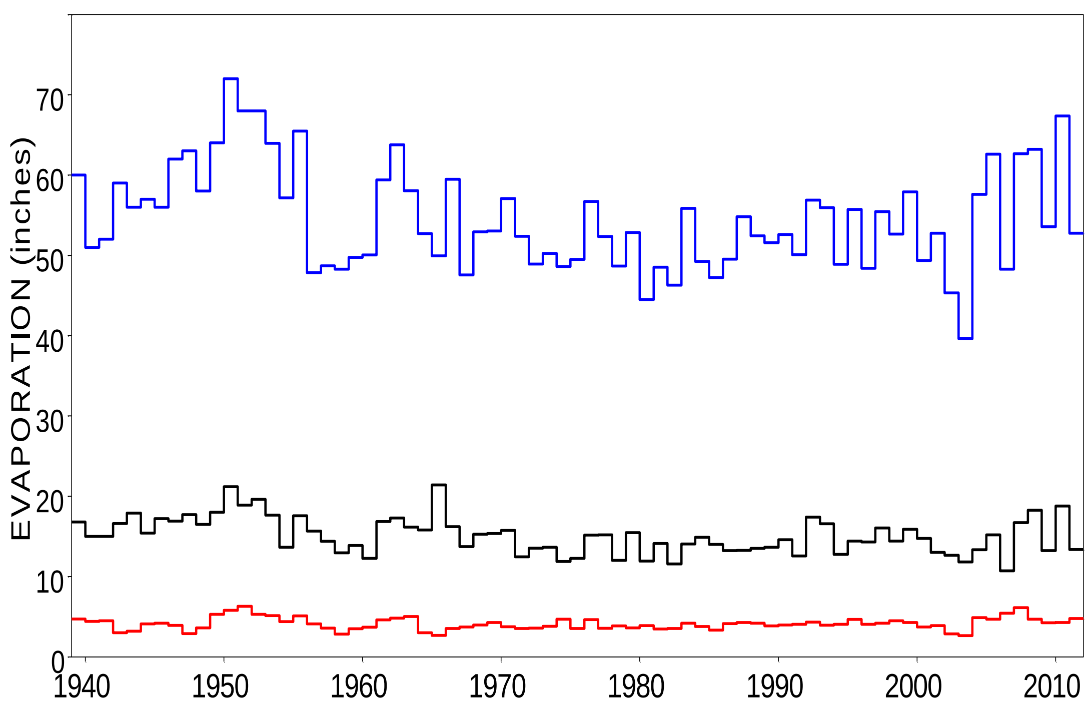
Monthly Evaporation for Quadrangle 709



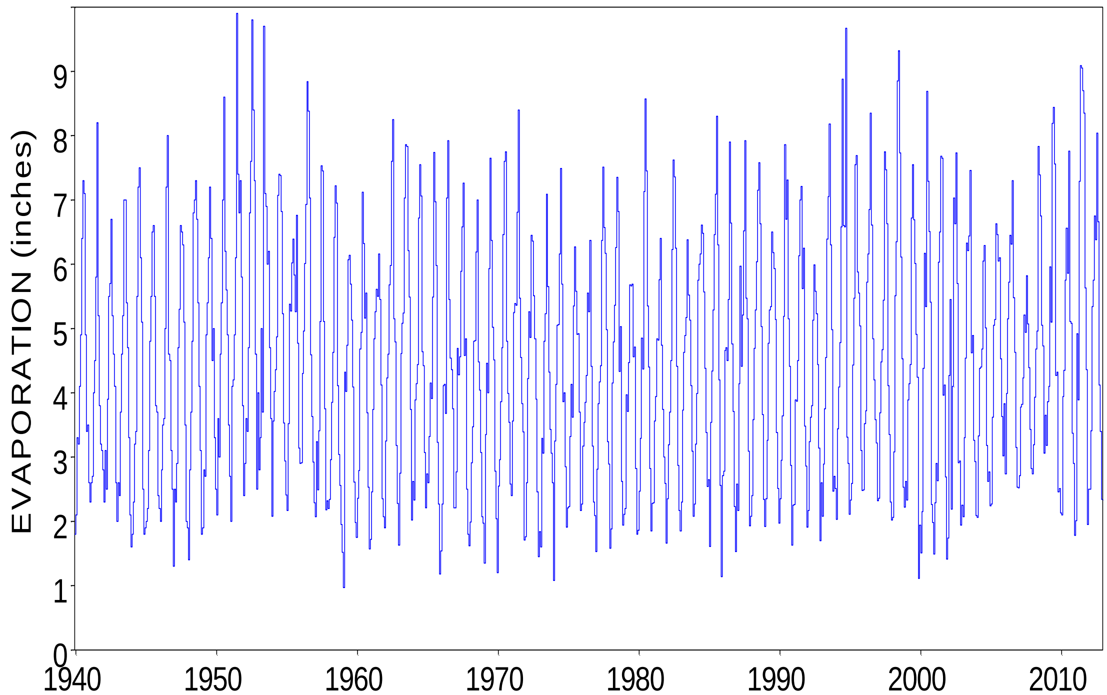
Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles 709



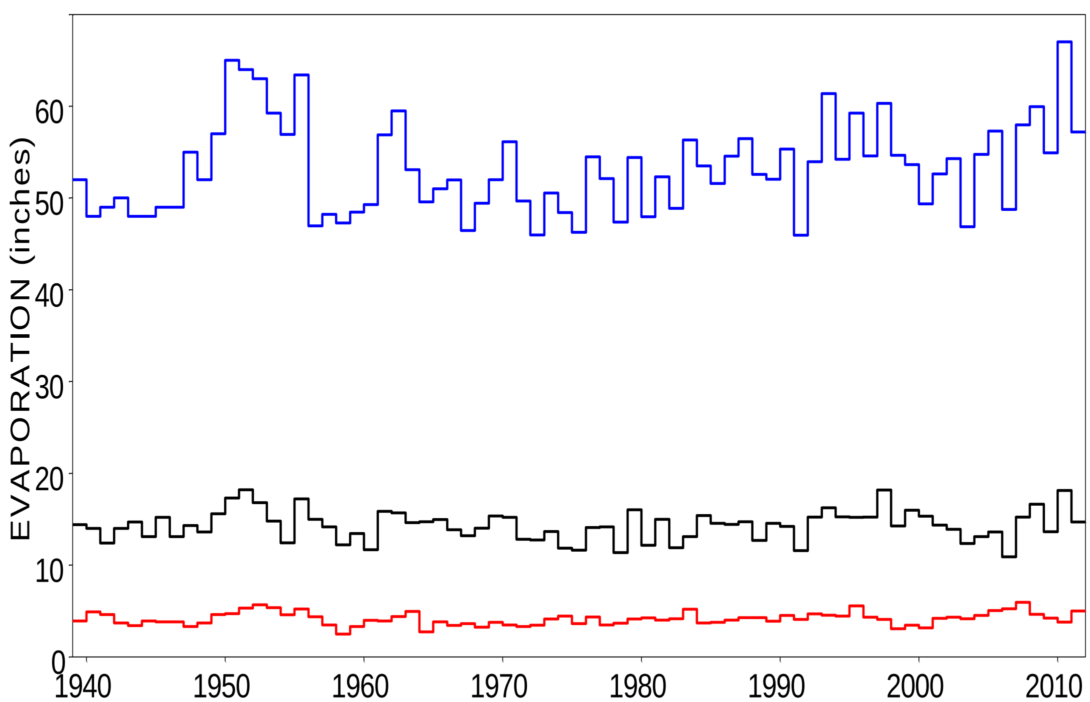
Monthly Evaporation for Quadrangle 710



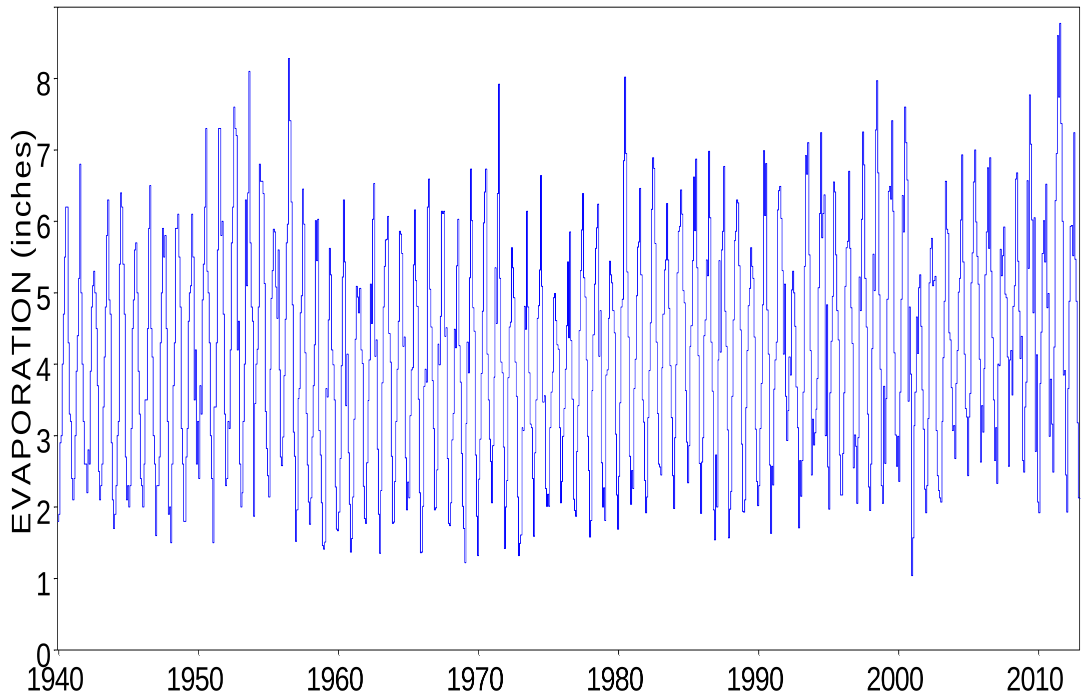
Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles 710



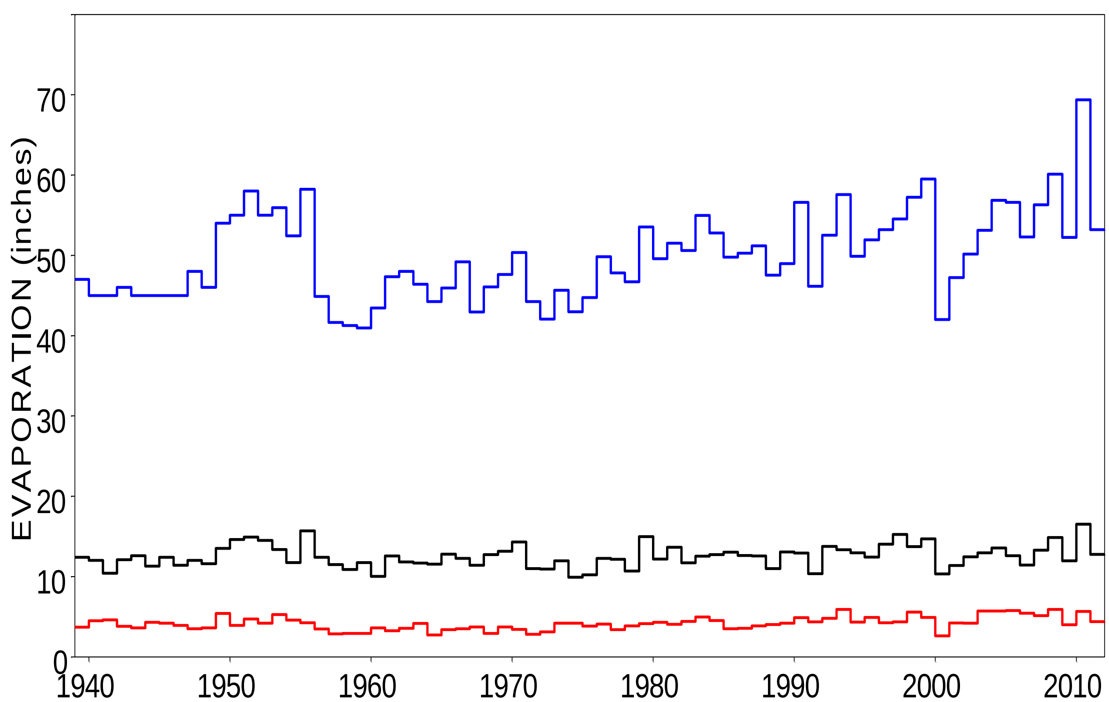
Monthly Evaporation for Quadrangle 711



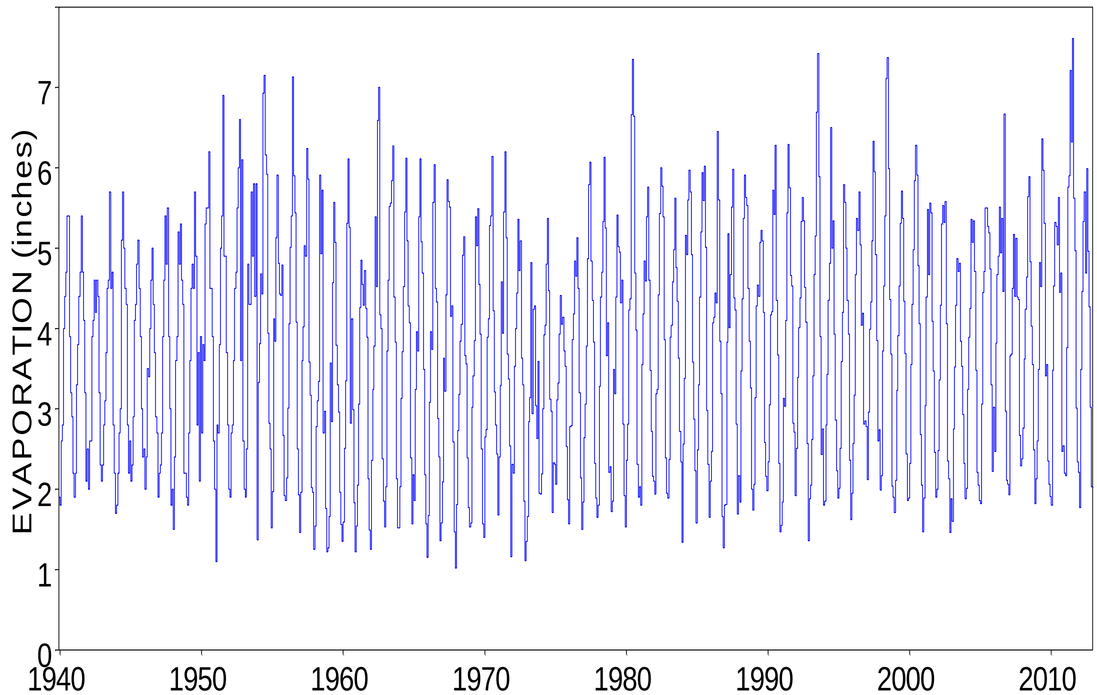
Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles 711



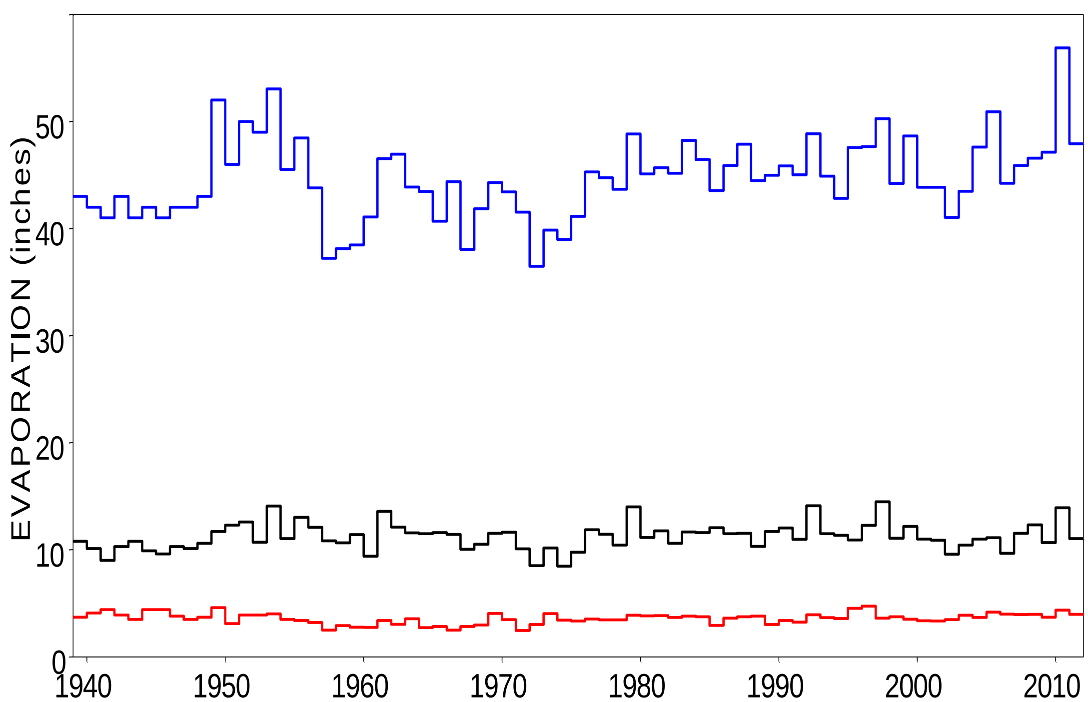
Monthly Evaporation for Quadrangle 712



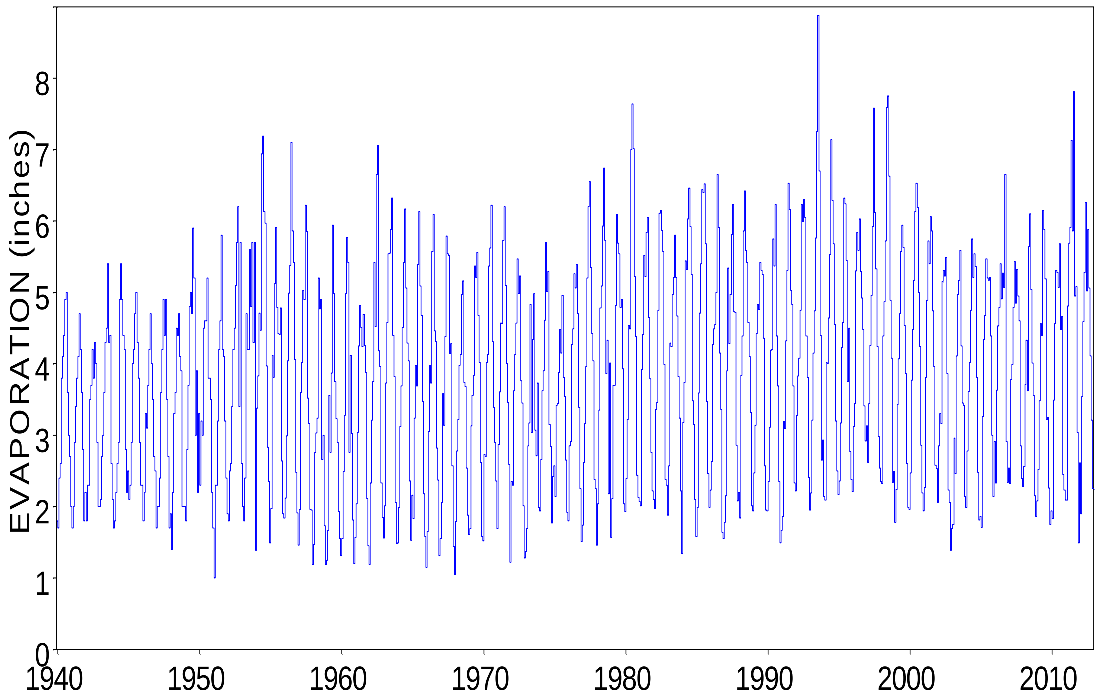
Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles 712



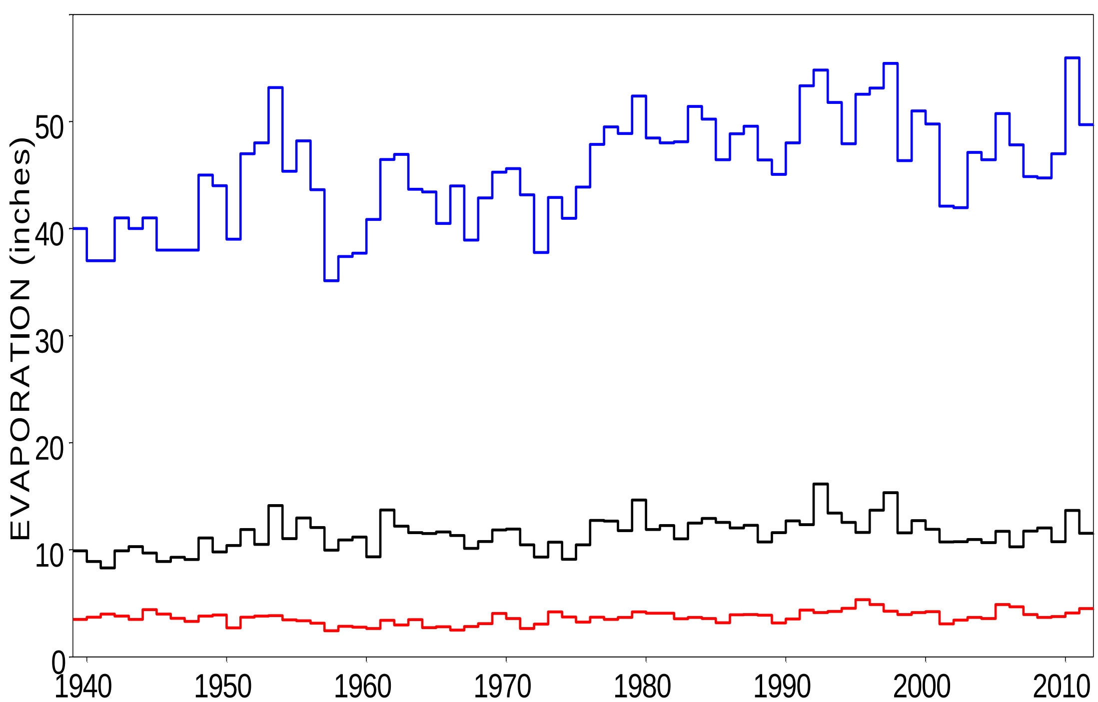
Monthly Evaporation for Quadrangle 713



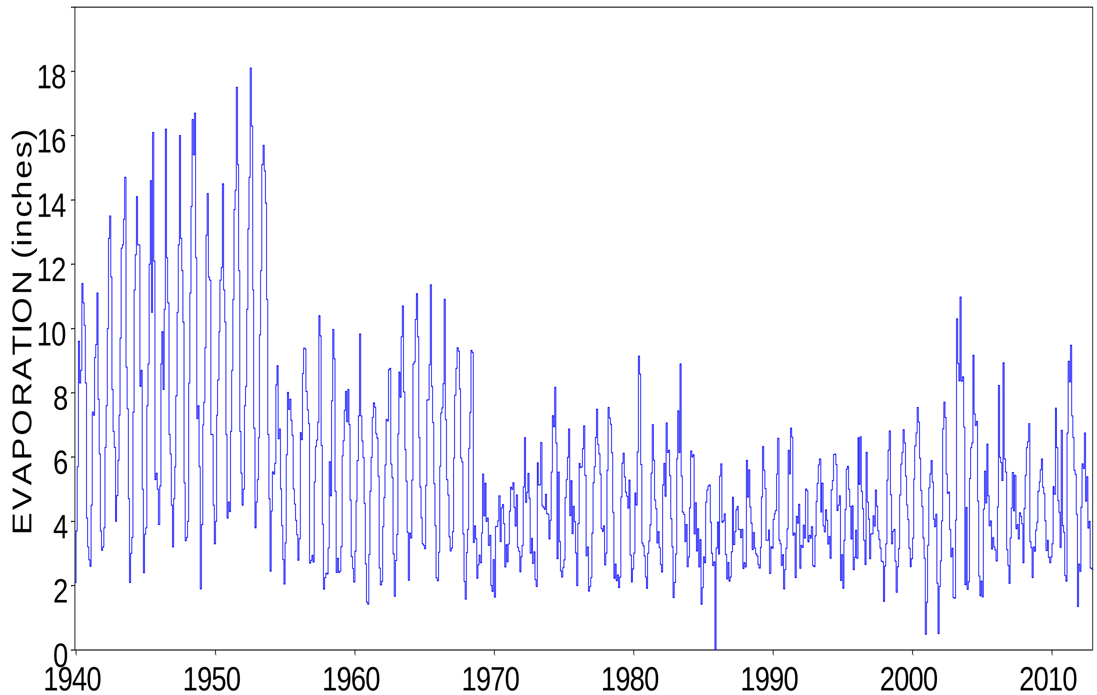
Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles 713



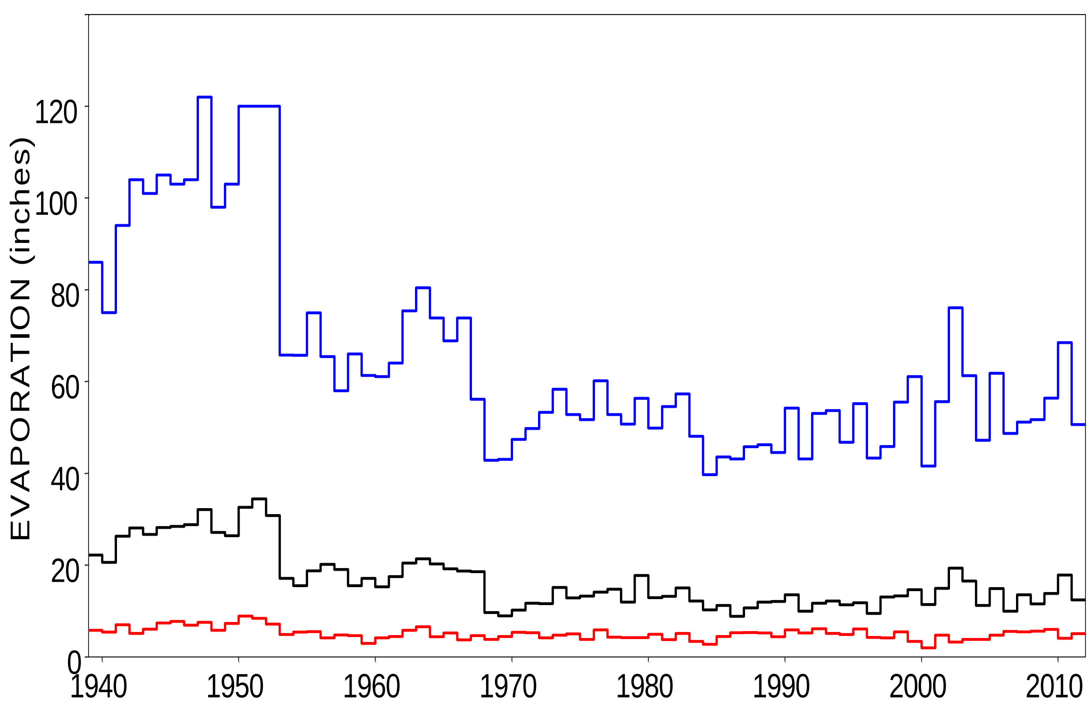
Monthly Evaporation for Quadrangle 714



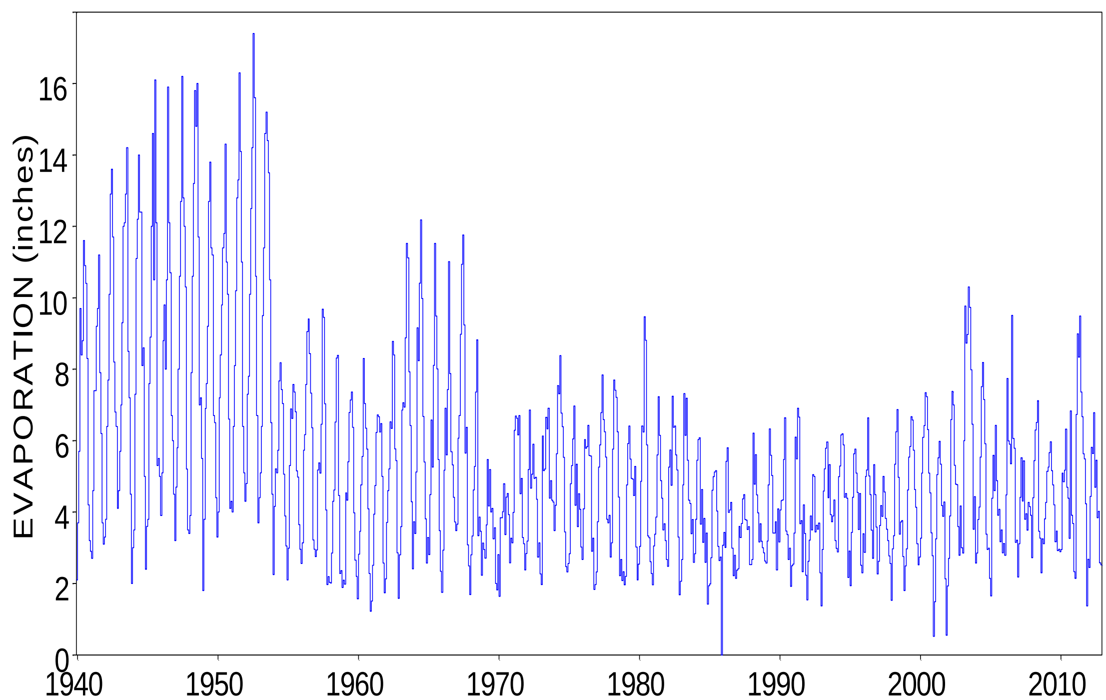
Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles 714



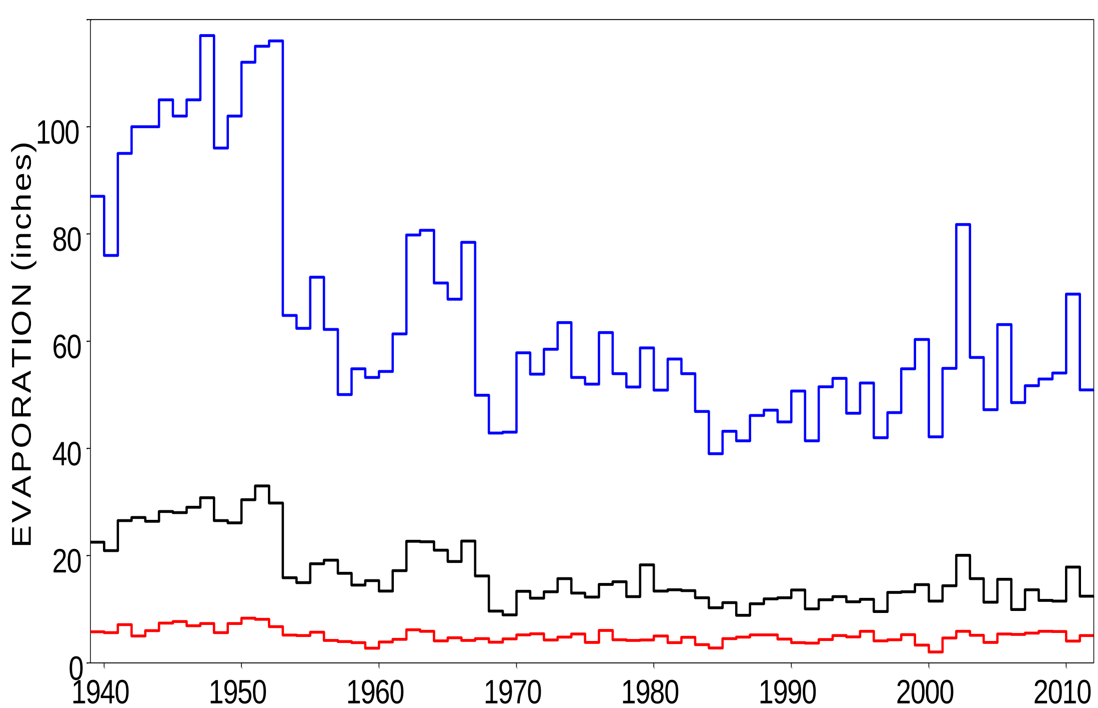
Monthly Evaporation for Quadrangle 803



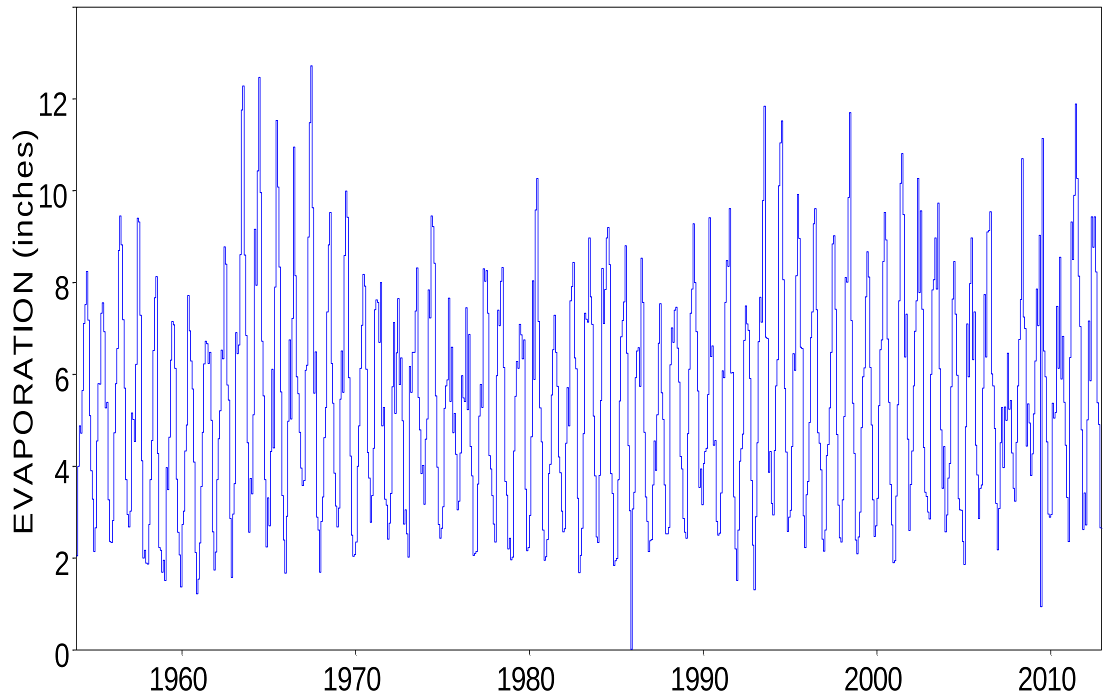
Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles 803



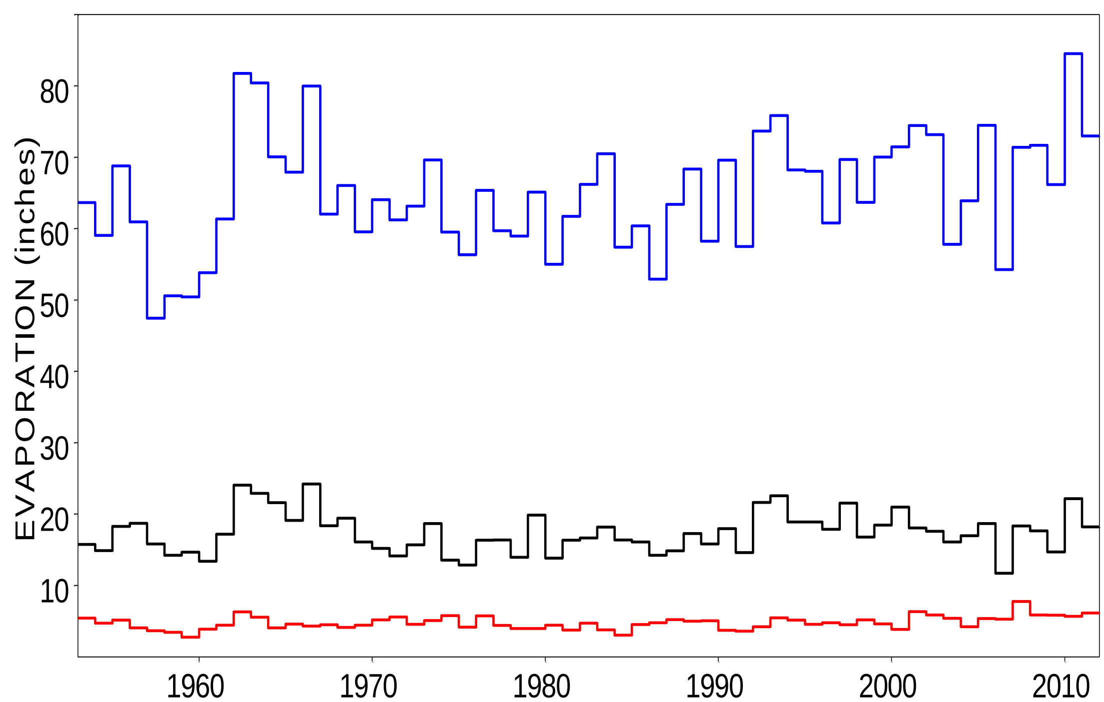
Monthly Evaporation for Quadrangle 804



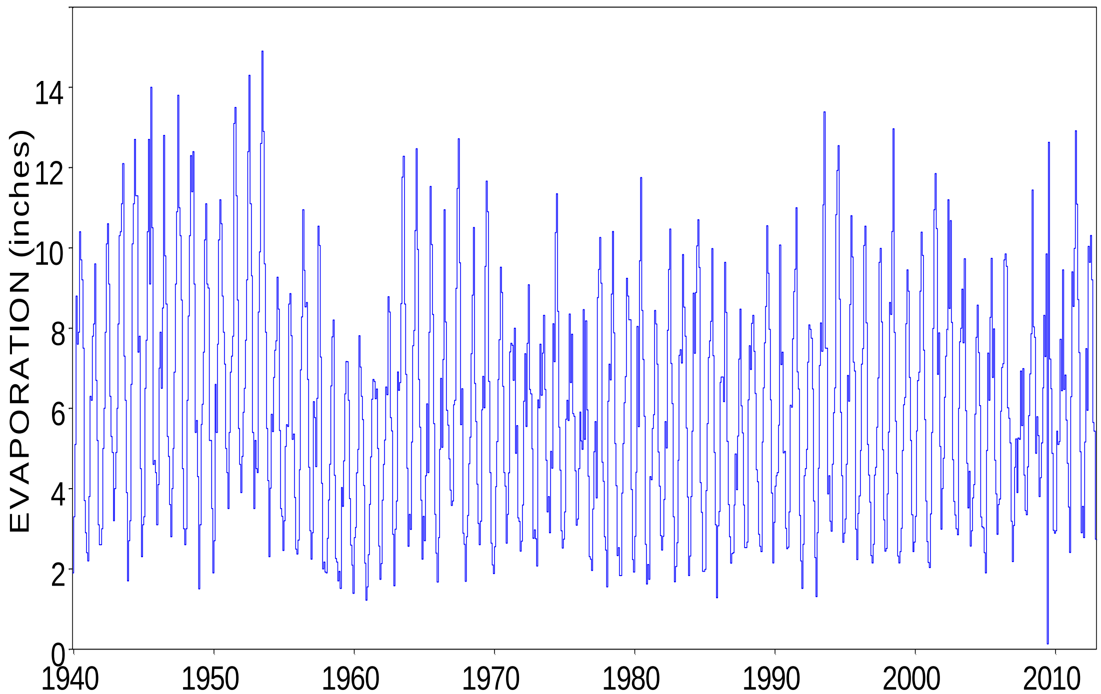
Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles 804



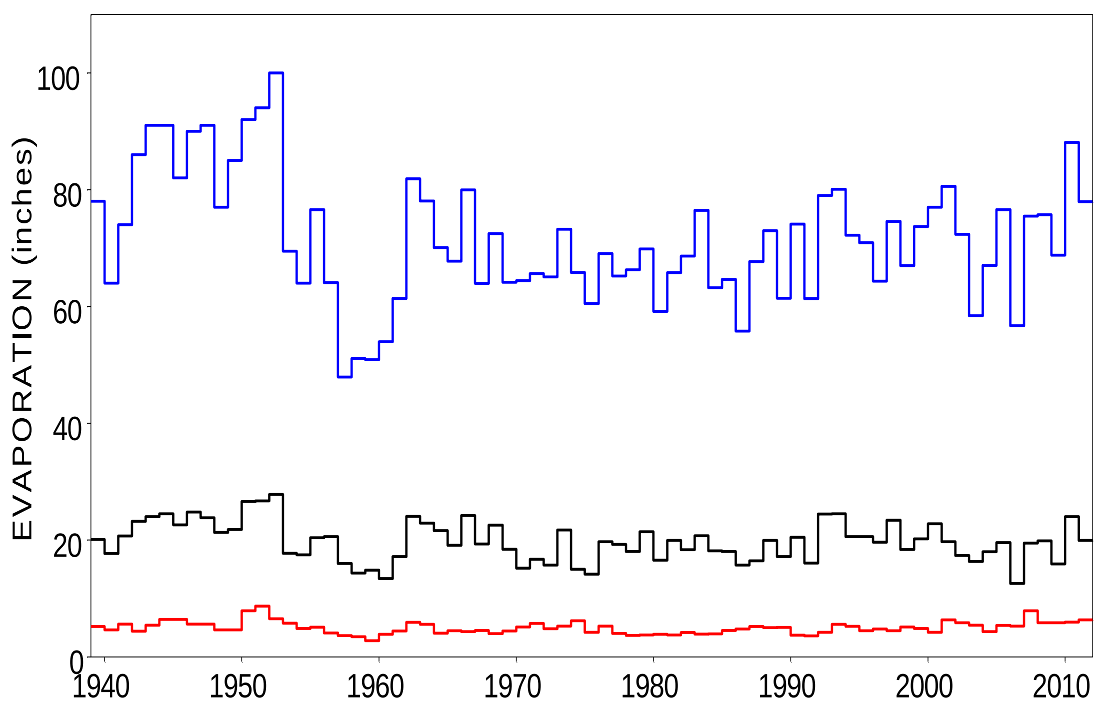
Monthly Evaporation for Quadrangle 805



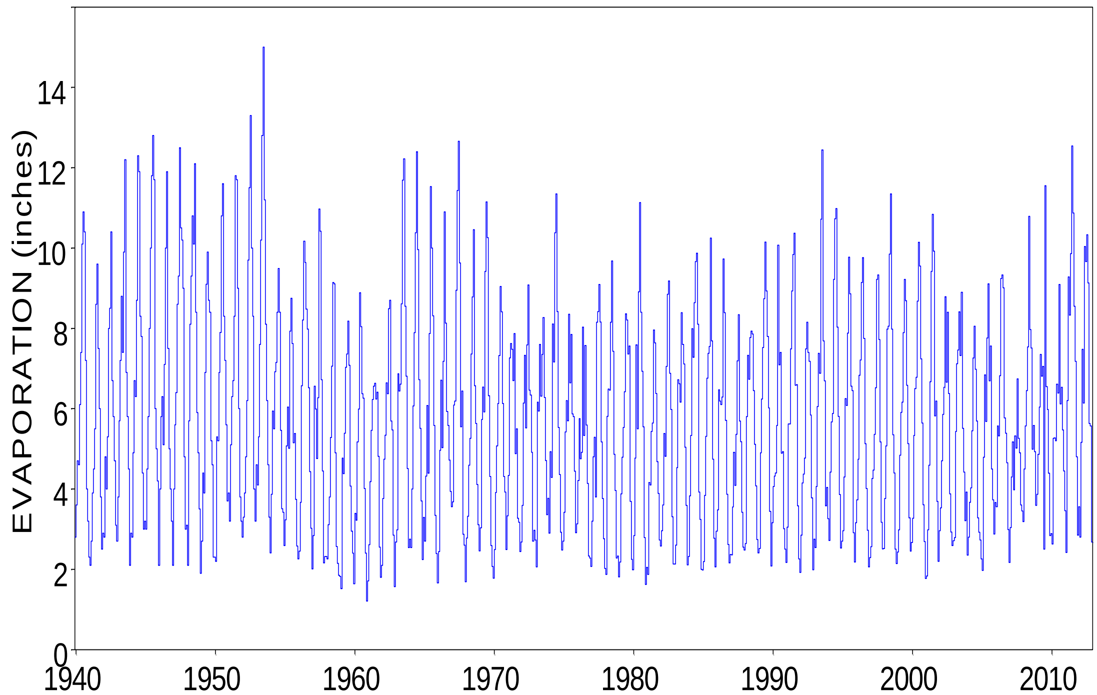
Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles 805



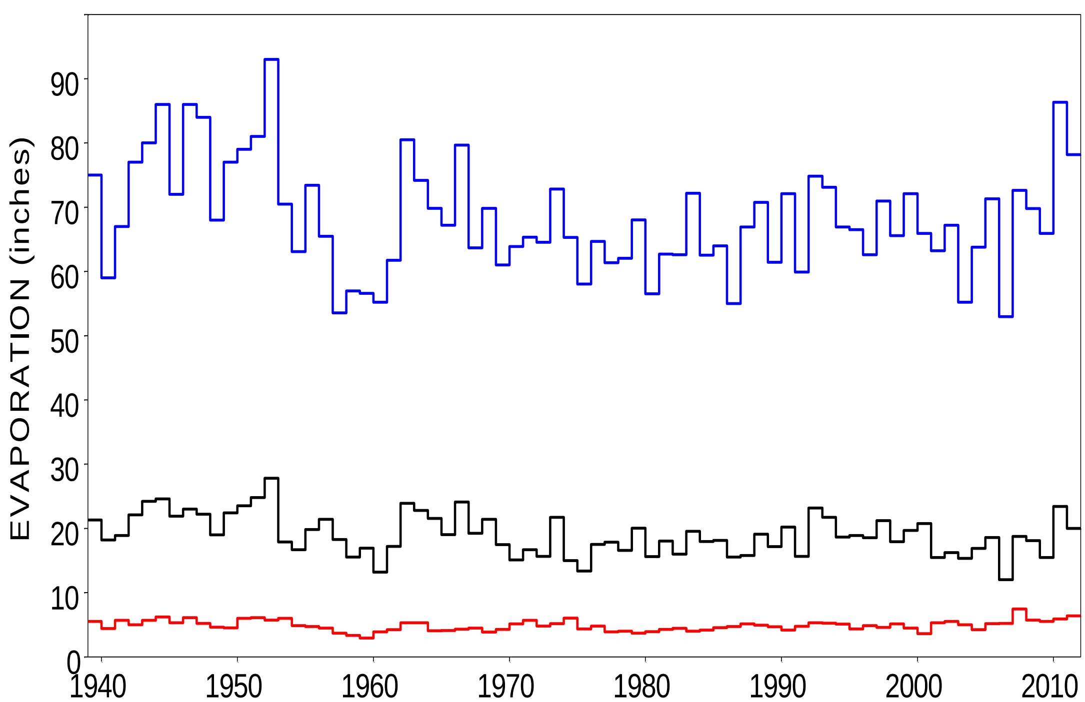
Monthly Evaporation for Quadrangle 806



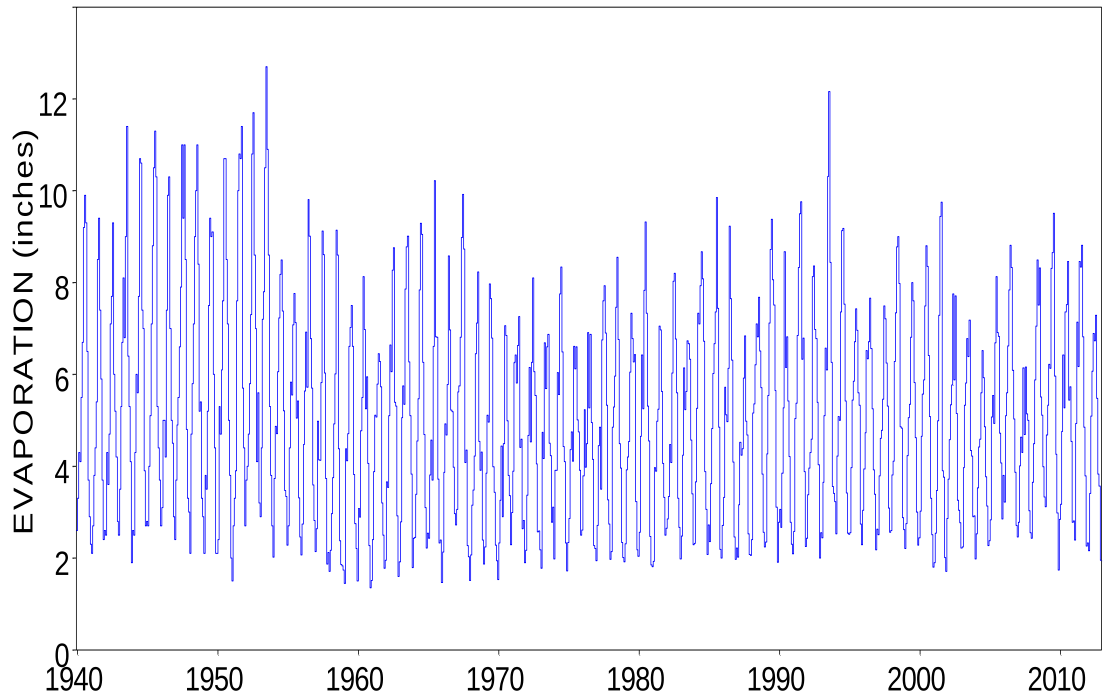
Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles 806



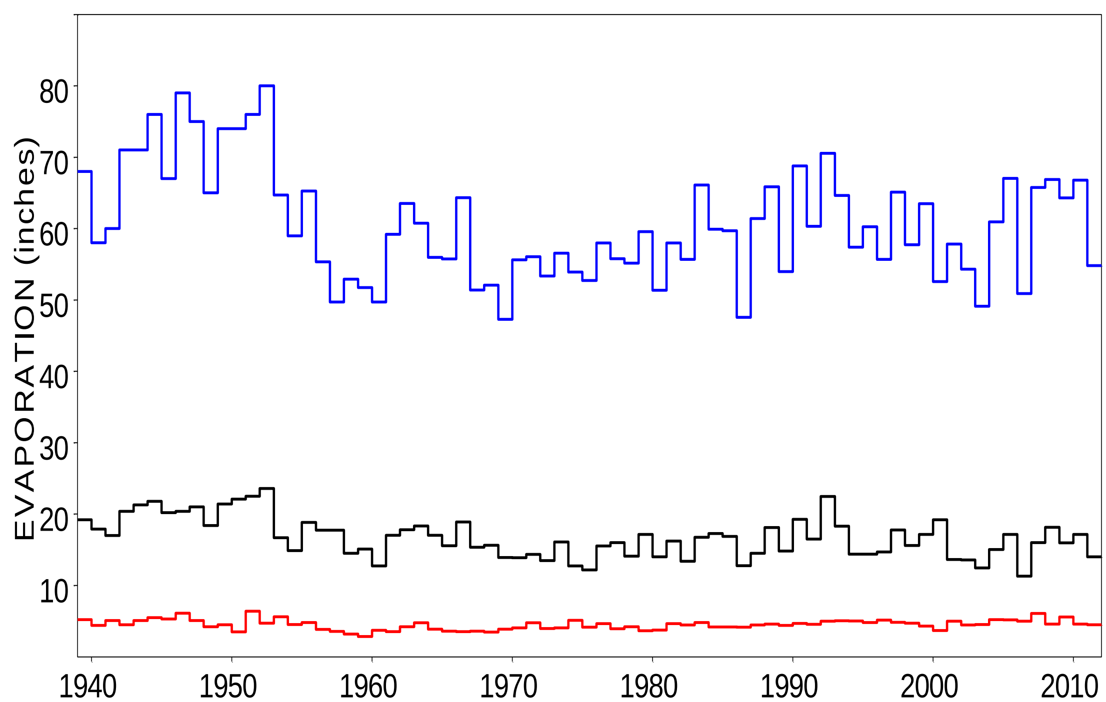
Monthly Evaporation for Quadrangle 807



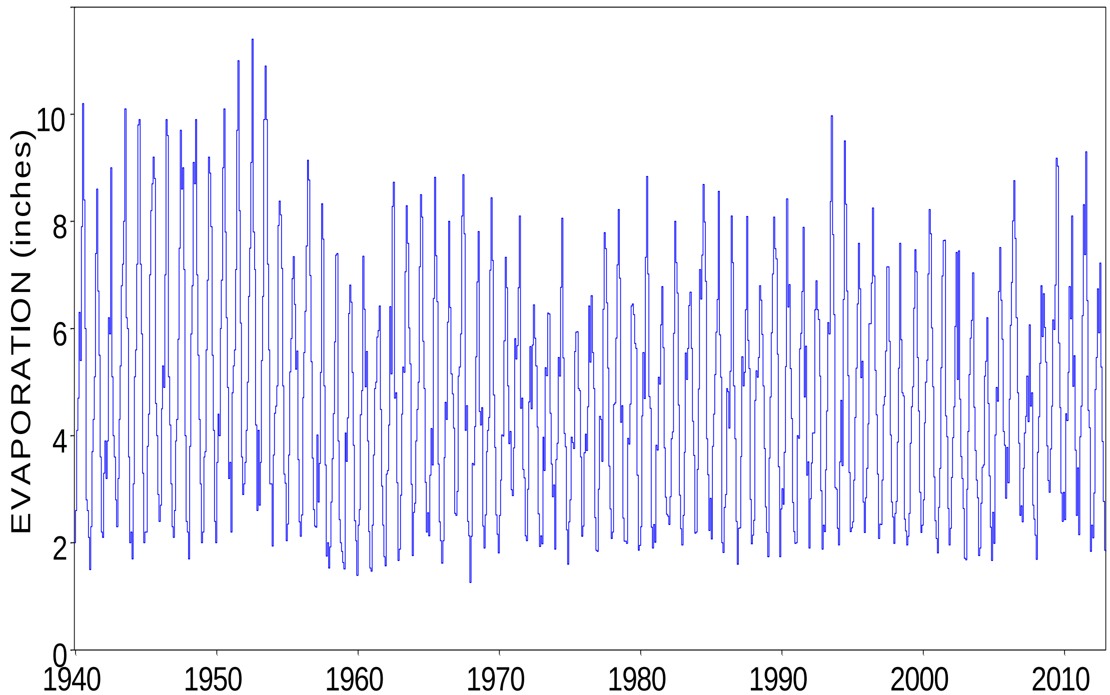
Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles 807



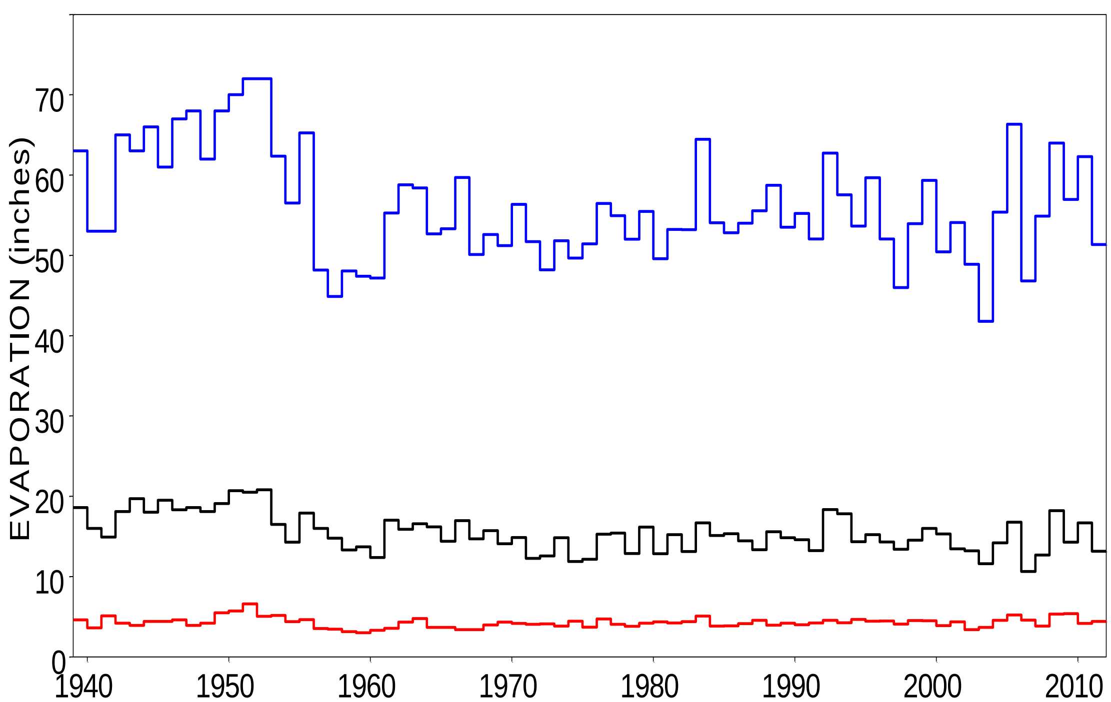
Monthly Evaporation for Quadrangle 808



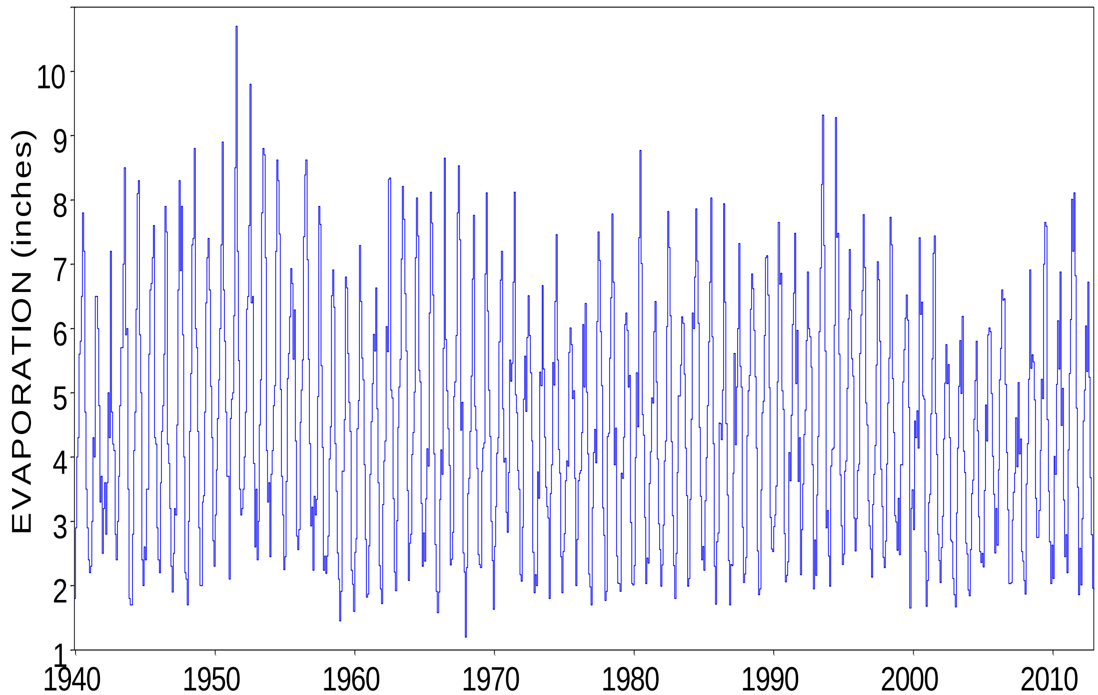
Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles 808



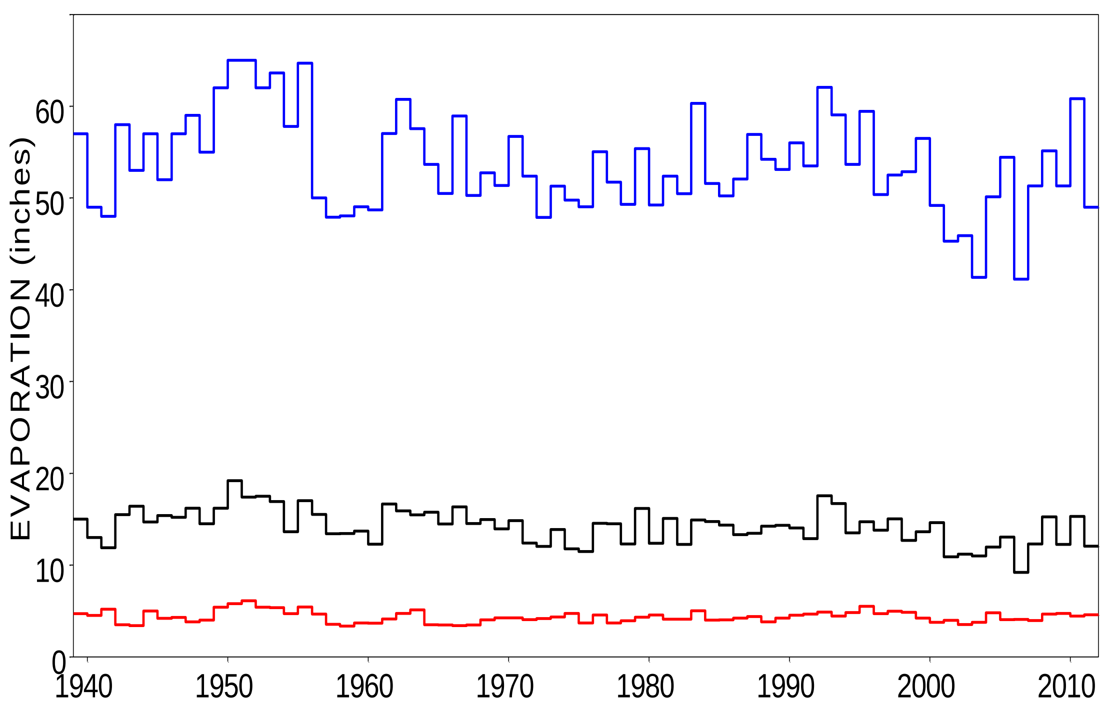
Monthly Evaporation for Quadrangle 809



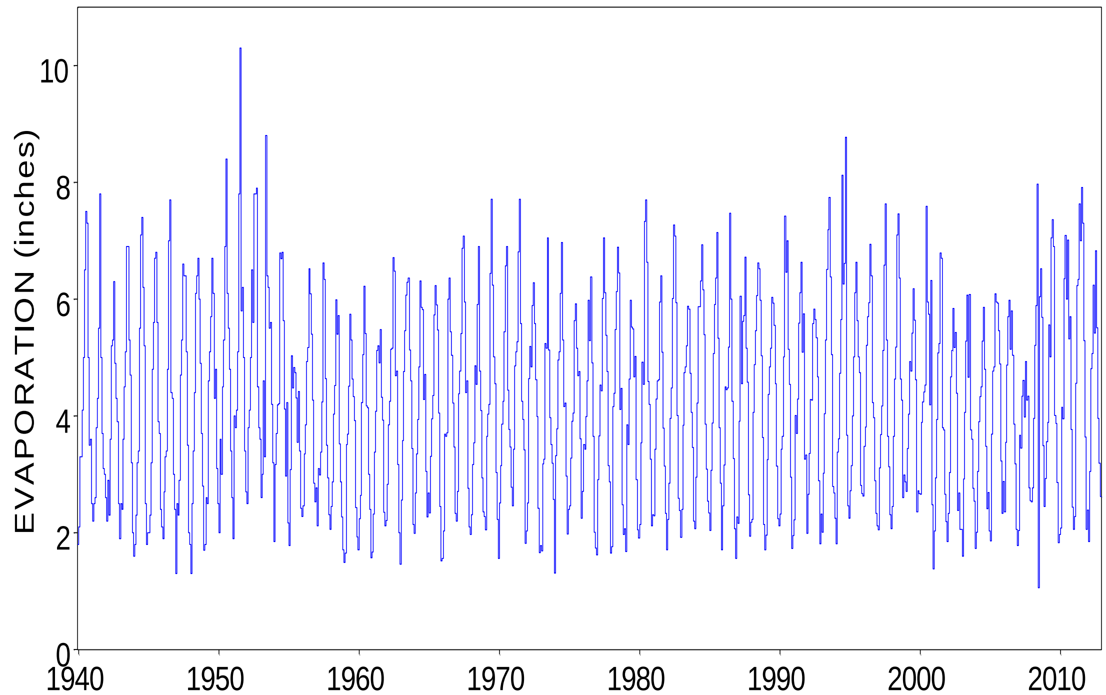
Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles 809



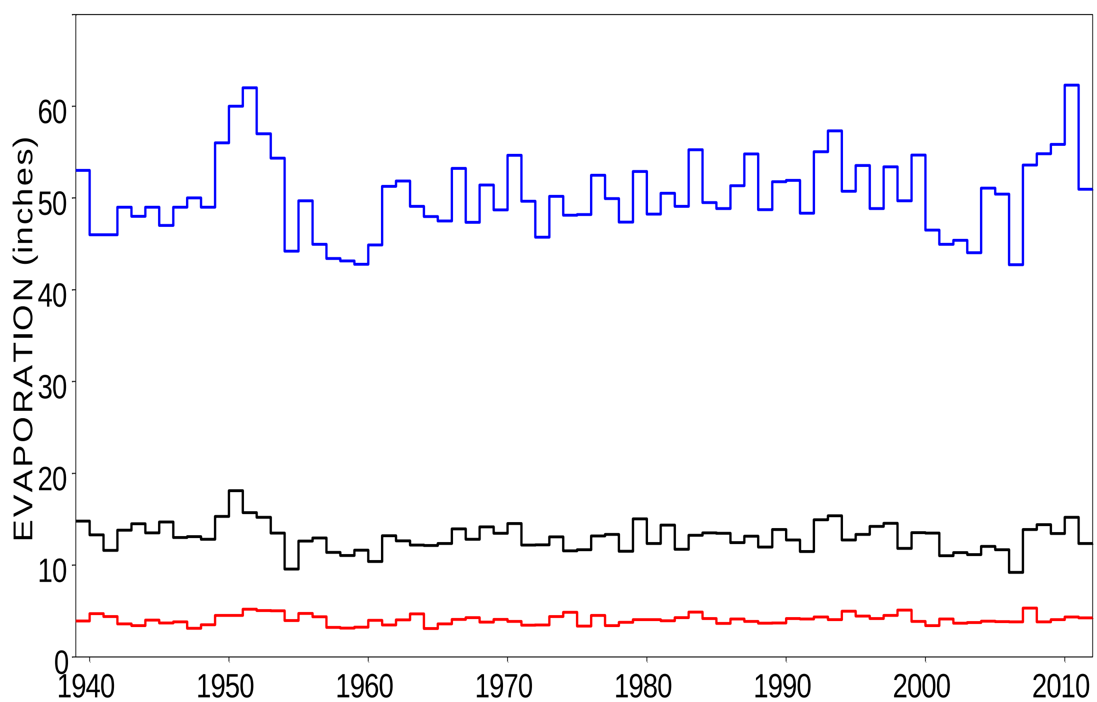
Monthly Evaporation for Quadrangle 810



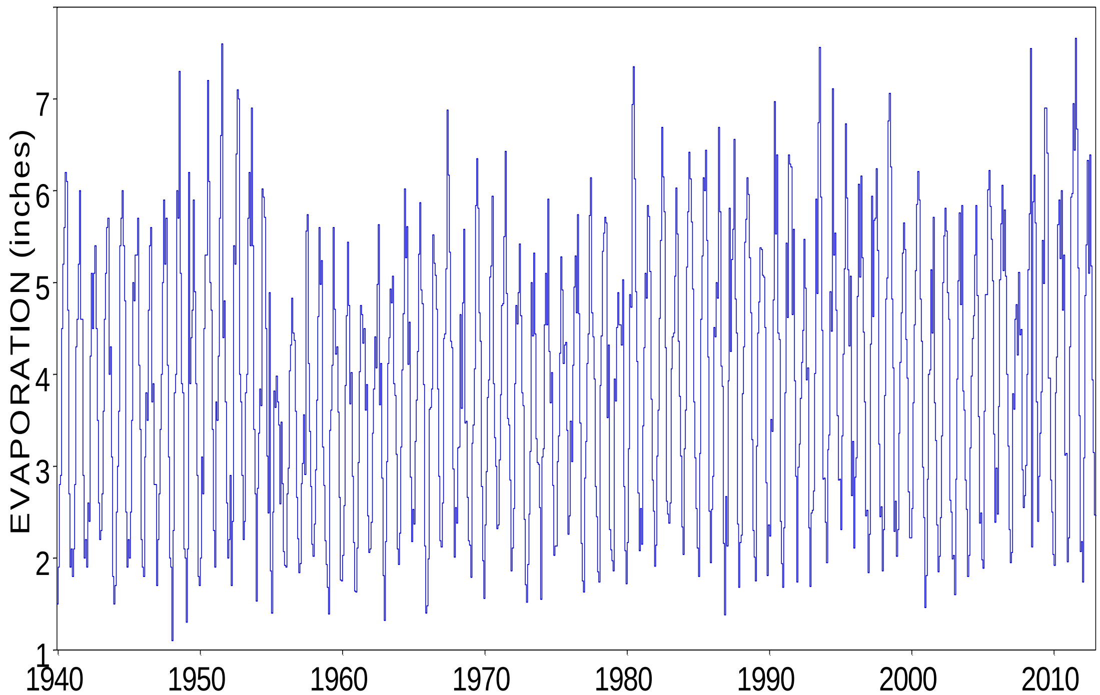
Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles 810



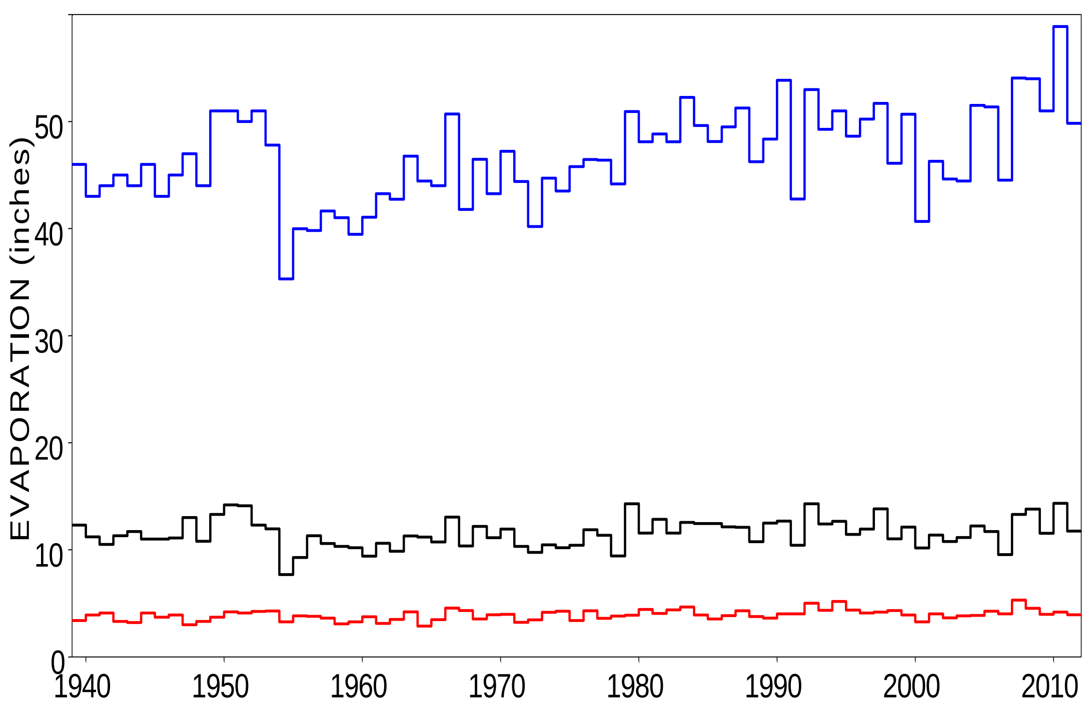
Monthly Evaporation for Quadrangle 811



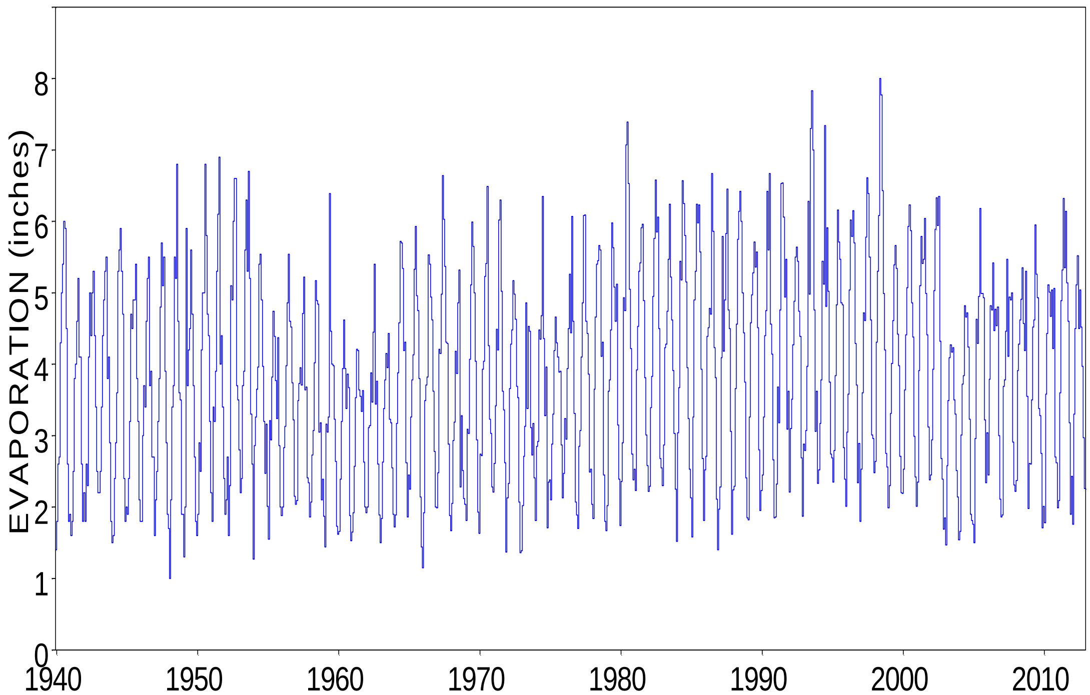
Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles 811



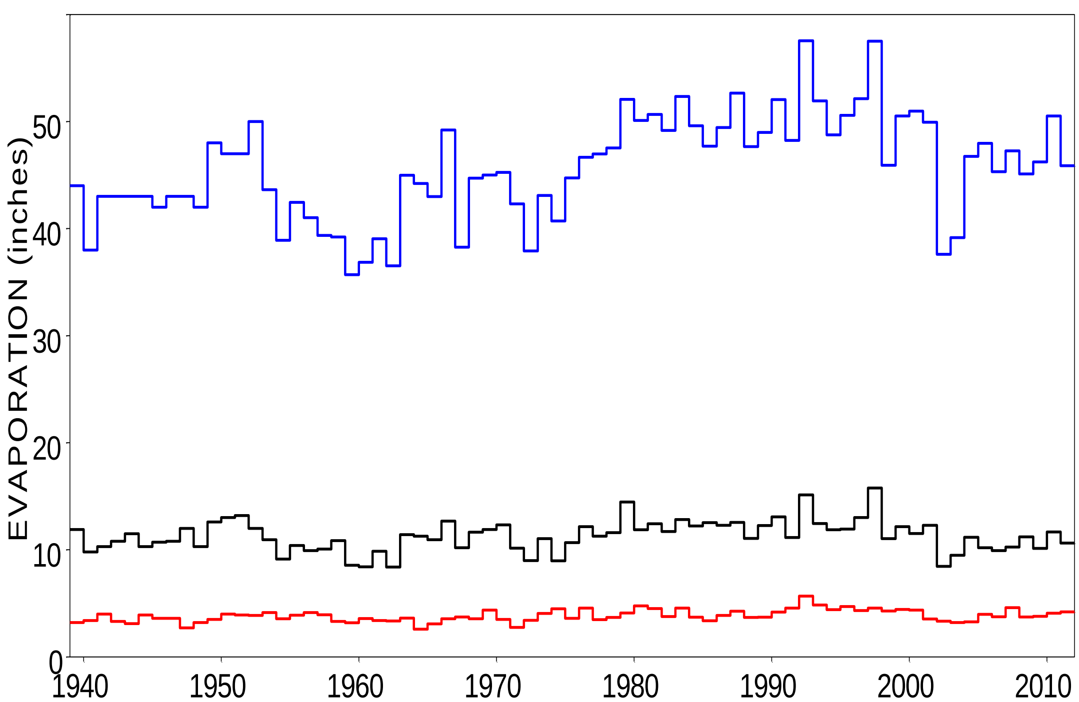
Monthly Evaporation for Quadrangle 812



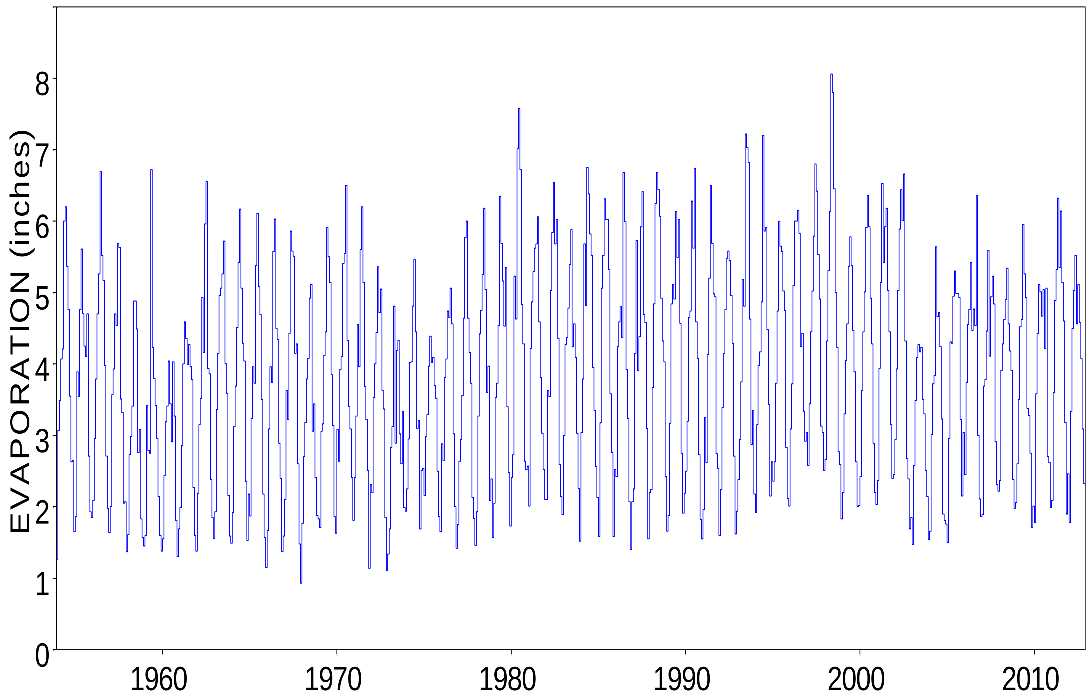
Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles 812



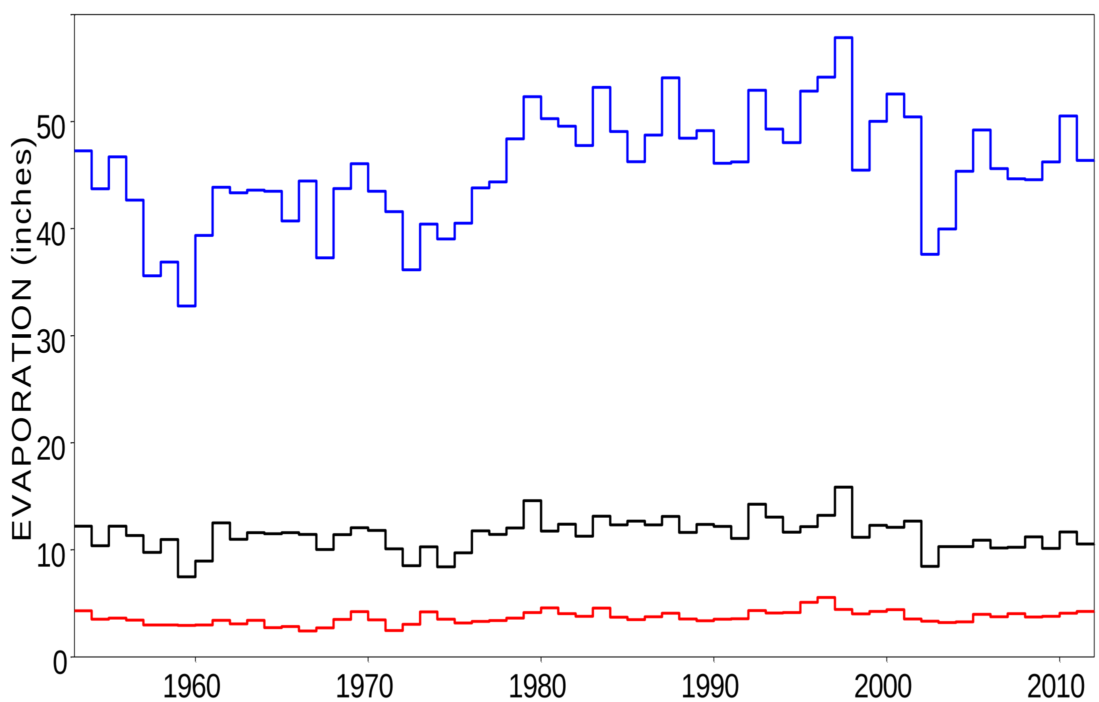
Monthly Evaporation for Quadrangle 813



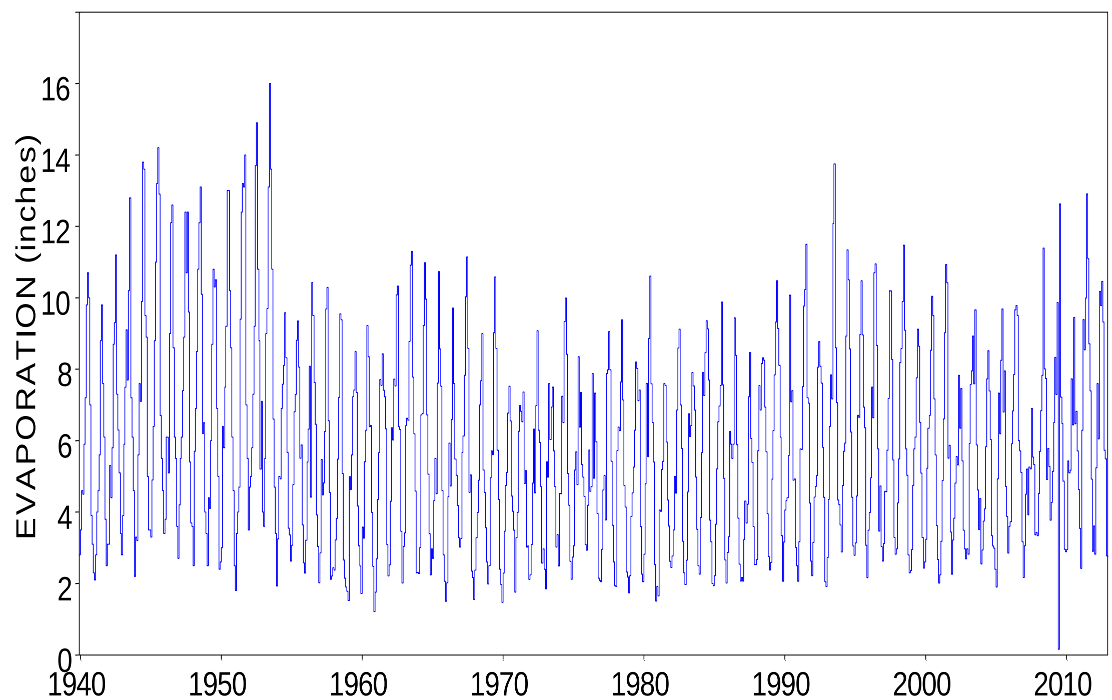
Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles 813



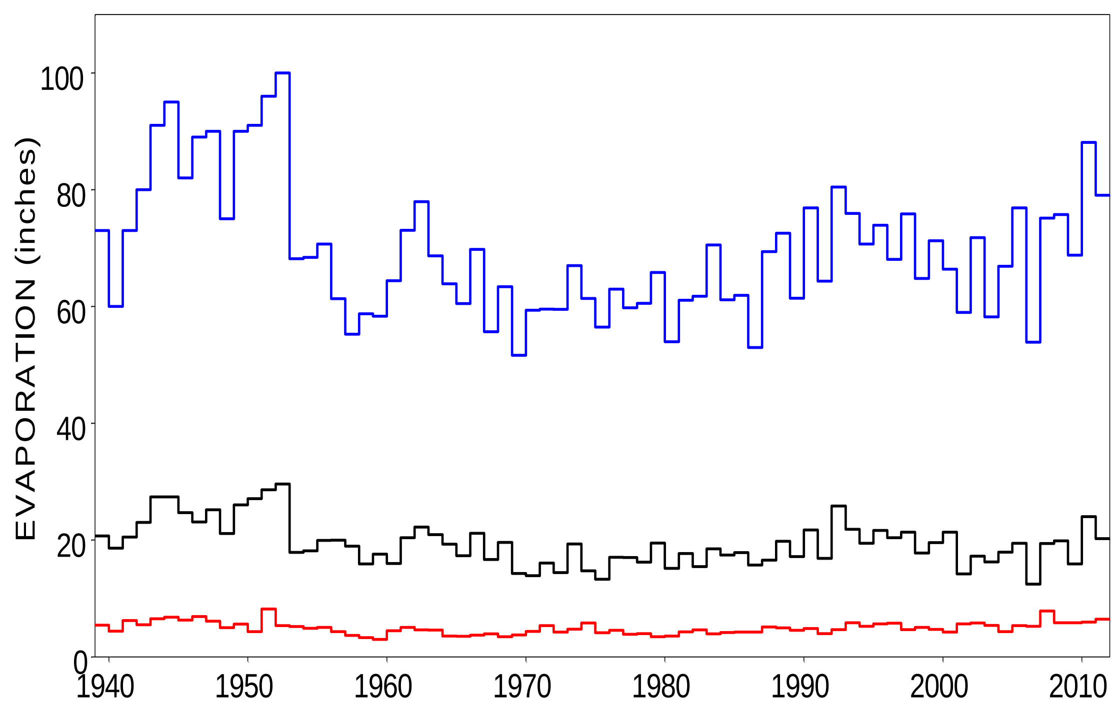
Monthly Evaporation for Quadrangle 814



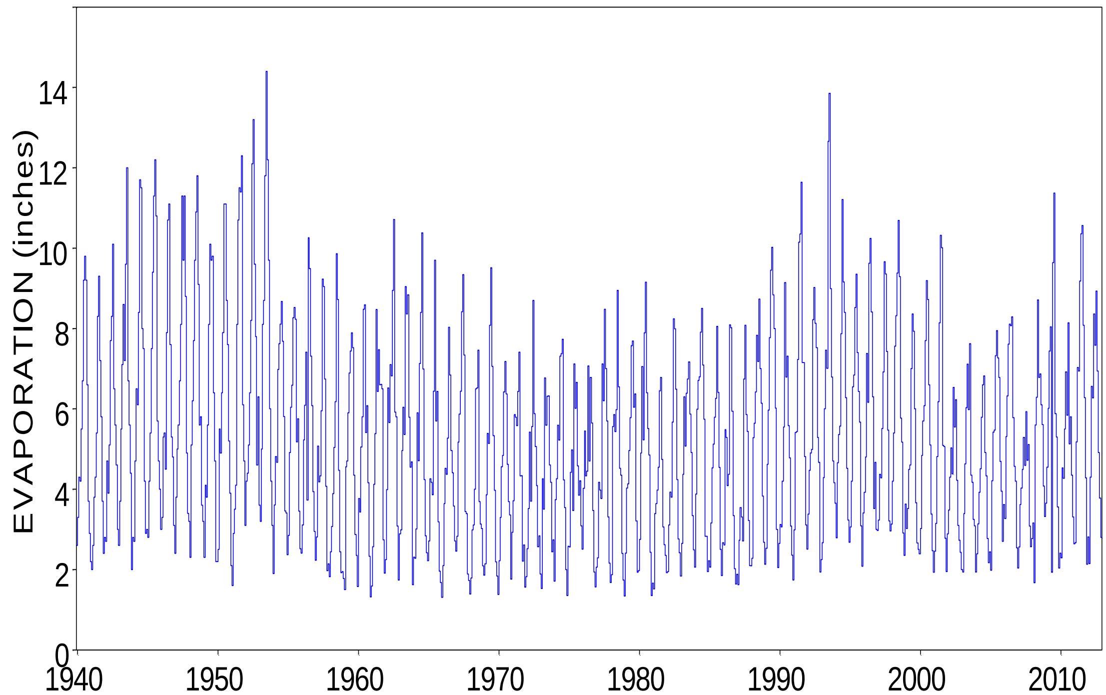
Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles 814



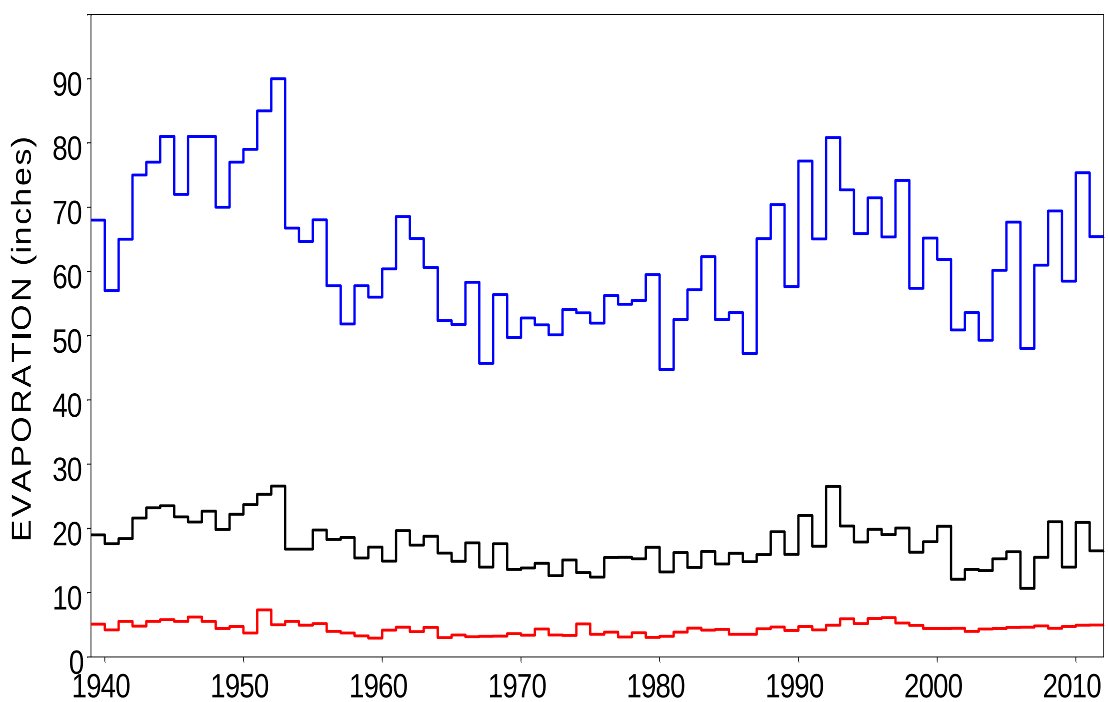
Monthly Evaporation for Quadrangle 907



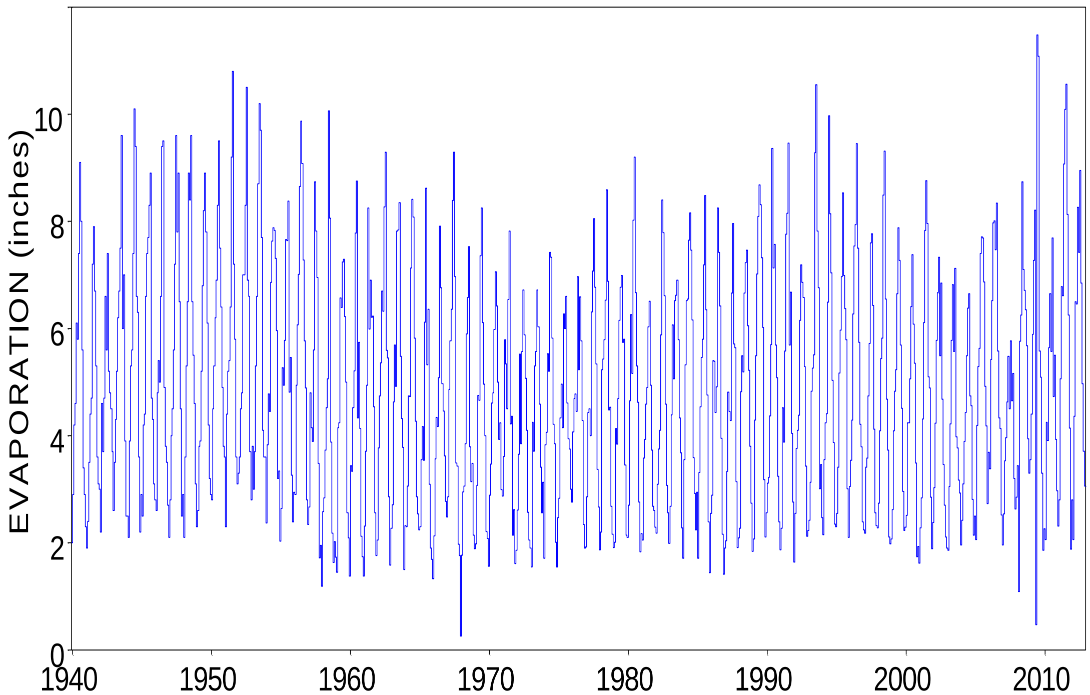
Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles 907



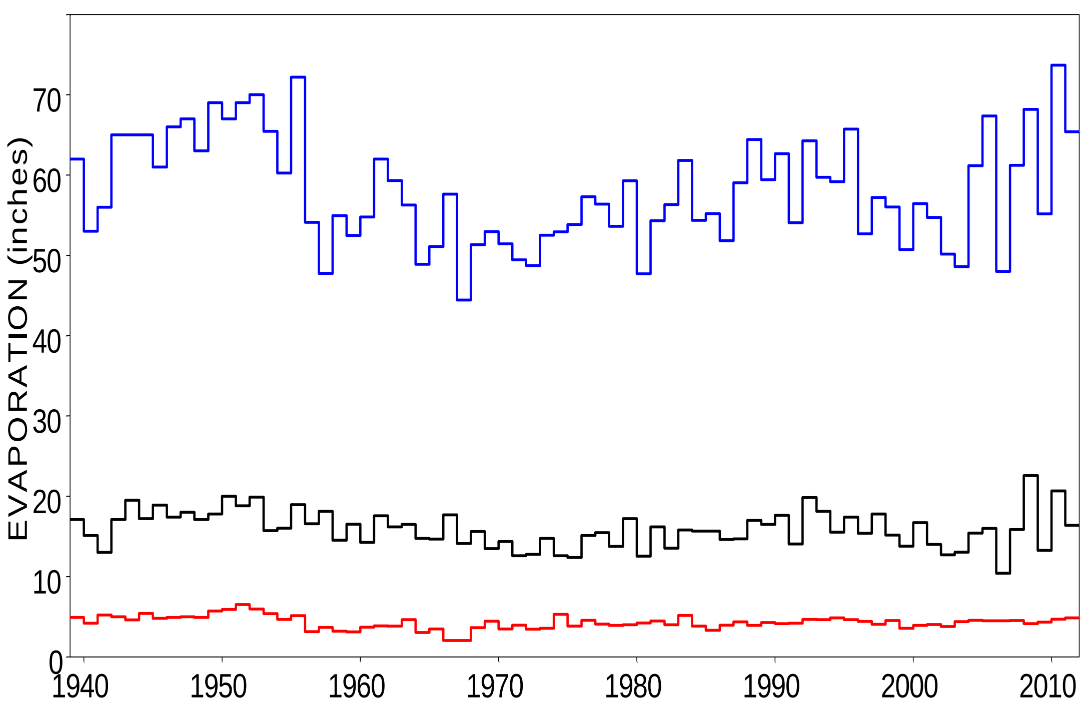
Monthly Evaporation for Quadrangle 908



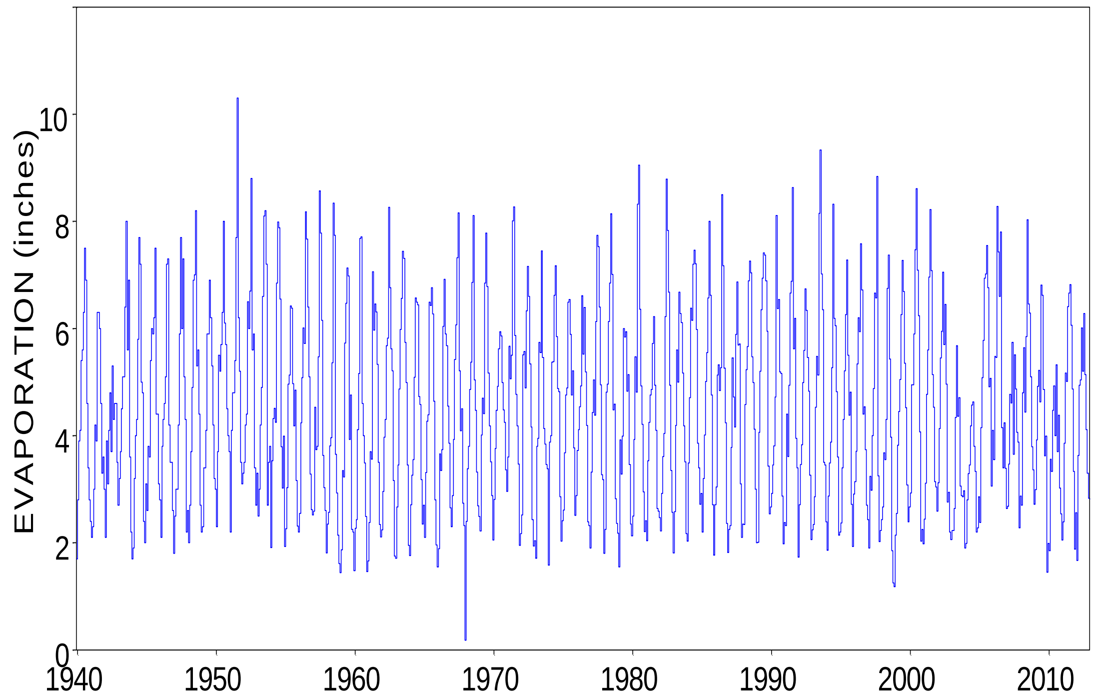
Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles 908



