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Hydrologic Analysis Before and After Reservoir Alteration at the Big Bend Reach, Rio Grande/Rio Bravo

by

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EXECUTIVE SUMMARY

The Rio Grande/Bravo basin is located in North America between two riparian nations, the United States (U.S.) and Mexico. The Big Bend reach, is located along the Rio Grande/Bravo, between the cities of Presidio/Ojinaga to Amistad international Reservoir. Important habitats such as the Big Ben national and state park in the U.S. and Maderas del Carmen, Cañon de Santa Elena and Ocampo in Mexico form part of this reach, and depend on the water in the river for their environmental requirements. The Treaty of 1944 establishes the water allocation in this region; unfortunately, this regulation does not consider the environment as an integral part of the water management. As a result, the environmental condition in this reach has been deteriorated. One sign of the deterioration is the continuous channel narrowing in this reach. Prior 1946, the Big Bend reach used to maintained a wide, sandy, multi-thread channel. Frequent floods moved sediments and prevented any substantial accumulation. In the 1940's, the construction of the Caballo (completed in 1938) and Francisco I. Madero (completed in 1949) reservoirs altered its hydraulic properties, becoming a narrower and single-thread river. Channel narrowing was temporally interrupted by large floods that re-widen the channel. In addition, because of the reservoirs, floods were also less frequent in time and magnitude.

Two are the main objectives of this study: 1) characterize and compare *extreme flood events, normal and drought flows* in the Big Bend reach for two periods, prior the dams alteration (pre-1946) and after (post-1946); and 2) propose an annual hydrograph that mimics the prior alteration hydrologic characteristics. Each period has been analyzed to determine its hydrologic characteristics. For extreme flood events we are concerned with peak flows, frequency, return periods and the volume of water required to trigger river widening. For normal and drought flows, three benchmarks are used: median monthly flows, high flows and small floods. The magnitude, timing and frequencies of these benchmarks are obtained and compared between periods of analysis. Based on the analysis and comparison of both periods, an annual hydrograph is proposed in order to: 1) mimic the hydrologic characteristics of the pre-1946 conditions, and 2) try to restore the environmental conditions in the Big Bend reach. The following sections are a summary of the results found. More detailed information of the methods used and results founded are presented in the main document.

Extreme Flood Events

Extreme flood events (EFE) have been analyzed at the Big Bend reach using Johnson Ranch gauge station. These events typically occur in late August, September and early October.

Prior 1946, four EFE occurred in late August early September (1904, 1932, 1938, and 1942), durations range from 8 to 30 days and peak daily flows from 1,560 to 3,851 m^3/s; the total flow in any flooding event is larger than $1{,}000X10^6$ m^3. These occurrences, along with frequent smaller floods moved sediment and prevented any substantial accumulation in the canal, maintaining a wide, sandy multi-threaded river with regular resetting events.

After 1946, four EFE occurred in September (1958, 1978, 1990-1991 and 2008), durations range from 21 to 38 days and peak daily flows from 1,410 to 1,850 m^3/s; the total flow in any flooding event is larger than $1,000X10^6$ m^3. These EFE have re-widen the channel after period of agradation and channel narrowing between extreme flood events.

After analyzing and comparing EFE between both periods, these are the conclusions:

- EFE that re-widen the channel have: a) a peak flow larger than 1,400 m^3/s and b) a total flow $1,000X10^6$ m^3 for the whole flooding event.
- EFE post-1946 are less frequent than pre-1946, they happen in the double of time they used to; once every 15~16 years in the post-1946 compared to once every 7~8 years in the pre-1946 period.
- Peak flows post-1946 are lower than post-1946, about half of the magnitude (on average 48%) (Figure ES-1)
- EFE happen three weeks later in the post-1946 period, from October 1-7th in the pre-1946 to October 21-28th in the post-1946.

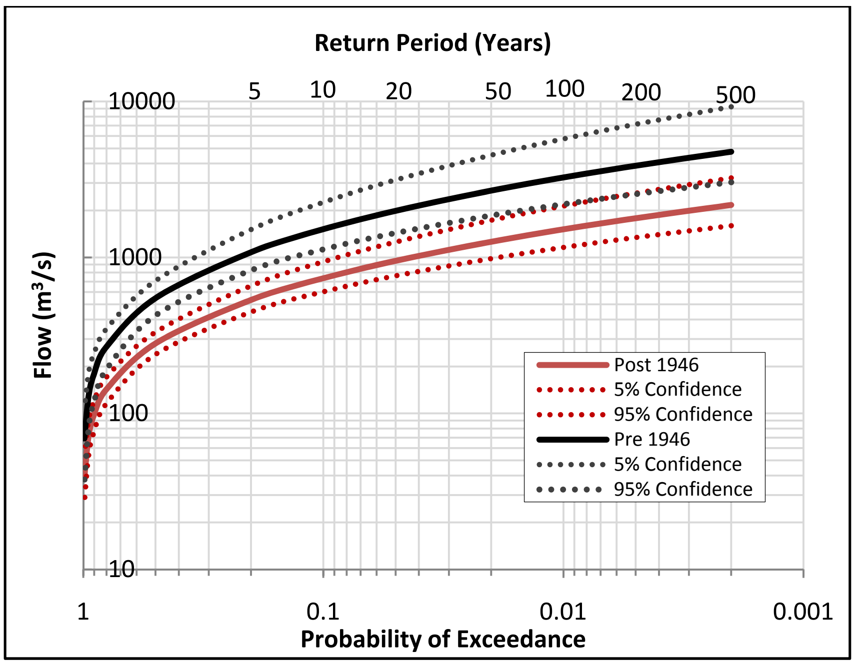

Figure ES-1. Log-Pearson III distributions, Pre-1946 and Post-1946

Figure ES-1 show the Log-Pearson type III distribution for annual maximum flows in both periods. HEC-SSP, software developed by the US Army Corps of Engineers, is used to examine EFE in this region. The Log-Pearson distributions show that post-1946 maximum annual flows are about half (48%) of the pre-1946 maximum annual flows for the same return period.

Analysis of Normal and Drought Conditions

In order to characterize normal and drought conditions, the mean daily flows at Johnson Ranch have been analyzed. Flows have been categorized according to the following *benchmarks*.

- *Median monthly flow* is the median value of the mean daily flows for each month.
- *High flows* are flows with a peak between the 75th (56 m^3/s) and 95th (224 m^3/s) percentile of the mean daily flows for the pre-1946 period.
- *Small floods* are flows with a peak between the 95th percentile (224 m^3/s) of the mean daily flows for the pre-1946 period and 1,100 m^3/s, which is a threshold to account for the levees upstream the Big Bend reach at Presidio/Ojinaga cities; maximum flow of 1,190 m^3/s (42,000 cfs).
- *Large floods* are flows with a peak above 1,100 m^3/s. These large floods will definitely threaten the safety of the levees in the Ojinaga/Presidio Valley.

The thresholds for the benchmarks have been defined using the pre-1946 data in order to: 1) determine the characteristics (frequency, peak flows and duration) of the benchmarks that occurred prior the alteration of the channel, and 2) compare the frequency of these benchmarks prior alteration (pre-1946) with the post alteration period (post-1946). The median values have been used to determine characteristics hydrographs of high flows and small floods for each month and period of analysis (pre-1946 and post-1946).

Two hydrologic periods have been analyzed: 1) pre-1946, a 30 year period of analysis (Jan/1901 to Dec/1913 and Jan/1930 to Dec/1946); and 2) post-1946, which data also for 30 years (Jan/1980 to Dec/2009). For the post-1946 the last thirty year period has been chosen with the aim of analyze the hydrological characteristics of the immediate hydrology. This period contains a wide range of hydrologic conditions, from the wet period of the 80's (1984-1993) to the severe and extended drought of the 90's (1994-2007).

The Indicators of Hydraulic Alteration (IHA) software has been used to label the different flows along the periods of analysis. High flows and small floods have been characterized by determining their hydrograph for each period of analysis. Return periods for high flows and small flood have been calculated using the frequency of these benchmarks in the respective period of analysis.

Normal Hydrologic Conditions

The daily mean flow values at Johnson Ranch for both periods has been analyzed in order to determine a characteristic hydrograph for the following return periods (T):a) 1 year, b)2 to 3 years, c) 5 to10 years, and d) more than 10 years.

Prior 1946, median monthly values varied from 11 m^3/s in April to 98 m^3/s in September. A median of 7 high flows occurred per year. High flows occurred every year in July, August, October and December and once every 2-3 year in the rest of the months. A median of 2 small floods occurred every year, one fixed in September (peak flow=407 m^3/s) and another small flood variable in time that usually happened in July (peak flow=405 m^3/s), August (peak flow=396 m^3/s) or October (peak flow=422 m^3/s). The combination of two small floods may have contributed to maintaining the Rio Grande/Bravo as a wide sandy multi-threaded river. Figure ES-2 shows a proposed annual hydrograph for the pre-1946 conditions; it includes the benchmarks for 1 and 2-3 year return period (T). This hydrograph have the fixed small flood in September and the moving small flood in July. The volume of the 1 and 2-3 year return period is 1,292X10^6 m^3 and 197X10^6 m^3 respectively;

thus, the annual hydrograph shown in Figure ES-2 has a volume of 1,489X10^6 m^3. Values for the median monthly flow and the peak flows of the benchmarks are also included in the figure.

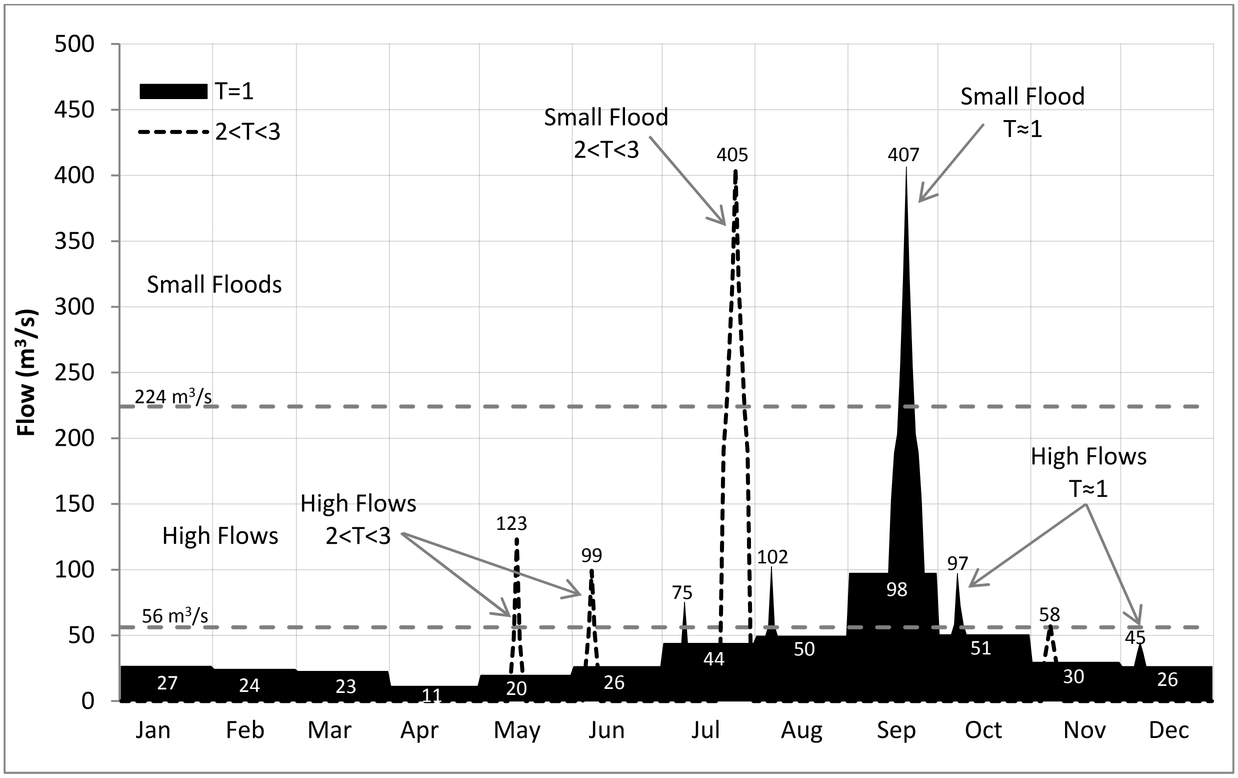

Figure ES-2. Pre-1946 annual hydrograph

Post-1946, median monthly values varied from 8 m^3/s in April to 24 m^3/s in September. A median of 8 high flows occurred per year. High flows occur every year from May to August; and once every 2-3 year in March, April, September and October. A median of 0.5 small floods occurred every year, meaning that certain year one small flood may occur September (peak flow=341 m^3/s), and the following year may not happen any small flood. The reduction in the frequency and magnitude of small floods contributed to the deterioration of the environmental conditions at the Big Bend reach. This deterioration has been evident by the progressive channel narrowing and vertical acreation. Figure ES-3 shows a proposed annual hydrograph for the post-1946 conditions; it includes the benchmarks for 1 and 2-3 year return period (T). This hydrograph only have one small flood in September that is smaller in magnitude than the pre-1946 value. The volume of the 1 and 2-3 year return period is 492X10^6 m^3 and 94X10^6 m^3 respectively; thus, the annual hydrograph shown in Figure ES-3 has a volume of 586X10^6 m^3. The median monthly values are also smaller, than the pre-1946 values. Values for the median monthly flow and the peak flows of the benchmarks are also included in the figure.