Monthly Evaporation for Quadrangle 909



Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles 909



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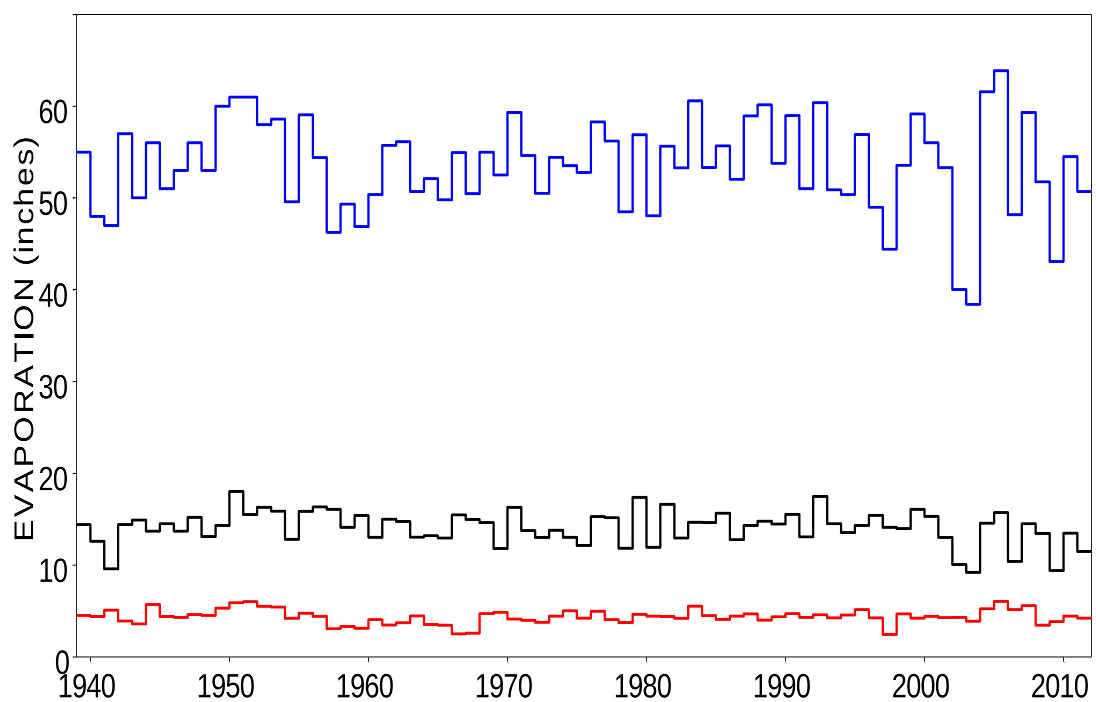
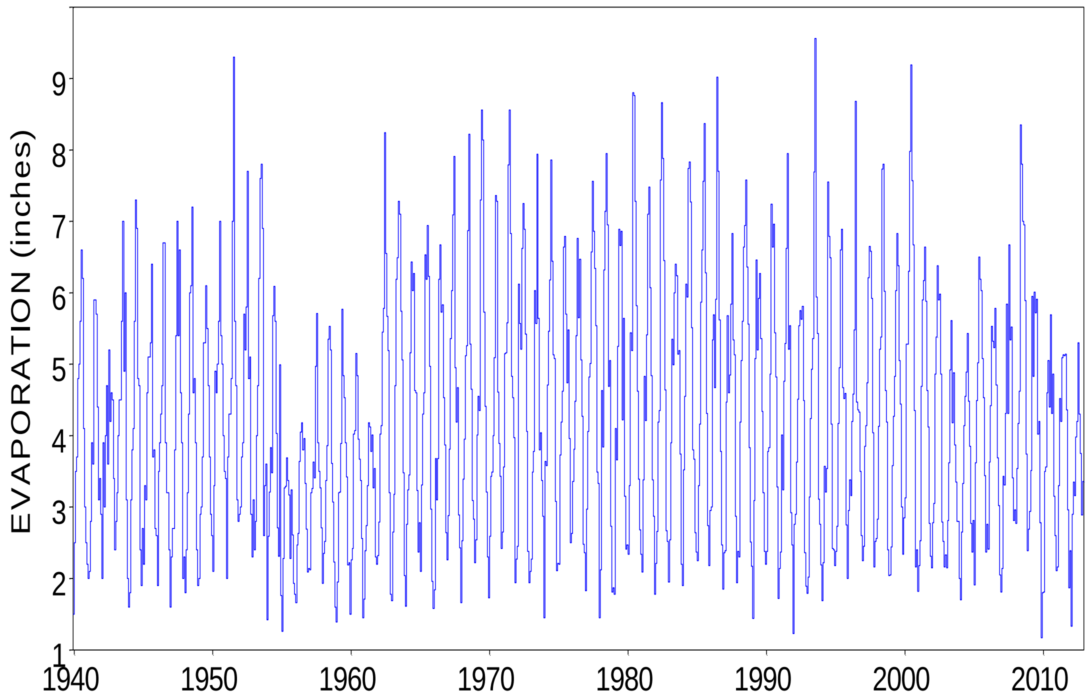
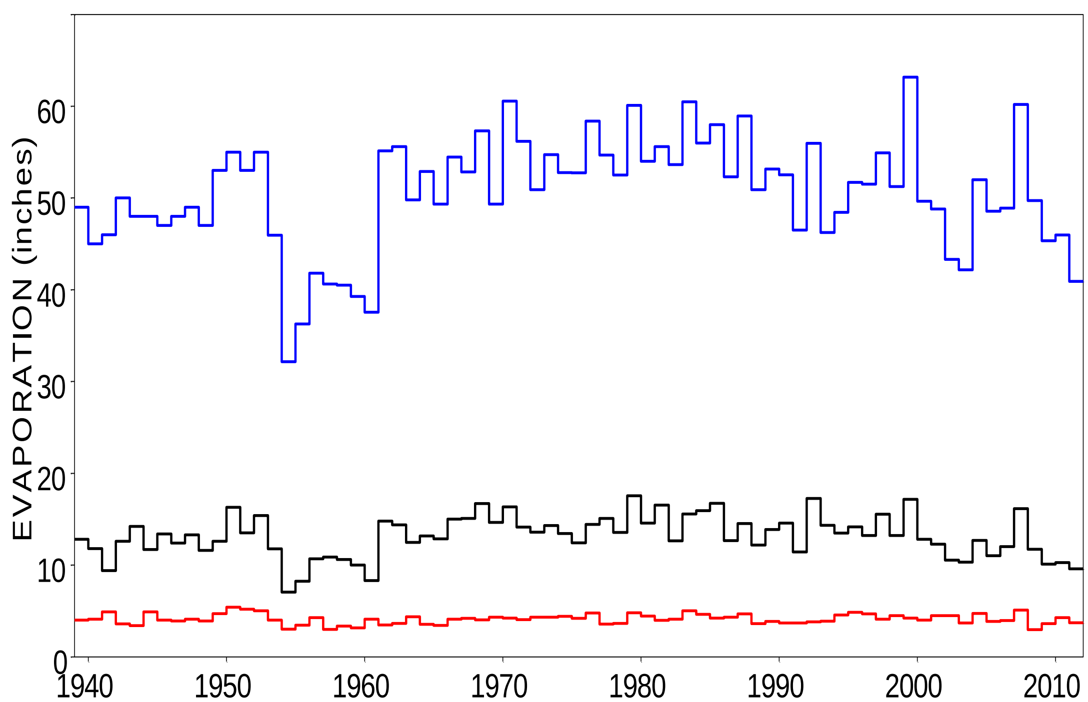


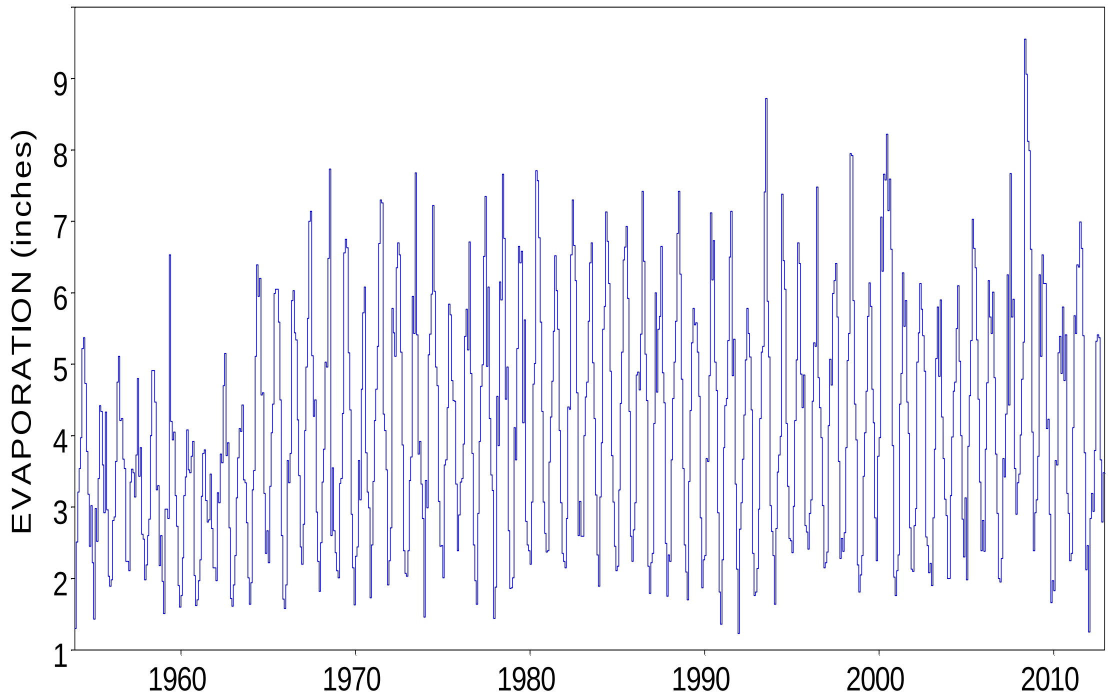
Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles 910



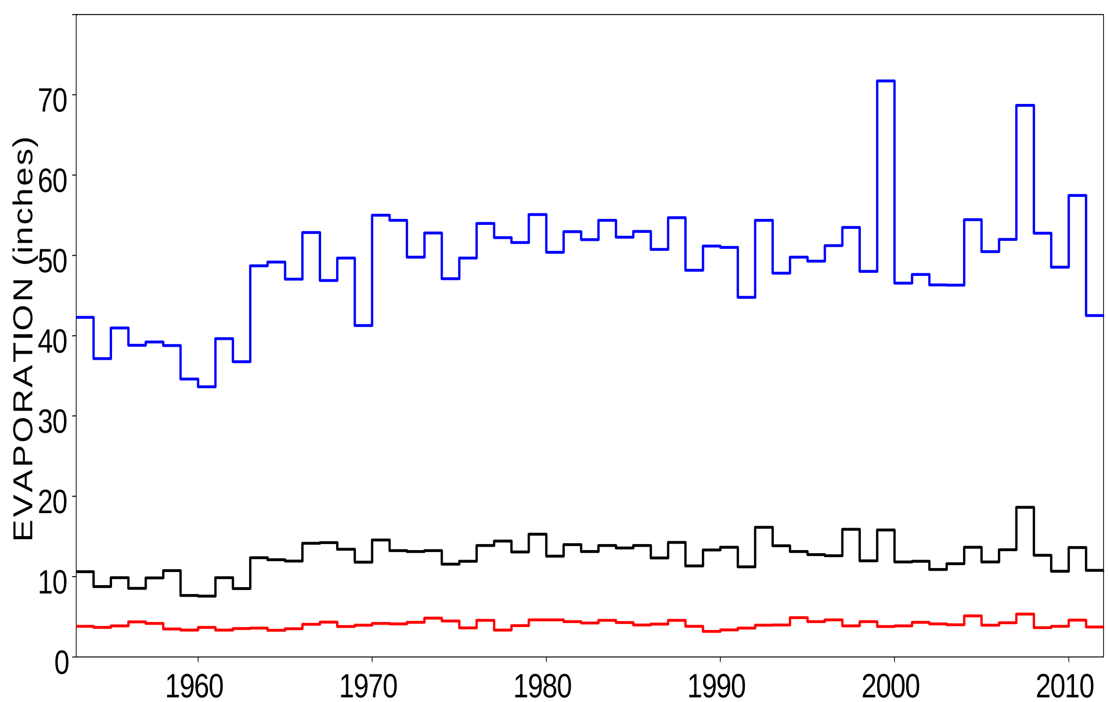
Monthly Evaporation for Quadrangle 911



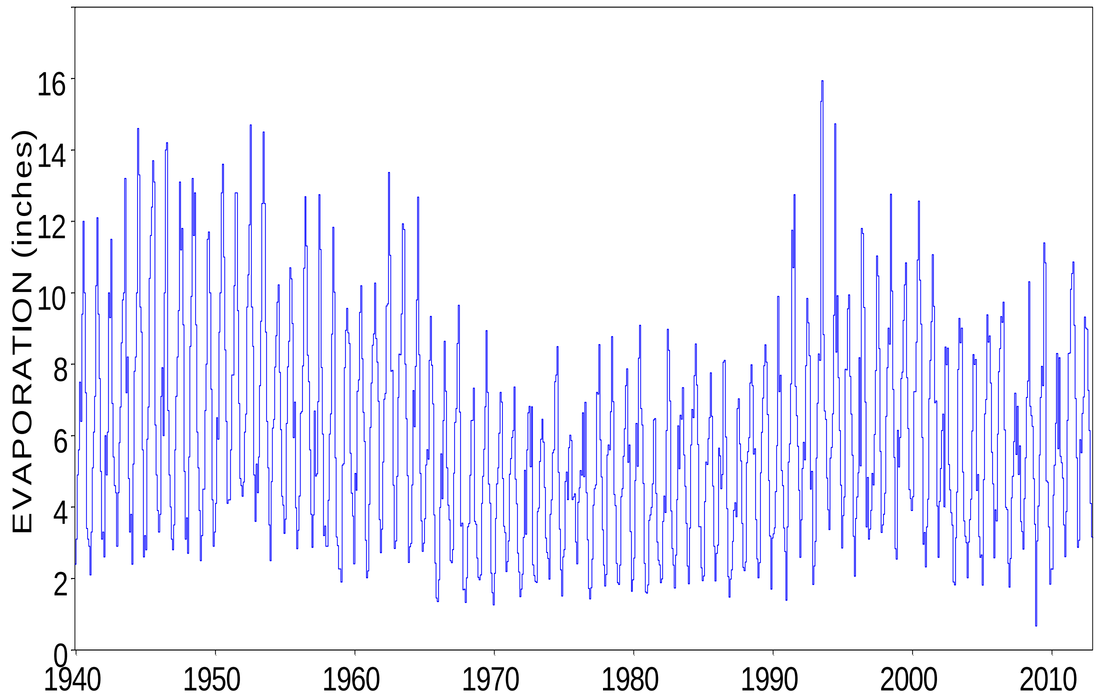
Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles 911



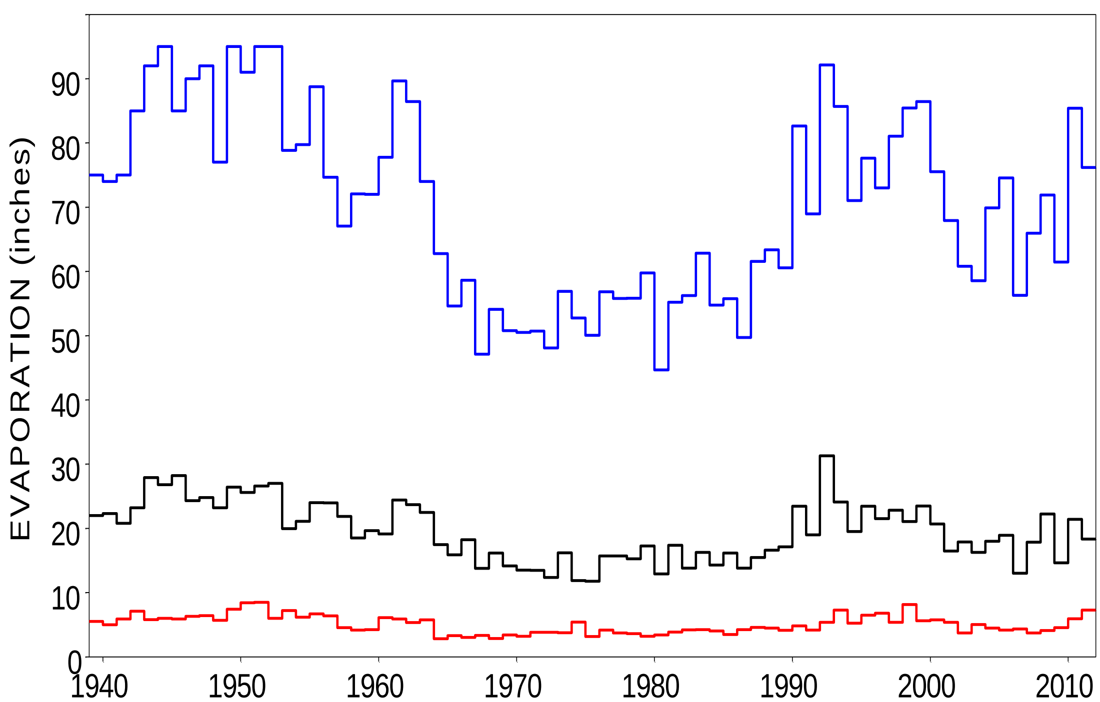
Monthly Evaporation for Quadrangle 912



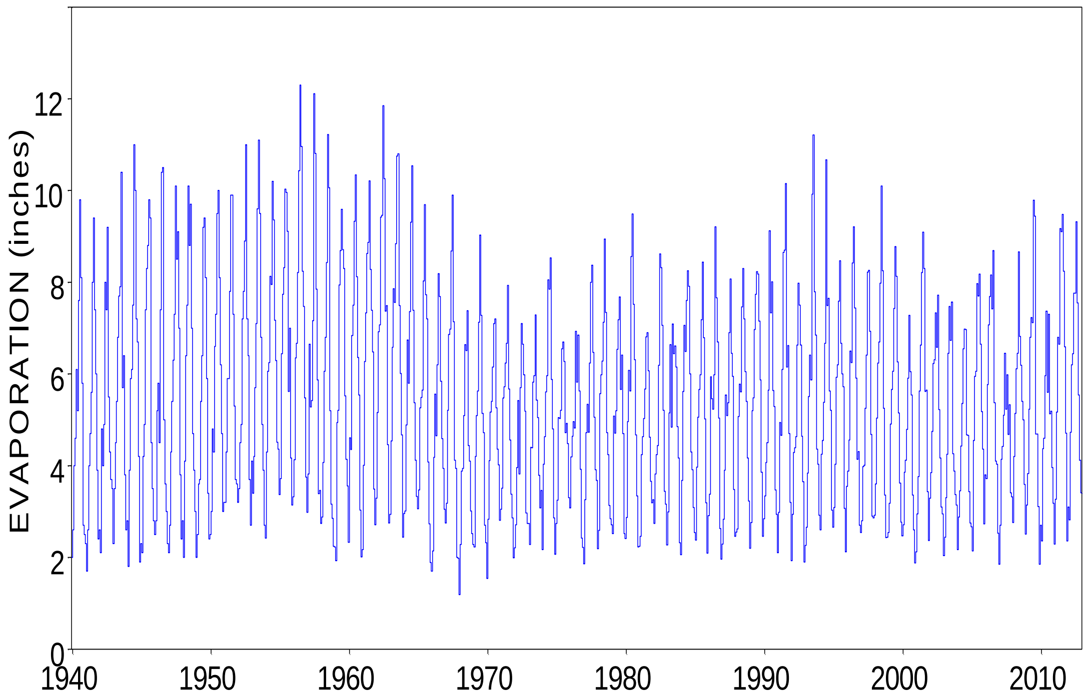
Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles 912



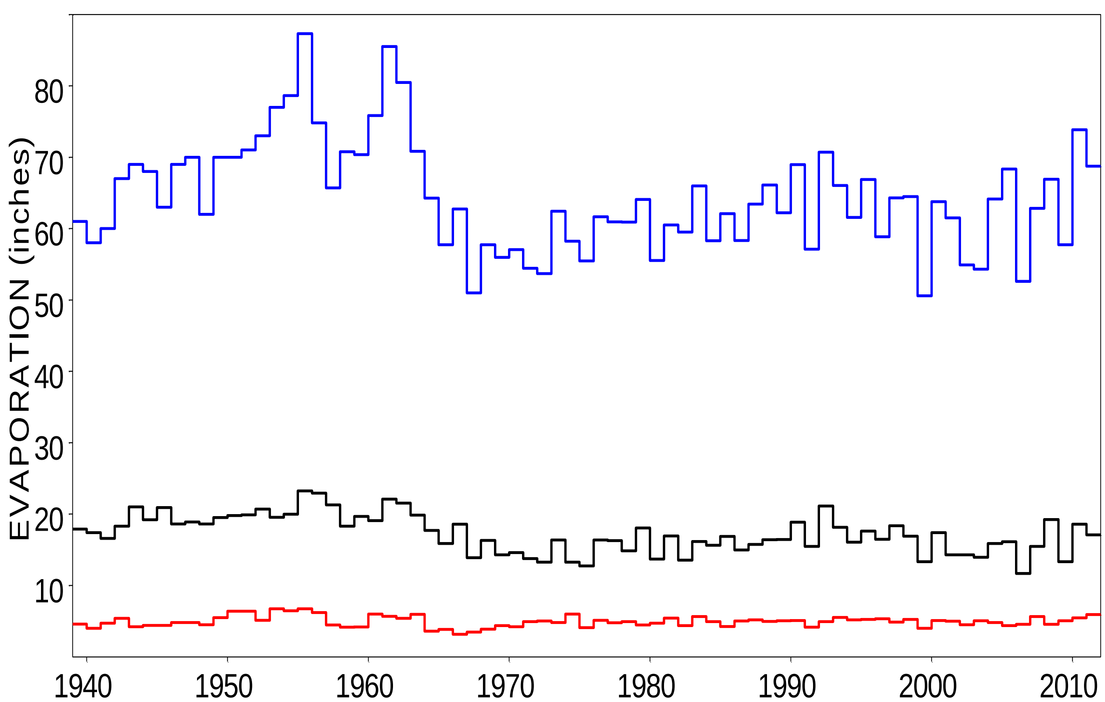
Monthly Evaporation for Quadrangle 1008



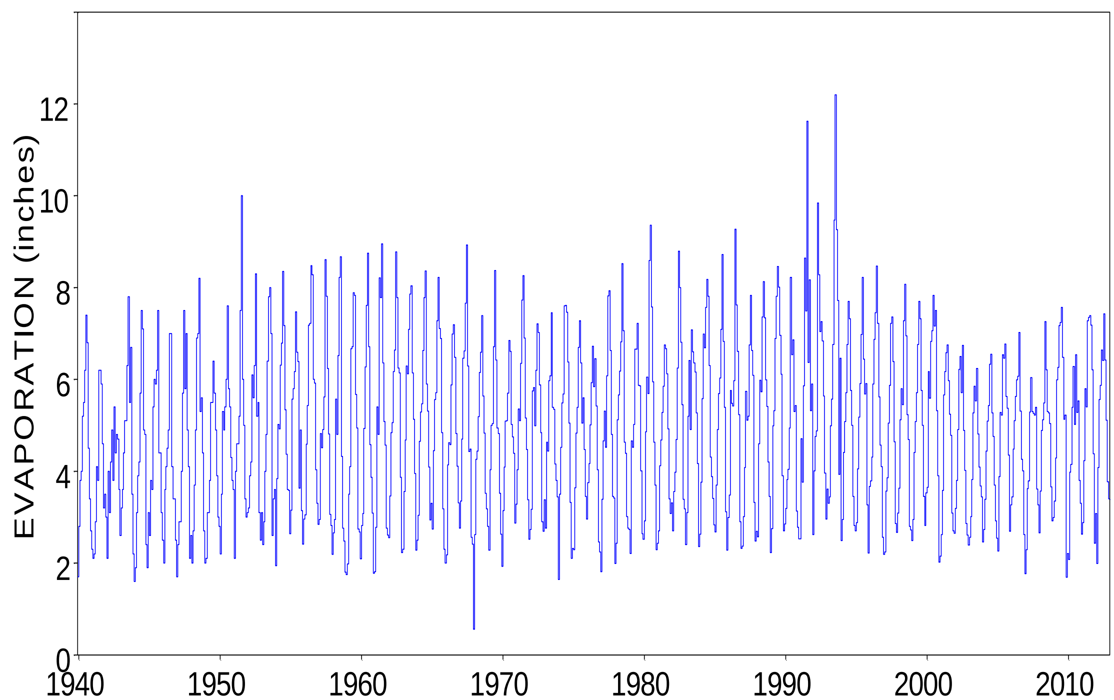
Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles 1008



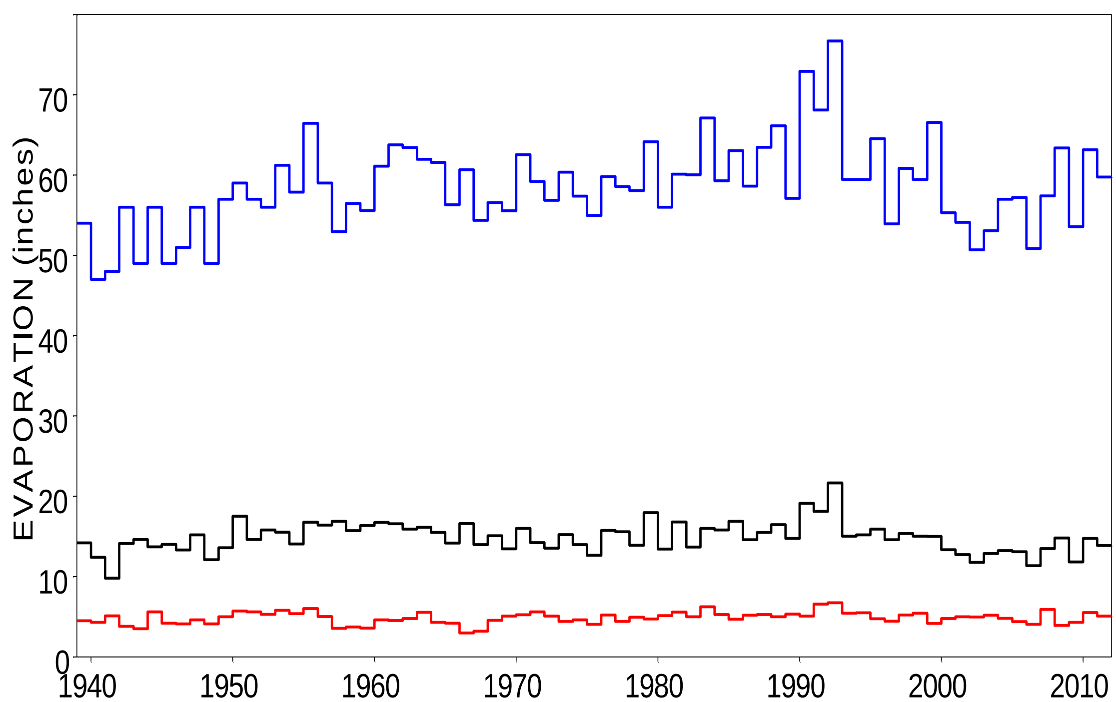
Monthly Evaporation for Quadrangle 1009



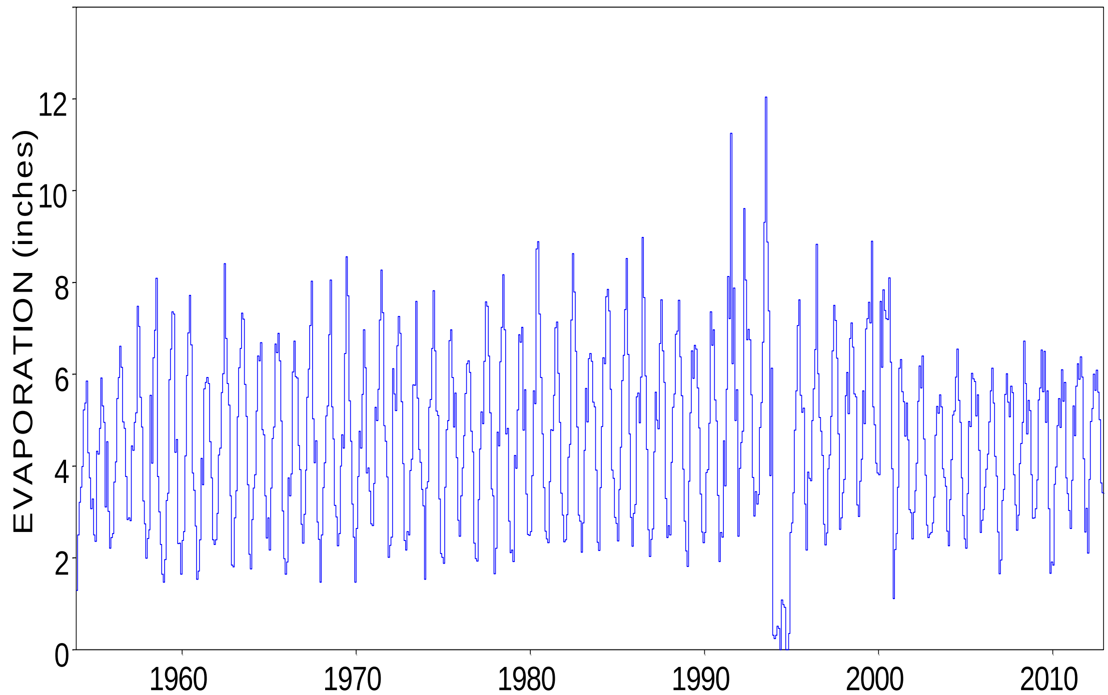
Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles 1009



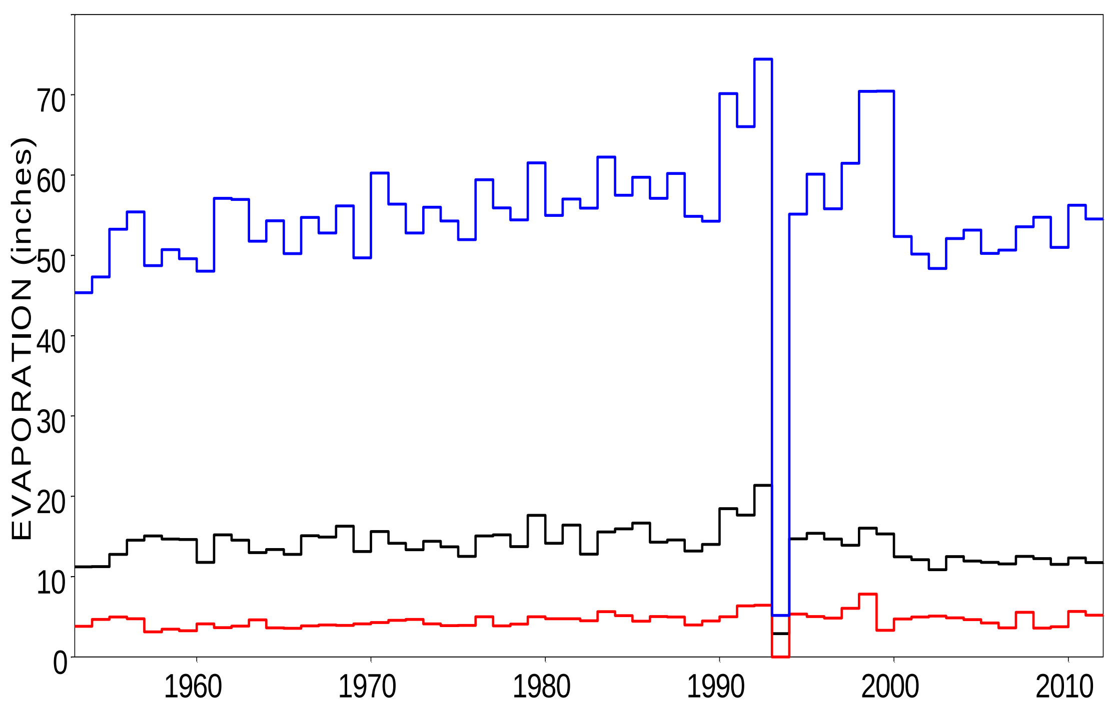
Monthly Evaporation for Quadrangle 1010



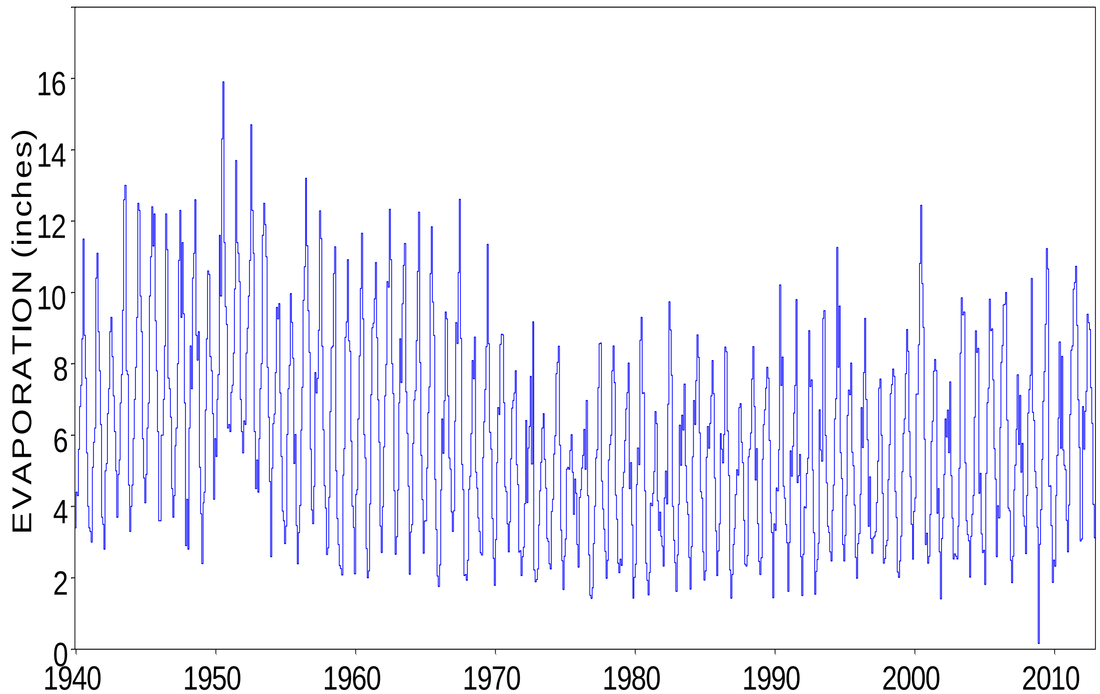
Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles 1010



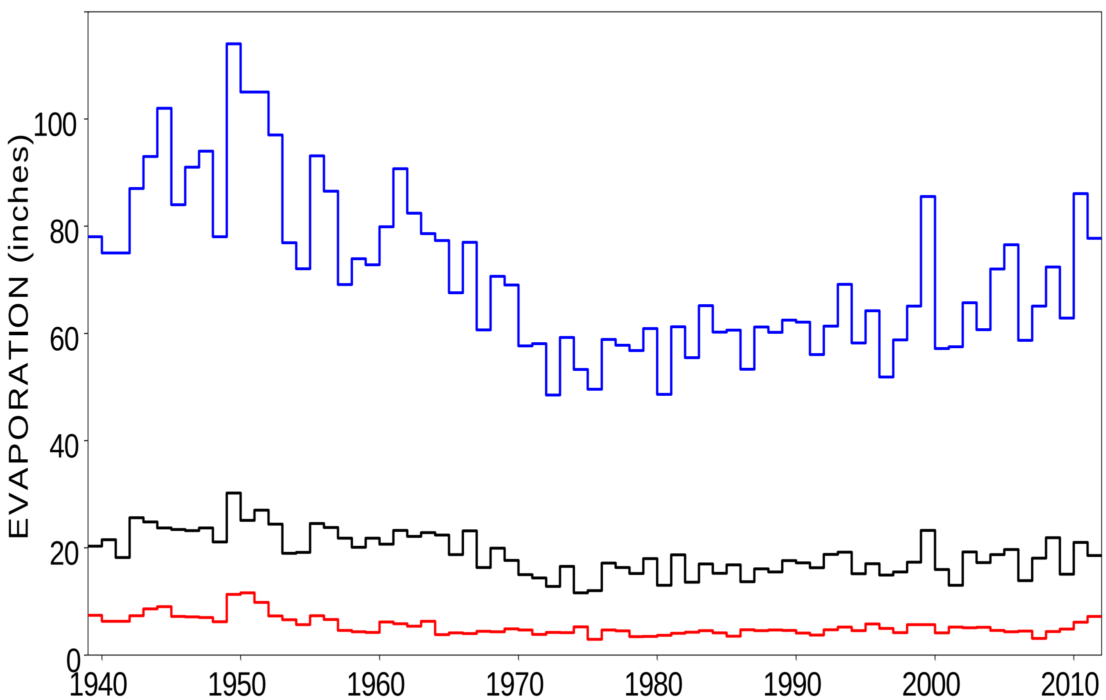
Monthly Evaporation for Quadrangle 1011



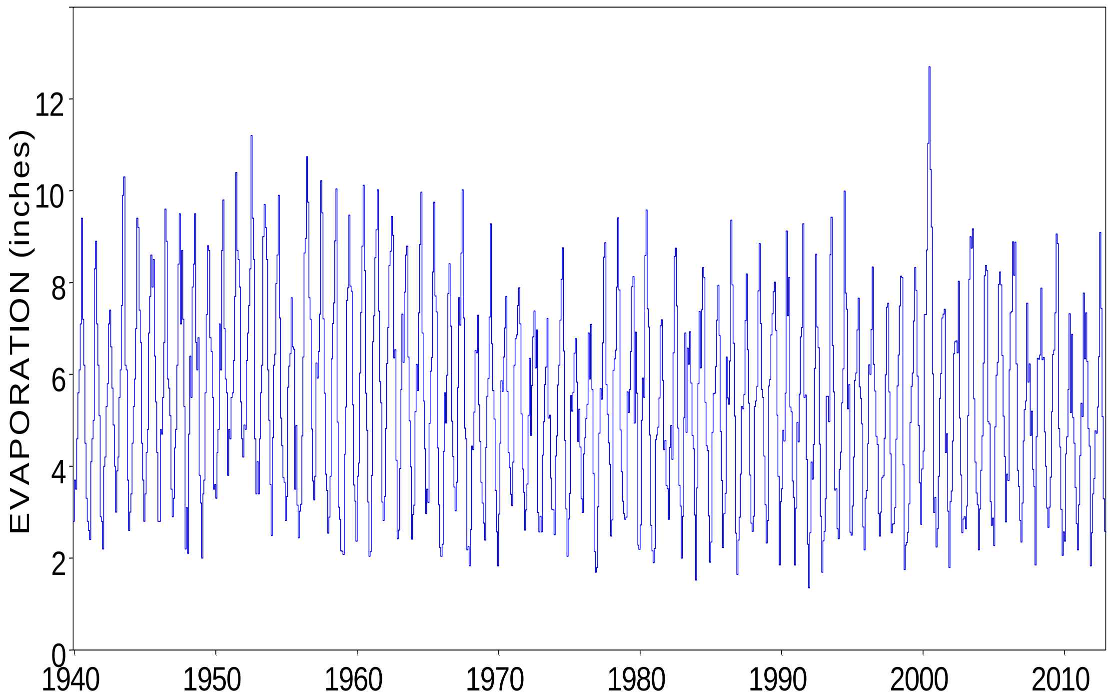
Monthly Evaporation for Quadrangle 1011



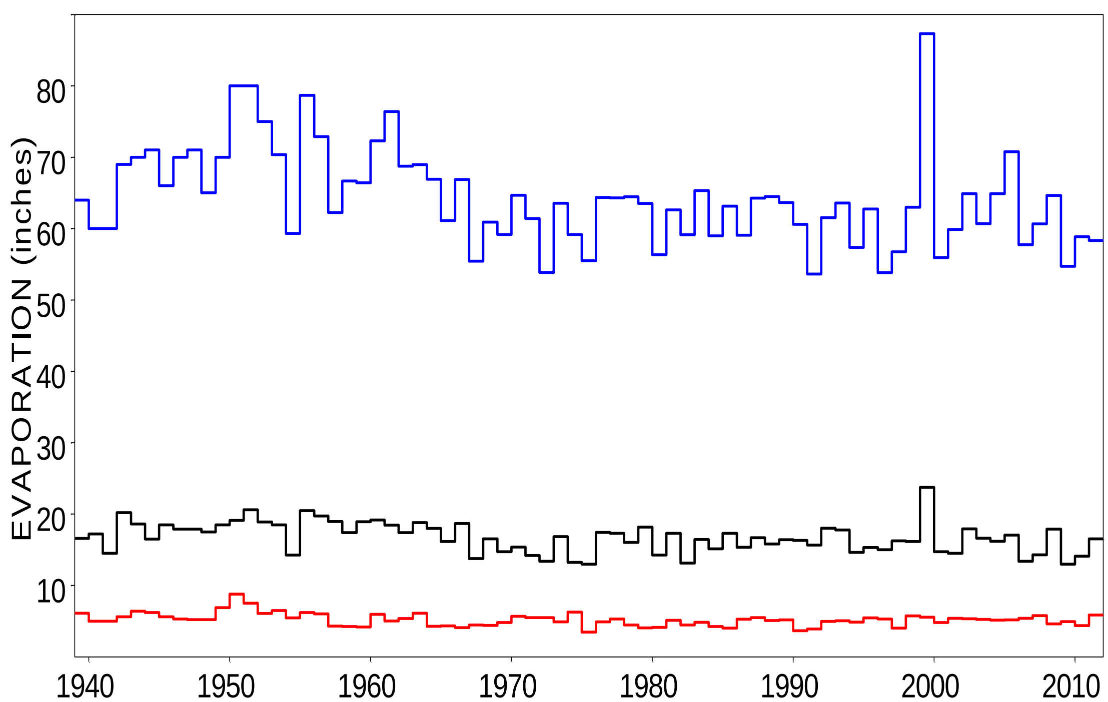
Monthly Evaporation for Quadrangle 1108



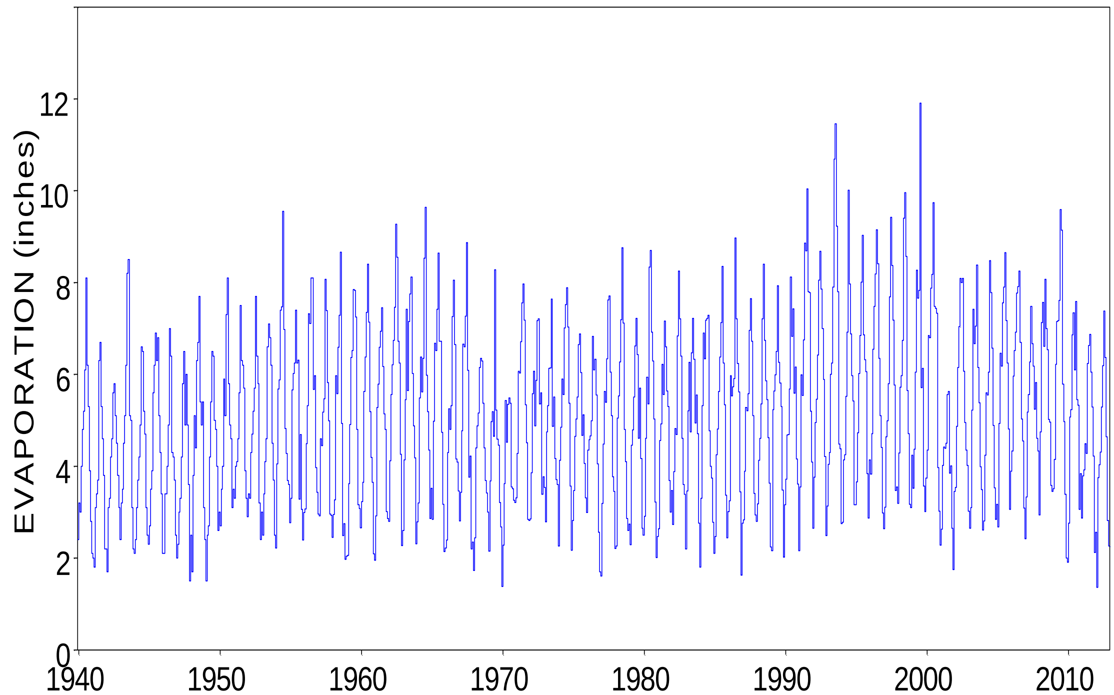
Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles 1108



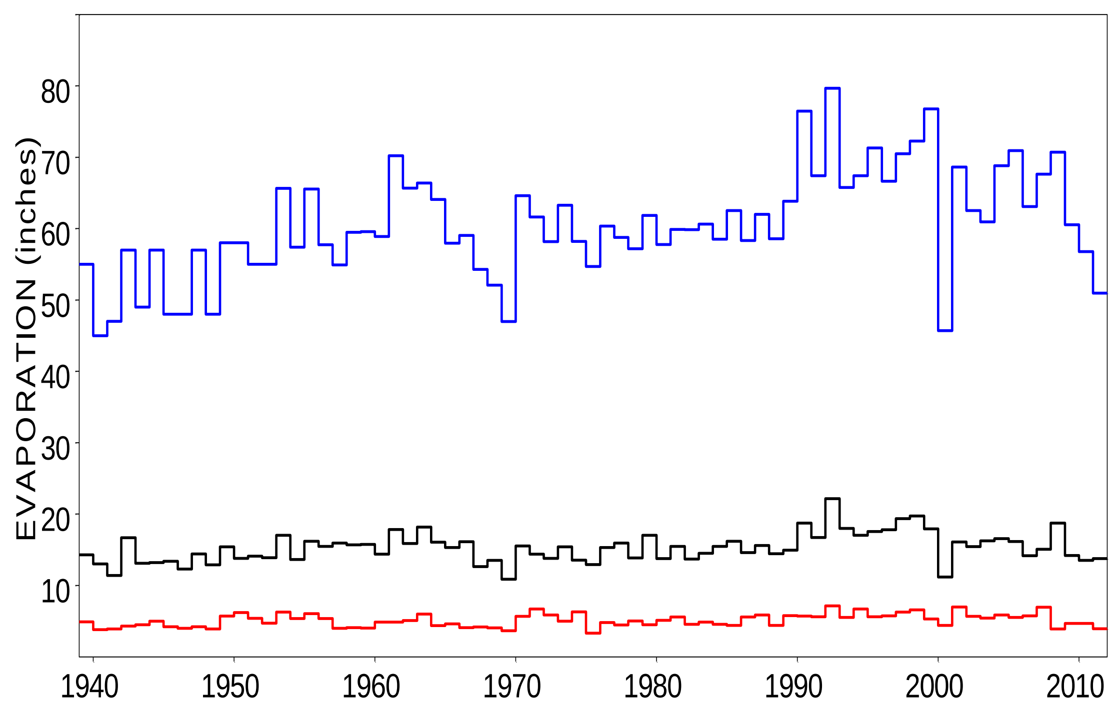
Monthly Evaporation for Quadrangle 1109



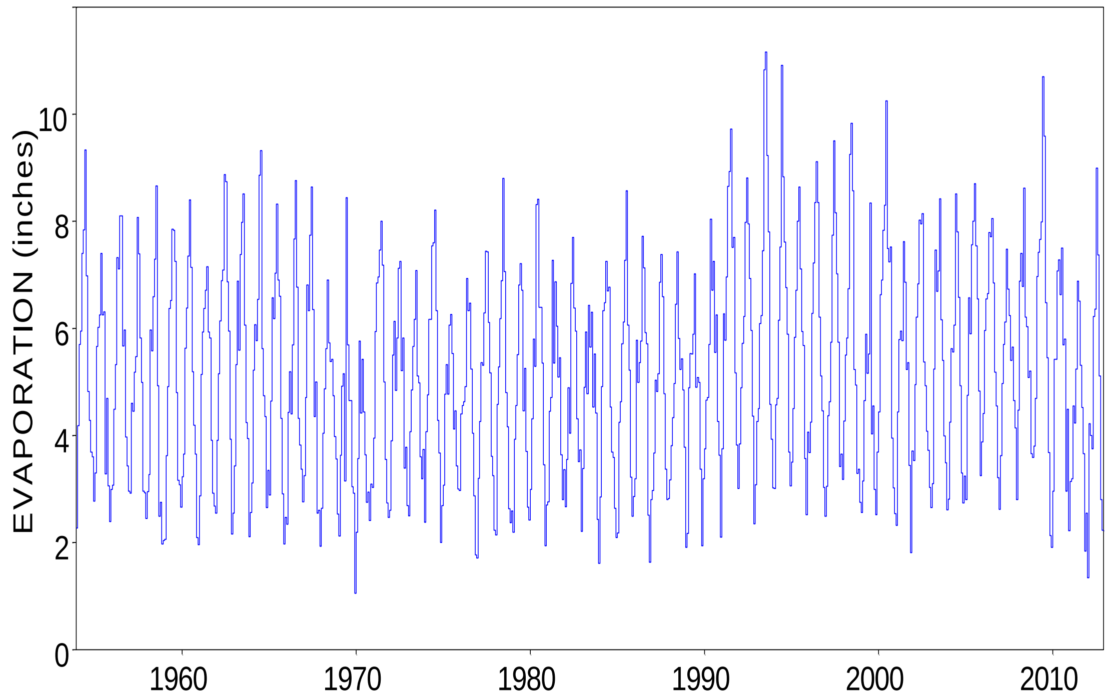
Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles 1109



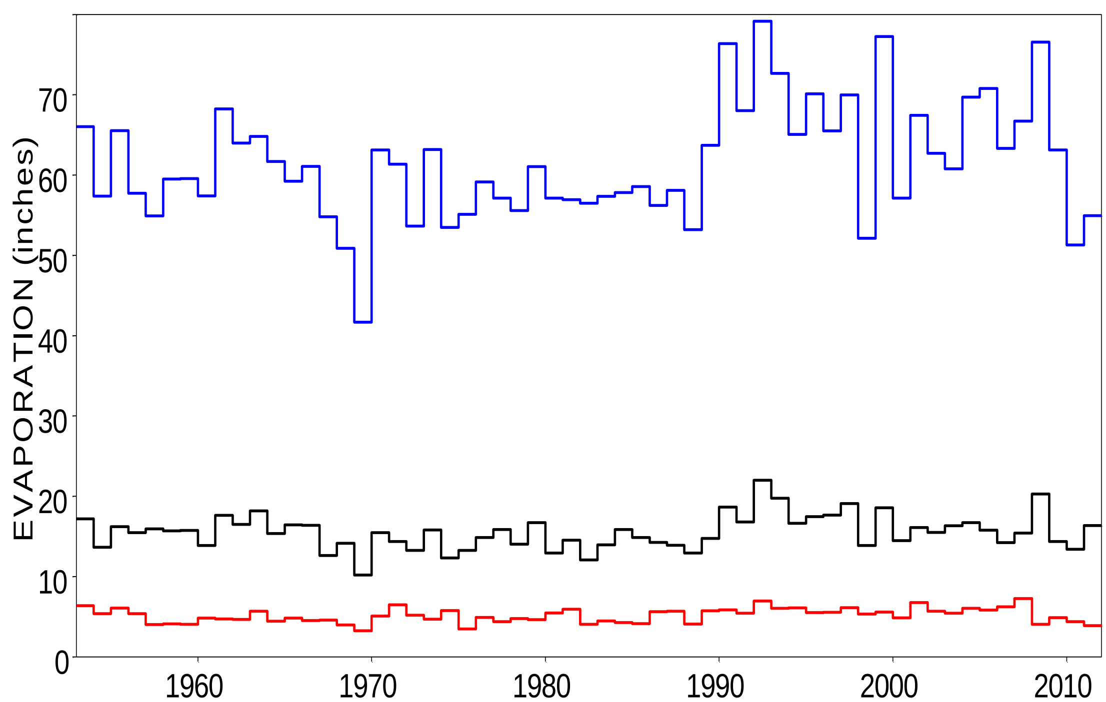
Monthly Evaporation for Quadrangle 1110



Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles 1110



Monthly Evaporation for Quadrangle 1210



Annual Total, 2-Month Maximum, and 2-Month Minimum Evaporation for Quadrangles 1210

APPENDIX C

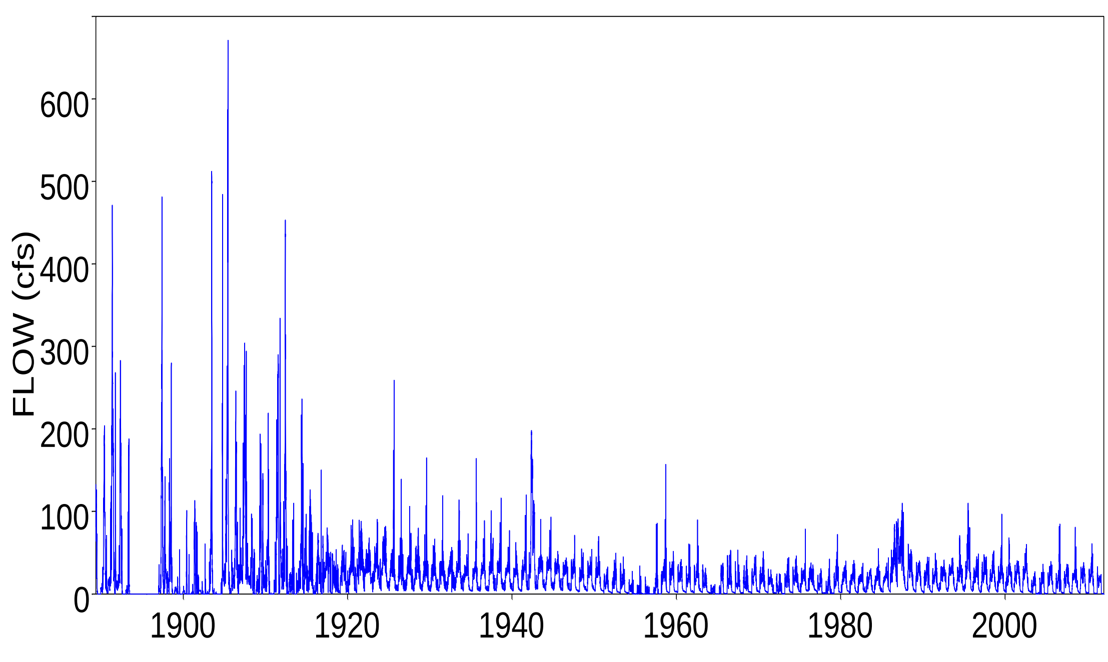
PLOTS OF DAILY, MONTHLY, AND ANNUAL OBSERVED STREAM FLOW

AT 35 GAGING STATIONS

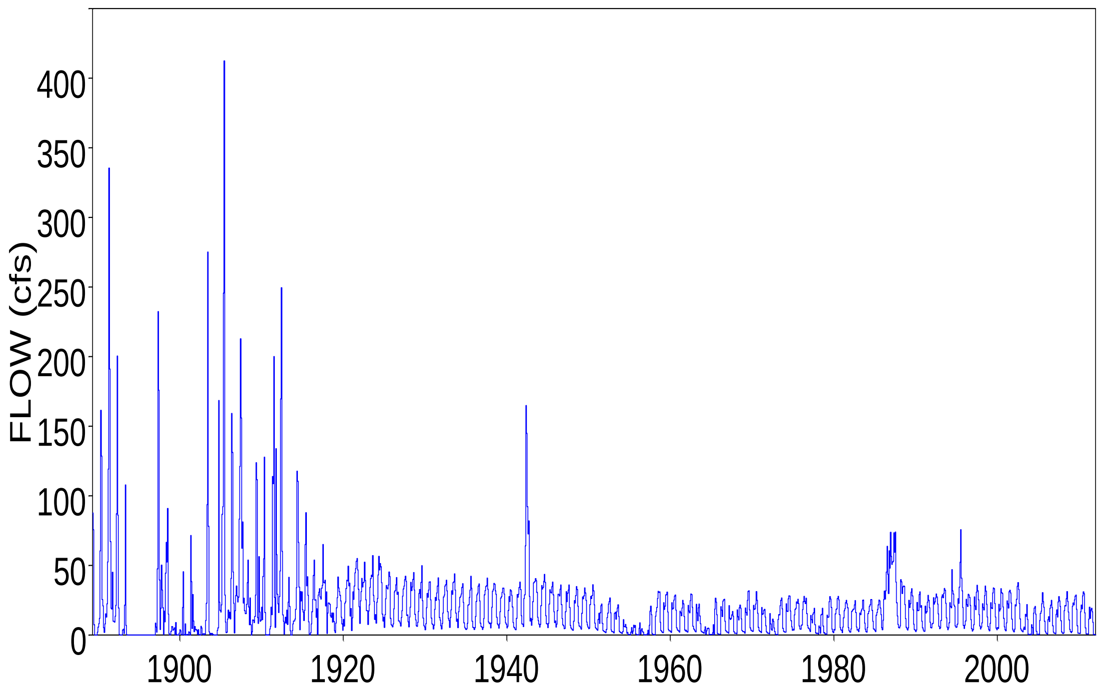
1
Rio Grande at El Paso
IBWC gage 08-3640.00
El Paso County, Texas
Latitude 31°48'10", Longitude 106°32'25"
Gage datum 1,134.6 feet above msl

This gage is located on the Rio Grande 1,256 river miles above its outlet at the Gulf of Mexico, 5.5 miles above the del Norte Bridge between El Paso and Juarez, and 1.7 miles above the American Dam at El Paso.Elephant Butte Reservoir on the Rio Grande 125 miles upstream of El Paso accounts for most of the conservation storage controlling flows at this gage site. With a storage capacity of 2,065,000 acre-feet, this is the largest reservoir in New Mexico. Elephant Butte Reservoir is operated by the U.S. Bureau of Reclamation primarily to supply irrigation. Initial impoundment was in 1915.

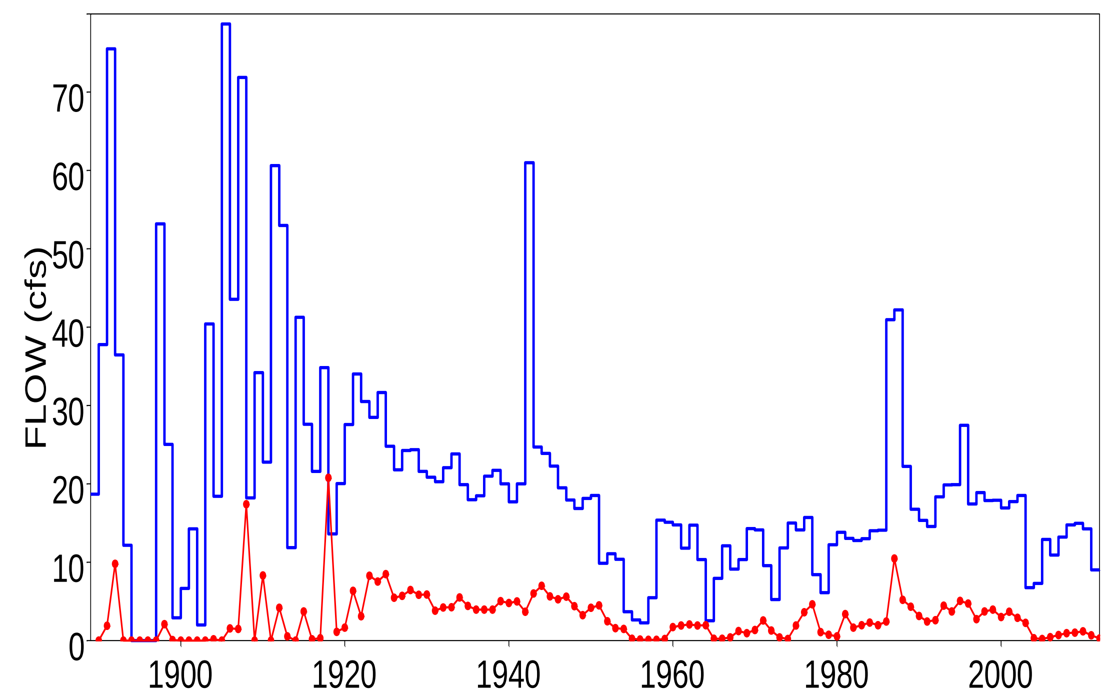
Period-of-record of daily flows: 1889/5/10 to 2011/12/31



Daily Flows of Rio Grande at El Paso



Monthly Flows of Rio Grande at El Paso

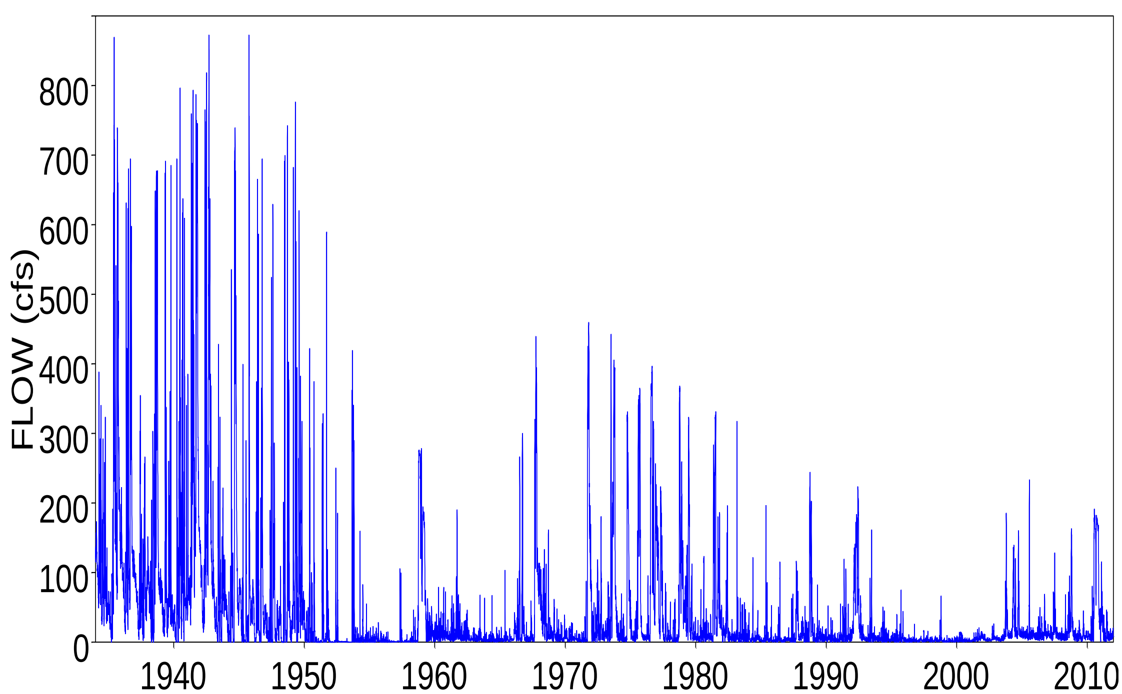


Annual Flows and the Minimum Monthly Flow Each Year

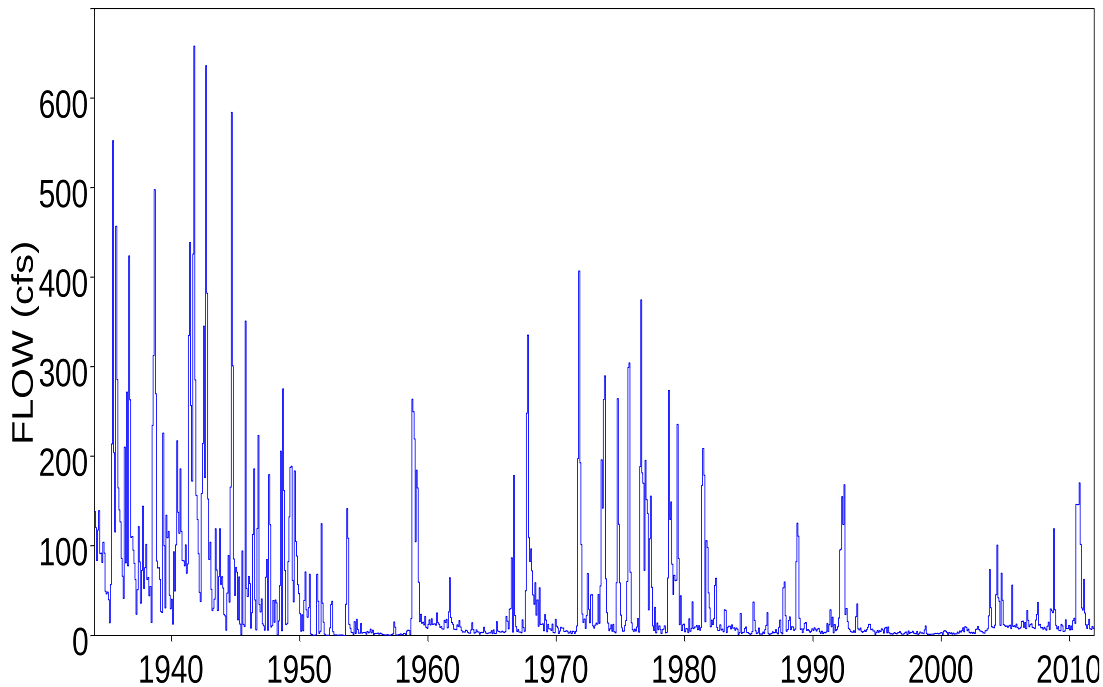
2
Rio Grande at Brownsville
IBWC gage 08-4750.00
Cameron County, Texas
Drainage area 356,000 square miles
Contributing drainage area 176,000 square miles
Latitude 25°52'33", Longitude 97°27'18"
Gage datum is at mean sea level.

This gage is located on the Rio Grande 49 river miles above the river outlet at the Gulf of Mexico, 0.2 mile downstream of El Jardin pumping plant, 7 miles downstream of the international bridge between Brownsville, Texas and Matamoros, Tamaulipas, and 226 miles below Falcon Dam. Flows of the Lower Rio Grande are regulated by International Falcon and Amistad Reservoirs. Falcon and Amistad Dams at river miles 275 and 574 on the Rio Grande have conservation storage capacities of 2,654,000 and 3,151,000 acre-feet and flood control capacities of 510,000 and 2,654,000 acre-feet. The projects are operated by the International Boundary and Water Commission (IBWC) for water supply, hydropower, and flood control. Initial impoundment of Falcon and Amistad Reservoirs occurred in 1953 and 1969.

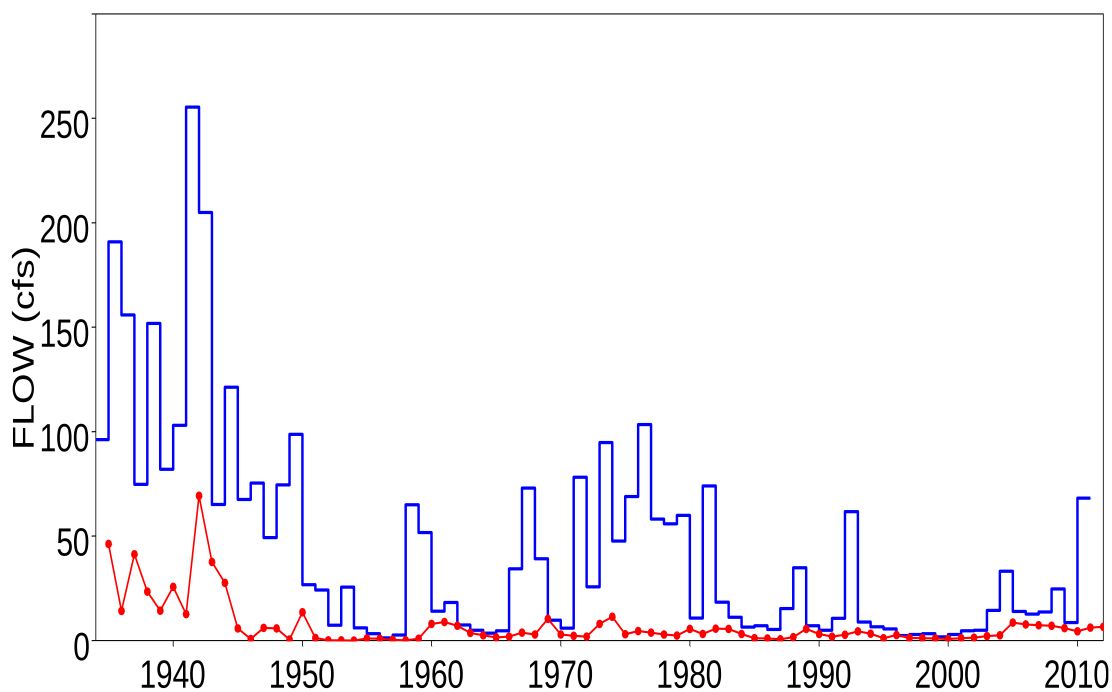
Period-of-record of daily flows: 1933/5/10 to 2011/12/31



Daily Flows of Rio Grande at Brownsville



Monthly Flows of Rio Grande at Brownsville



Annual Flows and the Minimum Monthly Flow Each Year

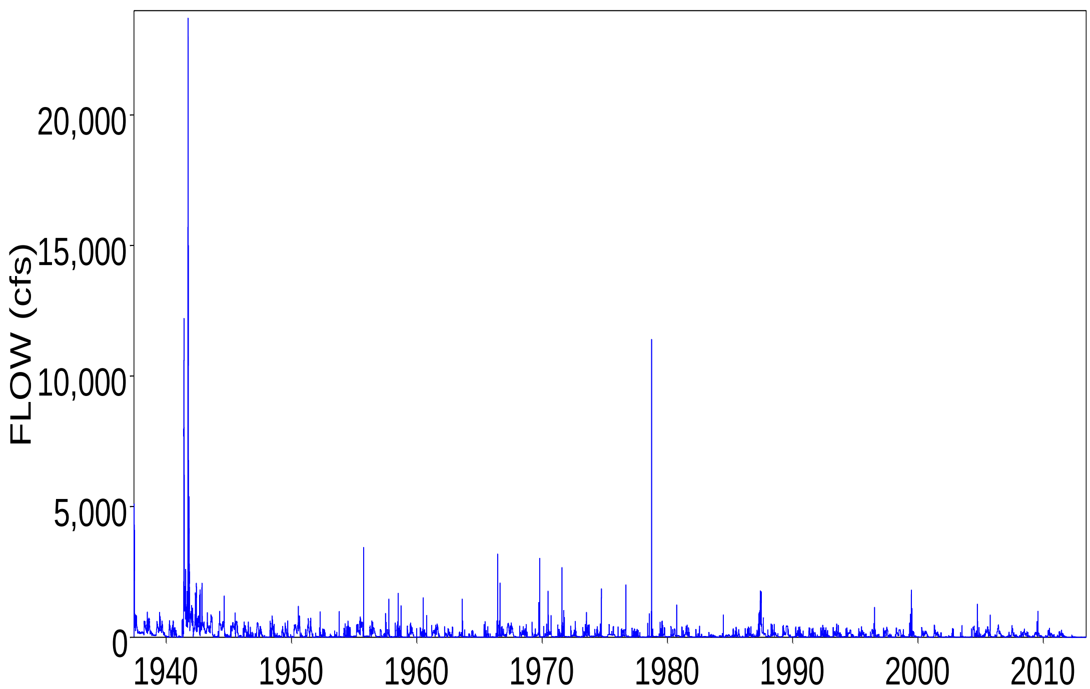
3
Pecos River at Orla
USGS 08412500
Reeves County, Texas

Drainage area 25,070 square miles
Contributing drainage area 21,229 square miles

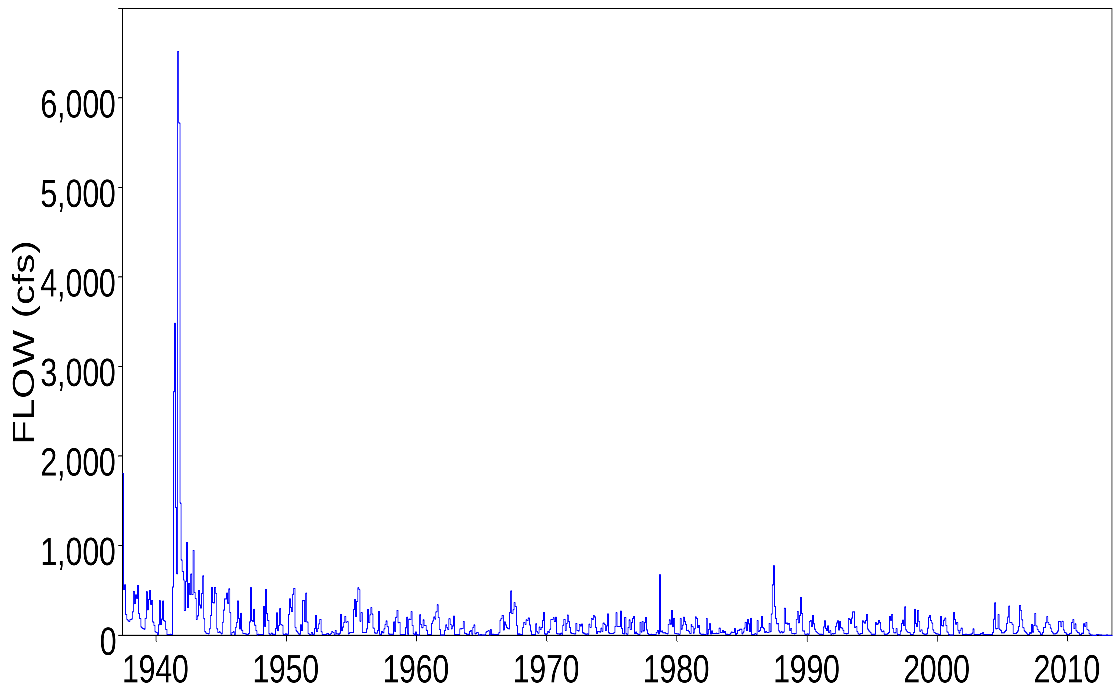
Latitude 31°52'21", Longitude 103°49'52" NAD27
Gage datum 2,730.86 feet above NGVD29

The gage is located below FM Highway 652 about ten miles below Red Bluff Dam.

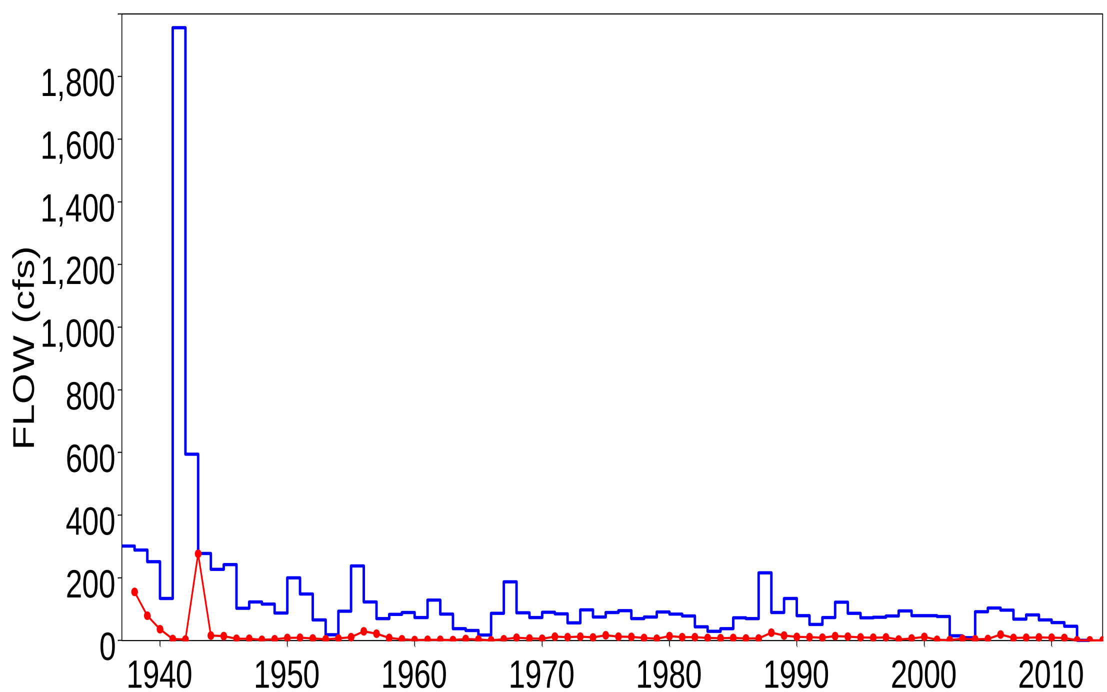
Period-of-record of daily flows: 1937/6/1 to present (2013/6/1)



Daily Flows of Pecos River at Orla



Monthly Flows of Pecos River at Orla



Annual Flows and the Minimum Monthly Flow Each Year

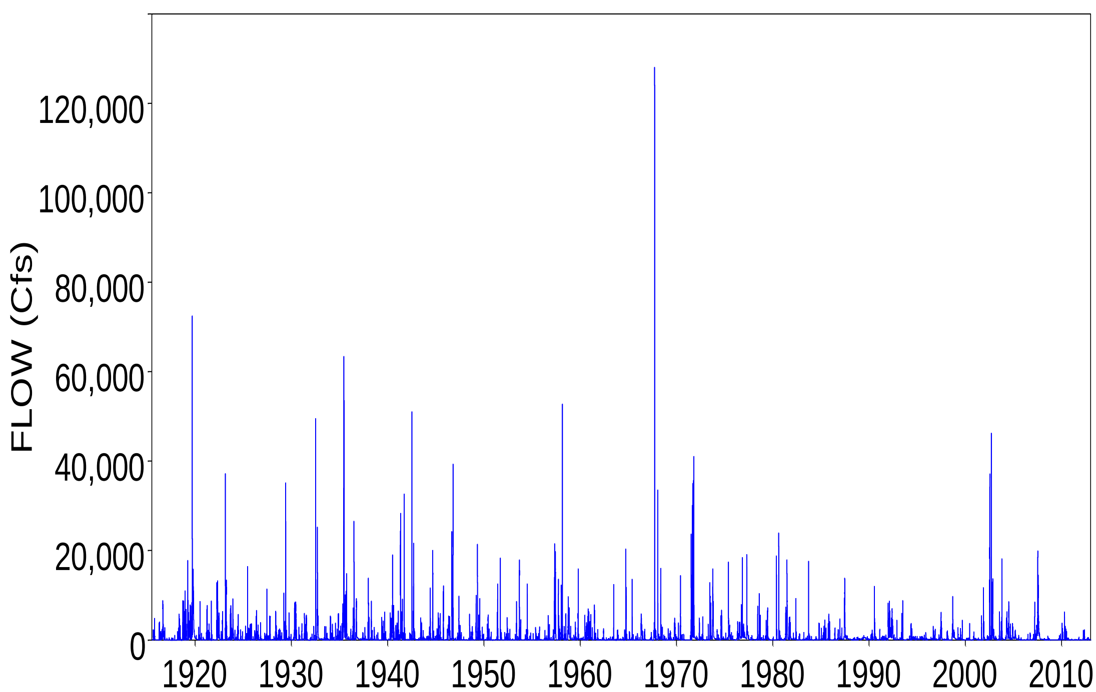
4
Nueces River at Three Rivers
USGS 08210000
Live Oak County, Texas

Drainage area 15,427 square miles
Contributing drainage area 15,427 square miles

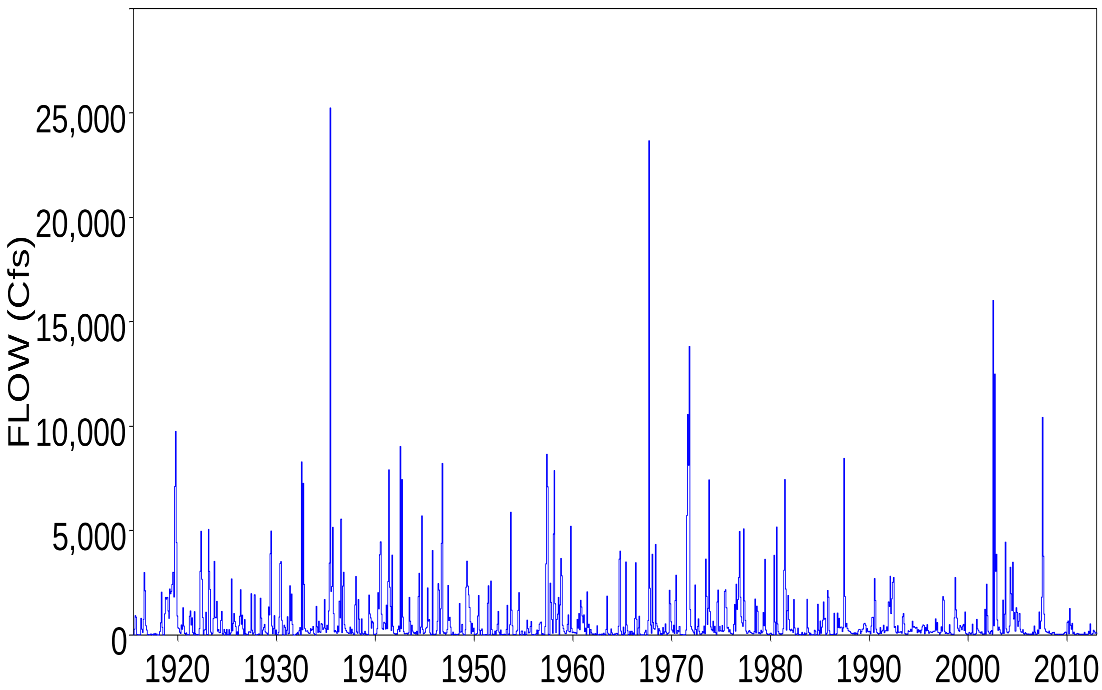
Latitude 28°25'38", Longitude 98°10'40" NAD27
Gage datum 99.26 feet above NGVD29

The gage on the Nueces River is just below the Frio River confluence south (downstream) of the city of Three Rivers. Choke Canyon Reservoir is located upstream of Three Rivers.

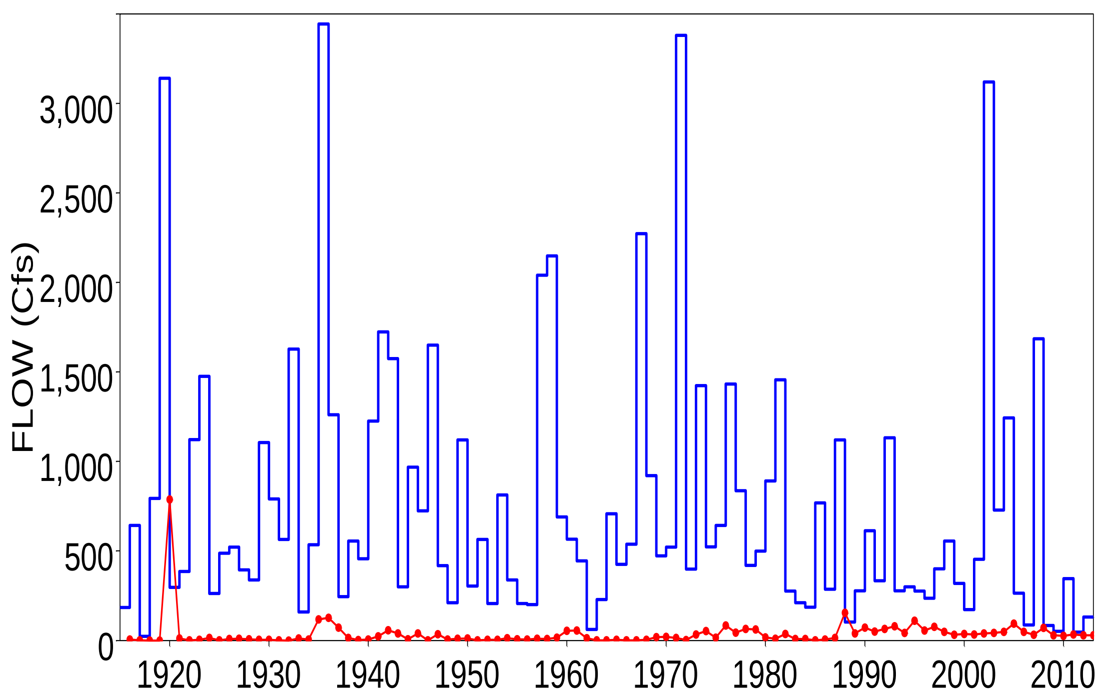
Period-of-record of daily flows: 1915/7/01 to present (2012/12/31)



Daily Flows of the Nueces River at Three Rivers



Monthly Flows of the Nueces River at Three Rivers



Annual Flows and the Minimum Monthly Flow Each Year

5
Nueces River at Mathis

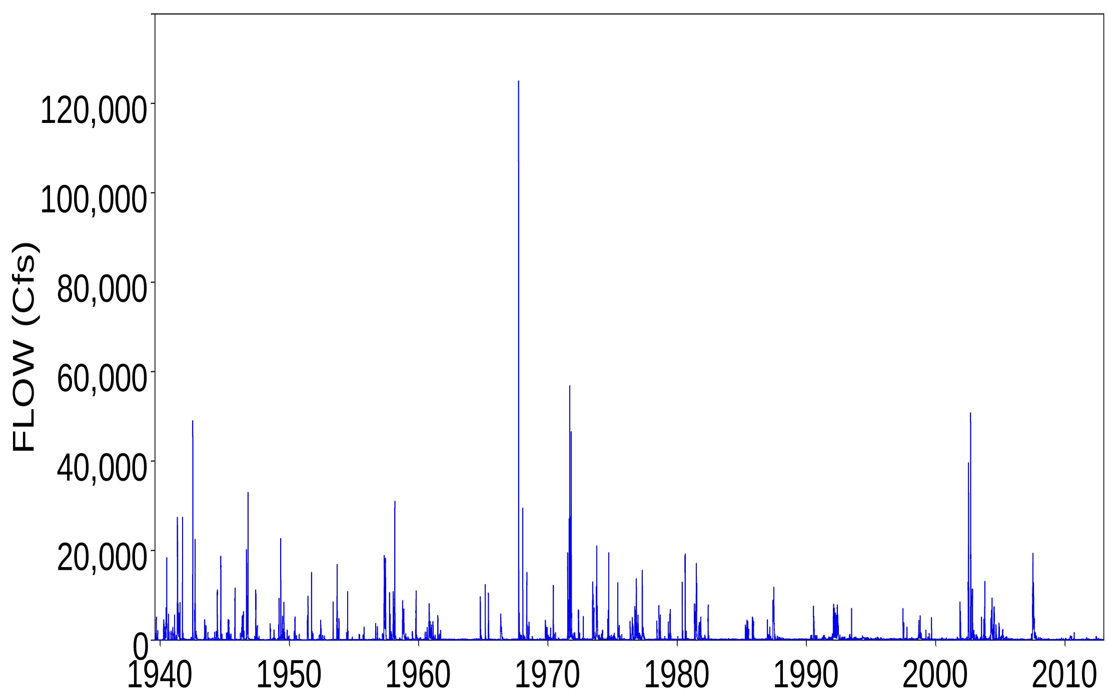
USGS 08211000
San Patricio County, Texas

Drainage area 16,503 square miles
Contributing drainage area 16,503 square miles

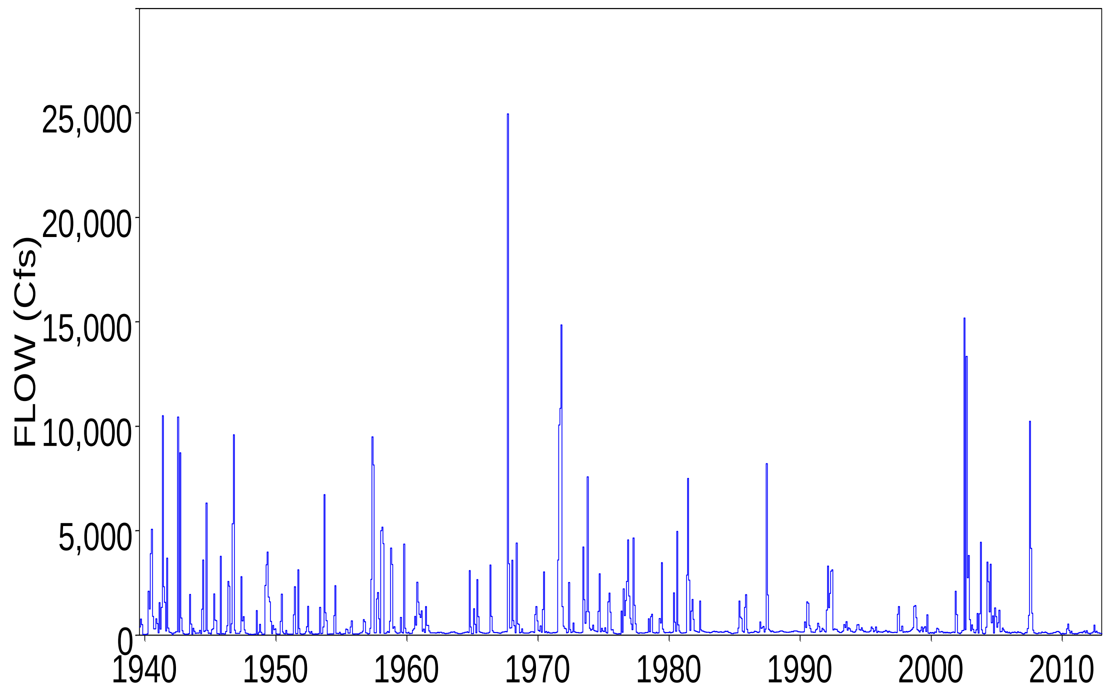
Latitude 28°02'17", Longitude 97°51'36" NAD27
Gage datum 26.53 feet above NGVD29

The gage is below Hwy 359 about a half mile below Mathis Dam and Lake Corpus Christi.

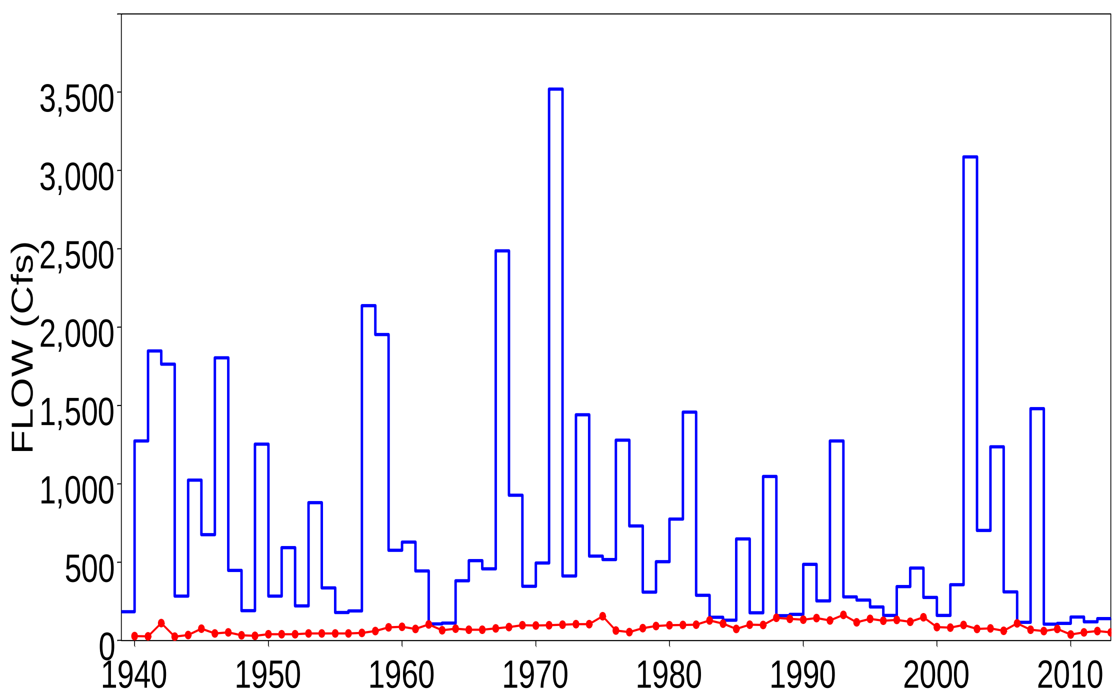
Period-of-record of daily flows: 1939/8/01 to present (2012/12/31)



Daily Flows of the Nueces River at Mathis



Monthly Flows of the Nueces River at Mathis



Annual Flows and the Minimum Monthly Flow Each Year

6
San Antonio River at Falls City

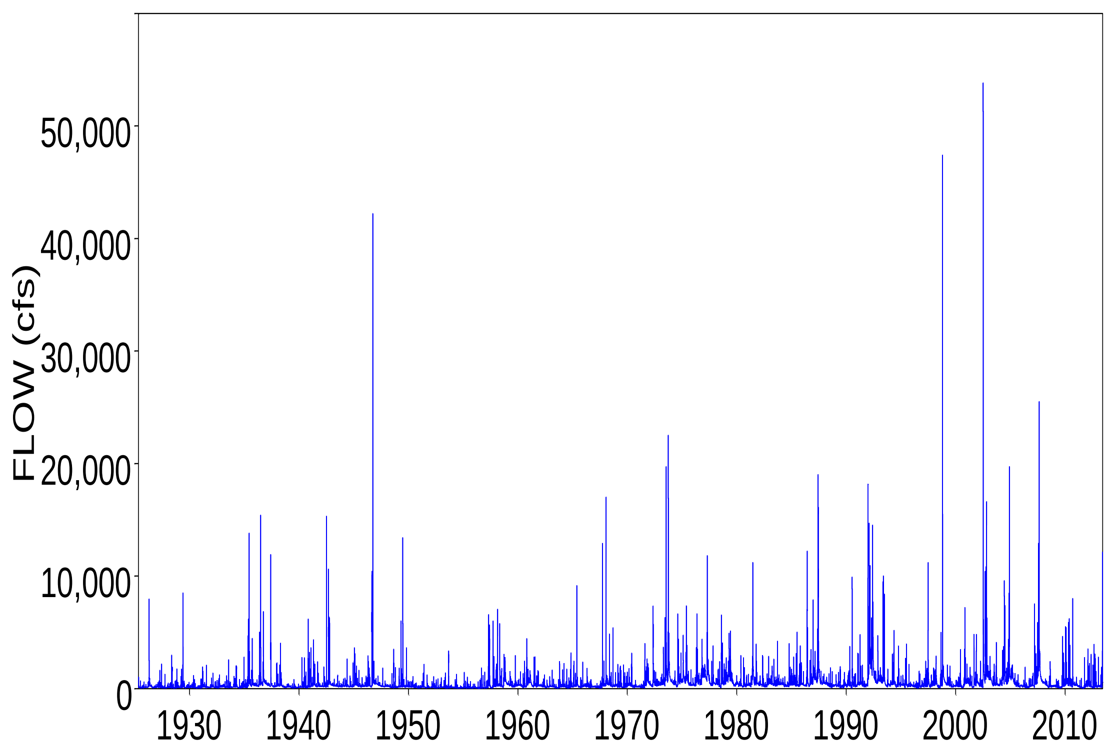
USGS 08183500
Karnes County, Texas

Drainage area 2,113 square miles
Contributing drainage area 2,113 square miles

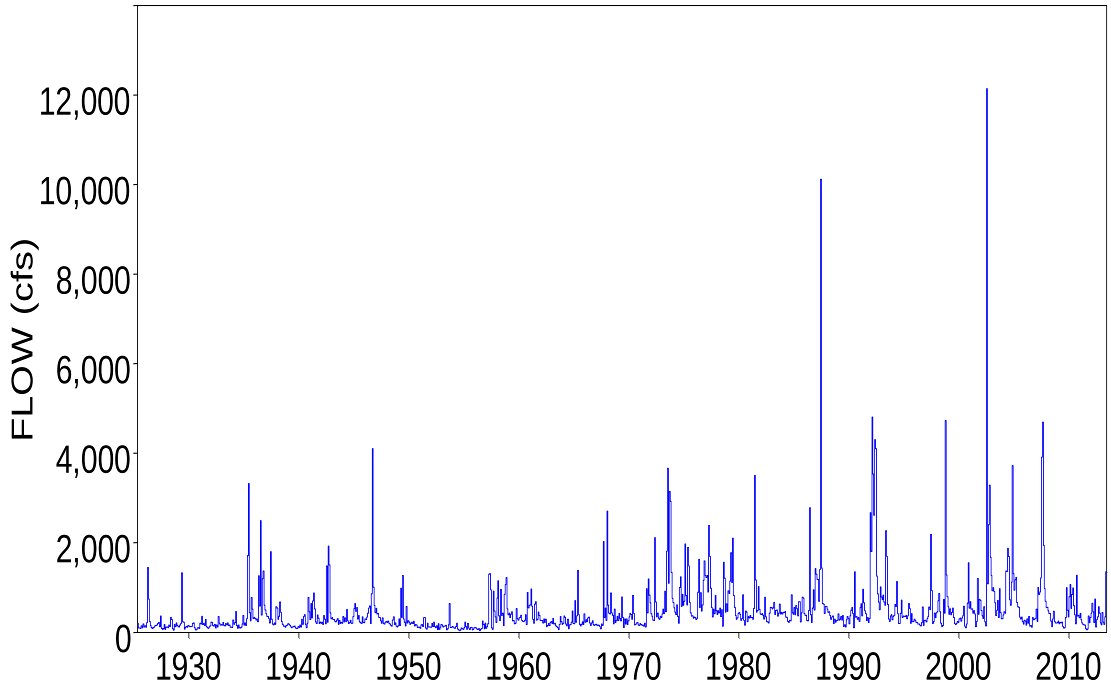
Latitude 28°57'05", Longitude 98°03'50" NAD27
Gage datum 285.49 feet above NGVD29

The gage is at FM Hwy 791 about fifty miles downstream of downtown San Antonio.

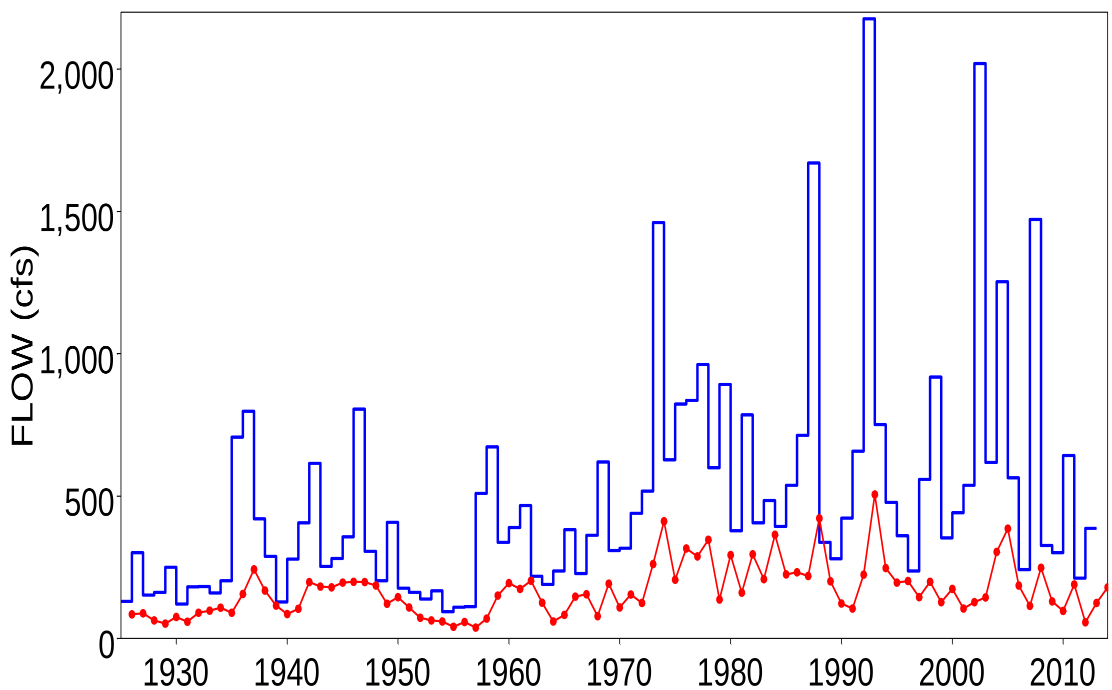
Period-of-record of daily flows: 1925/5/01 to present (2013/6/1)



Daily Flows of San Antonio River at Falls City



Monthly Flows of San Antonio River at Falls City



Annual Flows and the Minimum Monthly Flow Each Year

7
San Antonio River at Goliad

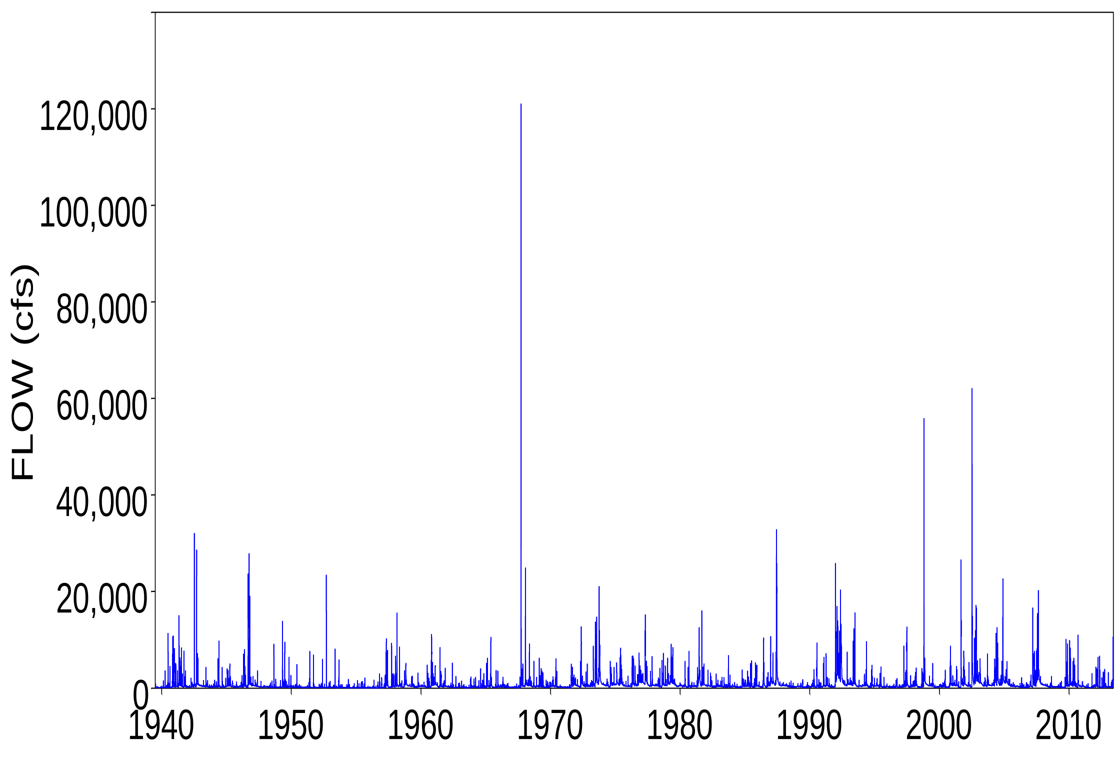
USGS 08188500
Goliad County, Texas

Drainage area 3,921 square miles
Contributing drainage area 3,921 square miles

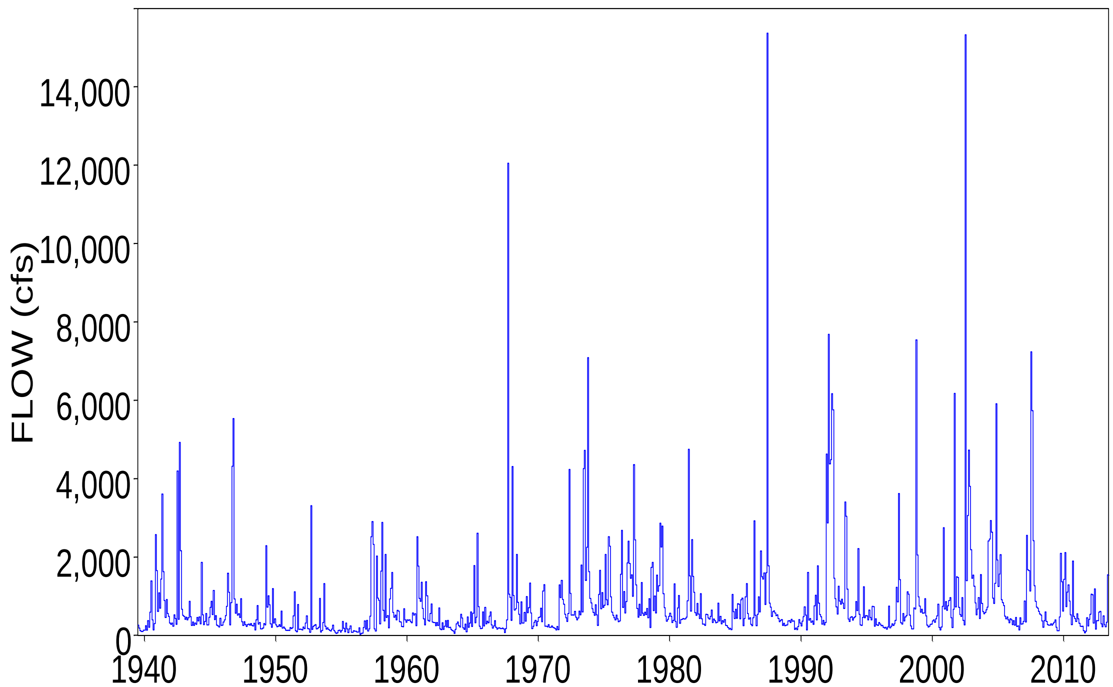
Latitude 28°38'57.43", Longitude 97°23'05.49" NAD83
Gage datum 91.08 feet above NGVD29

The gage is at Hwy 183 five miles downstream of Hwy 59 about forty miles above the confluence with the Guadalupe River.

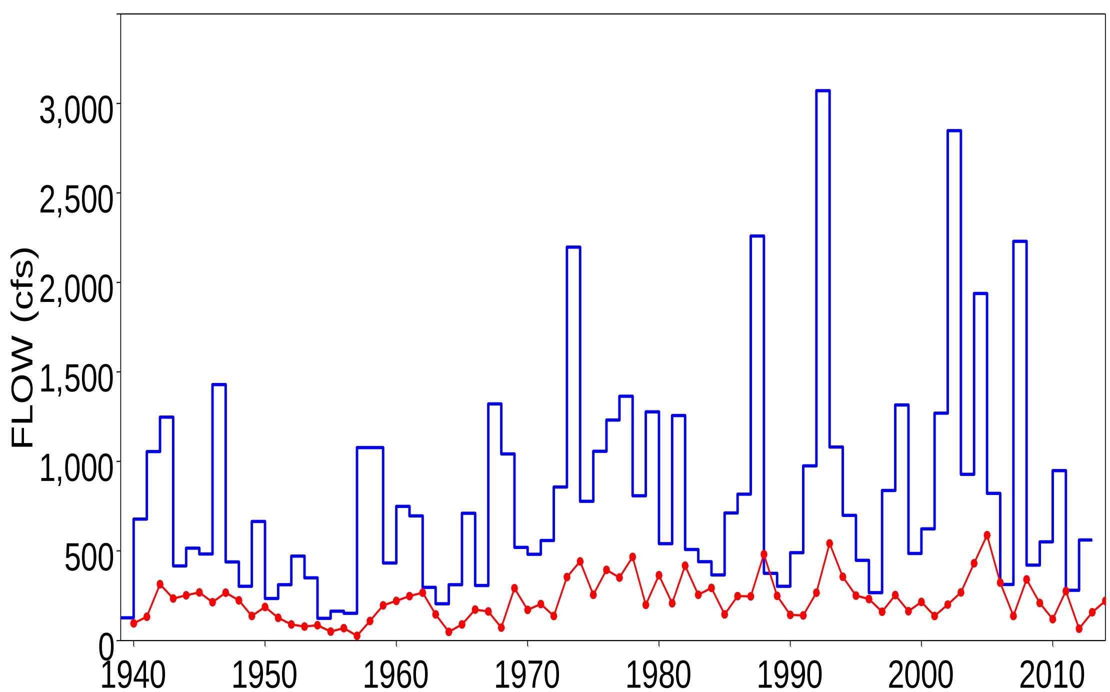
Period-of-record of daily flows: 1939/7/01 to present (2013/6/1)



Daily Flows of San Antonio River at Goliad



Monthly Flows of San Antonio River at Goliad



Annual Flows and the Minimum Monthly Flow Each Year

8
Guadalupe River at Spring Branch

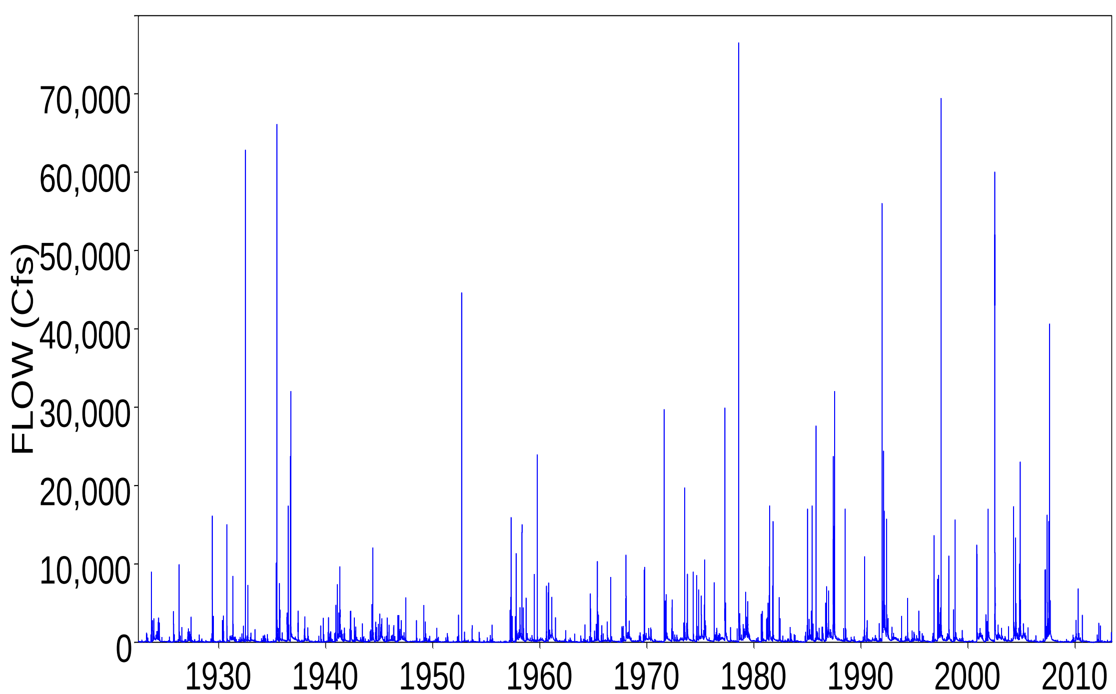
USGS 08167500
Comal County, Texas

Drainage area 1,315 square miles
Contributing drainage area 1,315 square miles

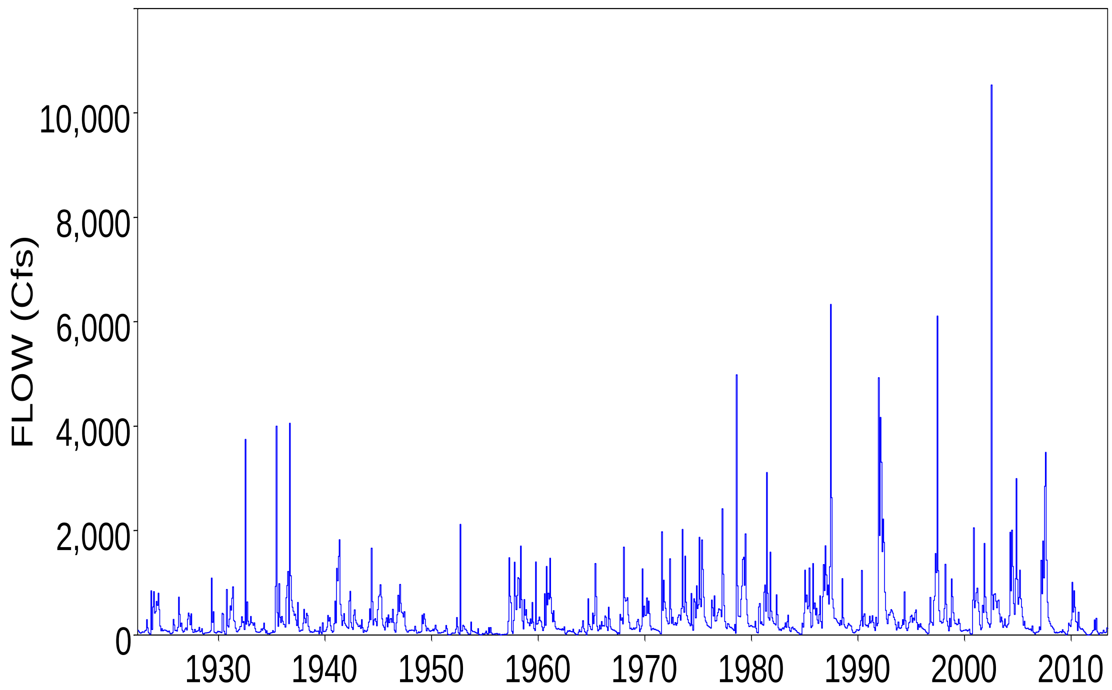
Latitude 29°51'37", Longitude 98°23'00" NAD27
Gage datum 948.10 feet above NGVD29

The gage is one mile below Hwy 281 and several miles above Canyon Lake.

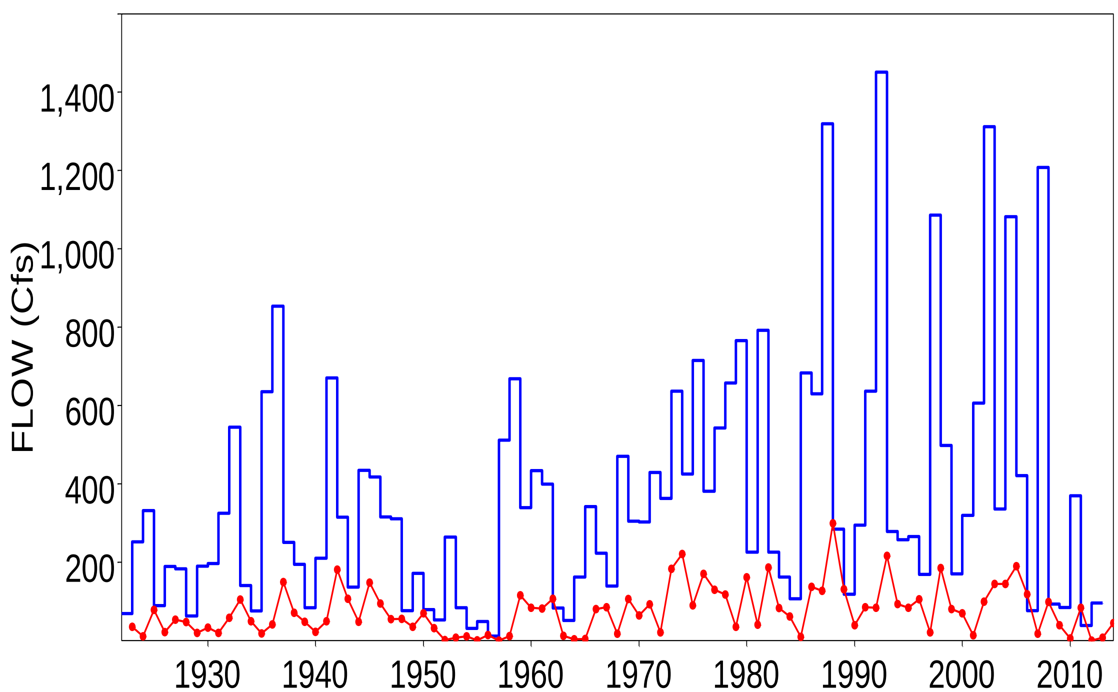
Period-of-record of daily flows: 1922/6/01 to present (2012/6/1)



Daily Flows of Guadalupe River at Spring Branch



Monthly Flows of Guadalupe River at Spring Branch



Annual Flows and the Minimum Monthly Flow Each Year

9
Guadalupe River at Victoria

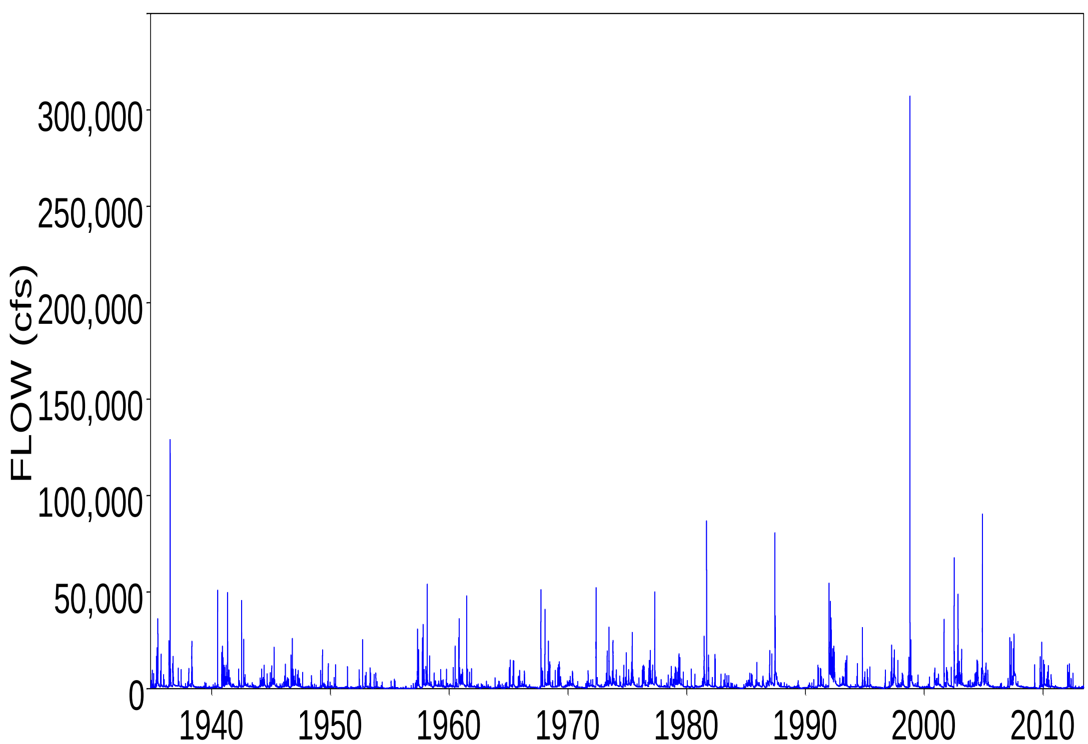
USGS 08176500
Victoria County, Texas

Drainage area 5,198 square miles
Contributing drainage area 5,198 square miles

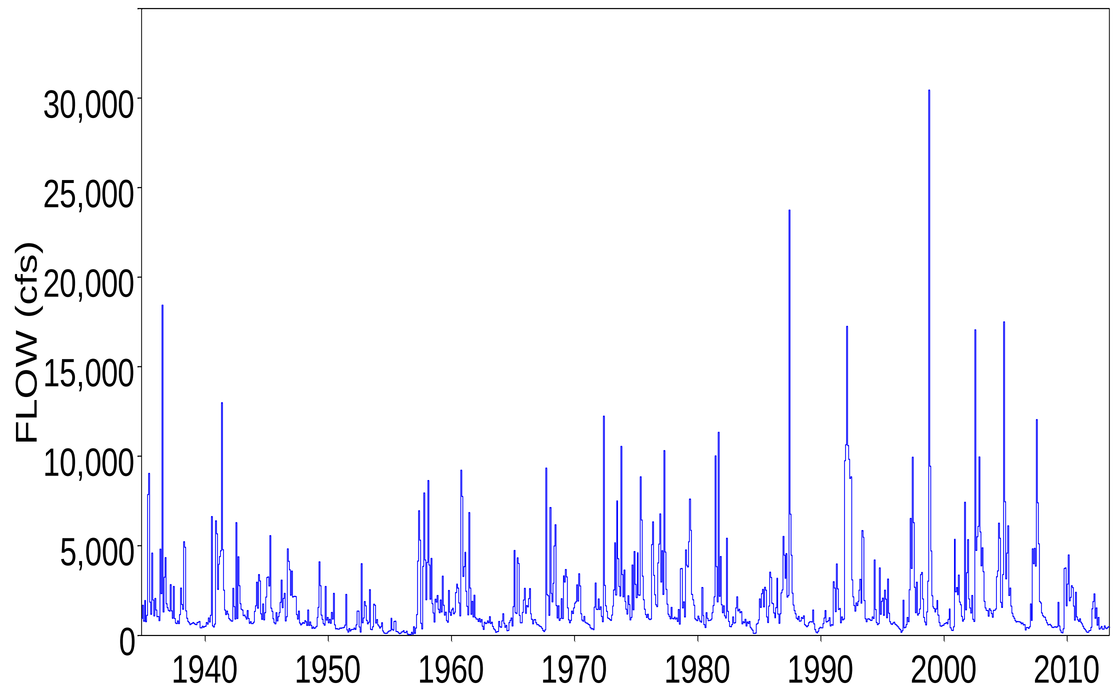
Latitude 28°47'34", Longitude 97°00'46" NAD27
Gage datum 29.15 feet above NGVD29

The gage is at Hwy 59 in Victoria thirty miles above the San Antonio River confluence.

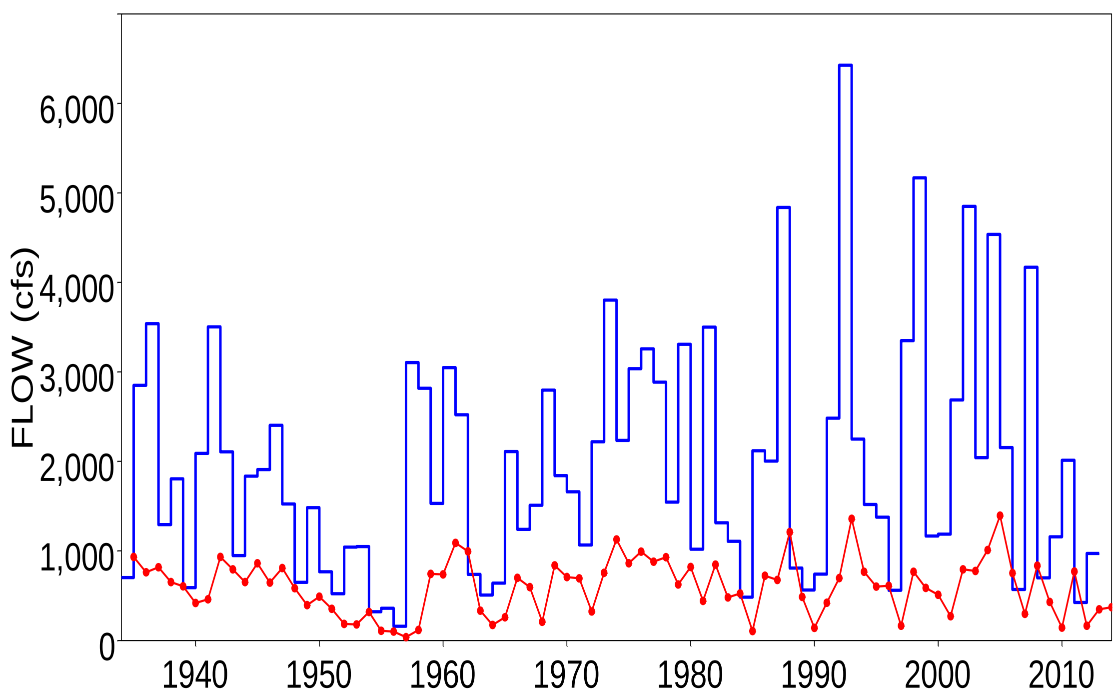
Period-of-record of daily flows: 1934/11/01 to present (2013/6/1)



Daily Flows of Guadalupe River at Victoria



Monthly Flows of Guadalupe River at Victoria



Annual Flows and the Minimum Monthly Flow Each Year

10
Lavaca River near Edna

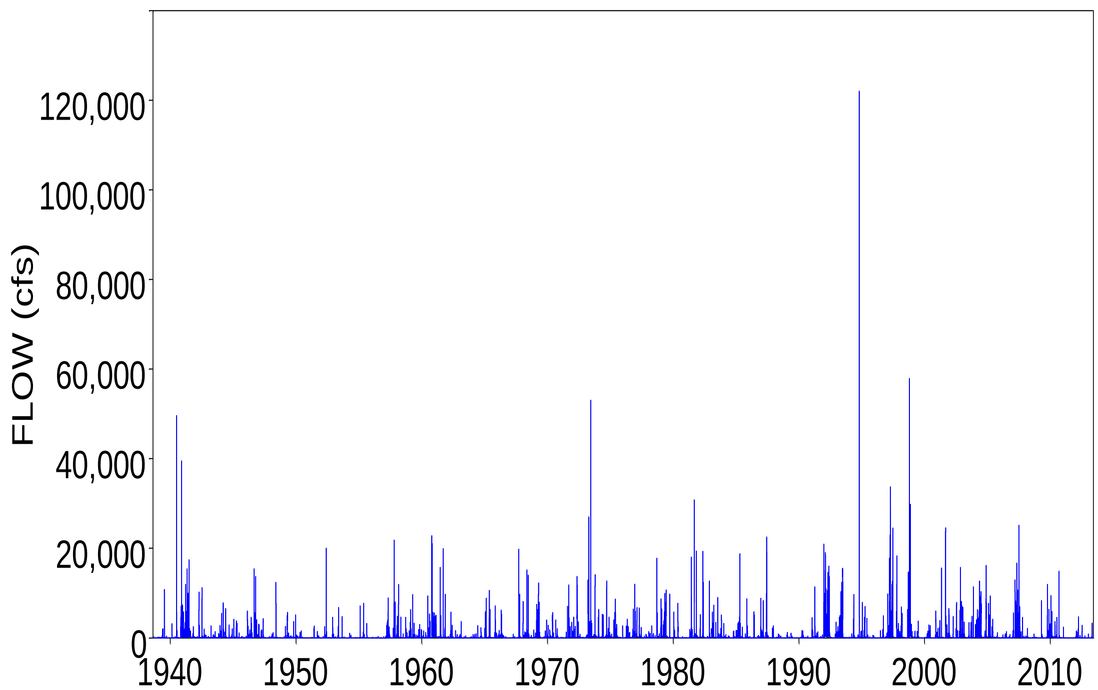
USGS 08164000
Jackson County, Texas

Drainage area 817 square miles
Contributing drainage area 817 square miles

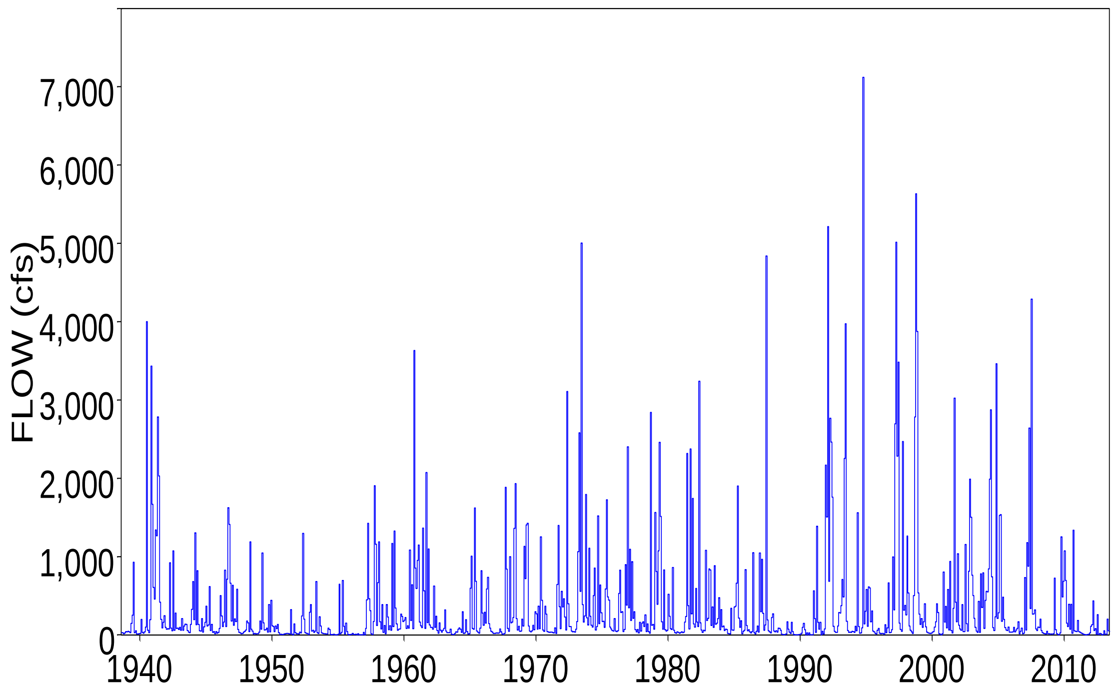
Latitude 28°57'35", Longitude 96°41'10" NAD27
Gage datum 14.10 feet above NGVD29

The gage is at Hwy 59 ten miles above the Navidad River confluence.

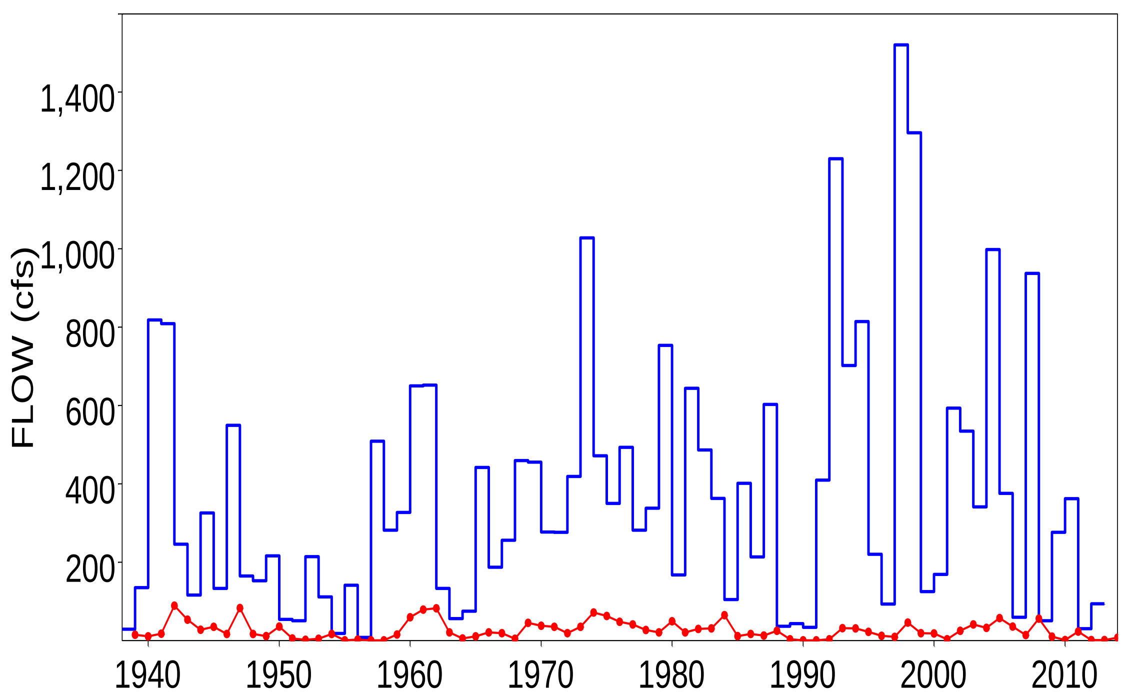
Period-of-record of daily flows: 1938/8/01 to present (2013/6/1)



Daily Flows of Lavaca River near Edna



Monthly Flows of Lavaca River near Edna



Annual Flows and the Minimum Monthly Flow Each Year

11
Colorado River near San Saba

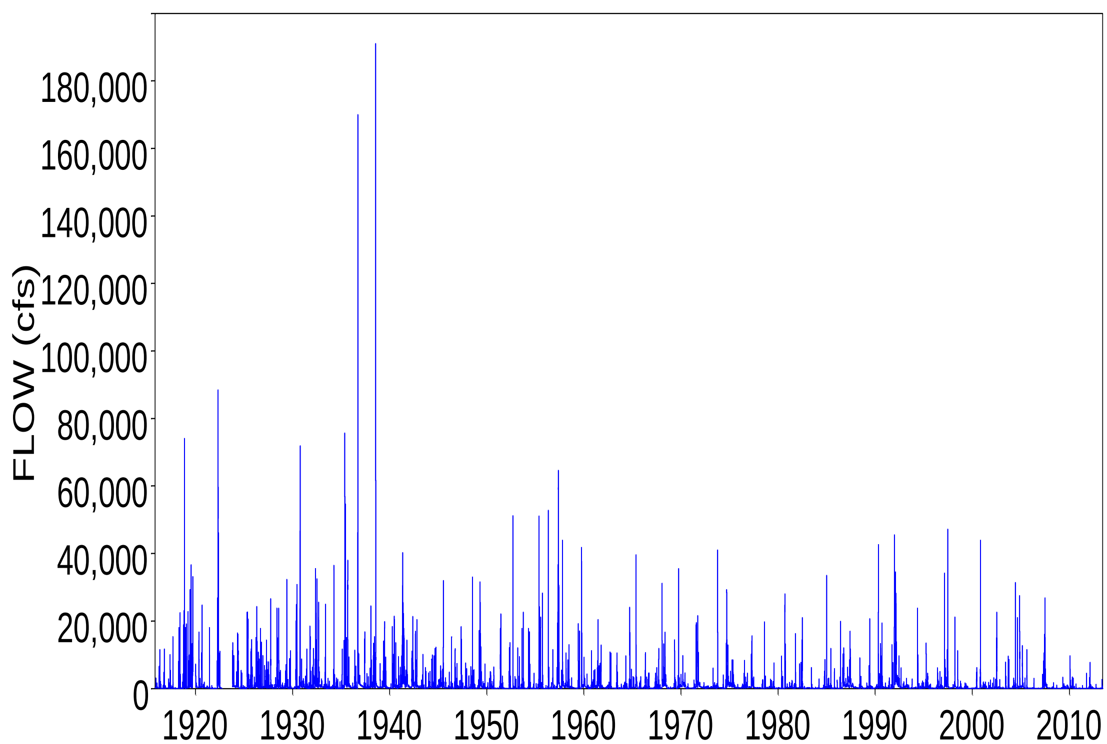
USGS 08147000
Lampasas County, Texas

Drainage area 31,217 square miles
Contributing drainage area 19,819 square miles

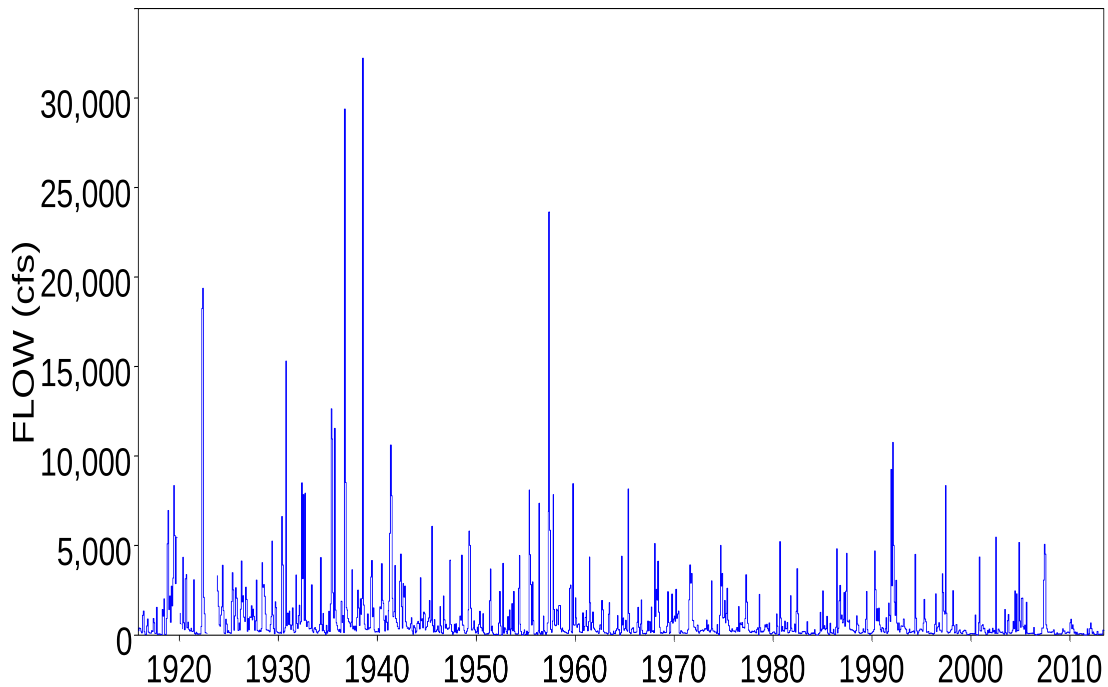
Latitude 31°13'04", Longitude 98°33'51" NAD27
Gage datum 1,096.22 feet above NGVD29

The gage is at Hwy 190 about sixty miles upstream of Buchanan Dam.

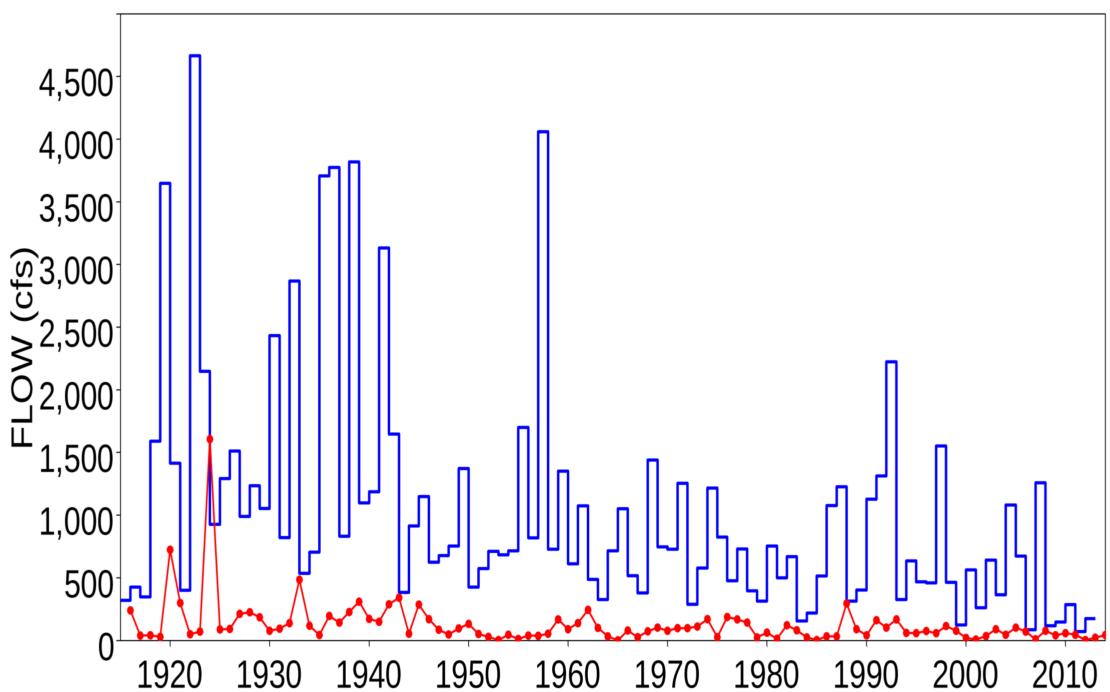
Period-of-record of daily flows: 1915/11/1 to present (2013/6/1)



Daily Flows of Colorado River near San Saba



Monthly Flows of Colorado River near San Saba



Annual Flows and the Minimum Monthly Flow Each Year

12
Colorado River at Austin

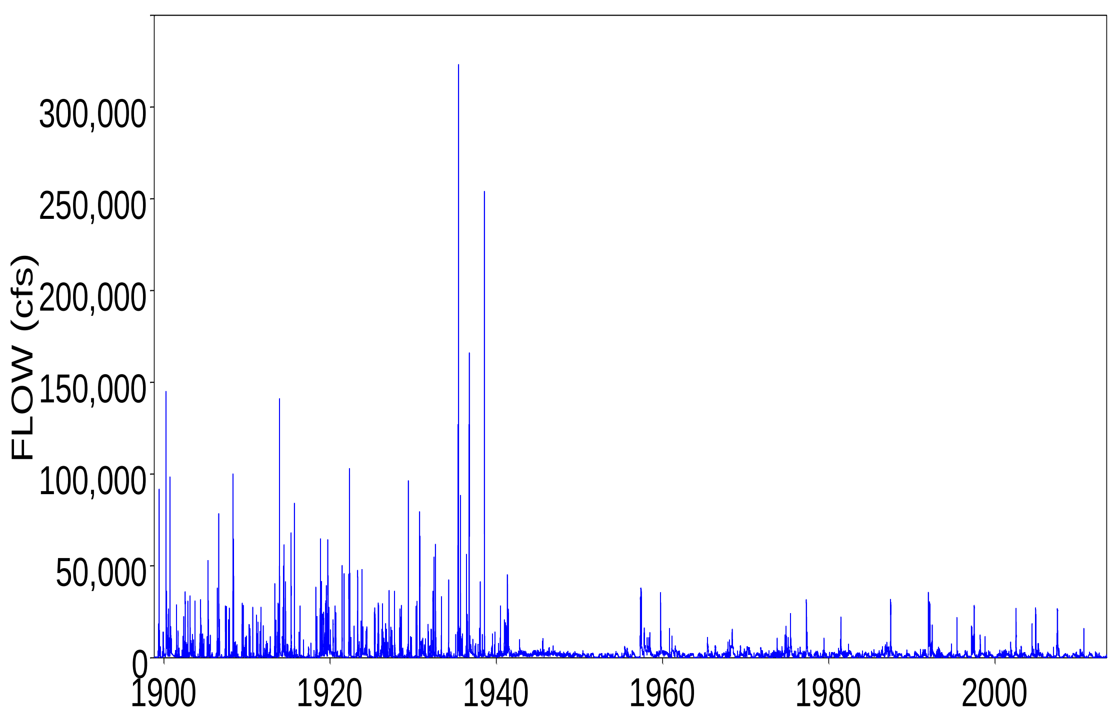
USGS 08158000
Travis County, Texas

Drainage area 39,009 square miles
Contributing drainage area 27,606 square miles

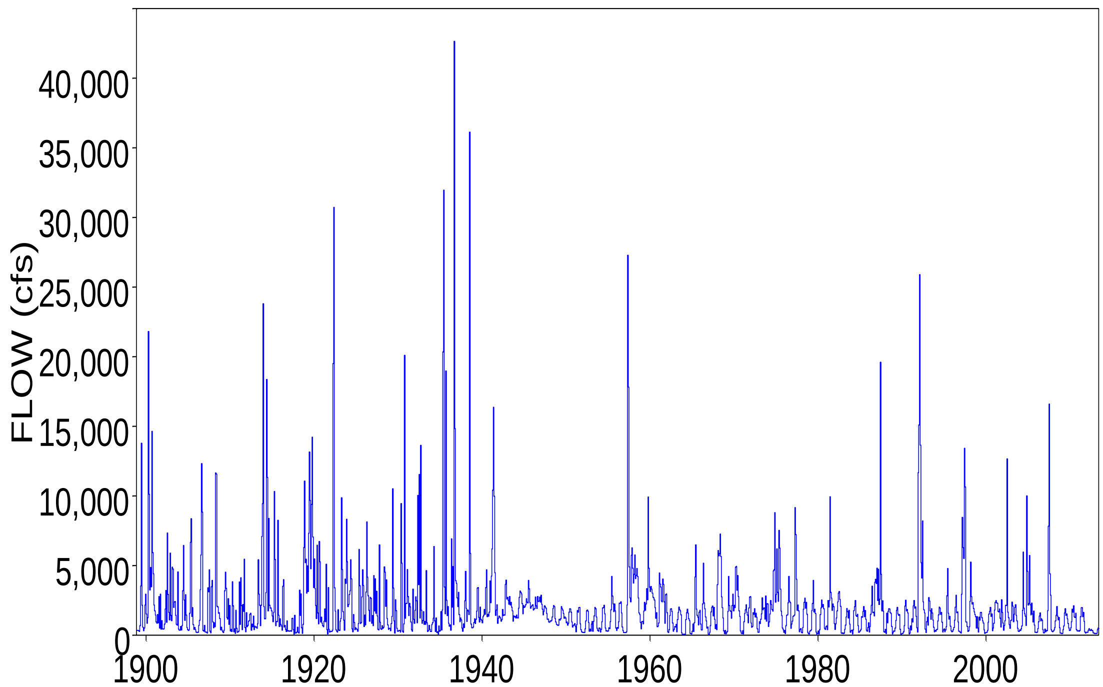
Latitude 30°14'46.1", Longitude 97°40'48.2" NAD83
Gage datum 391.96 feet above NAVD88

The gage site is near downtown Austin a half mile below Hwy 183. Flows at this site are regulated by Lakes Buchanan, Inks, LBJ, Marbles Falls, Travis, and Austin on the Colorado River operated by the Lower Colorado River Authority. Many other reservoirs on tributaries entering the Colorado River upstream of Austin are operated by other entities.

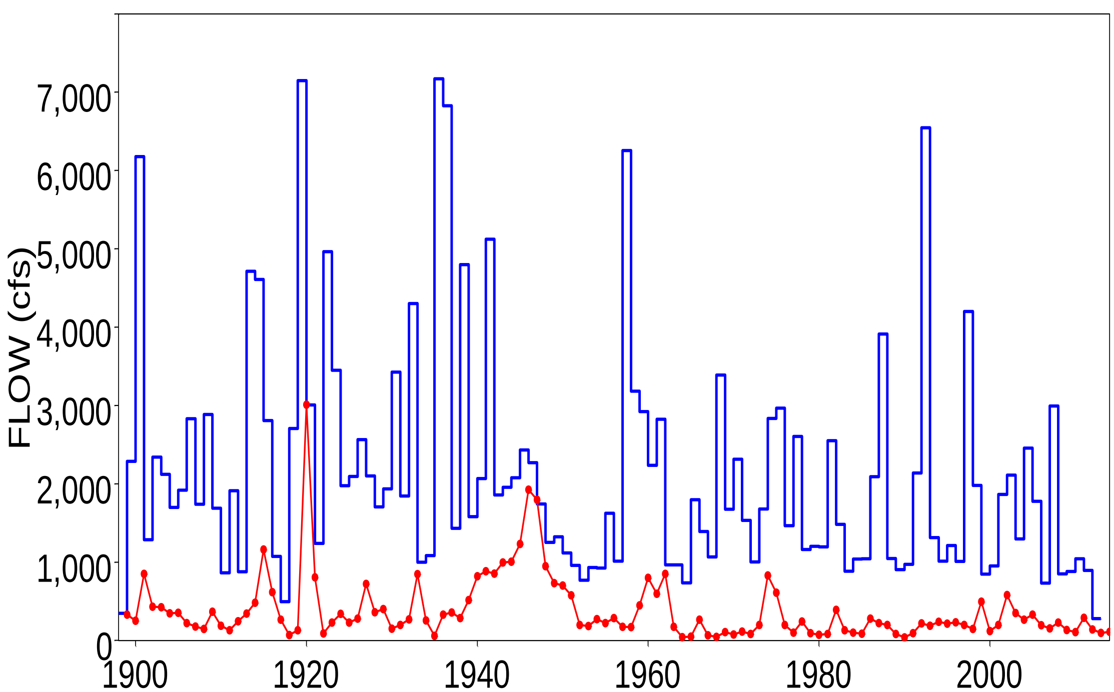
Period-of-record of daily flows: 1898/3/01 to present (2013/6/1)



Daily Flows of Colorado River at Austin



Monthly Flows of Colorado River at Austin



Annual Flows and the Minimum Monthly Flow Each Year

13
Colorado River at Columbus

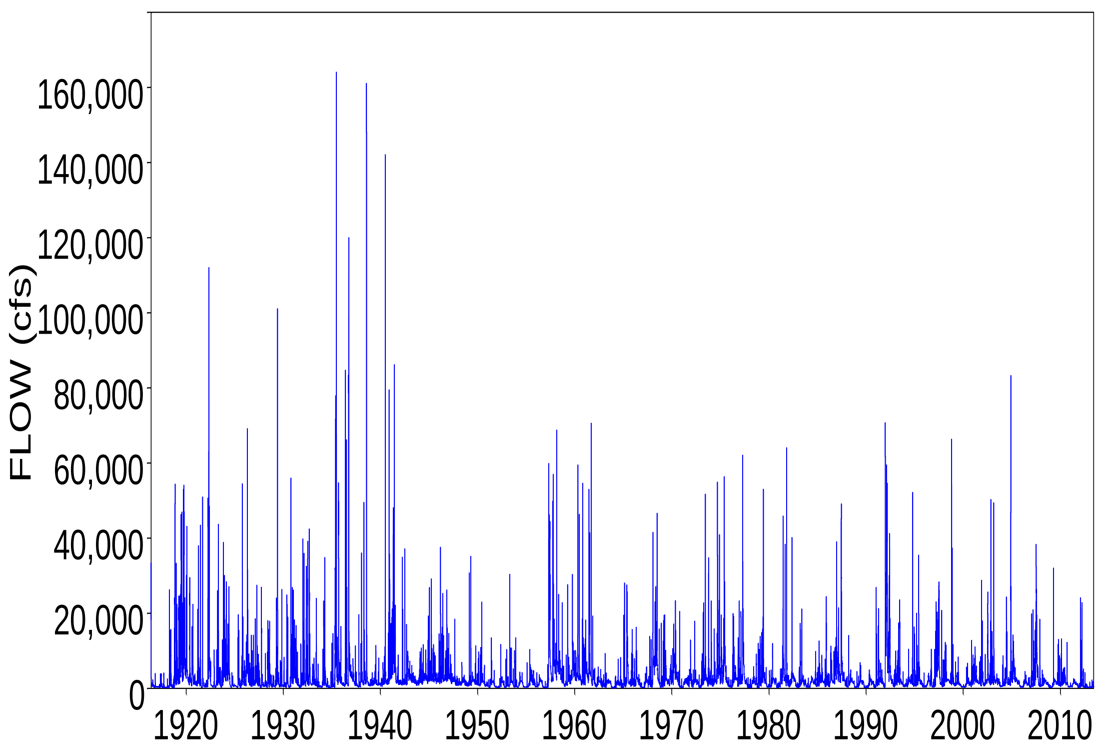
USGS 08161000
Colorado County, Texas

Drainage area 41,640 square miles
Contributing drainage area 30,237 square miles

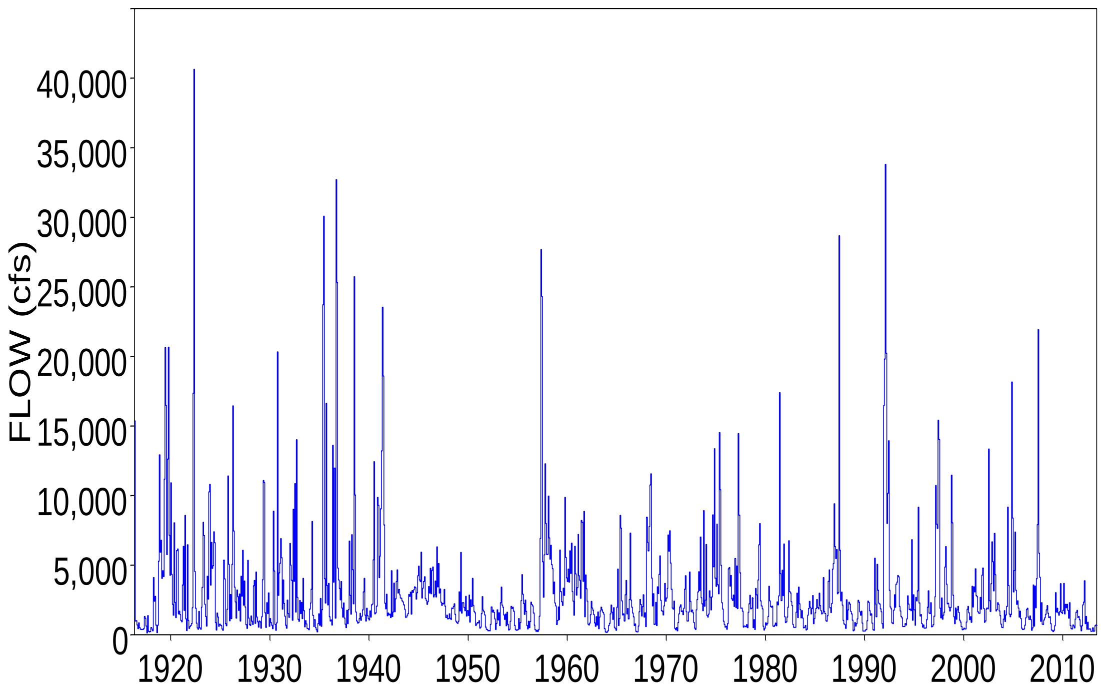
Latitude 29°42'22", Longitude 96°32'12" NAD27
Gage datum 145.52 feet above NGVD29

The gage is at Hwy 90 upstream of IH 10 in Columbus about a hundred miles below Austin and sixty miles upstream of Bay City.

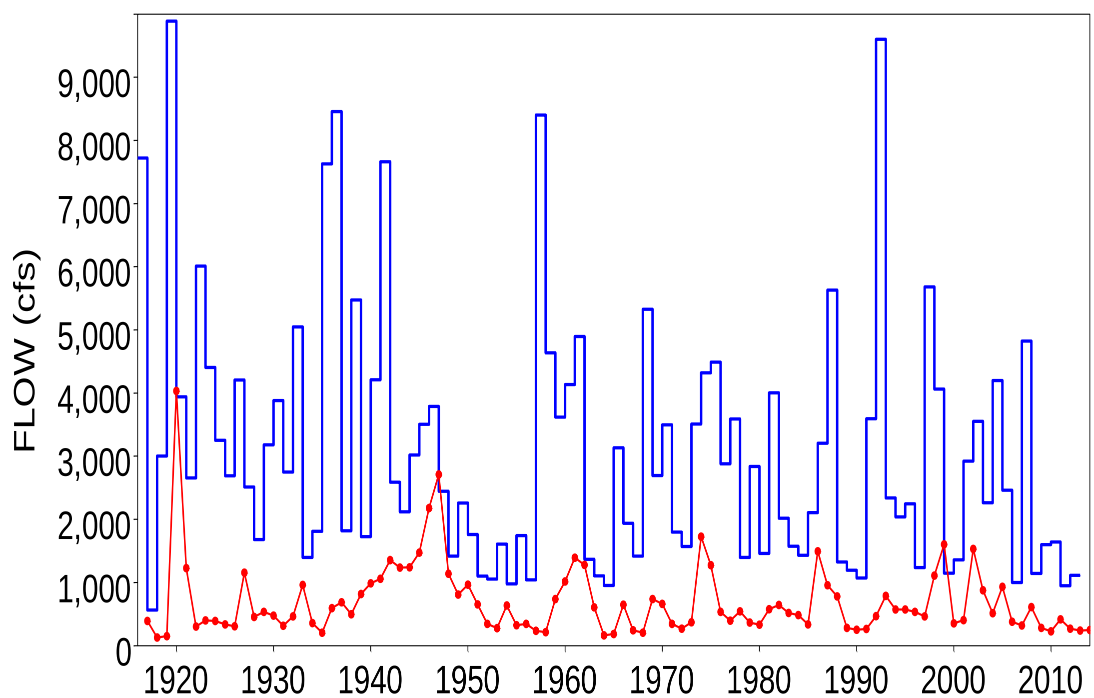
Period-of-record of daily flows: 1916/5/01 to present (2013/6/1)



Daily Flows of Colorado River at Columbus



Monthly Flows of Colorado River at Columbus



Annual Flows and the Minimum Monthly Flow Each Year

14
Colorado River near Bay City

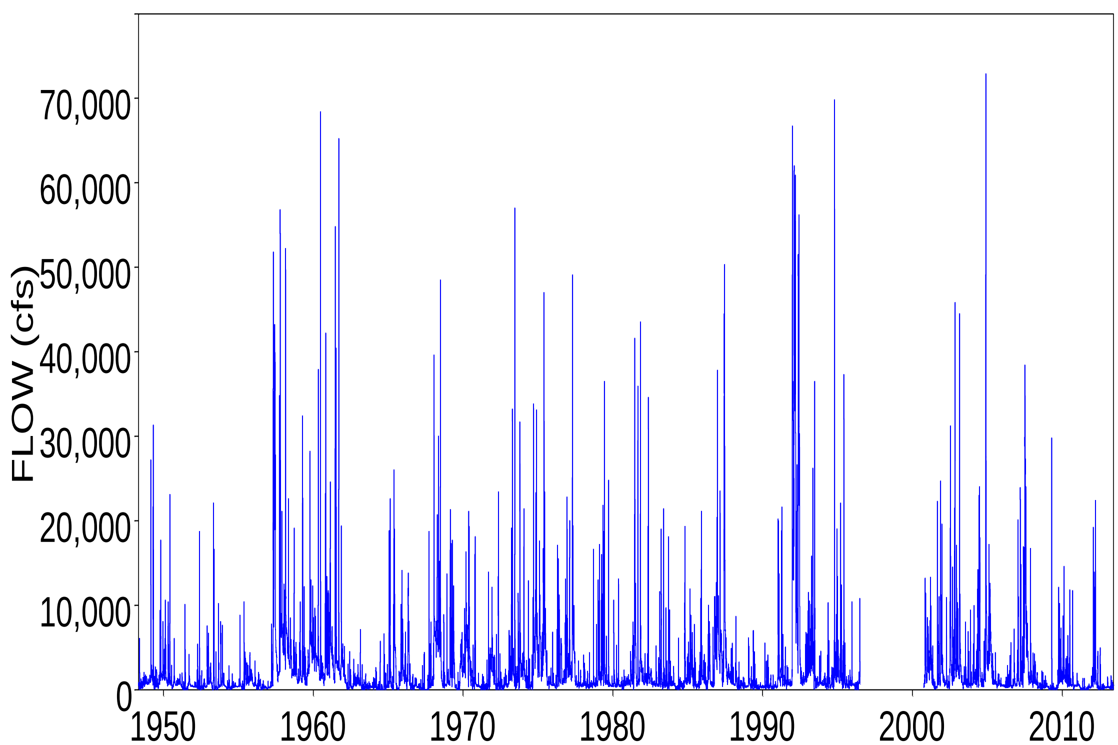
USGS 08162500
Matagorda County, Texas

Drainage area 42,240 square miles
Contributing drainage area 30,837 square miles

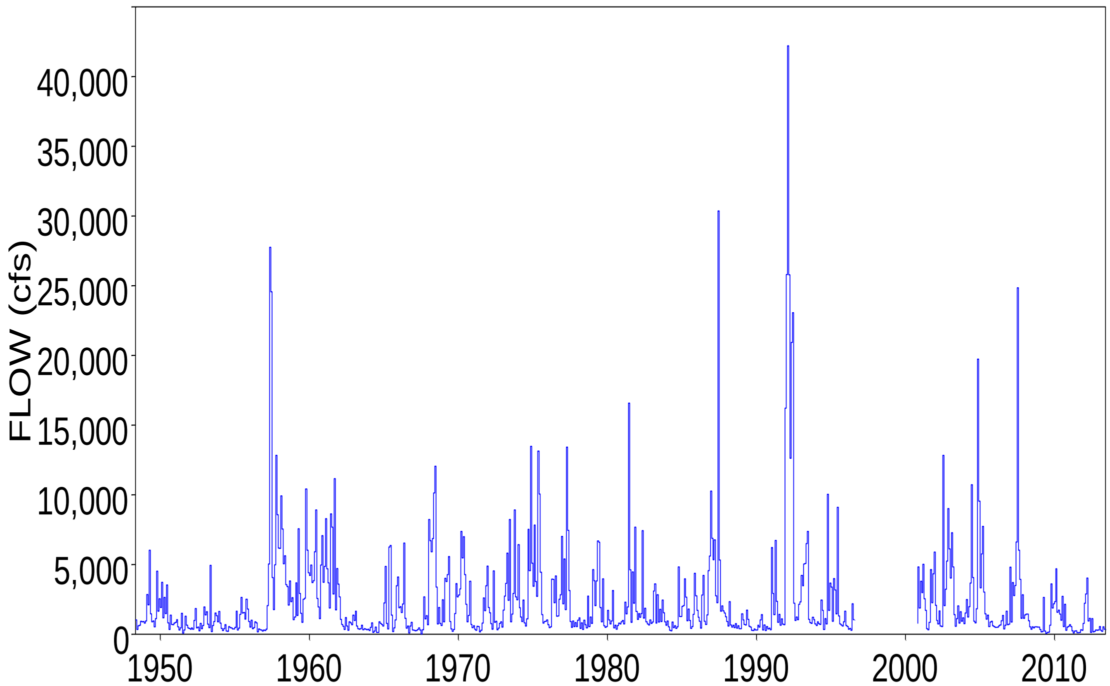
Latitude 28°58'26", Longitude 96°00'44" NAD27
Gage datum 0 feet above NGVD29

The gage is below Hwy 35 thirty miles above the river outlet at Matagorda Bay south of Bay City.

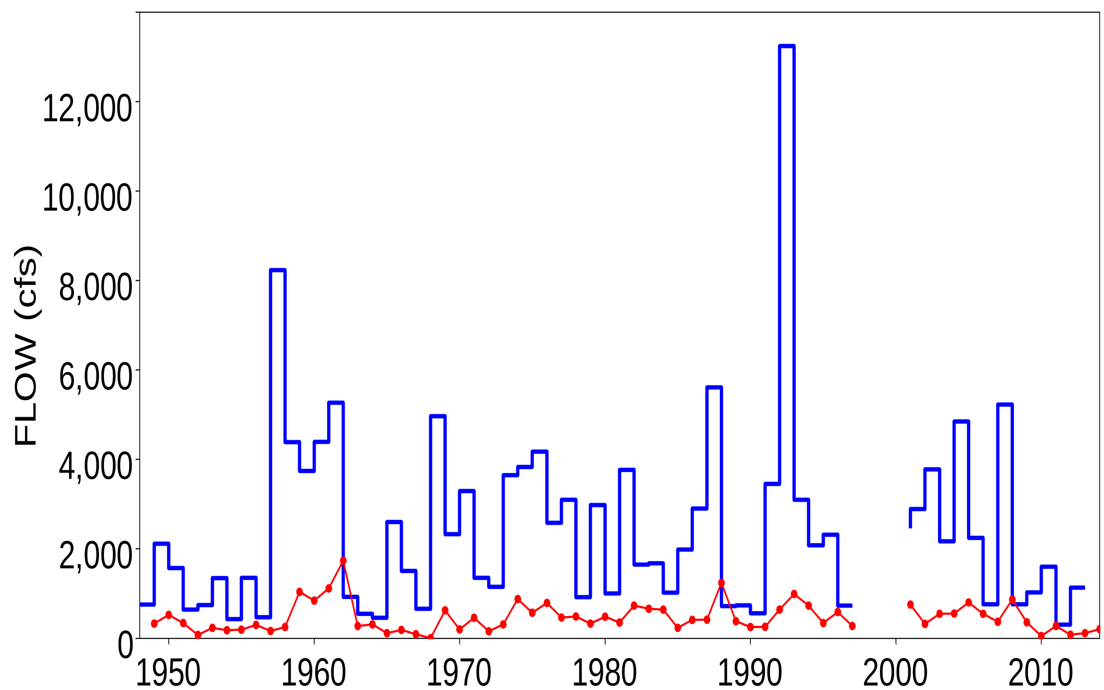
Period-of-record of daily flows: 1942/5/01 to present (2013/6/1)



Daily Flows of Colorado River near Bay City



Monthly Flows of Colorado River near Bay City



Annual Flows and the Minimum Monthly Flow Each Year

15
Brazos River at Seymour

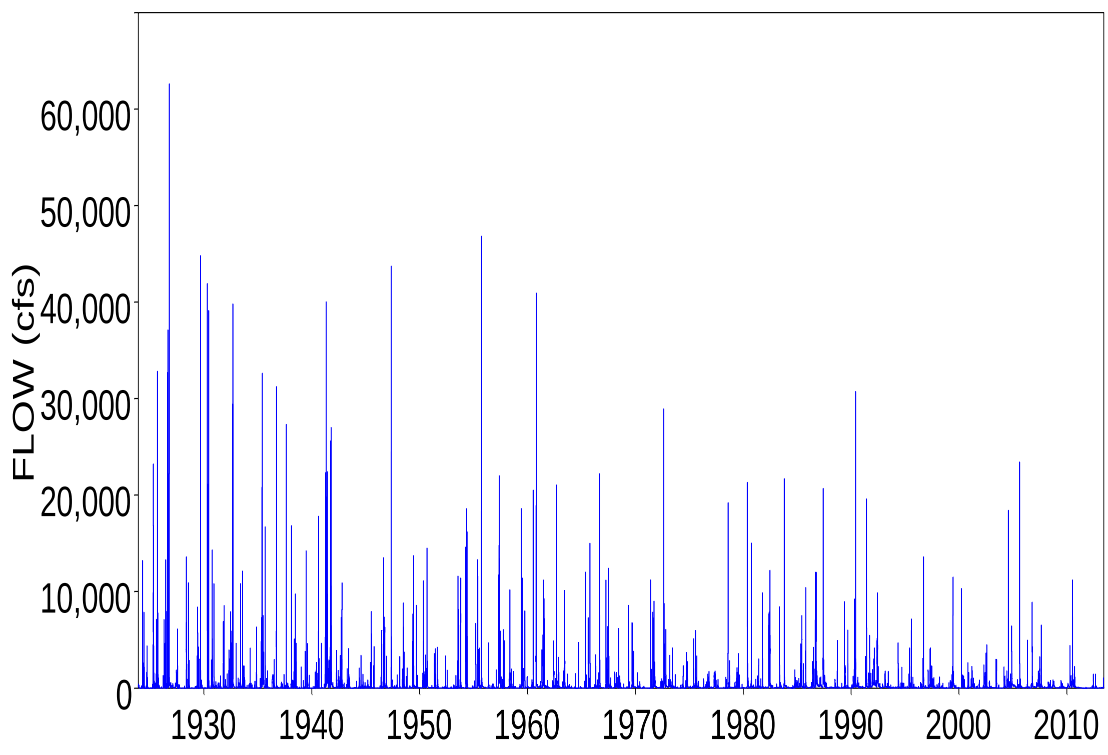
USGS 08082500
Baylor County, Texas

Drainage area 15,538 square miles
Contributing drainage area 5,972 square miles

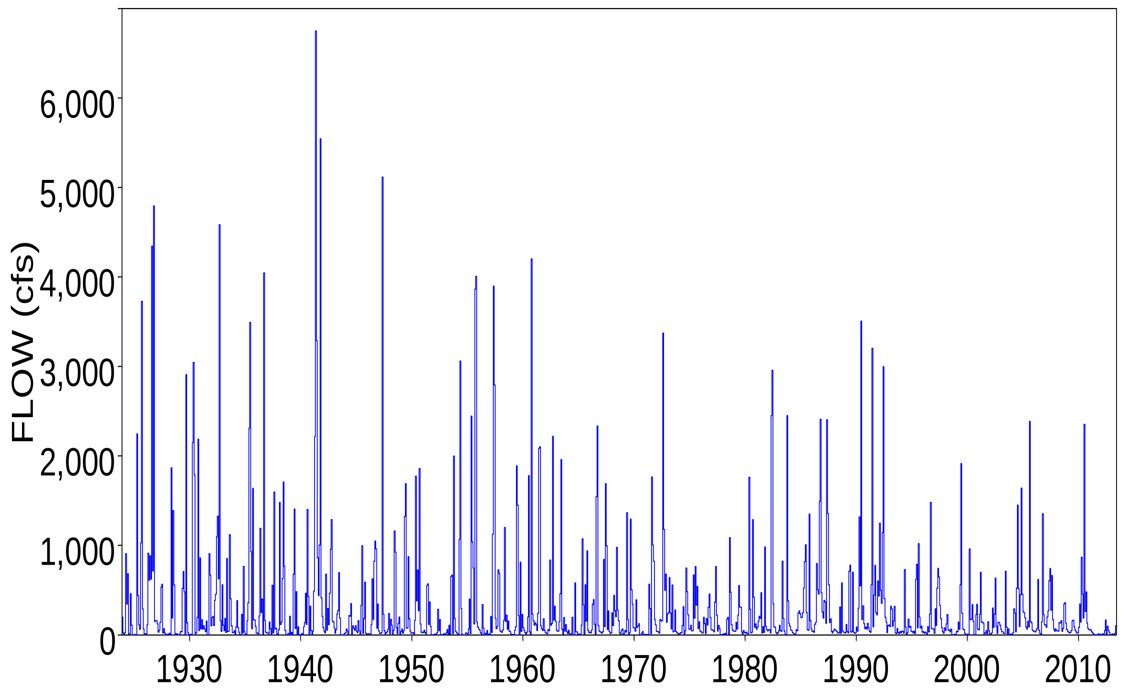
Latitude 33°34'51", Longitude 99°16'02" NAD27
Gage datum 1,238.97 feet above NGVD29

The gage is at County Road 403 just north of Hwy 277. The gage is on the Brazos River about sixty miles above the Hubbard Creek confluence and fifty miles below the confluence of the Salt Fork and Double Mountain Fork of the Brazos River.

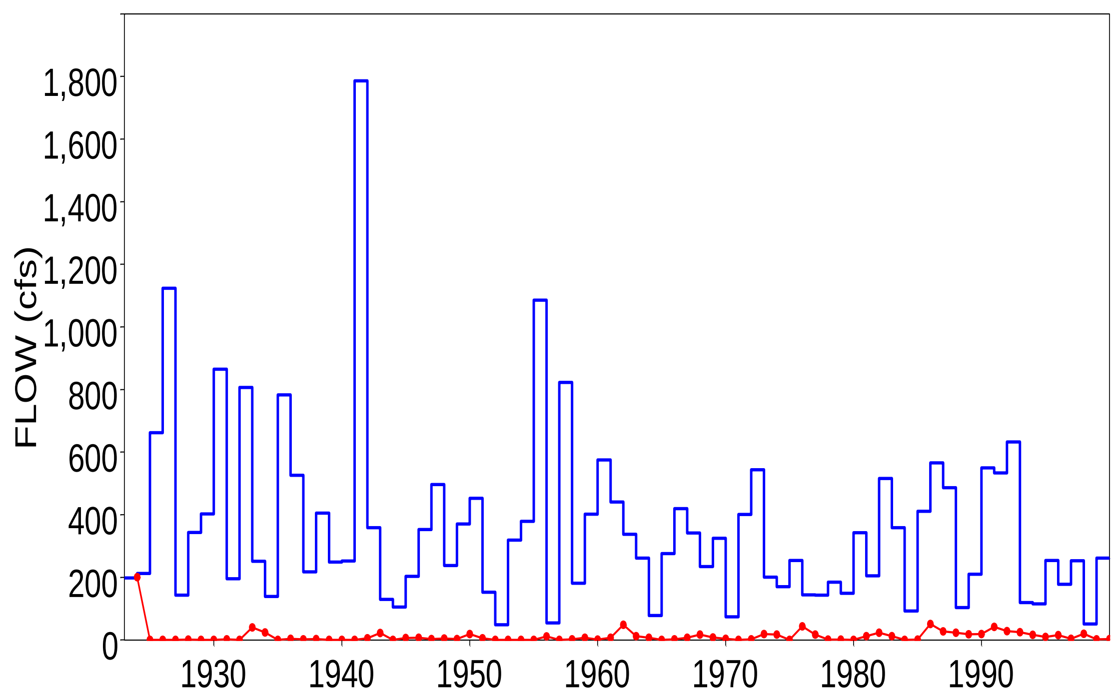
Period-of-record of daily flows: 1923/12/01 to present (2013/6/1)



Daily Flows of Brazos River at Seymour



Monthly Flows of Brazos River at Seymour



Annual Flows and the Minimum Monthly Flow Each Year

16
Brazos River at Waco

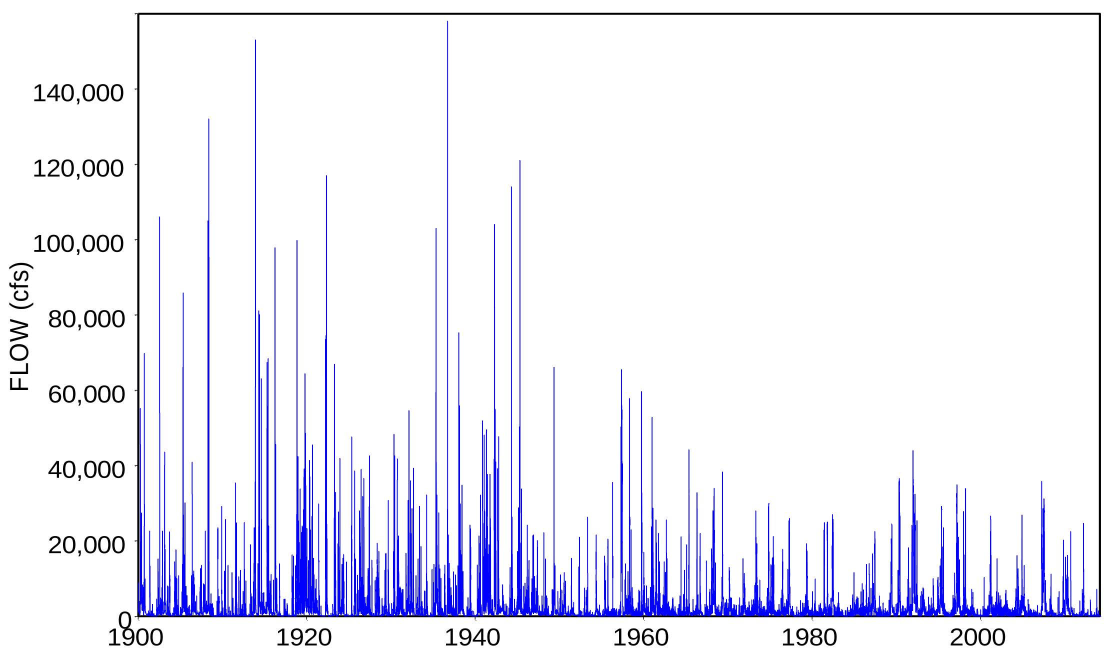
USGS 08096500
Mclennan County

Drainage area 29,559 square miles
Contributing drainage area 19,983 square miles

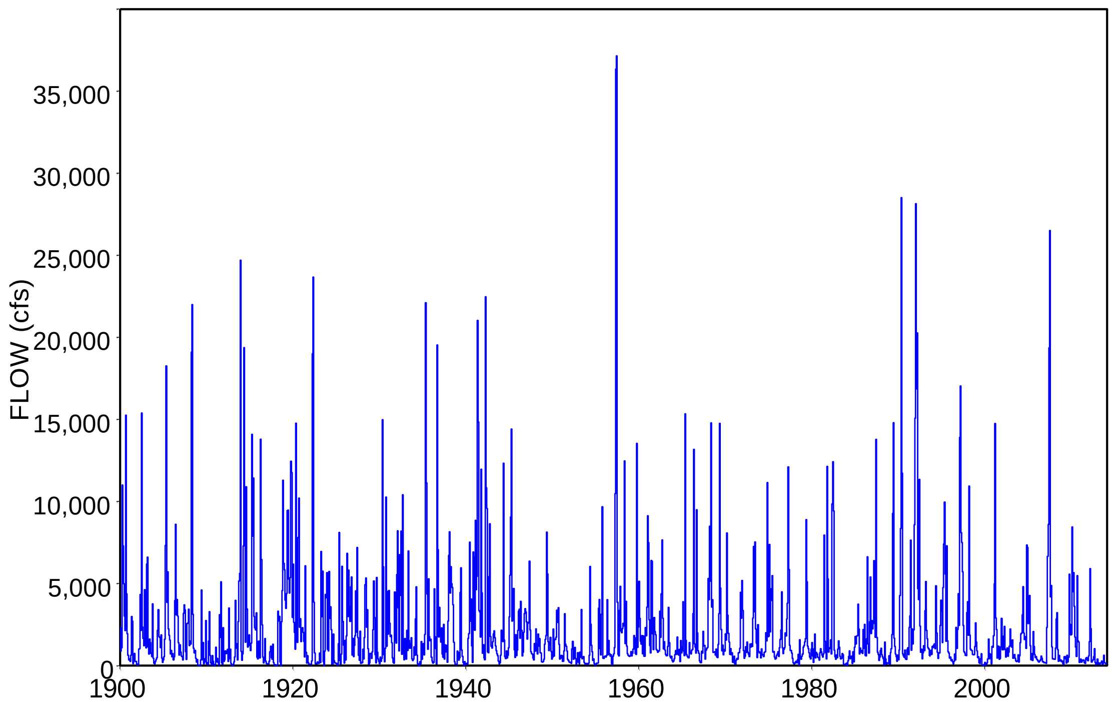
The gage site on the Brazos River is just downstream of the City of Waco and about five miles downstream of the Bosque River confluence. The gage is at the South Loop 340 Highway about a mile south of Texas Highway 6.

A maximum allowable non-flooding discharge of 25,000 cfs at the Brazos River gage at Waco is designated by the U.S. Army Corps of Engineers (USACE) Fort Worth District (FWD) for purposes of reservoir flood control operations. The USACE FWD uses this gage along with other downstream gages on the Brazos River in operating the flood control pools of the multipurpose Lakes Waco, Aquilla, and Whitney which are located upstream of this site. Many other water supply reservoirs are also located upstream of this gage site.

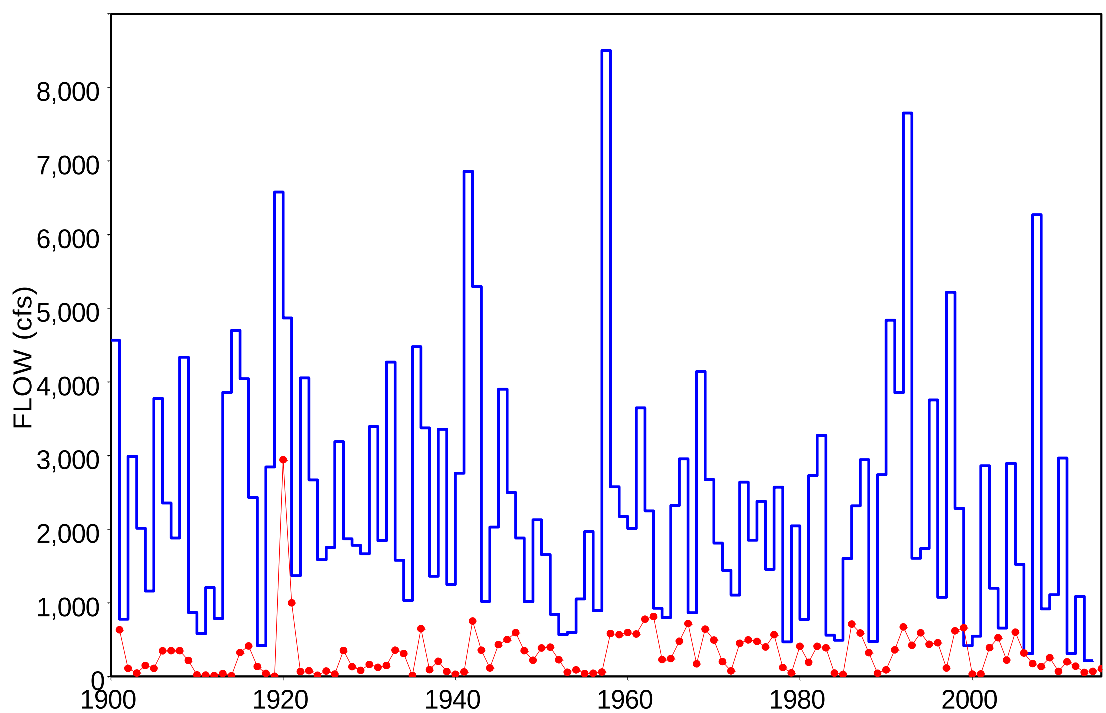
Period-of-record of daily flows: 1898/10/01 to present (2013/6/1)



Daily Flows of the Brazos River at the Gage at Waco



Monthly Flows of the Brazos River at the Gage at Waco



Annual Flows and the Minimum Monthly Flow Each Year

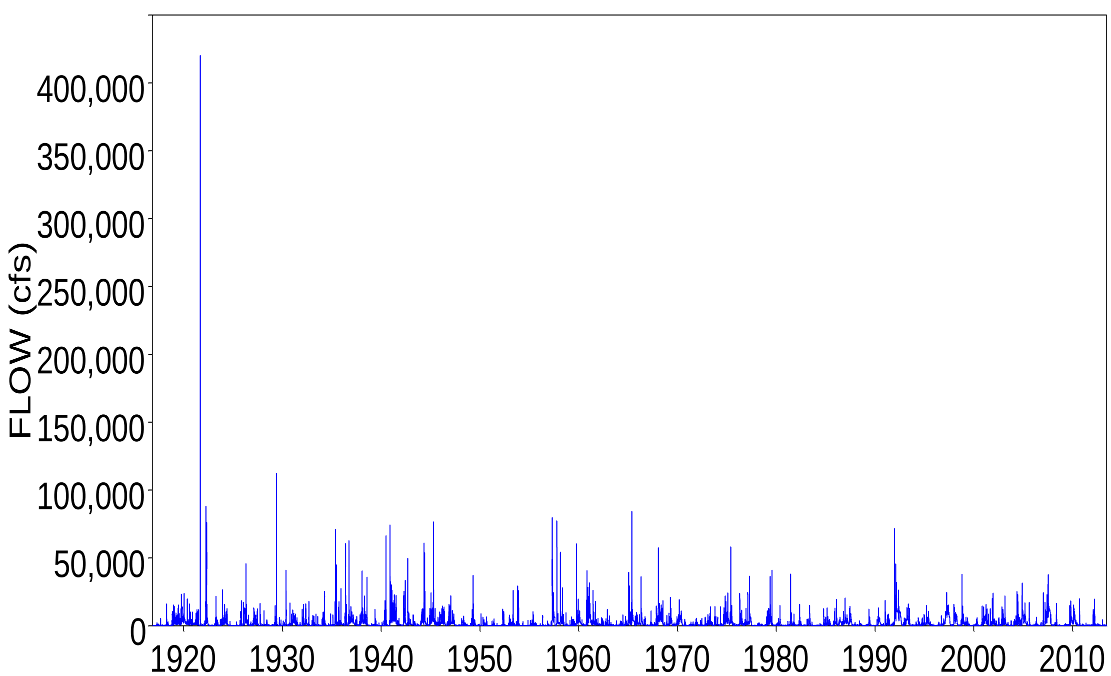
17
Little River at Cameron

USGS 08106500
Milam County, Texas

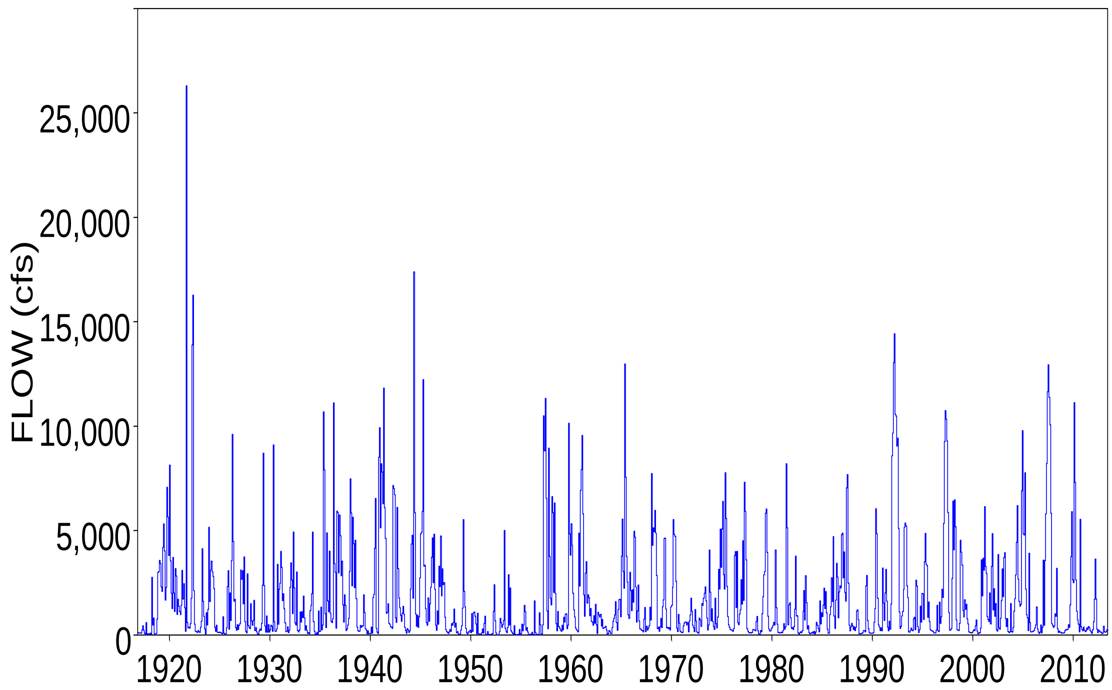
Drainage area 7,065 square miles
Contributing drainage area 7,065 square miles
Latitude 30°50'06", Longitude 96°56'47" NAD27
Gage datum 281.89 feet above NGVD29

The gage is at Hwy 190 about eight miles below the San Gabriel River confluence and thirty miles above the outlet at the Brazos River.
A maximum allowable non-flooding discharge of 10,000 cfs at the Little River gage at Cameron is designated by the U.S. Army Corps of Engineers (USACE) Fort Worth District (FWD) for purposes of reservoir flood control operations. The USACE FWD uses this gage along with other gage sites in operating the flood control pools of the multipurpose Lakes Proctor, Belton, Stillhouse Hollow, Georgetown, and Granger which are located upstream of this site.

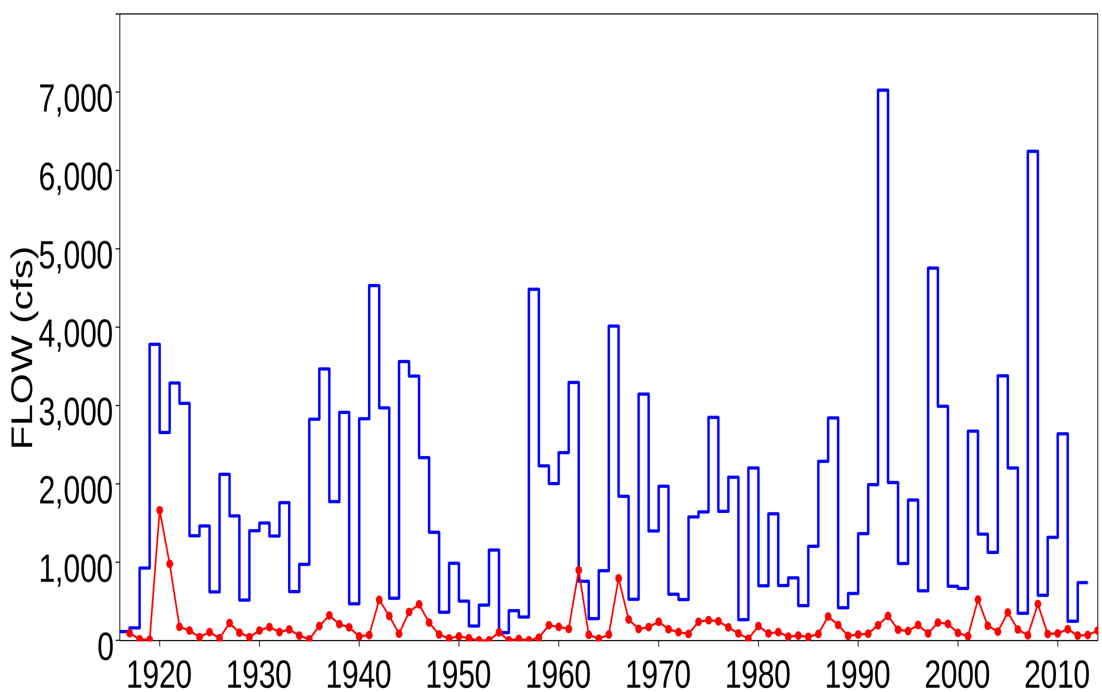
Period-of-record of daily flows: 1916/11/01 to present (2013/6/1)



Daily Flows of Little River at Cameron



Monthly Flows of Little River at Cameron



Annual Flows and the Minimum Monthly Flow Each Year

18

Navasota River at Easterly

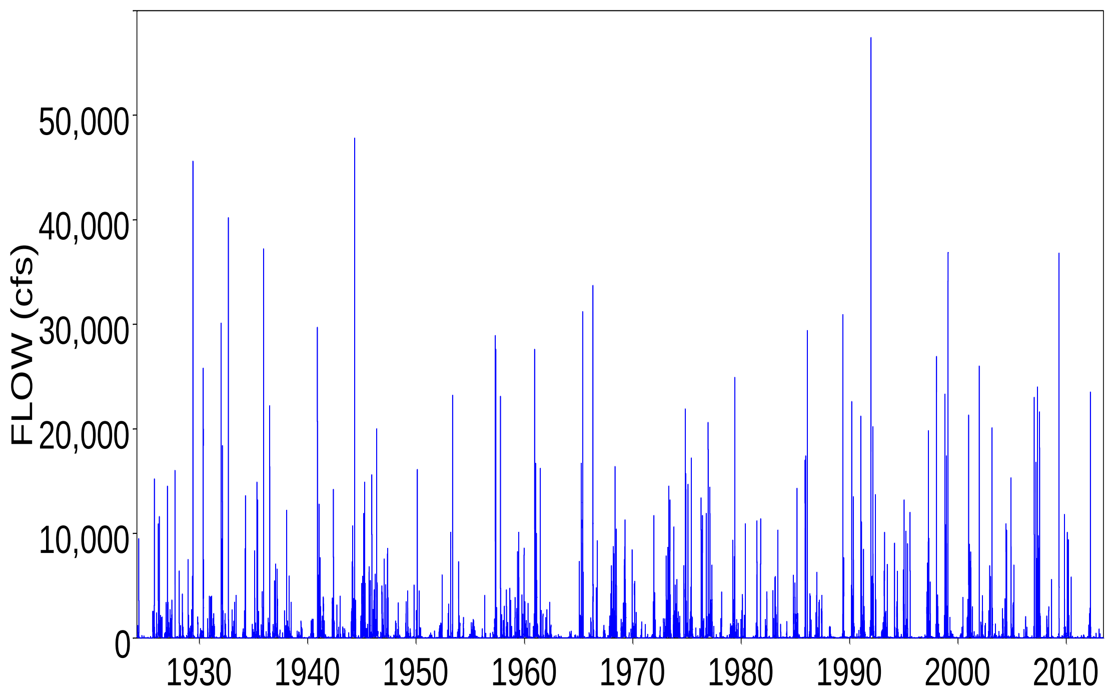
USGS 08110500
Leon County, Texas

Drainage area 968 square miles
Contributing drainage area 968 square miles

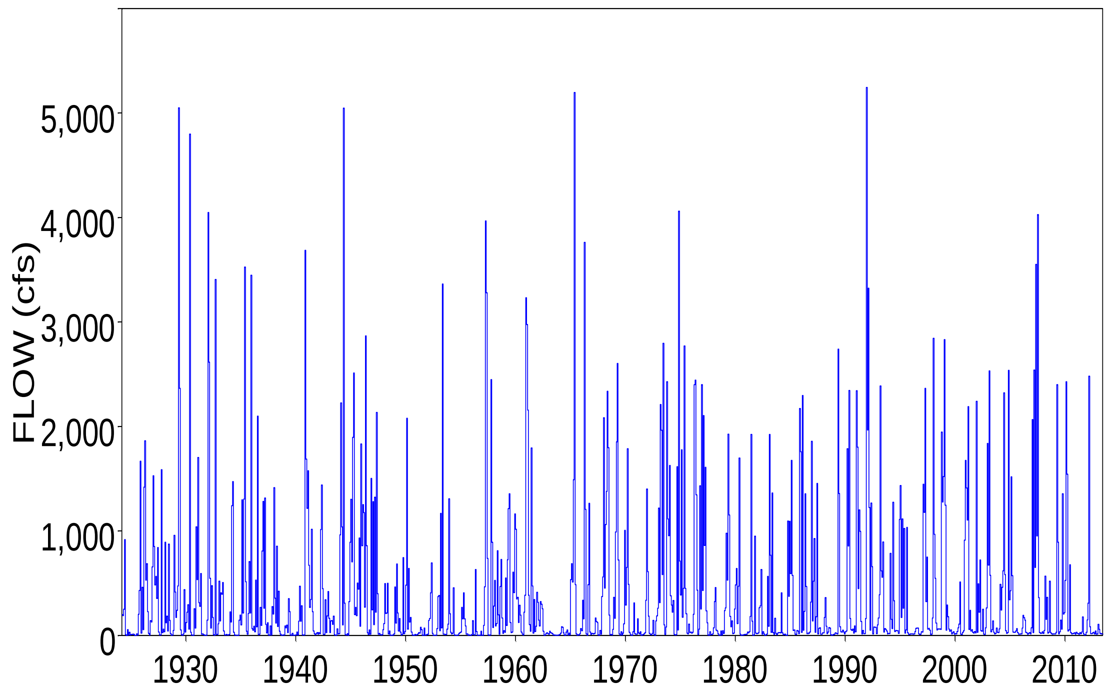
Latitude 31°10'12", Longitude 96°17'51" NAD27
Gage datum 271.46 feet above NGVD29

The gage is at Hwy 79 about eleven miles below Limestone Dam which is operated by the Brazos River Authority for water supply.