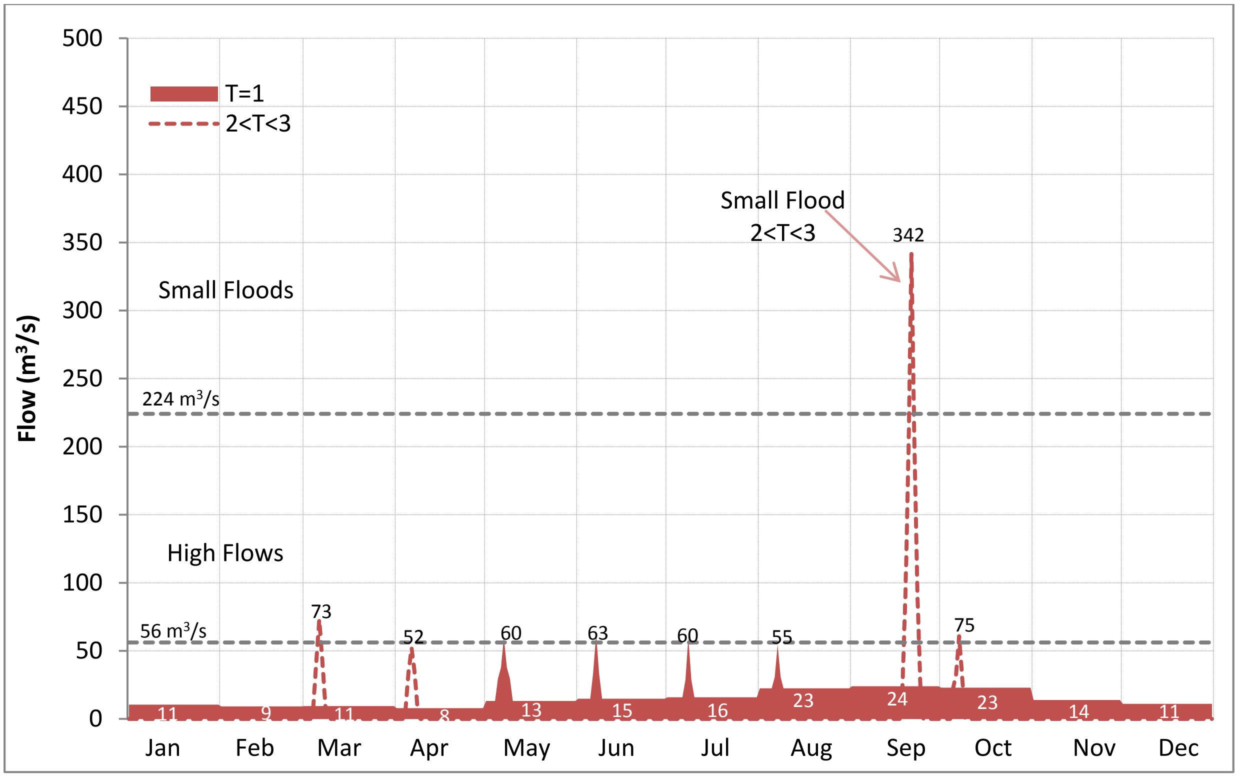

Figure ES-3. Post-1946 annual hydrograph

Comparing both hydrographs it can be concluded that part of what happened every year in the pre-1946 period (annual hydrograph with 2 small floods) now it is happening every 2-3 years in the post-1946 period (annual hydrograph with only one small flood). In fact, the post-1946 hydrograph represents the 40% of the pre-1946 volume. In the post-1946 hydrograph there is a proliferation of high flows but not of small floods. After analyzing different annual hydrographs for different return periods, these are the conclusions:

- The annual volume of median monthly flows decreased by 656.8 X10^6 m^3, or 59.0% of the pre-1946 annual quantity.
- Small floods in the pre-1946 conditions were frequent (peak flow=400 m^3/s), twice per year; one fixed in September and at least another in July, August or October. There is a lack of small floods in the post-1946 conditions, a median of less than one event per year.
- High flows and small floods that occurred every year (T=1) in the pre-1946 conditions happen every 2-3 years in post-1946. Similarly, high flows and small flows that occurred every 2-3 years (2<T<3) in the pre-1946 period happen every 5 years in the post-1946.

Drought Hydrologic Conditions

Drought year (annual volume<median) have been identified for both periods; pre-1946 (1901-1913 and 1930-1946) and post-1946 (1980-2009). Similarly to the previous analysis, daily mean flow values at Johnson Ranch for drought years have been analyzed in order to determine annual hydrographs for the following return periods (T):a) 1 year, b)2 to 3 years, c) 5 to10 years, and d) more than 10 years.

During drought years in the pre-1946, median monthly values varied from 10 m³/s in April to 45 m³/s in September. The annual volume of median monthly flows decreases during drought years from 1,130X10⁶ m³ to 782X10⁶ m³ compared to the pre-1946 normal hydrologic conditions. The decrease in the median monthly flows is the main difference between the normal and drought conditions of the pre-1946. A median of 8 high flows still occurred per year during drought years. High flows occurred every year in July, August, September and December and once every 2-3 year in the rest of the months. Similarly, a median of 2 small floods occurred every year, one fixed in September (peak flow=380 m³/s) and another small flood variable in time that usually happened in August (peak flow=270 m³/s) or October (peak flow=422 m³/s). These two small floods contributed to maintaining the Rio Grande/Bravo as a wide sandy multi-threaded river in spite of the drought conditions. Figure ES-4 shows a proposed annual hydrograph for the pre-1946 conditions during drought years; it includes the benchmarks for 1 and 2-3 year return period (T). This hydrograph have the fixed small flood in September and the moving small flood in October. The volume of the 1 and 2-3 year return period is 954X10⁶ m³ and 111X10⁶ m³ respectively; thus, the annual hydrograph shown in Figure ES-4 has a volume of 1,065X10⁶ m³. Values for the median monthly flow and the peak flows of the benchmarks are also included in the figure.

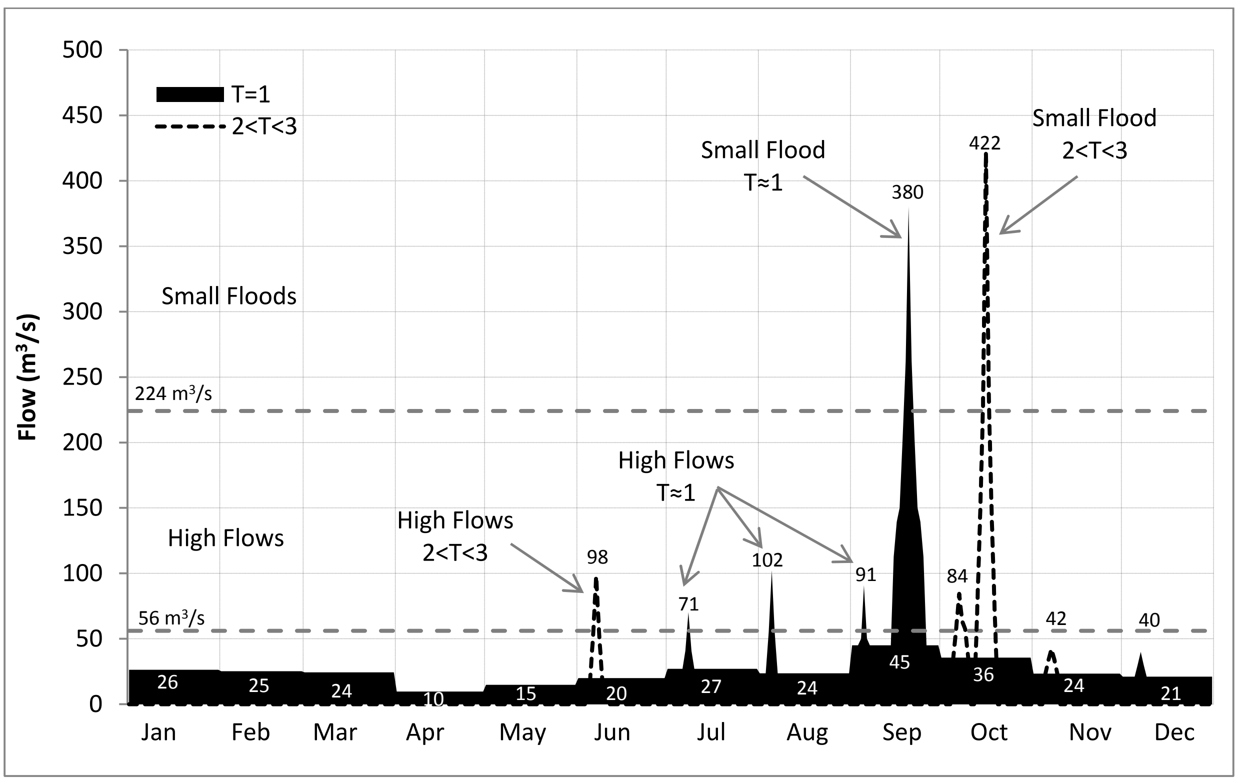

Figure ES-4. Pre-1946 annual hydrograph during drought years

During drought years in the post-1946, median monthly values varied from 3 m³/s in April to 13 m³/s in September. The annual volume of median monthly flows decreases during drought years from 463X10⁶ m³ to 250X10⁶ m³ compared to the post-1946 normal hydrologic conditions. For the post-1946, the decrease in the median monthly flows is the most significant difference between the normal and drought conditions. A median of 7 high flows occur per year during drought years. High flows occurred every year in May, June, July and August and once every 2-3 year in September and October. A median of 0 small floods occurred during drought years and if they occurred, these event happened mostly in June (peak flow=310 m^3/s). The characteristics extended drought periods of the Rio Grande/Bravo basin coupled with the significant reduction in frequency and magnitude of small floods during drought years definitely contributed to the deterioration of the environmental conditions at the Big Bend reach. During drought periods the channel narrowing and vertical acreation must be exacerbated due to the scarce frequency of small floods. Figure ES-5 shows a proposed annual hydrograph for the post-1946 conditions during drought years; it includes the benchmarks for 1 and 2-3 year return period (T). This hydrograph only have one small flood in June that is smaller in magnitude than the pre-1946 value and out of timing. The volume of the 1 and 2-3 year return period is 282X10^6 m^3 and 71X10^6 m^3 respectively; thus, the annual hydrograph shown in Figure ES-5 has a volume of 353X10^6 m^3. The median monthly values are much smaller than the pre-1946 values during drought period. Values for the median monthly flow and the peak flows of the benchmarks are also included in the figure.