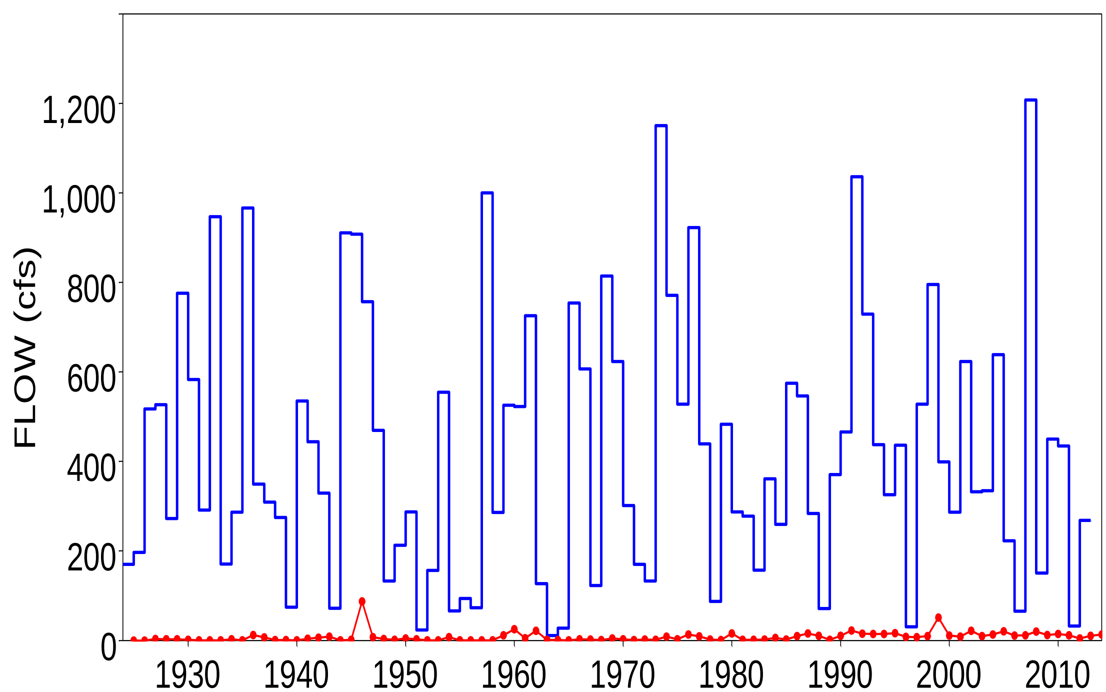
Period-of-record of daily flows: 1924/3/27 to present (2013/6/1)



Daily Flows of Navasota River at Easterly



Monthly Flows of Navasota River at Easterly



Annual Flows and the Minimum Monthly Flow Each Year

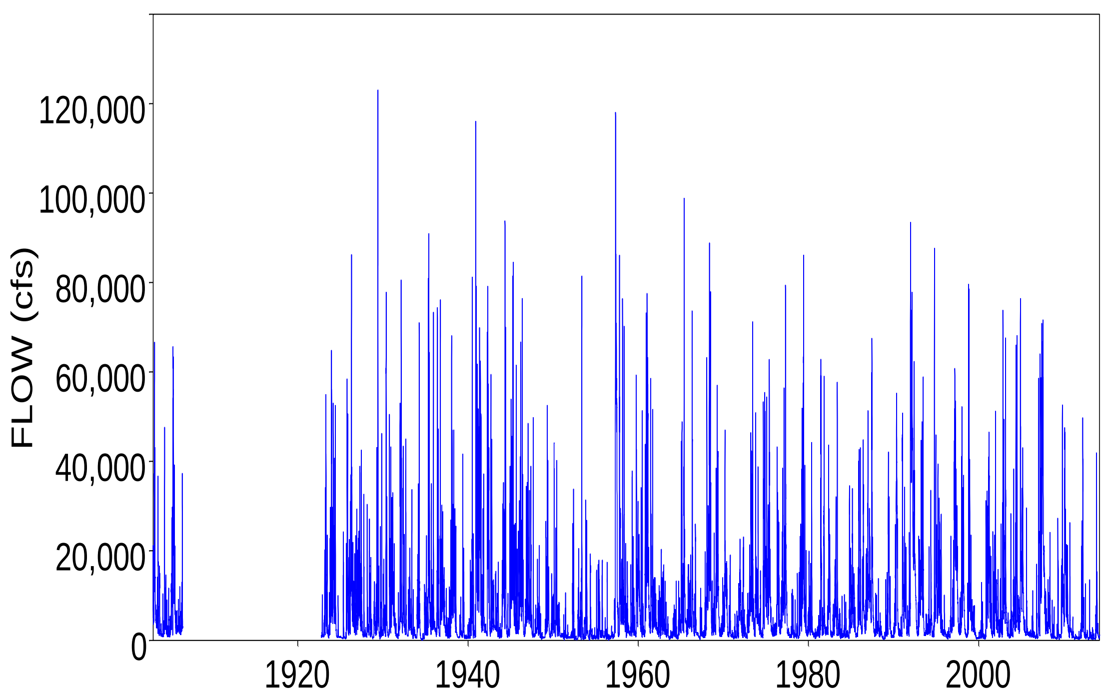
19
Brazos River at Richmond

USGS 08114000
Fort Bend County, Texas
Drainage area 45,107 square miles
Contributing drainage area 35,541 square miles

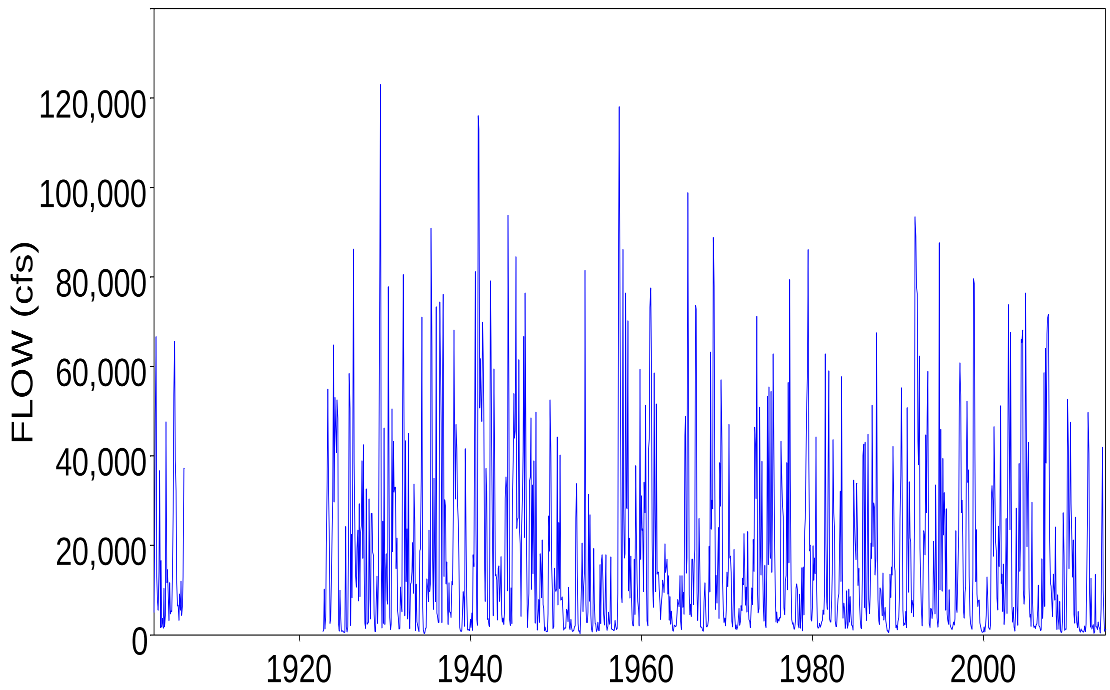
Latitude 29°34'56", Longitude 95°45'27" NAD27
Gage datum 27.94 feet above NGVD29
The gage is near Hwy 90 about 60 miles above the Brazos River outlet near Freeport.

A maximum allowable non-flooding discharge of 60,000 cfs at the Brazos River gage at Richmond is designated by the U.S. Army Corps of Engineers (USACE) Fort Worth District (FWD) for purposes of reservoir flood control operations. The USACE FWD uses this gage along with other gage sites in operating the flood control pools of the system nine federal multipurpose reservoirs located on the Brazos River and its tributaries. Many other nonfederal water supply reservoirs are located upstream of this gage site.

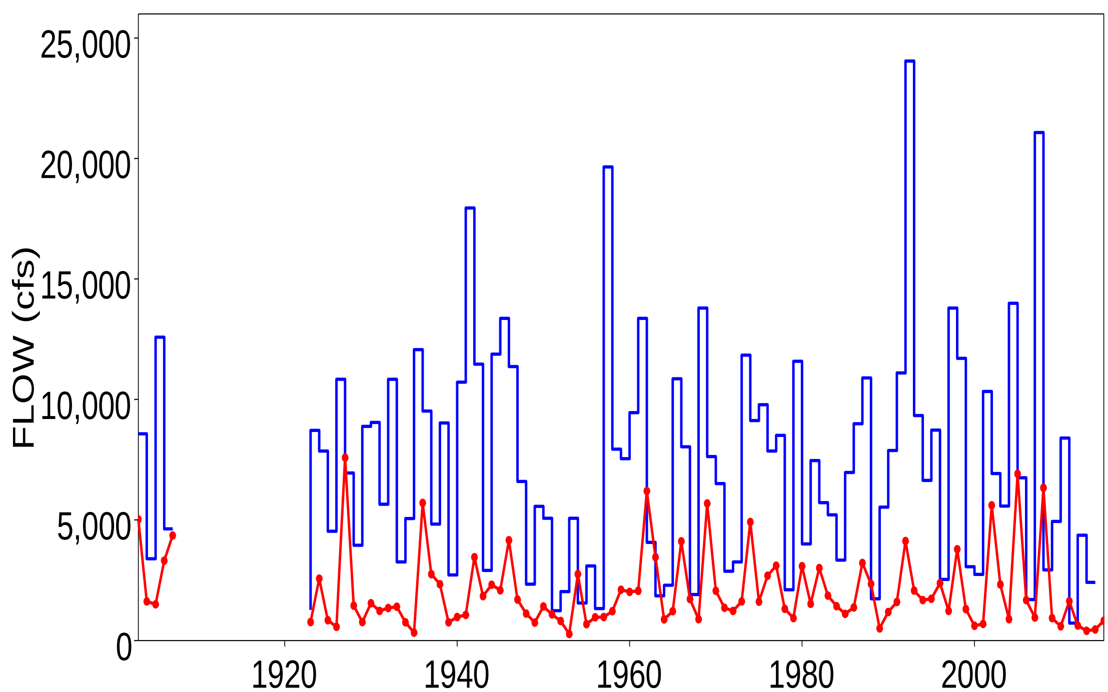
Period-of-record of daily flows: 1903/11/01 to present (2014/3/8)



Daily Flows of Brazos River at Richmond



Monthly Flows of Brazos River at Richmond



Annual Flows and the Minimum Monthly Flow Each Year

20
Buffalo Bayou in Houston

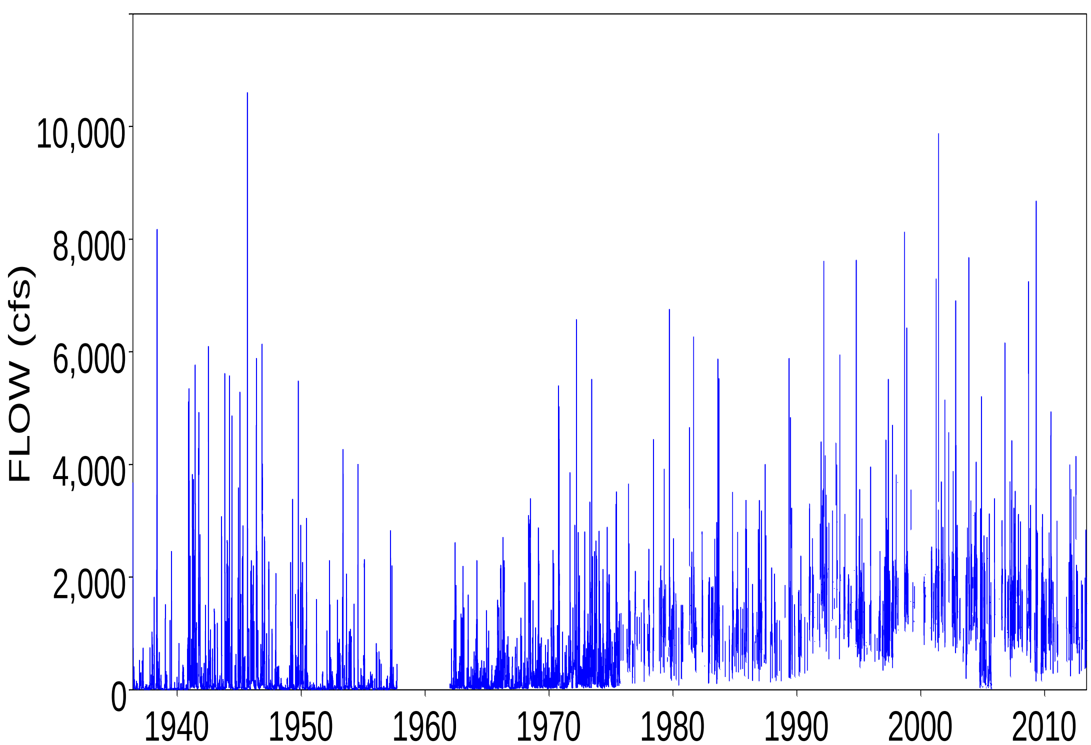
USGS 08074000
Harris County, Texas

Drainage area 336 square miles
Contributing drainage area 336 square miles

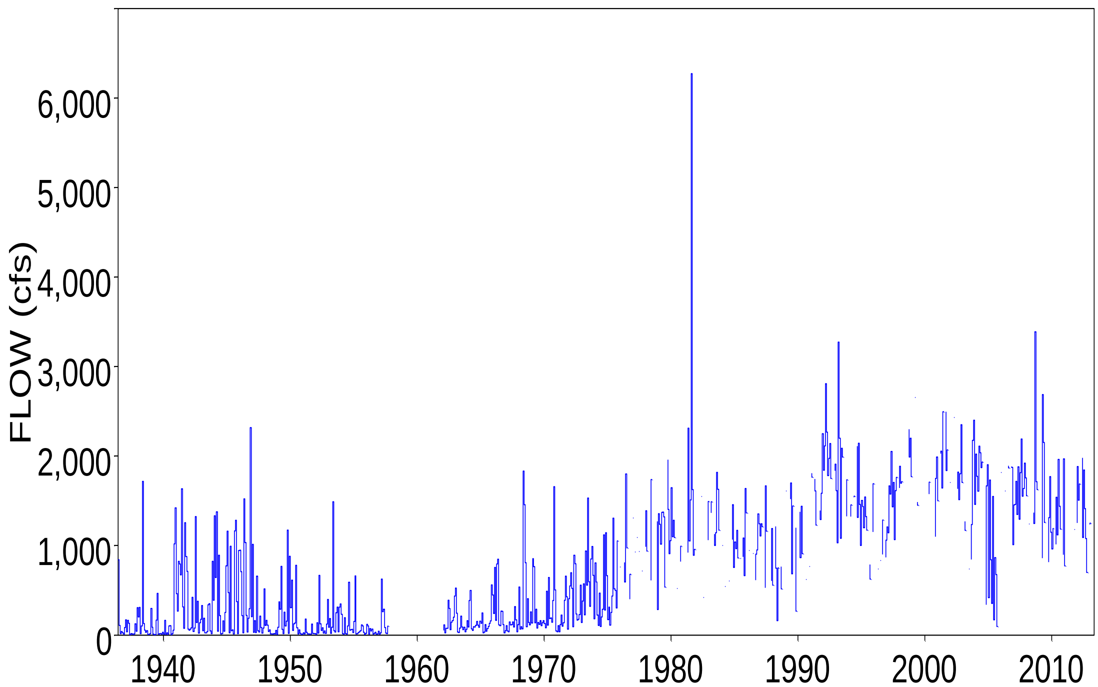
Latitude 29°45'36", Longitude 95°24'30" NAD27
Gage datum 0.00 feet above NAVD88

The gage is at Shepard Drive west (upstream) of downtown Houston three miles east (downstream) of IH 610. Barker and Addicks Dams are about sixteen miles upstream of the gage. Barker and Addicks Dams are operated only for flood control with no storage for water supply.

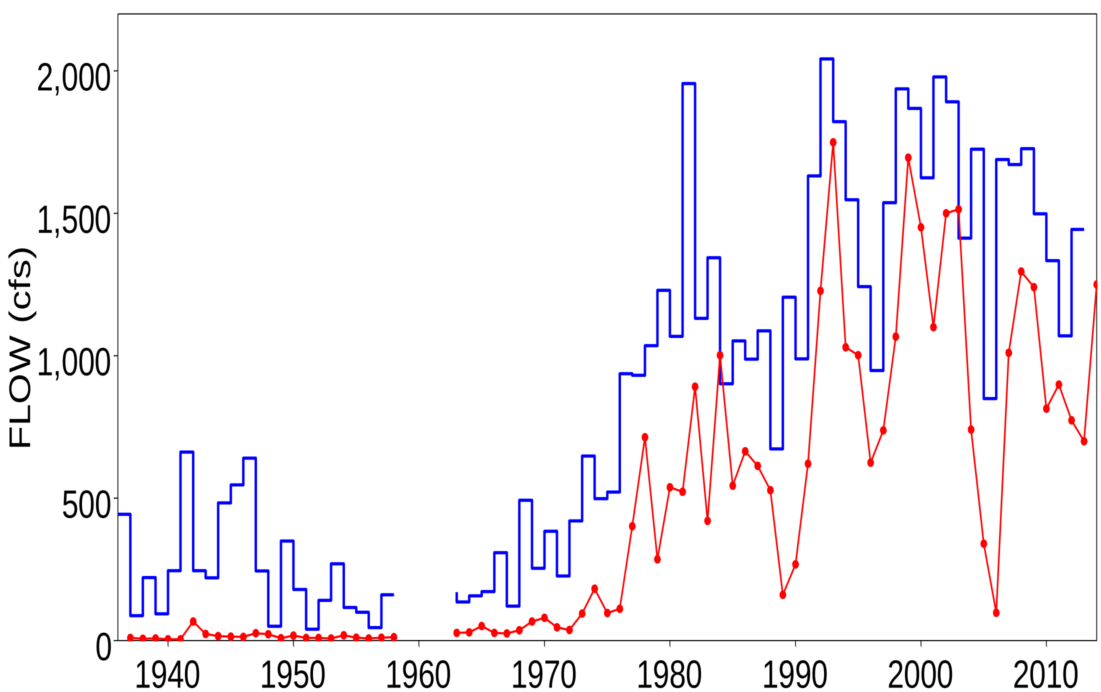
Period-of-record of daily flows: 1936/6/01 to present (2013/5/19)



Daily Flows of Buffalo Bayou in Houston



Monthly Flows of Buffalo Bayou in Houston



Annual Flows and the Minimum Monthly Flow Each Year

21
West Fork San Jacinto River near Conroe

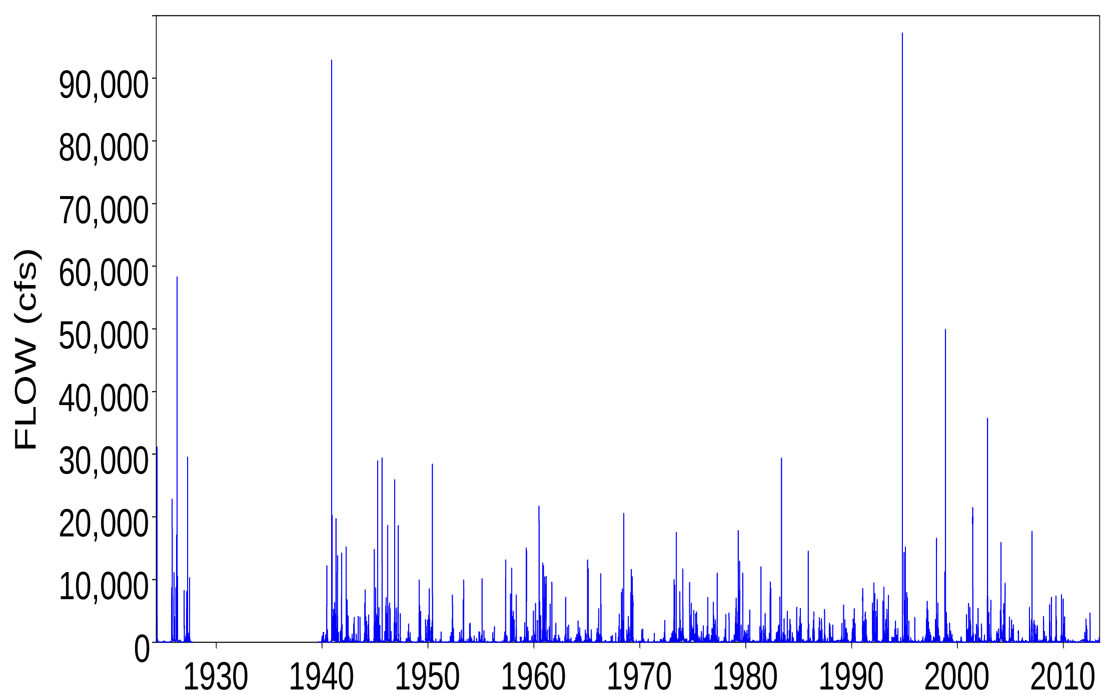
USGS 08068000
Montgomery County, Texas

Drainage area 828 square miles
Contributing drainage area 828 square miles

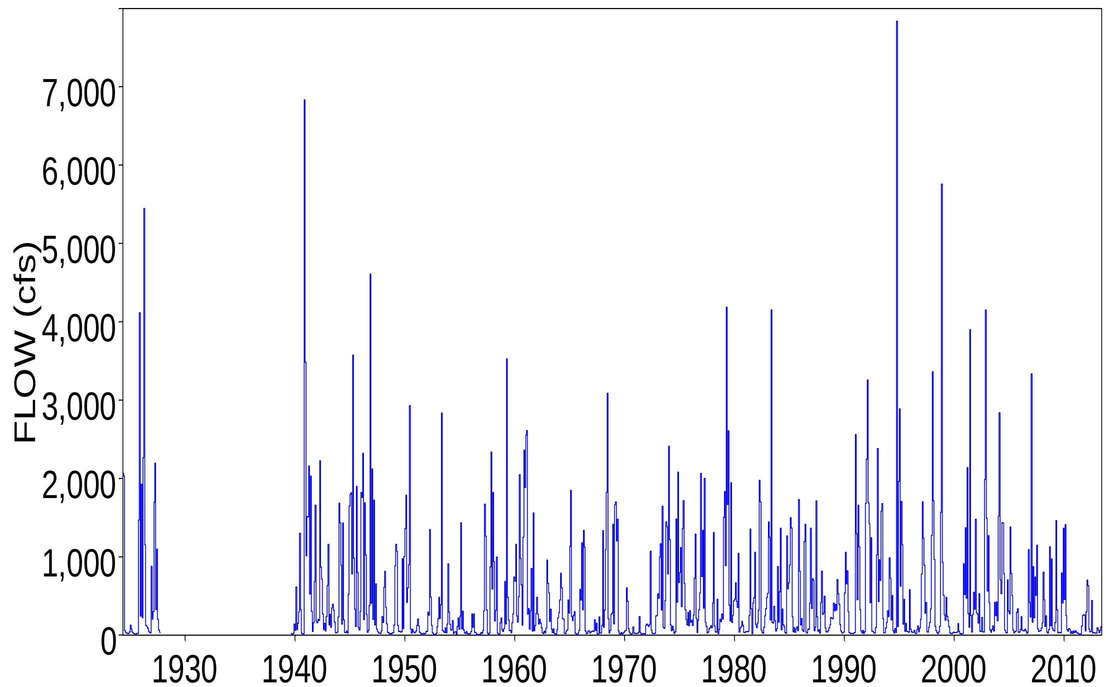
Latitude 30°14'40", Longitude 95°27'25" NAD27
Gage datum 00.00 feet above NAVD88

The gage is at IH 45 ten miles below the dam at Lake Conroe.

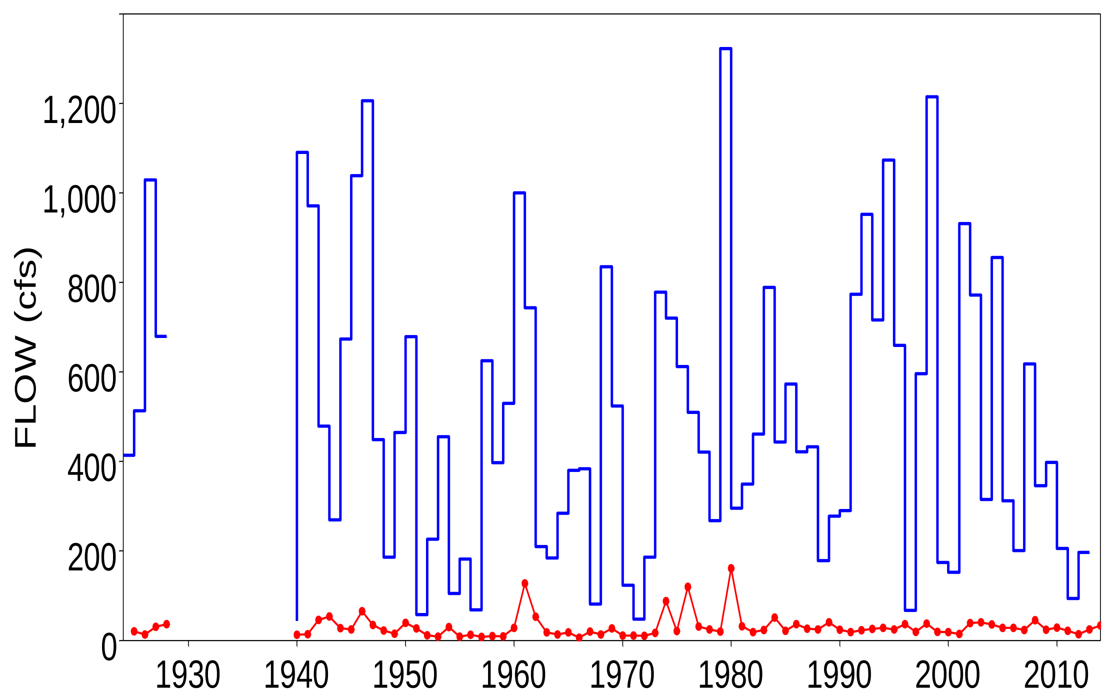
Period-of-record of daily flows: 1924/5/01 to present (2013/6/1)



Daily Flows of West Fork San Jacinto River near Conroe



Monthly Flows of West Fork San Jacinto River near Conroe



Annual Flows and the Minimum Monthly Flow Each Year

22
West Fork of the Trinity River at Fort Worth

USGS 08048000
Tarrant County, Texas

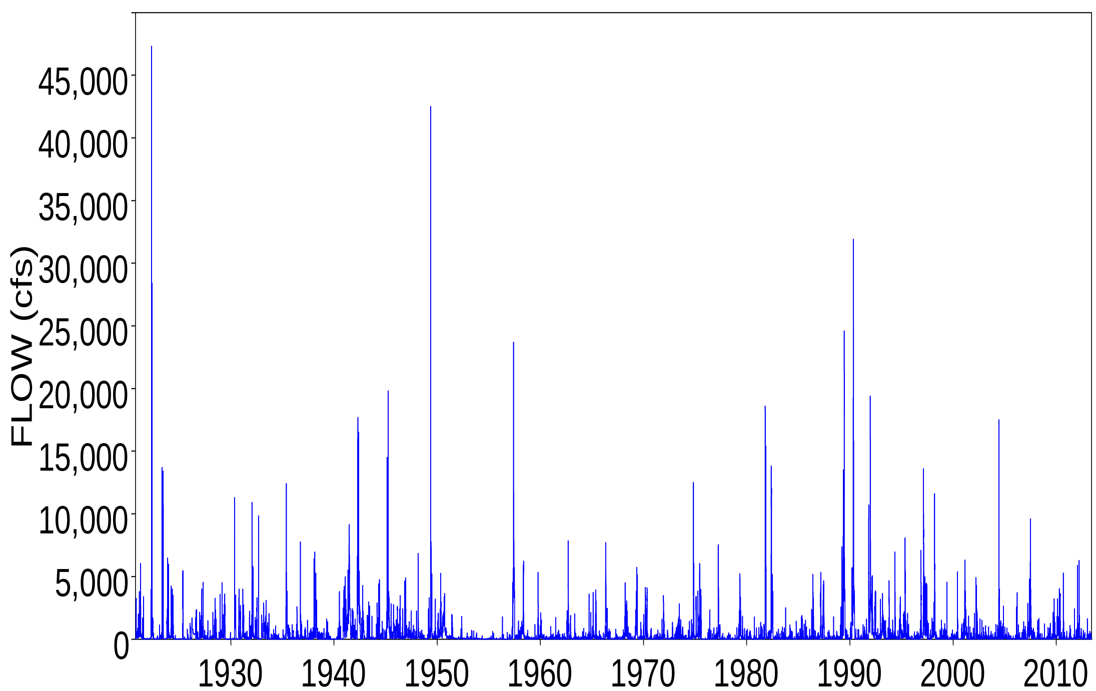
Drainage area 2,615 square miles
Contributing drainage area 2,615 square miles

Latitude 32°45'39", Longitude 97°19'56" NAD27
Gage datum 519.24 feet above NGVD29

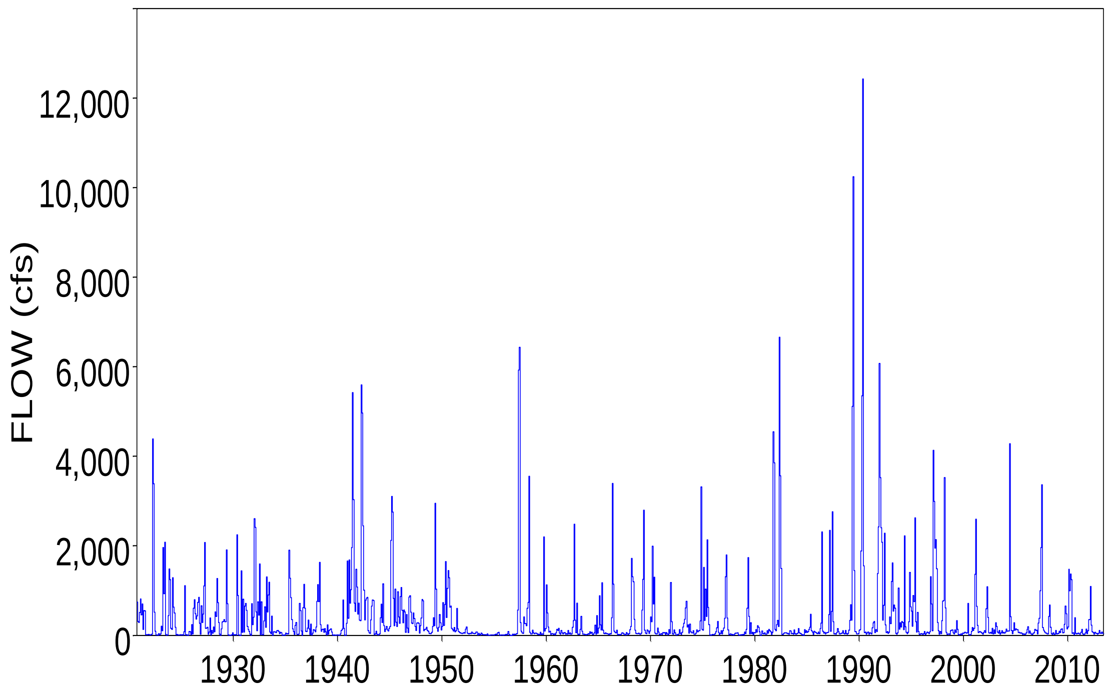
The gage is south of Hwy 287 north of downtown Fort Worth.

A maximum allowable non-flooding discharge of 3,000 cfs at this gage site is designated by the U.S. Army Corps of Engineers (USACE) Fort Worth District (FWD) for purposes of reservoir flood control operations. The USACE FWD uses this gage along with other gage sites in operating the flood control pool Ben Brook Reservoir.

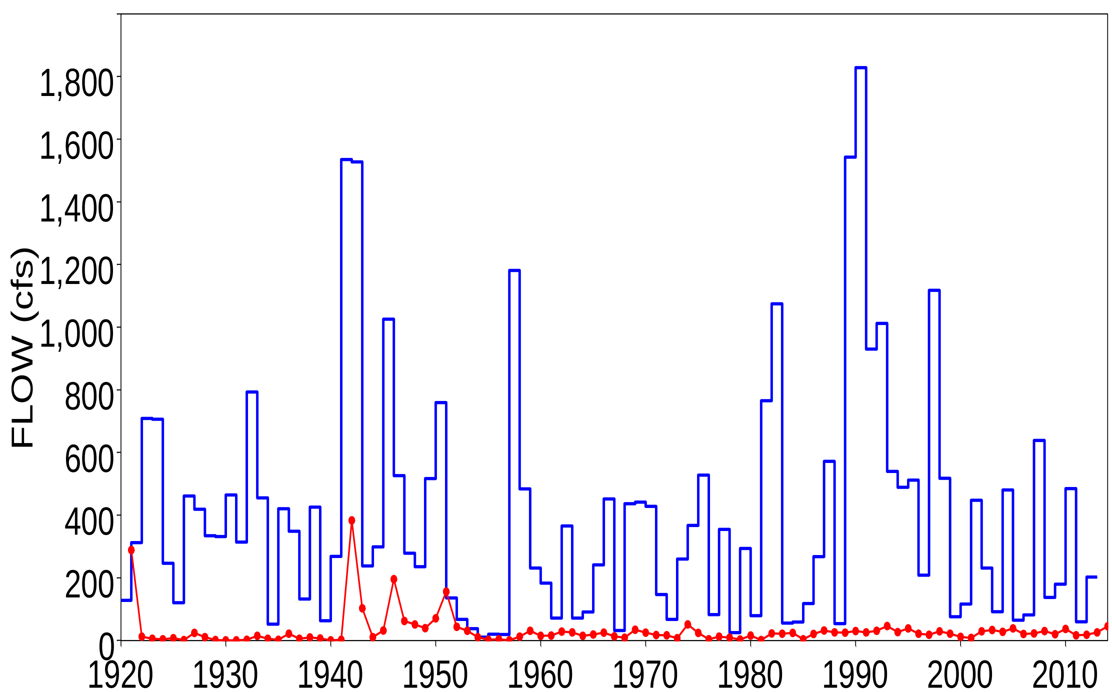
Period-of-record of daily flows: 1920/10/01 to present (2013/6/1)



Daily Flows of West Fork Trinity River at Fort Worth



Monthly Flows of West Fork Trinity River at Fort Worth



Annual Flows and the Minimum Monthly Flow Each Year

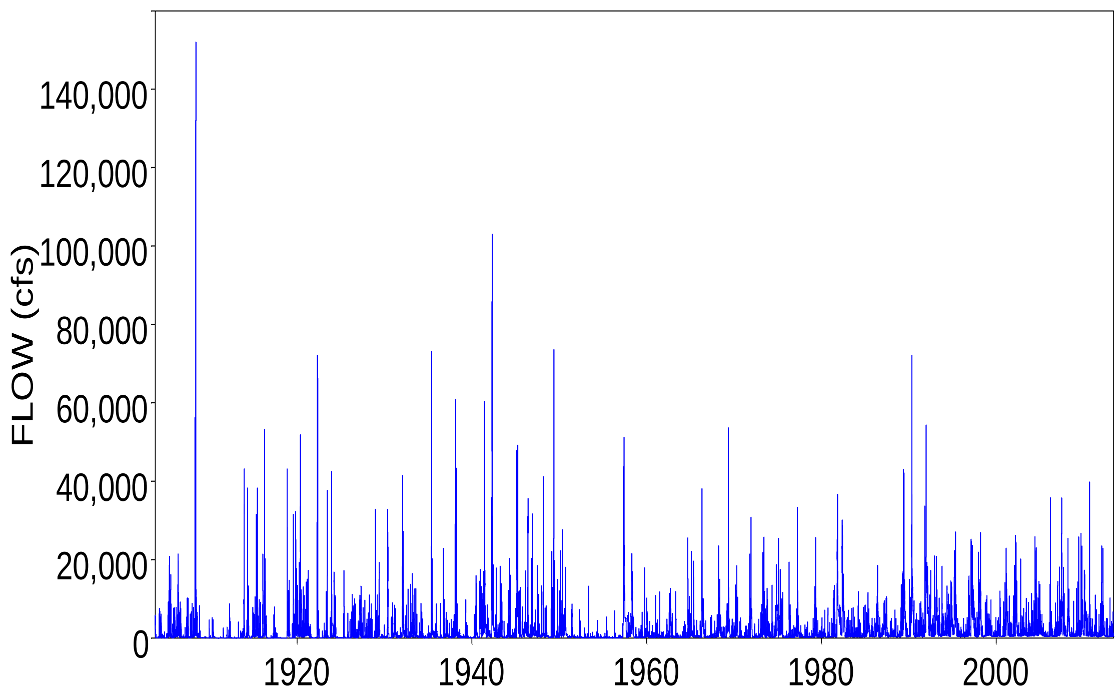
23
Trinity River at Dallas

USGS 08057000
Dallas County, Texas
Drainage area 6,106 square miles
Contributing drainage area 6,106 square miles

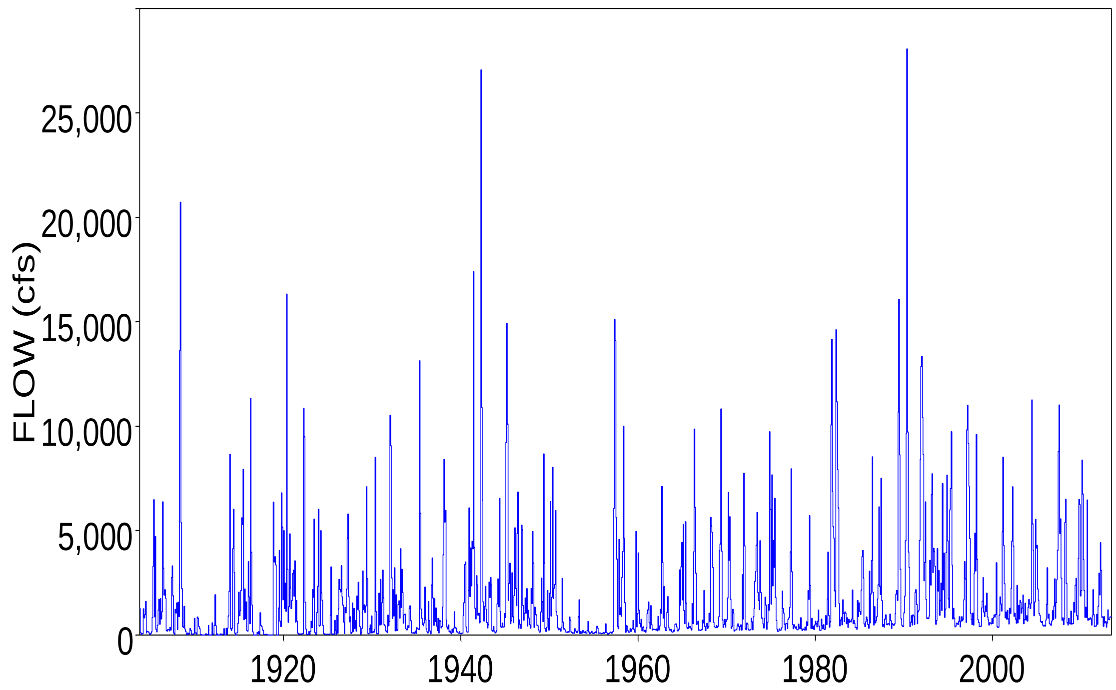
Latitude 32°46'29", Longitude 96°49'18" NAD27
Gage datum 368.02 feet above NGVD29

The gage is at West Commerce Street west of IH 35 and north of IH 30 just west of downtown.
A maximum allowable non-flooding discharge of 13,000 cfs at this gage site is designated by the Corps of Engineers for purposes of reservoir flood control operations. The USACE FWD uses this gage along with other gage sites in operating the flood control pools of the federal multiple-purpose Lakes Benbrook, Joe Pool, Ray Roberts, Lewisville, and Grapevine located upstream. A number of nonfederal water supply reservoirs are also located upstream of this gage site.

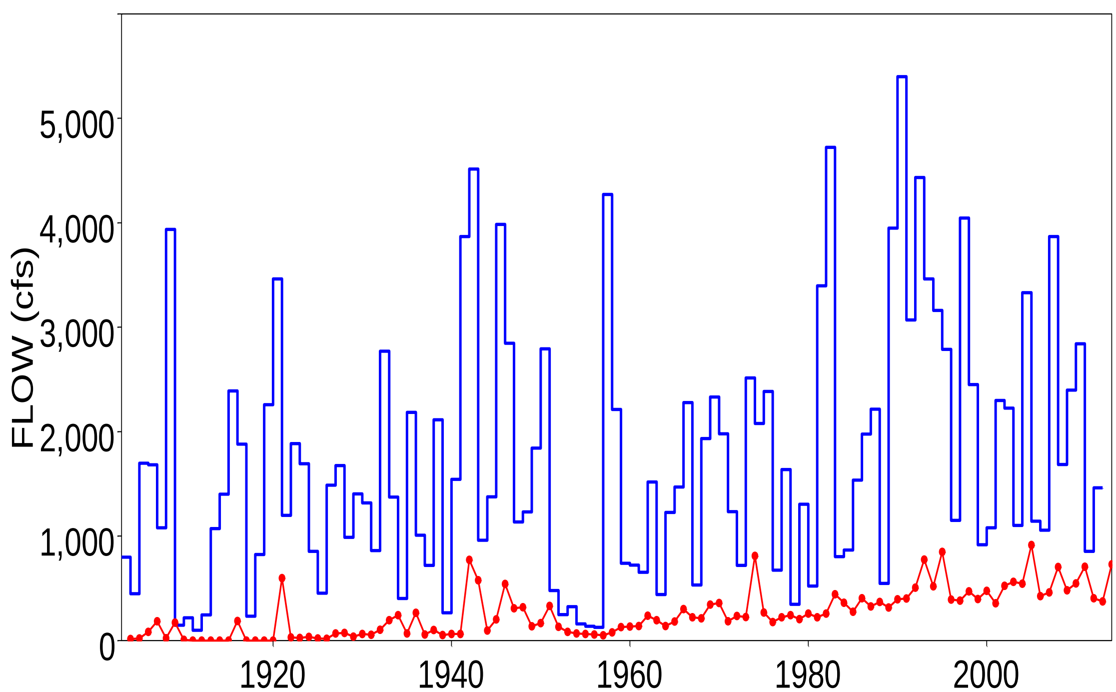
Period-of-record of daily flows: 1903/10/01 to present (2013/6/1)



Daily Flows of Trinity River at Dallas



Monthly Flows of Trinity River at Dallas



Annual Flows and the Minimum Monthly Flow Each Year

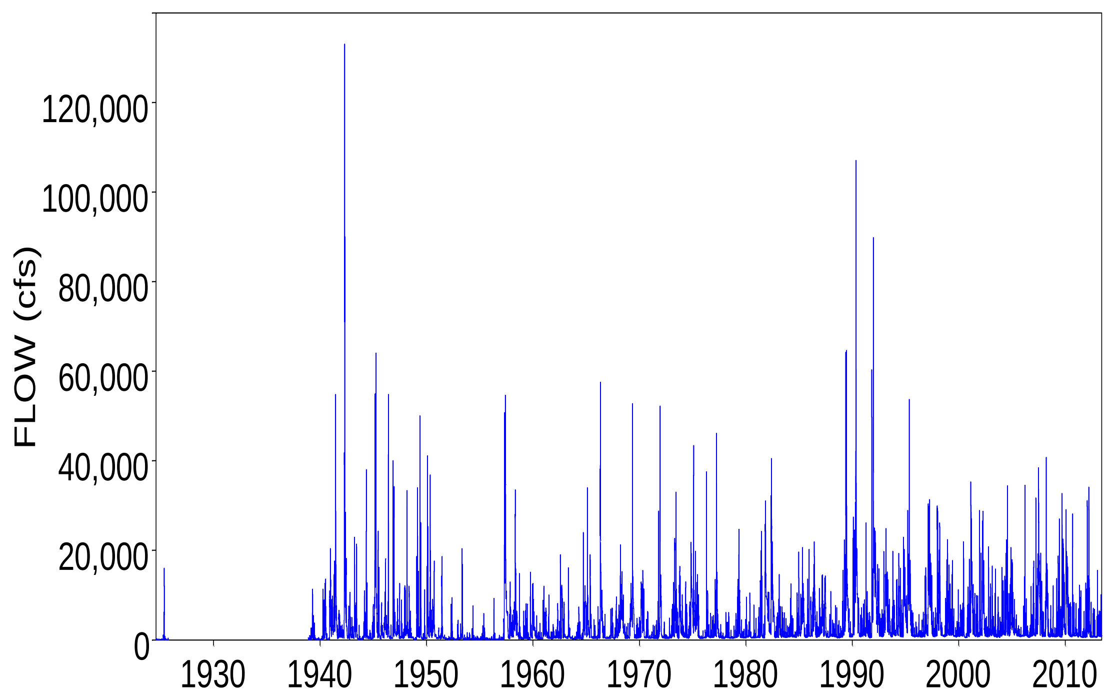
24
Trinity River near Rosser

USGS 08062500
Ellis County, Texas

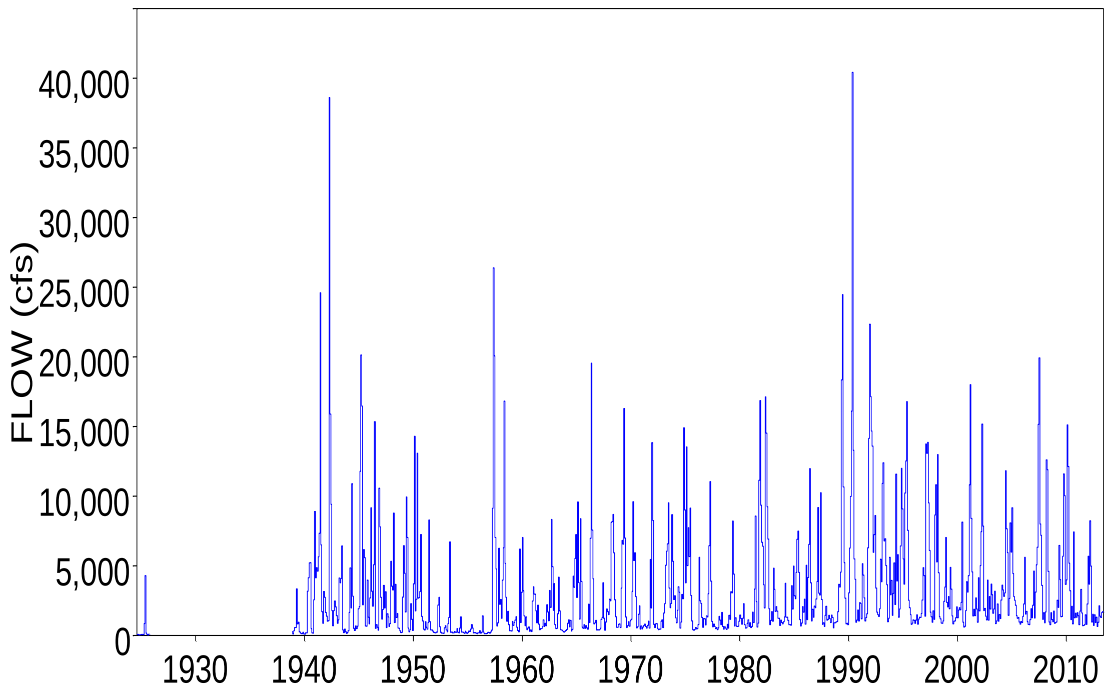
Drainage area 8,147 square miles
Contributing drainage area 8,147 square miles
Latitude 32°25'35", Longitude 96°27'46" NAD27
Gage datum 297.65 feet above NGVD29

The gage is at Hwy 34 thirty miles downstream of central downtown Dallas and thirty miles upstream of the Cedar Creek confluence with the Trinity River.
A maximum allowable non-flooding discharge of 15,000 cfs at this gage site is designated by the Corps of Engineers for purposes of reservoir flood control operations. The USACE FWD uses this gage along with other gage sites in operating the flood control pools of the federal multiple-purpose Lakes Benbrook, Joe Pool, Ray Roberts, Lewisville, Grapevine, and Lavon located upstream. A number of nonfederal water supply reservoirs are also located upstream of this gage.

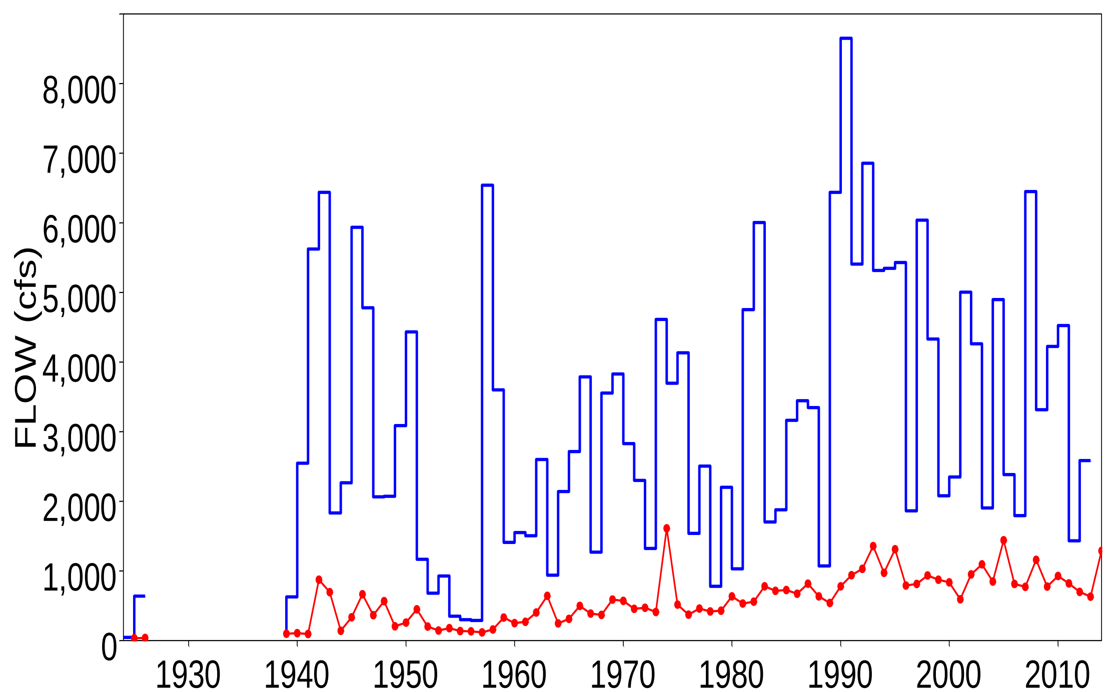
Period-of-record of daily flows: 1924/8/01 to present (2013/6/1)



Daily Flows of Trinity River near Rosser



Monthly Flows of Trinity River near Rosser



Annual Flows and the Minimum Monthly Flow Each Year

25
Trinity River near Oakwood

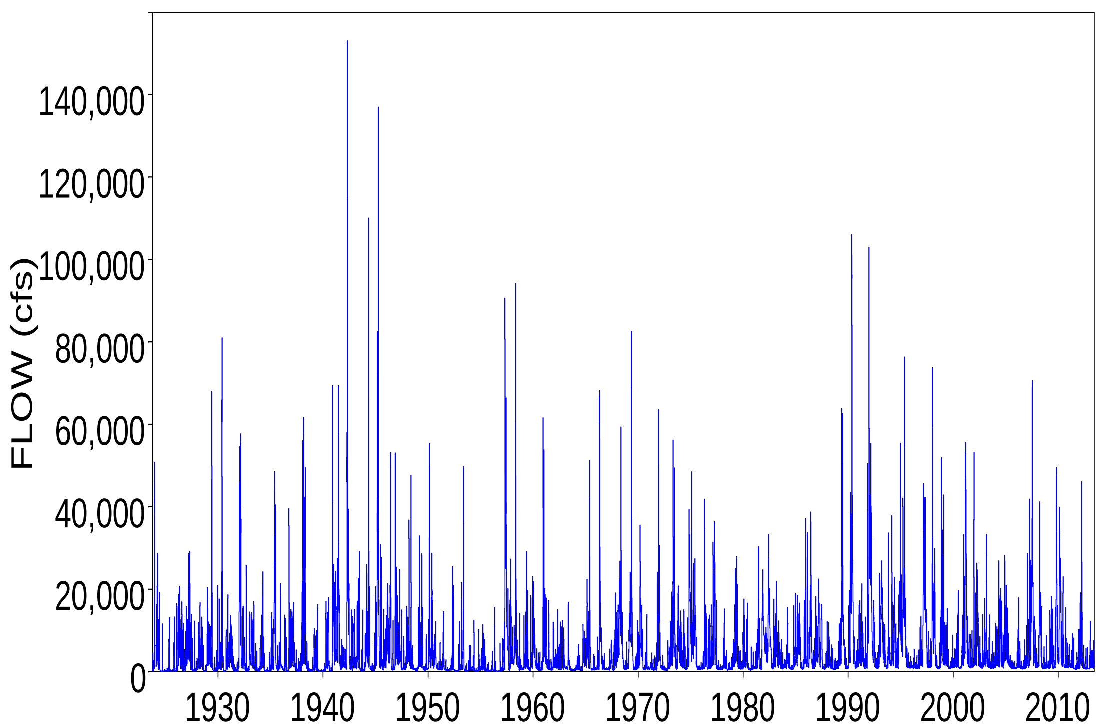
USGS 08065000
Anderson County, Texas

Drainage area 12,833 square miles
Contributing drainage area 12,833 square miles

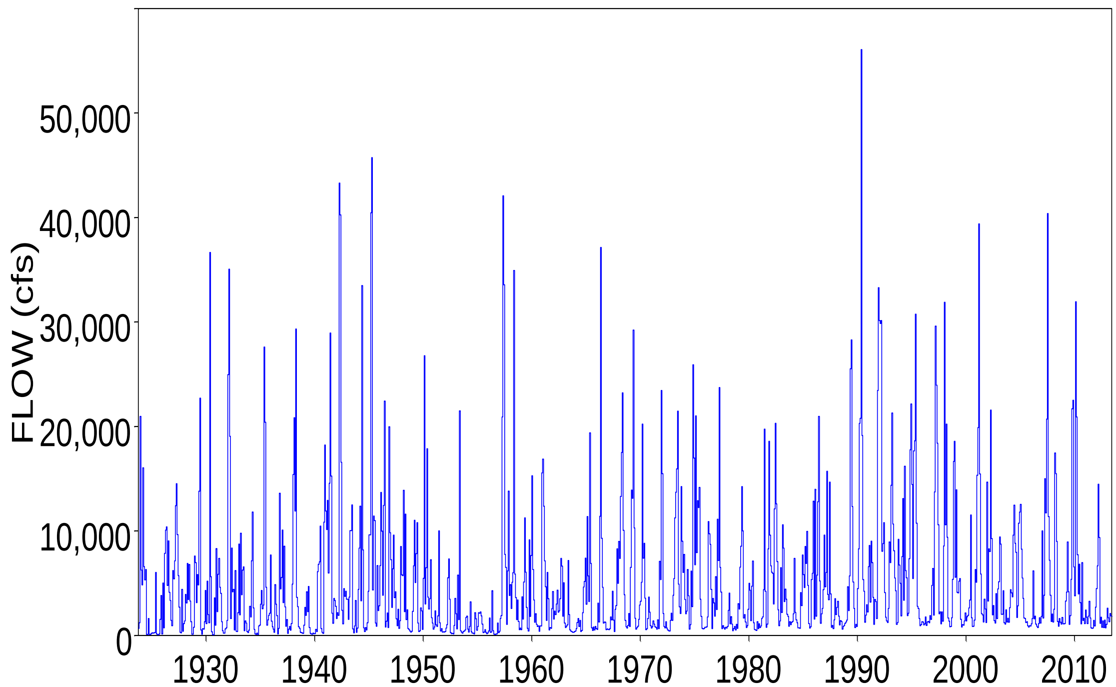
Latitude 31°38'54", Longitude 95°47'21" NAD27
Gage datum 175.06 feet above NGVD29

The gage is at Hwy 79 about forty miles below Richland Chambers Reservoir.

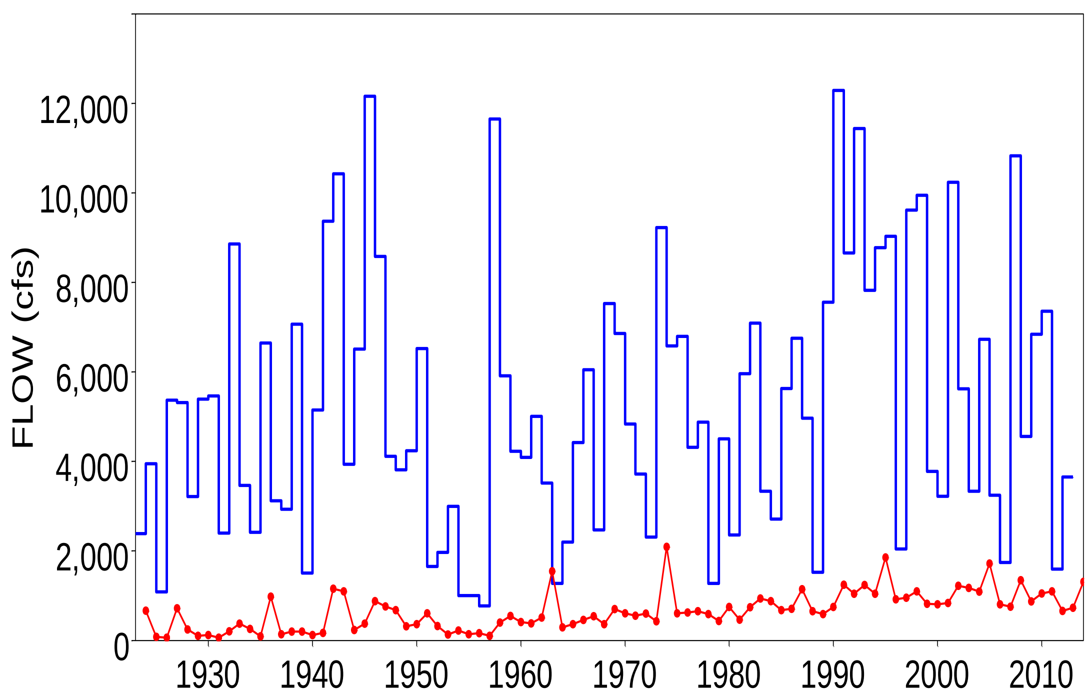
Period-of-record of daily flows: 1923/10/01 to present (2013/6/1)



Daily Flows of Trinity River near Oakwood



Monthly Flows of Trinity River near Oakwood



Annual Flows and the Minimum Monthly Flow Each Year

26
Trinity River at Romayor

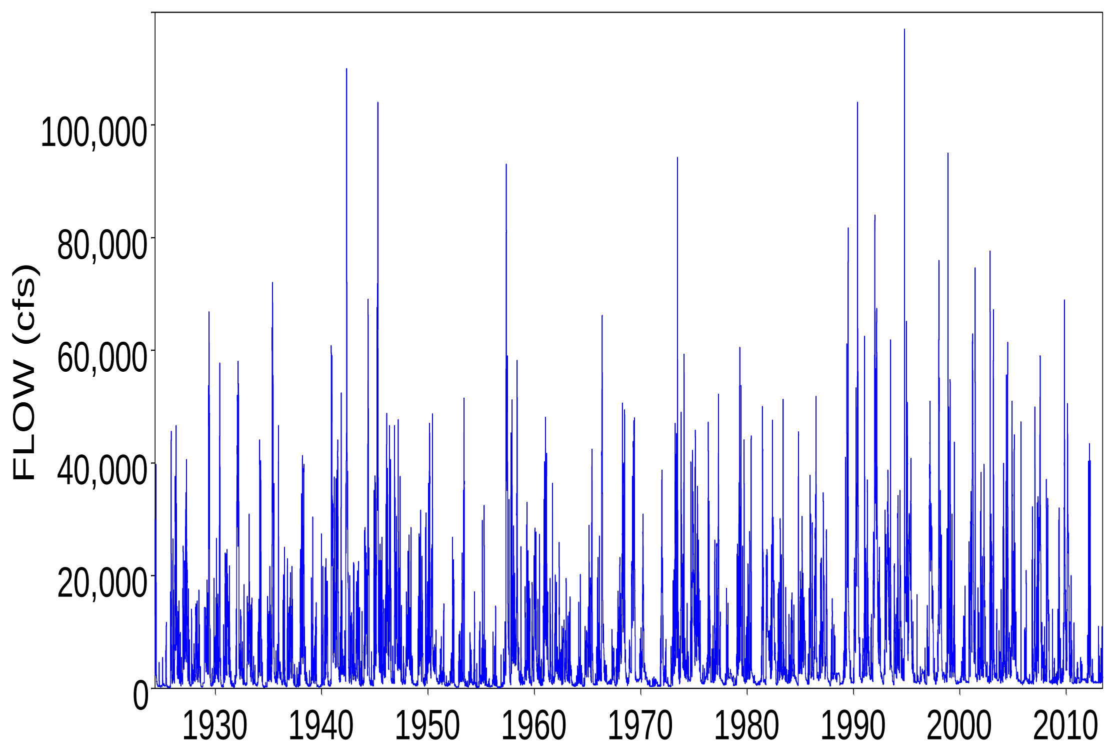
USGS 08066500
Liberty County, Texas

Drainage area 17,186 square miles
Contributing drainage area 17,186 square miles

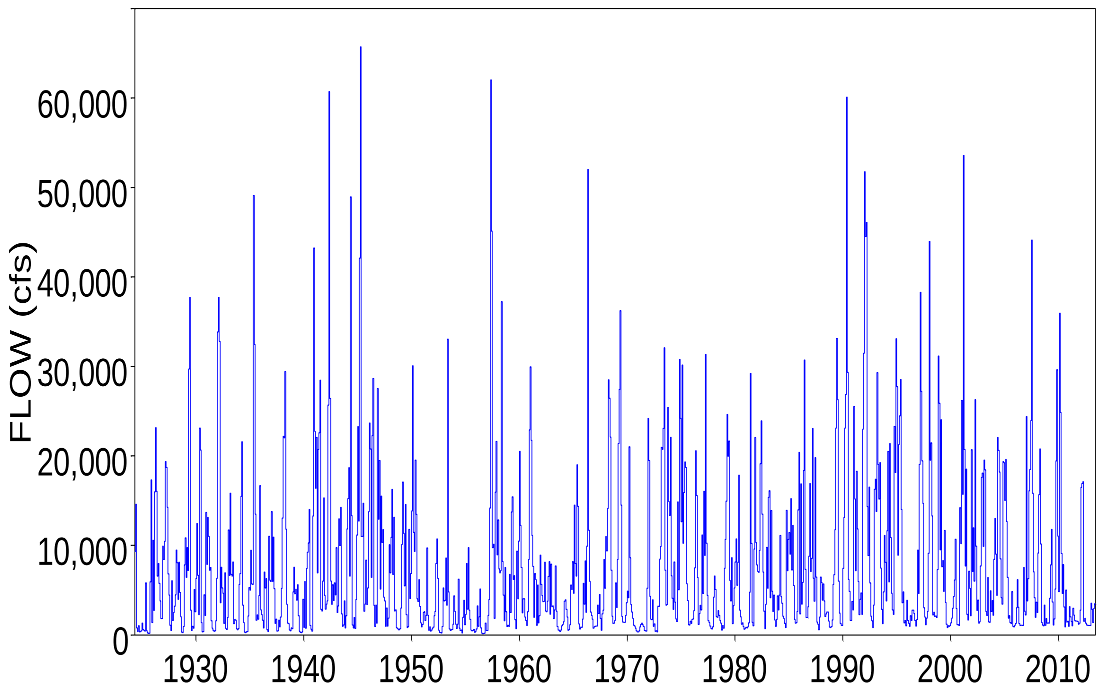
Latitude 30°25'30", Longitude 94°51'02" NAD27
Gage datum 25.92 feet above NGVD29

The gage is at FM 787 twenty miles below the dam at Lake Livingston and fifty miles above the Trinity River outlet at Galveston Bay.

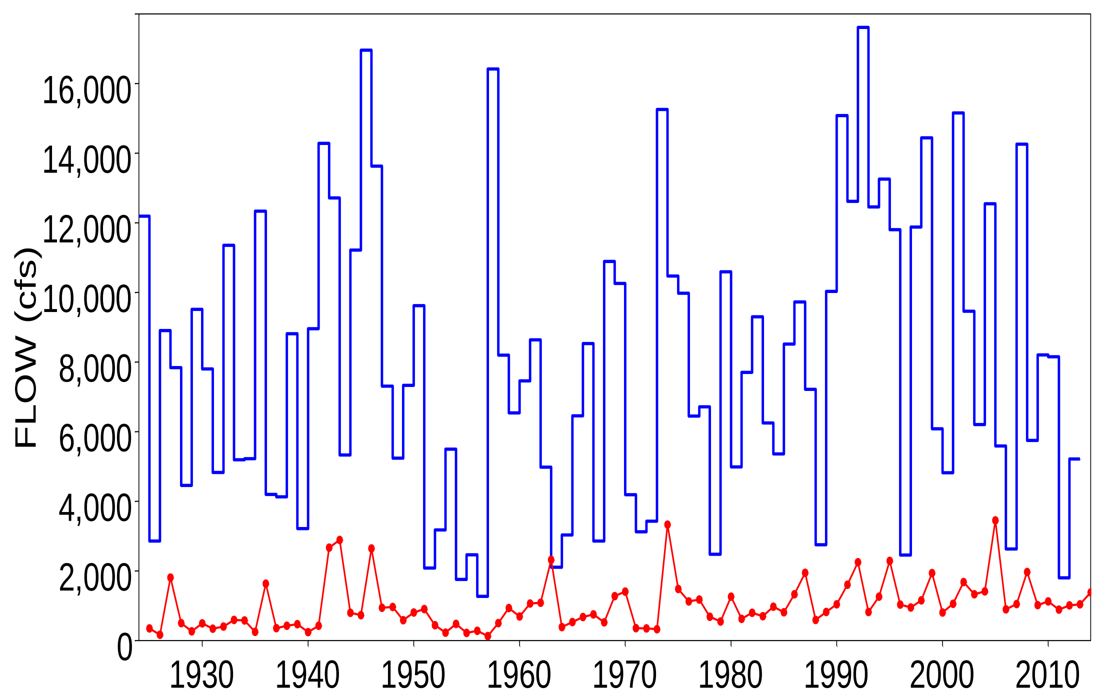
Period-of-record of daily flows: 1924/5/01 to present (2013/6/1)



Daily Flows of Trinity River at Romayor



Monthly Flows of Trinity River at Romayor



Annual Flows and the Minimum Monthly Flow Each Year

27
Neches River near Rockland

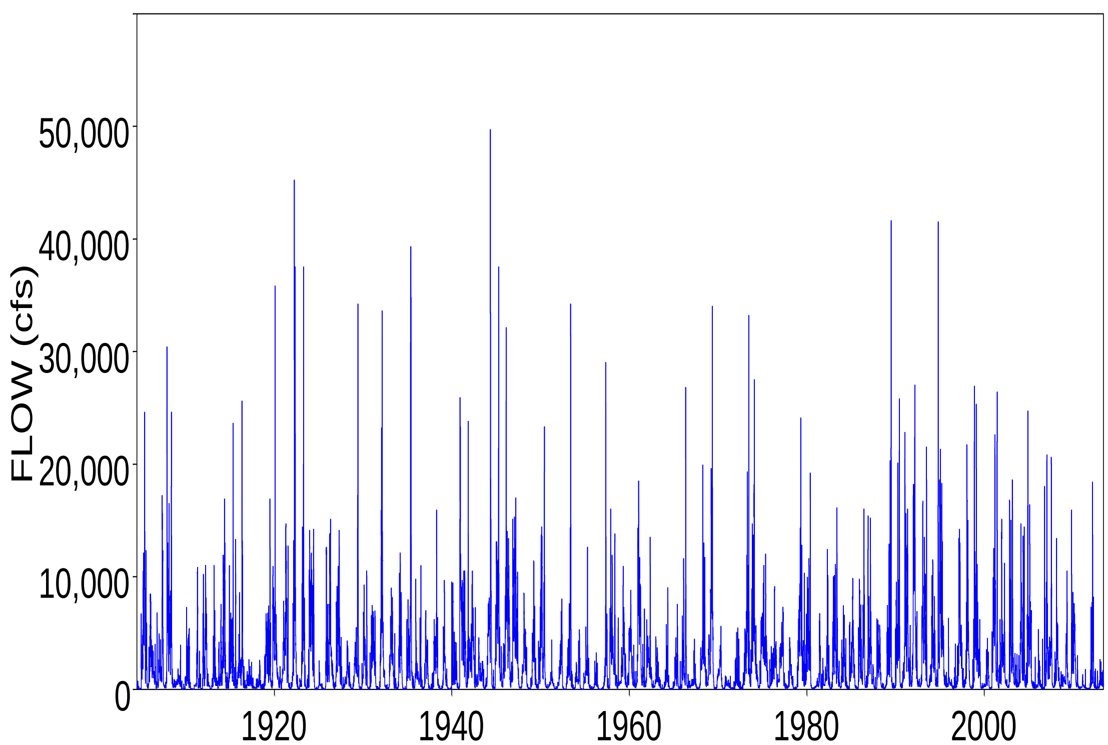
USGS 08033500
Tyler County, Texas

Drainage area 3,636 square miles
Contributing drainage area 3,636 square miles

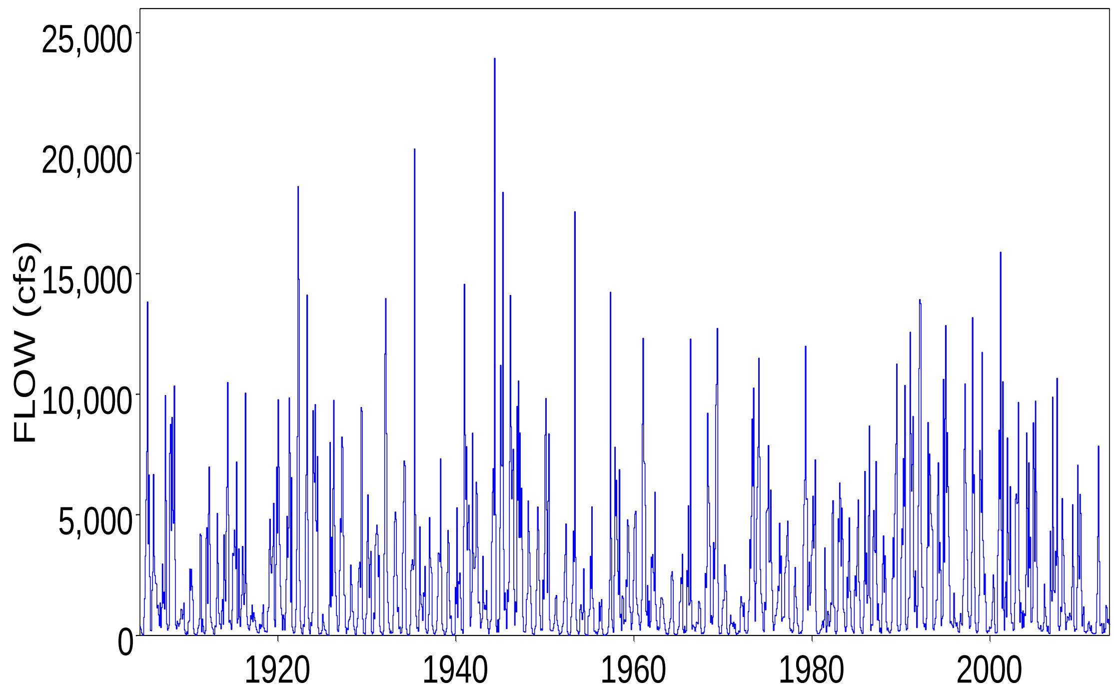
Latitude 31°01'30", Longitude 94°23'58" NAD83
Gage datum 88.41 feet above NGVD29

The gage is at Hwy 69 20 miles upstream of confluence of Angelina River with Neches River.

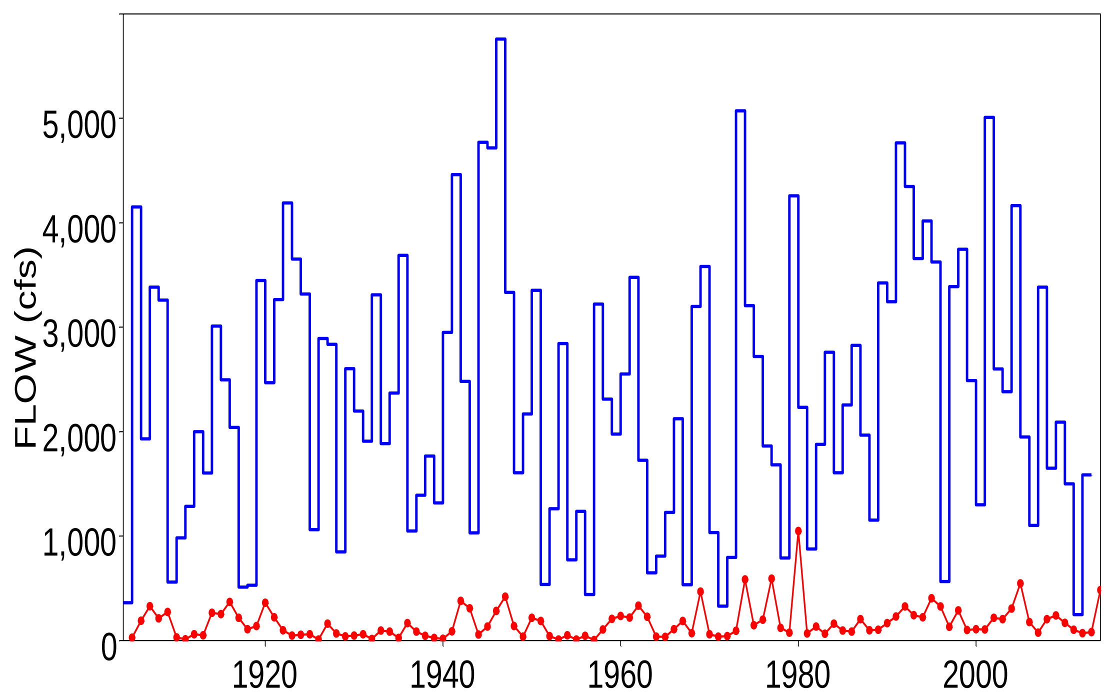
Period-of-record of daily flows: 1904/7/01 to present (2013/6/1)



Daily Flows of Neches River near Rockland



Monthly Flows of Neches River near Rockland



Annual Flows and the Minimum Monthly Flow Each Year

28
Neches River near Evansdale

USGS 08041000
Jasper County, Texas

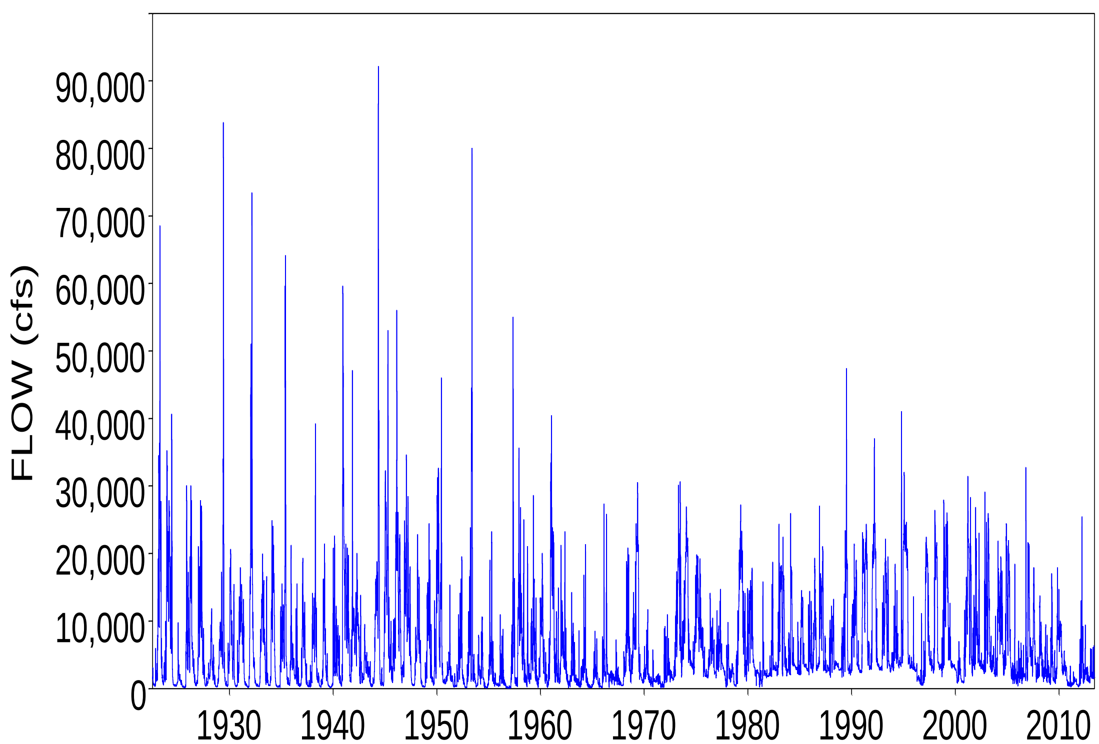
Drainage area 7,951 square miles
Contributing drainage area 7,951 square miles

Latitude 30°21'20", Longitude 94°05'35" NAD27
Gage datum 8.25 feet above NGVD29

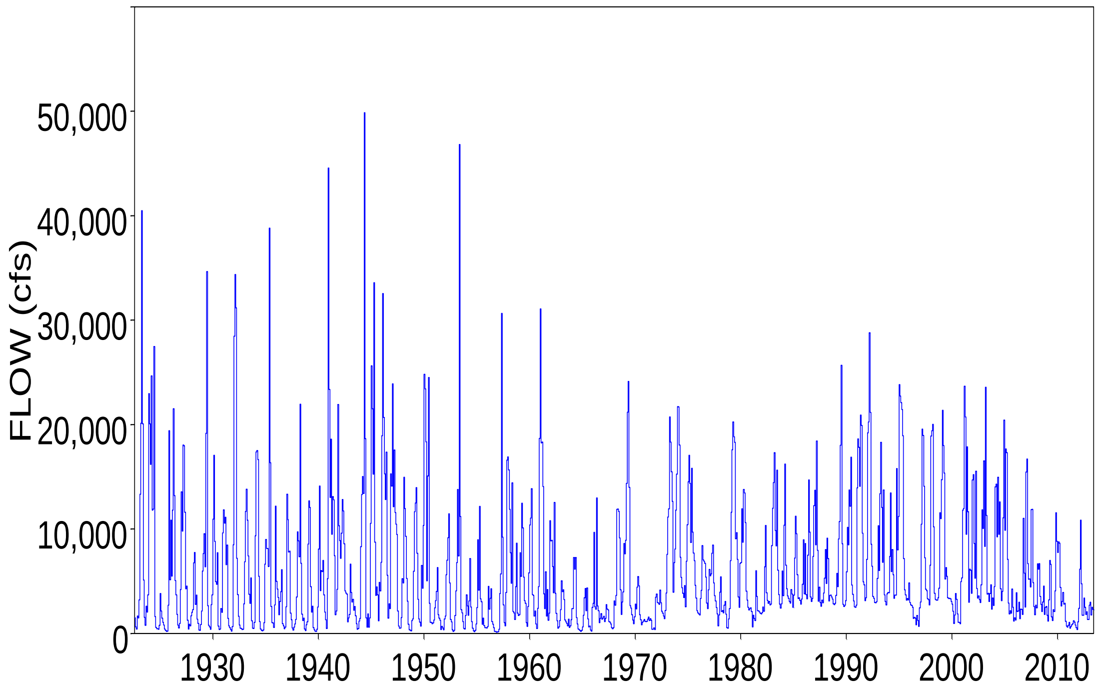
This gage is at Hwy 96 twenty-five miles upstream of IH 10 in Beaumont.

A maximum allowable non-flooding discharge of 20,000 cfs at this gage site is designated by the Corps of Engineers for purposes of reservoir flood control operations of the federal multiple-purpose Sam Rayburn Reservoir located upstream on the Angelina River.

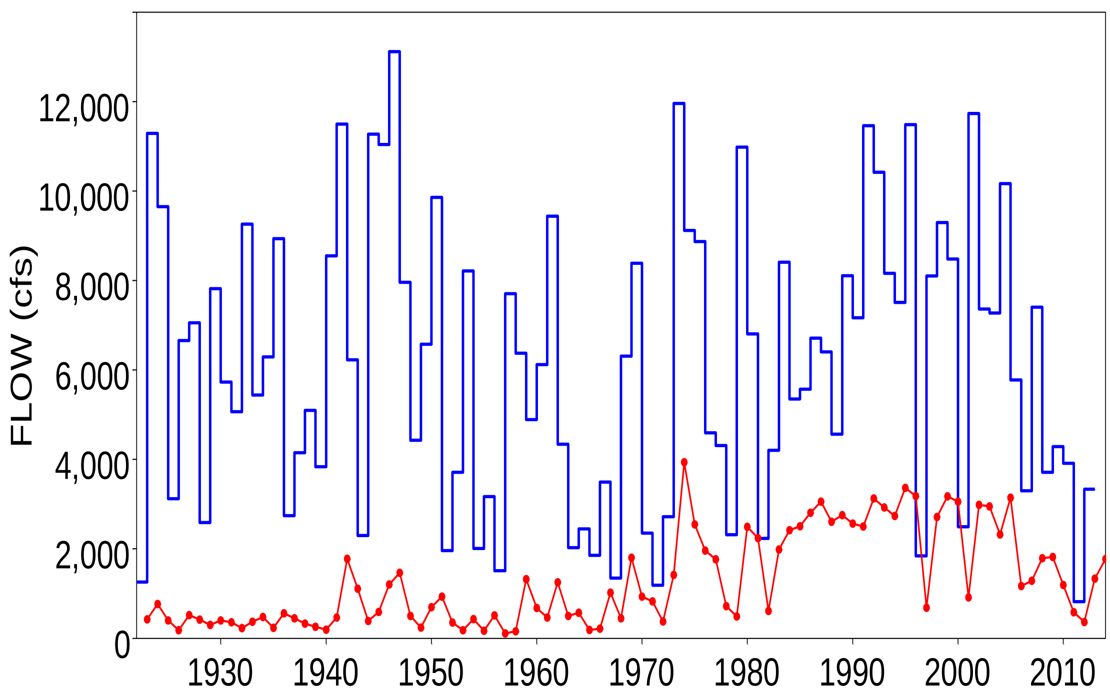
Period-of-record of daily flows: 1922/8/01 to present (2013/6/1)



Daily Flows of Neches River near Evansdale



Monthly Flows of Neches River near Evansdale



Annual Flows and the Minimum Monthly Flow Each Year

29
Sabine River near Beckville

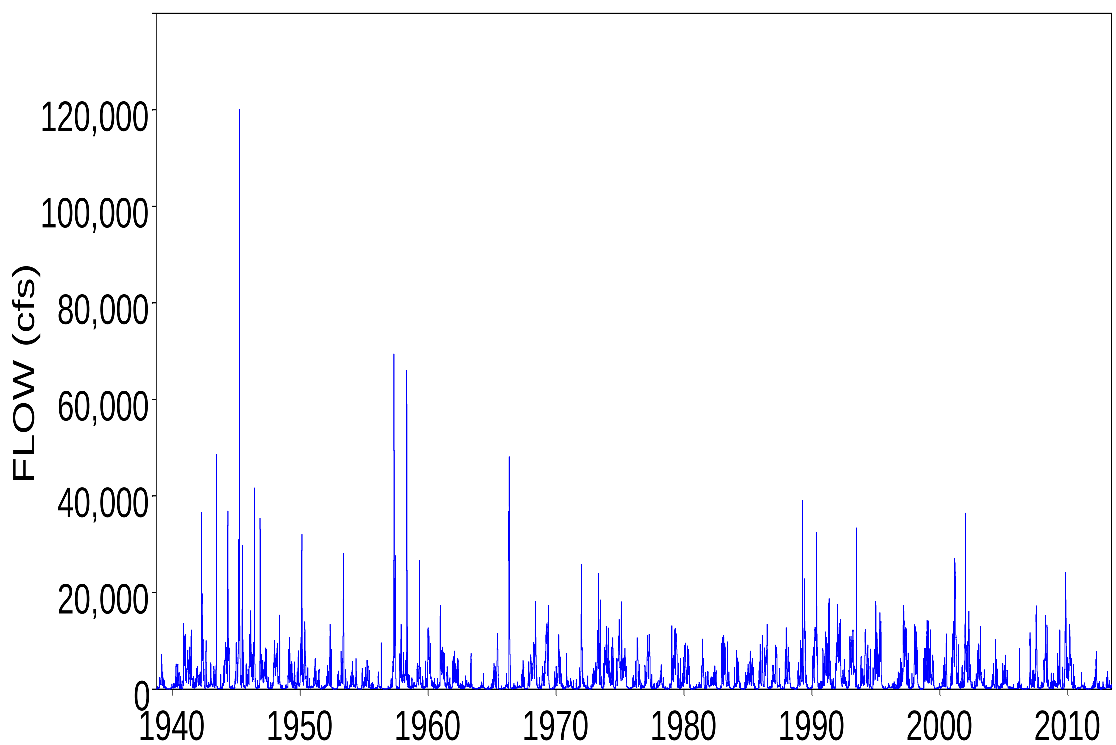
USGS 8022040
Panola County, Texas

Drainage area 3,589 square miles
Contributing drainage area 3,589 square miles

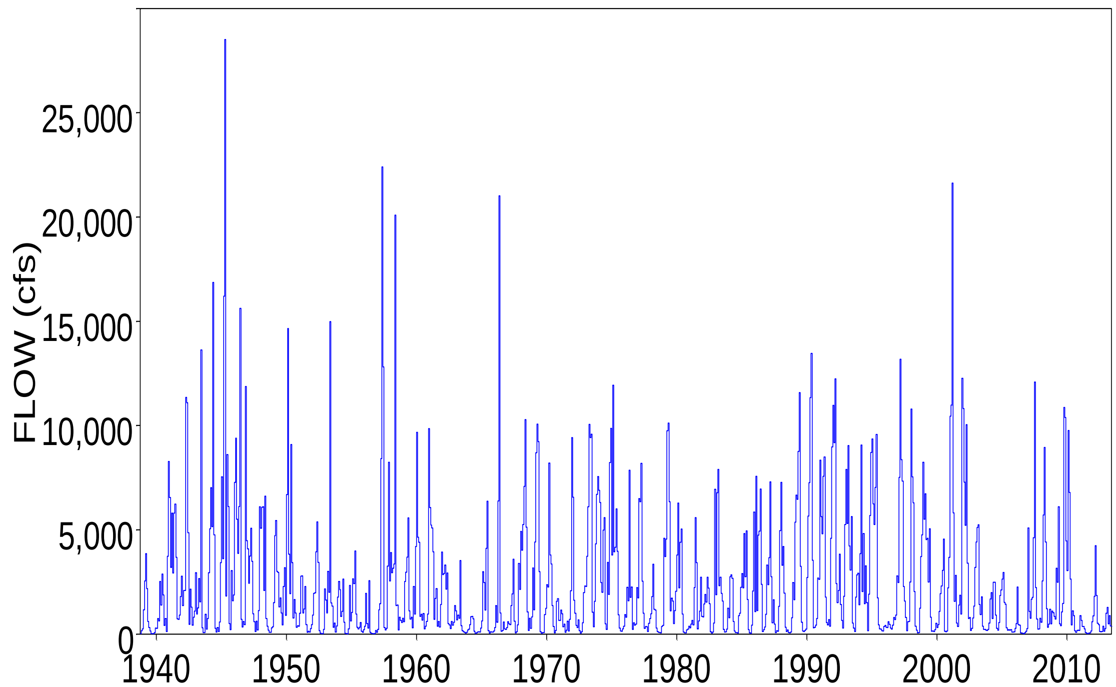
Latitude 32°19'38", Longitude 94°21'12" NAD27
Gage datum 190 feet above NGVD29

The gage is at Hwy 59 about 20 miles downstream of IH 20.

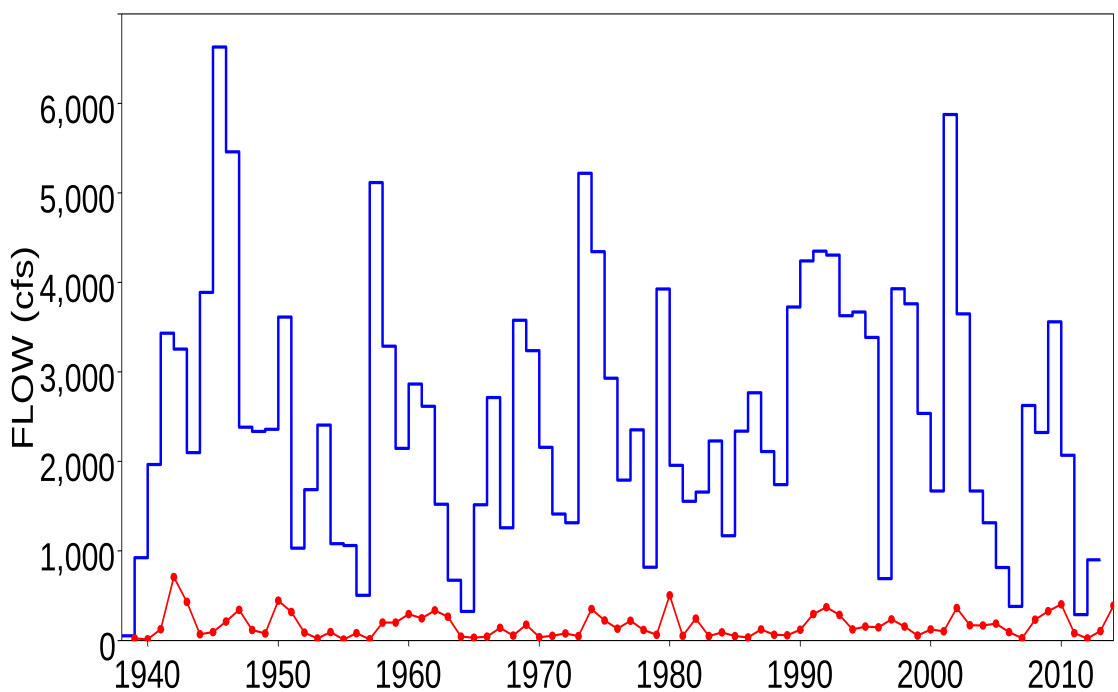
Period-of-record of daily flows: 1938/10/01 to present (2013/6/1)



Daily Flows of Sabine River near Beckville



Monthly Flows of Sabine River near Beckville



Annual Flows and the Minimum Monthly Flow Each Year

30
Sabine River near Ruliff

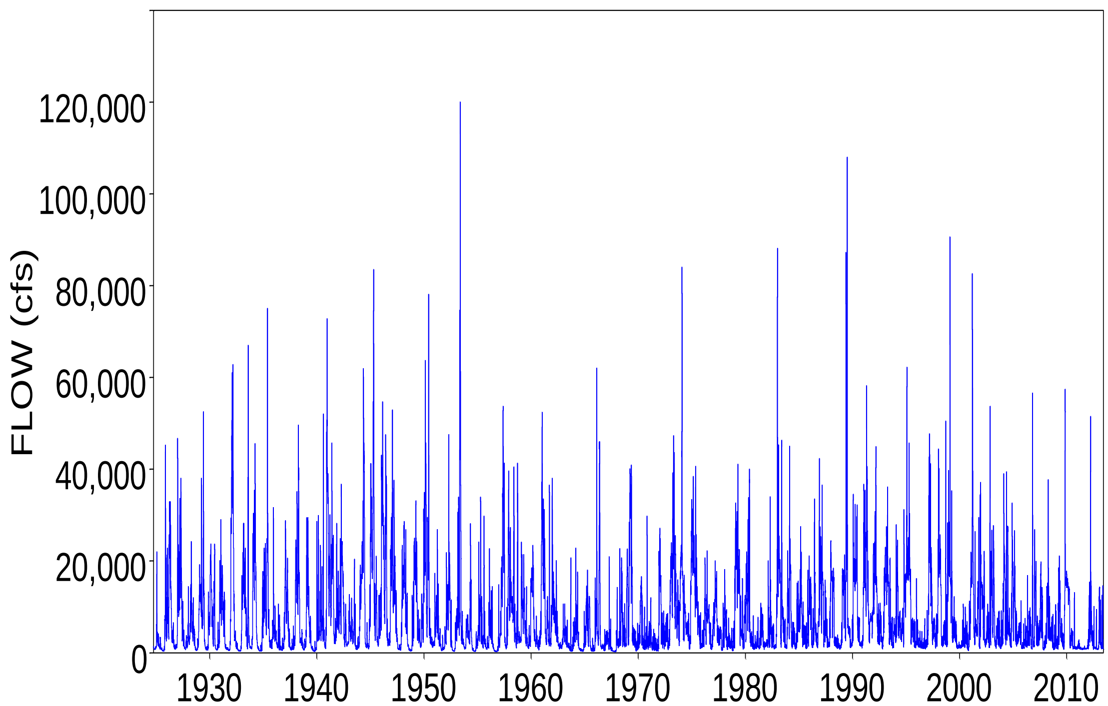
USGS 8030500
Newton County, Texas

Drainage area 9,329 square miles
Contributing drainage area 9,329 square miles

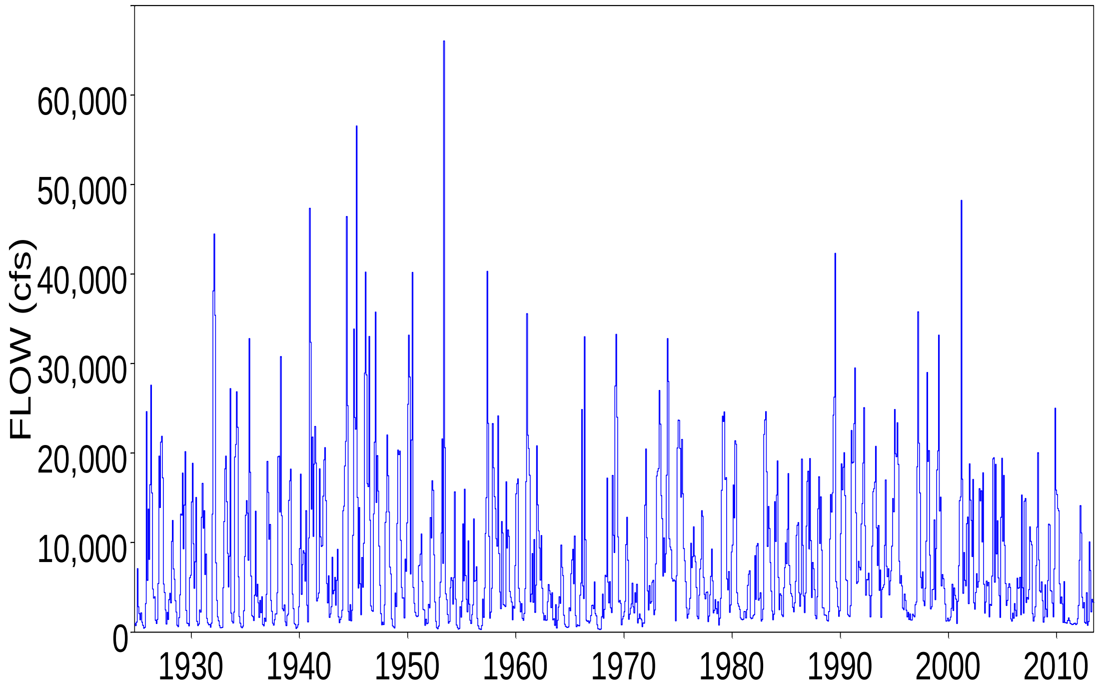
Latitude 30°18'13", Longitude 93°44'37" NAD27
Gage datum -5.92 feet above NGVD29

The gage is at Hwy 12 about 12 miles upstream if IH 10 which connects Beaumont and Lake Charles.

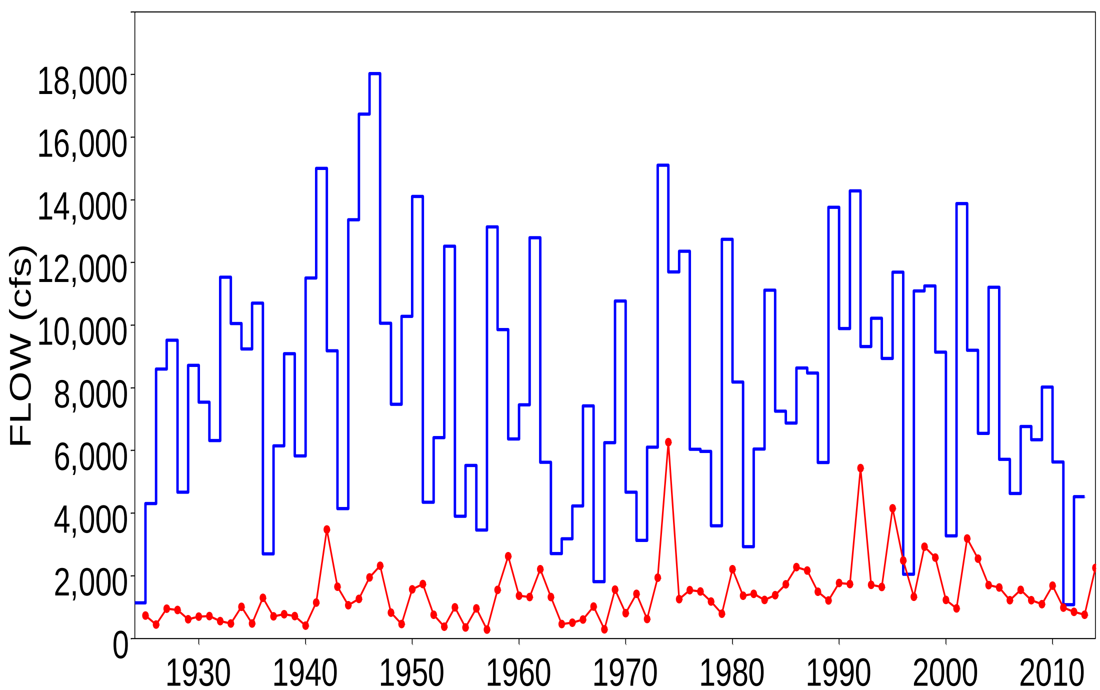
Period-of-record of daily flows: 1924/10/01 to present (2013/6/1)



Daily Flows of Sabine River near Ruliff



Monthly Flows of Sabine River near Ruliff



Annual Flows and the Minimum Monthly Flow Each Year

31
Big Cypress Bayou near Jefferson

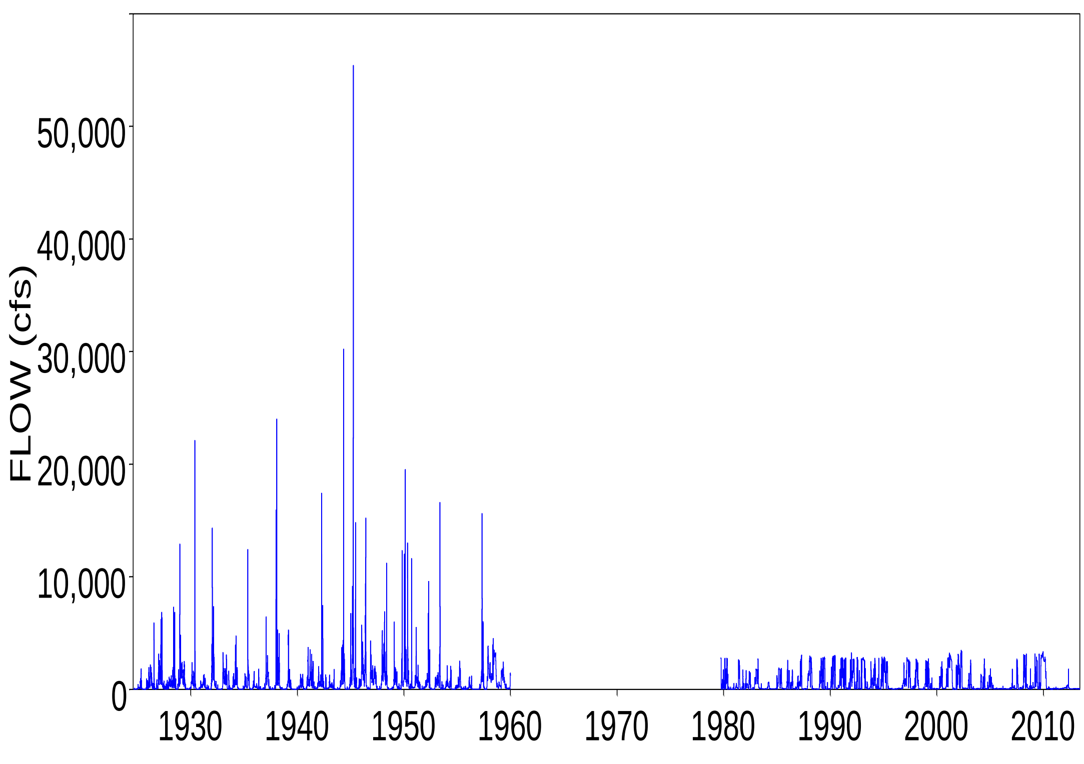
USGS 07346000
Marion County, Texas

Drainage area 850 square miles
Contributing drainage area 850 square miles

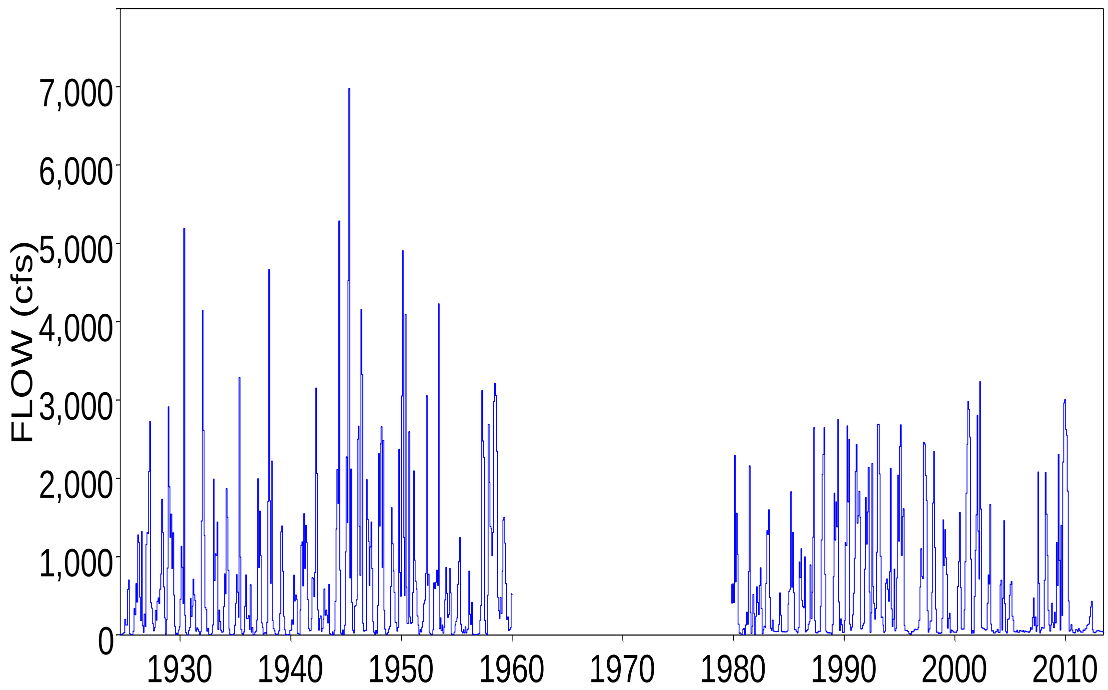
Latitude 32°44'58", Longitude 94°29'55" NAD27
Gage datum 180.00 feet above NGVD29

The gage is below the dam at Lake O the Pines. FM 726 is on the dam. The gage is about thirty miles upstream of the Louisiana border which crosses Caddo Lake.

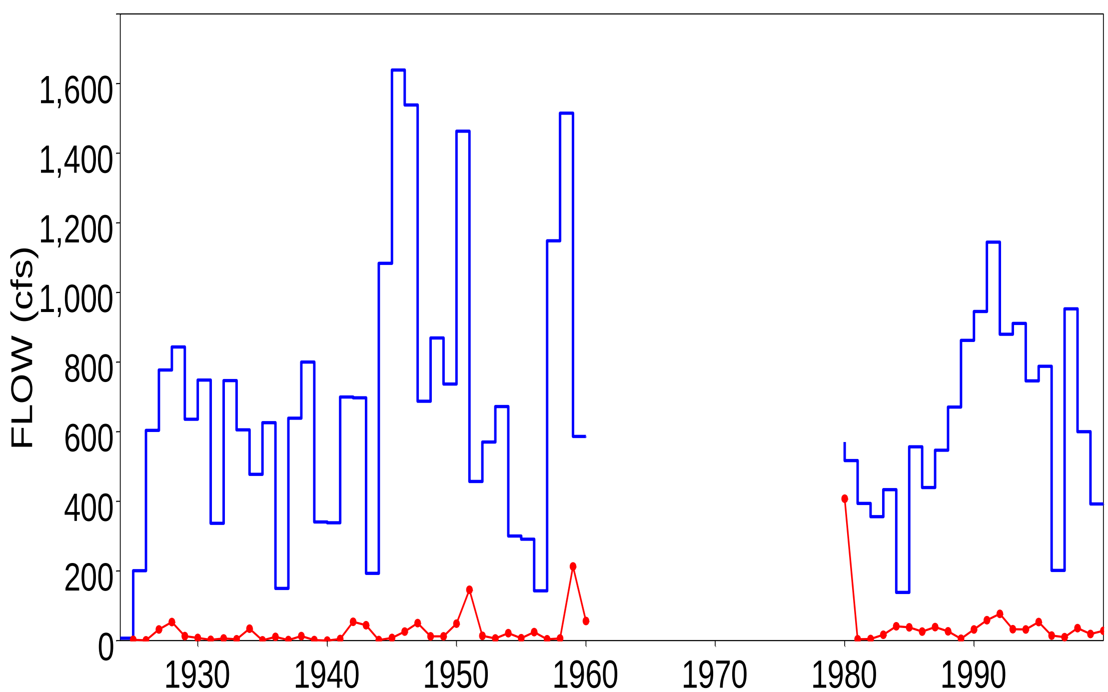
Period-of-record of daily flows: 1924/8/01 to present (2013/6/1)



Daily Flows of Big Cypress Bayou near Jefferson



Monthly Flows of Big Cypress Bayou near Jefferson



Annual Flows and the Minimum Monthly Flow Each Year

32

Red River near Terrel, Oklahoma

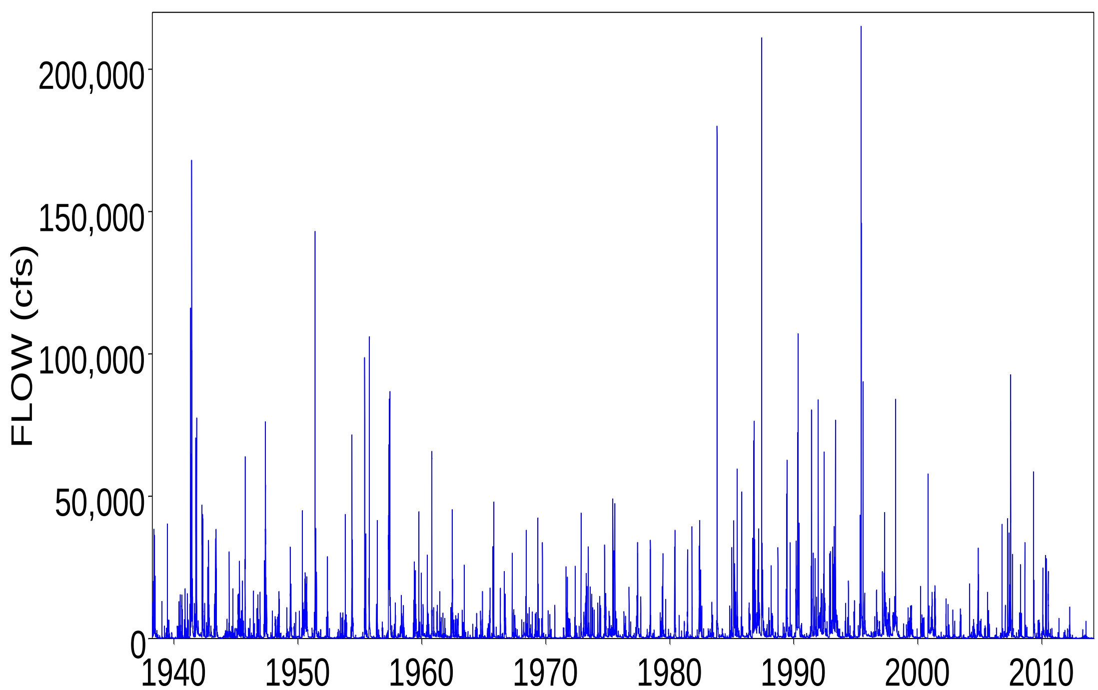
USGS 07315500
Jefferson County, Oklahoma

Drainage area 28,723 square miles
Contributing drainage area 22,787 square miles

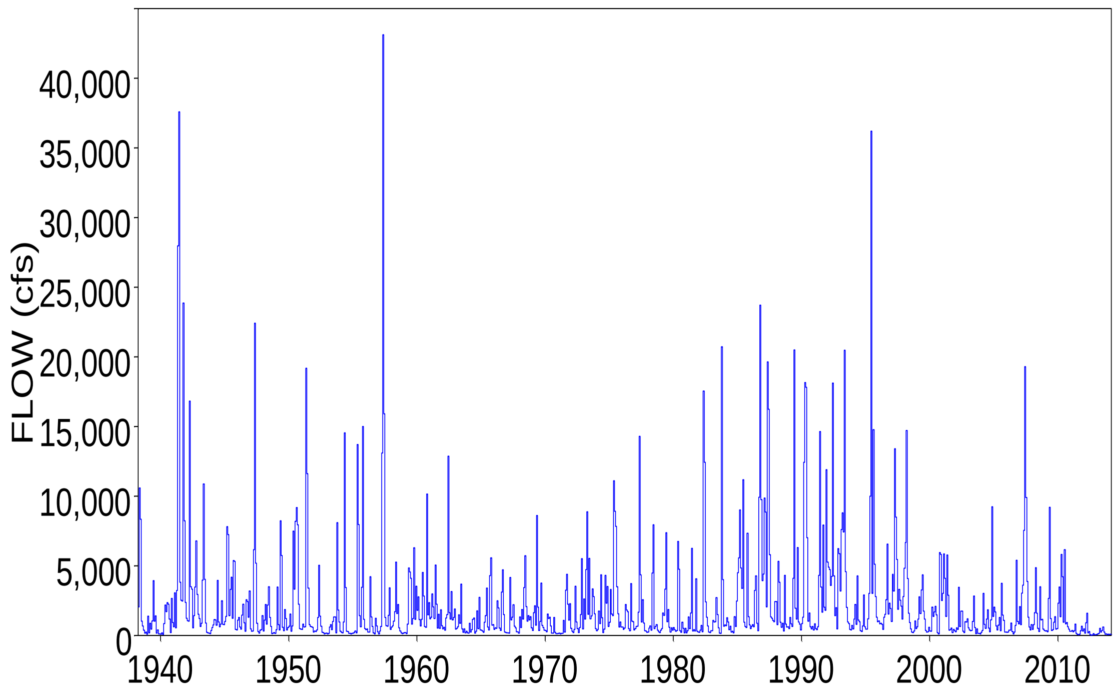
Latitude 33°52'43", Longitude 97°56'03" NAD27
Gage datum 770.31 feet above NGVD29

The gage is at Hwy 81 thirty miles east of the city of Wichita Falls.

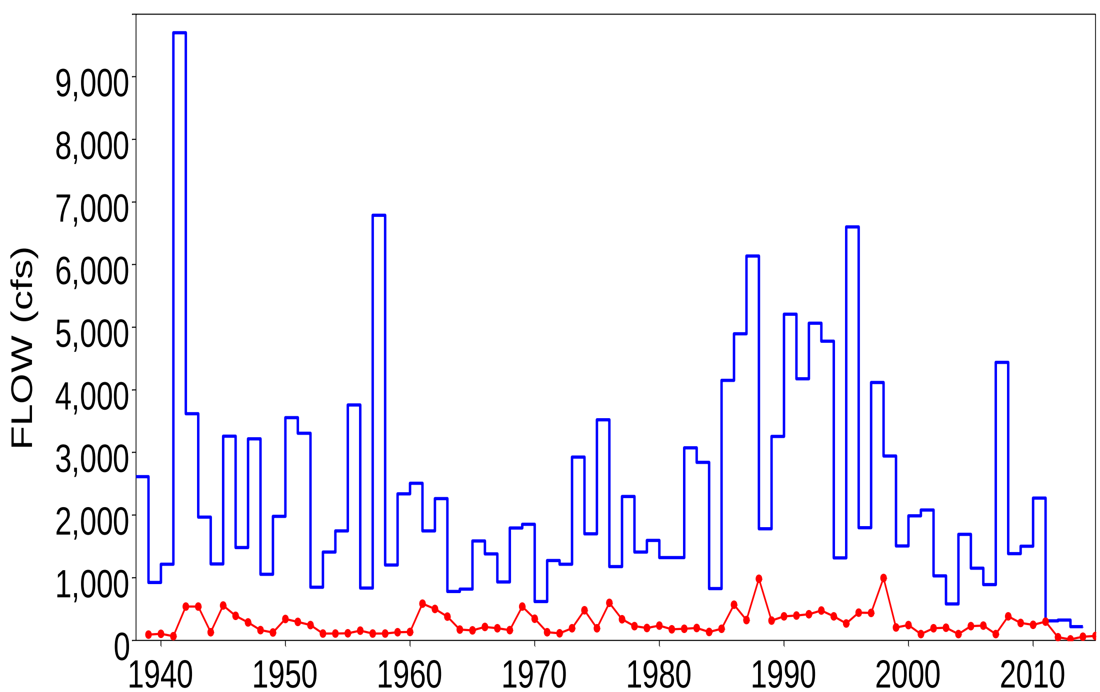
Period-of-record of daily flows: 1938/4/01 to present (2014/3/9)



Daily Flows of Red River near Terrel



Monthly Flows of Red River near Terrel



Annual Flows and the Minimum Monthly Flow Each Year

33
Red River at Arthur City

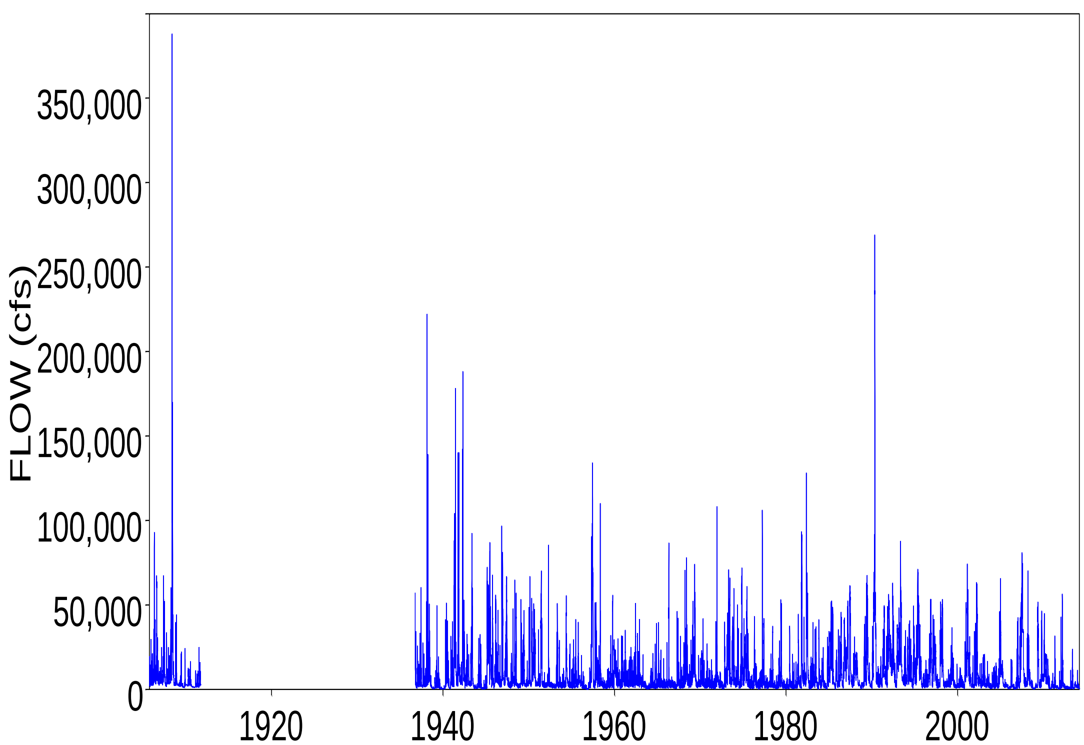
USGS 07335500
Choctaw County, Oklahoma

Drainage area 44,445 square miles
Contributing drainage area 36,517 square miles

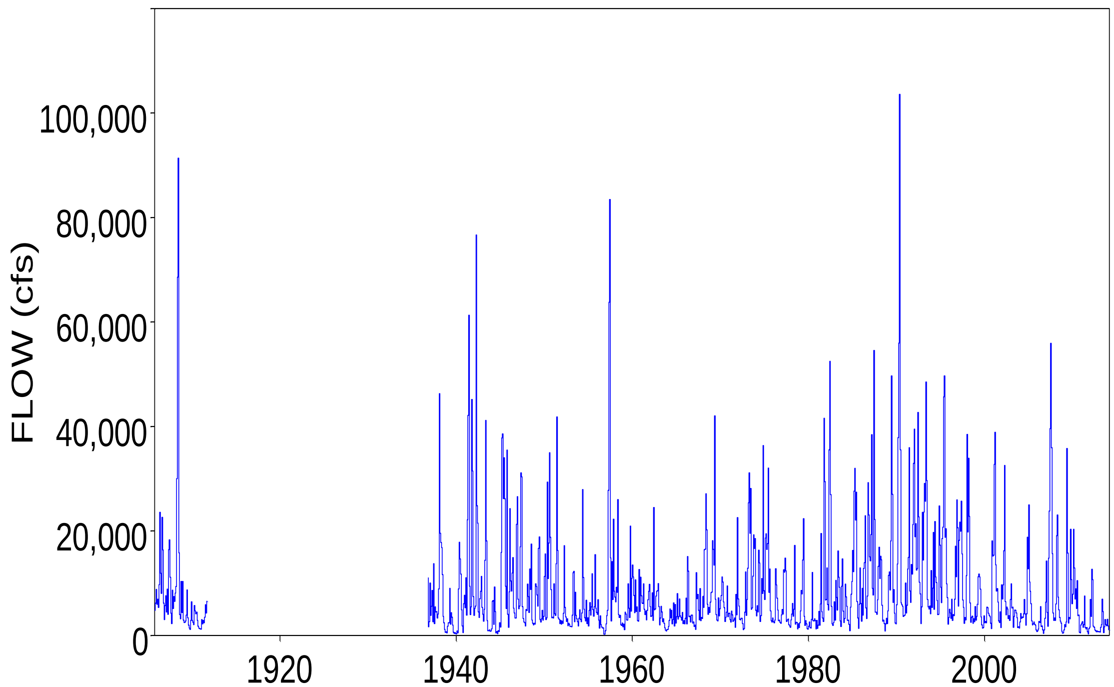
Latitude 33°52'30", Longitude 95°30'06" NAD27
Gage datum 375.07 feet above NGVD29

The gage is at Hwy 271 about 15 miles north of Paris and 60 miles upstream of the Oklahoma border.

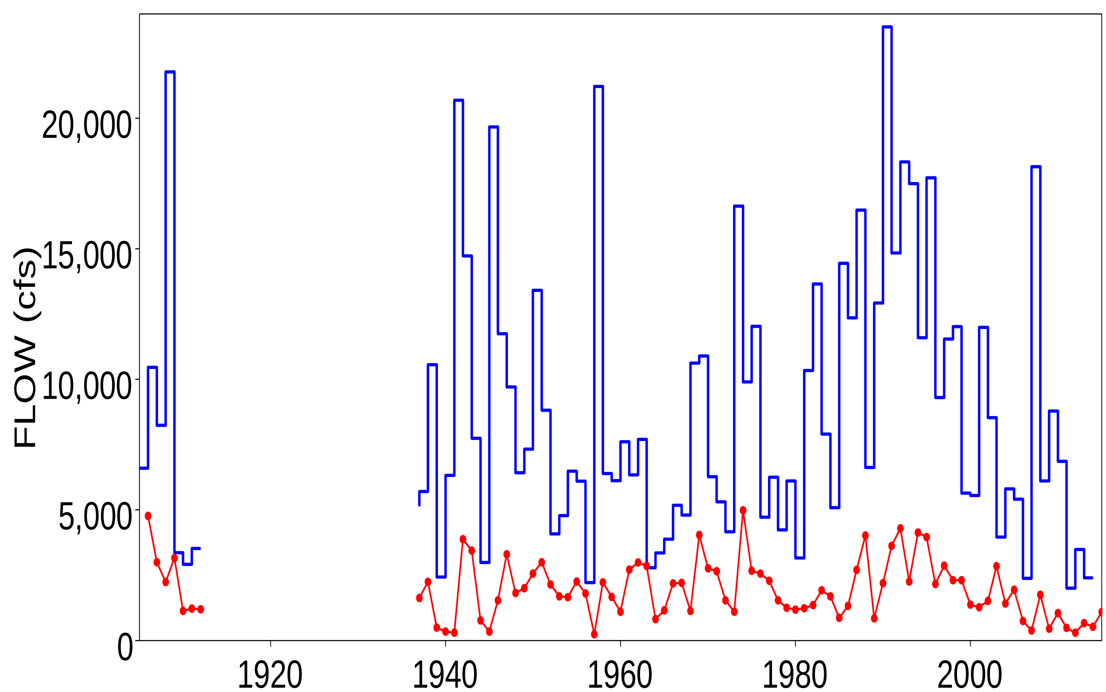
Period-of-record of daily flows: 1905/10/01 to present (2014/3/10)



Daily Flows of Red River at Arthur City



Monthly Flows of Red River at Arthur City



Annual Flows and the Minimum Monthly Flow Each Year

34
Canadian River near Amarillo

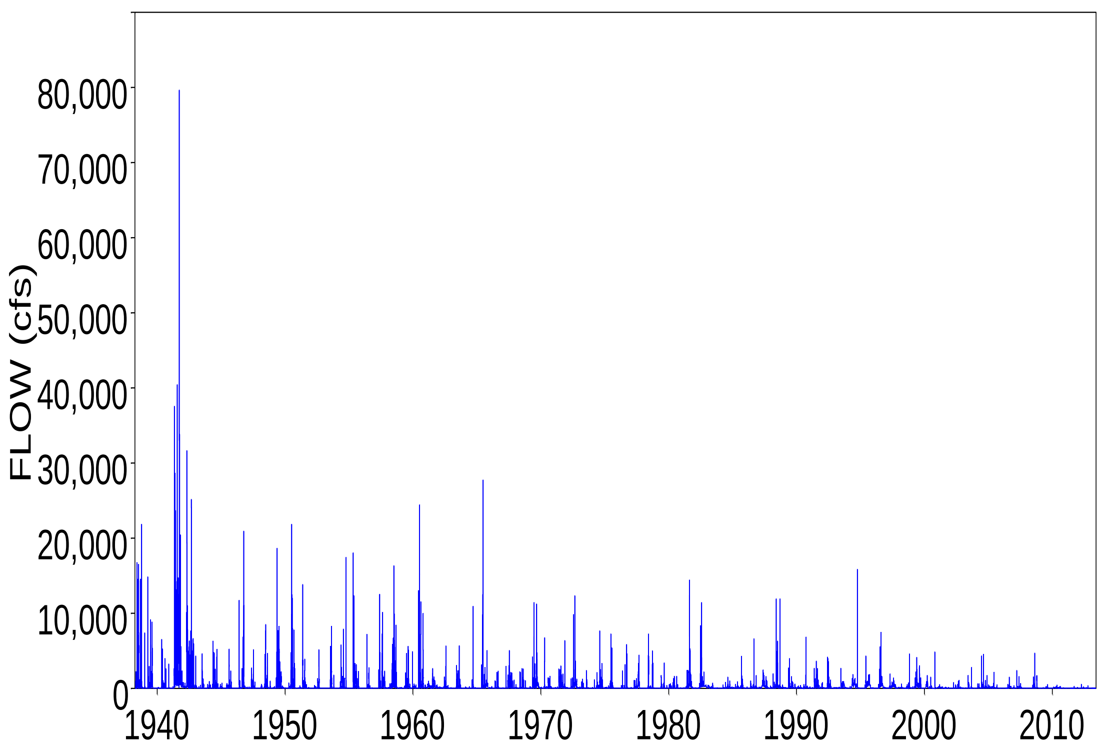
USGS 07227500
Potter County, Texas

Drainage area 19,445 square miles
Contributing drainage area 15,376 square miles

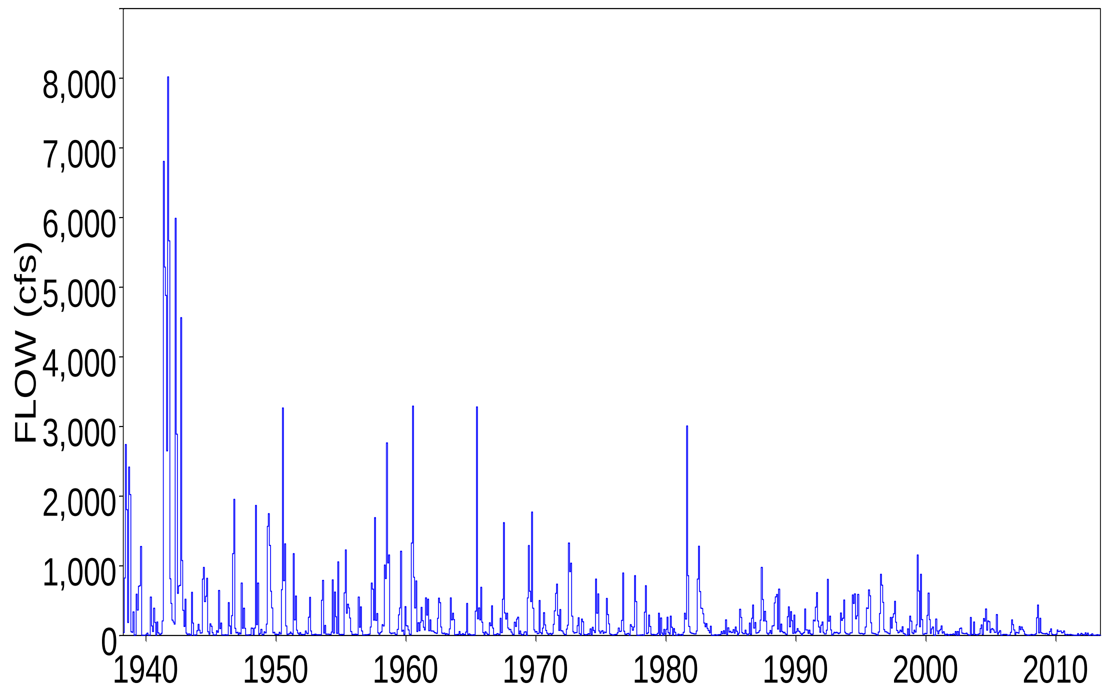
Latitude 35°28'13", Longitude 101°52'45" NAD27
Gage datum 2,989.16 feet above NGVD29

The gage is at Hwy 287 about 30 miles upstream of the dam of Lake Meredith and 80 miles downstream of the New Mexico border.

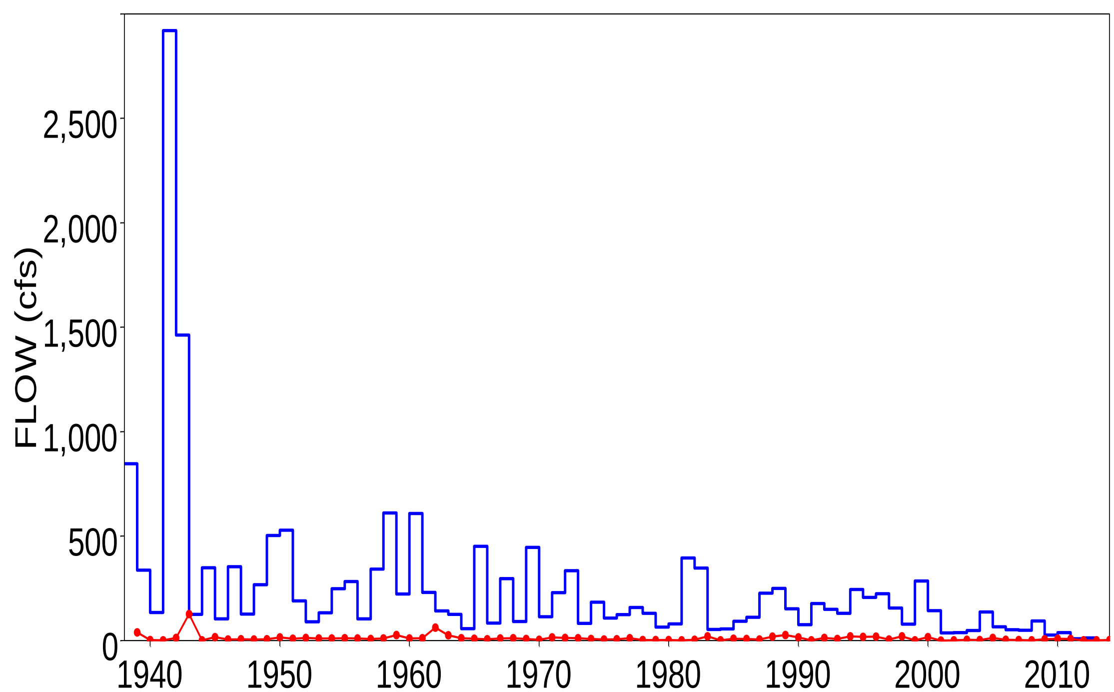
Period-of-record of daily flows: 1938/4/01 to present (2013/6/1)



Daily Flows of Canadian River near Amarillo



Monthly Flows of Canadian River near Amarillo



Annual Flows and the Minimum Monthly Flow Each Year

35
Canadian River near Canadian

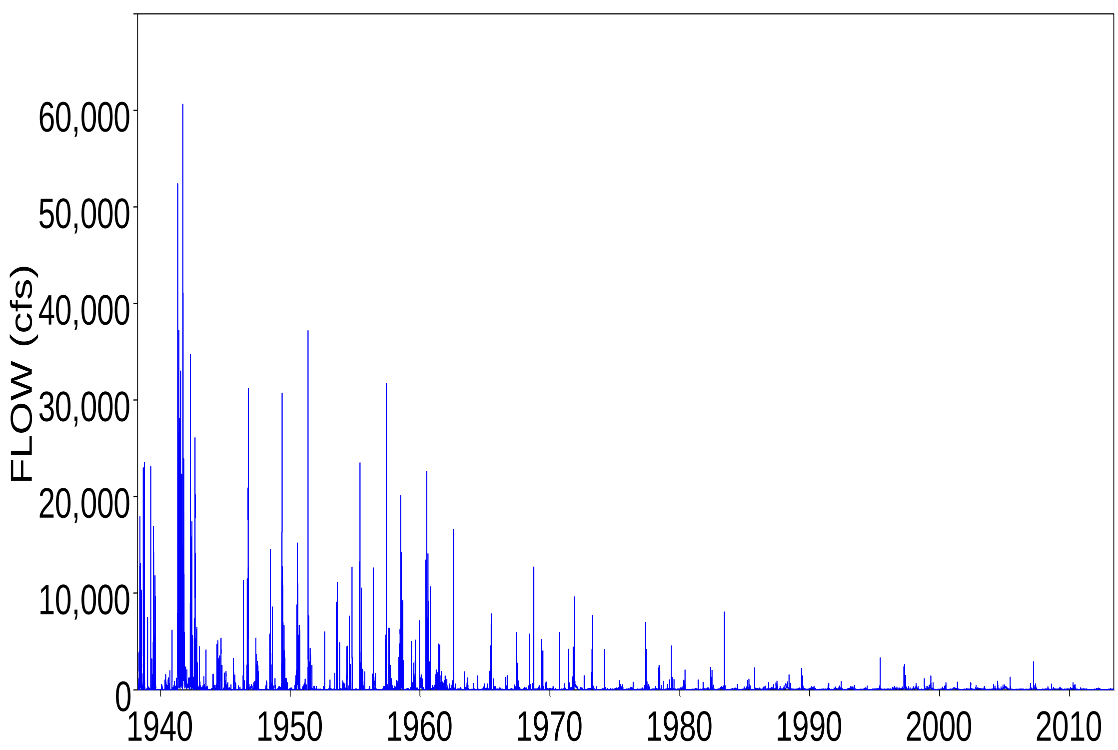
USGS 07228000
Hemphill County, Texas

Drainage area 22,866 square miles
Contributing drainage area 18,178 square miles

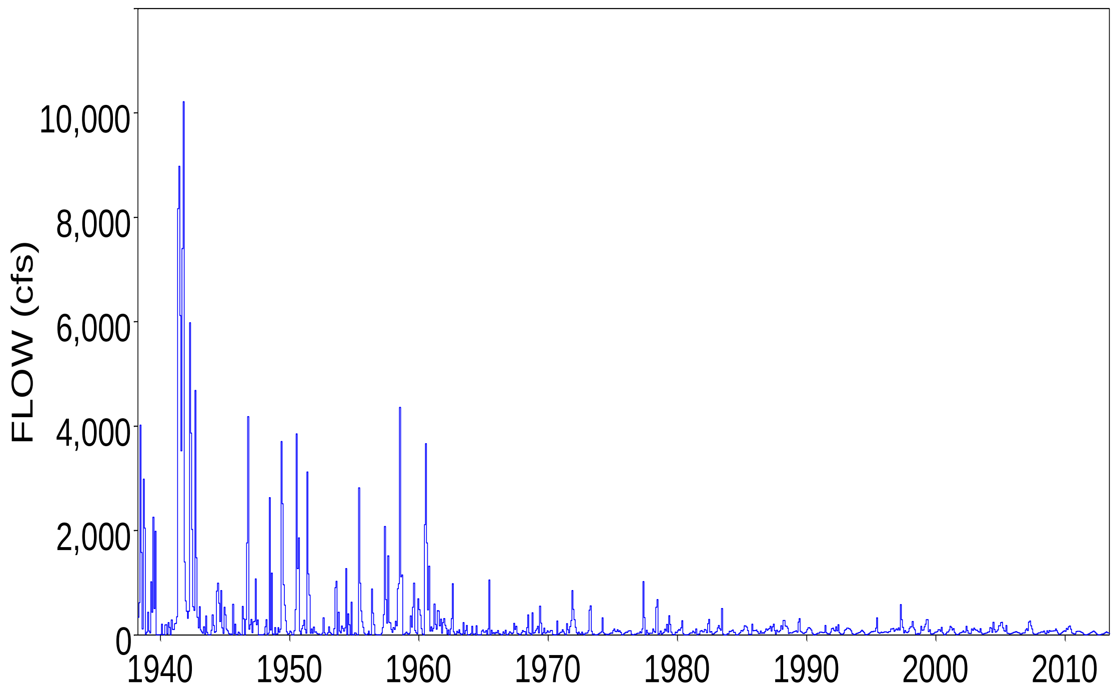
Latitude 35°56'06", Longitude 100°22'13" NAD27
Gage datum 2,301.50 feet above NGVD29

The gage is at Hwy 60 about 70 miles downstream of Lake Meredith and 20 miles upstream of the Oklahoma border.

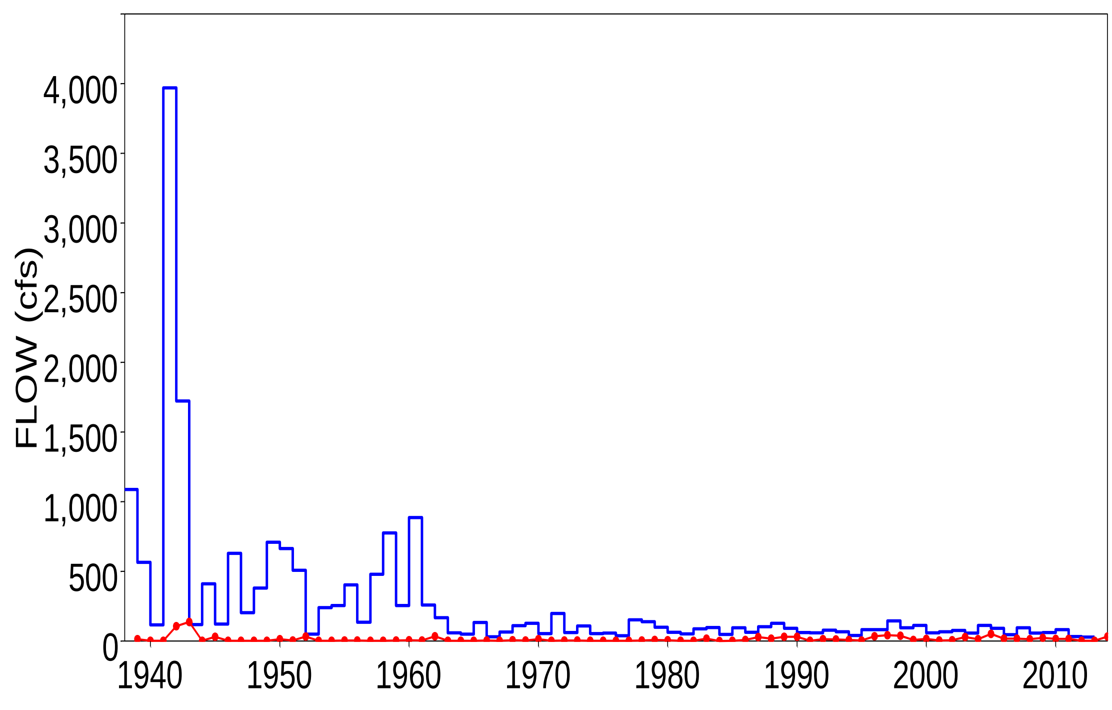
Period-of-record of daily flows: 1938/4/01 to present (2013/6/1)



Daily Flows of Canadian River near Canadian



Monthly Flows of Canadian River near Canadian

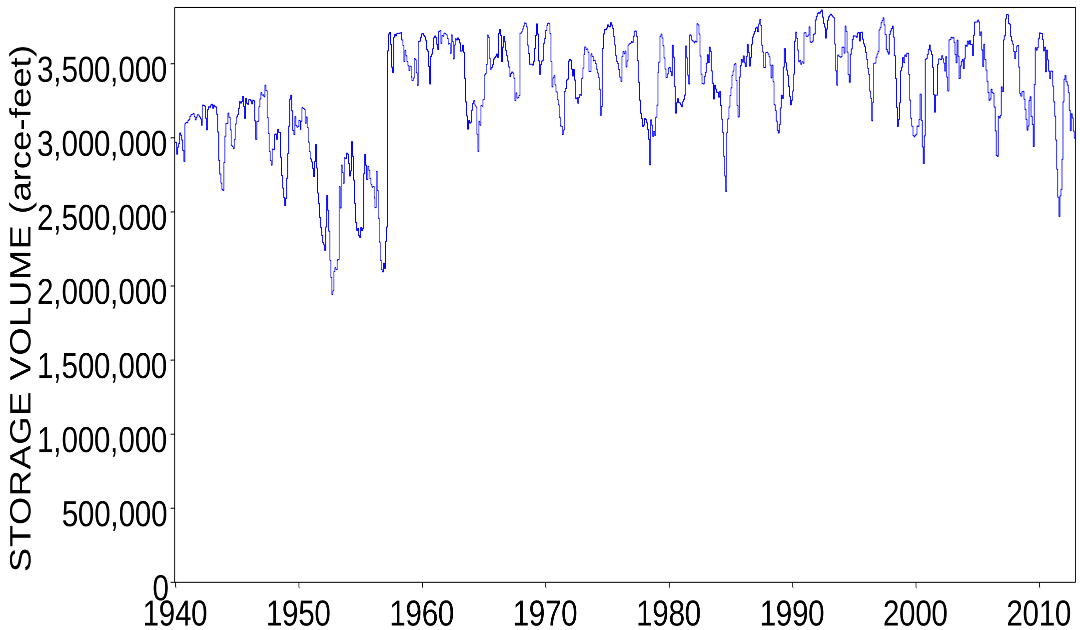


Annual Flows and the Minimum Monthly Flow Each Year

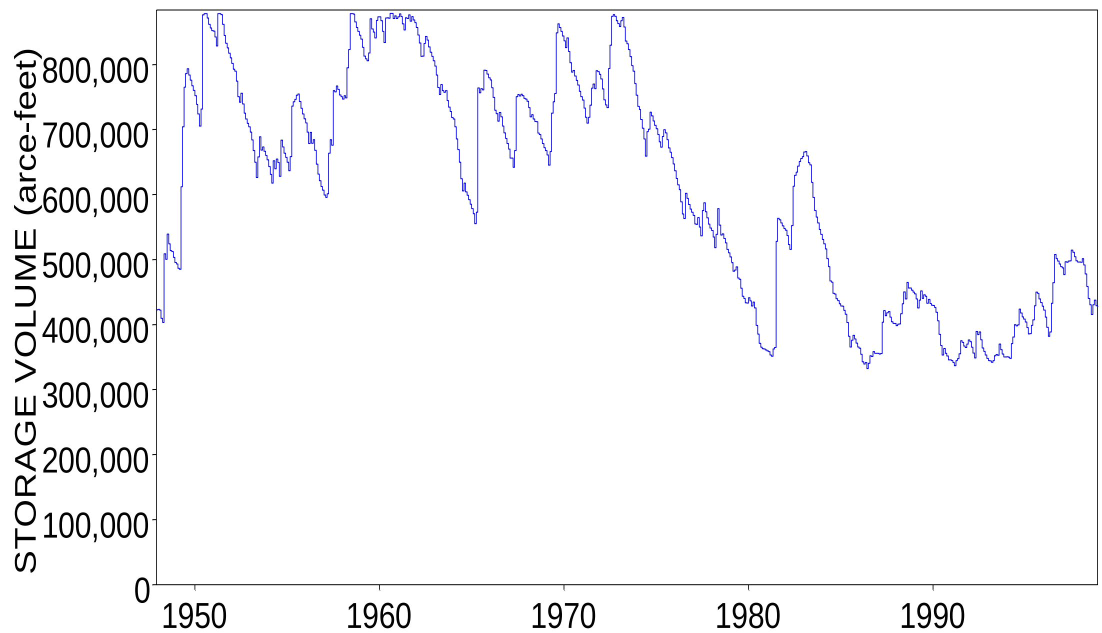
APPENDIX D

PLOTS OF SIMULATED MONTHLY RESERVOIR STORAGE VOLUMES

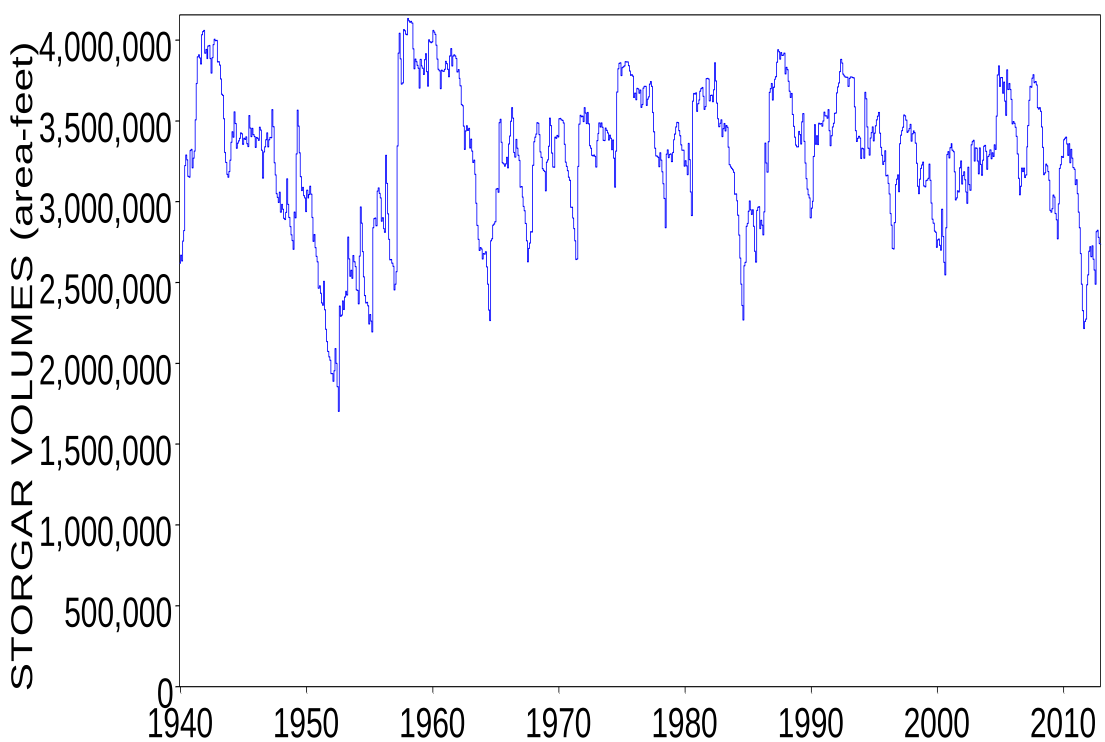
FOR 19 WAMS AS DISCUSSED IN CHAPTER 5



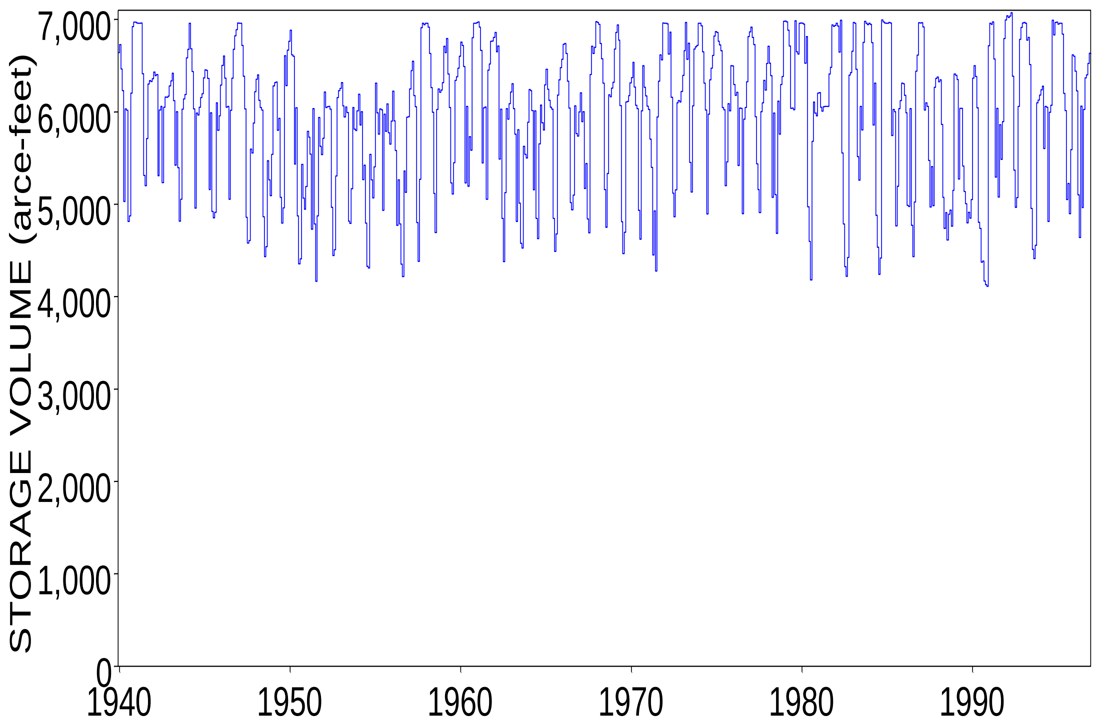
Total Storage all Reservoirs in the Brazos River Basin



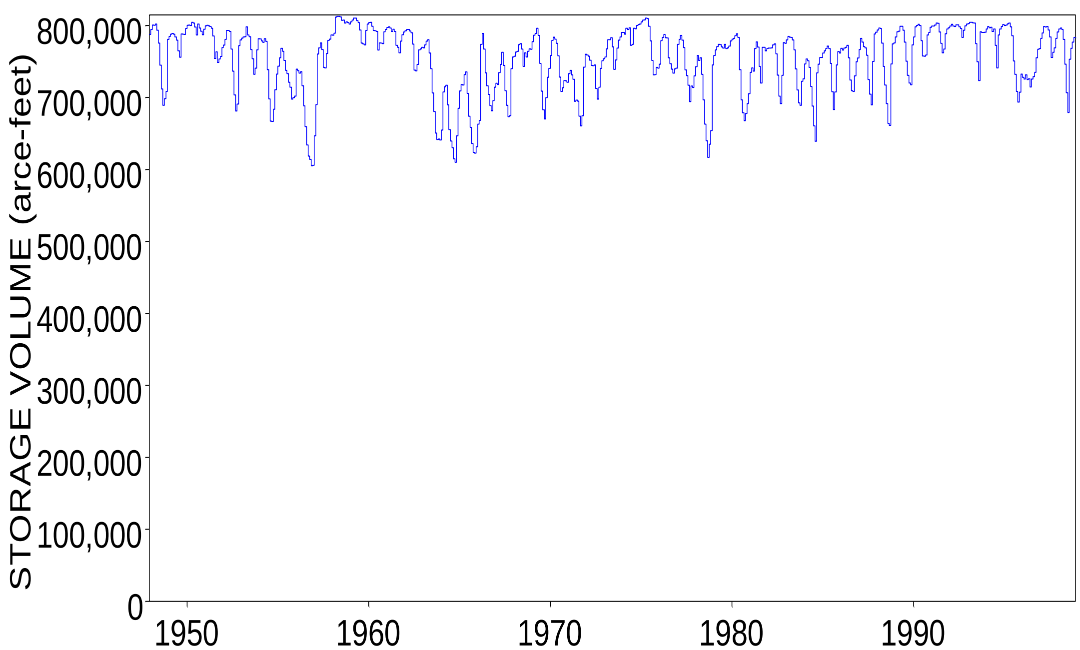
Total Storage all Reservoirs in the Canadian River Basin



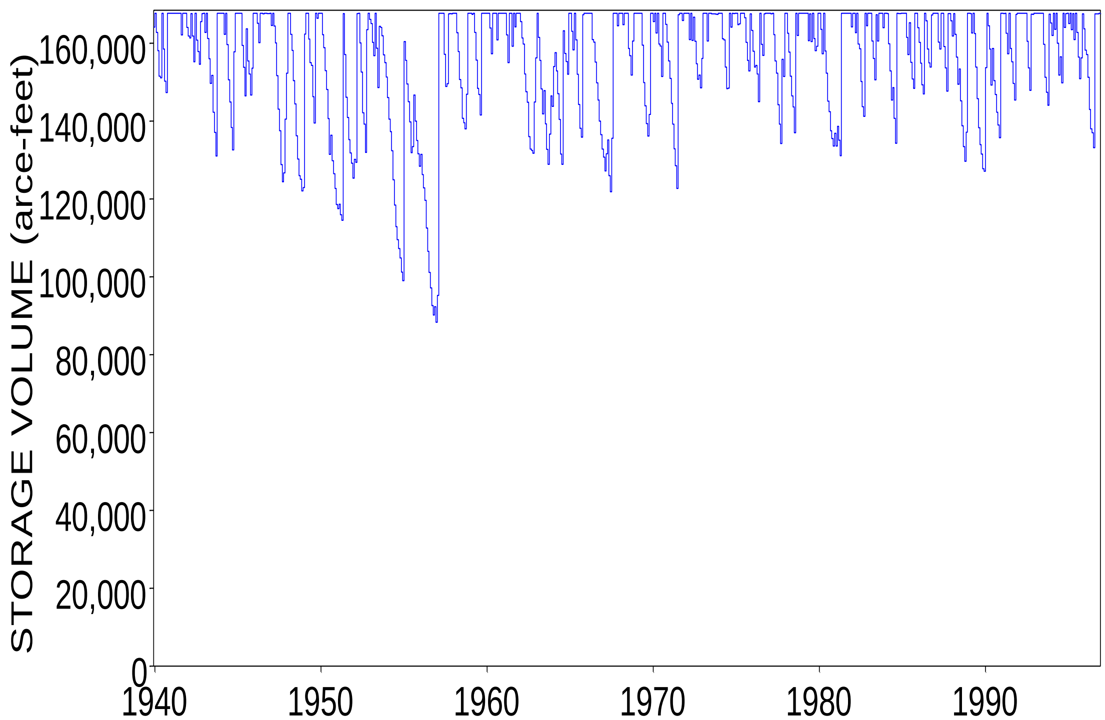
Total Storage all Reservoirs in the Colorado and Brazos-Colorado Coastal Basin



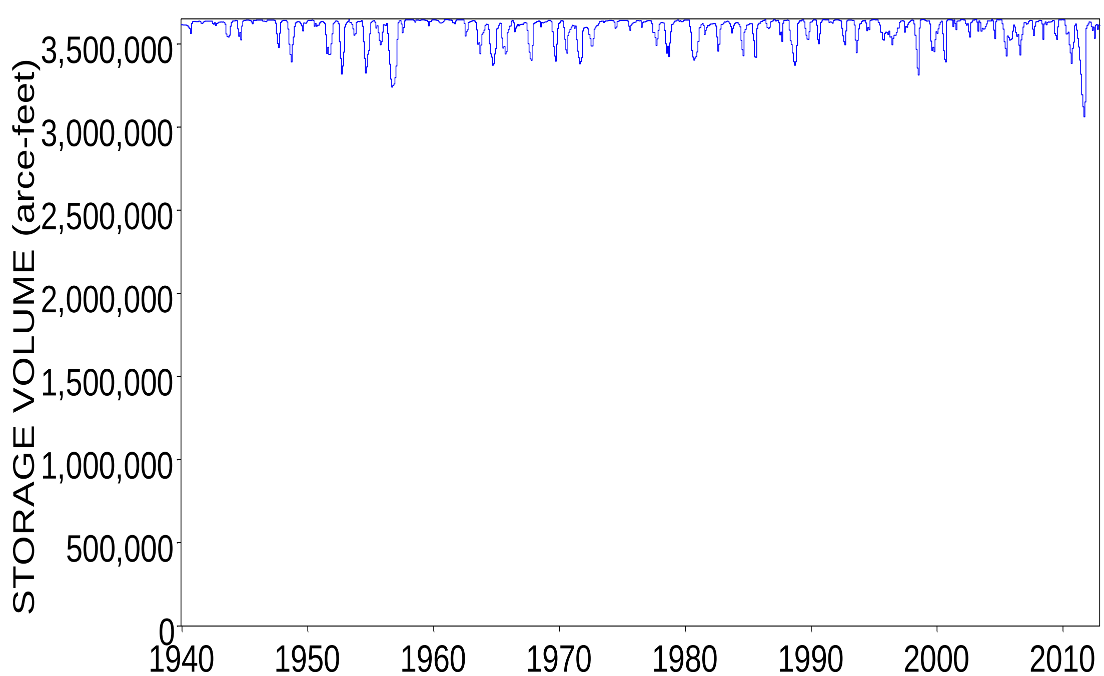
Total Storage all Reservoirs in the Colorado-Lavaca Coastal Basin



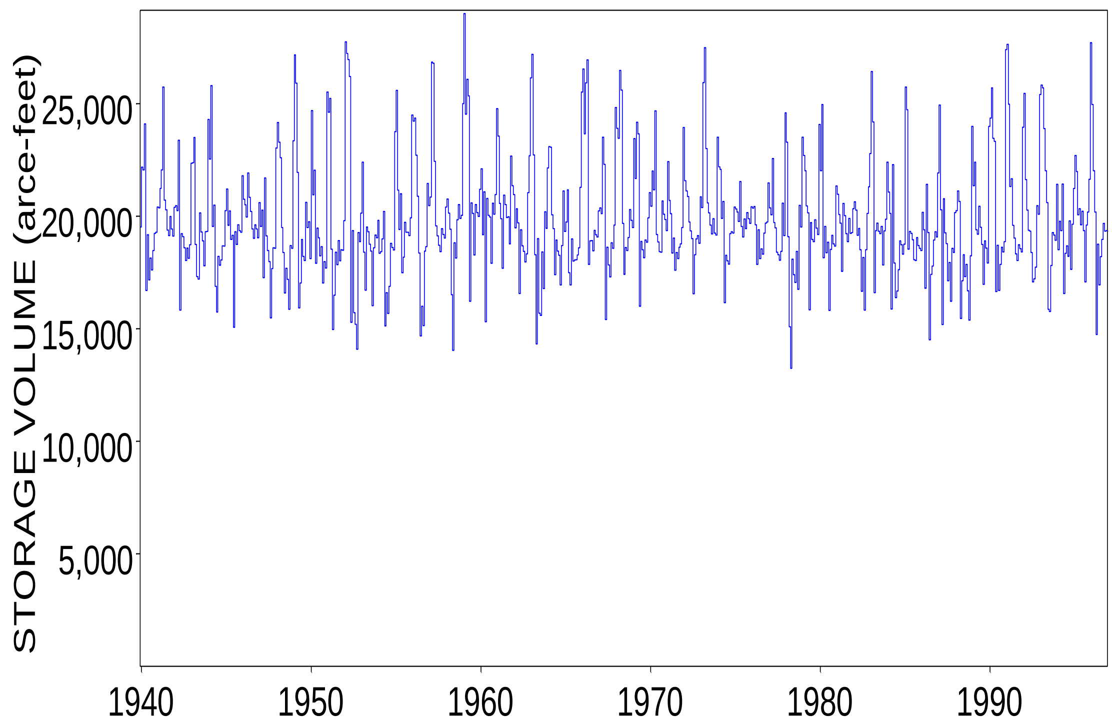
Total Storage all Reservoirs in the Cypress Bayou Basin



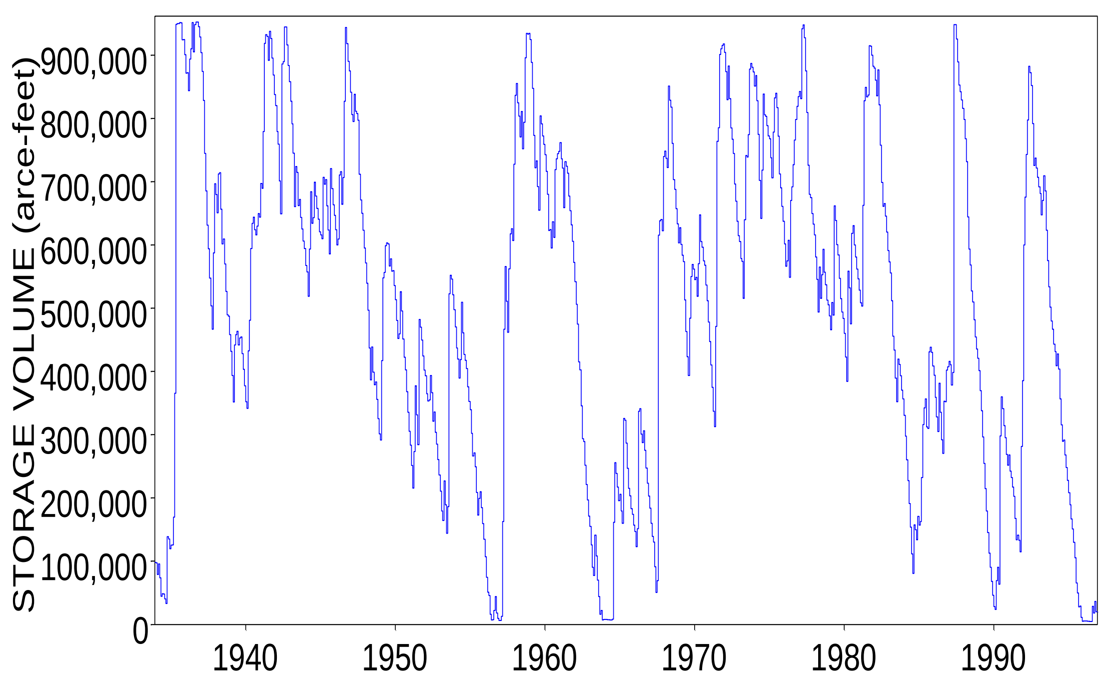
Total Storage all Reservoirs in the Lavaca River Basin



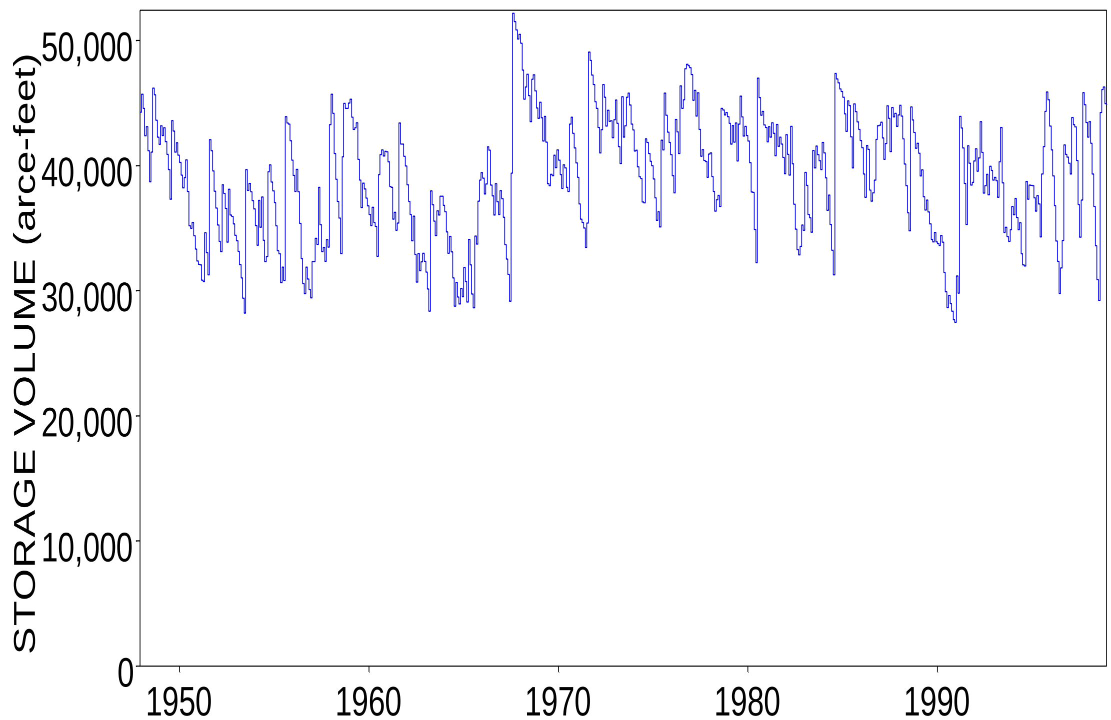
Total Storage all Reservoirs in the Neches River Basin



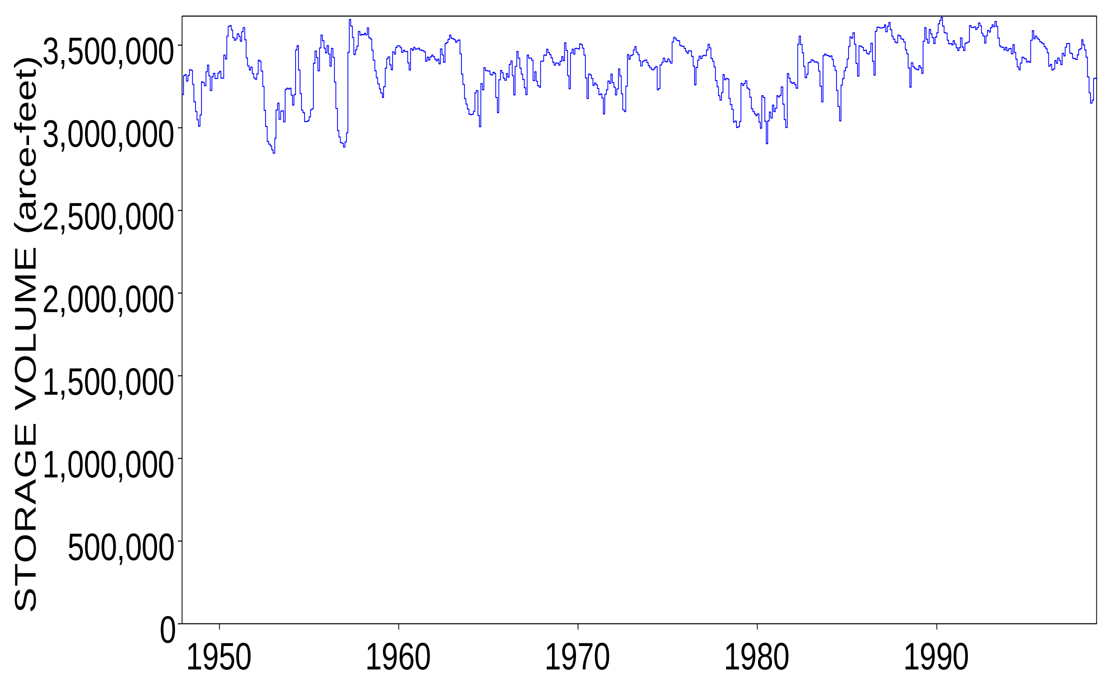
Total Storage all Reservoirs in the Neches-Trinity Coastal Basin



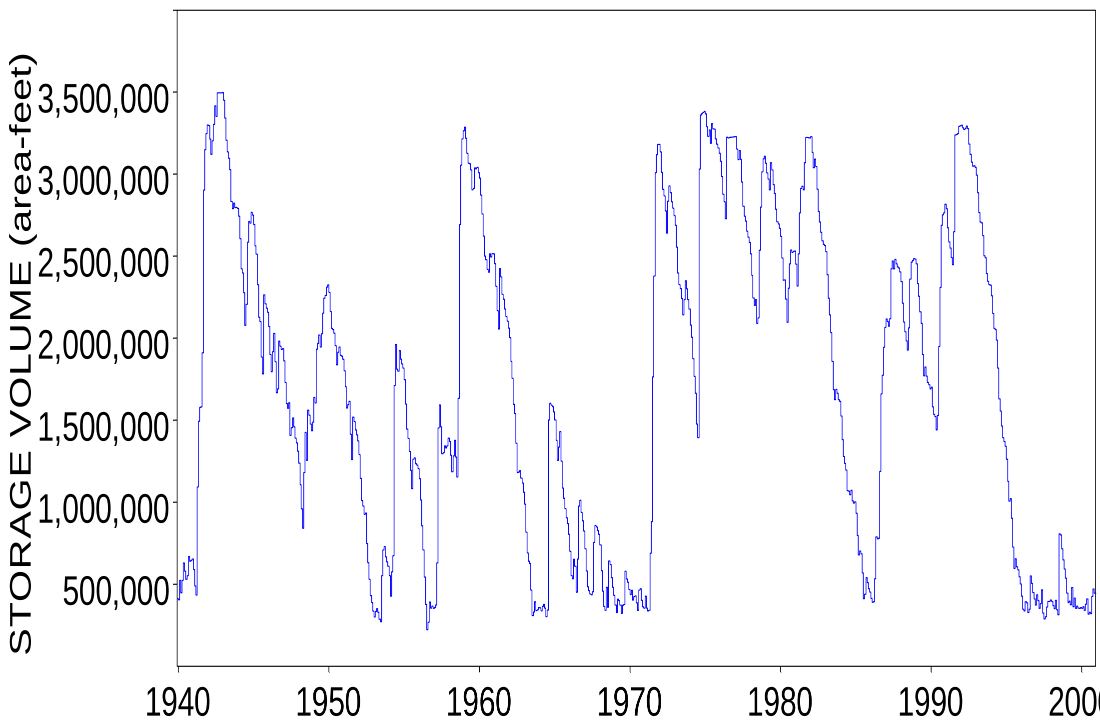
Total Storage all Reservoirs in the Nueces River Basin



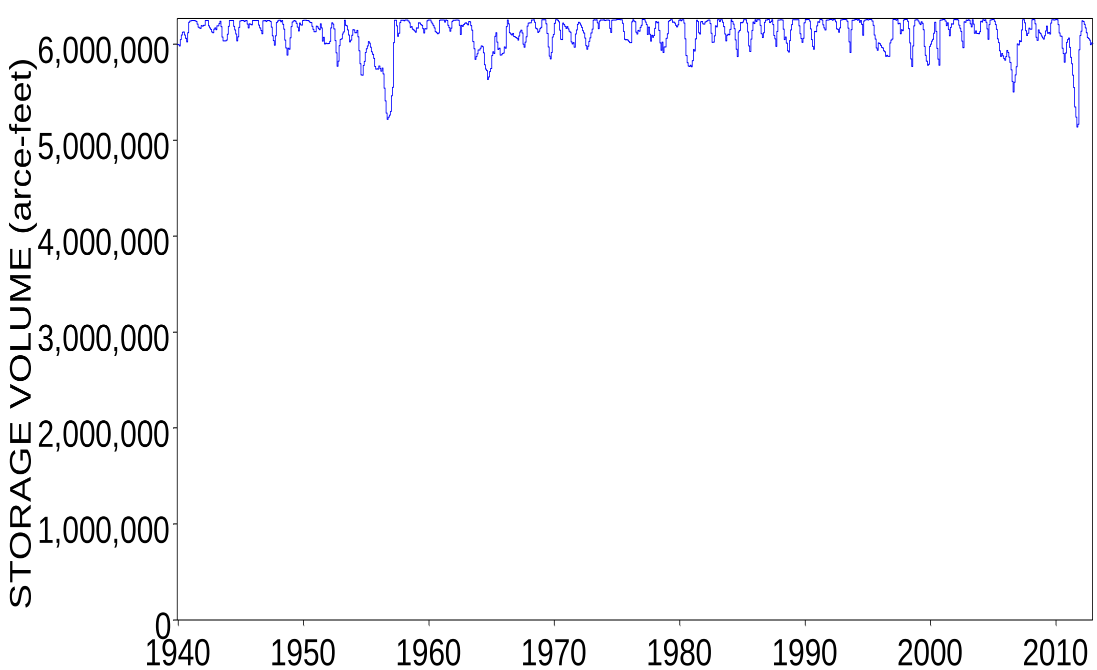
Total Storage all Reservoirs in the Nueces-Rio Grande Coastal Basin



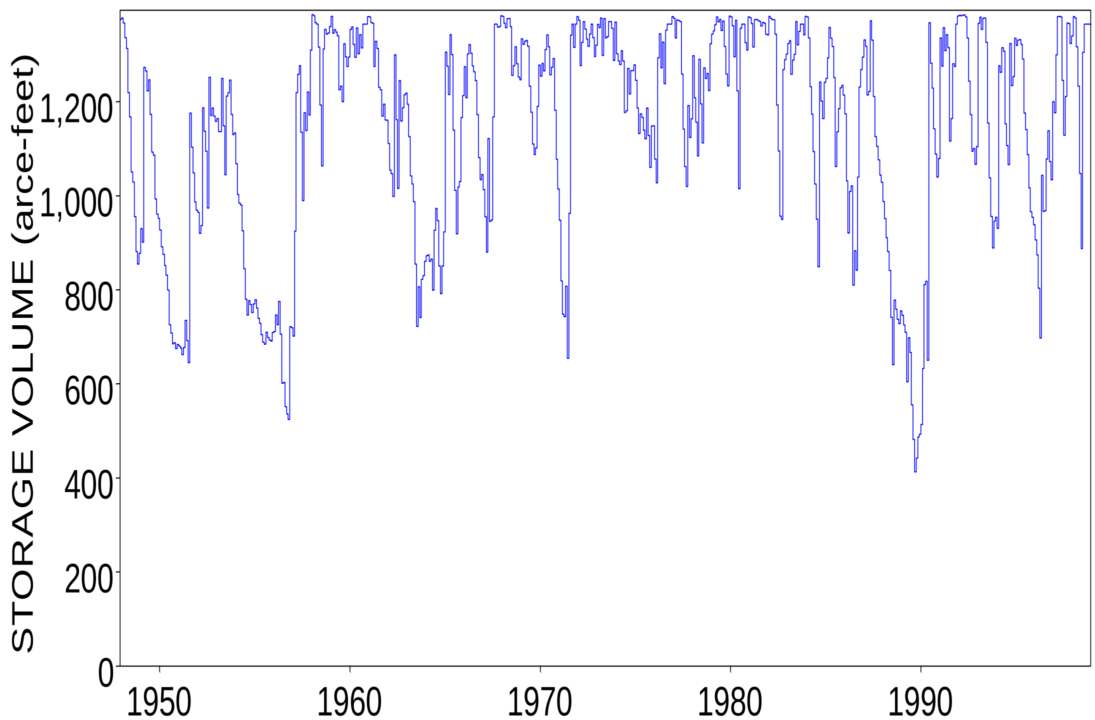
Total Storage all Reservoirs in the Red River Basin



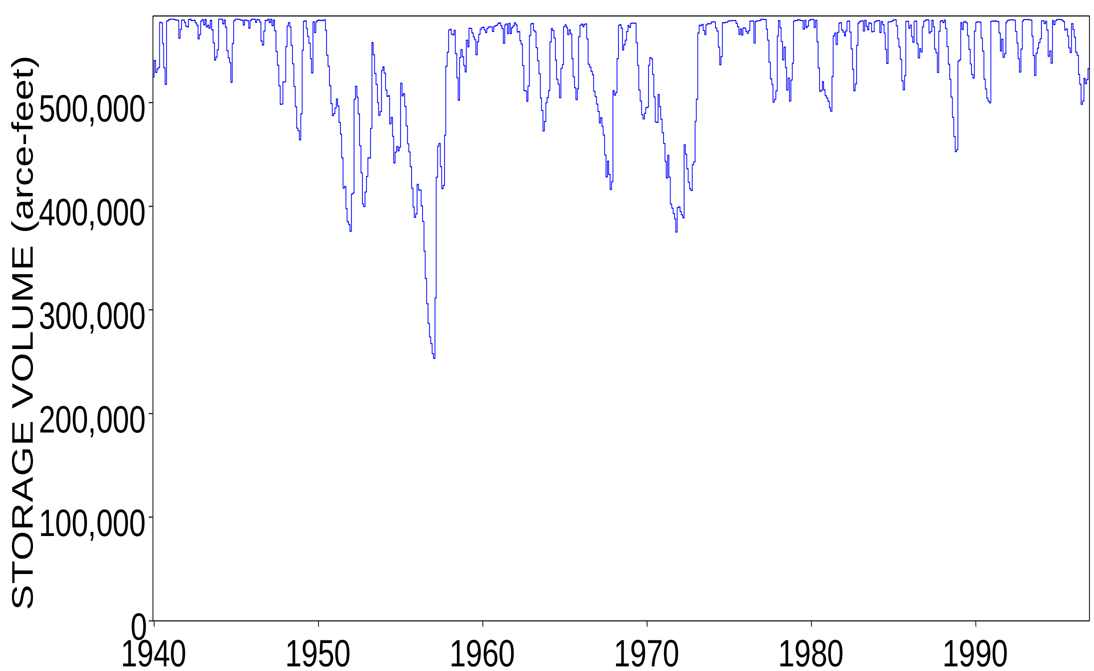
Total Storage all Reservoirs in the Rio Grande River Basin



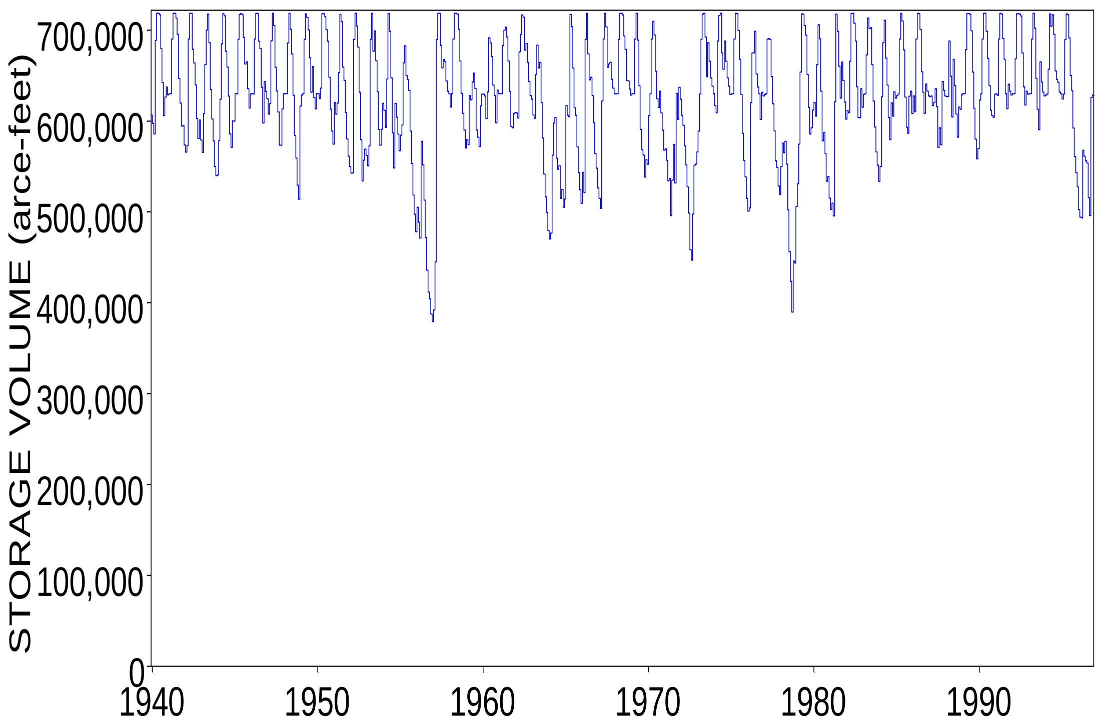
Total Storage all Reservoirs in the Sabine River Basin



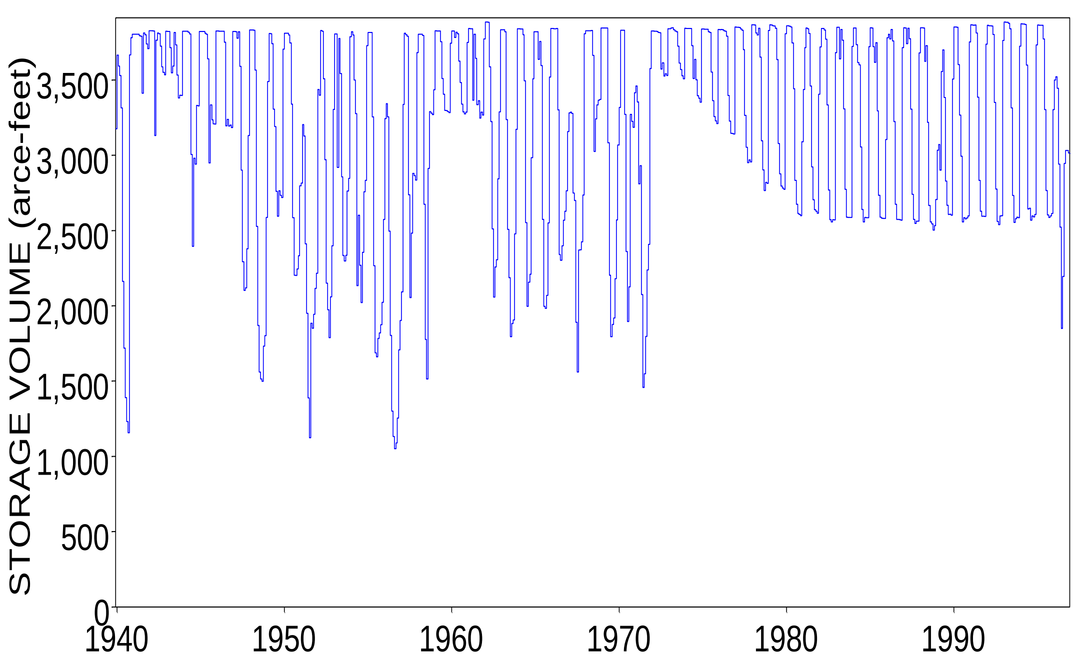
Total Storage all Reservoirs in the San Antonio-Nueces Coastal Basin



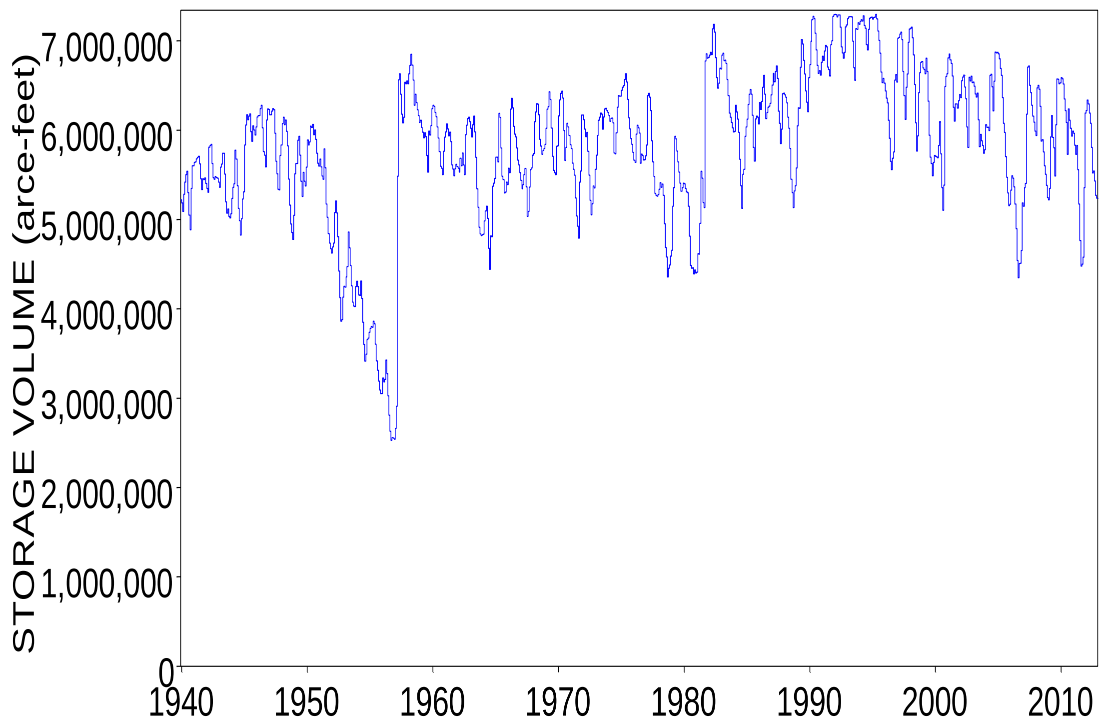
Total Storage all Reservoirs in the San Jacinto River Basin



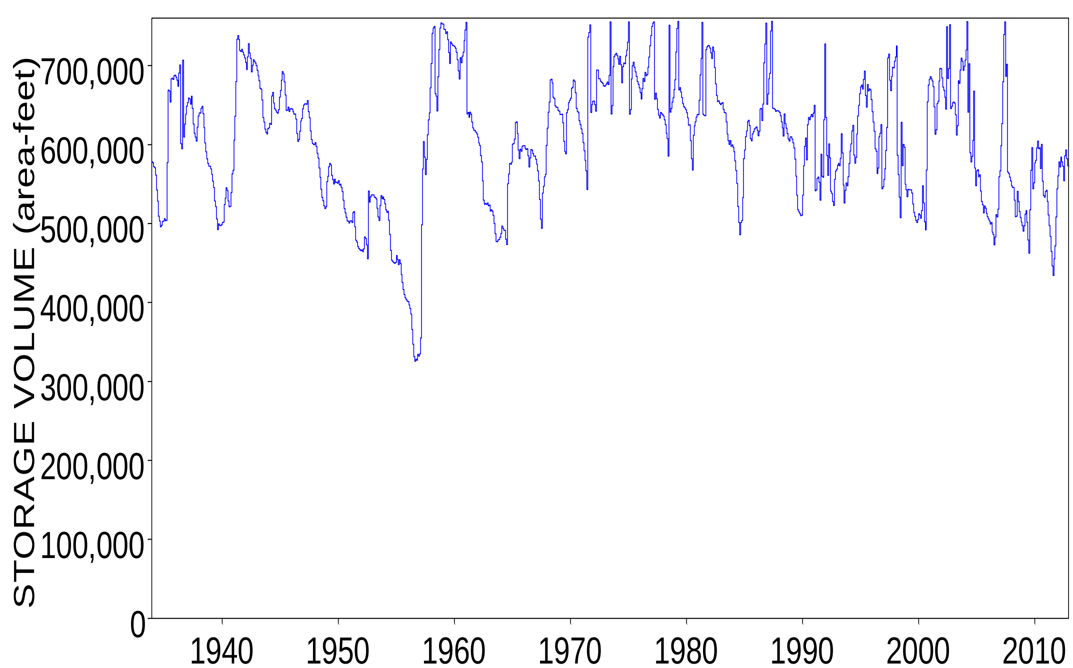
Total Storage all Reservoirs in the Sulphur River Basin



Total Storage all Reservoirs in the Trinity-San Jacinto Coastal Basin



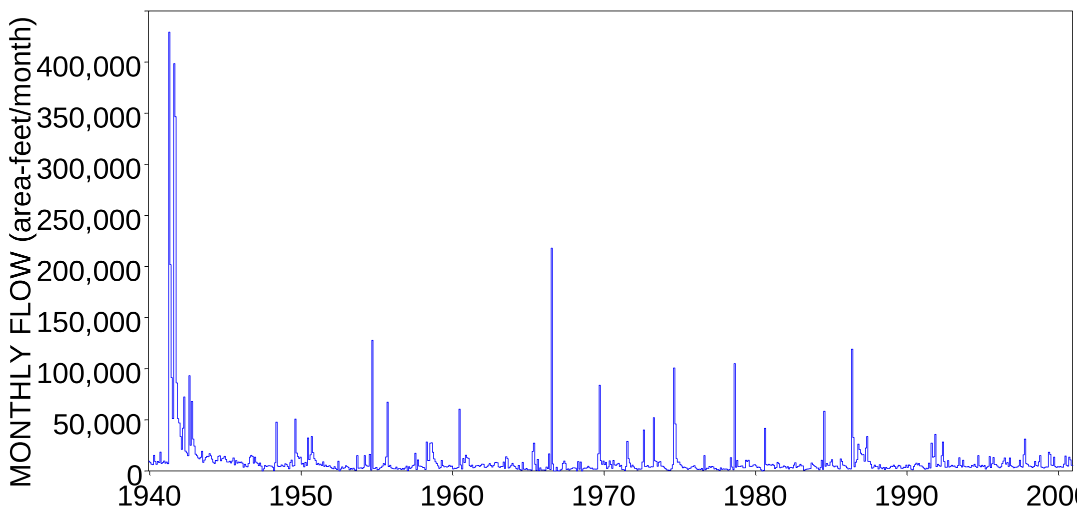
Total Storage all Reservoirs in the Trinity River Basin



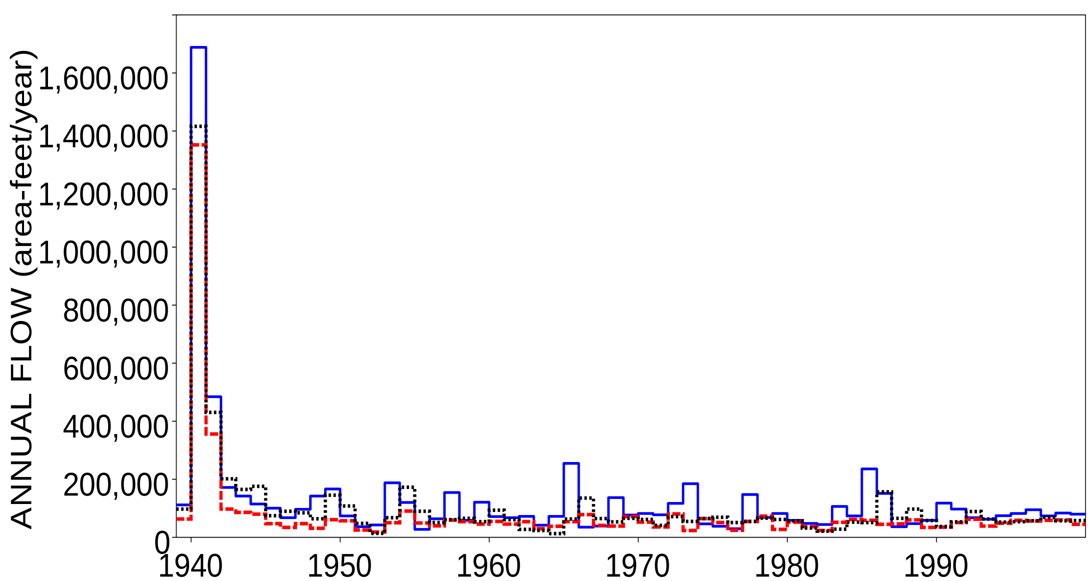
Total Storage all Reservoirs in the Guadalupe and San Antonio River Basin

APPENDIX E

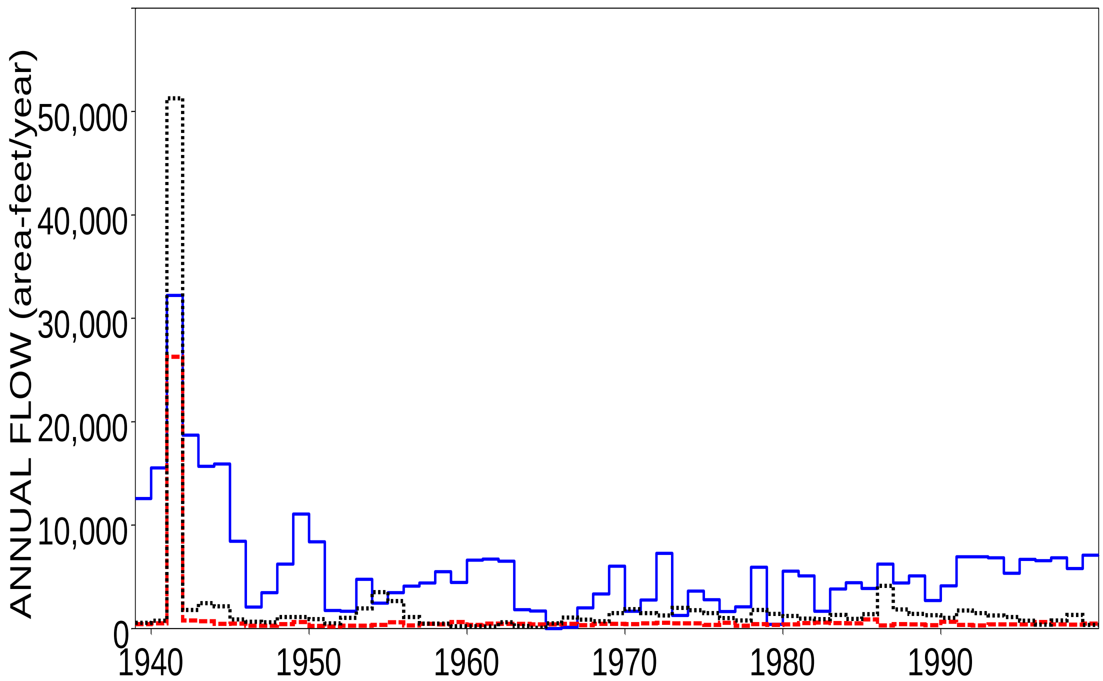
MONTHLY NATURALIZED, ANNUAL, 2-MONTH MINIMA, AND 2-MONTH MAXIMA OBSERVED, NATURALIZED, AND REGULATED FLOWS



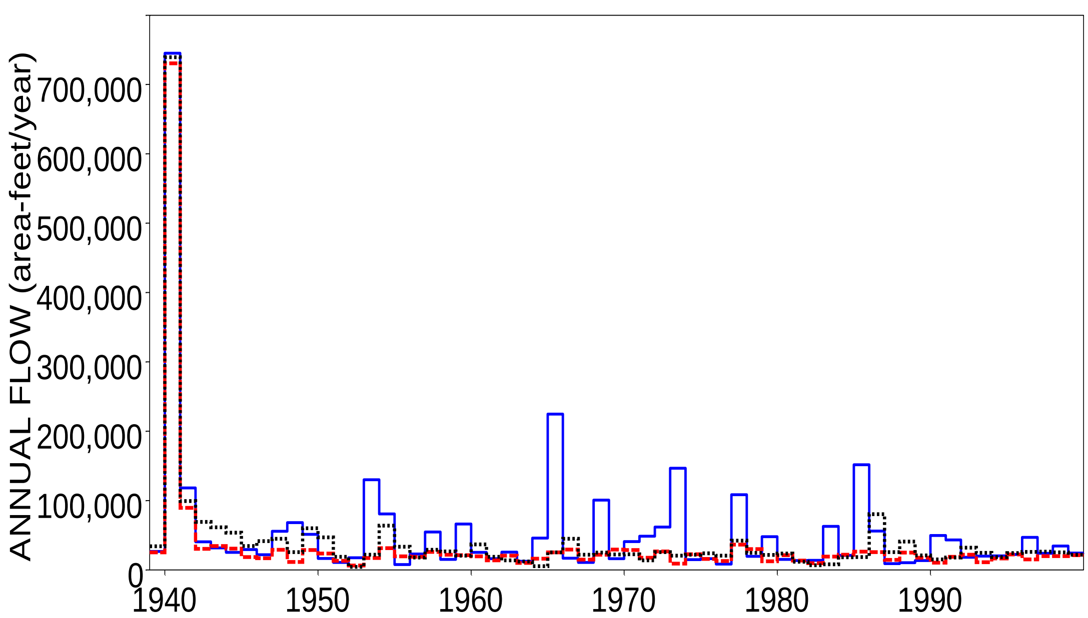
Naturalized Flows of Pecos River at Orla



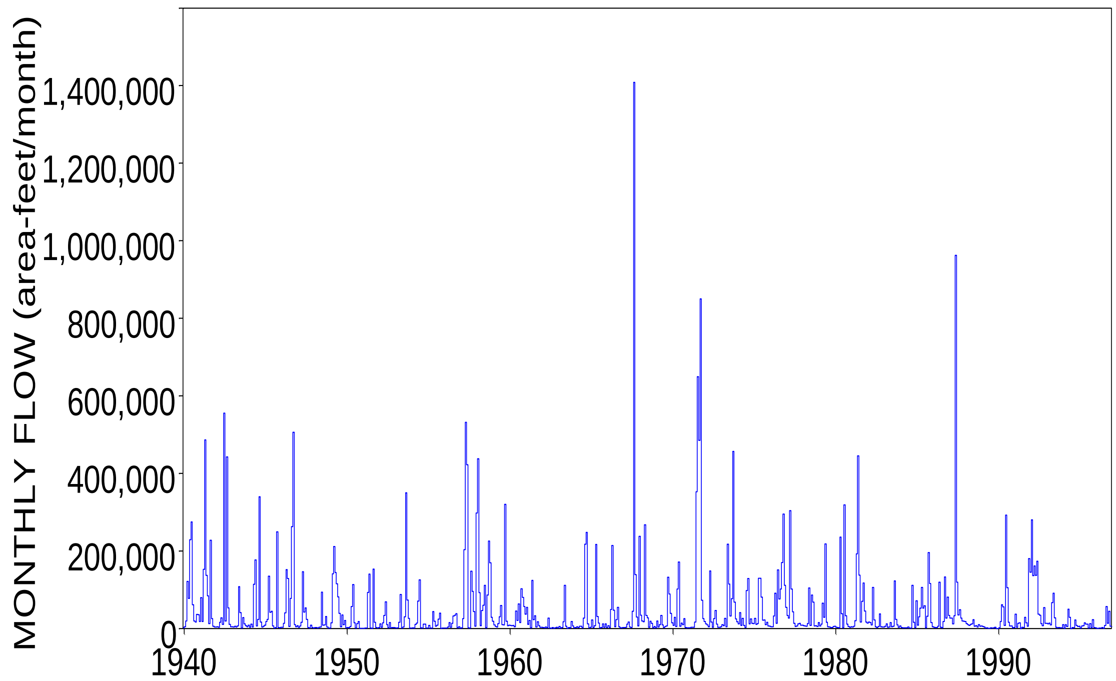
Naturalized (blue solid), Regulated (red dashed), and Observed (black dotted) Annual Flows for Pecos River at Orla



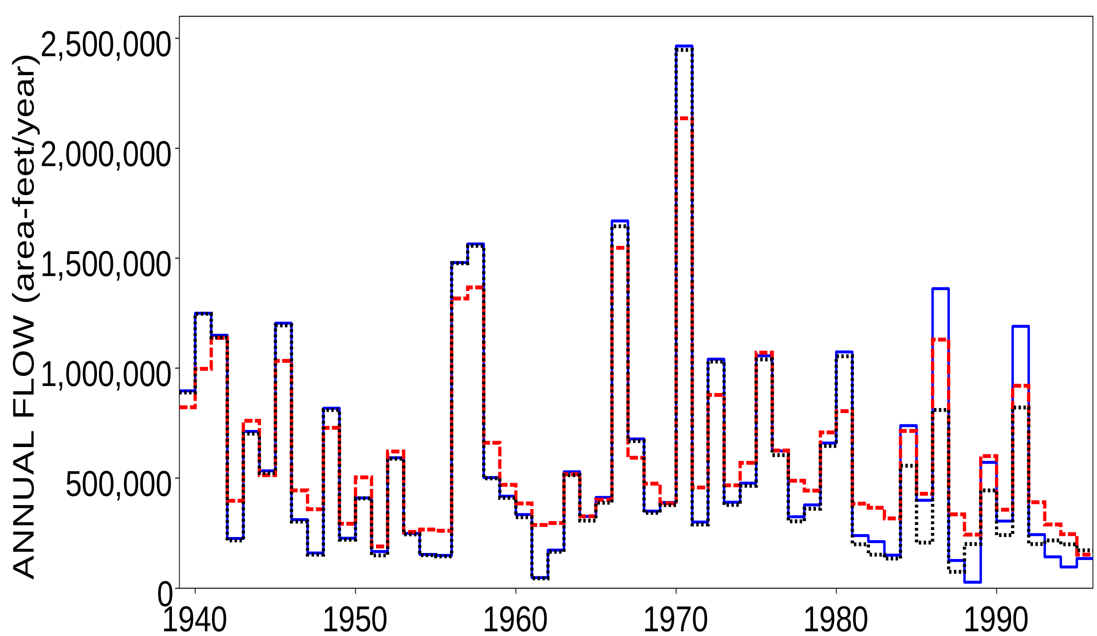
Naturalized (blue solid), Regulated (red dashed), and Observed (black dotted) 2-Month Minimum Annual Flows for Pecos River at Orla