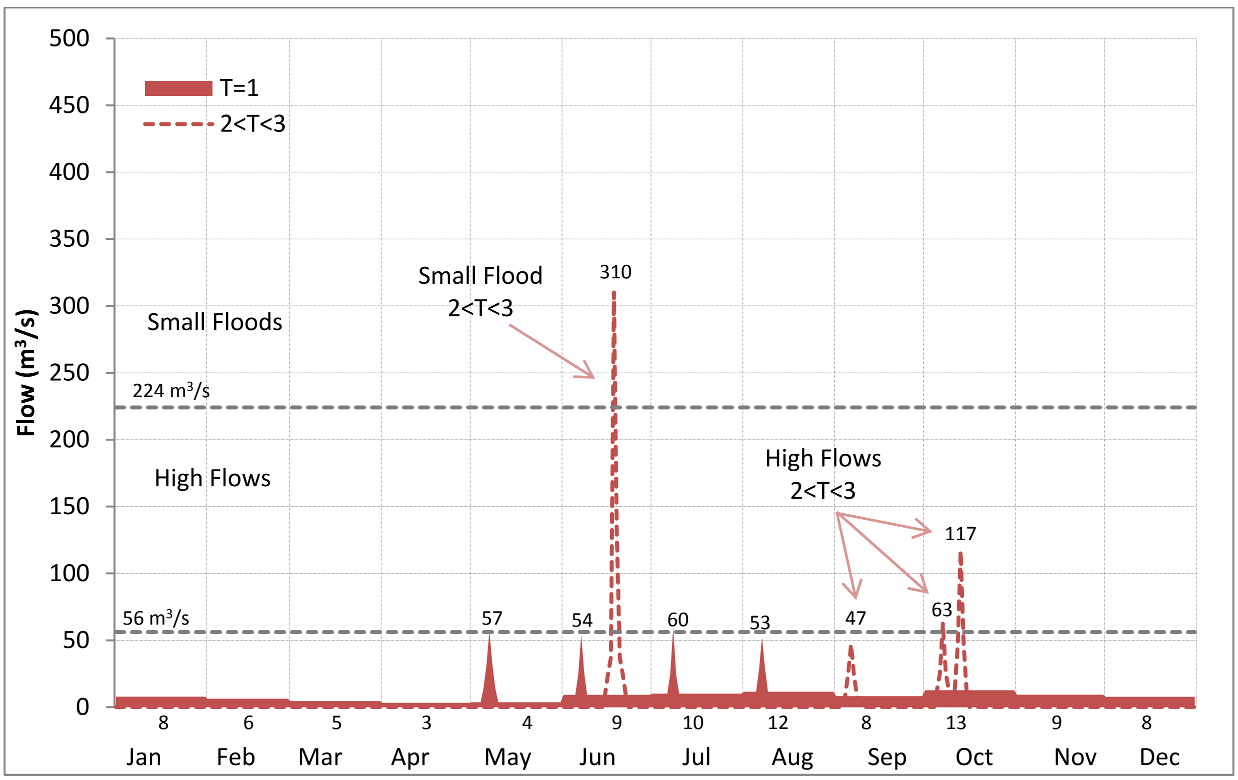

Figure ES-5. Post-1946 annual hydrograph during drought years

After analyzing the annual hydrographs during drought years for different return periods, these are the conclusions:

- In pre-1946, small floods occur during drought years, the fixed small flood of September (Flow peak = 380 m^3/s) still occurs during drought years preventing from agradation and channel narrowing.

- During drought years, small floods occurred more frequently in the pre-1946 conditions, a median of 2 events per year, meanwhile in the post-1946 conditions they frequency dropped to 0 events per year.
- Median monthly flows decreased significantly, by 68% of the pre-1946 annual quantity. In addition, the shape of the median values is altered; in the post-1946 the highest median value has shifted from September to October.

Proposed hydrograph for the Big Bend at Johnson Ranch

After the extensive analysis done at Johnson Ranch, these are the characteristics considered for the proposed hydrograph:

- Median monthly flows with a distribution similar to the pre-1946 period.
- Two small floods; one small flood fixed in September and another small flood in July, August, or October. The peak flow of these floods must be of 400 m^3/s.
- Four high flow pulses; one in each of the following months: July, August, October and December.

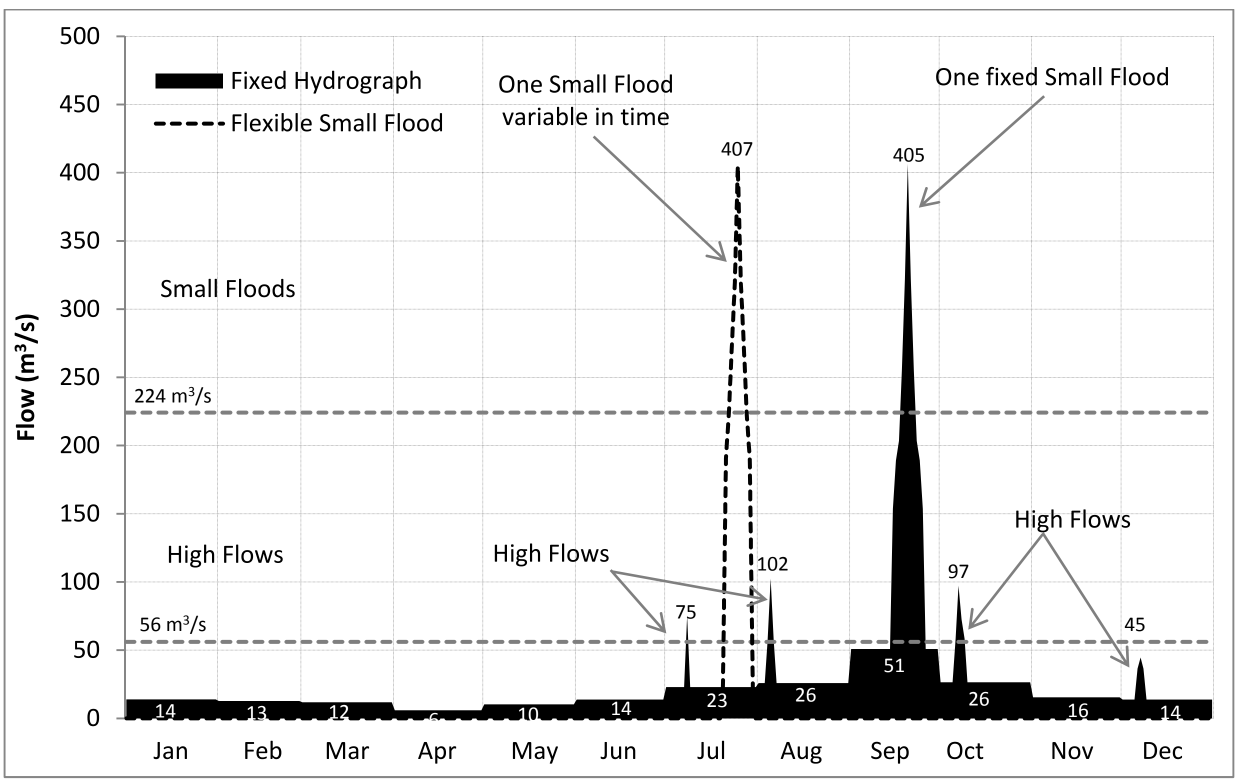

Figure ES-6. Annual hydrograph proposed for Johnson Ranch

From 1947 to 2009, the median annual flow at Johnson Ranch is 744X10^6 m^3. Considering this, an annual volume of 1,000X10^6 m^3 is proposed. Figure ES-6 shows the annual hydrograph proposed for Johnson Ranch. Table ES-1 shows the monthly and annual volume necessary to supply the hydrograph proposed.

Table ES-1. Monthly volume of the proposed hydrograph

	Volume (1X106 m3)												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Sum
Median	37	31	32	15	28	36	62	69	132	71	40	37	**589**
High Flows	---	---	---	---	---	---	5	12	---	16	---	7	**39**
Small Floods	---	---	---	---	---	---	191	---	181	---	---	---	**372**
Total	37	31	32	15	28	36	257	81	313	86	40	43	**1000**

Compared to the post-1946 conditions (Figure ES-3), main differences are in the median monthly flows, mostly from July to October, and in considering 2 small floods of 400 m^3/s approximately.

Conclusions

The characterization of extreme flood events (EFE), normal and drought conditions and the comparison of their results has show how significantly different is the hydrology prior and after alteration. The change in the hydrology is the result of the infrastructure and human water management that has completely modified the hydrologic characteristics of the river. For EFE, the quantity, frequency, and timing have been severely altered, magnitudes of peak flows have decreased by 50% and return periods have doubled. During normal and drought conditions, the annual flow volumes have decreased by alarming 59% and 68%, respectively. A lack of small floods is a constant in the post-1946 period. As a result, the environment has been deteriorated; one sign of this is the continuous narrowing of the channel. In order to revert this trend, an annual hydrograph has been proposed for environmental restoration.

The hydrograph proposed tries to match as much as possible the pre-1946 characteristics: i) two small floods, ii) several high flows and iii) median monthly flow similarly distributed as the pre-1946 normal conditions. In fact, the proposed hydrograph (Figure ES-6) is about the same volume as the drought years' hydrograph (Figure ES-4) for the pre-1946. Is it fair (or correct) to propose a hydrograph that used to be for drought conditions? Should we ask for the pre-1946 normal condition (Figure ES-2) hydrograph? Is it enough water left in the current system to supply any of the two hydrographs? How much water is still available in the system? How much of the available water can be managed by the infrastructure to meet this environmental flow restoration?

Unfortunately, there is no answer for any of the previous questions yet. However, research has been done to determine environmental restoration flows and how to operate the system in order to meet these flows. This report forms part of this effort to determine the environmental restoration flows. Results presented here are not definitive; on the contrary, they are intended to be the foundation of discussions and constructive opinions from academic, scientists and the environmental community. This is just one step of several that will be needed to determine the required flows for environmental restoration at the Big Bend reach.

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1. BACKGROUND

1.1 INTRODUCTION

The Rio Grande/Bravo basin is a transboundary basin between Mexico and the United States (U.S.) (Figure 1-1). The Rio Grande/Bravo is the principal source of water for over ten million people in the Rio Grande/Bravo basin. Withdrawals and diversions have been created to use water for drinking, irrigation, sanitation, manufacturing, and power generation. In its northern stretches, above Ojinaga/Presidio, the Rio Grande/Bravo is primarily fed by snowmelt from the Rocky Mountains. To the south, below Ojinaga/Presidio, the river is fed by tributaries in the basin, primarily the Rio Conchos. Between these sources lies the Big Bend, a 490 km stretch between the cities of Ojinaga/Presidio to Amistad reservoir. Environmental flows are of particular concern in the Big Bend region due to the wildlife reserves in the area. Important environmental habitats such as the Big Bend national and state park in the US, the Northern Chihuahuan desert, the Maderas del Carmen, the Cañon de Santa Elena and Ocampo natural reserves in Mexico are ecologically threatened because of the lack of environmental water management policies in the basin

Historically, this basin has been manipulated in an exclusive human water resource management, not considering the environmental needs for the native ecosystems. The Convention of 1906 signed between Mexico and the U.S. (IBWC 1906) and the Rio Grande Compact (TCEQ 1939) ratified in 1939 between the States of Colorado, New Mexico and Texas prove the fact that the water in this basin was thought to be used exclusively for human benefit. The water allocation in these agreements obeys exclusively the human concerns, leaving out the natural water requirements of the basin. As a result of the previous agreements, the quantity of water in the Rio Grande/Bravo reach between El Paso/Cd. Juarez to Presidio/Ojinaga were reduced so dramatically, that this reach is now referred as the “forgotten river” where almost no water flows.

Another example is the signature of the treaty of 1944 between Mexico and the U.S. (IBWC 1944). In this treaty, the environmental issues are not considered and the priority assigned to the environment is not even specified, leaving it in disadvantage with respect to the other water uses. In addition, because of the water scarcity in the basin and the high competition among water users for the resource, the environmental requirements has been denied or not even considered for a long time.

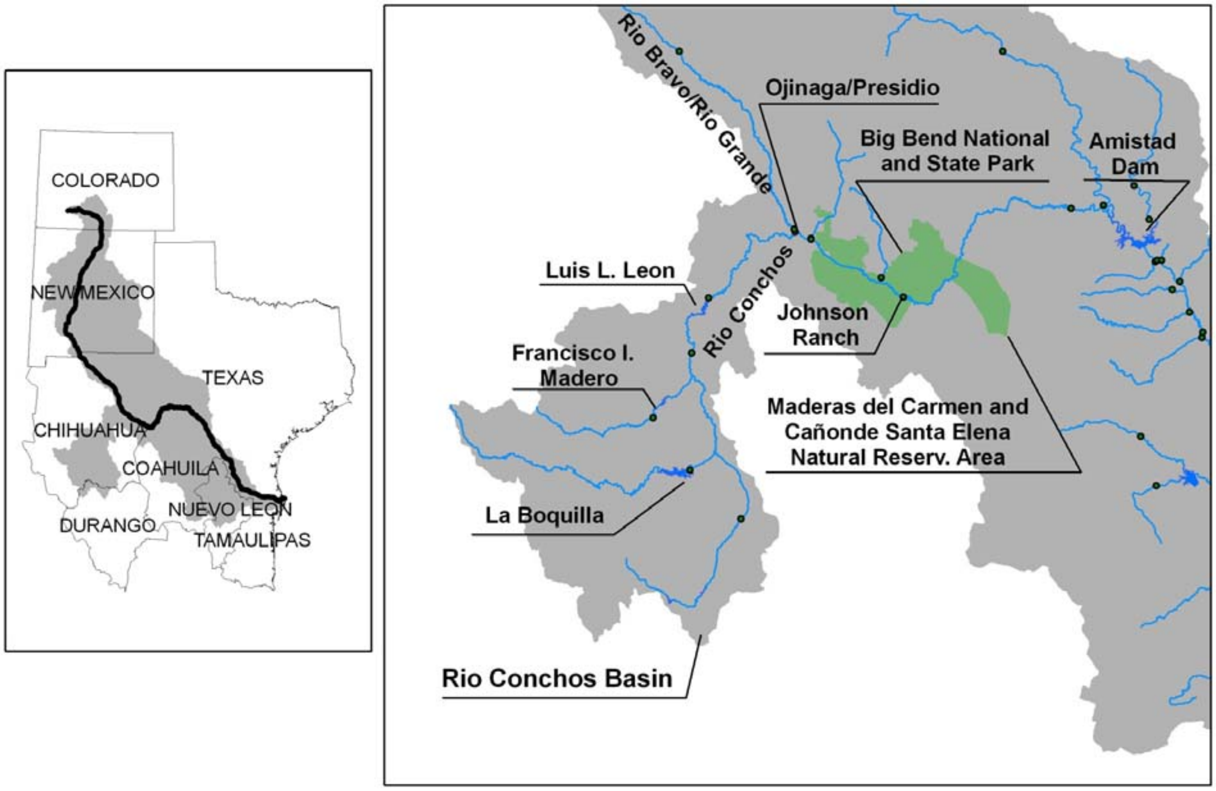

Figure 1-1: Rio Grande/Bravo Basin

Flooding is an integral part of the environmental cycle. Many ecological functions are performed when floodplains become inundated with water. High flows provide a spawning cue for fish. The shallow, nutrient rich, floodplains also provide an ideal habitat for feeding and spawning. Additionally, flooding helps maintain plant diversity. Periods of inundation allow for water tolerant plants to thrive while killing those who are less suited. In the absence of regular flooding, drought resistant plants dominate the riparian vegetation. Inundation also improves soil and water quality. Floods deliver nutrients to floodplains while washing away old topsoil. Inundation increases water purification by providing greater dispersion of pollutants and more contact with vegetation (Postel and Ritcher 2003).

Dean and Schmidt (2010) extensively examined the relationship between channel widening and extreme flood events by using aerial photographs of the Big Bend reach to establish a relationship between floods events and channel width. Figure 1-2 shows the channel width as function of time, as well as some of the feedback mechanisms that influence the channel width. Dean and Schmidt (2010) conclude that due to reductions in mean and peak stream flows, the channel of the lower Rio Grande/Bravo has narrowed by more than 50% since 40's

Reductions in mean flow and extreme flood events are product of dam construction. Prior 1946, the Big Bend reach used to maintained a wide, sandy, multi-thread channel (Dean and Schmidt 2010). Frequent floods moved sediments and prevented any substantial accumulation. In the 1940's, the construction of the Caballo (completed in 1938) and Francisco I. Madero (completed in 1949) reservoirs altered its hydraulic properties, becoming narrower and single-thread river. Channel narrowing has been temporally interrupted by large floods that re-widen the channel. Not only mean flows but also extreme flood events have been reduced in frequency and magnitude.

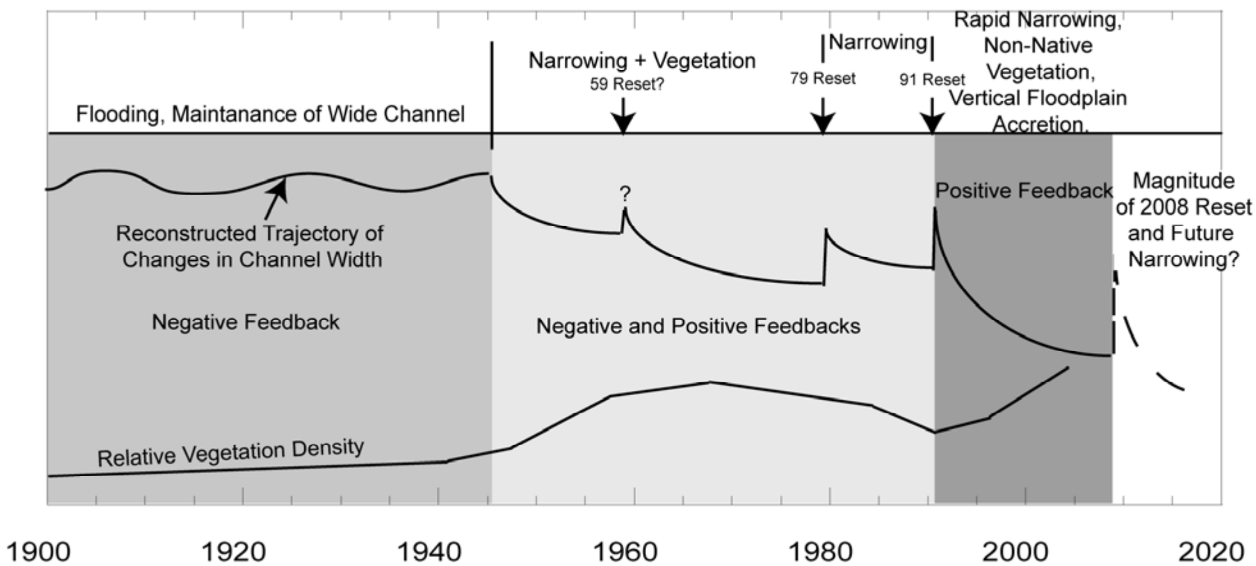

Figure 1-2: Reconstructed channel widths (Dean and Schmidt, 2010)

This document describes the hydrologic characteristics of the Rio Grande/Bravo in the Big Bend reach for two periods: 1) before 1946, when the river used to be wide, sandy, and multi-threaded river; and 2) after 1946, when the river become narrower and single-thread channel. The hydrologic characteristics analyzed in this document are: a) extreme flood events; b) normal flows and c) drought flows.

1.2 Hydrologic Period of Analysis

The length of the hydrologic period of analysis considered in this study is 93 years, from January 1901 to December 1913 and from January 1930 to December 2009.Prior to 1936, no stream flow data exists at Johnson Ranch; thus the data has been calculated using a regression based on flows at the gage station Rio Grande below Ojinaga which exist for this time period. A more detailed explanation about the calculated data is provided in Appendix A. Also, between 1914 and 1929 no data was recorded at either station, so no data is available for this time period.

The primary year of concern is 1946. In the 1940's the construction of the Caballo (completed in 1938) and Francisco I. Madero (completed in 1949) reservoirs altered the hydraulic properties of the channel at the Big Bend. These alterations are reflected in both the recorded flows and channel geomorphology as presented in Dean and Schmidt (2010). This study compares the periods of pre-alteration (1901-1946) and post-alteration (1947-2009) flow conditions.

For normal and drought conditions, the period of 1980-2009 is analyzed. The main objective is to compare the pre-alteration hydrology with the last 30 year hydrology at the Big Bend reach. Both periods of analysis were selected to match the period length prior to 1946 (1901-1913, 1930-1946), which is also 30 years. All water years begin in January.

1.3 Data Sources

Johnson Ranch gage station, located in the Big Bend, is used as the point of analysis for the project. Mean daily discharge data for this and other control points can be gathered from the International Water Boundary Commission (IWBC) database (IBWC 2009).

2. EXTREME FLOOD EVENTS

In this section, extreme flood events are analyzed at the Big Bend reach using Johnson Ranch gauge station. Extreme flow events at Johnson Ranch come from the Rio Conchos, which is a major tributary of the Rio Grande/Bravo. This tributary receives the majority of the runoff in the Mexican portion of the basin. During the monsoon season, runoff causes high flows in the Rio Conchos and soon after in the Rio Grande/Bravo. These extreme floods typically occur in late September to early October. HEC-SSP, software developed by the US Army Corps of Engineers, is used to examine extreme flood events in this region.

2.1. BEFORE 1946

Prior to 1946, there are four extreme flooding events, occurring in 1904, 1932, 1938, and 1942 as shown in Figure 2-1. Table 2-1 presents a summary of the main characteristic of the flooding events. There is little uniformity between the incidents as durations range from 8 to 30 days and peak daily flows from 1,560 m^3/s (55,091 cfs) to 3,851 m^3/s (135,997 cfs). However, the total flow in any flooding event is larger than approximately 1,000X10^6 m^3 (810,713 acre-feet). Flood events begin in late August to early September. These occurrences, along with frequent smaller floods moved sediment and prevented any substantial accumulation in the canal, maintaining a wide, sandy multi-threaded river with regular resetting events (Schmidt 2010).

Table 2-1: Summary of extreme events pre-1946

	Extreme Flooding Event			
	1904	1932	1938	1942
Start Date	9/5	9/10	9/3	8/22
End Date	9/22	10/11	10/4	10/4
Duration (days)	8	30	14	19
Total Flow (1X$10^6$$m^3$)	1249	1349	986	1368
Peak Flow (m^3/s)	3851	2282	1560	1610
Return Period (years)	126	23	9	10

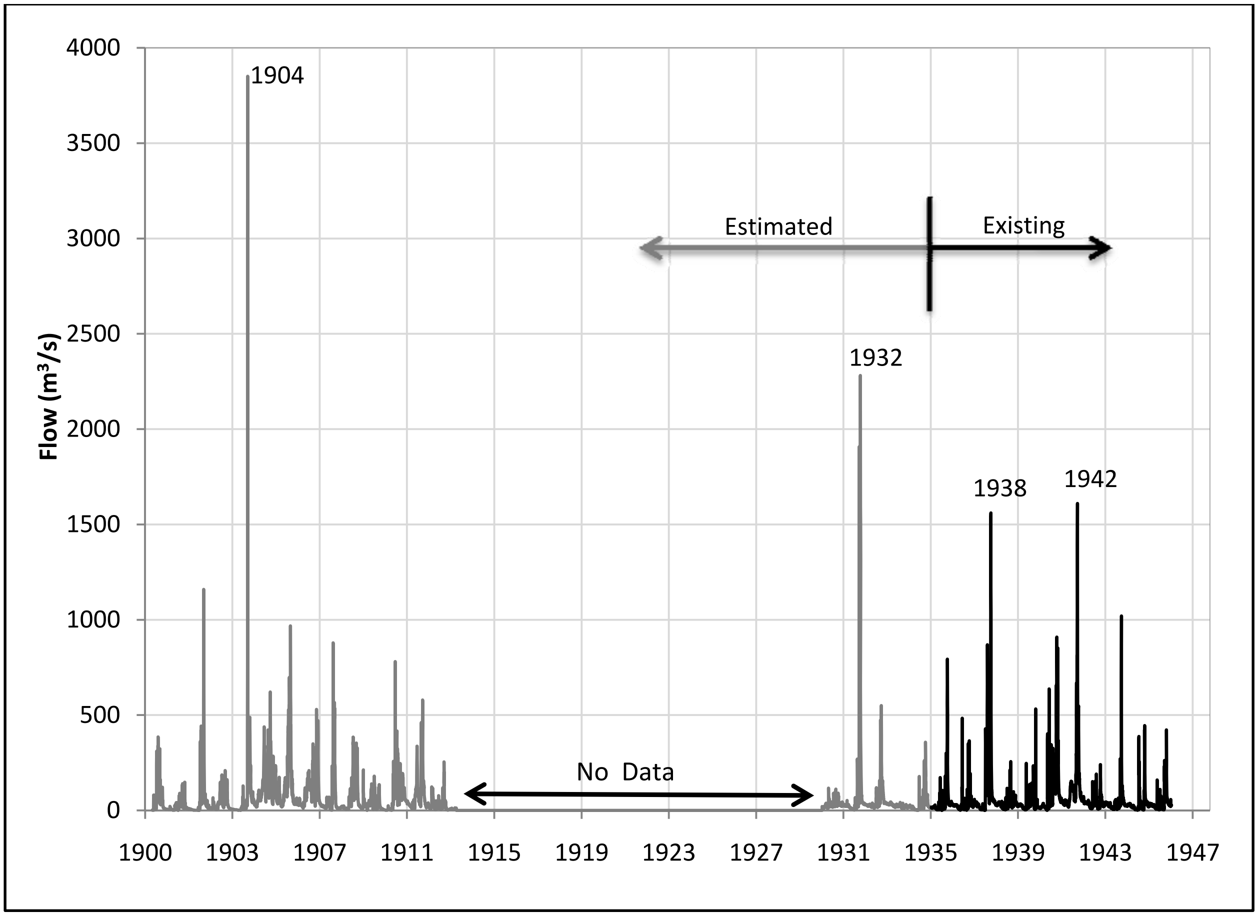

Figure 2-1: Reconstructed discharge data for Johnson Ranch 1900-1946

2.2. AFTER 1946

After 1946, there are four extreme flooding events, occurring in 1958, 1978, 1990-1991 and 2008 (as shown in Figure 2-2). Table 2-2 shows a summary of these events. The peak flow threshold for widening for a one year event is 1,400 m^3/s, with a typical duration of approximately three weeks. Three of the four flood events begin in late September with the other occurring earlier in the month.

Following the construction of dams in the basin, peak flows decreased compared to the pre-1946 state. The absence of regular flooding, led to accumulation of sediment and rapid channel agradation. After 1946, progressive narrowing of the channel cross-section continued, interrupted intermittently by three extreme flooding events causing widening. Similar to the pre 1946 conditions, the total flow in any flooding event is larger than 1,000X 10^6 m^3/s (810,713 acre-feet), approximately. The largest widening event in 1990-1991 corresponds with high flow events in consecutive years.