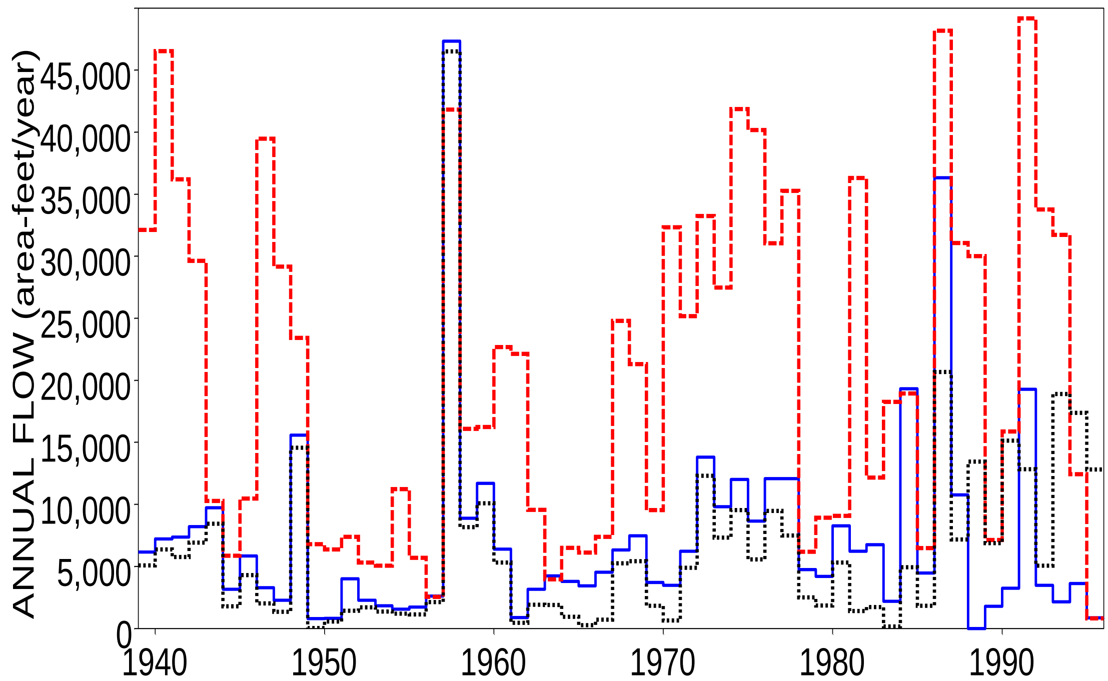
Naturalized (blue solid), Regulated (red dashed), and Observed (black dotted) 2-Month Maximum Annual Flows for Pecos River at Orla



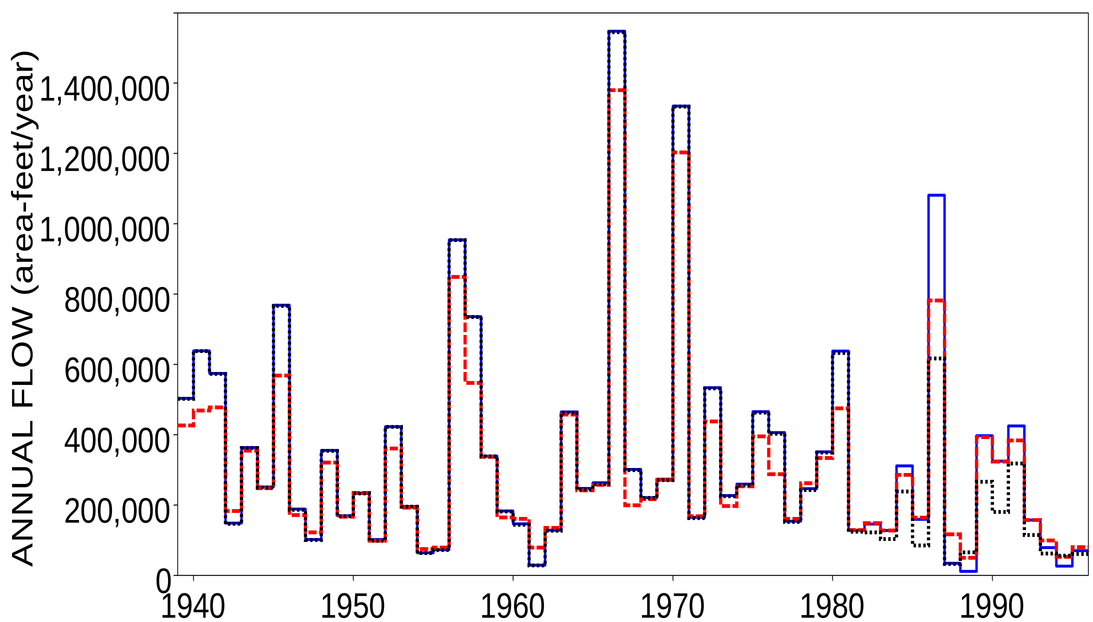
Naturalized Flows of Nueces River at Three Rivers



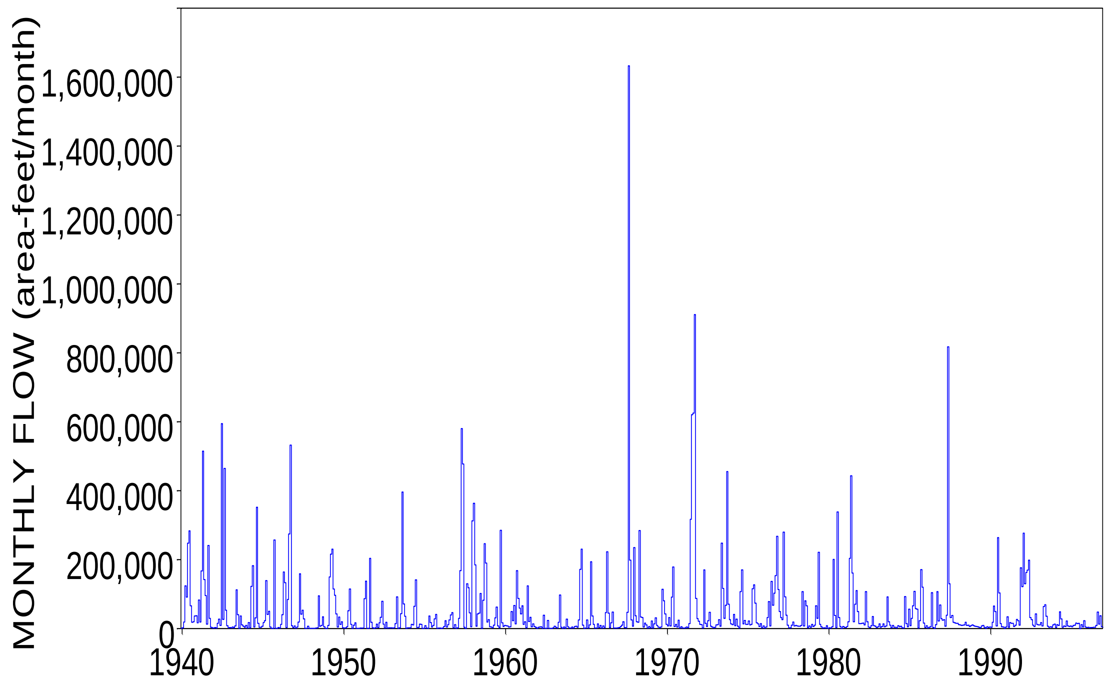
Naturalized (blue solid), Regulated (red dashed), and Observed (black dotted) Annual Flows for Nueces River at Three Rivers



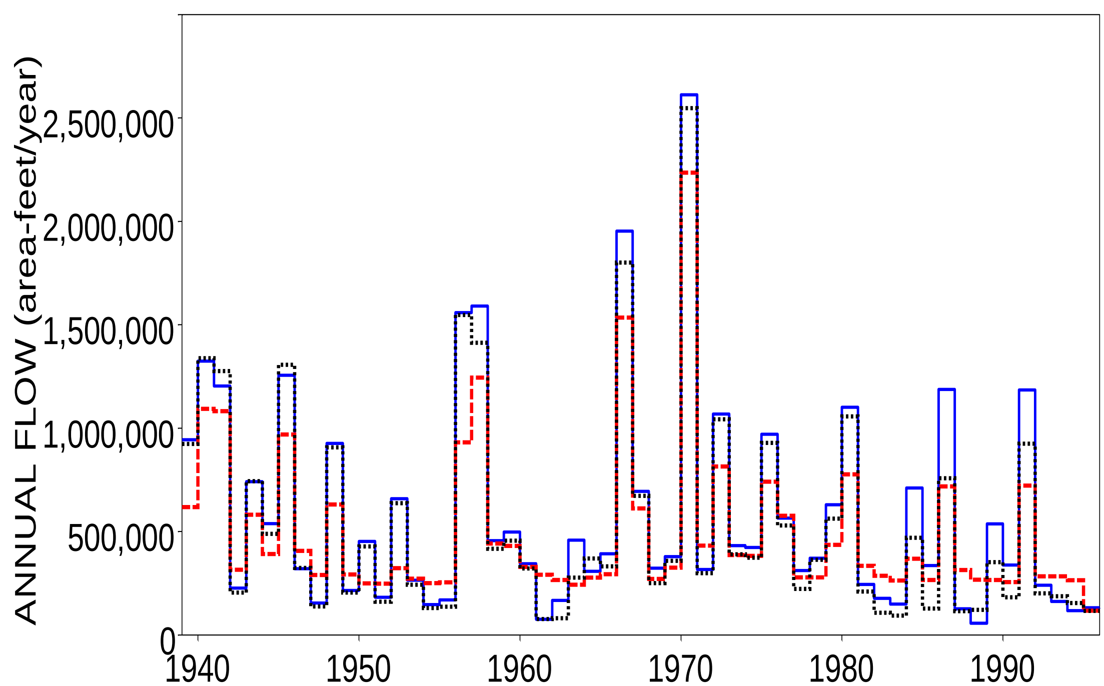
Naturalized (blue solid), Regulated (red dashed), and Observed (black dotted) 2-Month Minimum Annual Flows for Nueces River at Three Rivers



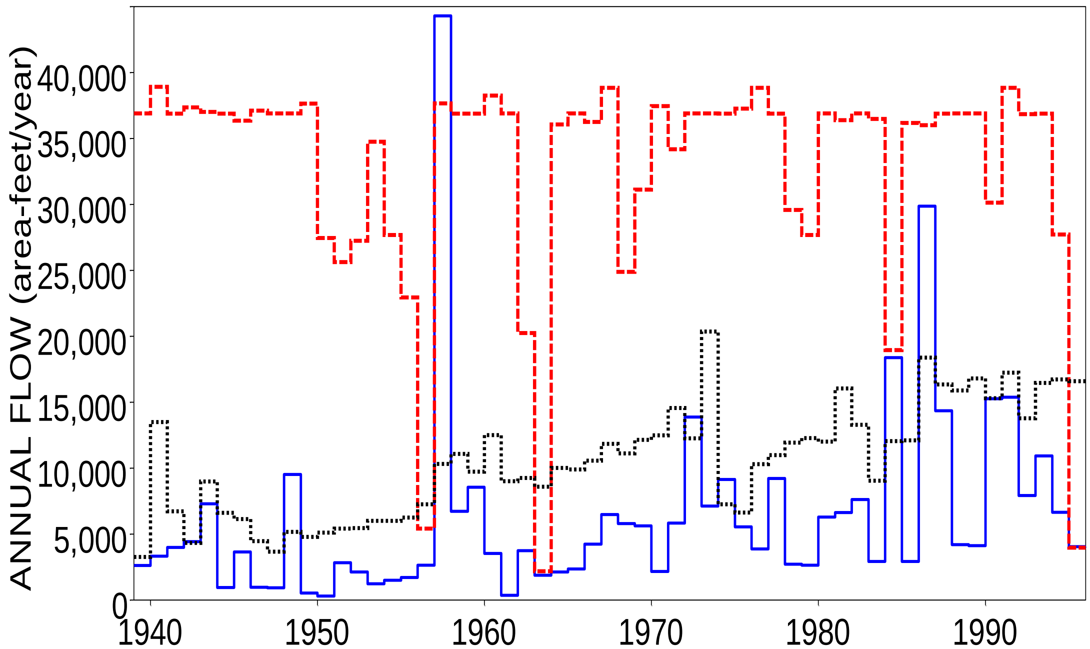
Naturalized (blue solid), Regulated (red dashed), and Observed (black dotted) 2-Month Maximum Annual Flows for Nueces River at Three Rivers



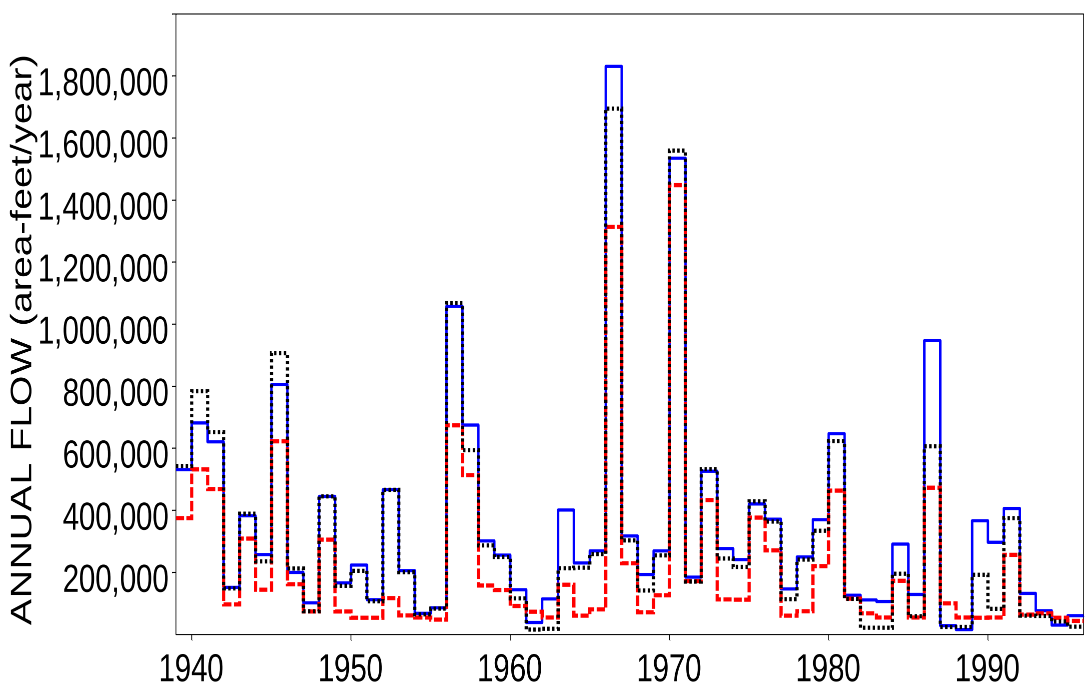
Naturalized Flows of Nueces River at Mathis



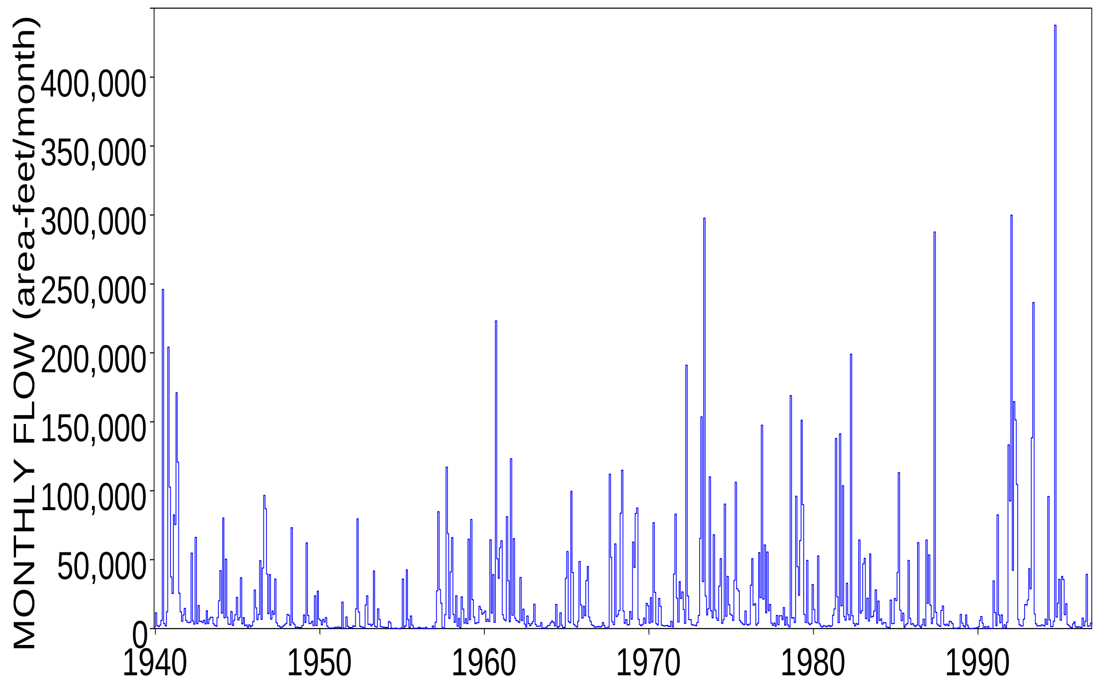
Naturalized (blue solid), Regulated (red dashed), and Observed (black dotted) Annual Flows for Nueces River at Mathis



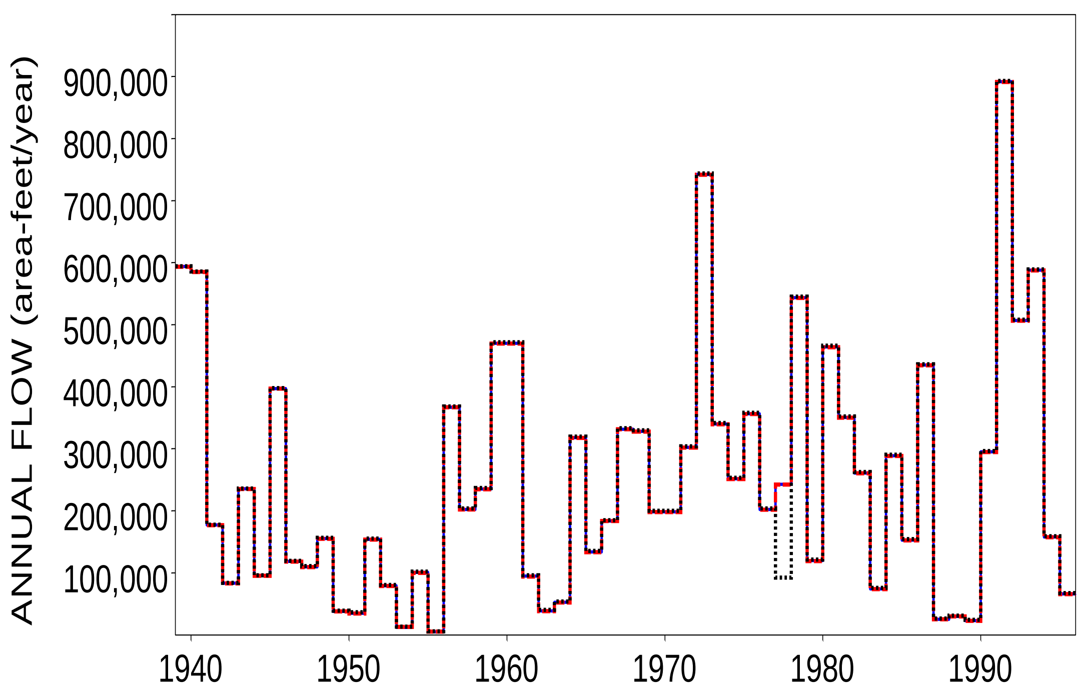
Naturalized (blue solid), Regulated (red dashed), and Observed (black dotted) 2-Month Minimum Annual Flows for Nueces River at Mathis



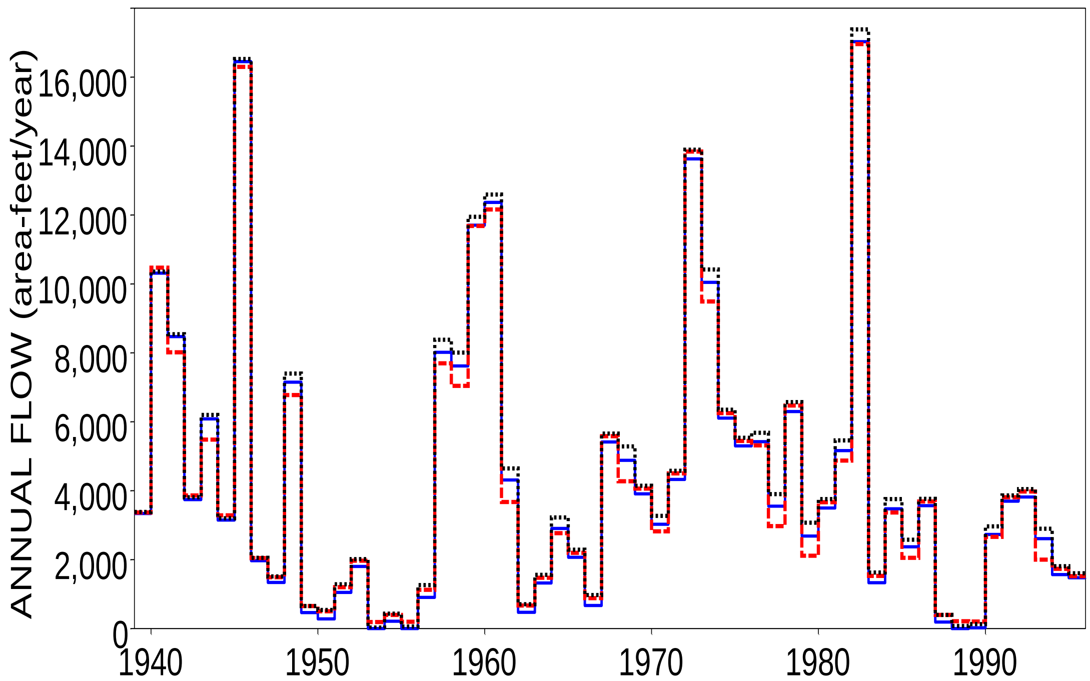
Naturalized (blue solid), Regulated (red dashed), and Observed (black dotted) 2-Month Maximum Annual Flows for Nueces River at Mathis



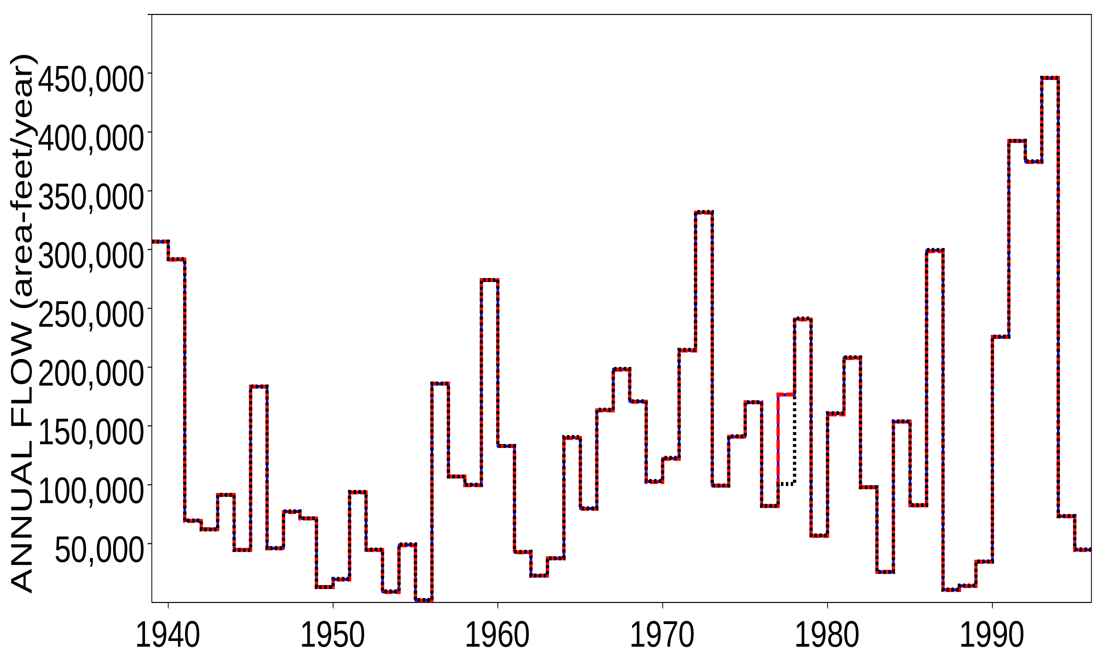
Naturalized Flows of Lavaca River near Edna



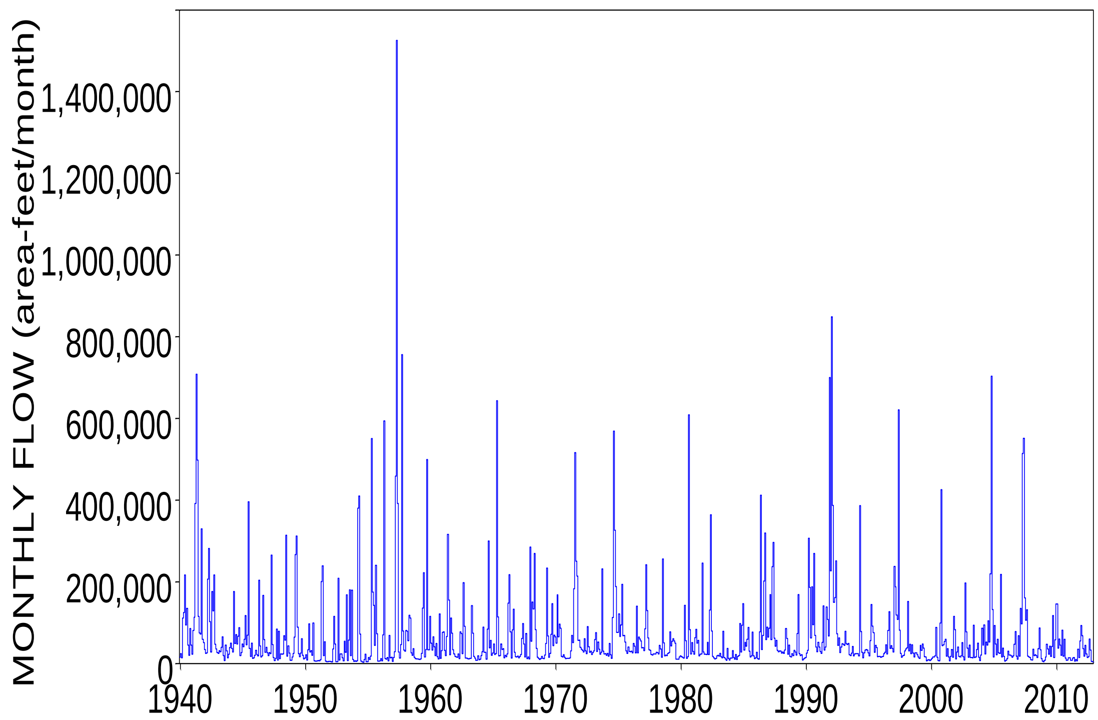
Naturalized (blue solid), Regulated (red dashed), and Observed (black dotted) Annual Flows for Lavaca River near Edna



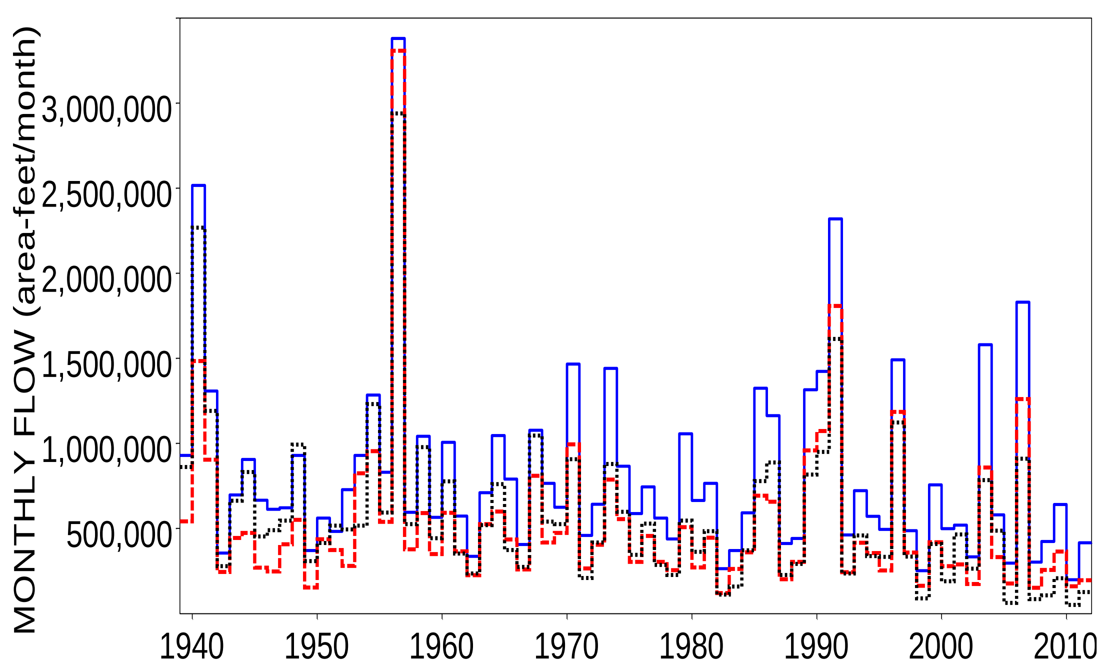
Naturalized (blue solid), Regulated (red dashed), and Observed (black dotted) 2-Month Minimum Annual Flows for Lavaca River near Edna



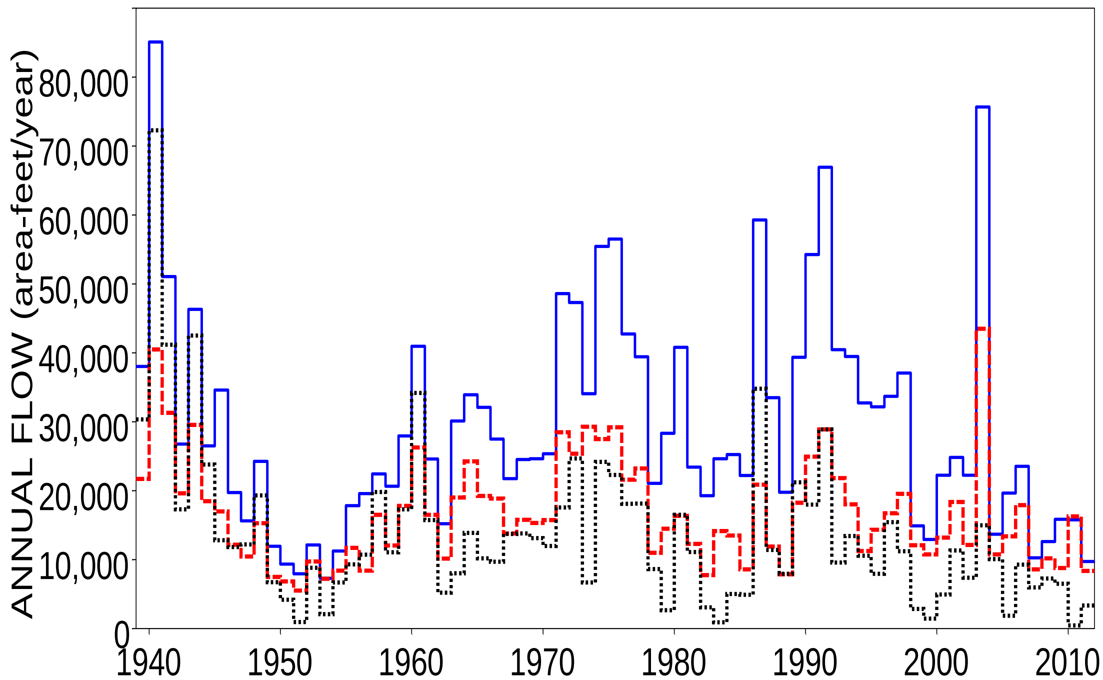
Naturalized (blue solid), Regulated (red dashed), and Observed (black dotted) 2-Month Maximum Annual Flows for Lavaca River near Edna



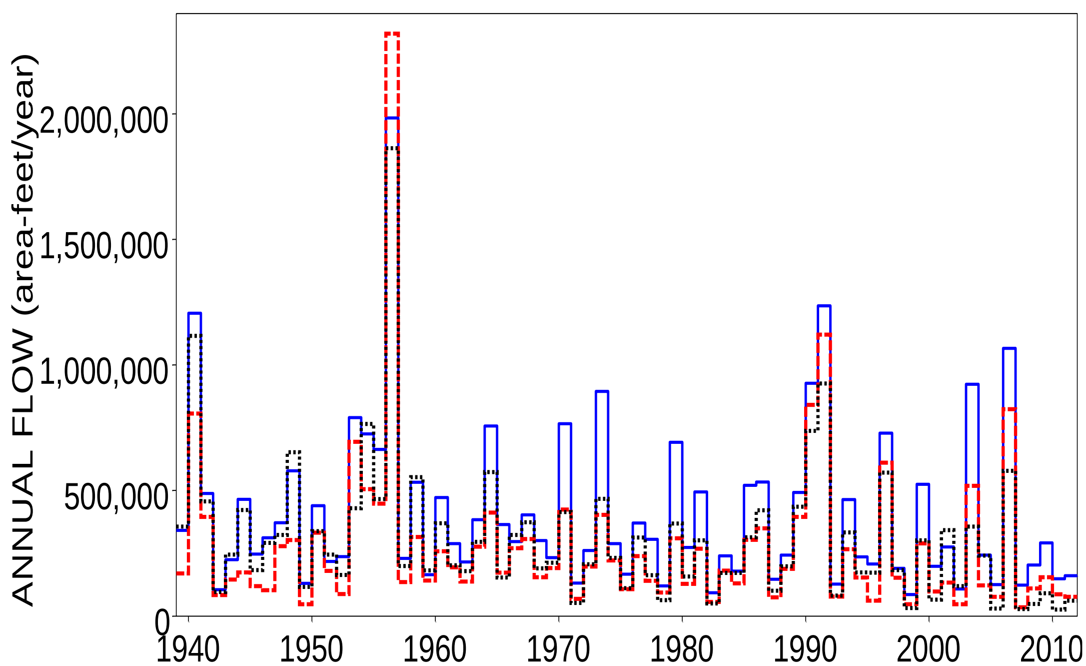
Naturalized Flows of Colorado River near San Saba



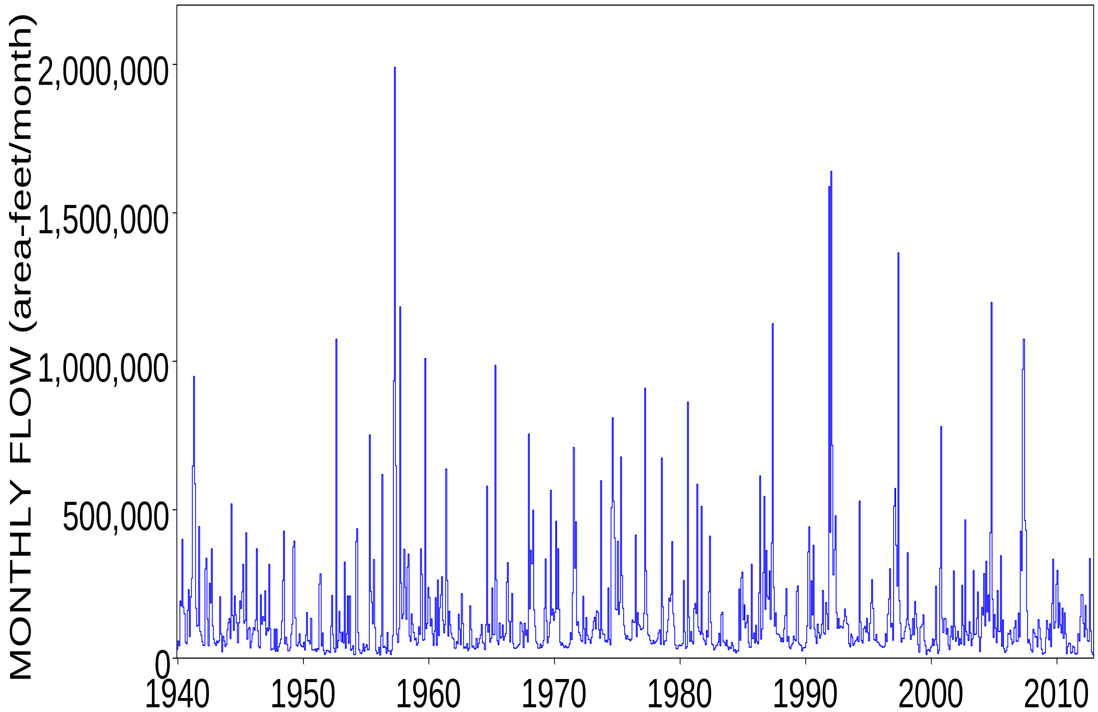
Naturalized (blue solid), Regulated (red dashed), and Observed (black dotted) Annual Flows Annual Flows for Colorado River at San Saba gage (F10000)



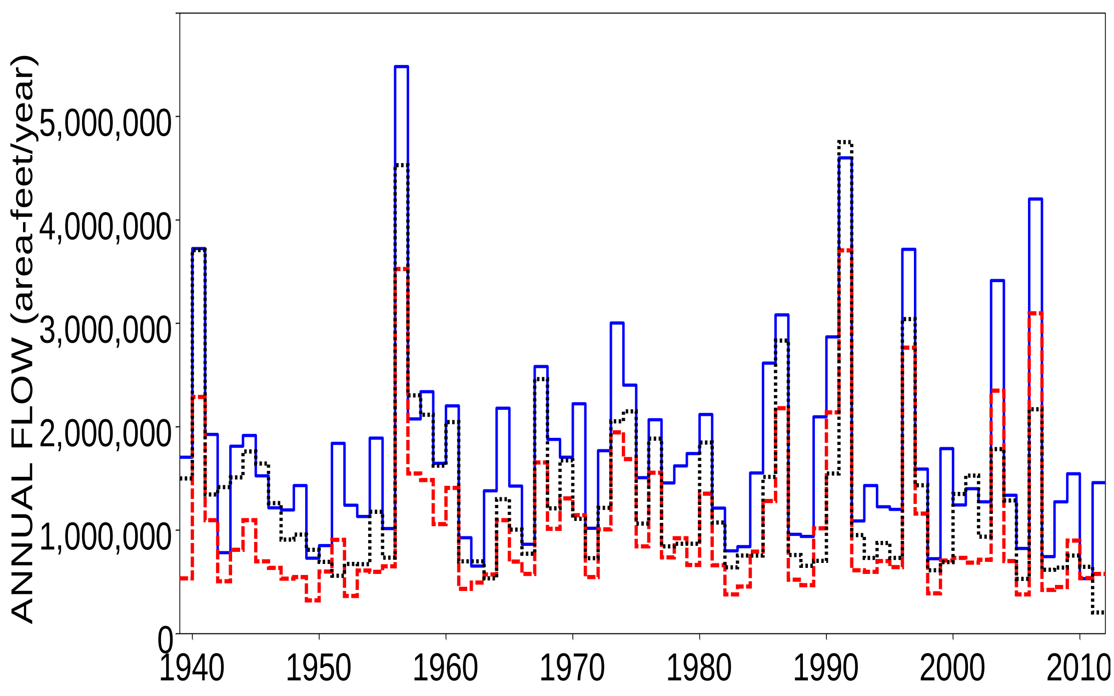
Naturalized (blue solid), Regulated (red dashed), and Observed (black dotted) 2-Month Minimum Annual Flows for Colorado River at San Saba gage (F10000)



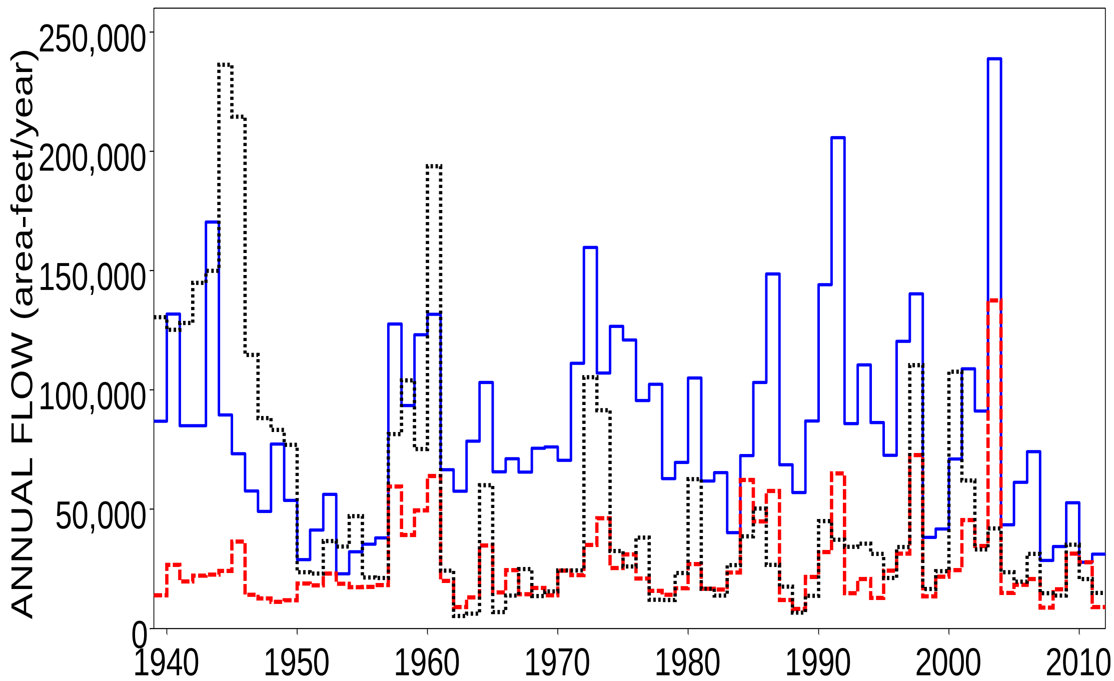
Naturalized (blue solid), Regulated (red dashed), and Observed 2-Month Maximum Annual Flows for Colorado River at San Saba gage (F10000)



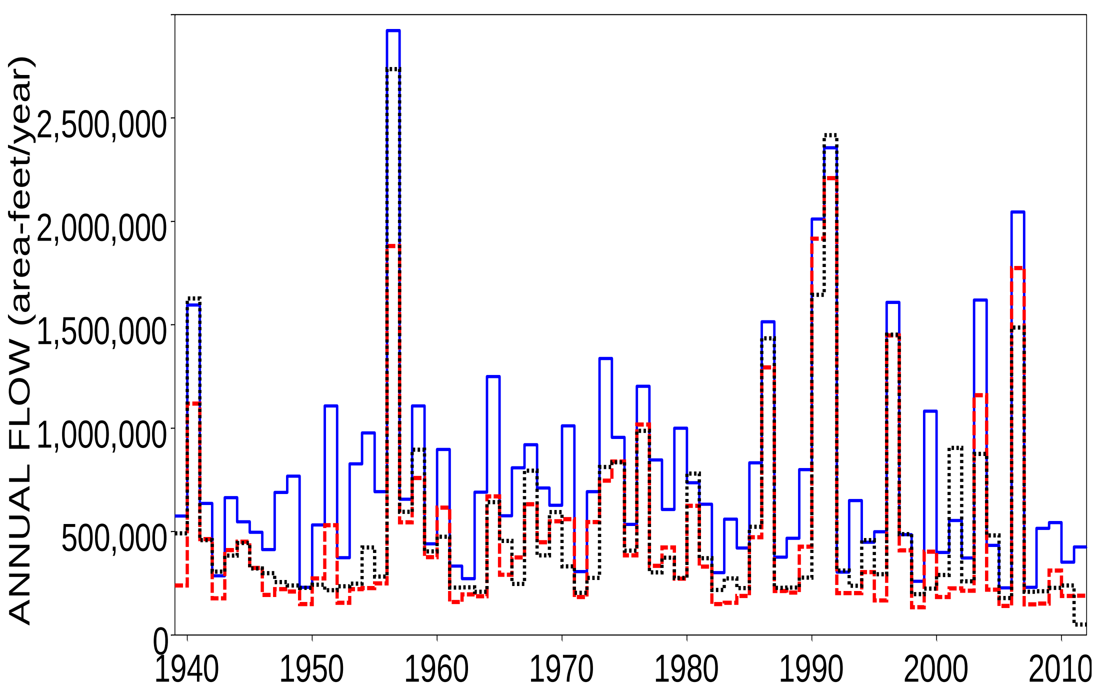
Naturalized Flows of Colorado River at Austin



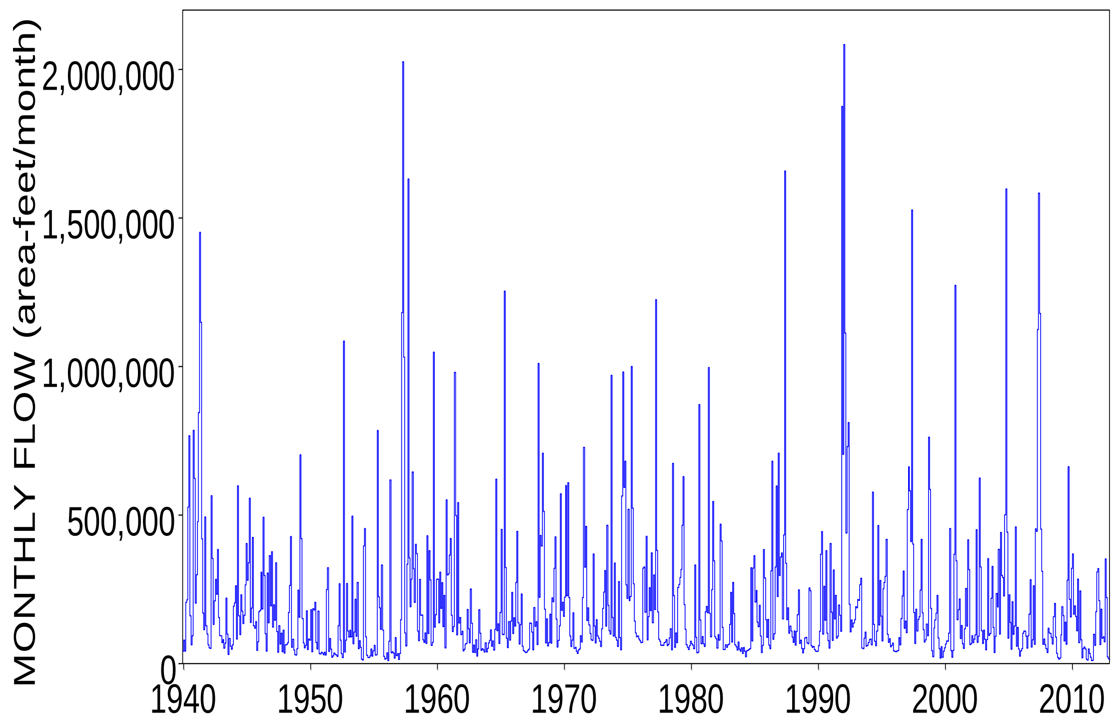
Naturalized (blue solid), Regulated (red dashed), and Observed (black dotted) Annual Flows for Colorado River at Austin



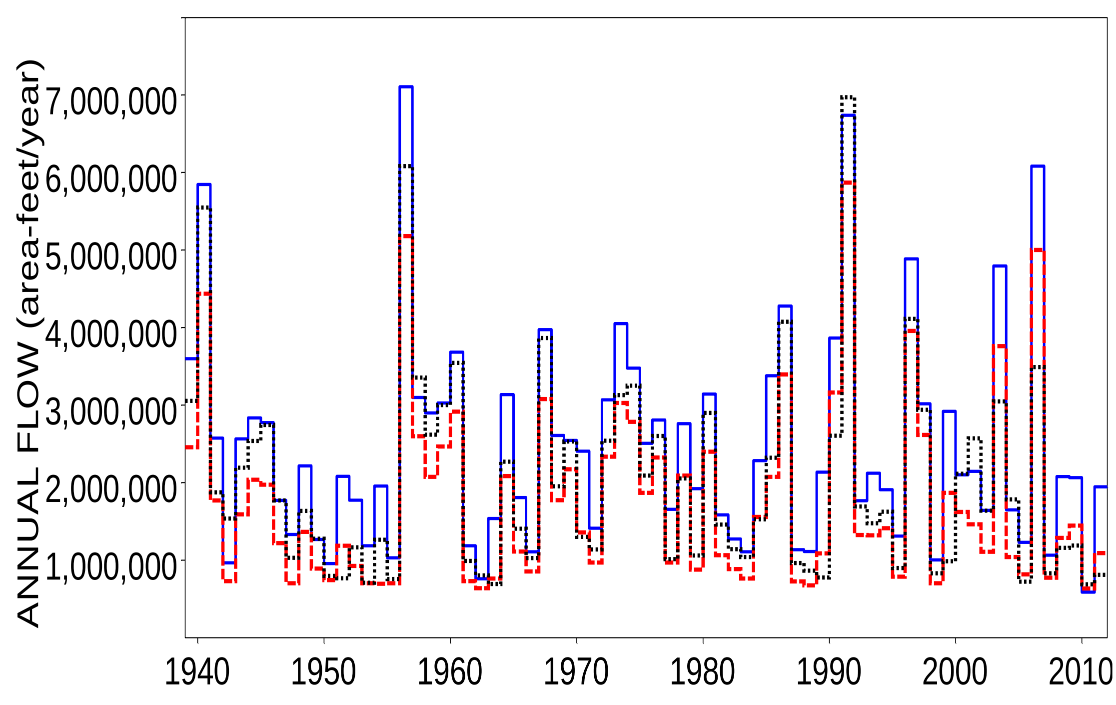
Naturalized (blue solid), Regulated (red dashed), and Observed (black dotted) 2-Month Minimum Annual Flows for Colorado River at Austin



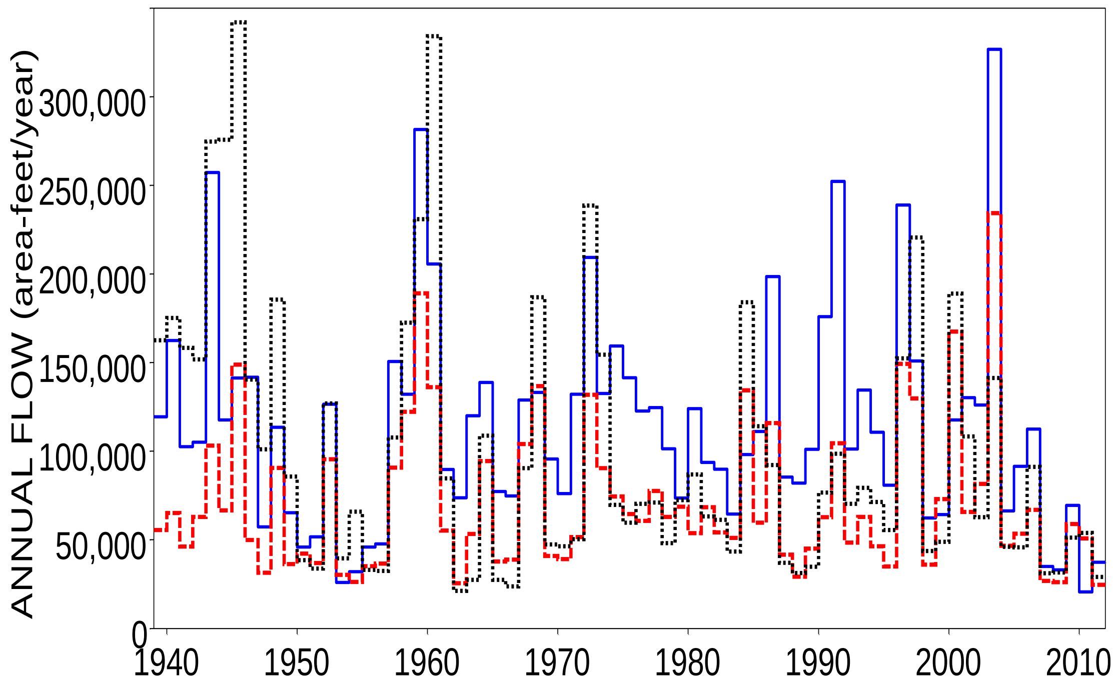
Naturalized (blue solid), Regulated (red dashed), and Observed (black dotted) 2-Month Maximum Annual Flows for Colorado River at Austin



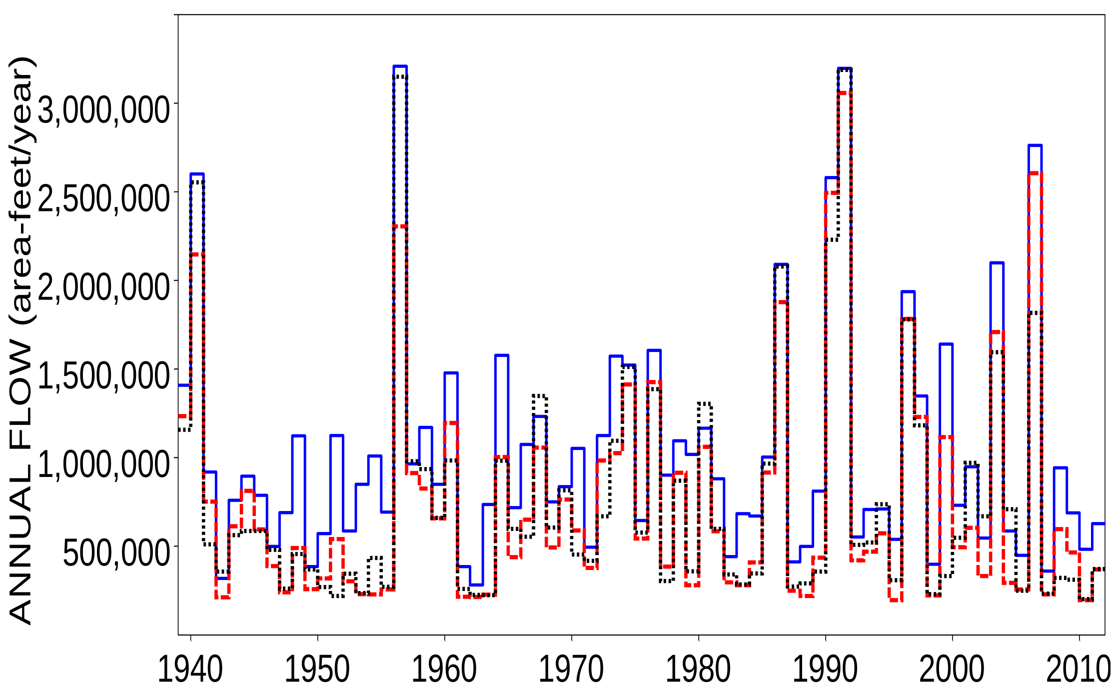
Naturalized Flows of Colorado River at Columbus



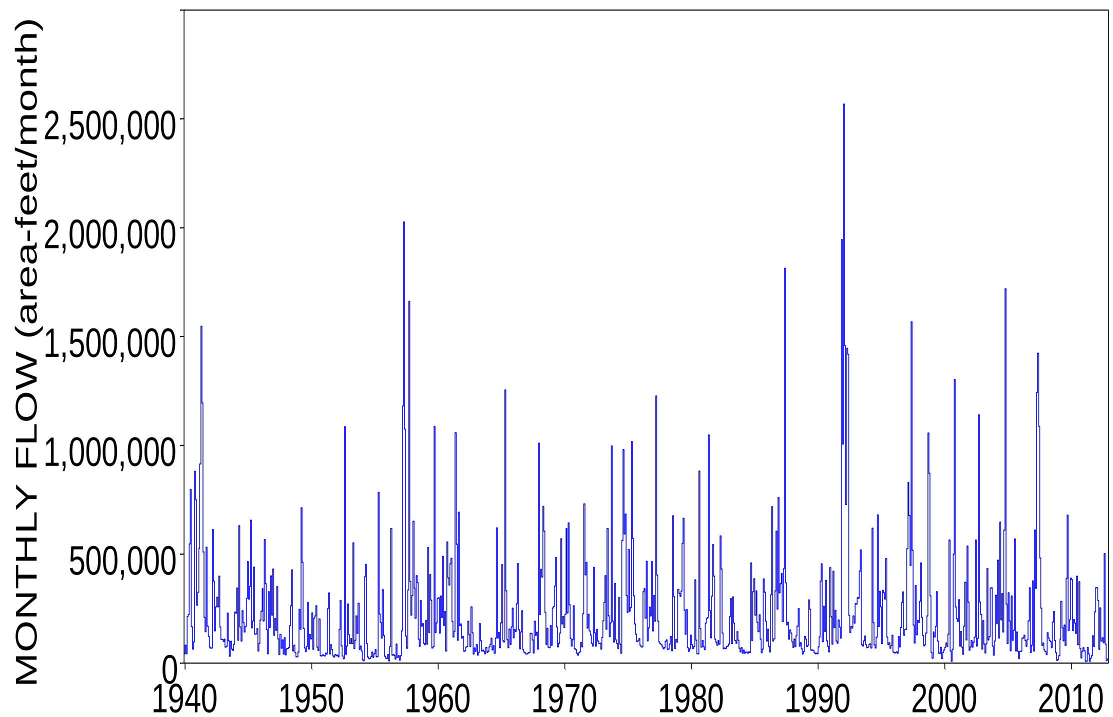
Naturalized (blue solid), Regulated (red dashed), and Observed (black dotted) Annual Flows for Colorado River at Columbus



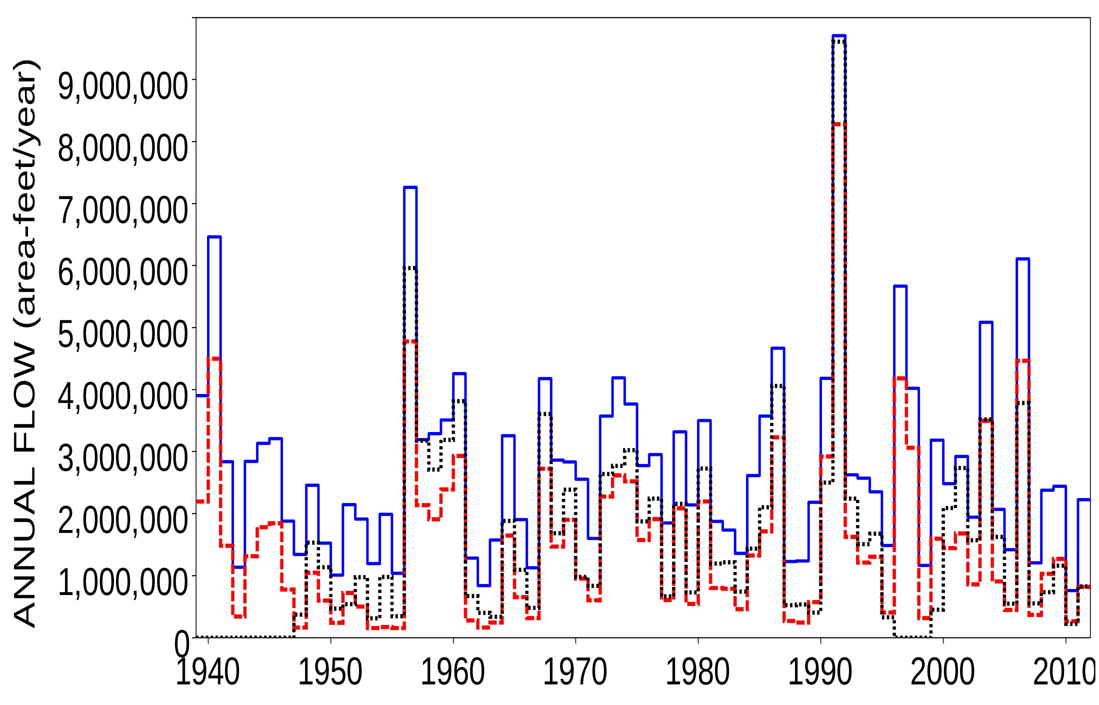
Naturalized (blue solid), Regulated (red dashed), and Observed (black dotted) 2-Month Minimum Annual Flows for Colorado River at Columbus



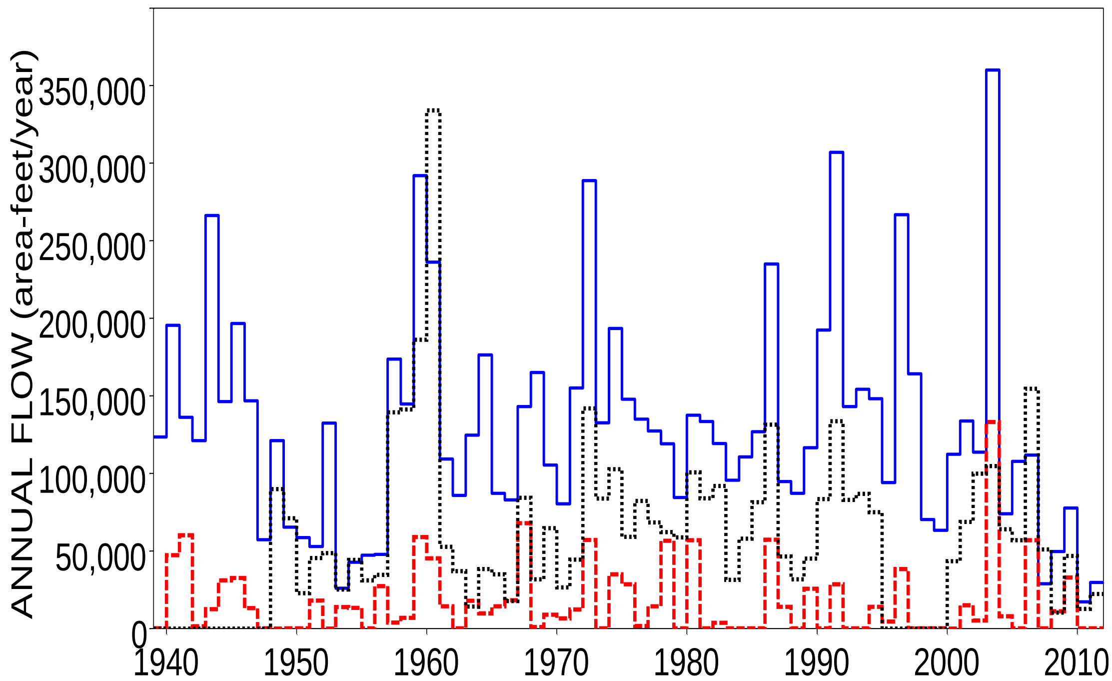
Naturalized (blue solid), Regulated (red dashed), and Observed (black dotted) 2-Month Maximum Annual Flows for Colorado River at Columbus



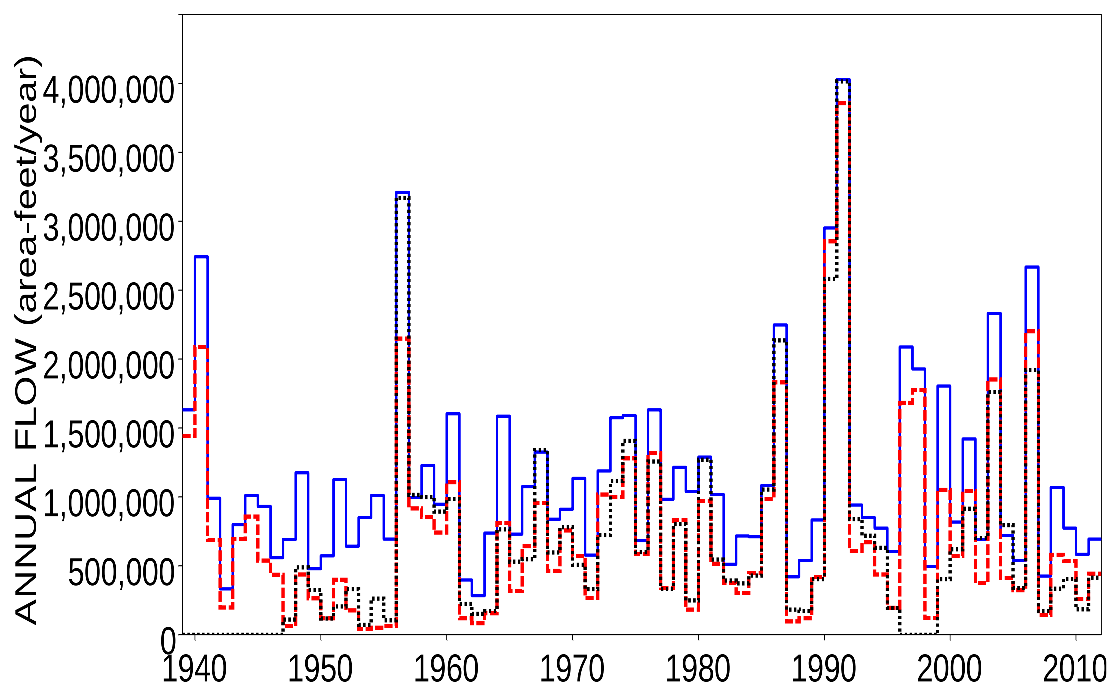
Naturalized Flows of Colorado River near Bay City



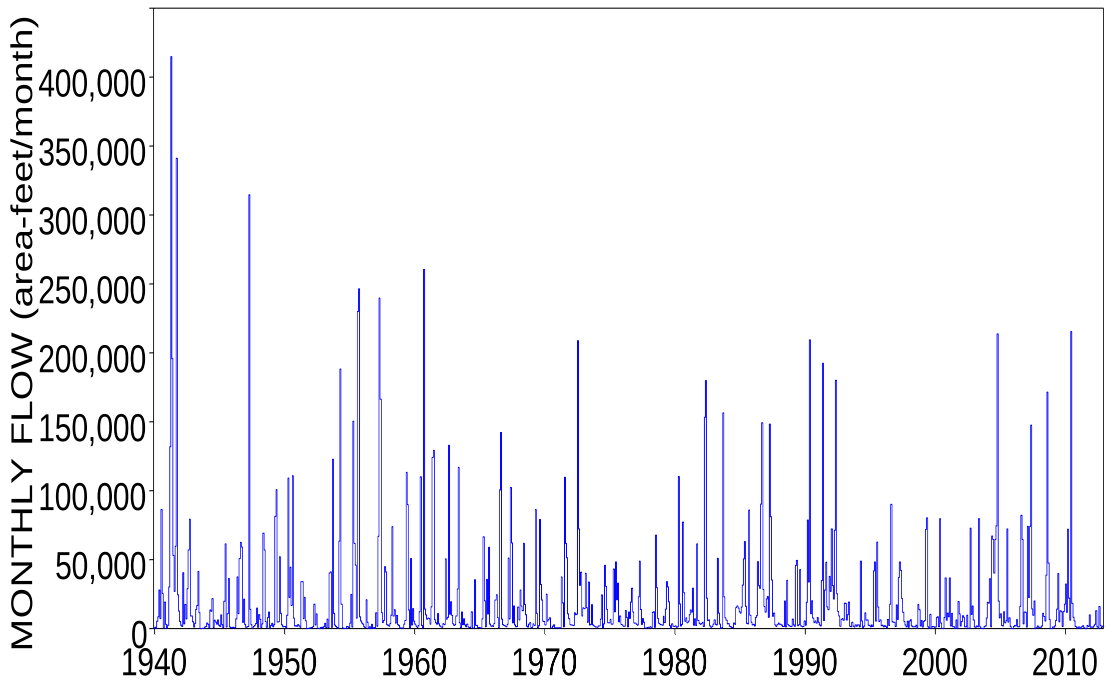
Naturalized (blue solid), Regulated (red dashed), and Observed (black dotted) Annual Flows for Colorado River near Bay City



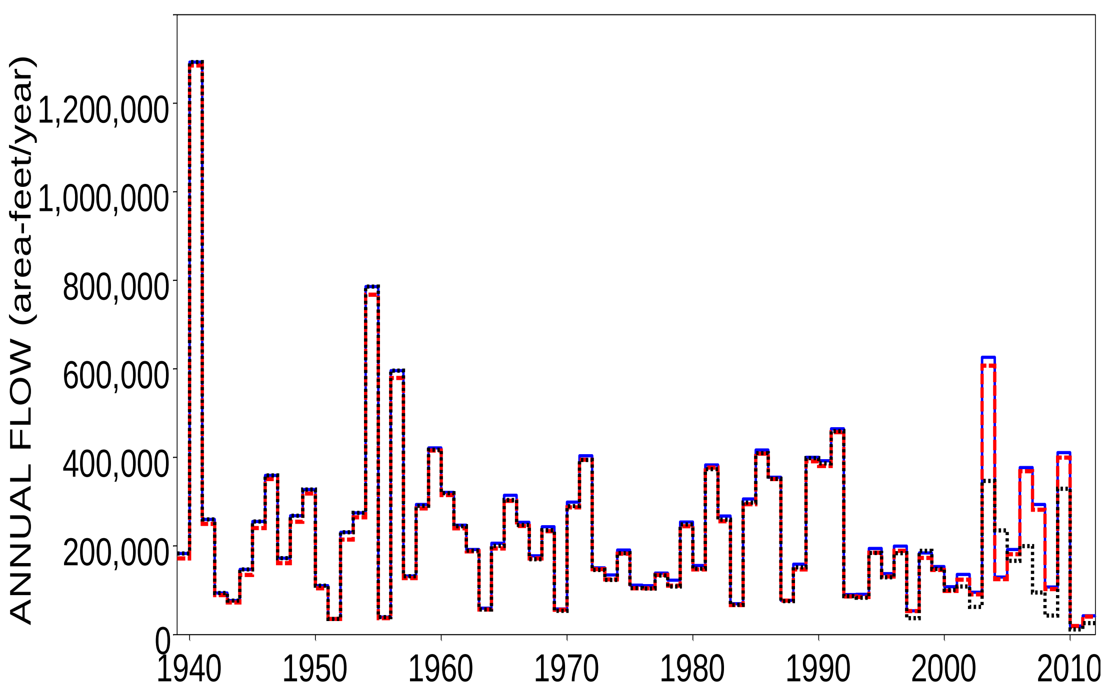
Naturalized (blue solid), Regulated (red dashed), and Observed (black dotted) 2-Month Minimum Annual Flows for Colorado River near Bay City



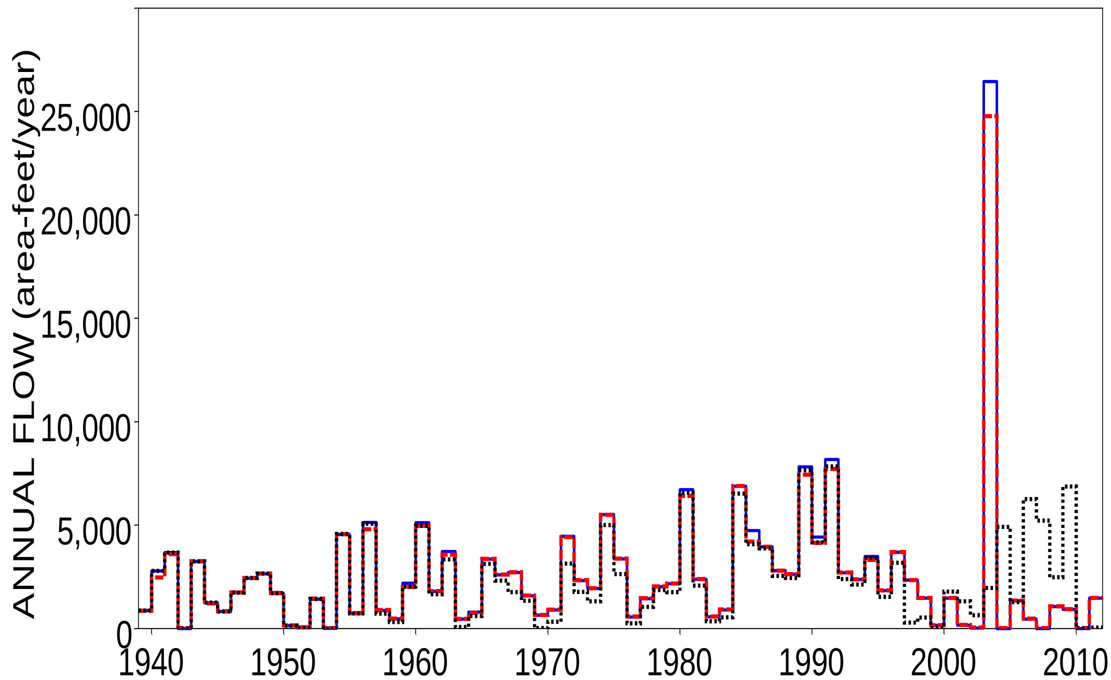
Naturalized (blue solid), Regulated (red dashed), and Observed (black dotted) 2-Month Maximum Annual Flows for Colorado River near Bay City



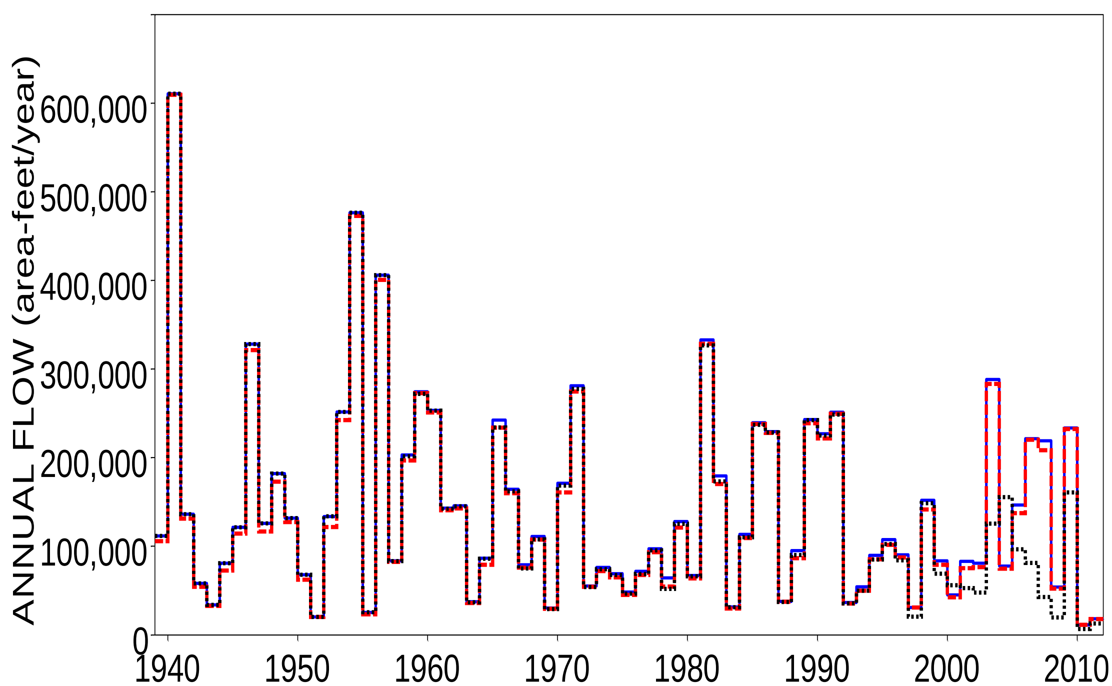
Naturalized Flows of Brazos River at Seymour



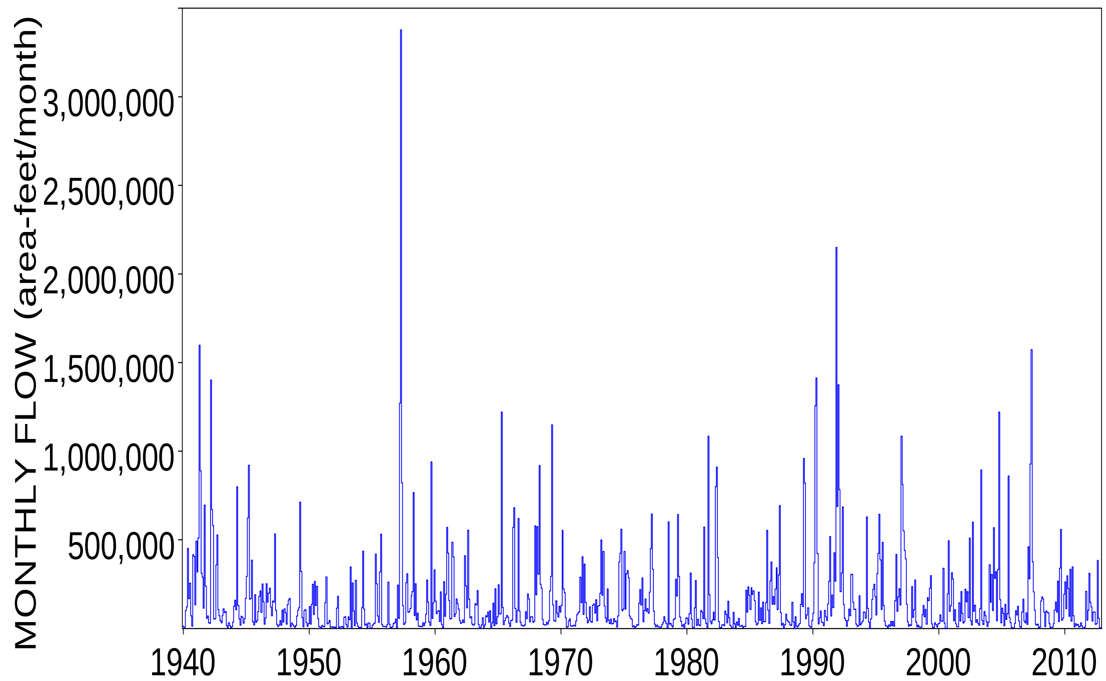
Naturalized (blue solid), Regulated (red dashed), and Observed (black dotted) Annual Flows for Brazos River at Seymour



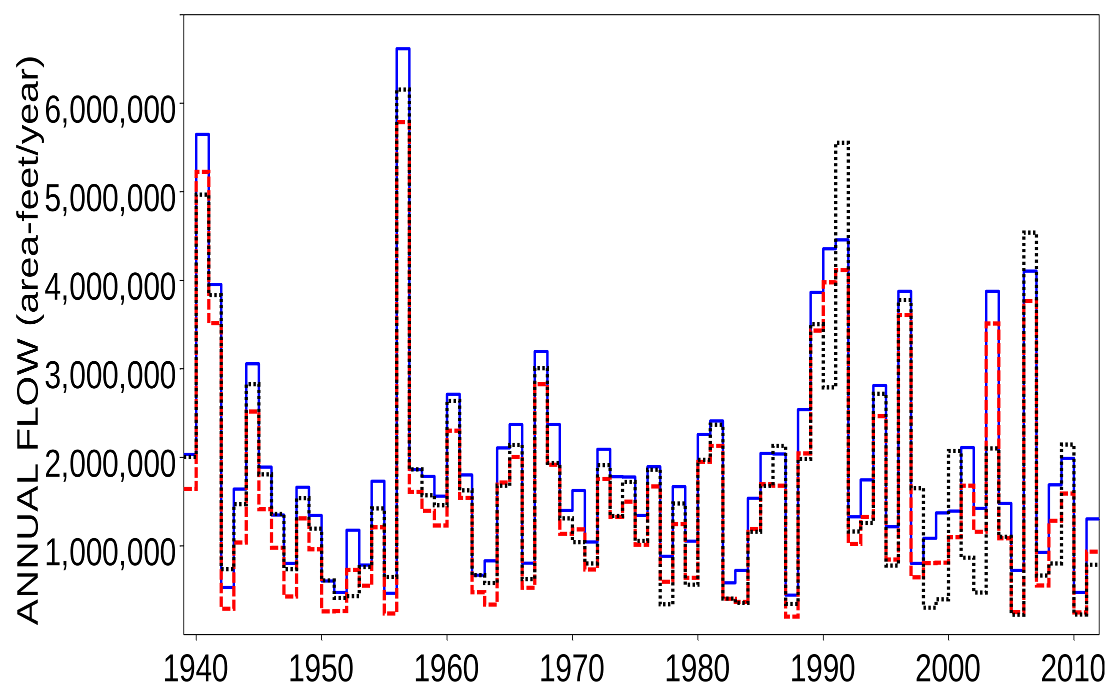
Naturalized (blue solid), Regulated (red dashed), and Observed (black dotted) 2-Month Minimum Annual Flows for Brazos River at Seymour



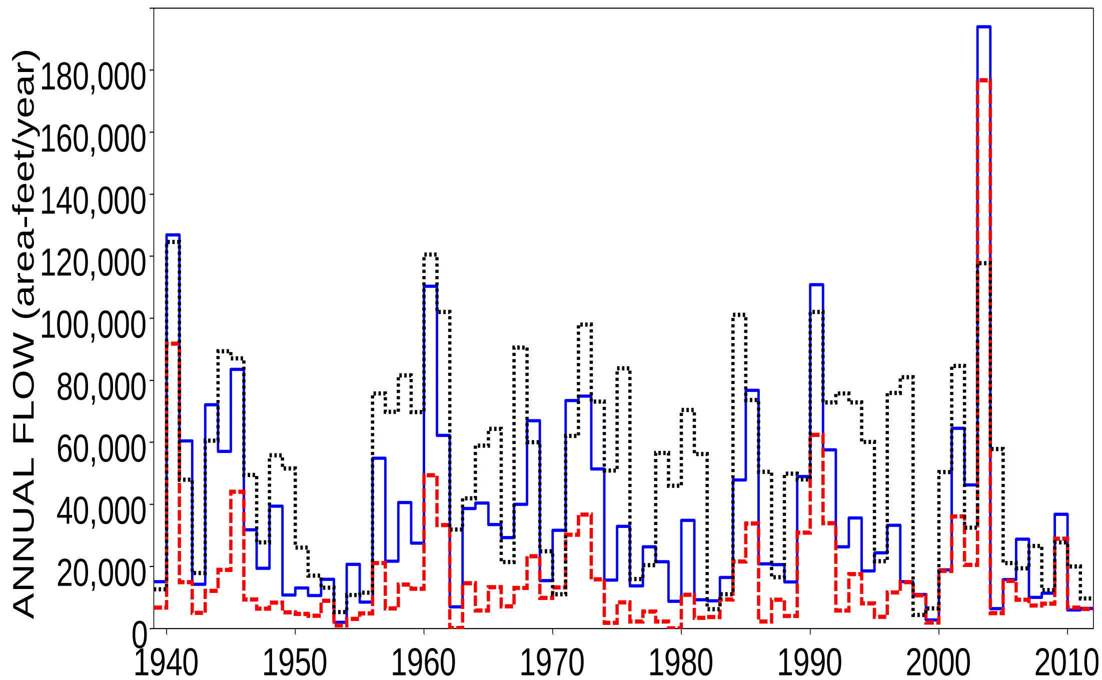
Naturalized (blue solid), Regulated (red dashed), and Observed (black dotted) 2-Month Maximum Annual Flows for Brazos River at Seymour



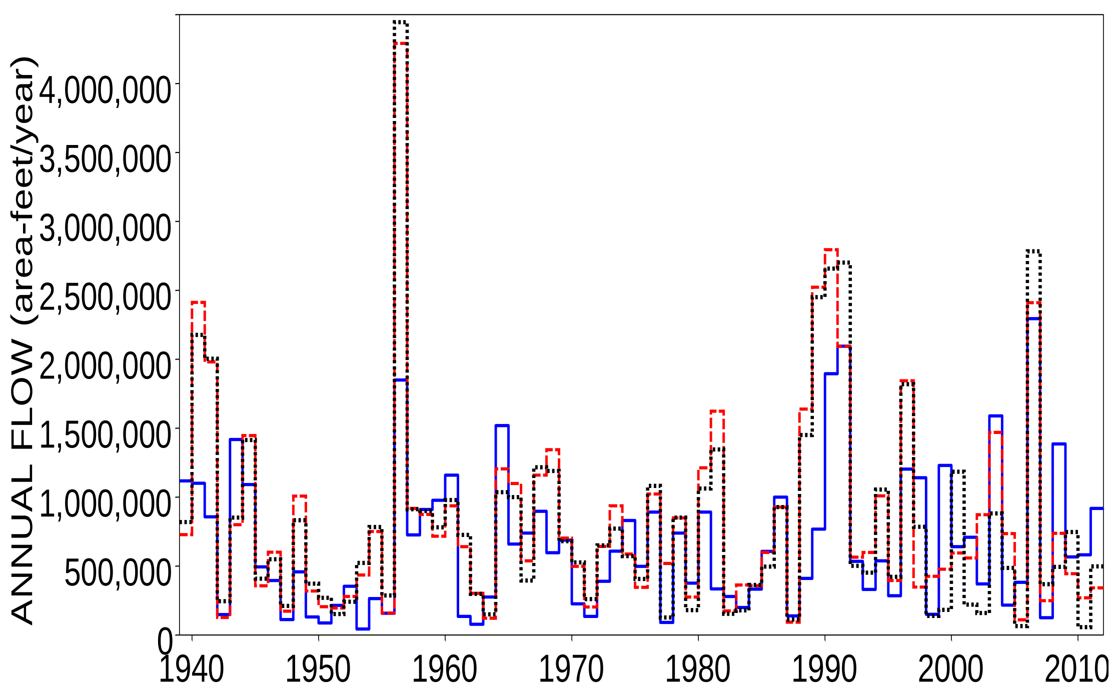
Naturalized Flows of Brazos River Waco



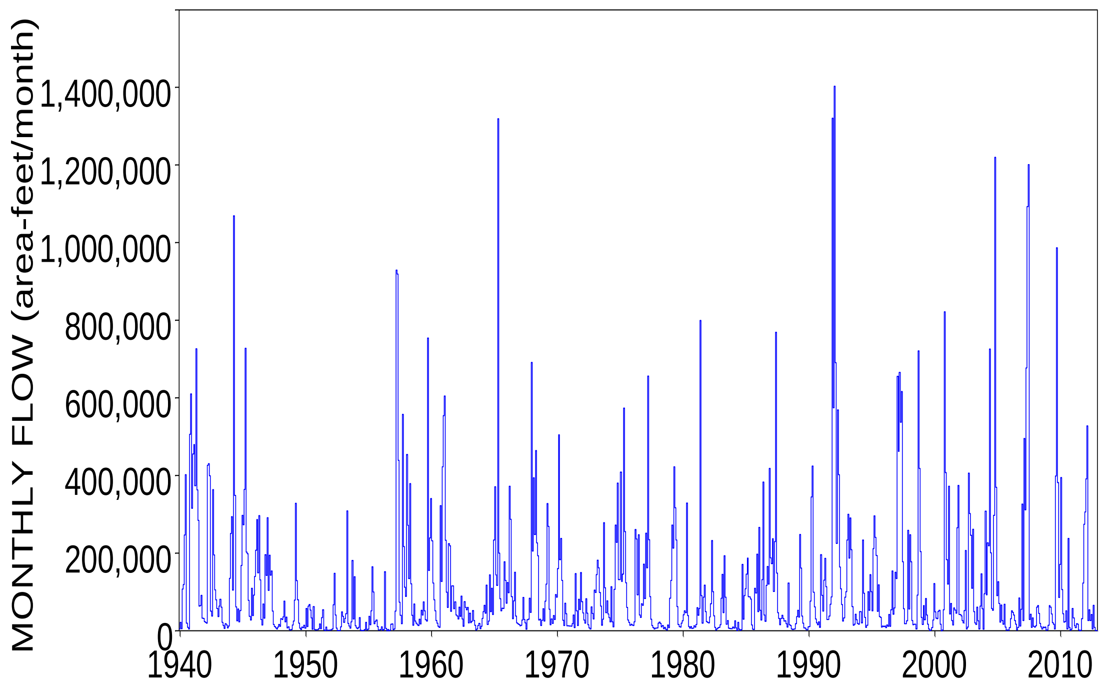
Naturalized (blue solid), Regulated (red dashed), and Observed (black dotted) Annual Flows for Brazos River Waco



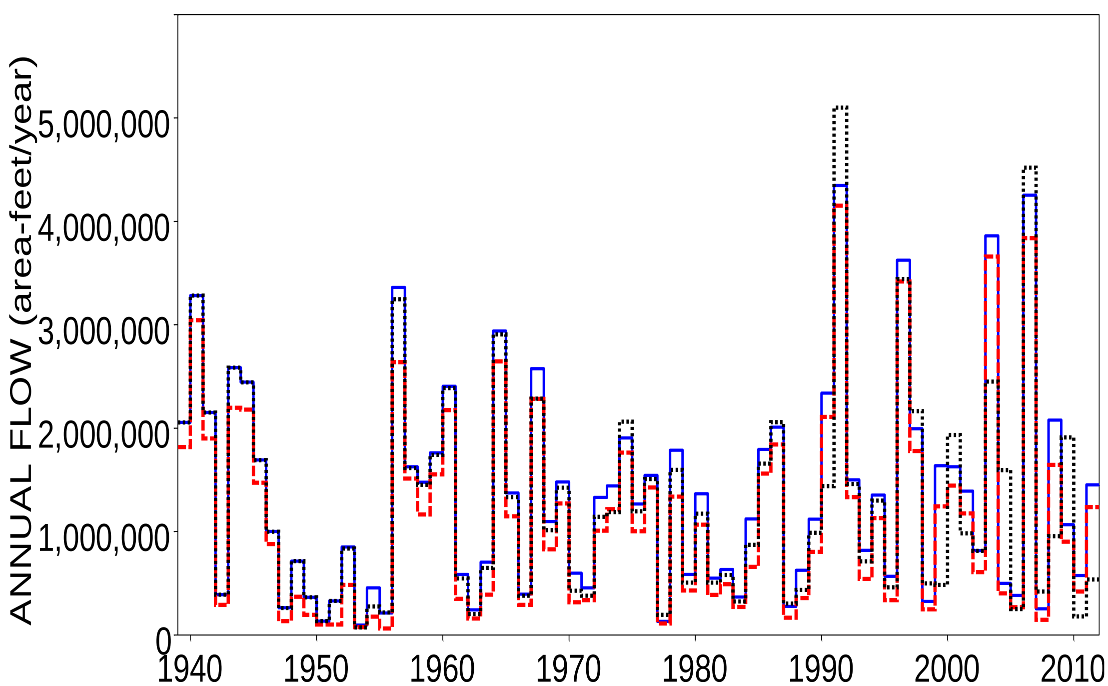
Naturalized (blue solid), Regulated (red dashed), and Observed (black dotted) 2-Month Minimum Annual Flows for Brazos River Waco



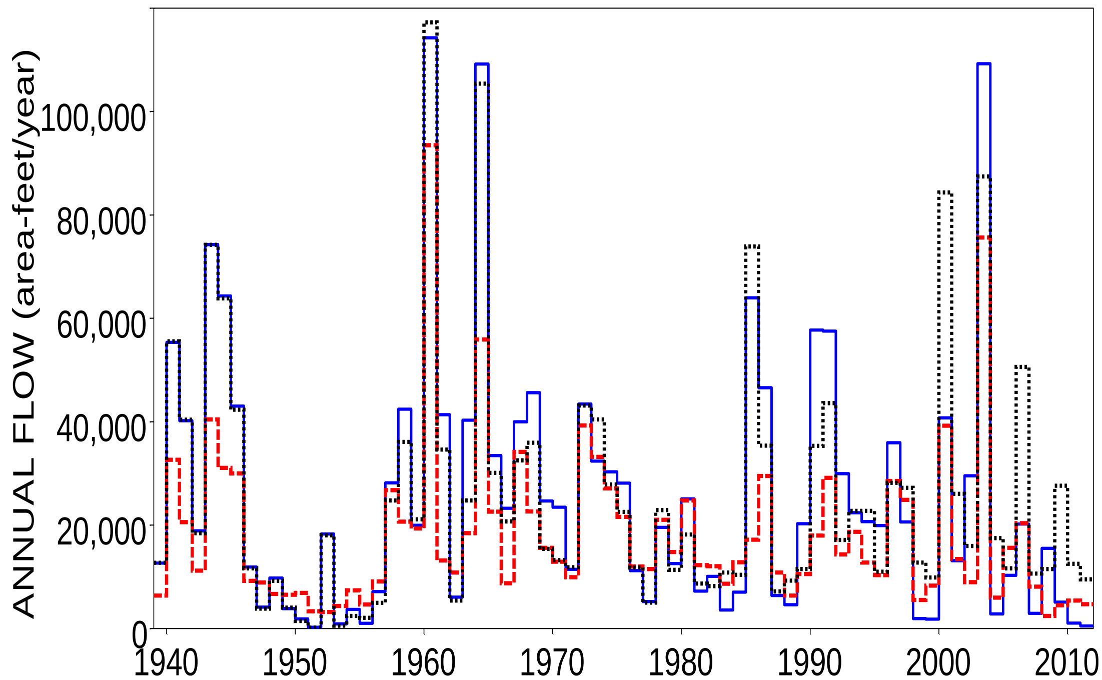
Naturalized (blue solid), Regulated (red dashed), and Observed (black dotted) 2-Month Maximum Annual Flows for Brazos River Waco



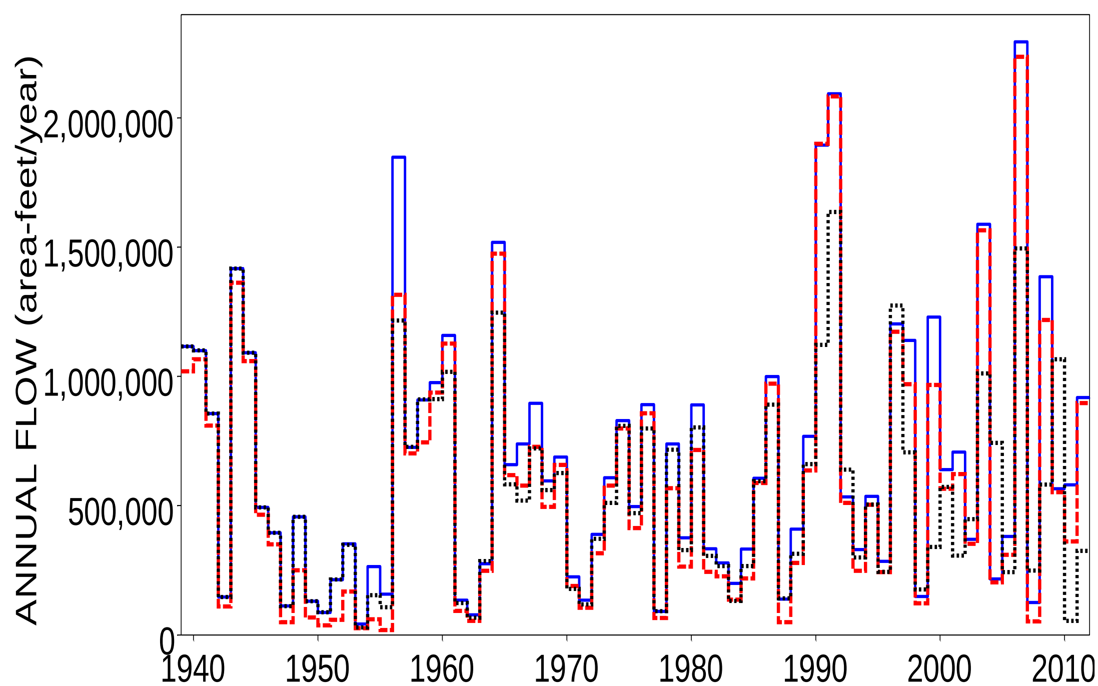
Naturalized Flows of Little River at Cameron



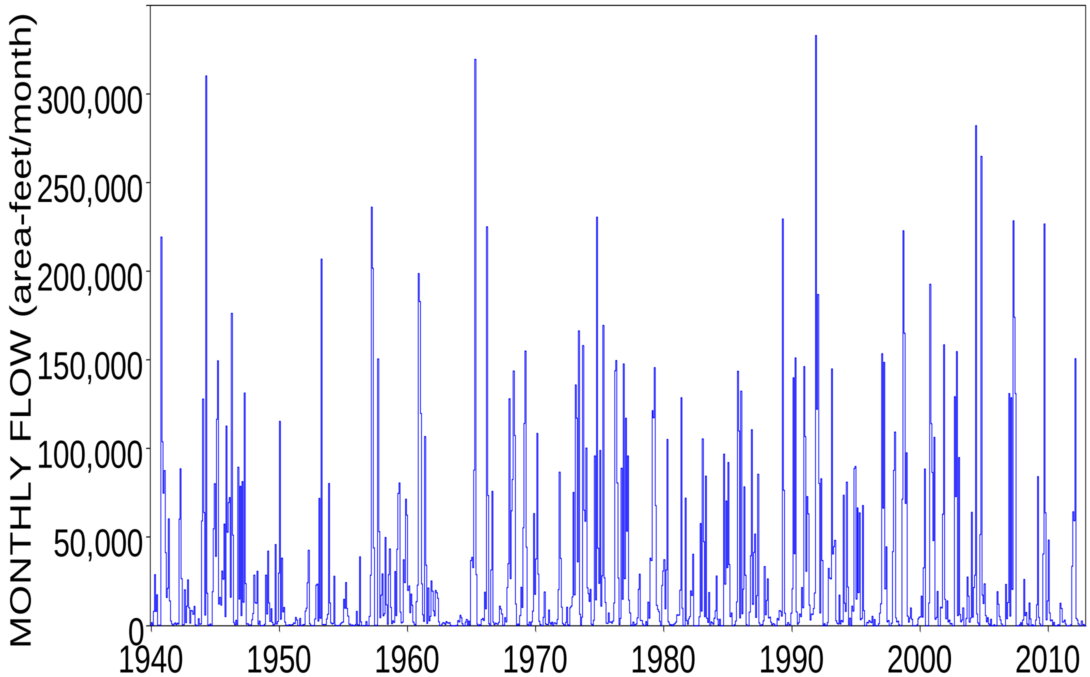
Naturalized (blue solid), Regulated (red dashed), and Observed (black dotted) Annual Flows for Little River at Cameron