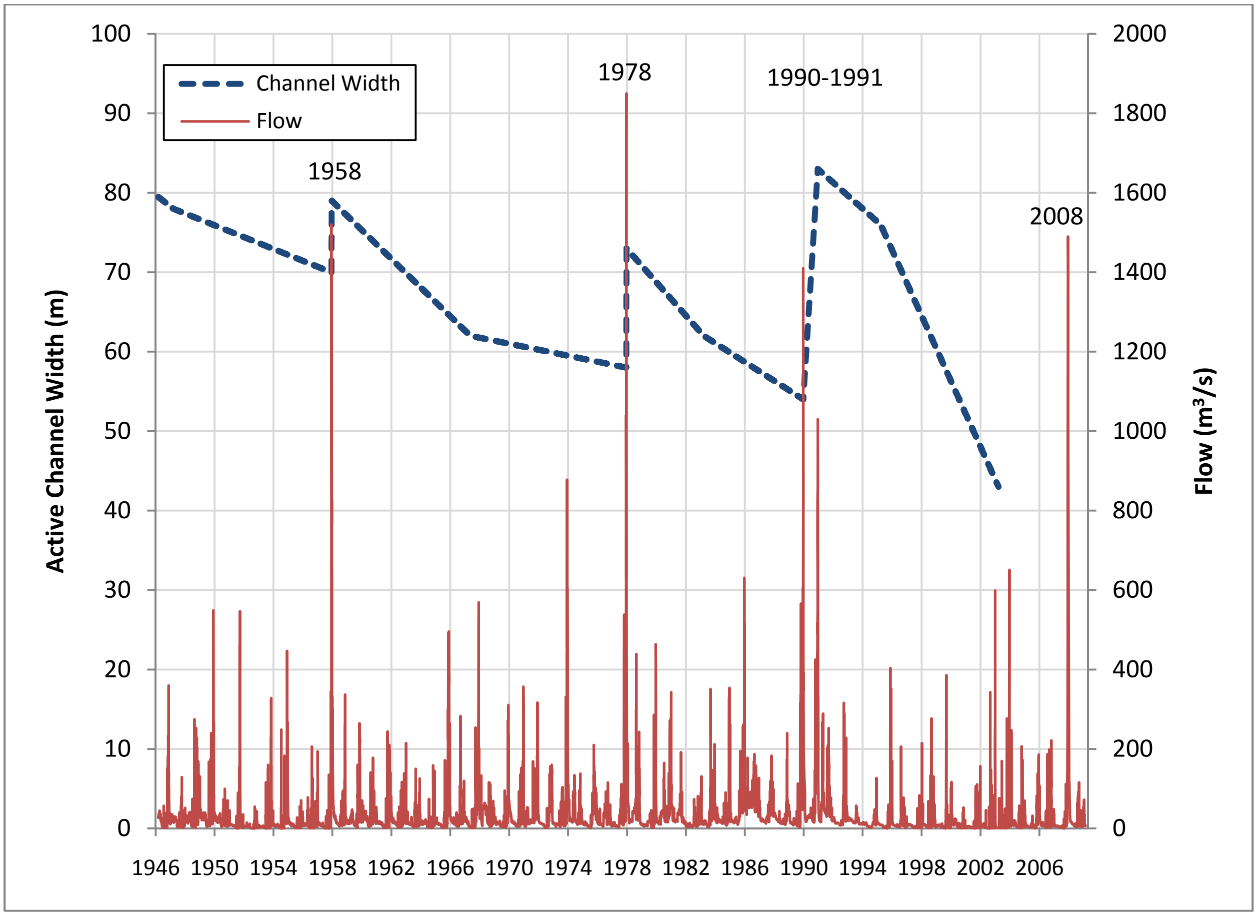

Figure 2-2: Discharge data for Johnson Ranch plotted against channel width 1946-2009 (Dean and Schmidt 2010)

Table 2-2: Summary of extreme events post-1946

	Extreme Flooding Event				
	1958	1978	1990	1991	2008
Start Date	9/24	9/25	9/20	9/4	9/3
End Date	10/14	10/14	10/11	10/11	10/3
Duration (days)	21	20	22	38	31
Total Flow ($1X10^6 m^3$)	1580	1159	968	1573	2144
Peak Flow (m^3/s)	1520	1850	1410	1030	1490
Widening (m)	9	15	29		N/A
Return Period (years)	48	82	40	19	46

2.3. COMPARISON

In order to compare the extreme flood events, a Log-Pearson Type III analysis has been performed to both periods: pre-1946 and post-1946. This analysis compares the maximum annual flows corresponding to the expected return period. This analysis used a regional skew of -0.2 and a mean standard error of 0.35 (USGS 1996). Figure 2-3 show the flow probability of exceedance curves using the Log-Pearson type III analysis for both periods.

The Log-Pearson Type III analysis shows an alteration in the Rio Grande/Bravo basin. Table 2-3 compares the expected annual maximum flow of both periods of analysis. Peak flows post-1946 are lower than post-1946, about half of the magnitude (on average 48%). For instance, the 20 year return period flow for pre-1946 is 2,347 m^3/s while for the post-1946 is only 1,056 m^3/s which represents 45% of the pre-1946 conditions. In addition, the duration of the floods is more uniform in the post-1946 period, with all roughly 3 weeks in length. For the pre-1946 period this can vary from 8 days to a month. Moreover, flooding events occur on average two to three weeks later in the post-1946 conditions, from September 1-7th in the pre-1946 to September 21-28th in the post-1946. These discrepancies suggest that flood waters were stored in reservoirs and released at a later time and in more uniform quantities.

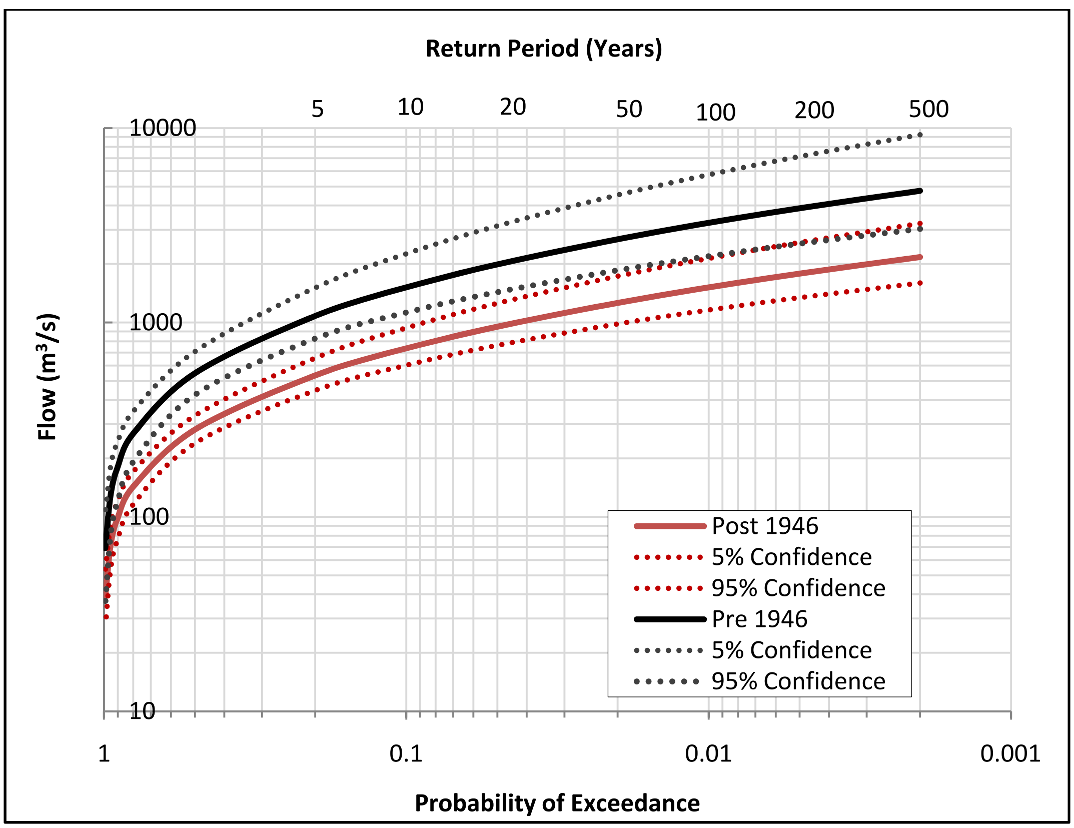

Figure 2-3: Summary of Log-Pearson III analysis

Table 2-3: Summary of Log Pearson III analysis

Return Period (years)	Expected Annual Max Flow (m^3/s)		
	1900-1946	1947-2009	Reduction
1	38	46	---
2	531	264	50%
5	1121	523	53%
10	1617	764	53%
20	2347	1056	55%
50	2957	1539	48%
100	3617	1993	45%
200	4326	2538	41%
500	5339	3424	36%
			48%

2.4. CONCLUSIONS

From the previous analysis of the flood events and the maximum annual flows, it can be concluded that:

- Pre-1946 extreme events (flow > 1,400 m^3/s) occurred more frequently, at least 4 events in 30 years approximately one event every 7~8 years; meanwhile for the post-1946 conditions, extreme events occurred less frequently, 4 events in 63 years, approximately one event every 15~16 years.
- Expected flows for a given return period decreased by an average of 48% after 1946.
- Total flow for the floods the periods are approximately the same around 1,000X 10^6 m^3 (810,713 acre-feet).
- Post-1946 durations are typically 3 weeks; while pre-1946 are more variable ranging from 8 to 30 days.
- Events happen two to three weeks later after 1946, from September 1-7th in the pre-1946 to September 21-28th in the post-1946. This is likely explained by the timing of reservoir releases.
- Peak flows decreased by an average of 37.5% post-1946, for the eight extreme events studied.

3. Normal Hydrologic Conditions

In this section are analyzed the daily mean flow values at Johnson Ranch. Flows have been categorized in: median flows, high flows, small floods and large floods.

- A *median monthly flow* is the median value of all the daily mean flows for the month and the hydrologic period analyzed.
- A *high flow* is a flow with a peak between the 75th and 95th percentile of daily flows for the pre-1946 hydrologic period of analysis.
- A small flood is a flow with a peak between the 95th percentile of daily flows for the pre-1946 period and 1,110 m^3/s, which is a threshold to account for the levees flow capacity upstream the Big Bend reach at Presidio/Ojinaga cities; maximum flow of 1,190 m3/s (42,000 cfs).
- A *large flood* is a flow with a peak flow greater than 1,100 m^3/s (38,846 cfs). These large floods will definitely threaten the safety of the levees in the Ojinaga/Presidio Valley. Flows bigger than this threshold have been analyzed in the previous section.

Two hydrologic periods are analyzed in this section: 1) before 1946, which has data for 30 years, from January 1901 to December 1913 and from January 1930 to December 1946; and 2) after 1946, which data also for 30 years, from January 1980 to December 2009. For the after 1946 period we chose the last thirty years because we would like to analyze the hydrological characteristics of the immediate hydrology. By doing this is possible to compare the hydrologic characteristics when the Rio Grande/Bravo was a wide sandy multi-threaded river, with the actual conditions, which are a narrower single-thread river with cohesive vertical banks (Dean and Schmidt 2010). In addition, this period contains a wide range of hydrologic conditions, from the wet period of the 80’s (1984-1993) to the severe and extended drought of the 90’s (1994-2007). The Indicators of Hydraulic Alteration (IHA) software is used to label the different flows along the periods of analysis. The frequency of each event (i.e. high flow, small and large floods) has been determined for each period of analysis. Return periods for each event have been calculated using the frequency of each event.

3.1. Monthly Medians

The median monthly flow is the median value of the daily mean flows for each month. One value for each month has been calculated for pre-1946 and post-1946 periods.

3.1.1. Before 1946

Table 3-1 provides a summary of median monthly flows prior to 1946. The peak monthly median flow occurred in September at 98 m3/s (3,443 cfs) and the minimum in April at 11 m3/s

(403 cfs). In September, it was expected that flows exceeded 226 m3/s (7,971 cfs) once every four years. Similarly in April, low flows below 5 m3/s (162 cfs) were likely to occur once every four years.

Table 3-1: Median monthly flows, pre-1946 period

	Pre 1946 Monthly Flows (m^3/s)		
	75th	Median	25th
Jan	34	27	14
Feb	32	24	17
Mar	31	23	14
Apr	23	11	5
May	54	20	7
Jun	75	26	9
Jul	108	44	21
Aug	125	50	21
Sep	226	98	38
Oct	102	51	27
Nov	43	30	16
Dec	39	26	14

3.1.2. After 1946

Table 3-2 provides summary of median monthly flows of the post-1940 period (last 30 years). The peak monthly median flow also occurs in September at 24 m^3/s (851 cfs) and the minimum in April at 8 m^3/s (279 cfs). In September it is expected that flows will exceed 67 m^3/s (2,355 cfs) once every four years. Similarly in April, low flows below 3 m^3/s (95 cfs) are likely to occur once every four years.

Table 3-2: Median monthly flows, 1980-2009 period

	1980-2009 Monthly Flows (m3/s)		
	75th	Median	25th
Jan	19	11	7
Feb	19	9	6
Mar	18	10	4
Apr	18	8	3
May	30	13	3
Jun	38	15	4
Jul	42	16	7
Aug	65	23	11
Sep	67	24	8
Oct	48	23	11
Nov	23	14	8
Dec	18	11	7

3.1.3. COMPARISON

Median monthly flows at Johnson Ranch have declined since 1946. Figure 3-1 shows monthly medians, 25th and 75th percentile flows for pre-1946 and post 1946 (1980-2009) periods. Median values are compared in Table 3-3. The annual median flow volume for the pre-1946 and post-1946 are 1130 X10^6 m^3 and 464 X10^6 m^3, respectively. Comparing these annual volumes of the periods, the resulting deficit is 666 X10^6 m^3 of water, or 59.0% of the pre-1946 quantity. Much of this deficit (62%) comes from high flow months July through October. The absence of high flows post 1980 suggest that these high flow events are being stored in basin reservoirs.

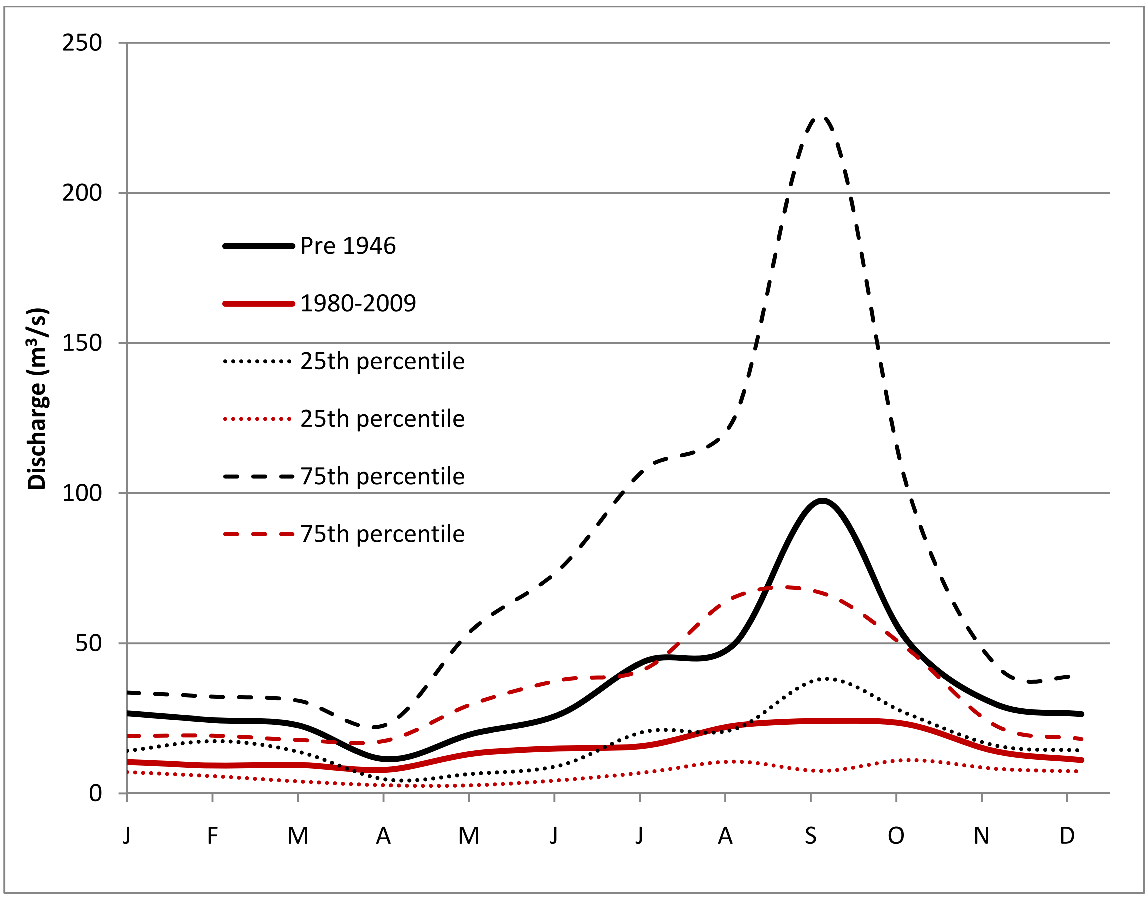

Figure 3-1: Comparison of median monthly flows, Normal Conditions

Table 3-3: Monthly median flows and deficits

	Monthly Median Flows (m^3/s)			
	Pre 1946	Post 1980	Deficit	% Deficit
Jan	27	11	16	61
Feb	24	9	15	62
Mar	23	10	13	58
Apr	11	8	3	31
May	20	13	7	33
Jun	26	15	11	43
Jul	44	16	28	64
Aug	50	23	27	55
Sep	98	24	74	75
Oct	51	23	28	55
Nov	30	14	16	53
Dec	26	11	15	58

3.2. HIGH FLOWS

High flows are defined as those that exceed the 75 percentile but are lower than the 95th percentile of daily flows for the pre-1946 period. The 75th and 95th percentile flows in the pre-1946 period are 56 m^3/s (1,978 cfs) and 224 m^3/s (7,910 cfs), respectively. These thresholds are also used in the post-1946 period in order to evaluate how frequently pre-1946 high flows occurred in the post-1946 period.

Flows that satisfy the previous thresholds have been identified, selected and analyzed individually by month and period of analysis (pre-1946 or post-1946). When analyzing high flows for every month, it was evident that two kinds of high flows occurred in this region: 1) small high flows pulses that occurred all year long as a result of small precipitation in the region or in the upper basin, and 2) large high flows that occurred in the monsoon season (Jun-Oct) as a result of moderate rains in the upper basin. For each kind of high flow (small or large), the median of the flows was estimated in order to obtain a characteristic hydrograph. This section presents the high flow hydrographs for each month, period (pre-1946 or post-1946) and type of high flow (small or large). For the pre-1946 the small high flows have a peak lower than 125 m^3/s; meanwhile for the post-1946, small high flows have a peak lower than 100 m^3/s.

3.2.1. Before 1946

Table 3-4 shows the high flow pulses with peaks lower than 125 m^3/s (4,414 cfs) for the pre-1946 period for different return periods (T). Small high flow pulses that happen:

- Every year (T<1.5 years) occur in July, August, October and December; with a duration of 1, 3, 4 and 3 days and peak flows of 75, 102, 97 and 45 m^3/s, respectively.
- Every 2 to 3 years (1.5 years < T < 3.5 years) occur in the rest of the months (January, February, March, April, May, June and November), with a duration of 3 days and peak flows of 37, 40, 41, 52, 123, 99, and 58 m^3/s, respectively.

Table 3-4: High flow pulses lower than 125 m^3/s, Pre-1946 period

	High Flow Pulses (m^3/s)											
Day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	33	34	33	47	48	52	75	57	---	58	44	36
2	37	40	41	52	123	99	---	102	---	97	58	45
3	32	34	33	47	48	52	---	57	---	73	44	36
4	---	---	---	---	---	---	---	---	---	58	---	---
5	---	---	---	---	---	---	---	---	---	---	---	---
6	---	---	---	---	---	---	---	---	---	---	---	---
Duration (days)	3	3	3	3	3	3	1	3	---	4	3	3
Peak (m^3/s)	**37**	**40**	**41**	**52**	**123**	**99**	**75**	**102**	**---**	**97**	**58**	**45**
Frequency	0.31	0.59	0.48	0.59	0.45	0.52	0.76	1.00	---	0.72	0.48	0.76
T (years)	**3.2**	**1.7**	**2.1**	**1.7**	**2.2**	**1.9**	**1.3**	**1.0**	**---**	**1.4**	**2.1**	**1.3**

Table 3-5 shows the high flow pulses larger than 125 m^3/s (4,414 cfs) for the prior 1946 period for different return periods (T). Large high flow pulses that happen:

- Every 5 to 10 years (3.5 years < T < 10) occur in June and July with a duration of 5 and 8 days and peak flows of 152 and 195 m^3/s, respectively.
- Every 10 years or more (T > 10 years) occur in August and September with duration of 7 and 5 days and peak flows of 169 and 202 m^3/s.

Table 3-5: High flow pulses larger than 125 m³/s, Pre-1946 period

Day	High Flow Pulses (m³/s)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	---	---	---	---	---	118	139	123	138	---	---	---
2	---	---	---	---	---	127	169	135	168	---	---	---
3	---	---	---	---	---	152	186	143	202	---	---	---
4	---	---	---	---	---	127	195	169	168	---	---	---
5	---	---	---	---	---	118	169	143	138	---	---	---
6	---	---	---	---	---	---	139	135	---	---	---	---
7	---	---	---	---	---	---	128	123	---	---	---	---
8	---	---	---	---	---	---	118	---	---	---	---	---
Duration (days)	---	---	---	---	---	5	8	7	5	---	---	---
Peak (m³/s)	**---**	**---**	**---**	**---**	**---**	**152**	**195**	**169**	**202**	**---**	**---**	**---**
Frequency	---	---	---	---	---	0.10	0.10	0.07	0.07	---	---	---
T (years)	**---**	**---**	**---**	**---**	**---**	**9.7**	**9.7**	**14.5**	**14.5**	**---**	**---**	**---**

3.2.2. After 1946

Table 3-6 shows the high flow pulses lower than 100 m³/s (3,531 cfs) for the after 1946 period for different return periods (T). Small high flow pulses that happen:

- Every year (T<1.5 years) occur in May, June, July and August, with a duration of 5, 3, 3, and 3 days and peak flows of 60, 63, 60 and 55 m³/s, respectively.
- Every 2 to 3 years (1.5 years < T < 3.5 years) occur in April, September and October, with a duration of 3 days and peak flows of 52, 50 to 61 m³/s, respectively.
- Every 5 to 10 years (3.5 years < T < 10) occur in February, March, November and December with a duration of 3 days and peak flows of 45, 73, 57 to 56 m³/s, respectively.
- Every 10 years or more (T > 10 years) occur in January with duration of 4 days and a peak flow of 84 m³/s.

Table 3-6: High flow pulses lower than 100 m³/s, Post-1946 period

Day	High Flow Pulses (m³/s)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	50	37	43	35	30	34	29	31	31	33	34	48
2	84	45	73	52	38	63	60	55	50	61	57	56
3	73	37	43	35	60	34	29	31	31	33	34	48
4	50	---	---	---	38	---	---	---	---	---	---	---
5	---	---	---	---	30	---	---	---	---	---	---	---
6	---	---	---	---	---	---	---	---	---	---	---	---
Duration (days)	4	3	3	3	5	3	3	3	3	3	3	3
Peak (m³/s)	**84**	**45**	**73**	**52**	**60**	**63**	**60**	**55**	**50**	**61**	**57**	**56**
Frequency	0.07	0.13	0.27	0.43	1.03	1.20	0.93	0.97	0.53	0.53	0.20	0.13
T (years)	**15.0**	**7.5**	**3.8**	**2.3**	**1.0**	**0.8**	**1.1**	**1.0**	**1.9**	**1.9**	**5.0**	**7.5**

Table 3-7 shows the high flow pulses larger than 100 m³/s (3,531 cfs) for the after 1946 period for different return periods (T). High flow pulses that happen:

- Every 2 to 3 years (1.5 years < T < 3.5 years) occur in July and August, with a duration of 5 days and peak flows of 119 and 142 m³/s, respectively.
- Every 5 to 10 years (3.5 years < T < 10) occur in June, September and October with a duration of 3, 5 and 3 days and peak flows of 191, 127 and 112 m³/s, respectively.