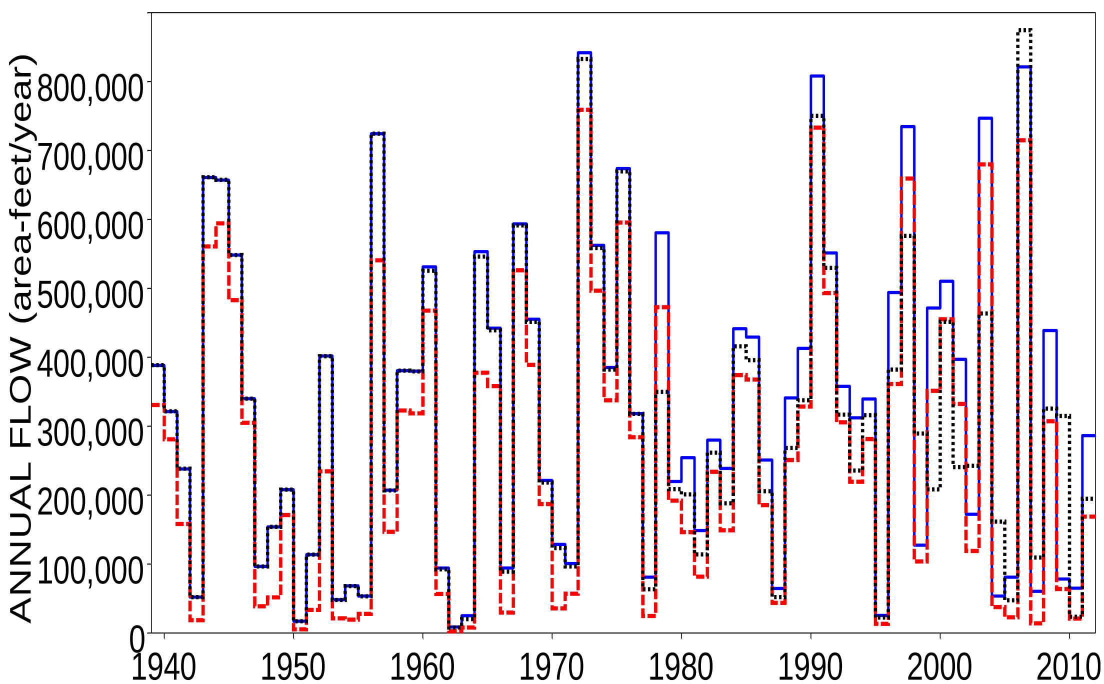
Naturalized (blue solid), Regulated (red dashed), and Observed (black dotted) 2-Month Minimum Annual Flows for Little River at Cameron



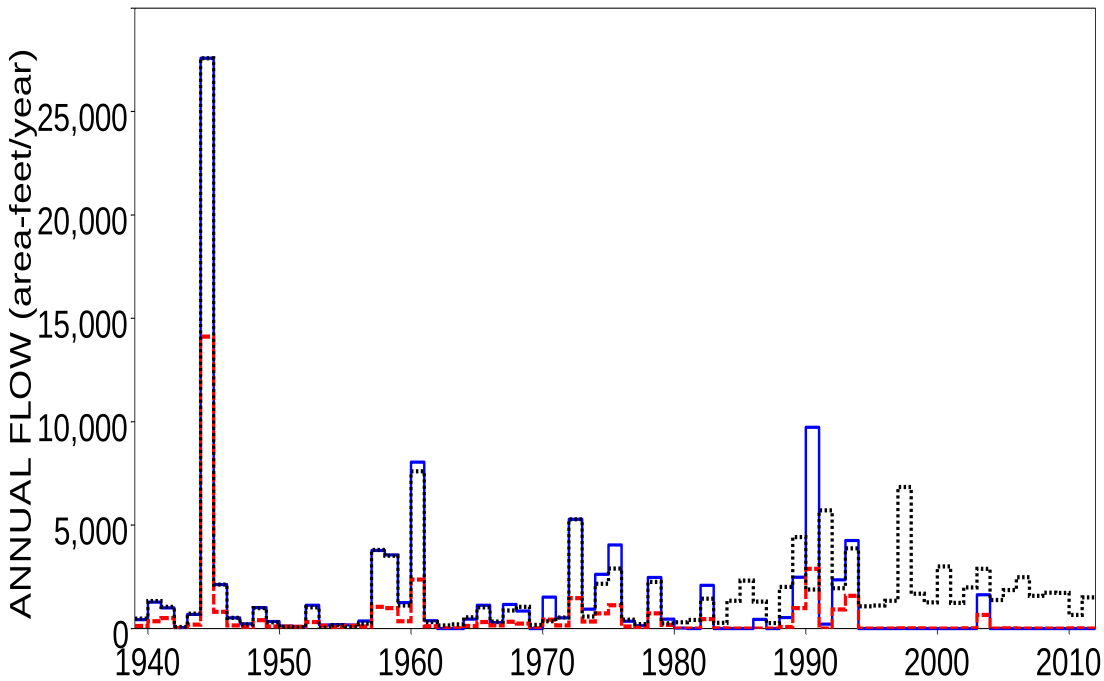
Naturalized (blue solid), Regulated (red dashed), and Observed (black dotted) 2-Month Maximum Annual Flows for Little River at Cameron



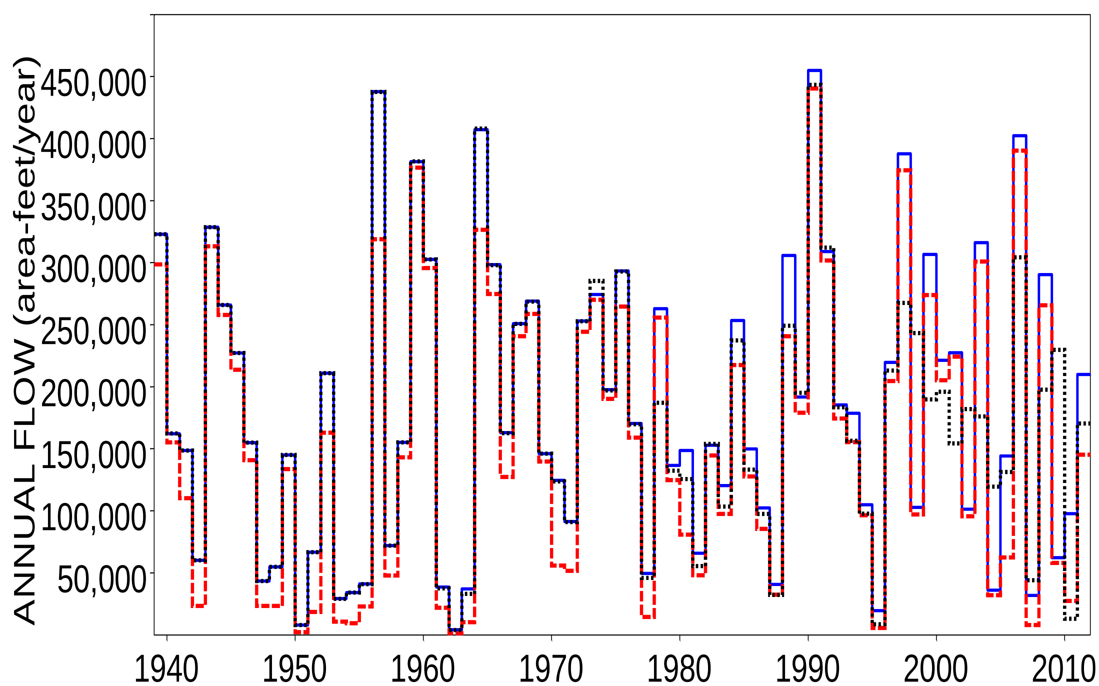
Naturalized Flows of Navasota River at Easterly



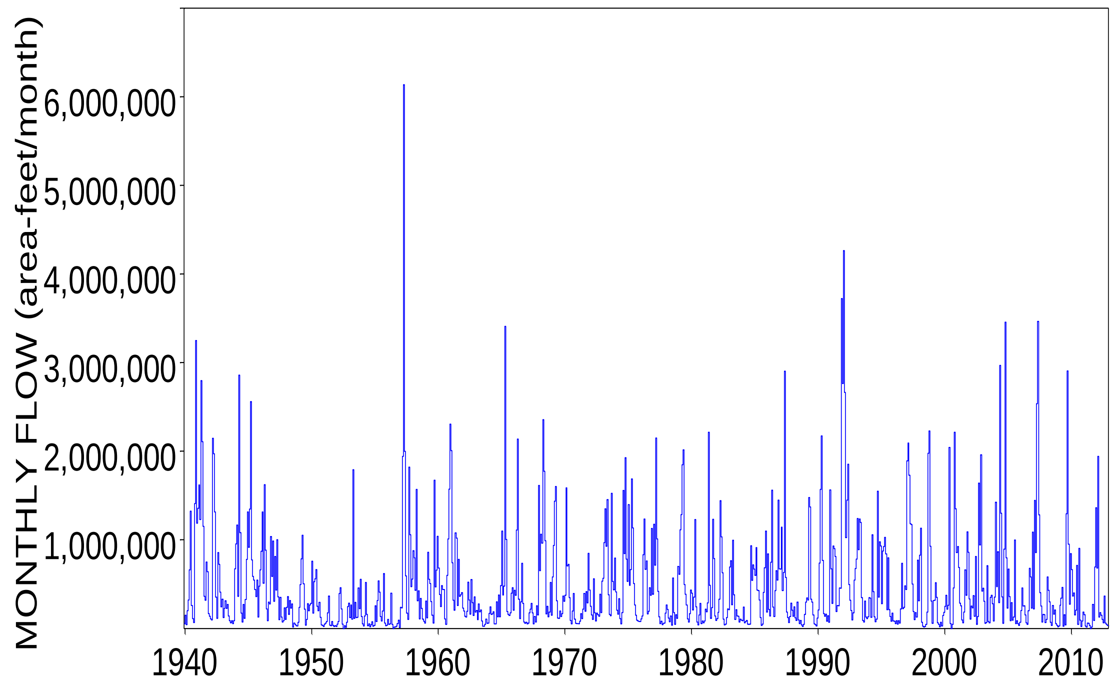
Naturalized (blue solid), Regulated (red dashed), and Observed (black dotted) Annual Flows for Navasota River at Easterly



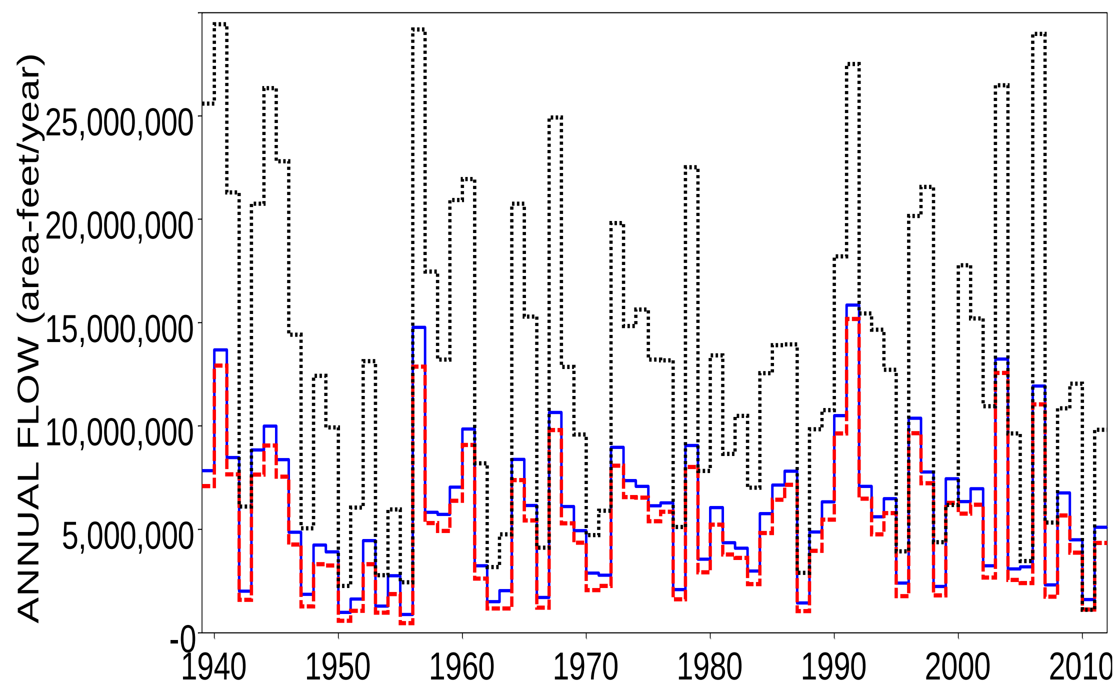
Naturalized (blue solid), Regulated (red dashed), and Observed (black dotted) 2-Month Minimum Annual Flows for Navasota River at Easterly



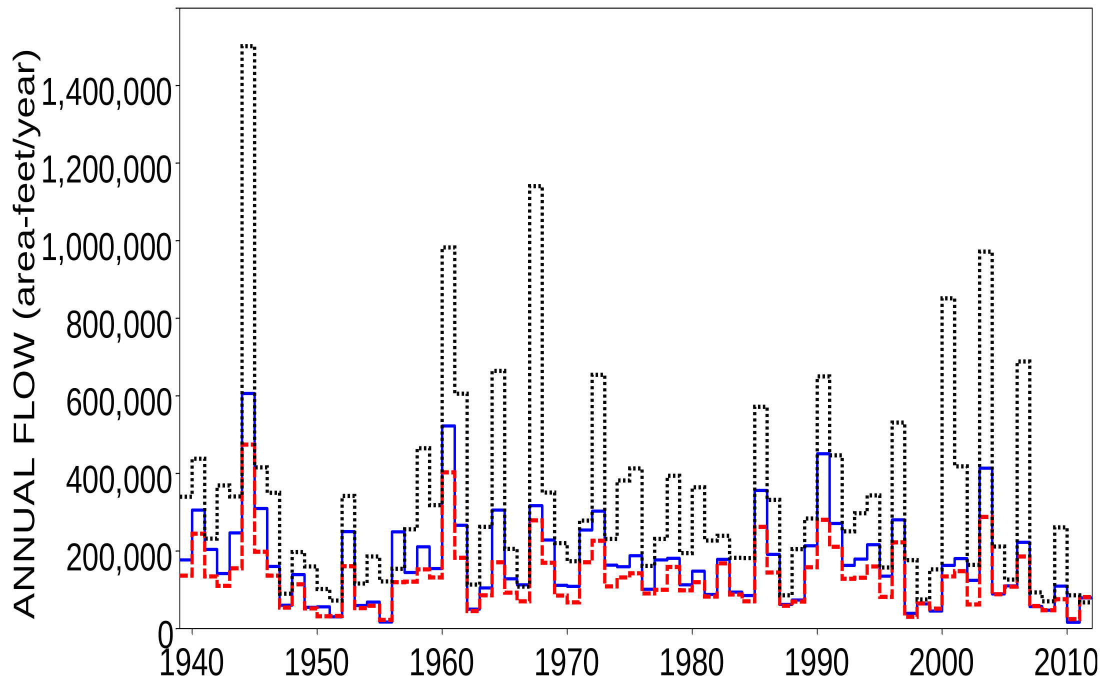
Naturalized (blue solid), Regulated (red dashed), and Observed (black dotted) 2-Month Maximum Annual Flows for Navasota River at Easterly



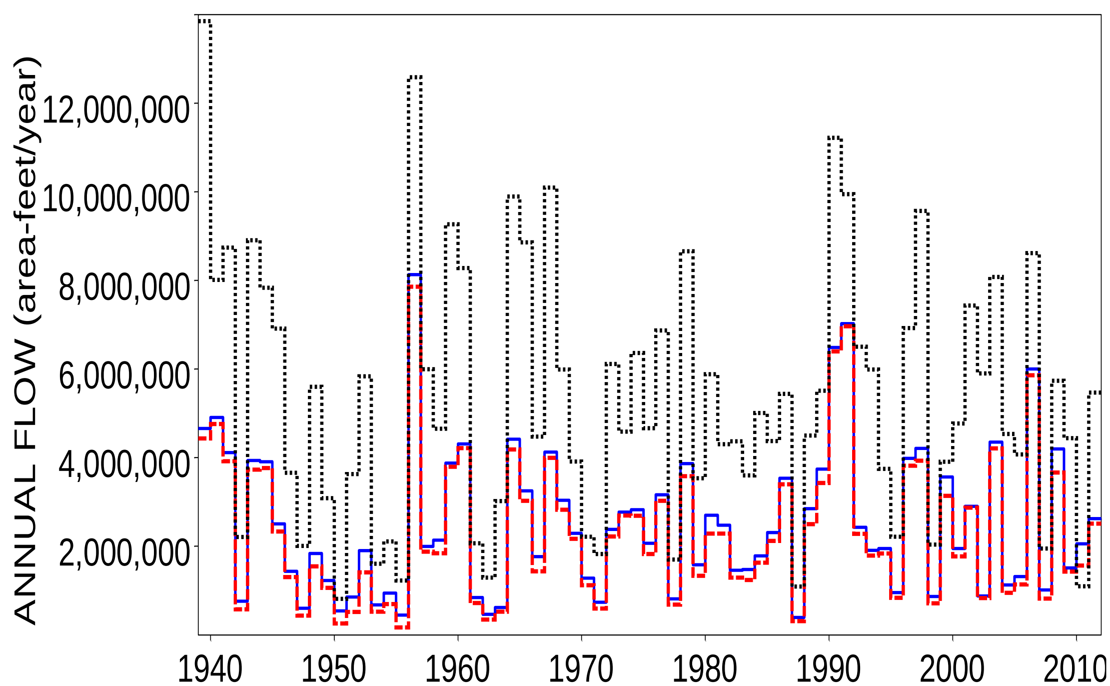
Naturalized Flows of Brazos River at Richmond



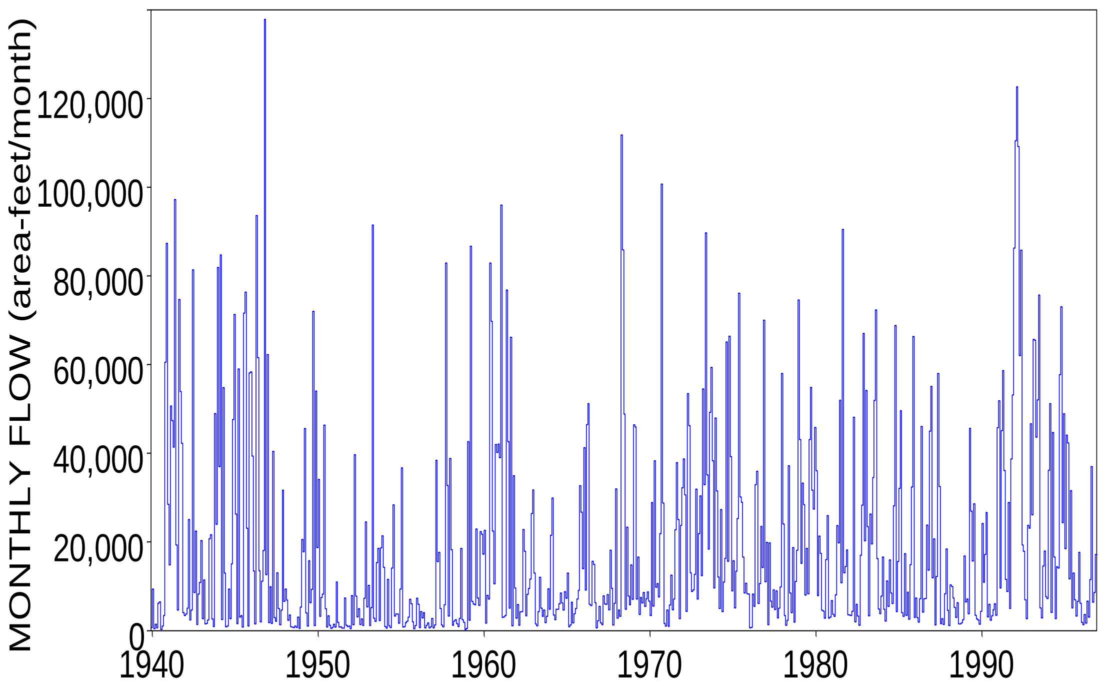
Naturalized (blue solid), Regulated (red dashed), and Observed (black dotted) Annual Flows for Brazos River at Richmond



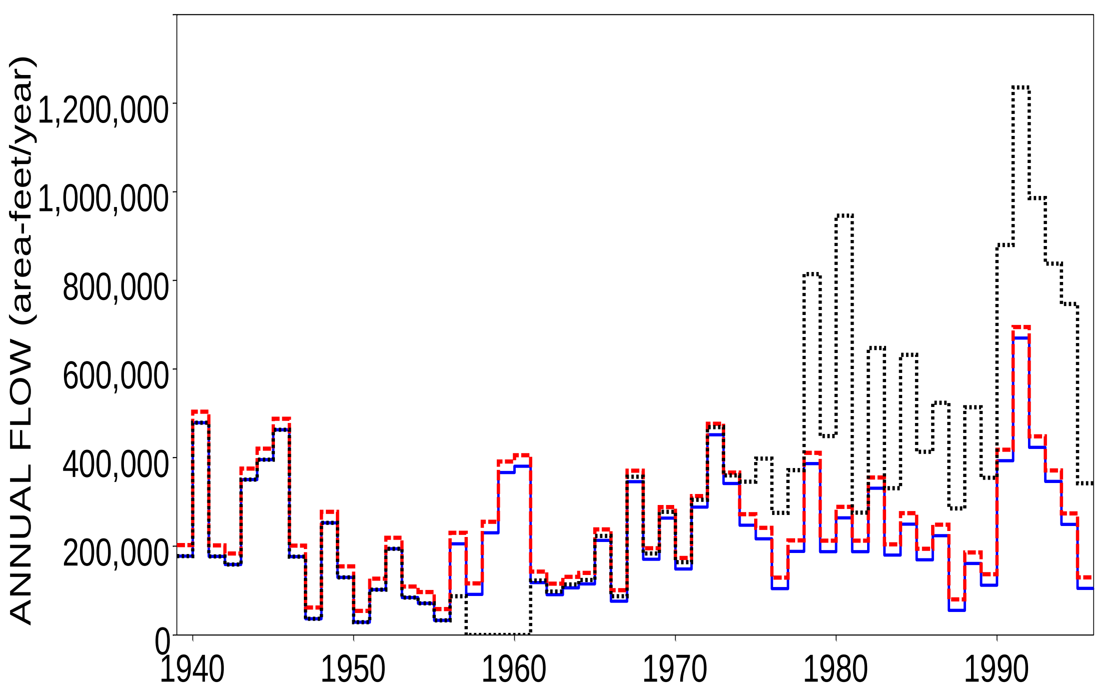
Naturalized (blue solid) and regulated (red dashed) Observed (black dotted) 2-Month Minimum Annual Flows for Brazos River at Richmond



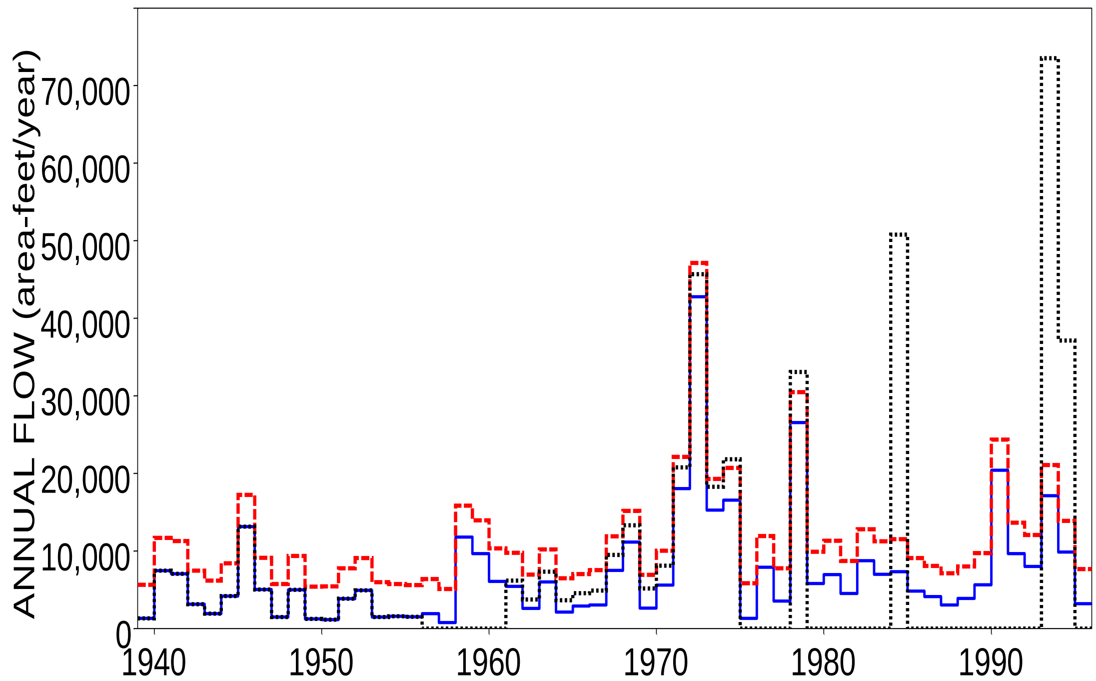
Naturalized (blue solid), Regulated (red dashed), and Observed (black dotted) 2-Month Maximum Annual Flows for Brazos River at Richmond



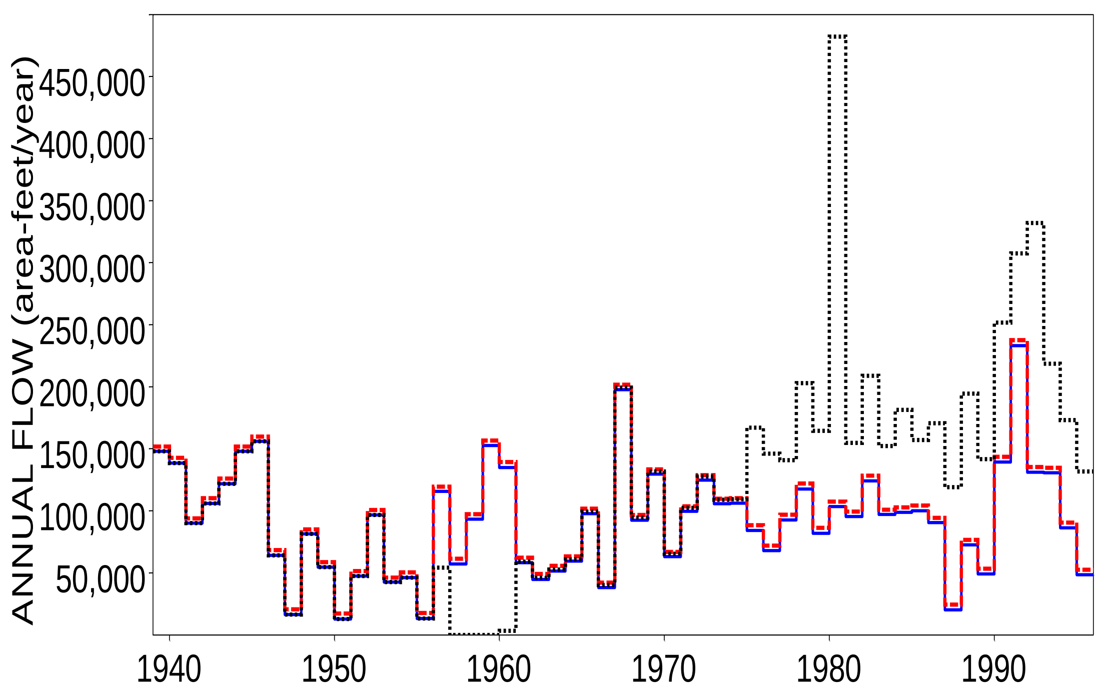
Naturalized Flows of Buffalo Bayou in Houston



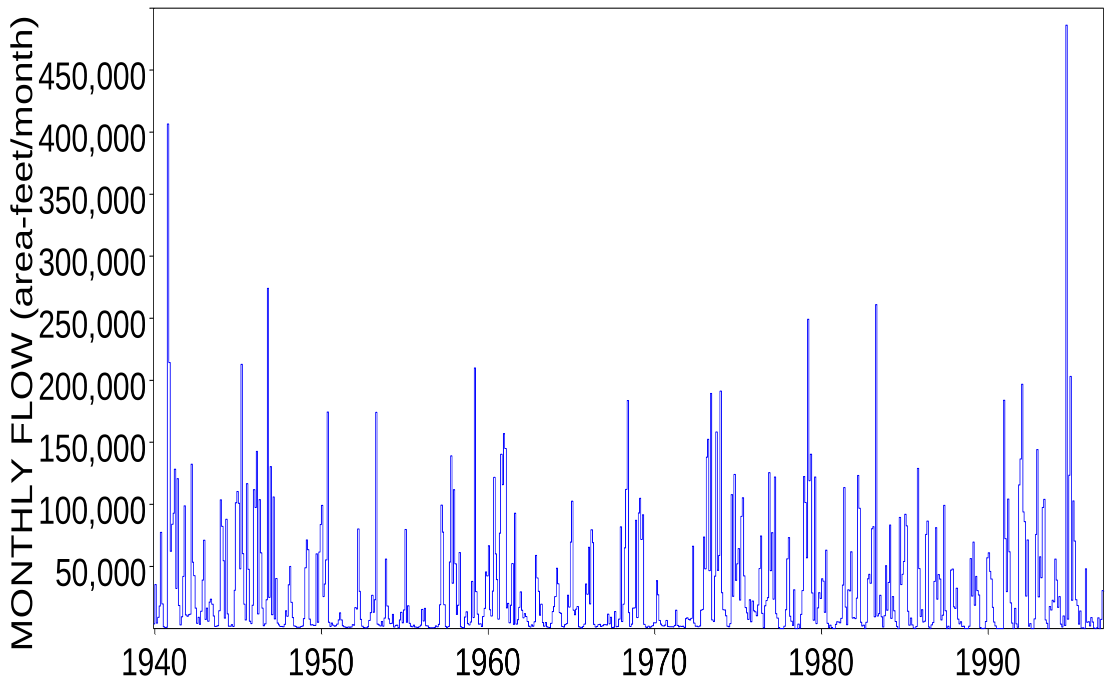
Naturalized (blue solid), Regulated (red dashed), and Observed (black dotted) Annual Flows for Buffalo Bayou in Houston



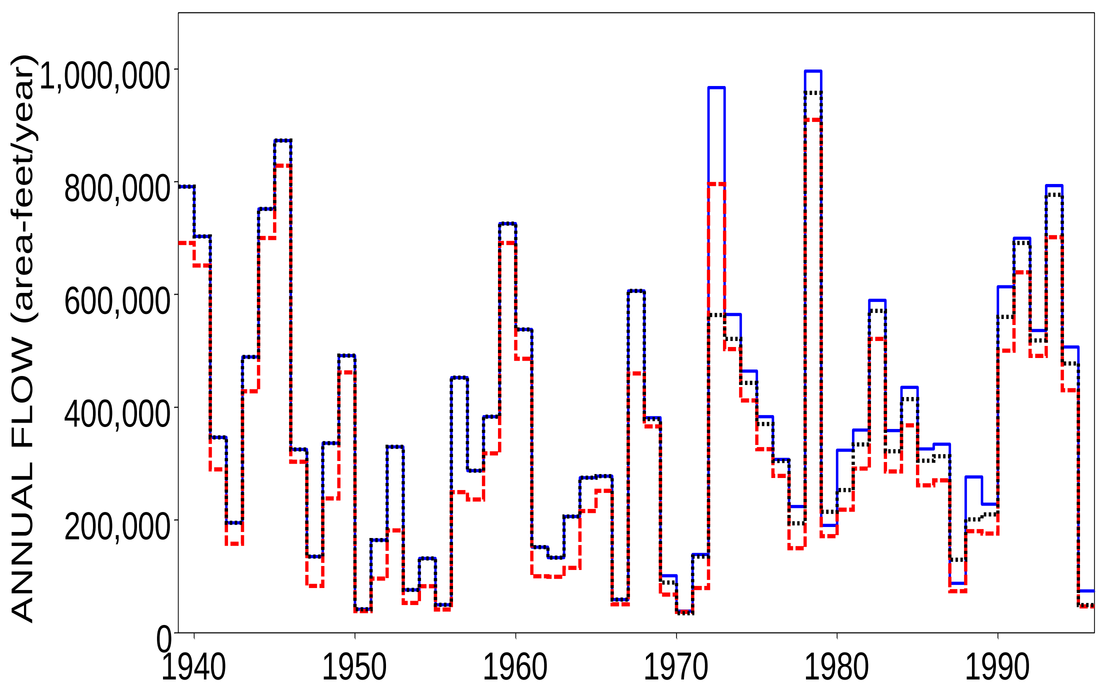
Naturalized (blue solid), Regulated (red dashed), and Observed (black dotted) 2-Month Minimum Annual Flows for Buffalo Bayou in Houston



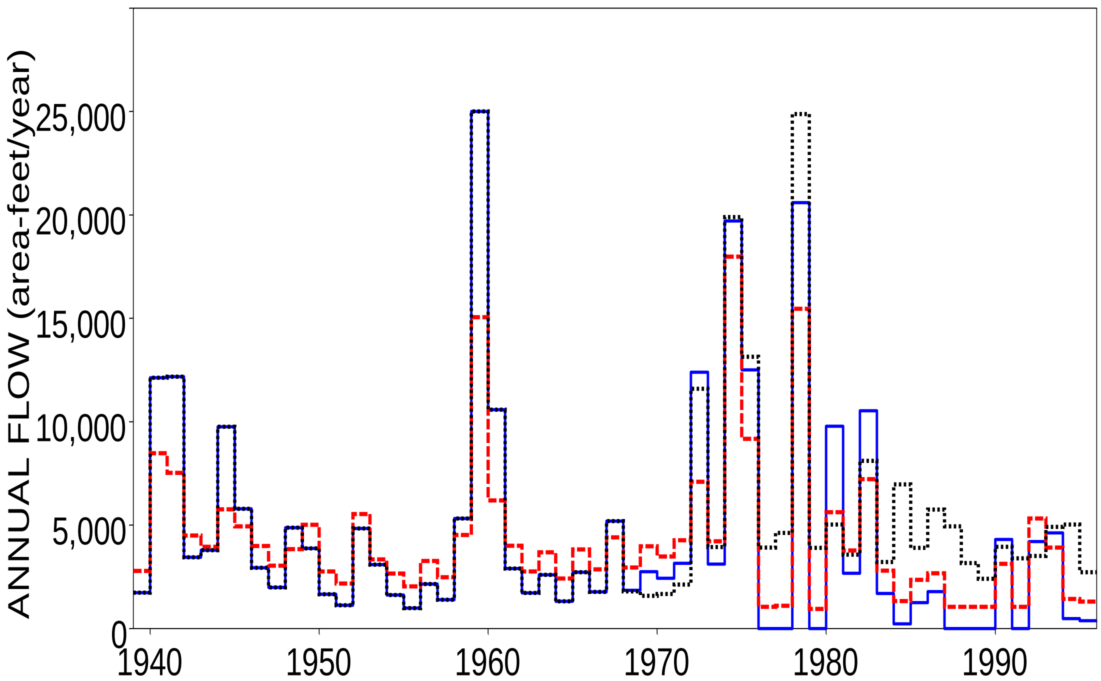
Naturalized (blue solid), Regulated (red dashed), and Observed (black dotted) 2-Month Maximum Annual Flows for Buffalo Bayou in Houston



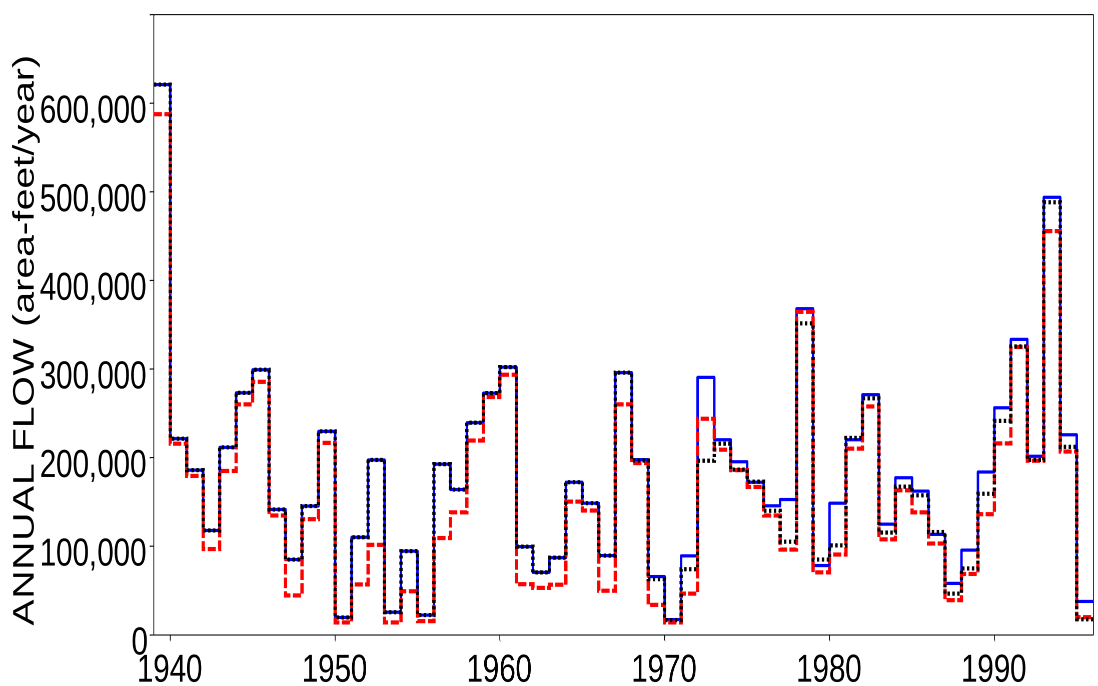
Naturalized Flows of West Fork San Jacinto near Conroe



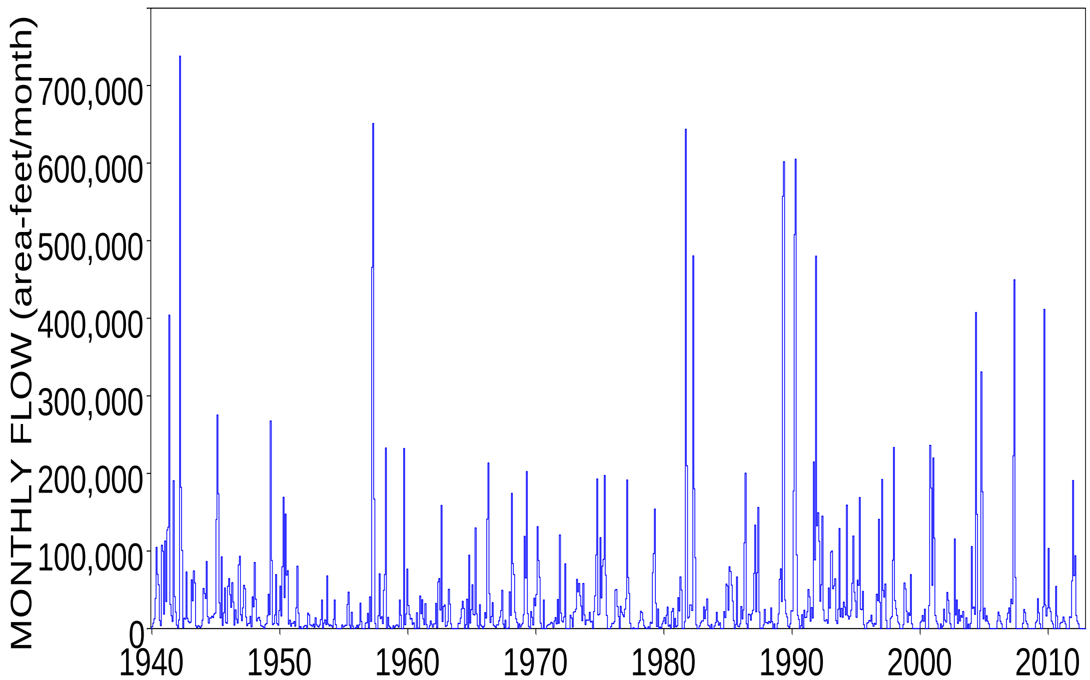
Naturalized (blue solid), Regulated (red dashed), and Observed (black dotted) Annual Flows for West Fork San Jacinto near Conroe



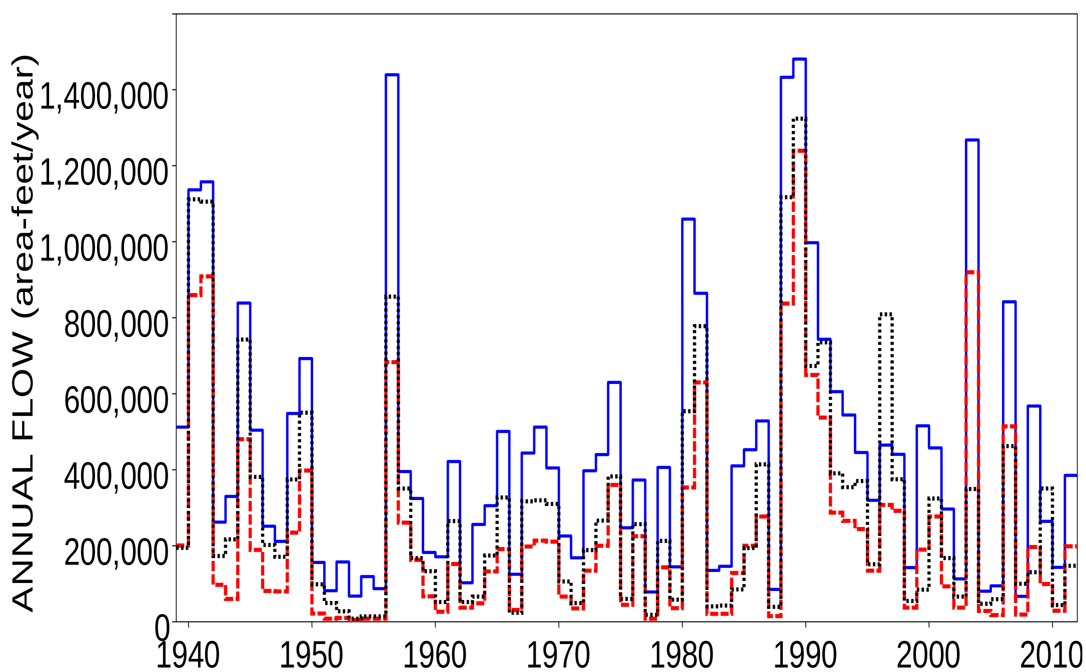
Naturalized (blue solid) and regulated (red dashed) Observed (black dotted) 2-Month Minimum Annual Flows for West Fork San Jacinto near Conroe



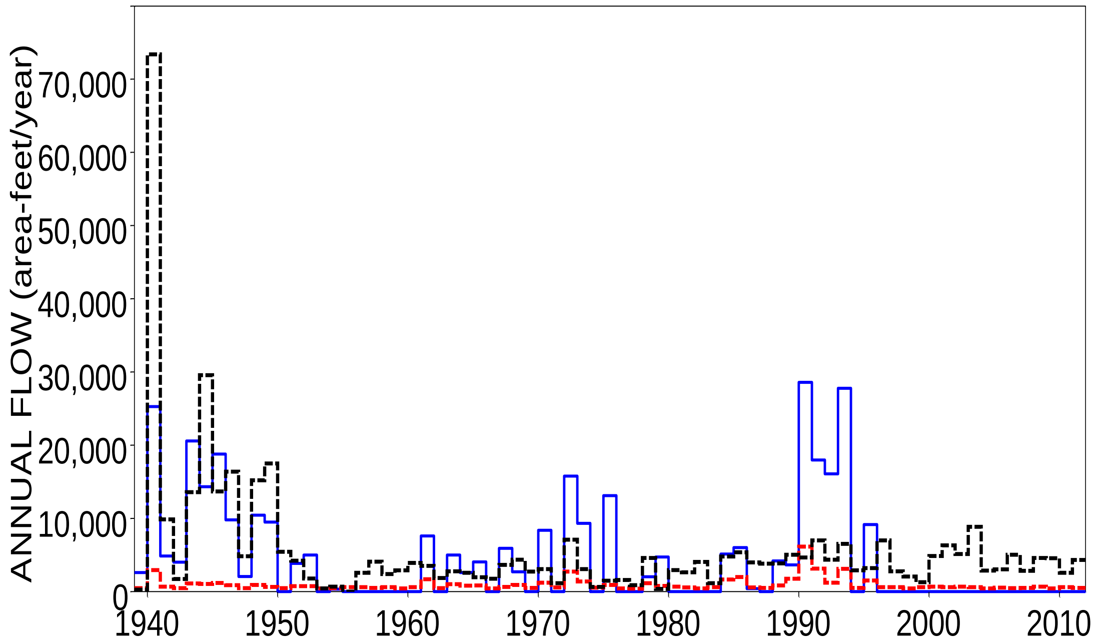
Naturalized (blue solid), Regulated (red dashed), and Observed (black dotted) 2-Month Maximum Annual Flows for West Fork San Jacinto near Conroe



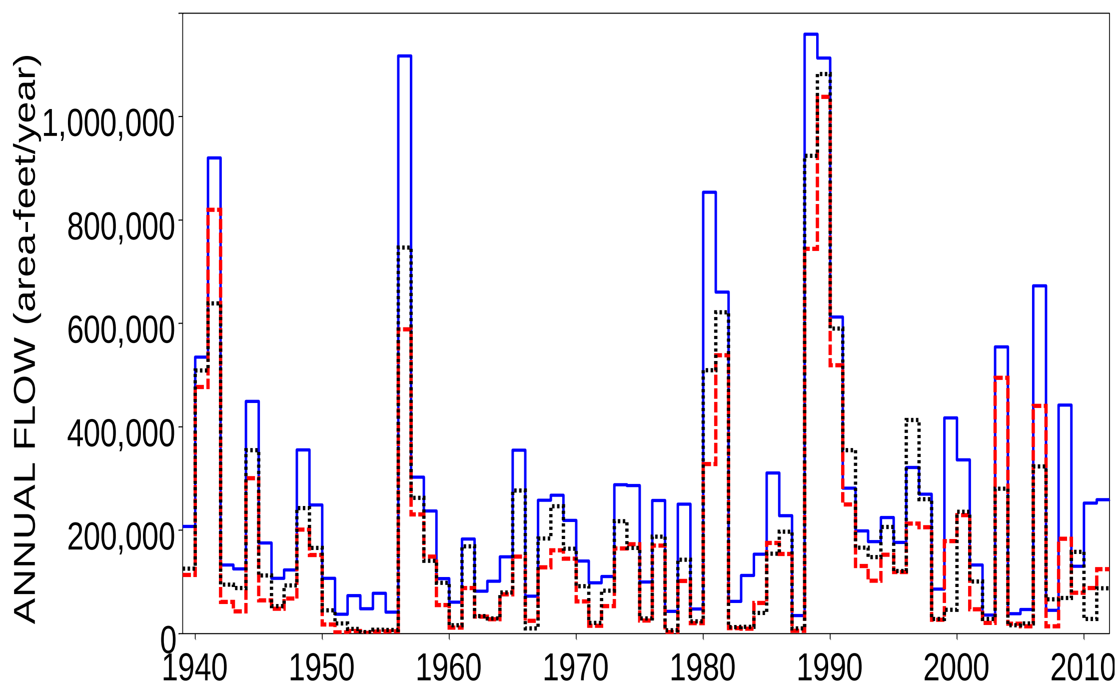
Naturalized Flows of West Fork Trinity at Fort Worth



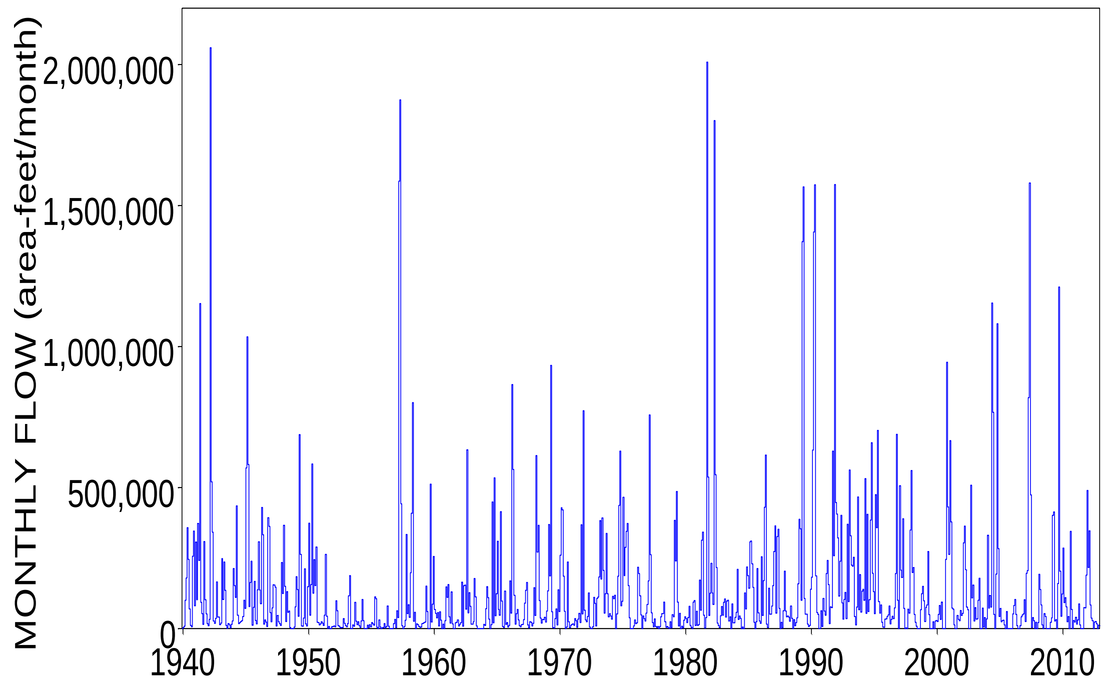
Naturalized (blue solid), Regulated (red dashed), and Observed (black dotted) Annual Flows for West Fork Trinity at Fort Worth



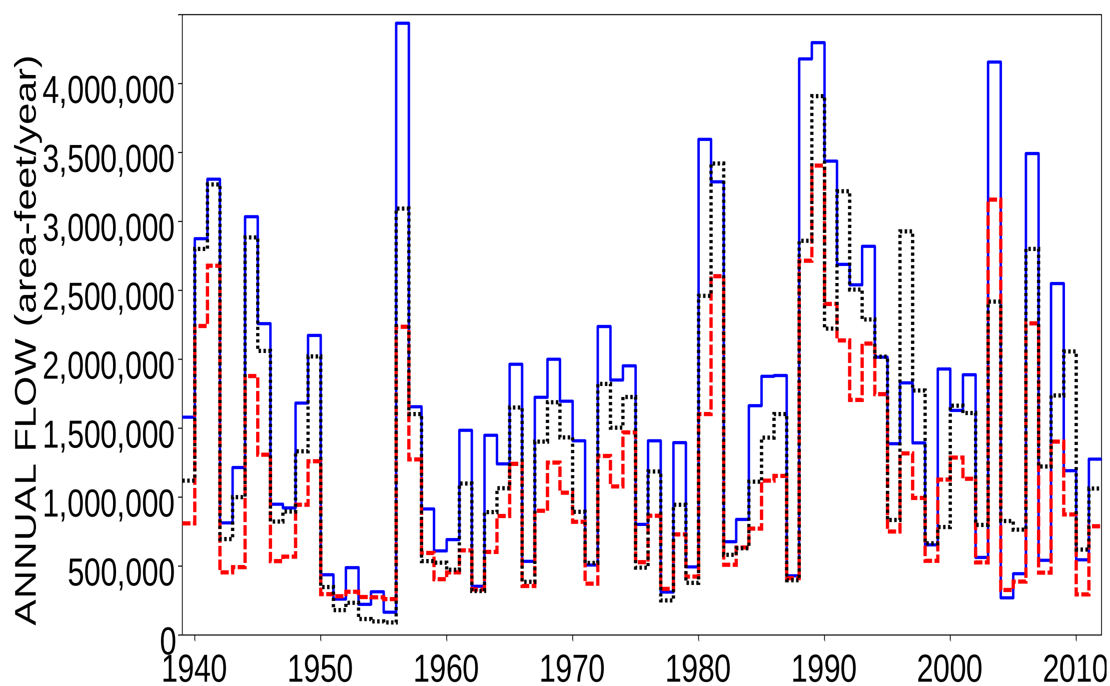
Naturalized (blue solid), Regulated (red dashed), and Observed (black dotted) 2-Month Minimum Annual Flows for West Fork Trinity at Fort Worth



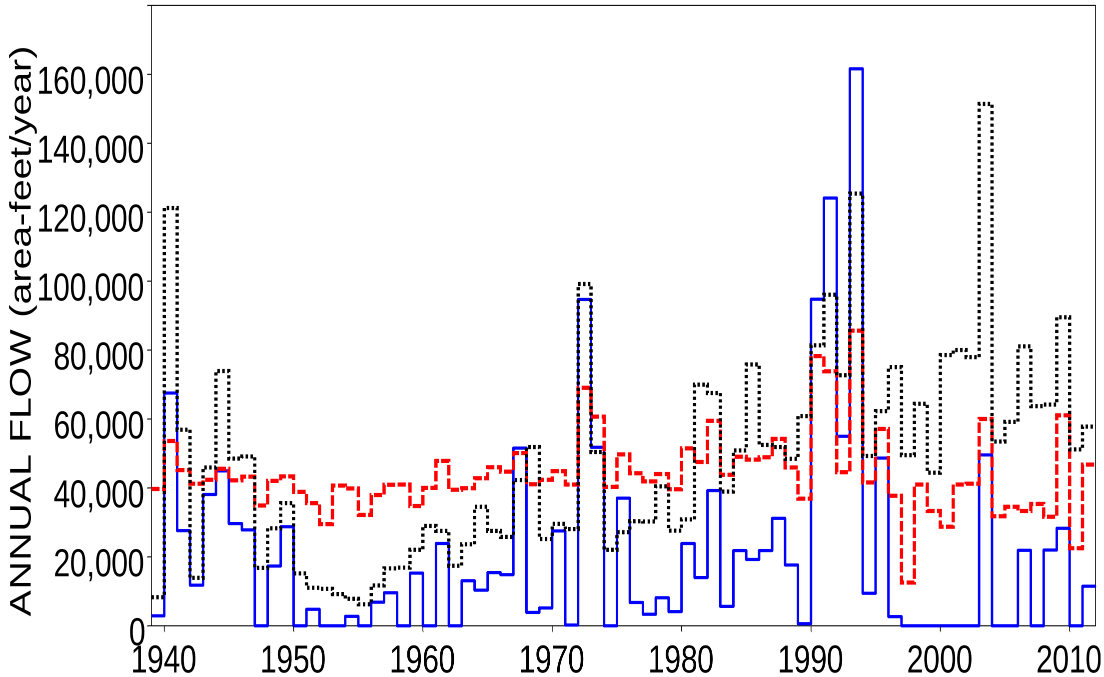
Naturalized (blue solid), Regulated (red dashed), and Observed (black dotted) 2-Month Maximum Annual Flows for West Fork Trinity at Fort Worth



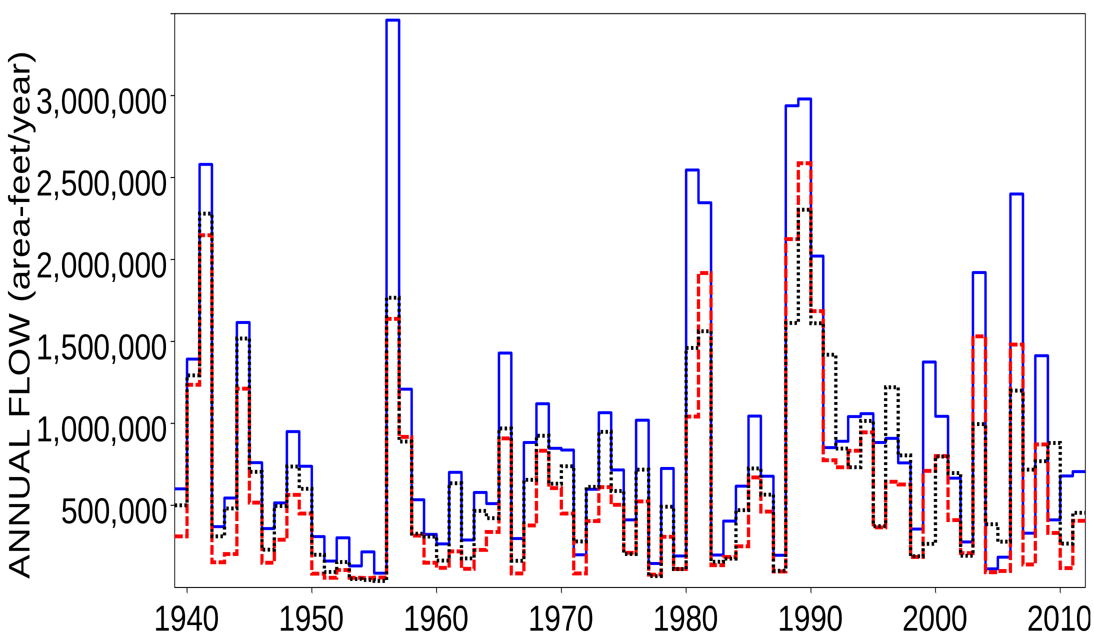
Naturalized Flows of Trinity River at Dallas



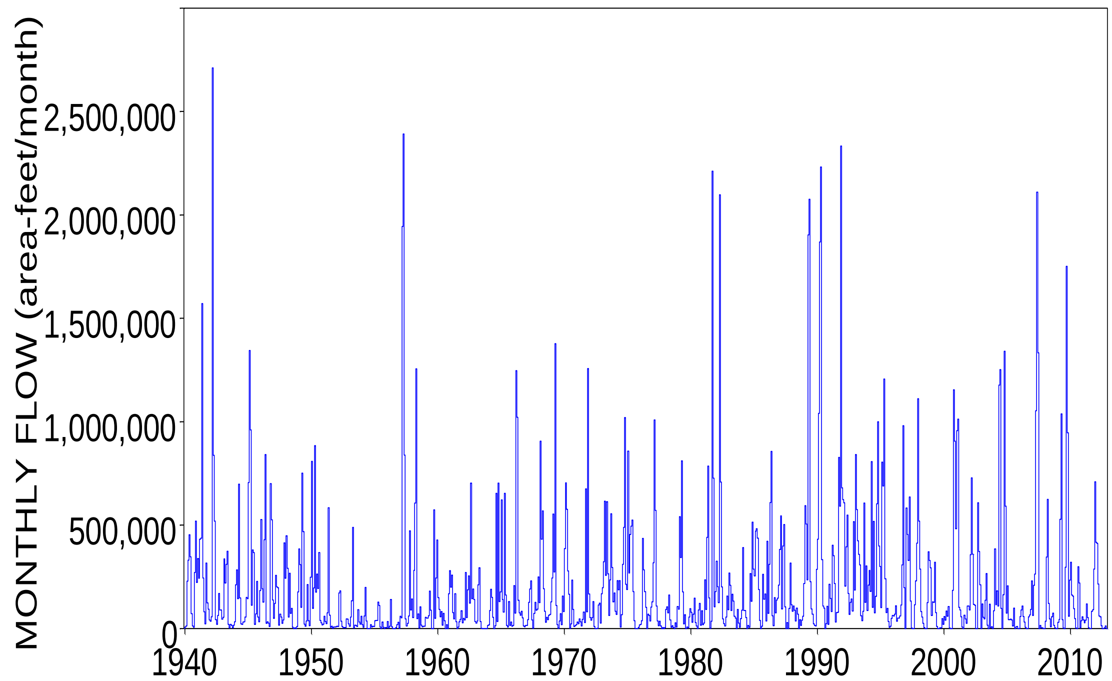
Naturalized (blue solid), Regulated (red dashed), and Observed (black dotted) Annual Flows for Trinity River at Dallas



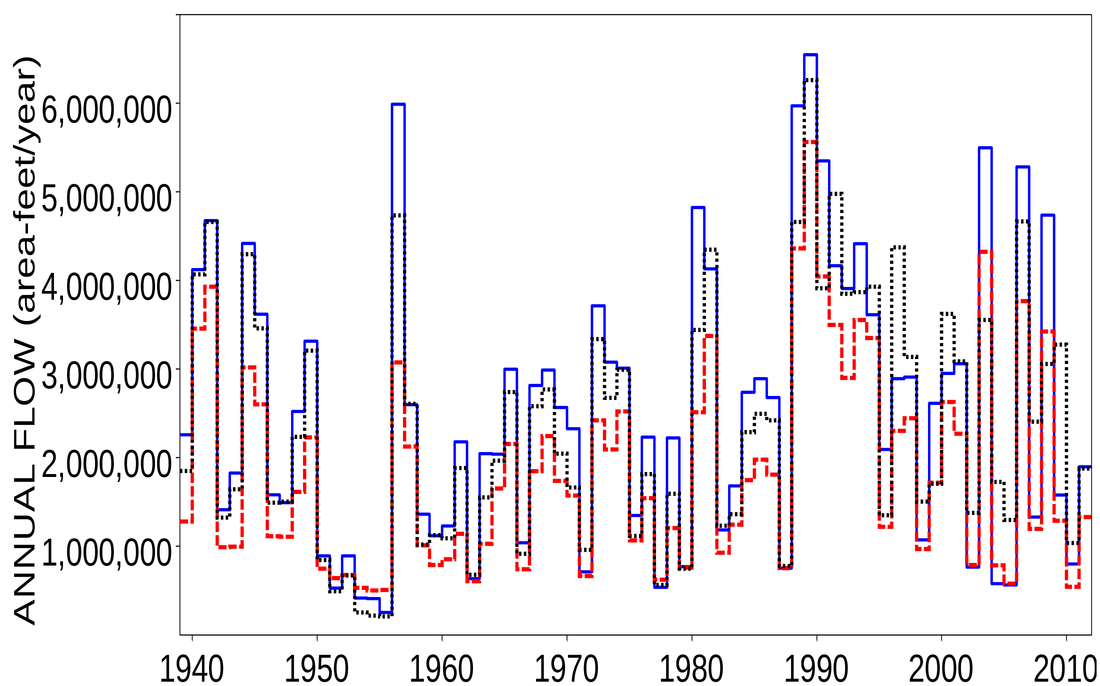
Naturalized (blue solid), Regulated (red dashed), and Observed (black dotted) 2-Month Minimum Annual Flows for Trinity River at Dallas



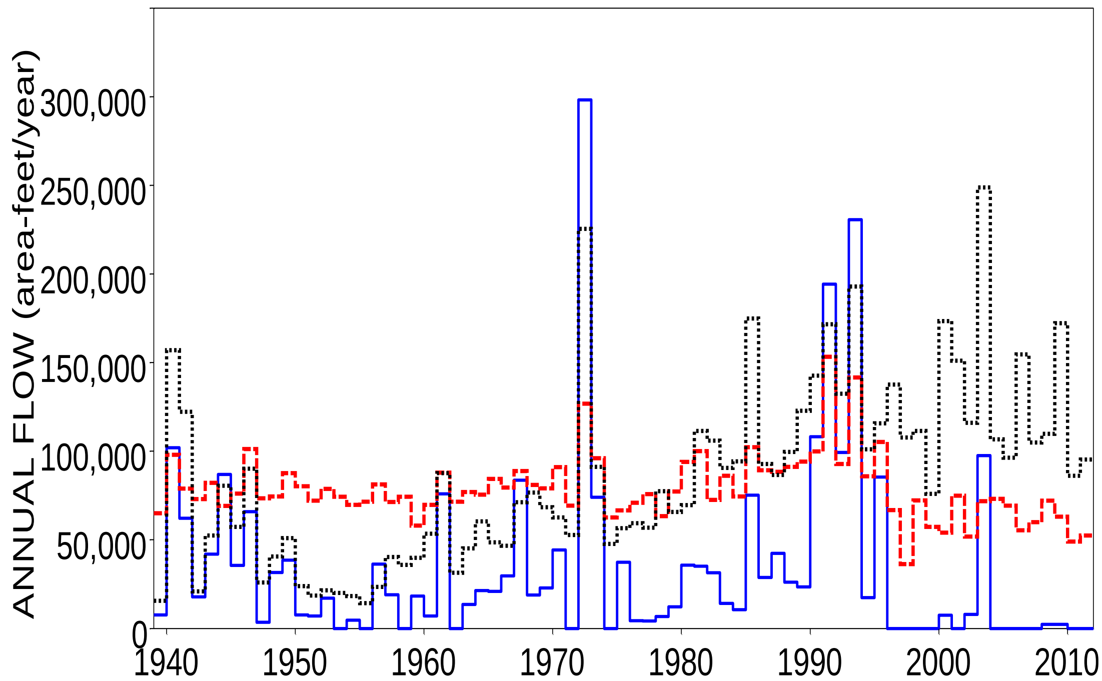
Naturalized (blue solid), Regulated (red dashed), and Observed (black dotted) 2-Month Maximum Annual Flows for Trinity River at Dallas



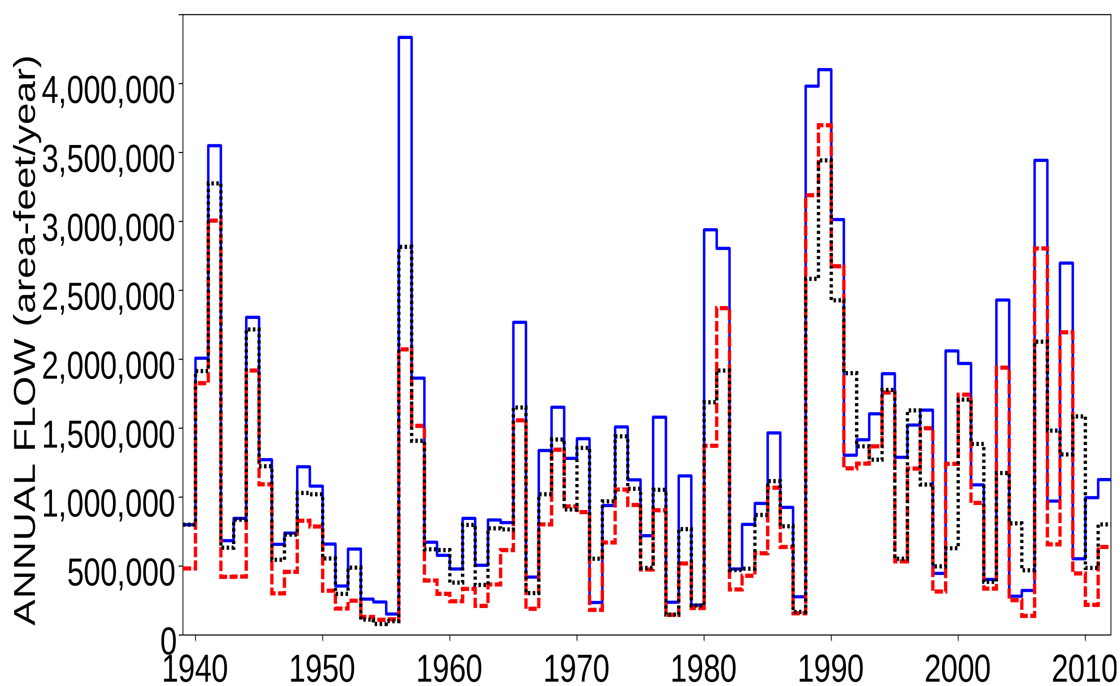
Naturalized Flows of Trinity River near Rosser



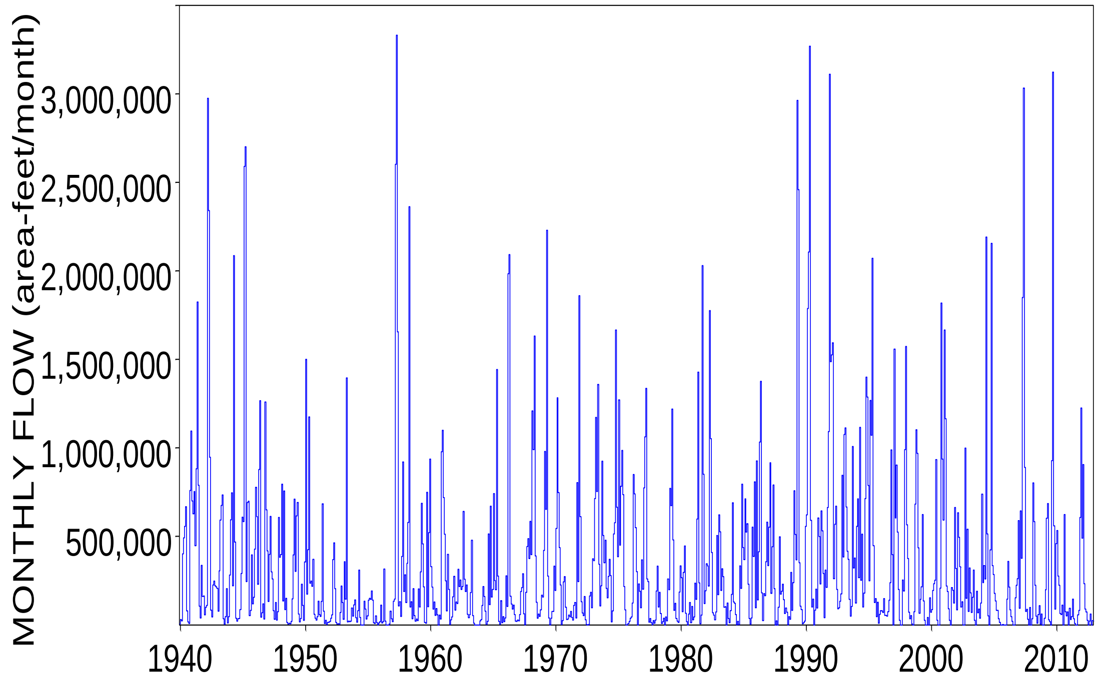
Naturalized (blue solid), Regulated (red dashed), and Observed (black dotted) Annual Flows for Trinity River near Rosser



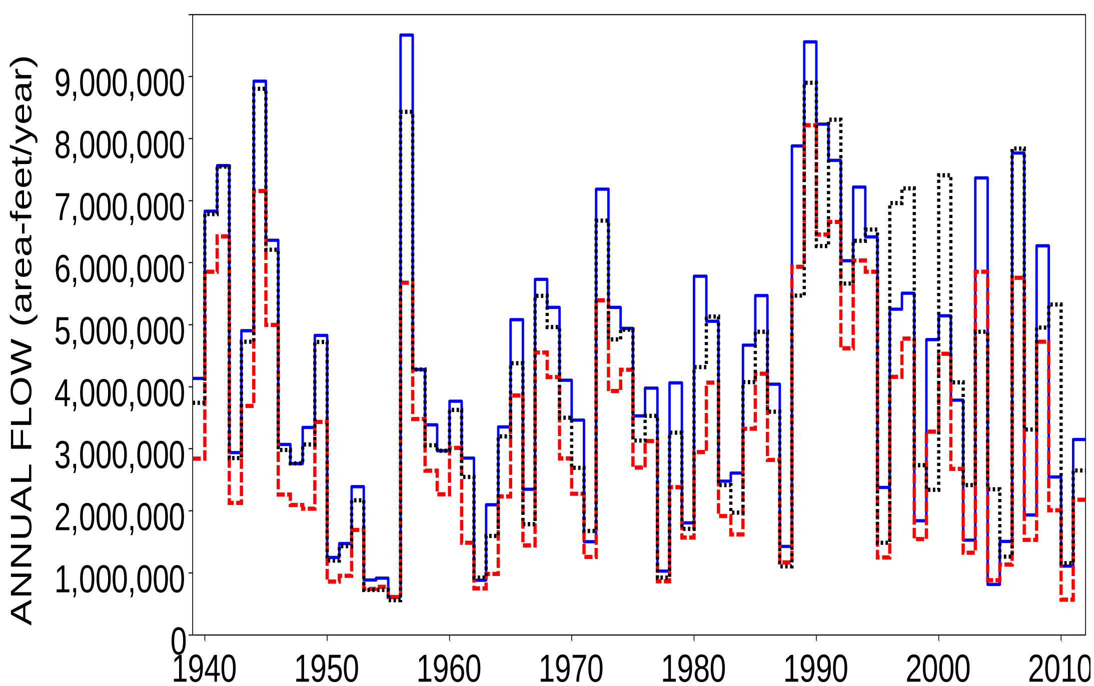
Naturalized (blue solid), Regulated (red dashed), and Observed (black dotted) 2-Month Minimum Annual Flows for Trinity River near Rosser



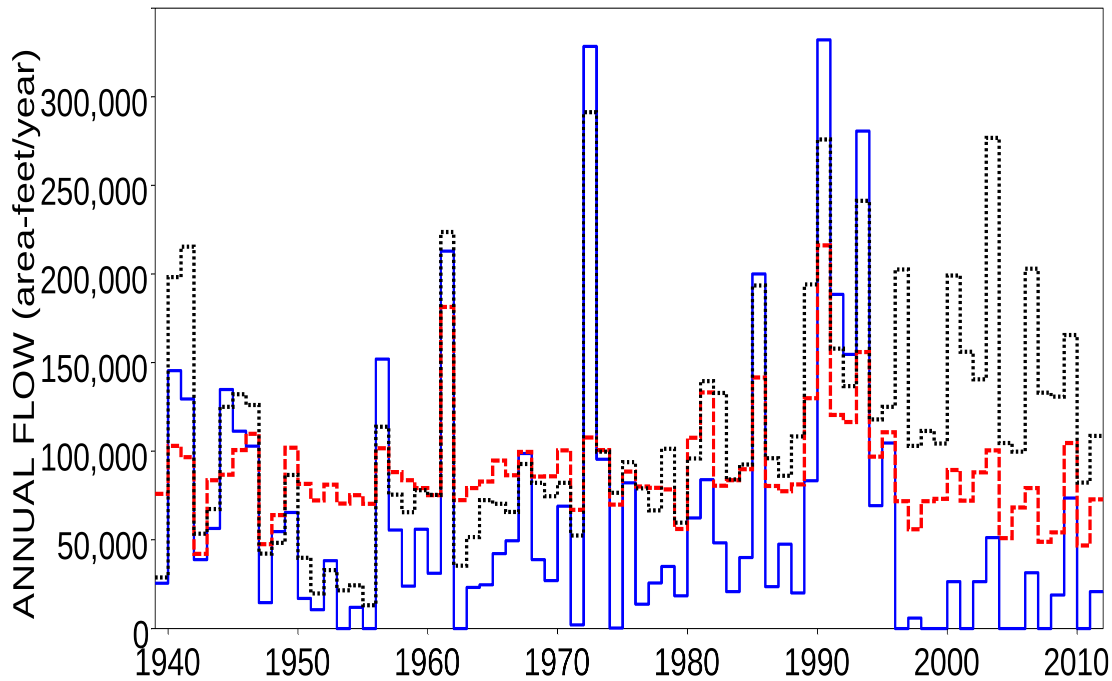
Naturalized (blue solid), Regulated (red dashed), and Observed (black dotted) 2-Month Maximum Annual Flows for Trinity River near Rosser



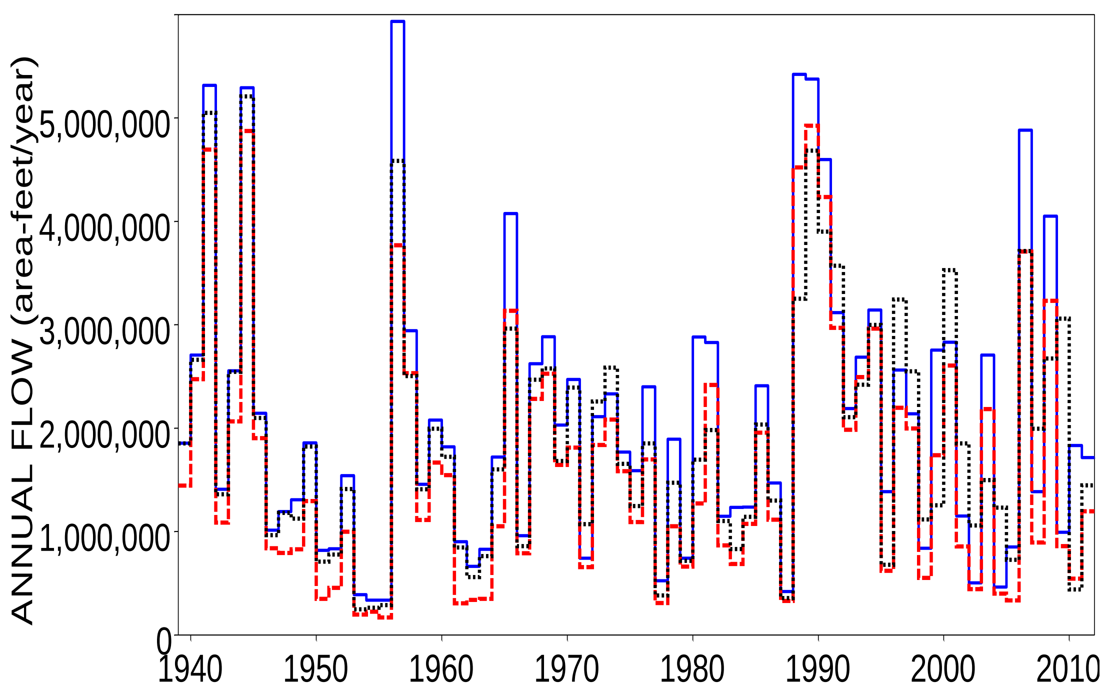
Naturalized Flows of Trinity River near Oakwood



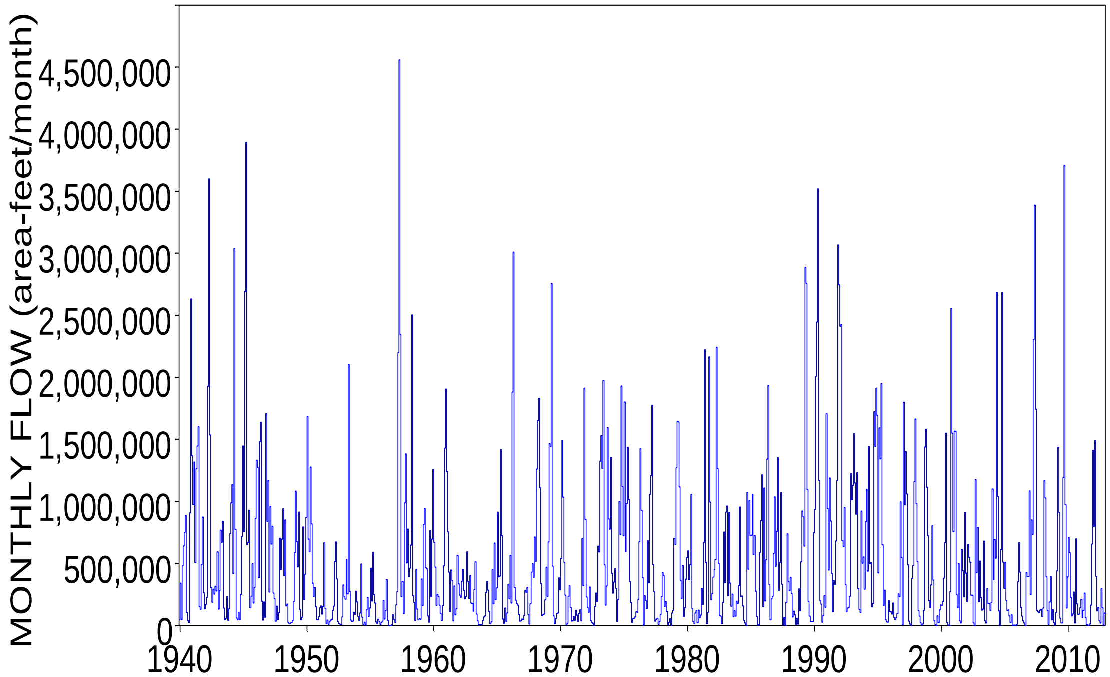
Naturalized (blue solid), Regulated (red dashed), and Observed (black dotted) Annual Flows for Trinity River near Oakwood



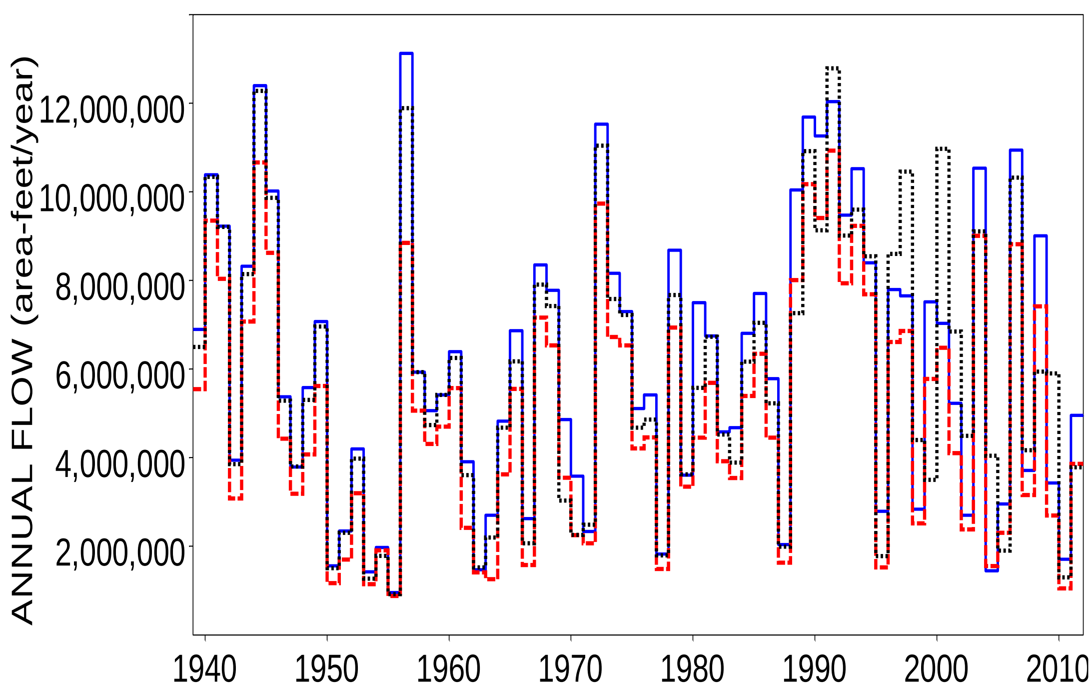
Naturalized (blue solid), Regulated (red dashed), and Observed (black dotted) 2-Month Minimum Annual Flows for Trinity River near Oakwood



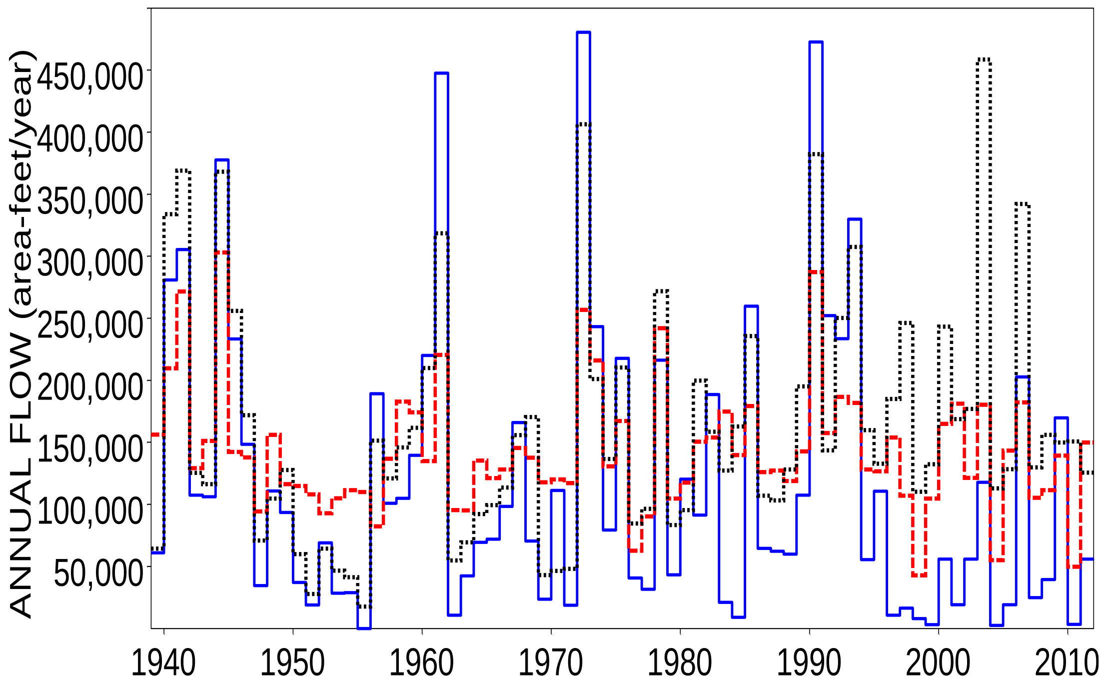
Naturalized (blue solid), Regulated (red dashed), and Observed (black dotted) 2-Month Maximum Annual Flows for Trinity River near Oakwood



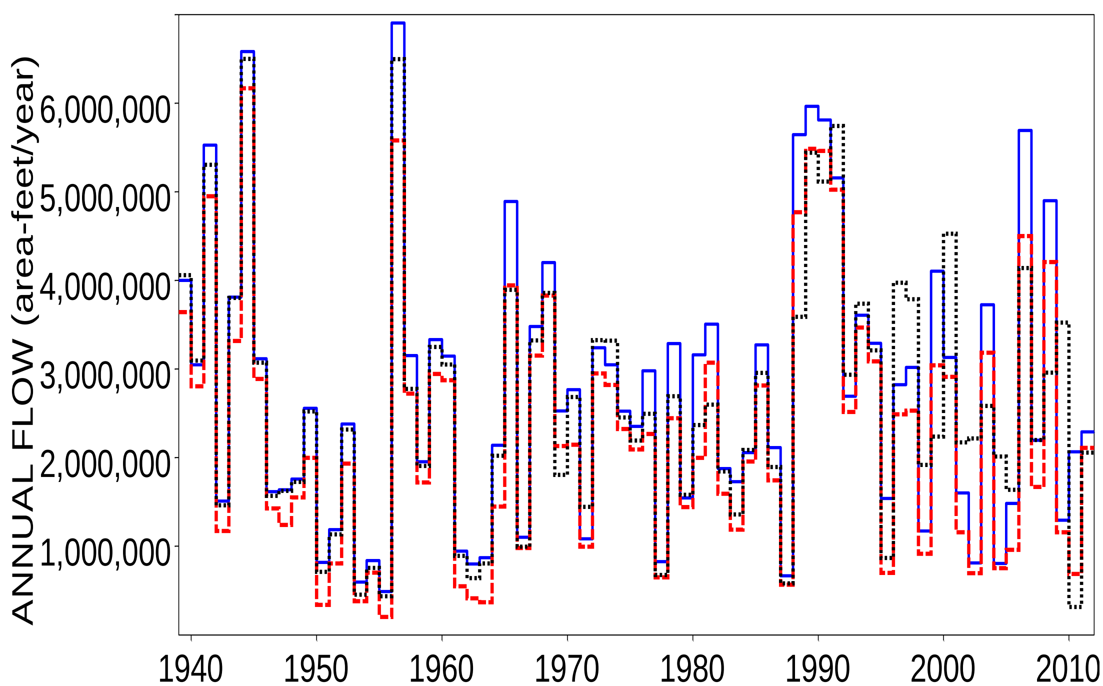
Naturalized Flows of Trinity River at Romayor



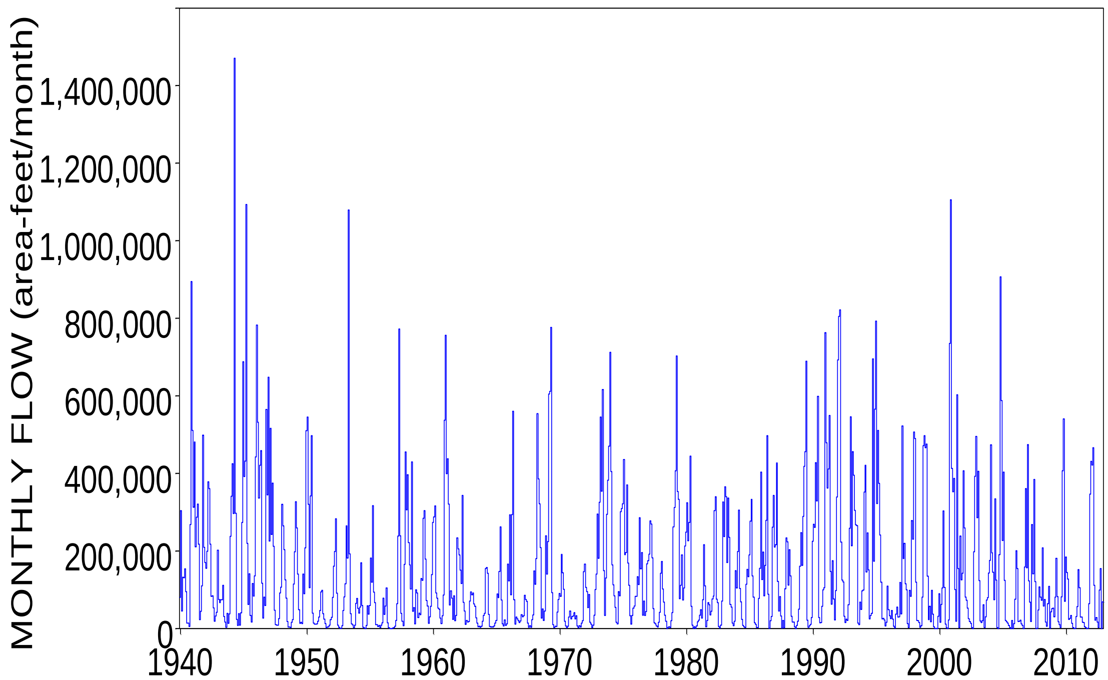
Naturalized (blue solid), Regulated (red dashed), and Observed (black dotted) Annual Flows for Trinity River at Romayor



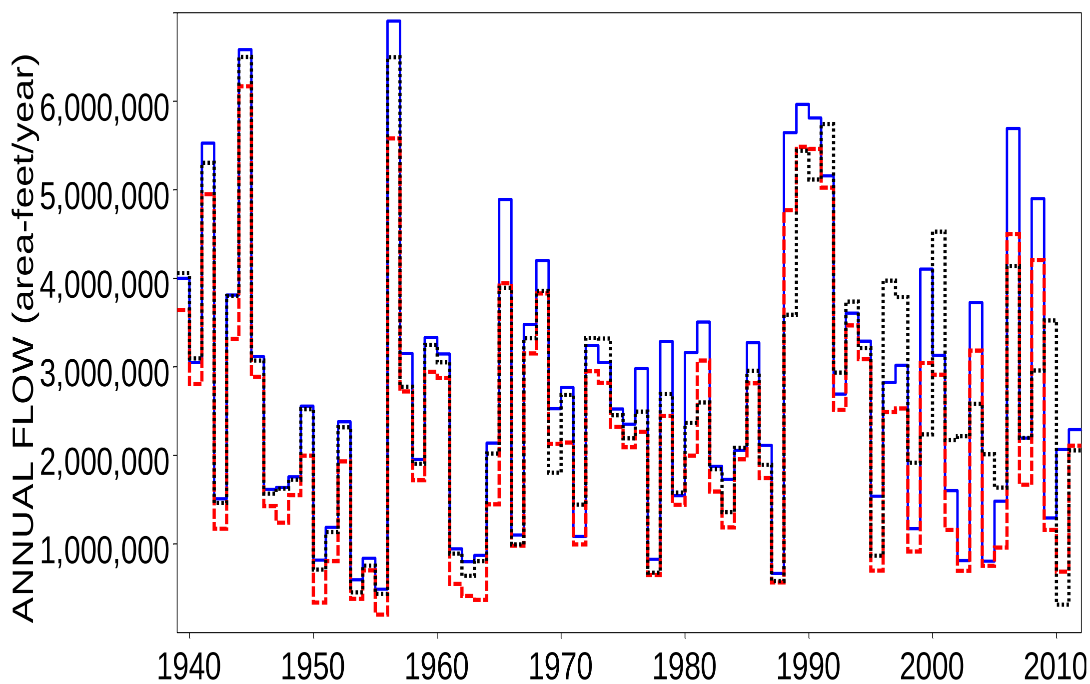
Naturalized (blue solid), Regulated (red dashed), and Observed (black dotted) 2-Month Minimum Annual Flows for Trinity River at Romayor



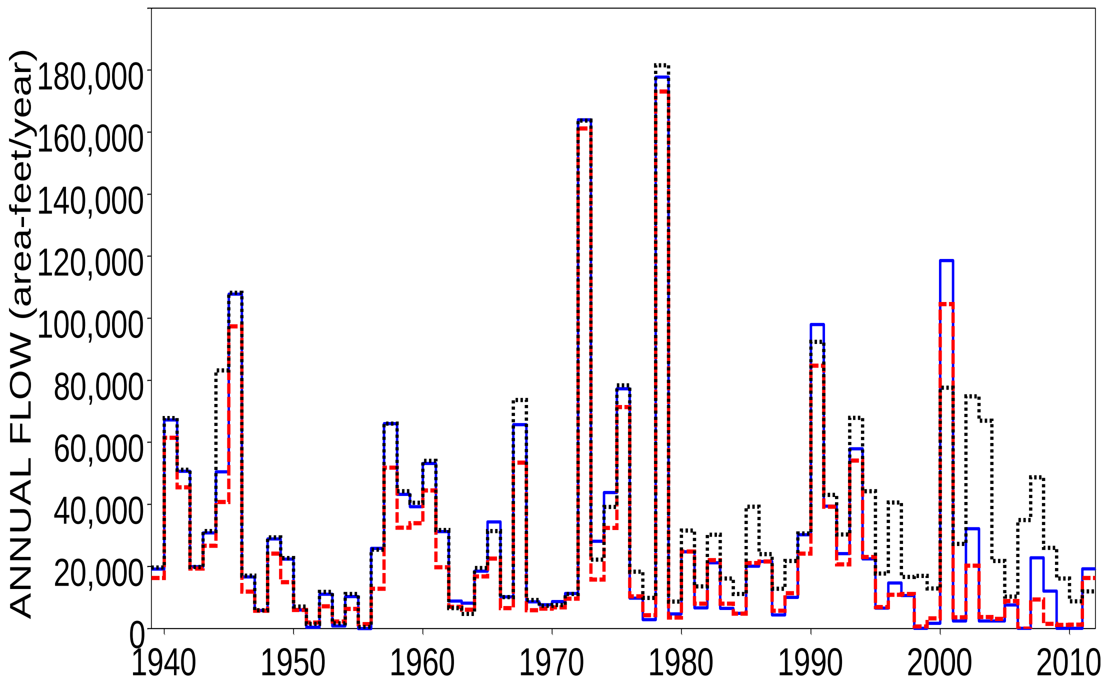
Naturalized (blue solid), Regulated (red dashed), and Observed (black dotted) 2-Month Maximum Annual Flows for Trinity River at Romayor



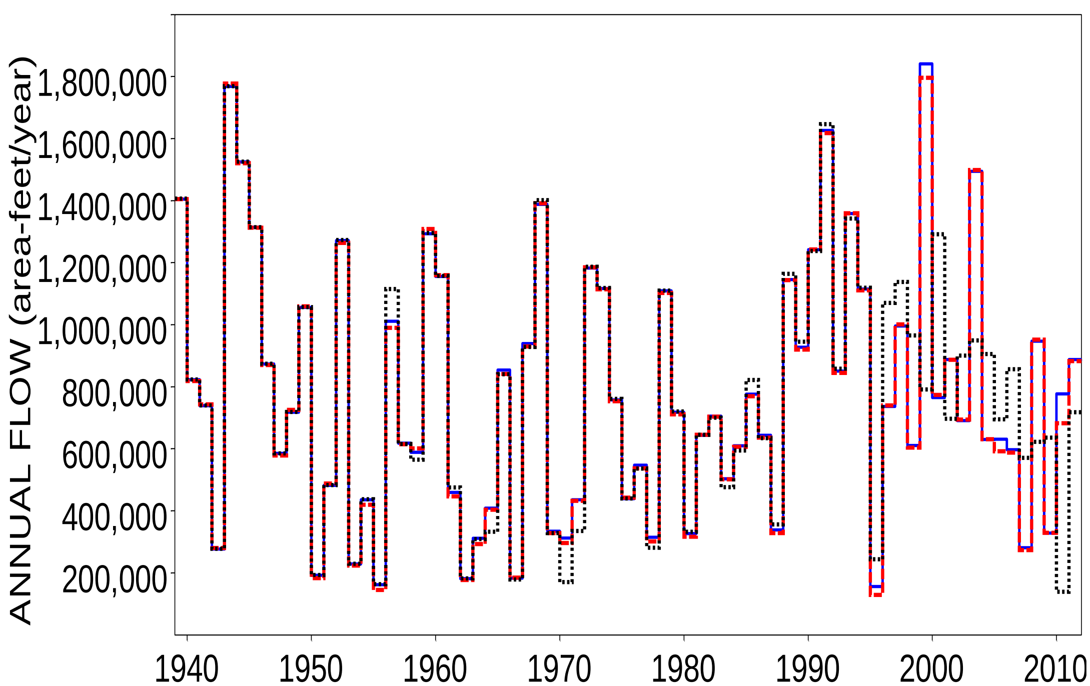
Naturalized Flows of Neches River near Rockland