Table 3-7: High flow pulses larger than 100 m³/s, Post-1946 period

	High Flow Pulses (m³/s)											
Day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	---	---	---	---	---	116	33	73	66	49	---	---
2	---	---	---	---	---	191	79	107	82	112	---	---
3	---	---	---	---	---	116	119	142	127	49	---	---
4	---	---	---	---	---	---	79	107	82	---	---	---
5	---	---	---	---	---	---	33	73	66	---	---	---
6	---	---	---	---	---	---	---	---	---	---	---	---
Duration (days)	---	---	---	---	---	3	5	5	5	3	---	---
Peak (m³/s)	**---**	**---**	**---**	**---**	**---**	**191**	**119**	**142**	**127**	**112**	**---**	**---**
Frequency	---	---	---	---	---	0.13	0.40	0.43	0.20	0.23	---	---
T (years)	**---**	**---**	**---**	**---**	**---**	**7.5**	**2.5**	**2.3**	**5.0**	**4.3**	**---**	**---**

3.2.3. Comparison

Examining the magnitude and frequency of high flow events provides further evidence of alteration. Table 3-8 and Figure 3-2 show a comparison of small high flows (peak flow < 125 m3/s). The majority of months see reductions up to 51% with a few notable exceptions. For the period of Dec-Mar, the intensity of flow pulses actually increased, up to 127% in January, probably caused by dam releases. Prior to 1946, there was a median of 7 small high flow pulse events per year (average of 7.4 events per year). Post-1946, the frequency dropped to 6.5 events per year (average of 6.5 events per year). For both time-frames, August had the most pulses and January the least.

Table 3-8: Magnitude and frequency of high flow pulses smaller than 125 m3/s

	Small High Flow Pulses				
	Peak Flow (m^3/s)			Return Period (years)	
	Pre 1946	Post 1980	% Reduction	Pre 1946	Post 1980
Jan	37	84	-127	3.2	15
Feb	40	45	-12	1.7	7.5
Mar	41	73	-77	2.1	3.8
Apr	52	52	0	1.7	2.3
May	123	60	51	2.2	1
Jun	99	63	36	1.9	0.8
Jul	75	60	20	1.3	1.1
Aug	102	55	46	1.0	1
Sep	91	50	45	1.3	1.9
Oct	97	61	37	1.4	1.9
Nov	58	57	2	2.1	5
Dec	45	56	-26	1.3	7.5

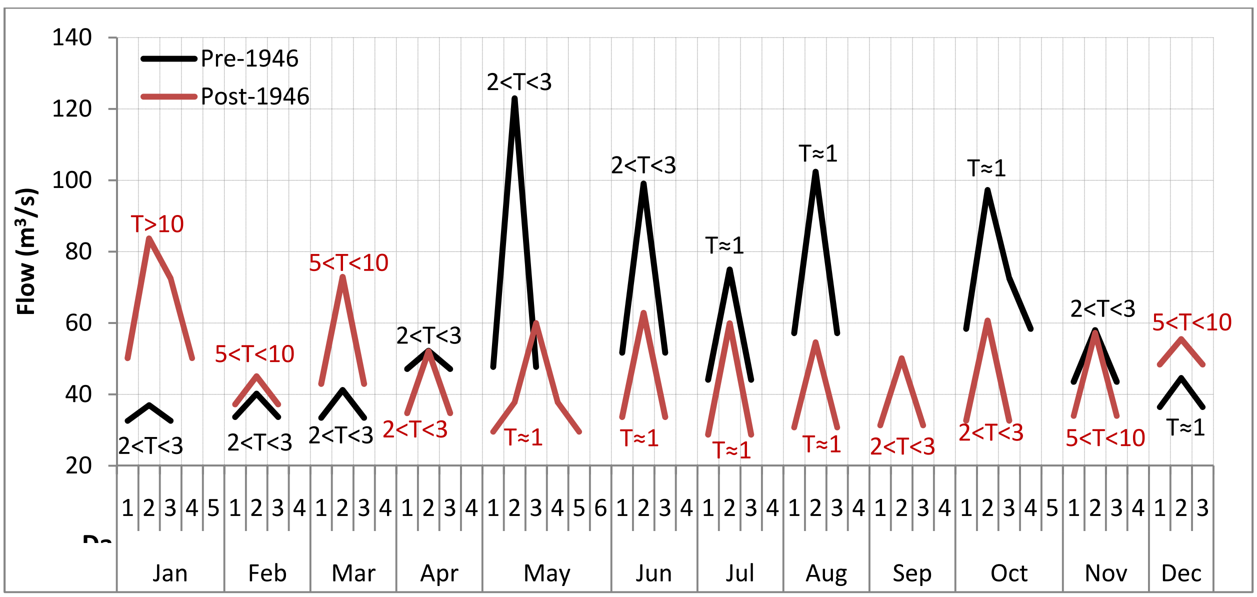

Figure 3-2: Duration, magnitude and frequency of high flow pulses smaller than 125 m³/s

A summary of large high flow pulses (peak flow> than 100 m3/s) is shown below in Table 3-9 and Figure 3-3. The maximum annual high pulse has decreased from 202 m3/s pre-1946 to 127 m3/s post-1980. The majority of months see reductions up to 39% with the exception of June which increases 26%. Prior to 1946, there was a median of 0 small high flow pulse events per year (average of 0.3 events per year). Post 1980, the frequency increased to 1 event per year (average of 1.4 events per year). Large high flow pulses (peak flow >100 m3/s) in the pre-1946 period are less frequent than in the post-1980 period. For instance, in July and August large high flow pulses occurred once every 2 or 3 years in the post-1946 period, meanwhile they occurred once every 5 to 10 years in the pre-1946 periods. This means that large high flow pulses (peak flow > 100 m3/s) were not very common in the pre-1946 conditions as they are now in the post-1946 conditions; this may be as a consequence of reservoir releases upstream.

Table 3-9: Peak flows and frequency of high flow pulses larger than 125 m³/s

	Large High Flow Pulses				
	Peak Flow (m³/s)			Return Period (years)	
	Pre 1946	Post 1980	% Reduction	Pre 1946	Post 1980
Jan					
Feb					
Mar					
Apr					
May					
Jun	152	191	-26%	9.7	7.5
Jul	195	119	39%	9.7	2.5
Aug	169	142	16%	14.5	2.3
Sep	202	127	37%	14.5	5
Oct		112			4.3
Nov					
Dec					

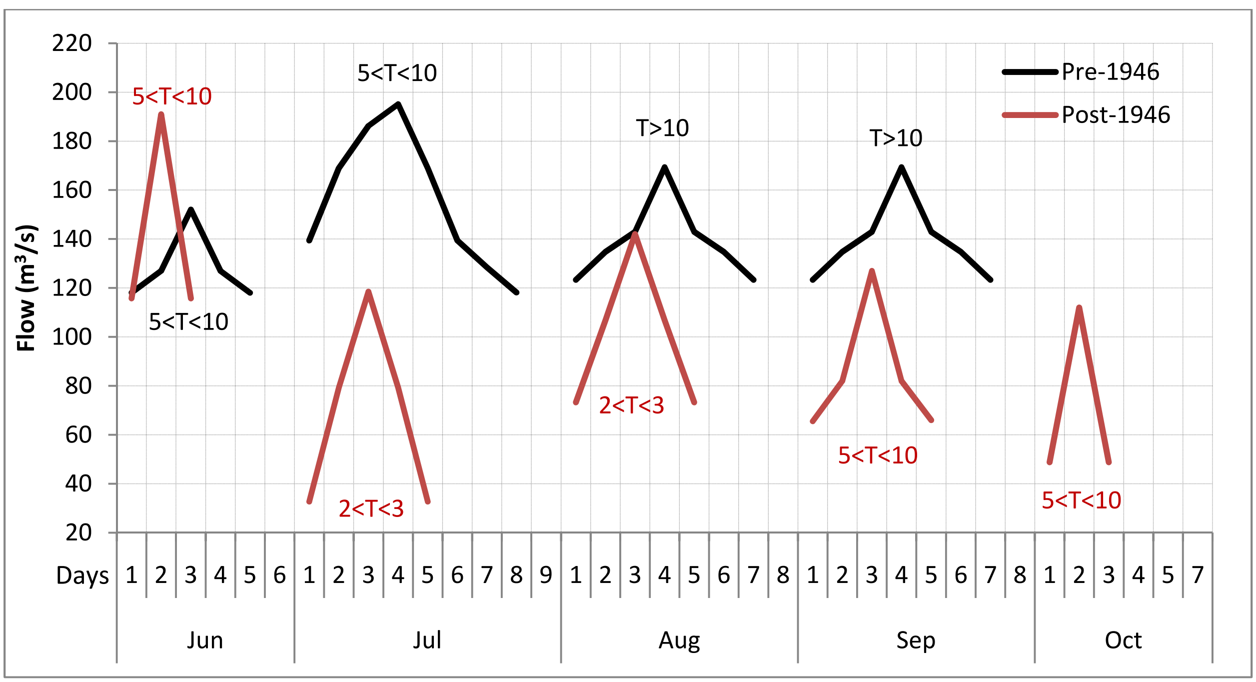

Figure 3-3: Duration, magnitude and frequency of high flow pulses larger than 100 m³/s

3.3. SMALL FLOODS

Small Floods are those that have a peak flow greater than the 95 percentile of daily flows for the whole period, but smaller than 1,100 m^3/s (38,846 cfs), which is a flow smaller than the Presidio/Ojinaga levees flow design, 1,190 m^3/s (42,000 cfs). The 95th percentile flow, 224 m^3/s (7,910 cfs) has been determined using the date of the pre-1946 period. This thresholds is also used in the post-1946 period in order to evaluate the how frequently high flows occurred in this period. Flows that satisfy the previous thresholds have been identified, selected and analyzed individually by month and period of analysis (pre1946 or post-1946). For each month, the median of the flows was estimated in order to obtain a characteristic small flood. This section presents the characteristics small floods for each month and period of analysis (pre-1946 or post-1946).

3.3.1. BEFORE 1946

Table 3-10 shows the small floods for the pre 1946 period and for different return periods (T). Small floods that happen:

- Every year (T<1.5 years) occur in September with a duration of 11 days and a median peak flow of 407 m^3/s.
- Every 2 to 3 years (1.5 years < T < 3.5 years) occur in July, August, and October with durations of 9, 13, and 7days and peak flows of 405, 396 and 422 m^3/s, respectively.
- Every 5 to 10 years (3.5 years < T < 10) occur in May, June, and November with a durations 3, 8, and 6 days and peak flows of 252, 433, and 284 m^3/s, respectively.
- Every 10 years or more (T > 10 years) occur in April and December with durations of 3 and 6 days and peak flows of 402 and 353 m^3/s, respectively.

3.3.2. AFTER 1946

Table 3-11 shows the small floods for the post 1946 period and for different return periods (T). Small floods that happen:

- Every 2 to 3 years (1.5 years < T < 3.5 years) occur in September with a duration of 5 days and a peak flow of 342 m^3/s.
- Every 5 to 10 years (3.5 years < T < 10) occur in June, July, August, and October with durations of 6, 7, 9, and 9 days and peak flows of 265, 293, 326 and 438 m^3/s, respectively.
- Every 10 years or more (T > 10 years) occur in February, May, and November with durations of 5 days and peak flows of 289, 203, and 239 m^3/s respectively.

Table 3-10: Small floods (224 m³/s <flow<1,100 m³/s), Pre-1946 period

	Small Floods (m³/s)											
Day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	---	---	---	278	59	52	190	133	154	159	167	157
2	---	---	---	402	252	330	223	166	189	193	188	261
3	---	---	---	278	59	433	273	201	203	301	284	353
4	---	---	---	---	---	330	320	215	255	422	259	289
5	---	---	---	---	---	267	405	247	322	301	188	261
6	---	---	---	---	---	177	320	316	407	193	167	157
7	---	---	---	---	---	159	273	396	322	159	---	---
8	---	---	---	---	---	141	223	316	255	---	---	---
9	---	---	---	---	---	---	190	247	203	---	---	---
10	---	---	---	---	---	---	---	215	189	---	---	---
11	---	---	---	---	---	---	---	201	154	---	---	---
12	---	---	---	---	---	---	---	166	---	---	---	---
13	---	---	---	---	---	---	---	133	---	---	---	---
Duration (days)	---	---	---	3	3	8	9	13	11	7	6	6
Peak (m³/s)	**---**	**---**	**---**	**402**	**252**	**433**	**405**	**396**	**407**	**422**	**284**	**353**
Frequency	---	---	---	0.03	0.10	0.21	0.48	0.41	1.00	0.31	0.10	0.07
T (years)	**---**	**---**	**---**	**29**	**9.7**	**4.8**	**2.1**	**2.4**	**1**	**3.2**	**9.7**	**14.5**

Table 3-11: Small floods (224 m³/s <flow<1,100 m³/s), Post-1946 period

	Small Floods (m³/s)											
Day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	---	123	---	---	112	63	110	91	94	70	95	---
2	---	176	---	---	137	101	153	114	198	90	207	---
3	---	289	---	---	203	265	211	179	342	111	239	---
4	---	176	---	---	137	162	293	210	198	193	207	---
5	---	123	---	---	112	101	211	326	94	438	95	---
6	---	---	---	---	---	63	153	210	---	193	---	---
7	---	---	---	---	---	---	110	179	---	111	---	---
8	---	---	---	---	---	---	---	114	---	90	---	---
9	---	---	---	---	---	---	---	91	---	70	---	---
10	---	---	---	---	---	---	---	---	---	---	---	---
Duration (days)	---	5	---	---	5	6	7	9	5	9	5	---
Peak (m³/s)	**---**	**289**	**---**	**---**	**203**	**265**	**293**	**326**	**342**	**438**	**239**	**---**
Frequency	---	0.03	---	---	0.03	0.27	0.2	0.23	0.33	0.2	0.03	---
T (years)	**---**	**30**	**---**	**---**	**30**	**3.5**	**5**	**4.3**	**3**	**5**	**30**	**---**

3.3.3. COMPARISON

A summary of small flooding events is show below in Table 3-12 and Figure 3-4. Note that one small flood in the pre-1946 occurred every September; meanwhile in the post-1946 conditions it occurs once every 3 years. Prior to 1946, there was a median of 2 small flood events per year (average of 2.7 events per year). Post 1980, the frequency drops by more than half to 0.5 events per year (average of 1.4 events per year). The maximum flows for each period are similar with a pre-1946 of 433 m^3/s and a post-1980 of 438 m^3/s. For the pre-1946 maximum value occurs in June, while the post-1980 occurs in October. There is a decrease in 6 of the 7 months, up to 39%, where small floods are present in both. For both periods, small floods are most common in September.