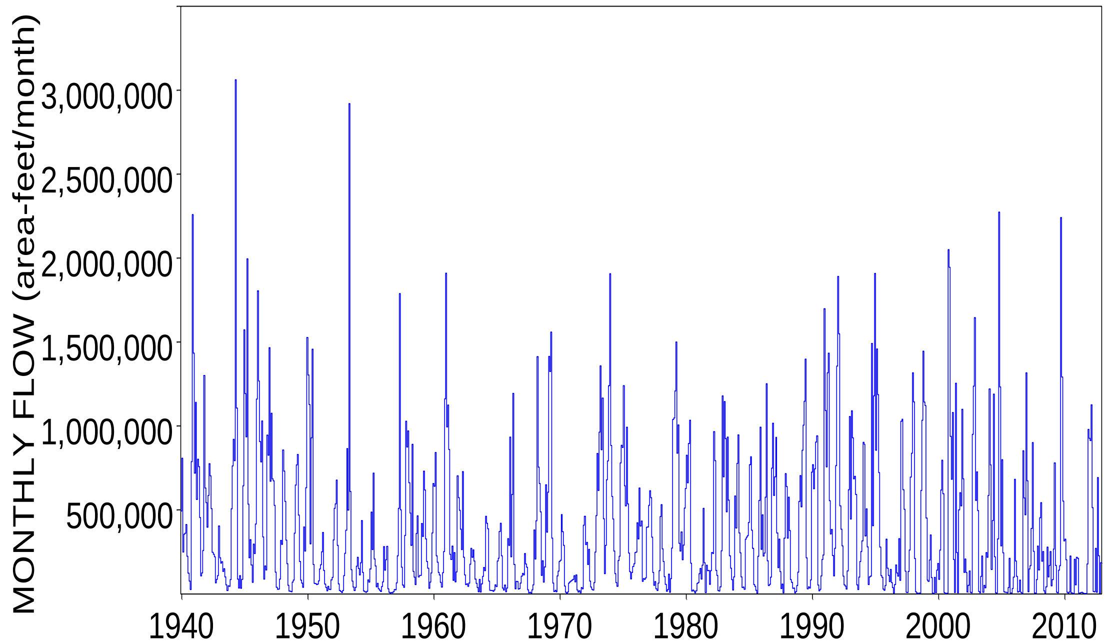
Naturalized (blue solid), Regulated (red dashed), and Observed (black dotted) Annual Flows for Neches River near Rockland



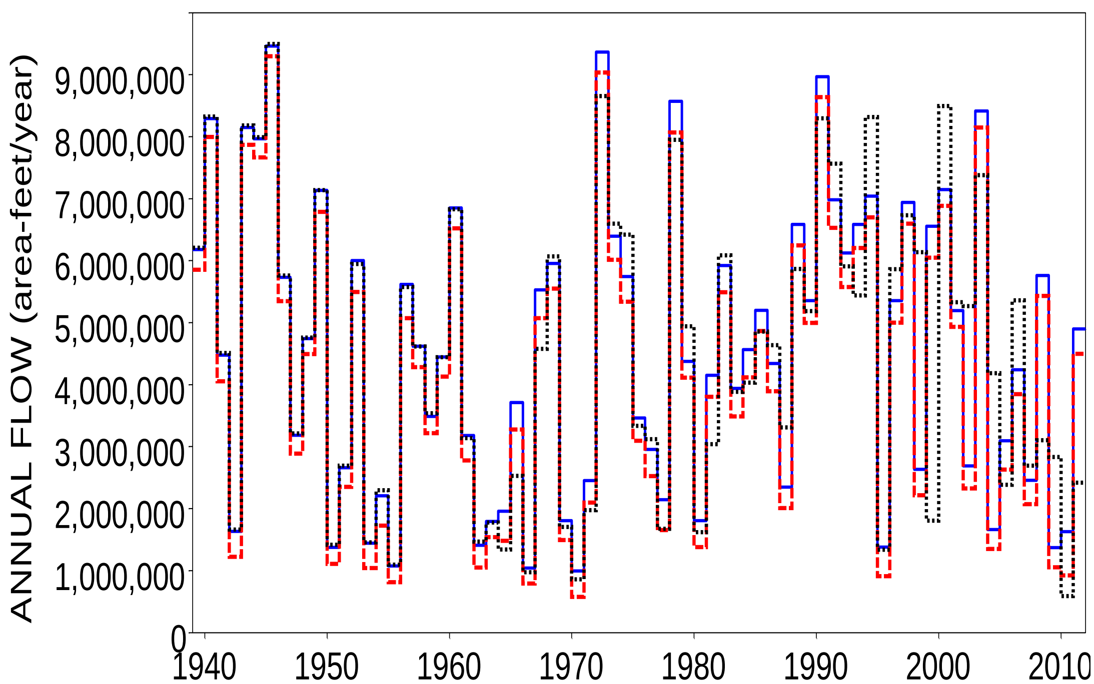
Naturalized (blue solid), Regulated (red dashed), and Observed (black dotted) 2-Month Minimum Annual Flows for Neches River near Rockland



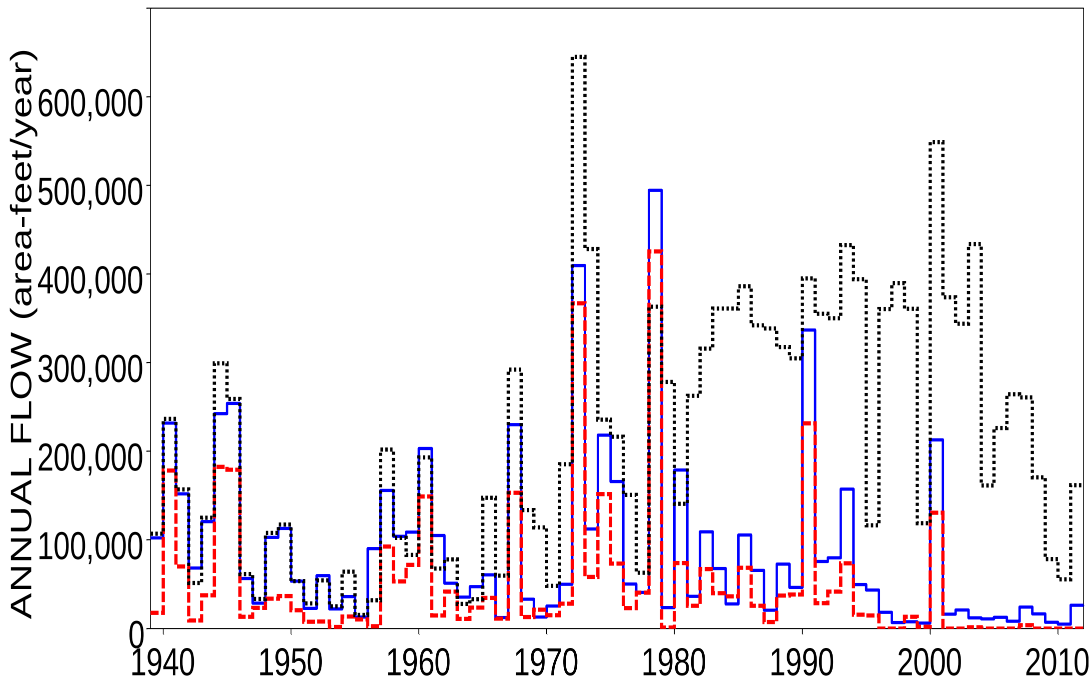
Naturalized (blue solid), Regulated (red dashed), and Observed (black dotted) 2-Month Maximum Annual Flows for Neches River near Rockland



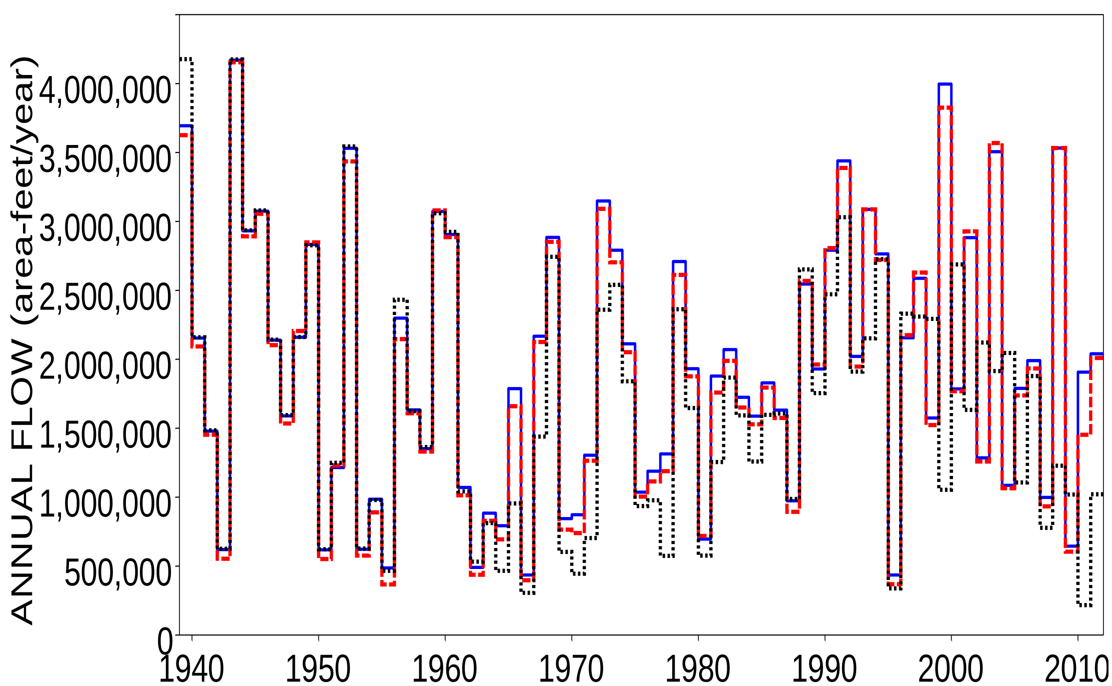
Naturalized Flows of Neches River near Evansdale



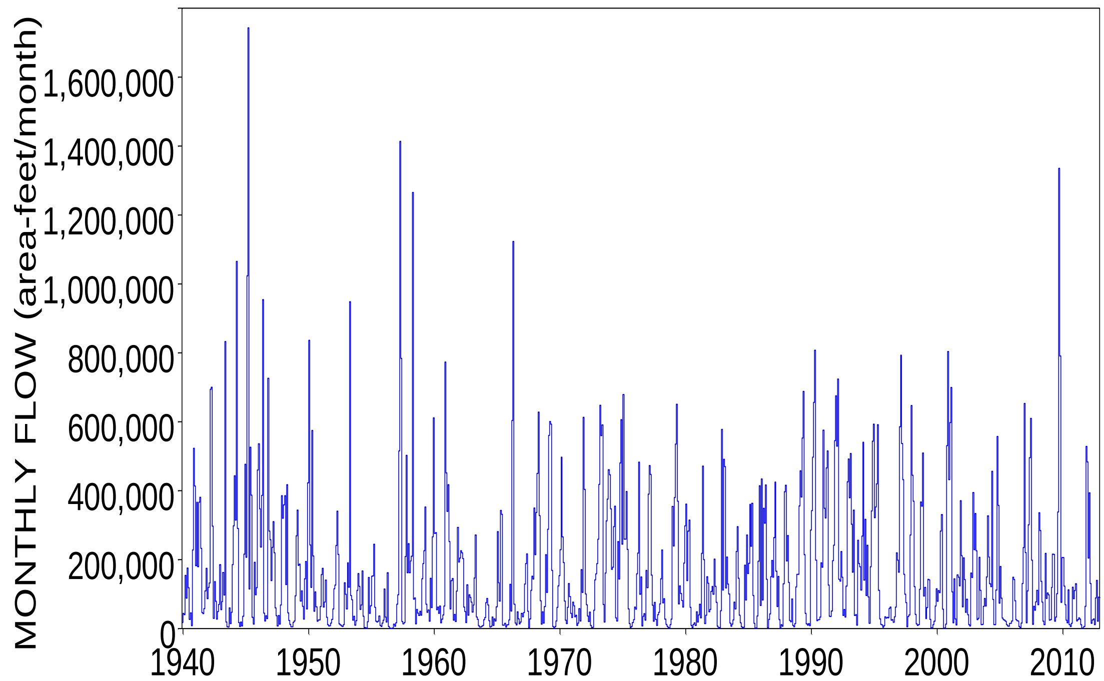
Naturalized (blue solid), Regulated (red dashed), and Observed (black dotted) Annual Flows for Neches River near Evansdale



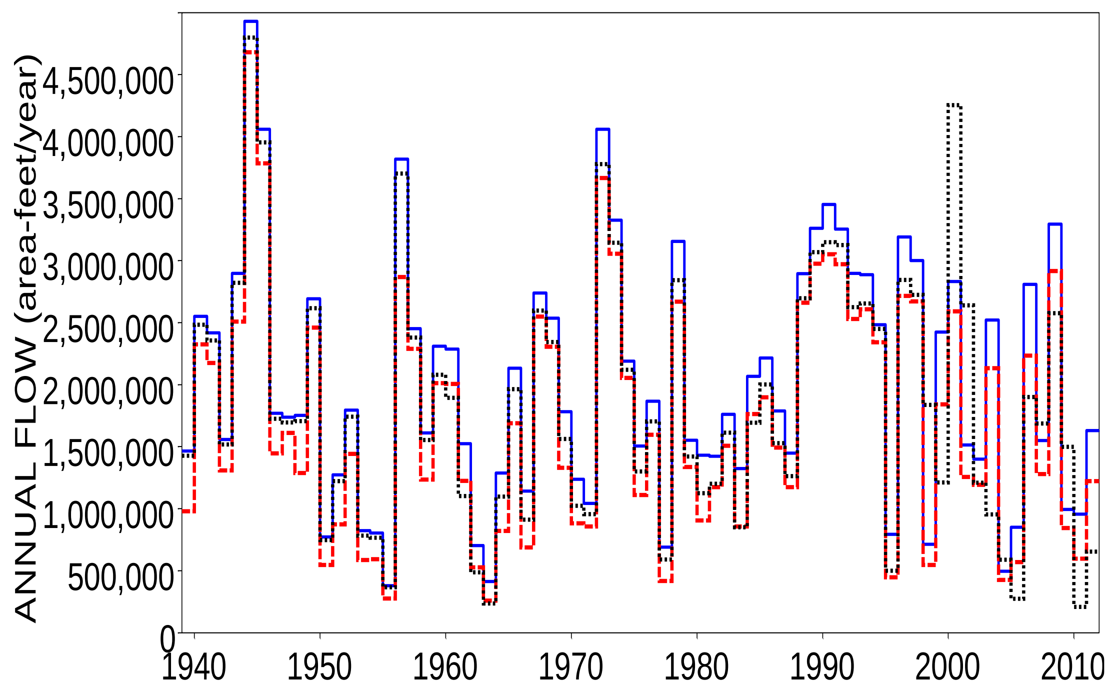
Naturalized (blue solid), Regulated (red dashed), and Observed (black dotted) 2-Month Minimum Annual Flows for Neches River near Evansdale



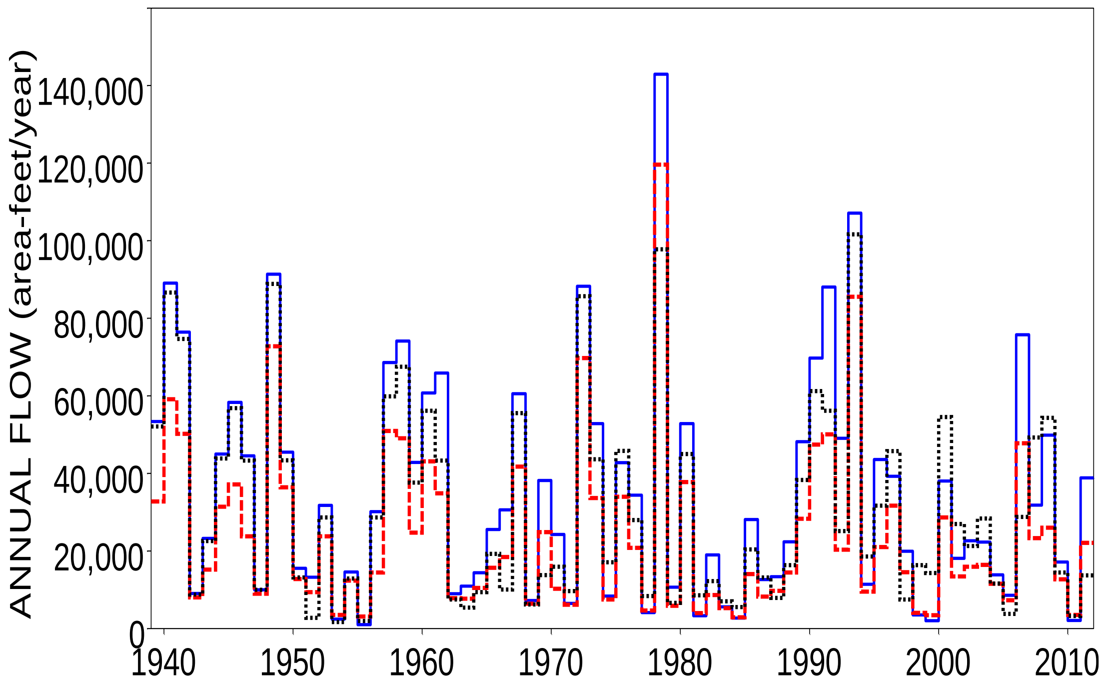
Naturalized (blue solid), Regulated (red dashed), and Observed (black dotted) 2-Month Maximum Annual Flows for Neches River near Evansdale



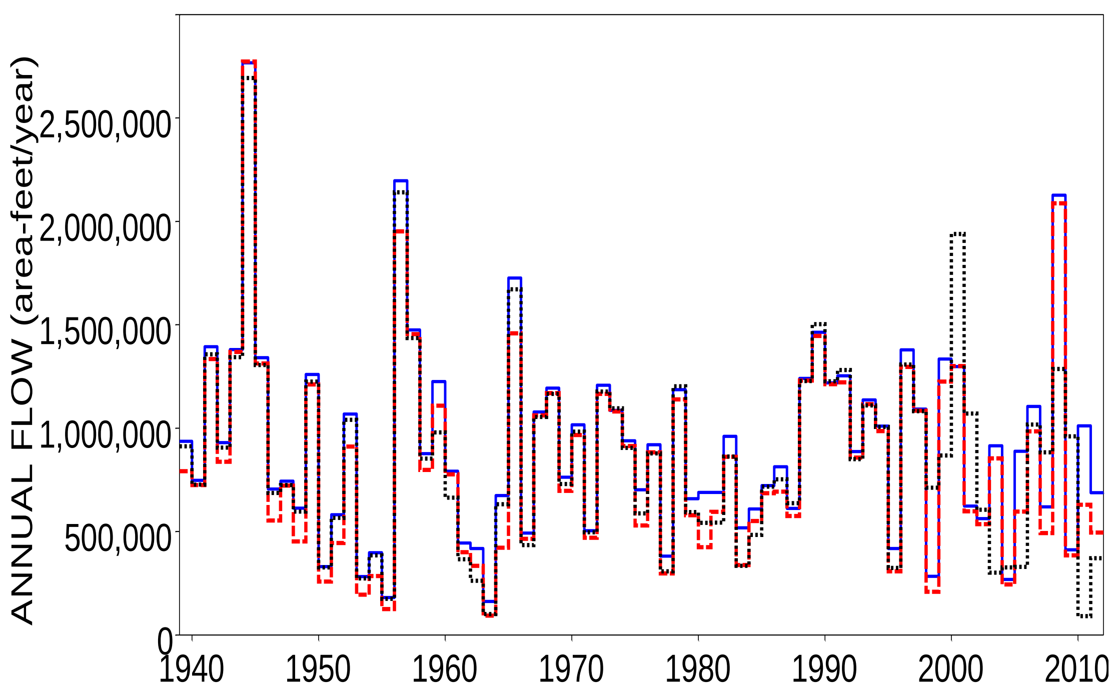
Naturalized Flows of Sabine River near Beckville



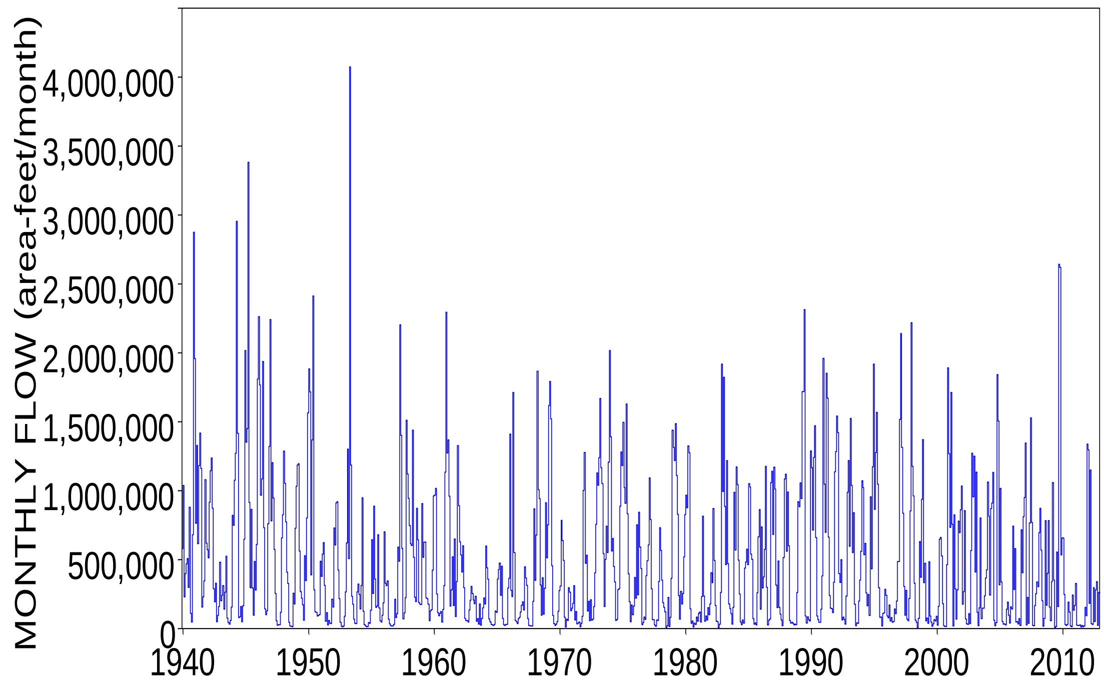
Naturalized (blue solid), Regulated (red dashed), and Observed (black dotted) Annual Flows for Sabine River near Beckville



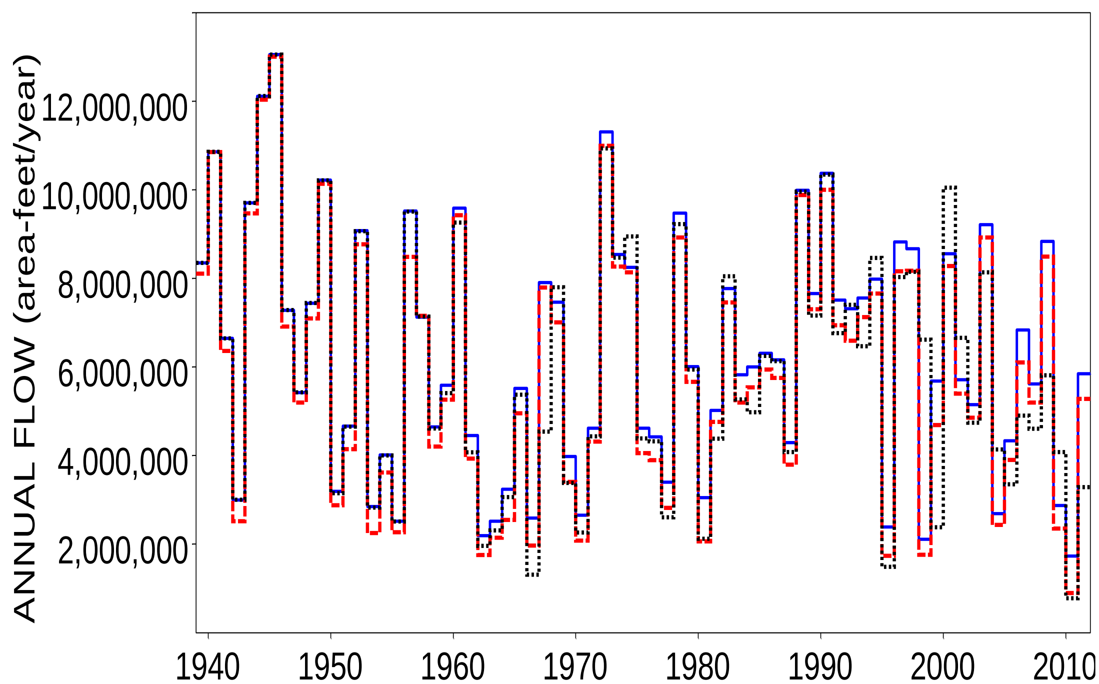
Naturalized (blue solid), Regulated (red dashed), and Observed (black dotted) 2-Month Minimum Annual Flows for Sabine River near Beckville



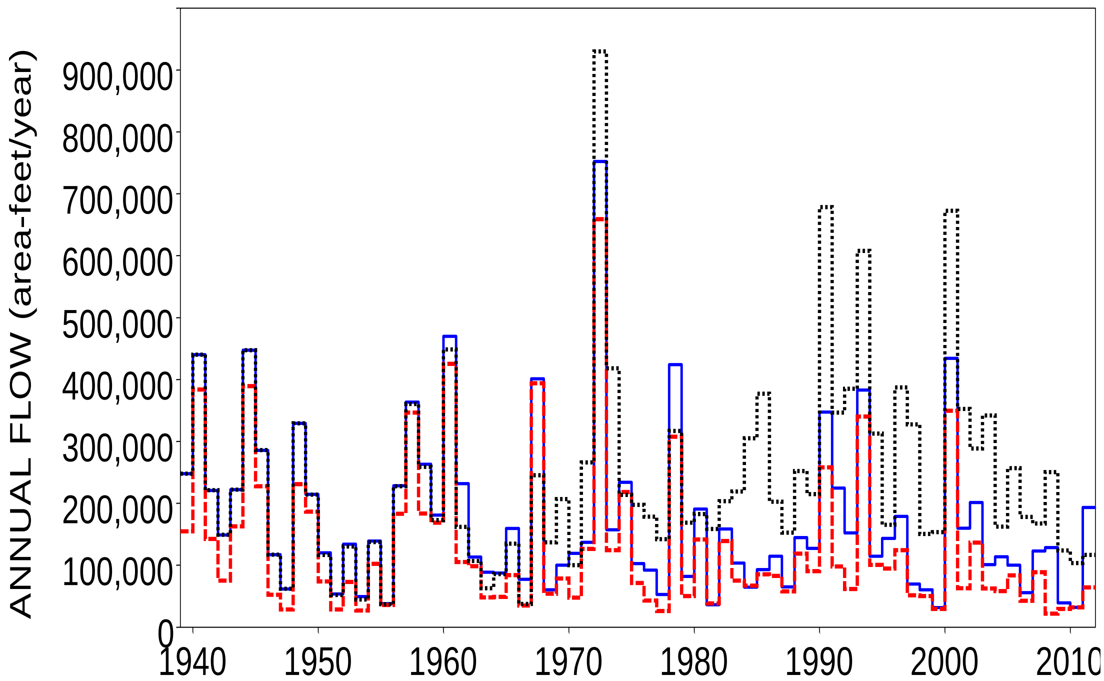
Naturalized (blue solid), Regulated (red dashed), and Observed (black dotted) 2-Month Maximum Annual Flows for Sabine River near Beckville



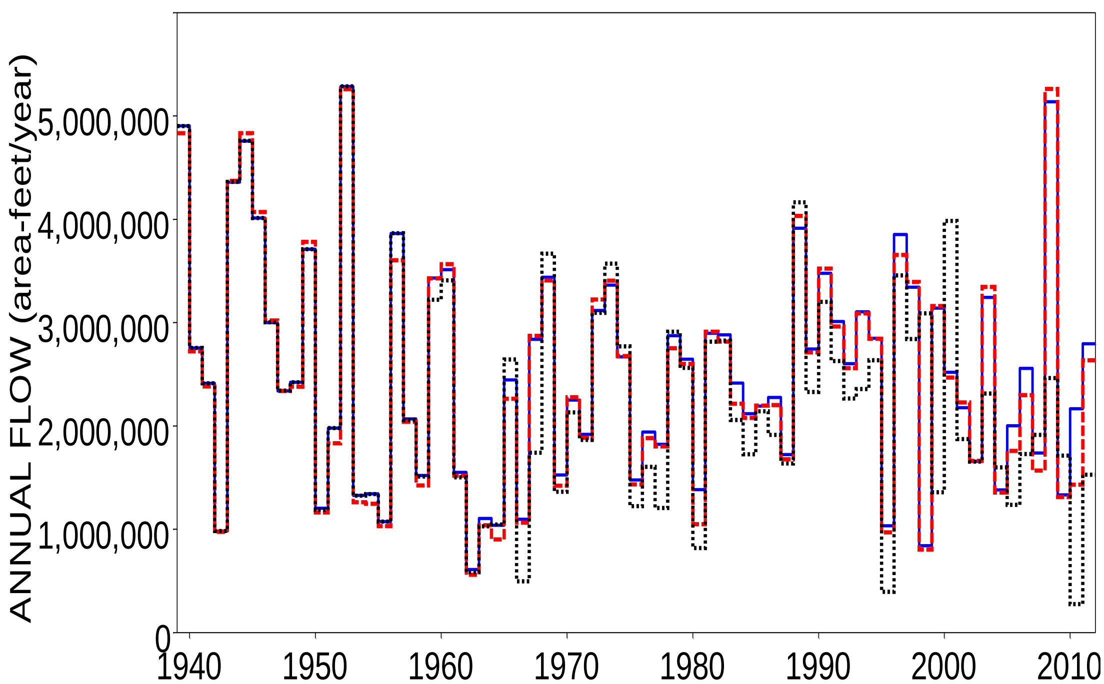
Naturalized Flows of Sabine River near Ruliff



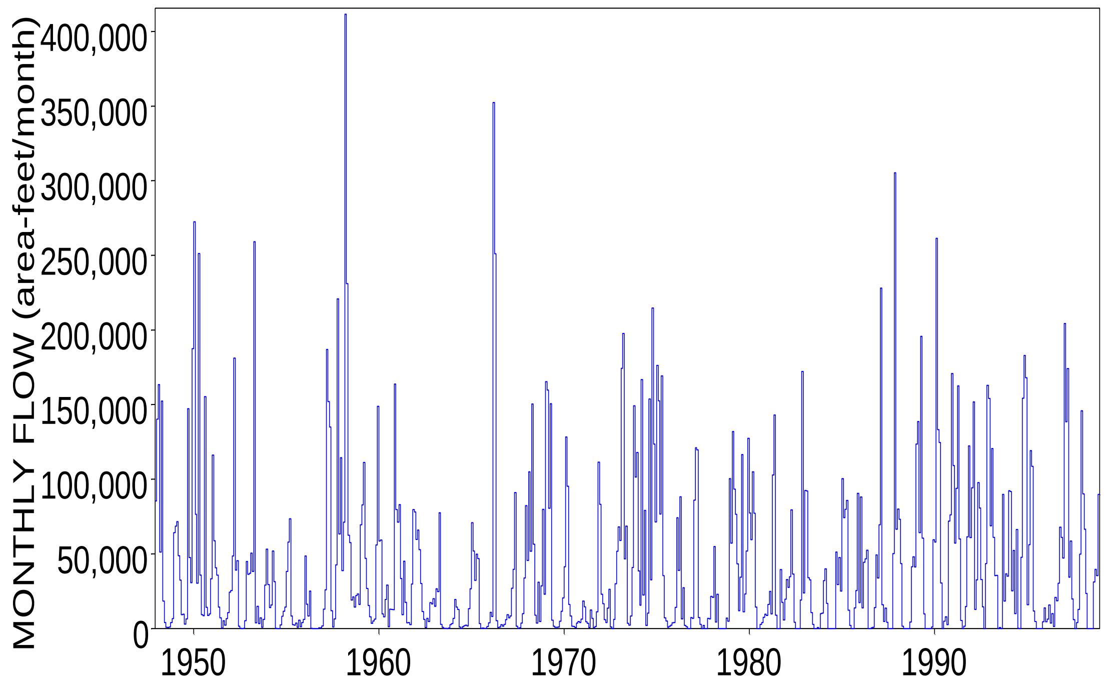
Naturalized (blue solid), Regulated (red dashed), and Observed (black dotted) Annual Flows for Sabine River near Ruliff



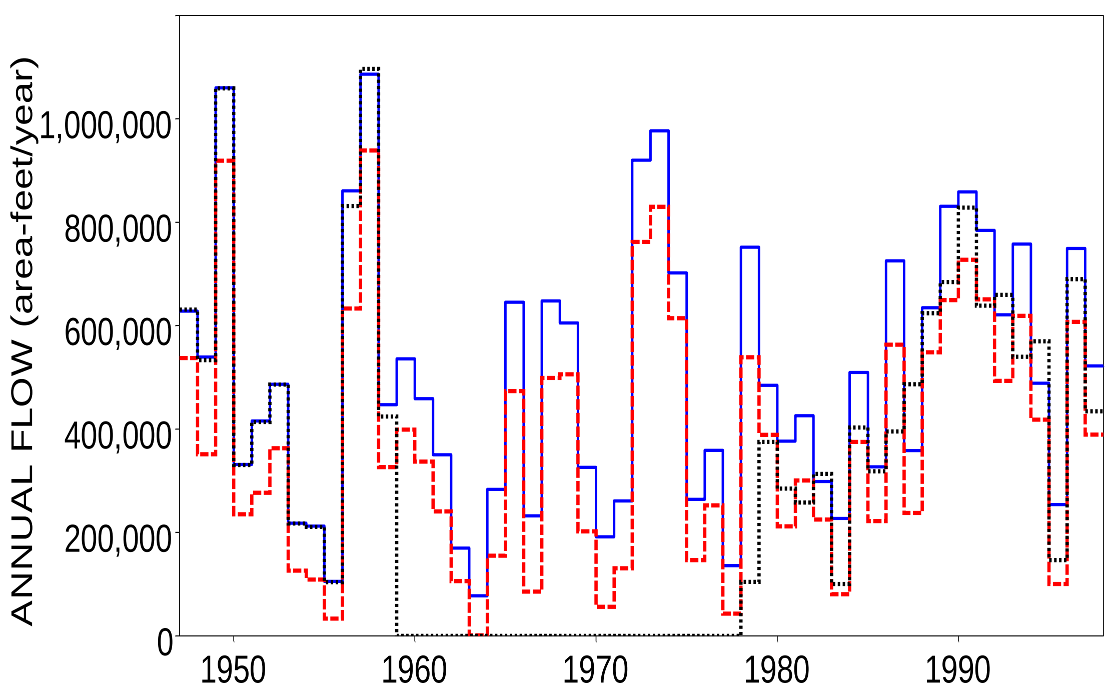
Naturalized (blue solid), Regulated (red dashed), and Observed (black dotted) 2-Month Minimum Annual Flows for Sabine River near Ruliff



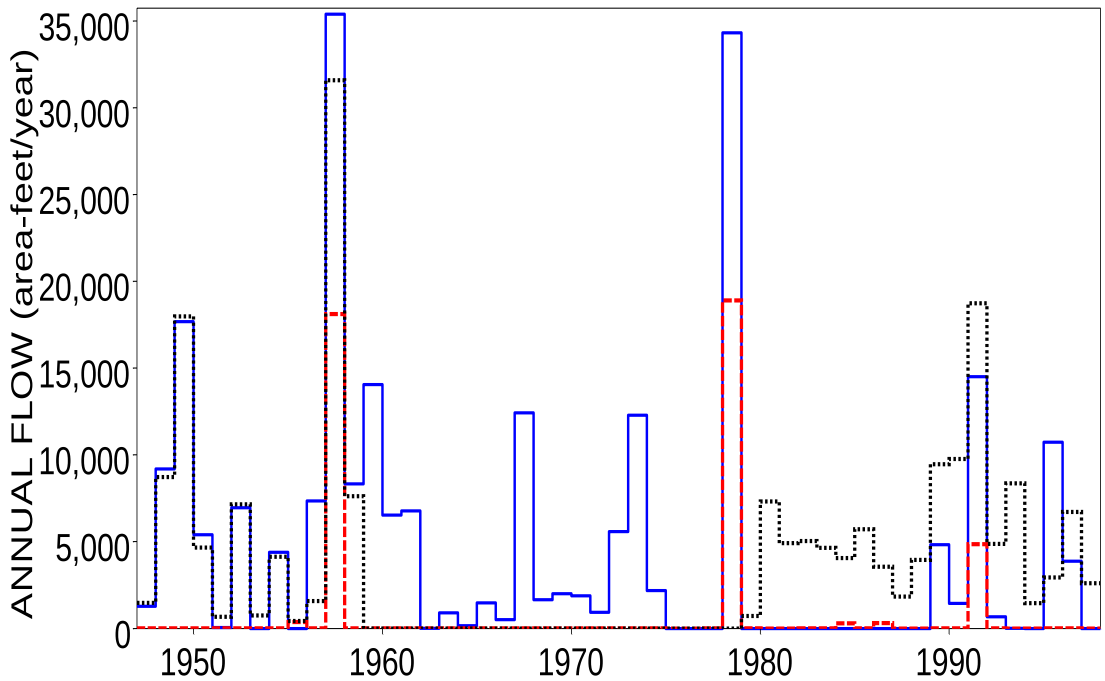
Naturalized (blue solid), Regulated (red dashed), and Observed (black dotted) 2-Month Maximum Annual Flows for Sabine River near Ruliff



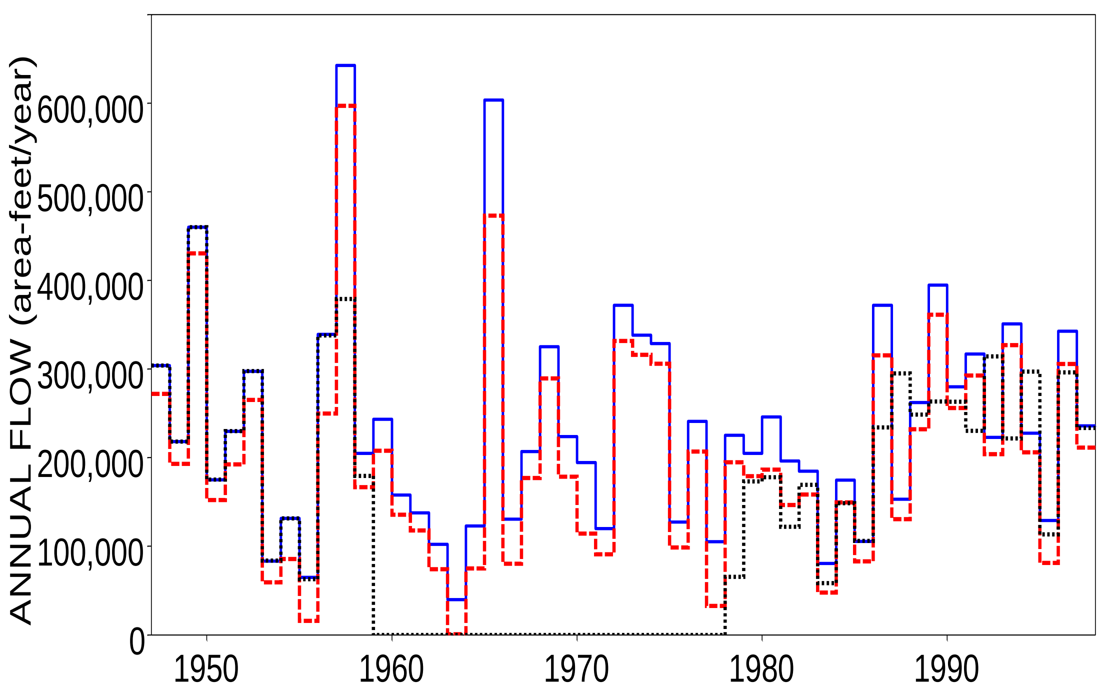
Naturalized Flows of Big Cypress Bayou at Jefferson



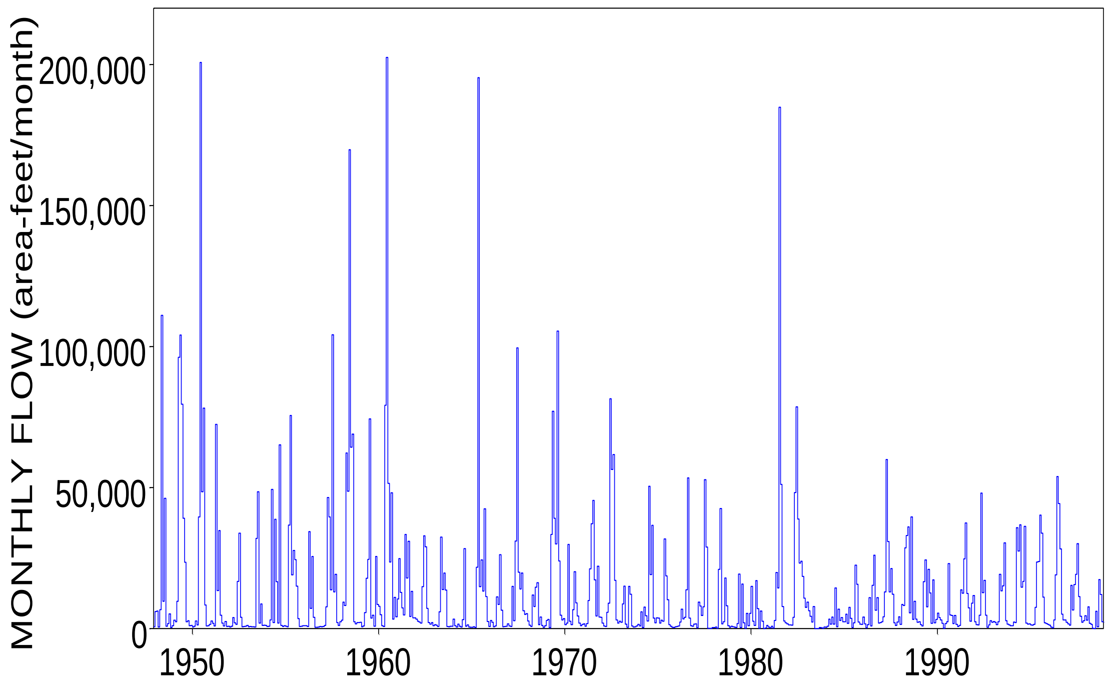
Naturalized (blue solid) and regulated (red dashed) Observed (black dotted) Annual Flows for Big Cypress Bayou at Jefferson



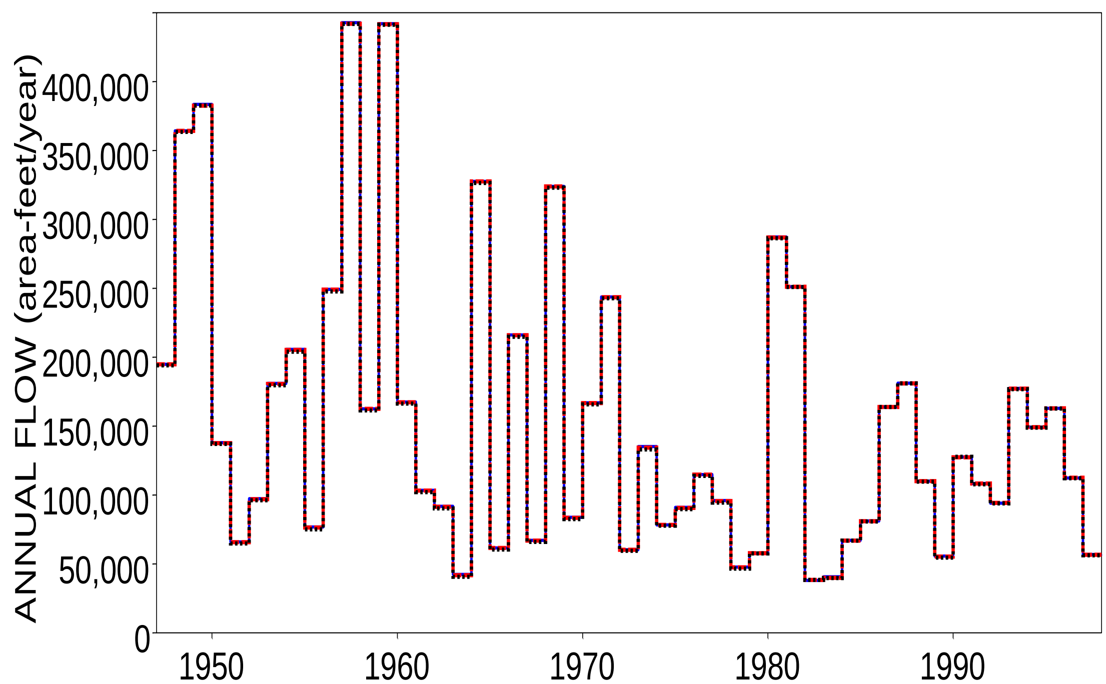
Naturalized (blue solid), Regulated (red dashed), and Observed (black dotted) 2-Month Minimum Annual Flows for Big Cypress Bayou at Jefferson



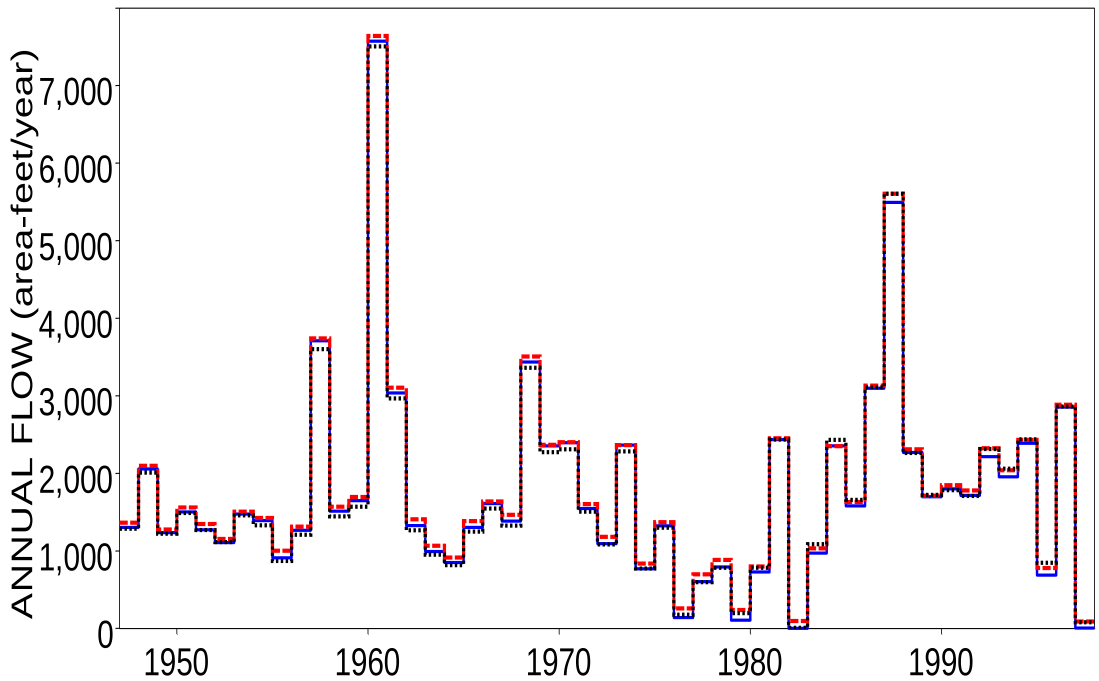
Naturalized (blue solid), Regulated (red dashed), and Observed (black dotted) 2-Month Maximum Annual Flows for Big Cypress Bayou at Jefferson



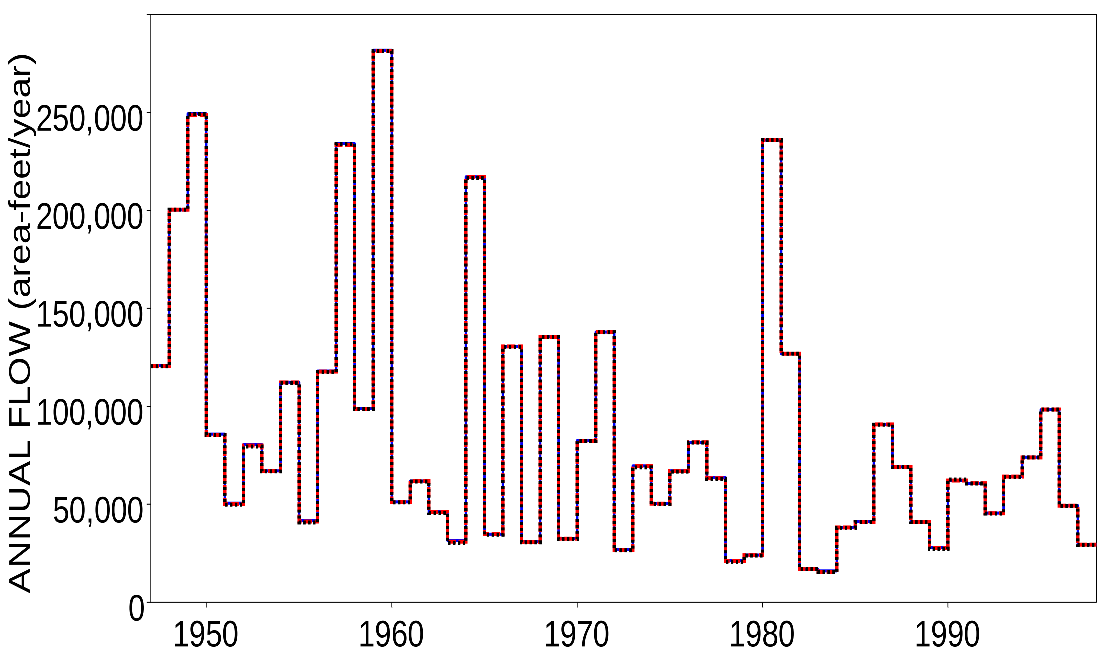
Naturalized Flows of Canadian River near Amarillo



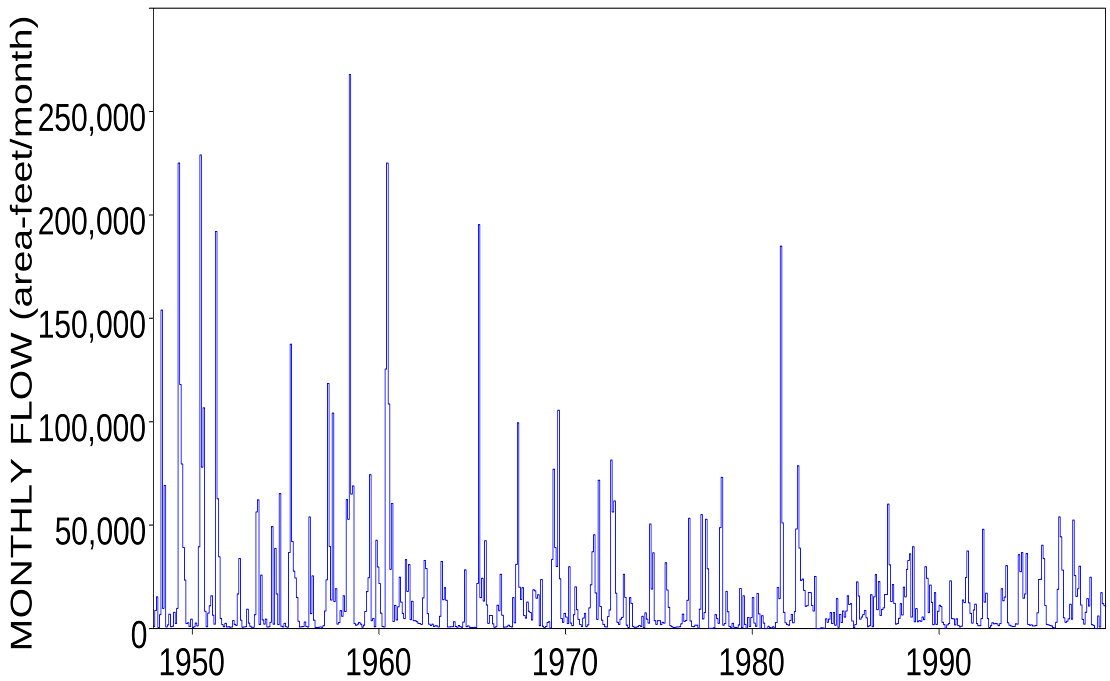
Naturalized (blue solid), Regulated (red dashed), and Observed (black dotted) Annual Flows for Canadian River near Amarillo



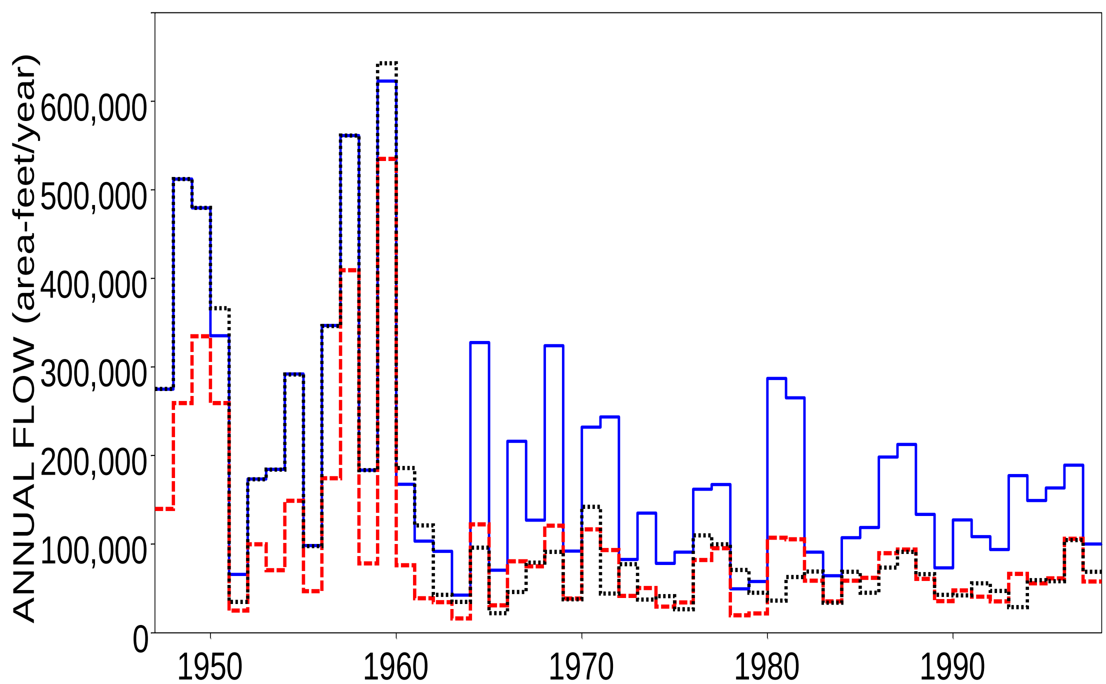
Naturalized (blue solid), Regulated (red dashed), and Observed (black dotted) 2-Month Minimum Annual Flows for Canadian River near Amarillo



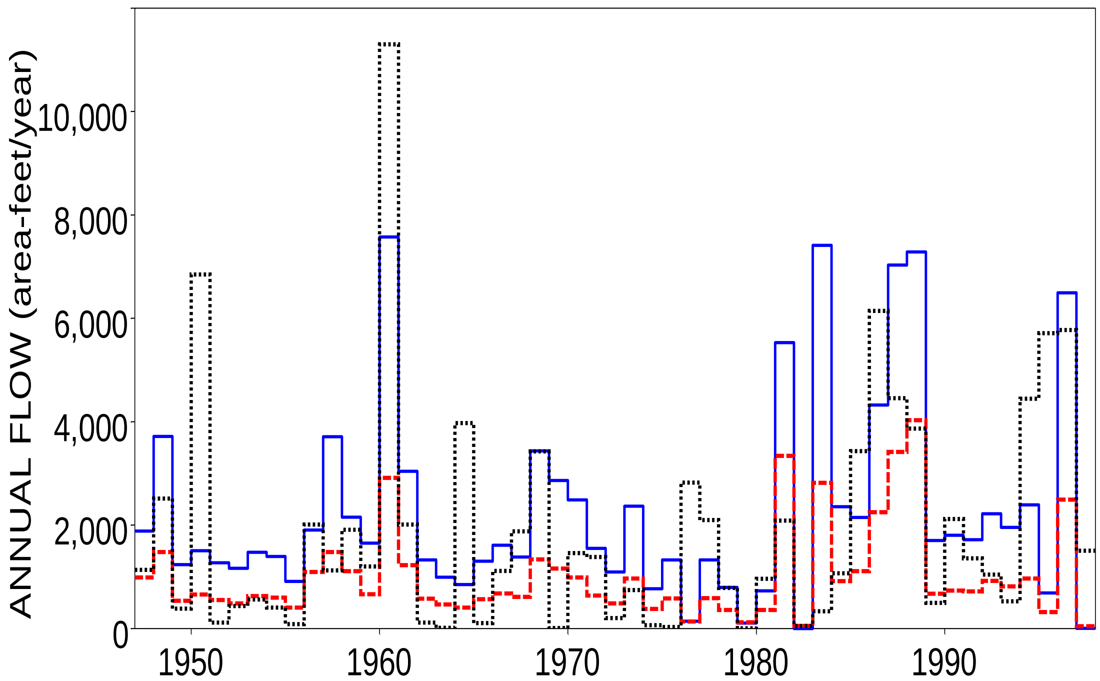
Naturalized (blue solid), Regulated (red dashed), and Observed (black dotted) 2-Month Maximum Annual Flows for Canadian River near Amarillo



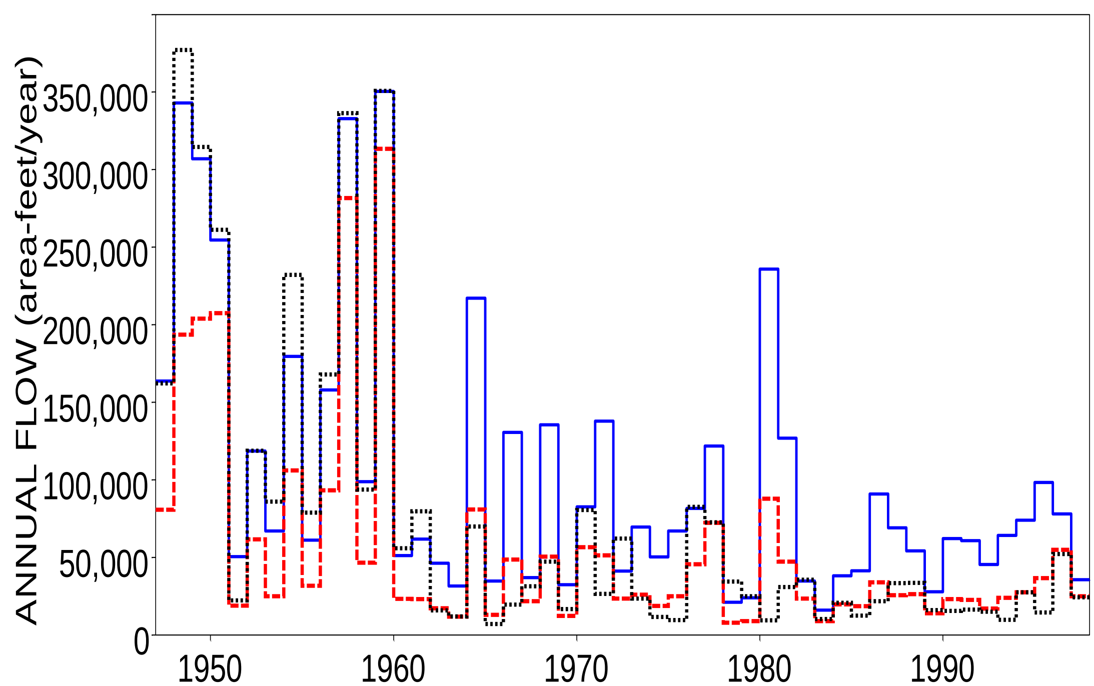
Naturalized Flows of Canadian River near Canadian



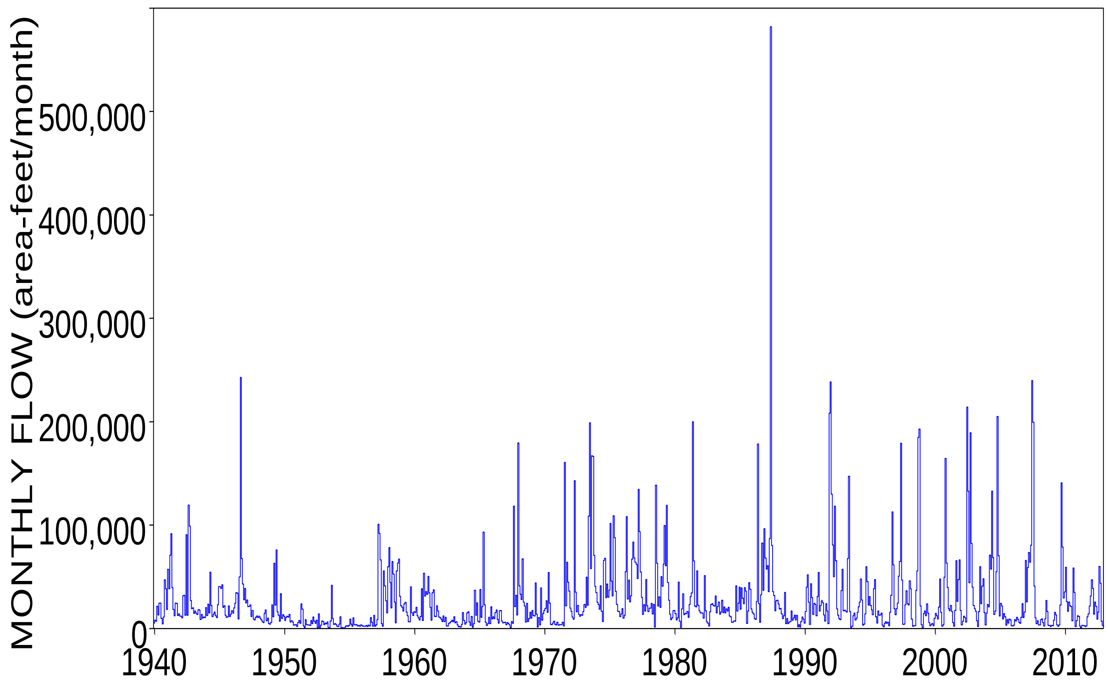
Naturalized (blue solid), Regulated (red dashed), and Observed (black dotted) Annual Flows for Canadian River near Canadian



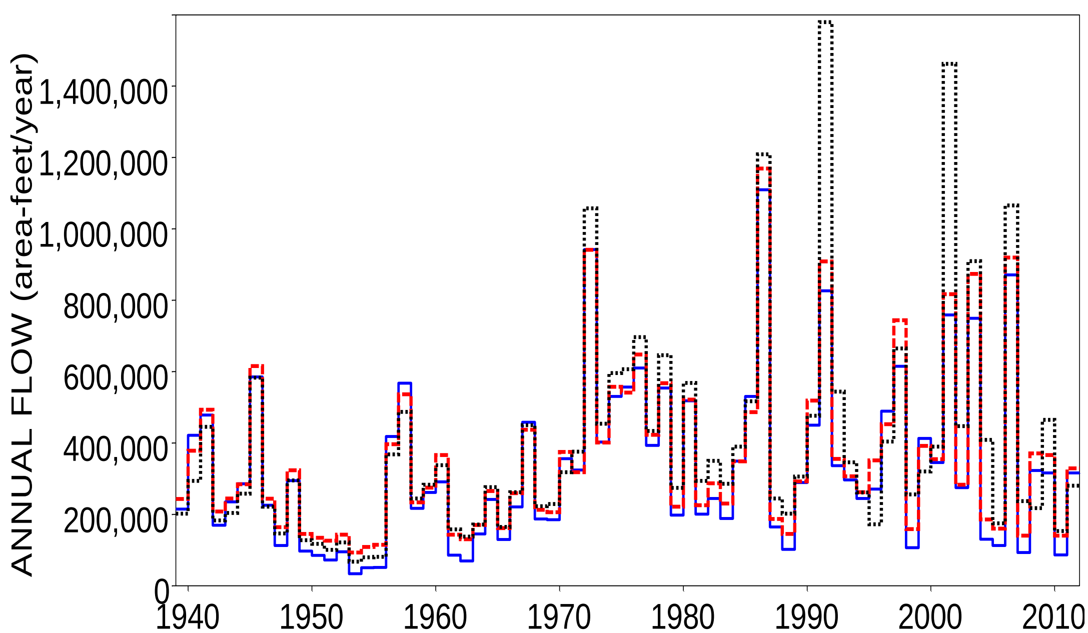
Naturalized (blue solid), Regulated (red dashed), and Observed (black dotted) 2-Month Minimum Annual Flows for Canadian River near Canadian



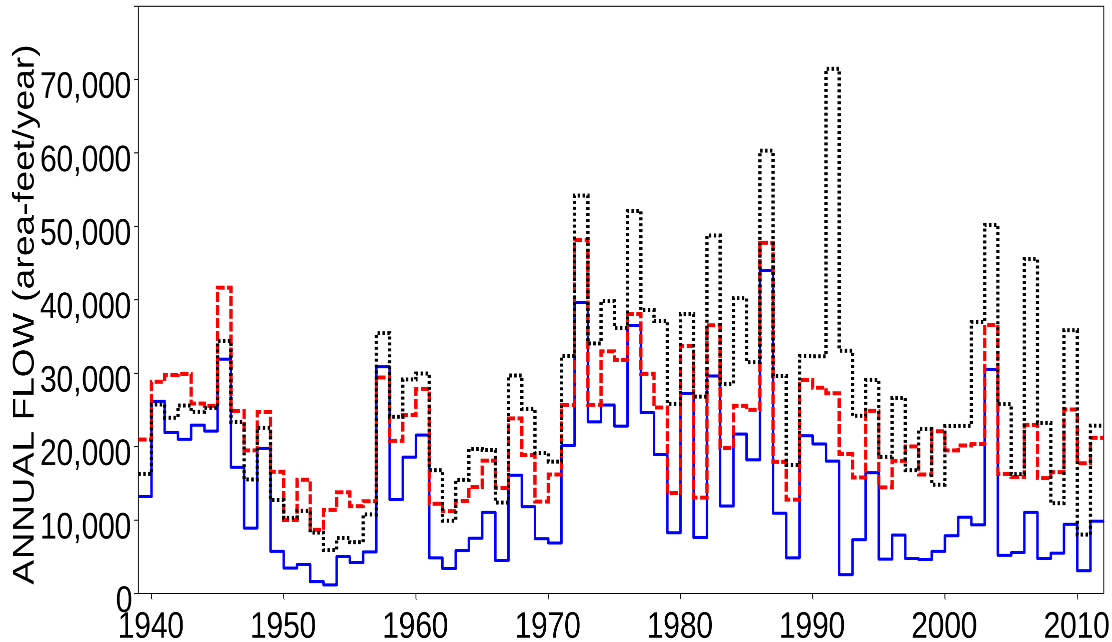
Naturalized (blue solid), Regulated (red dashed), and Observed (black dotted) 2-Month Maximum Annual Flows for Canadian River near Canadian



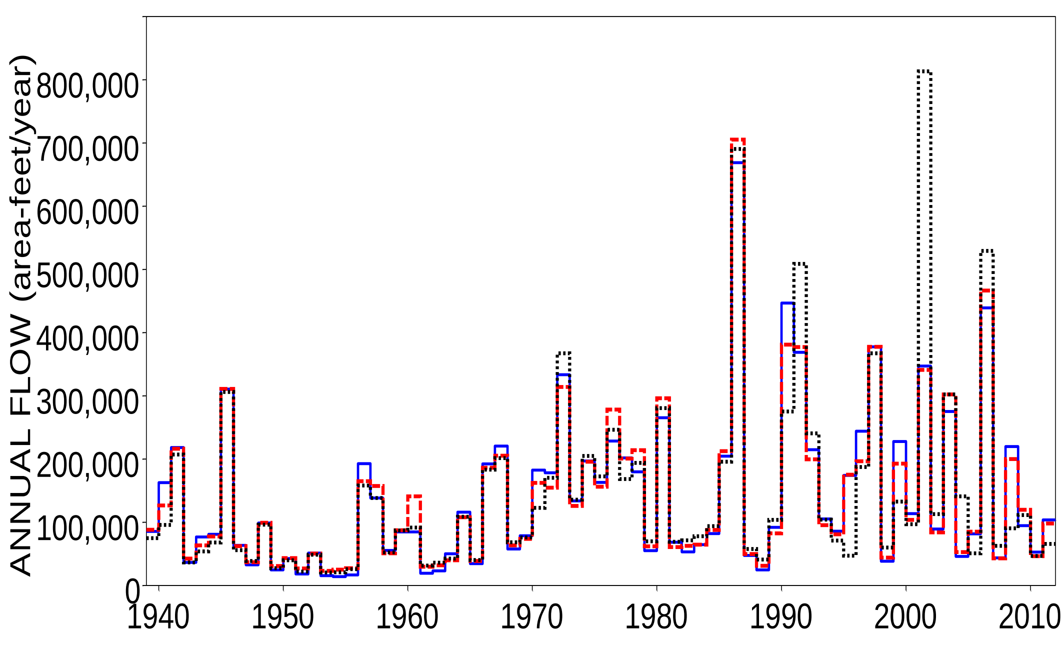
Naturalized Flows of San Antonio River at Falls City



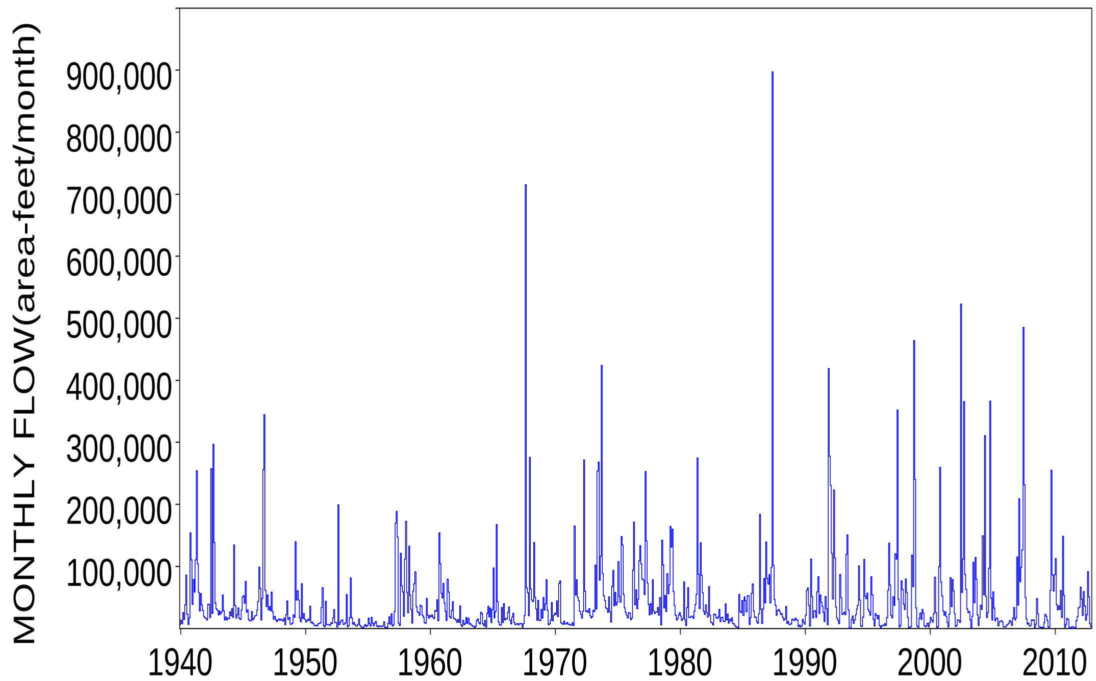
Naturalized (blue solid), Regulated (red dashed) and Observed (black dotted) Annual Flows for San Antonio River at Falls City



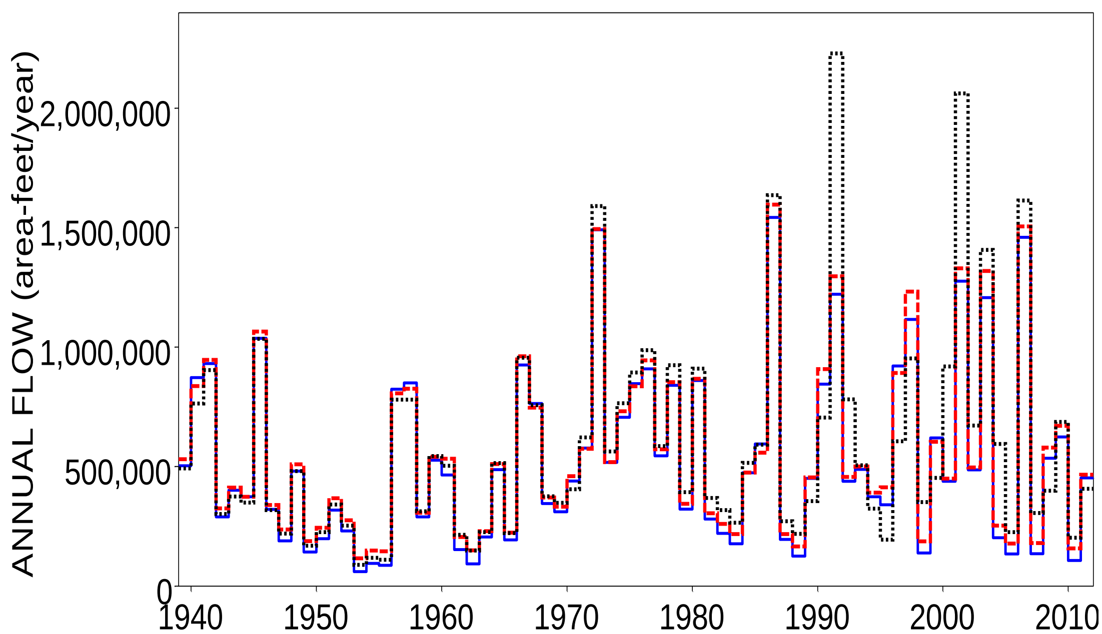
Naturalized (blue solid), Regulated (red dashed) and Observed (black dotted) 2-Month Minimum Annual Flows for San Antonio River at Falls City



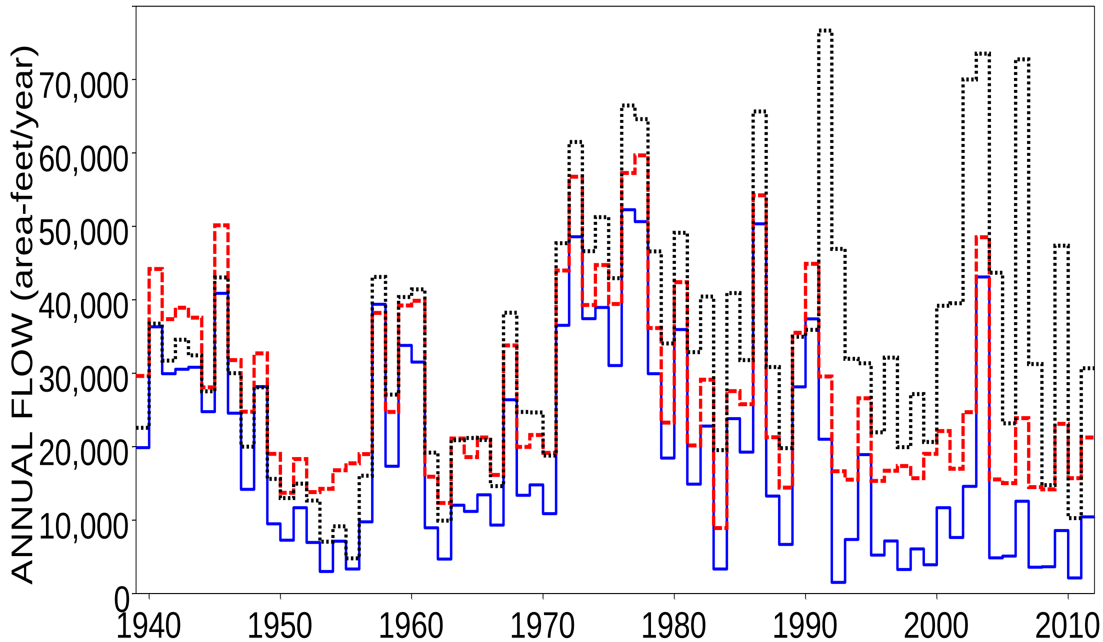
Naturalized (blue solid), Regulated (red dashed) and Observed (black dotted) 2-Month Maximum Annual Flows for San Antonio River at Falls City



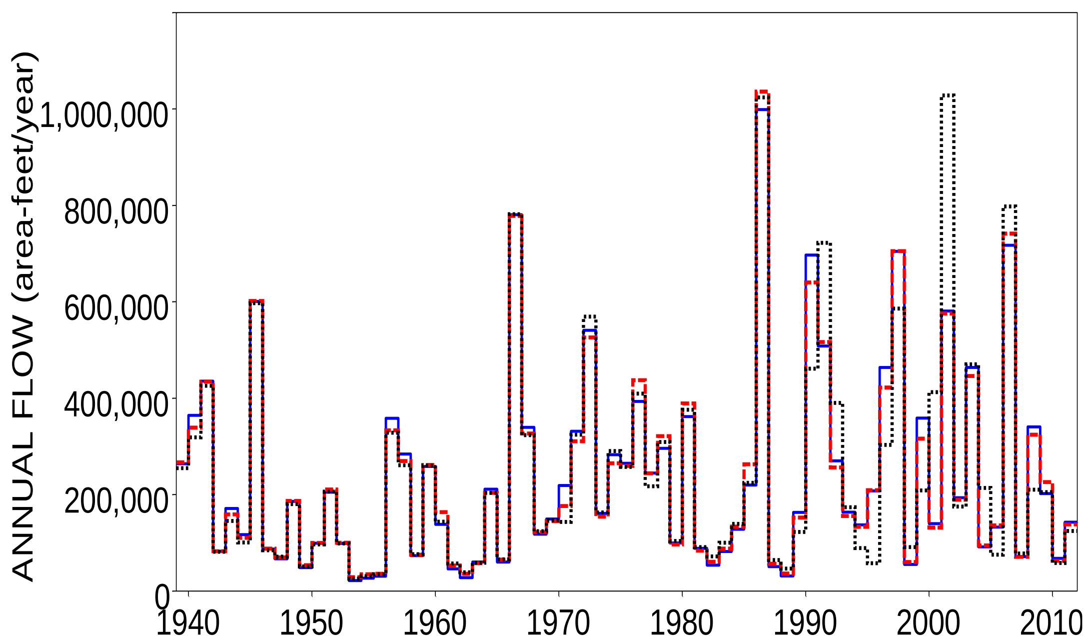
Naturalized Flows of San Antonio River at Goliad



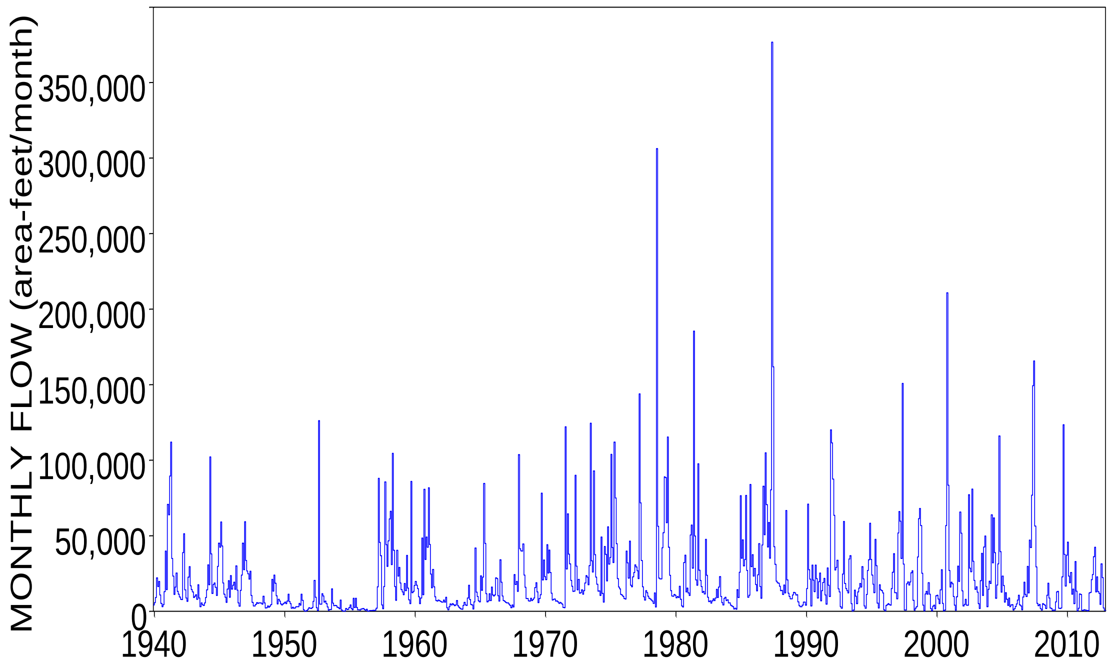
Naturalized (blue solid), Regulated (red dashed) and Observed Annual Flows for San Antonio River at Goliad



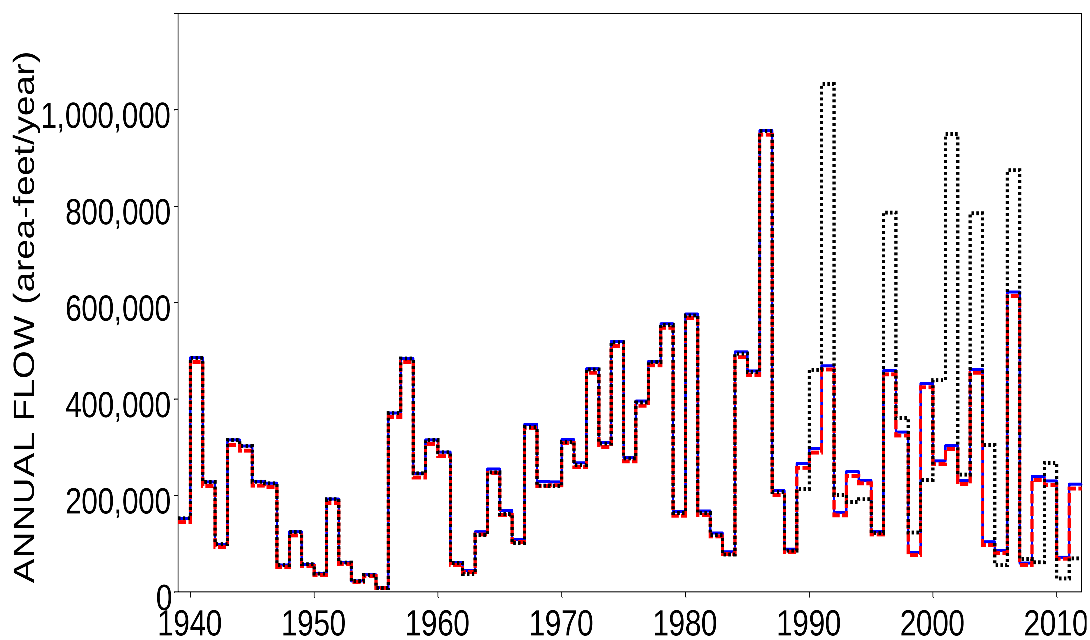
Naturalized (blue solid), Regulated (red dashed) and Observed (black dotted) 2-Month Minimum Annual Flows for San Antonio River at Goliad



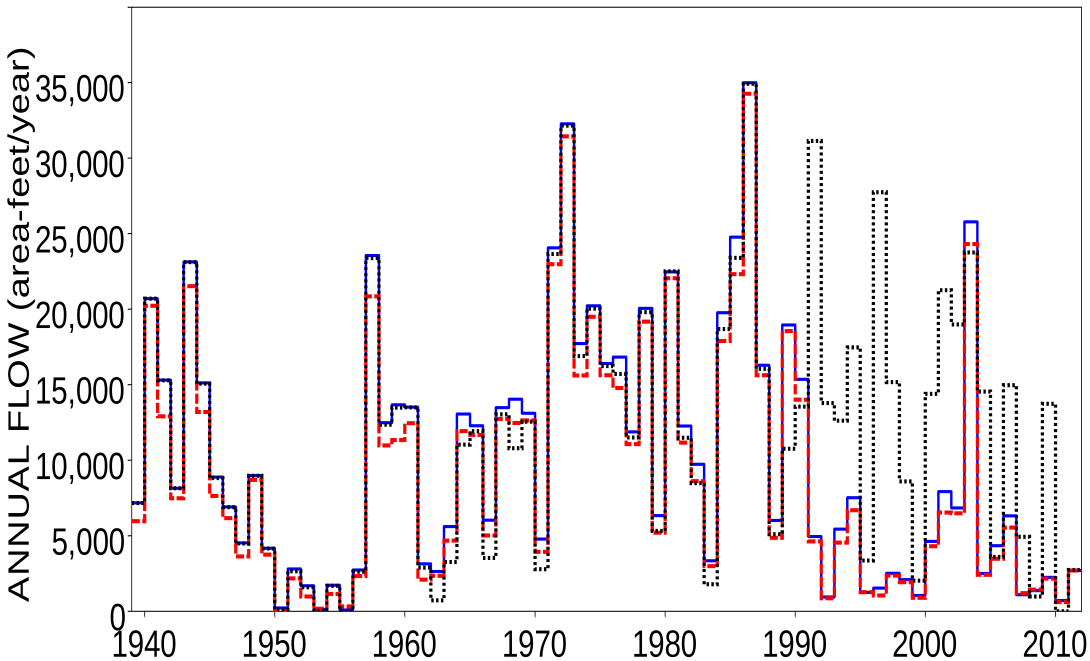
Naturalized (blue solid), Regulated (red dashed) and Observed (black dotted) 2-Month Maximum Annual Flows for San Antonio River at Goliad



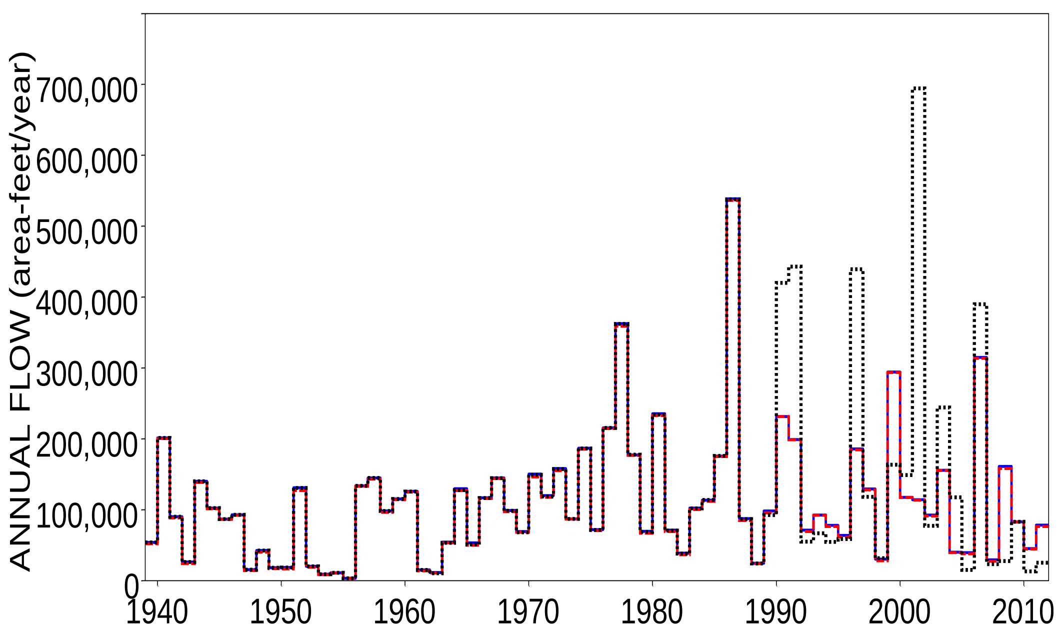
Naturalized Flows of Guadalupe River at Spring Branch



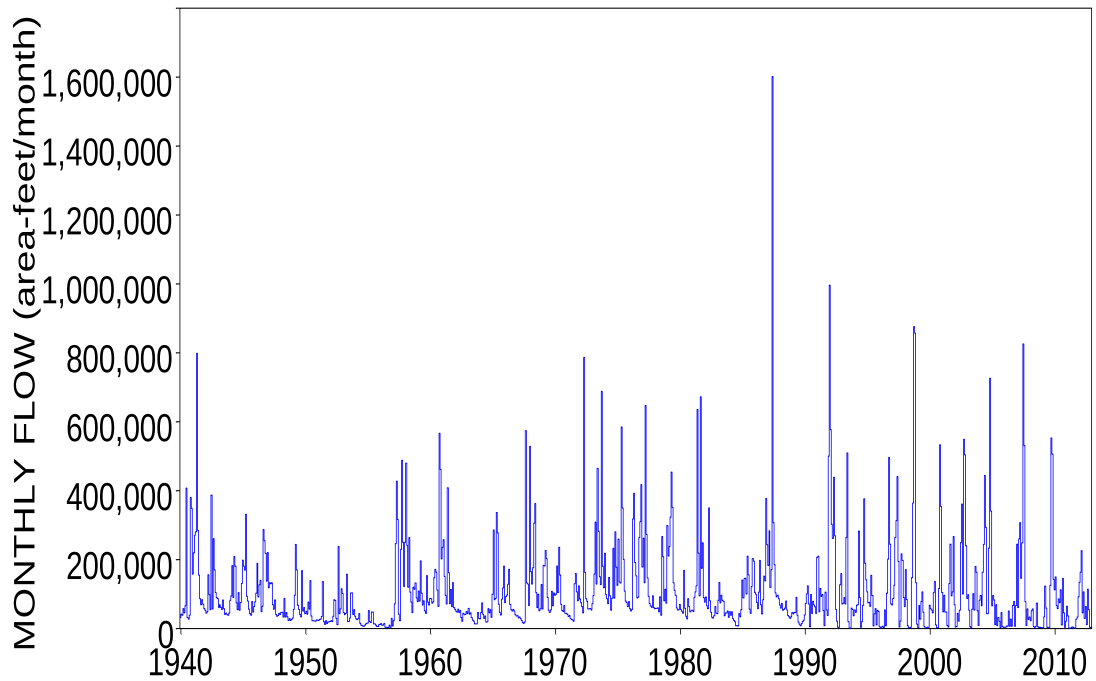
Naturalized (blue solid), Regulated (red dashed) and Observed (black dotted) Annual Flows for Guadalupe River at Spring Branc



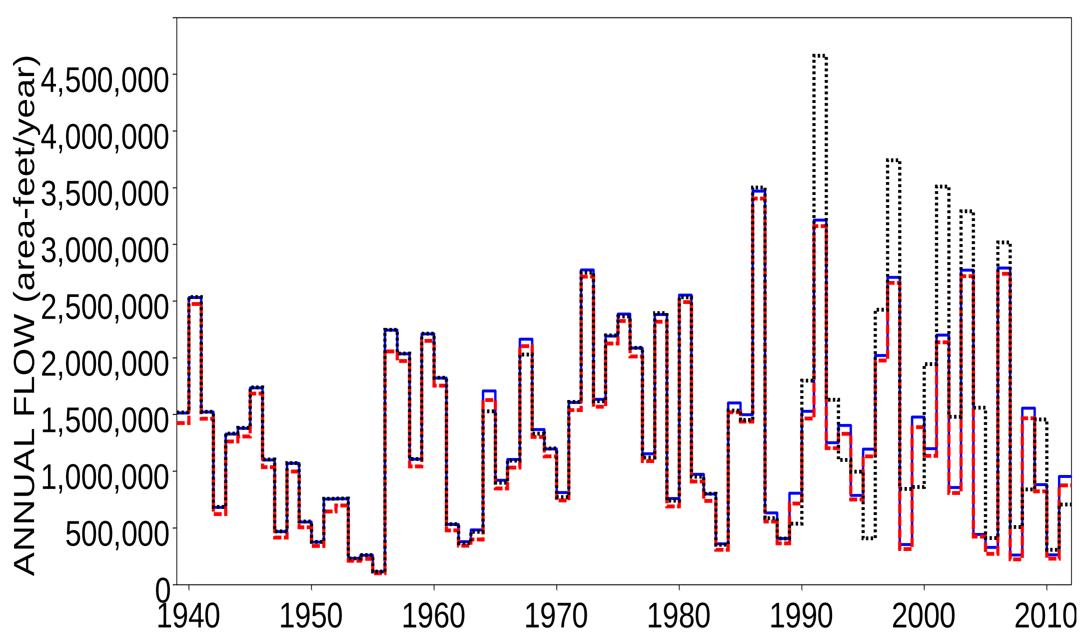
Naturalized (blue solid), Regulated (red dashed) and Observed (black dotted) 2-Month Minimum Annual Flows for Guadalupe River at Spring Branch



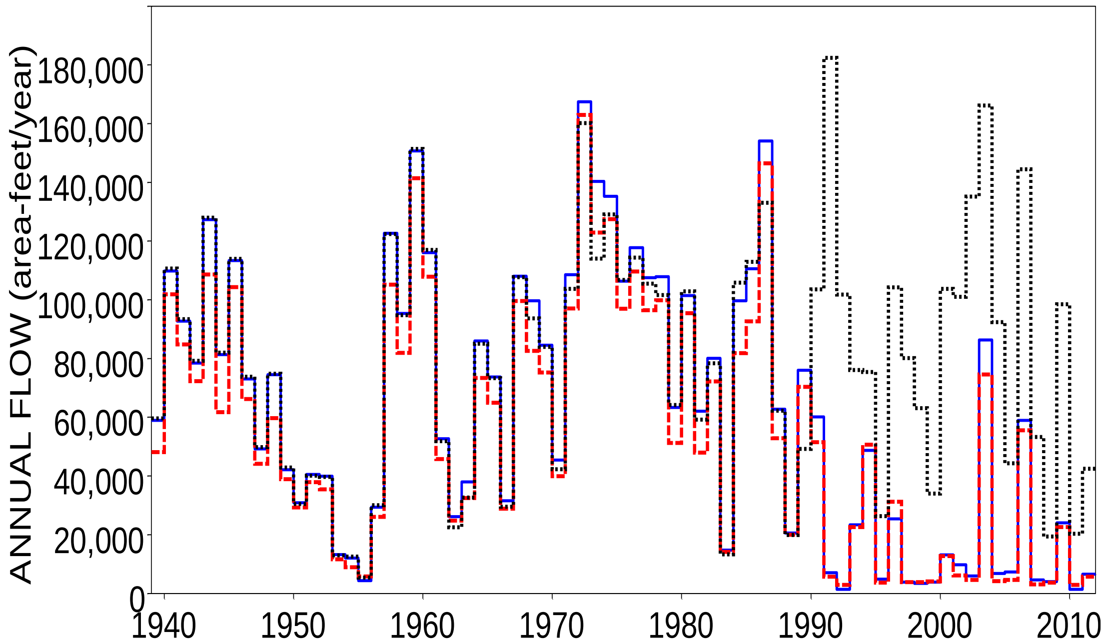
Naturalized (blue solid), Regulated (red dashed) and Observed (black dotted) 2-Month Maximum Annual Flows for Guadalupe River at Spring Branch



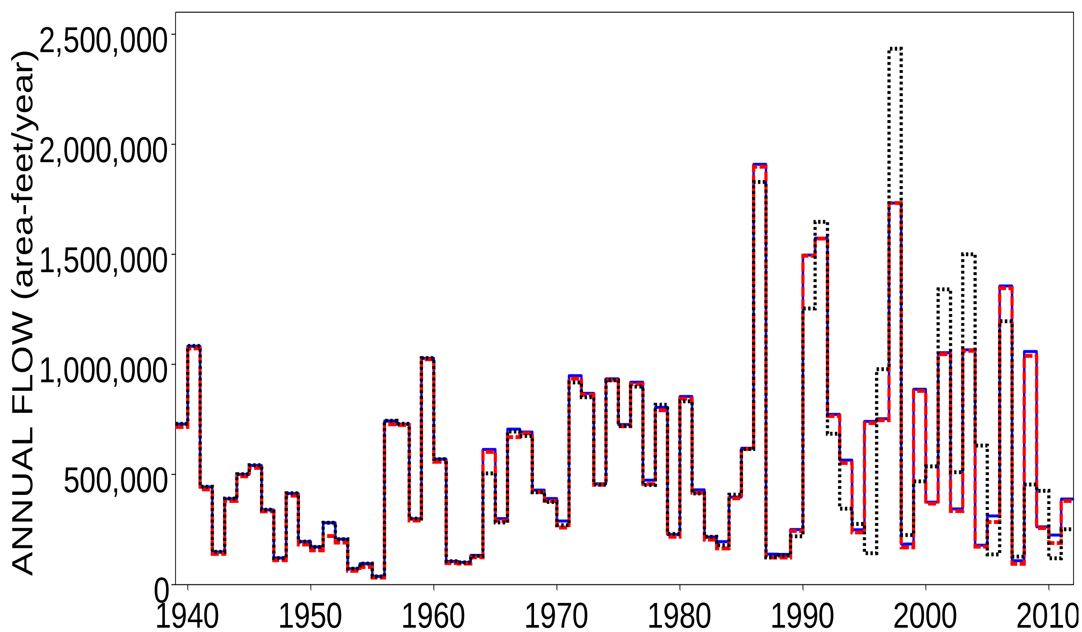
Naturalized Flows of Guadalupe River at Victoria



Naturalized (blue solid), Regulated (red dashed) and Observed (black dotted) Annual Flows for Guadalupe River at Victoria



Naturalized (blue solid), Regulated (red dashed) and Observed (black dotted) 2-Month Minimum Annual Flows for Guadalupe River at Victoria



Naturalized (blue solid), Regulated (red dashed) and Observed (black dotted) 2-Month Maximum Annual Flows for Guadalupe River at Victoria