Table 3-12: Peak flows and frequency of small floods

	Small Floods				
	Peak Flow (m^3/s)			Return Period (years)	
	Pre 1946	Post 1980	% Reduction	Pre 1946	Post 1980
Jan					
Feb		289			30
Mar					
Apr	402			29.0	
May	252	203	20%	9.7	30
Jun	433	265	39%	4.8	3.8
Jul	405	293	28%	2.1	5
Aug	396	326	18%	2.4	4.3
Sep	**407**	**342**	**16%**	**1.0**	**3**
Oct	422	438	-4%	3.2	5
Nov	284	247	13%	9.7	30
Dec	353			14.5	

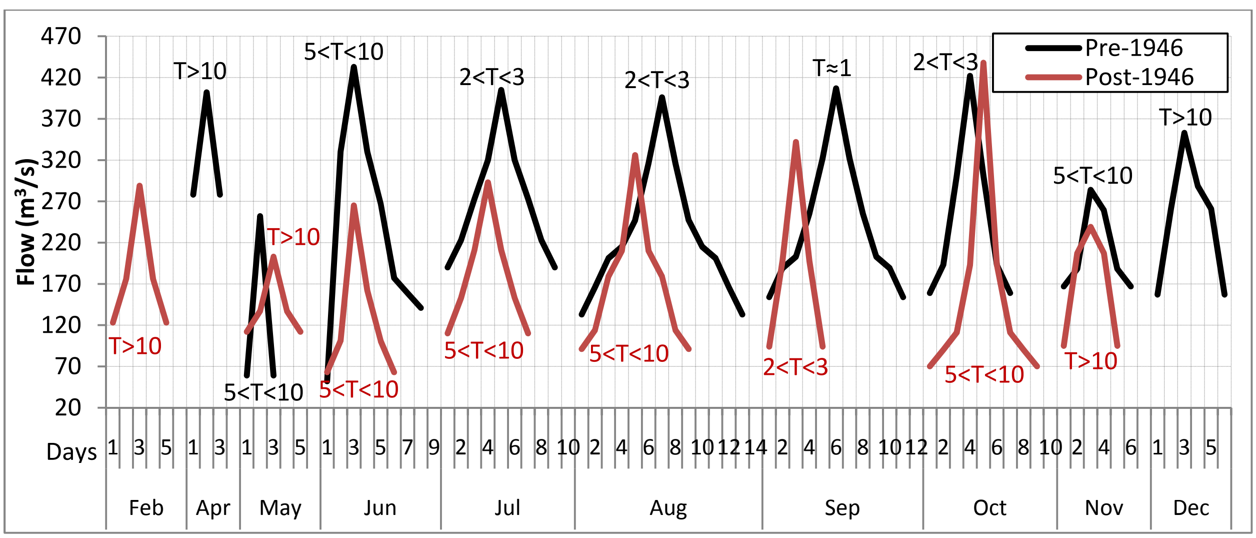

Figure 3-4: Duration, magnitude and frequency of small floods

3.4. INTEGRATION OF RESULTS

This section integrates the results of median monthly flows, high flows and small flood for the pre-1946 and post-1946 conditions.

3.4.1. BEFORE 1946

Figure 3-5 shows the annual hydrograph for flows with one year return period in the pre-1946 conditions. Table 3-13 shows the volume necessary to satisfy this annual hydrograph, which is 1,292X10^6 m^3 per year. Notice that one small flood in September always happened in the pre-1946 conditions.

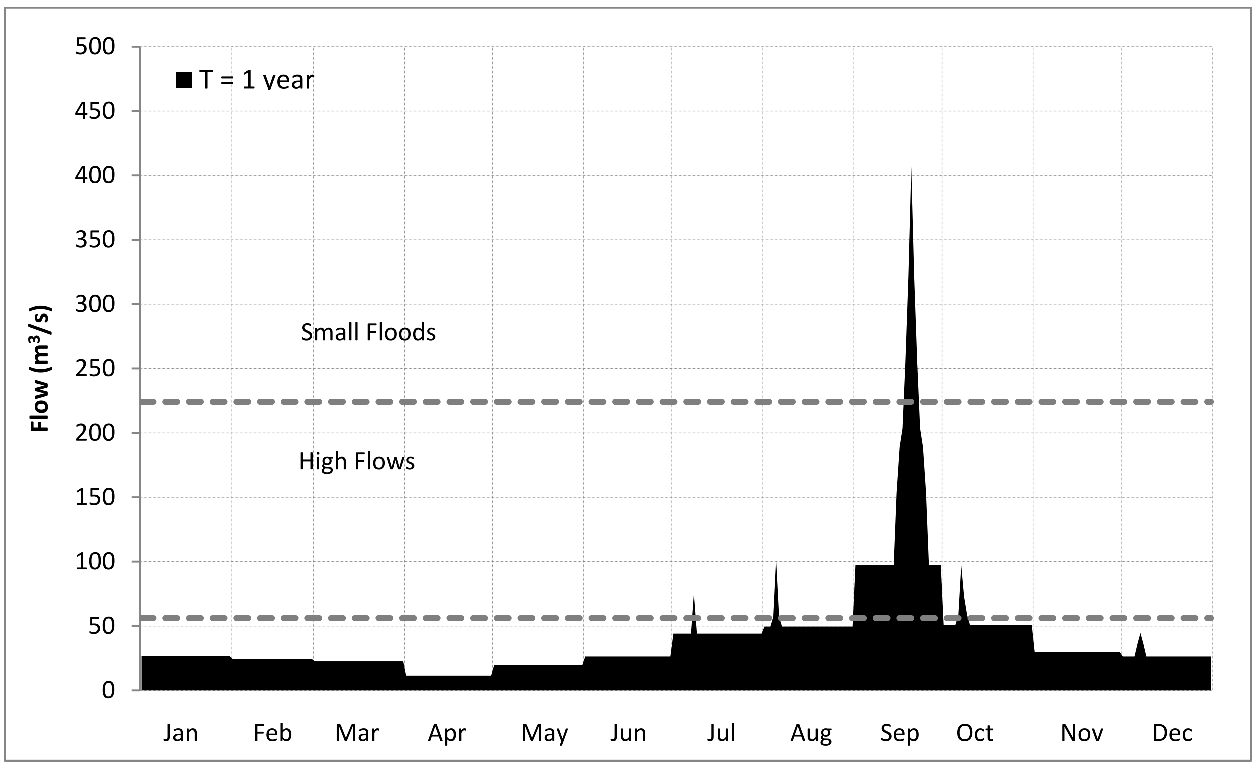

Figure 3-5: Annual Hydrograph, Return Period = 1 year, pre-1946 conditions

Table 3-13: Annual hydrograph volume for 1 year return period flows, pre-1946 conditions

	Volume ($1X10^6$ m^3)												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Sum
Median	72	59	61	30	53	68	118	133	253	136	77	71	1130
High Flows	---	---	---	---	---	---	3	6	---	7	---	10	26
Small Floods	---	---	---	---	---	---	---	---	136	---	---	---	136
Total	72	59	61	30	53	68	121	139	389	143	77	81	1292

Figure 3-6 shows the annual hydrograph for flows with one and two to three year return period in the pre-1946 conditions. Results show that small floods happened in July, August and November, once every 2-3 years. Considering that one small flood always occurred in September, the previous results suggest that two small floods happened every year, one in September and another in July, August or October. The combination of two small floods, one fixed in September and another moving in July, August or October may have contributed to maintaining the Rio Grande/Bravo as a wide sandy multi-threaded river.

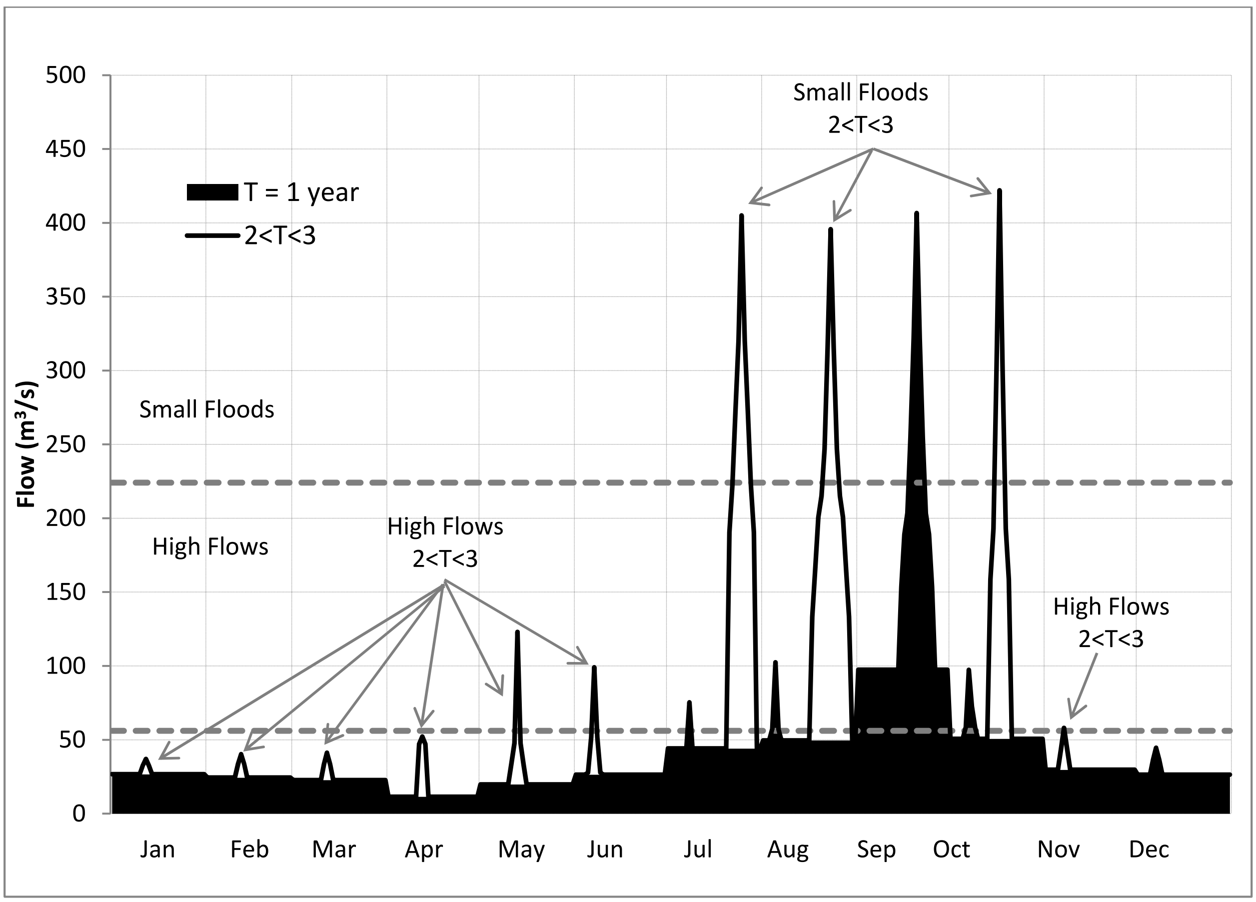

Figure 3-6: Annual Hydrograph, Return Period = 2-3 years, pre-1946 conditions

Figure 3-7 shows the annual hydrograph for flows with one and five to ten year return period in the pre-1946 conditions. Results show that small floods did not occur so frequently outside the monsoon season (June to October) nor large high flows (Peak flow > 125 m^3/s). Small floods and high flows showed in Figure 3-7 used to occur once every five to ten years.

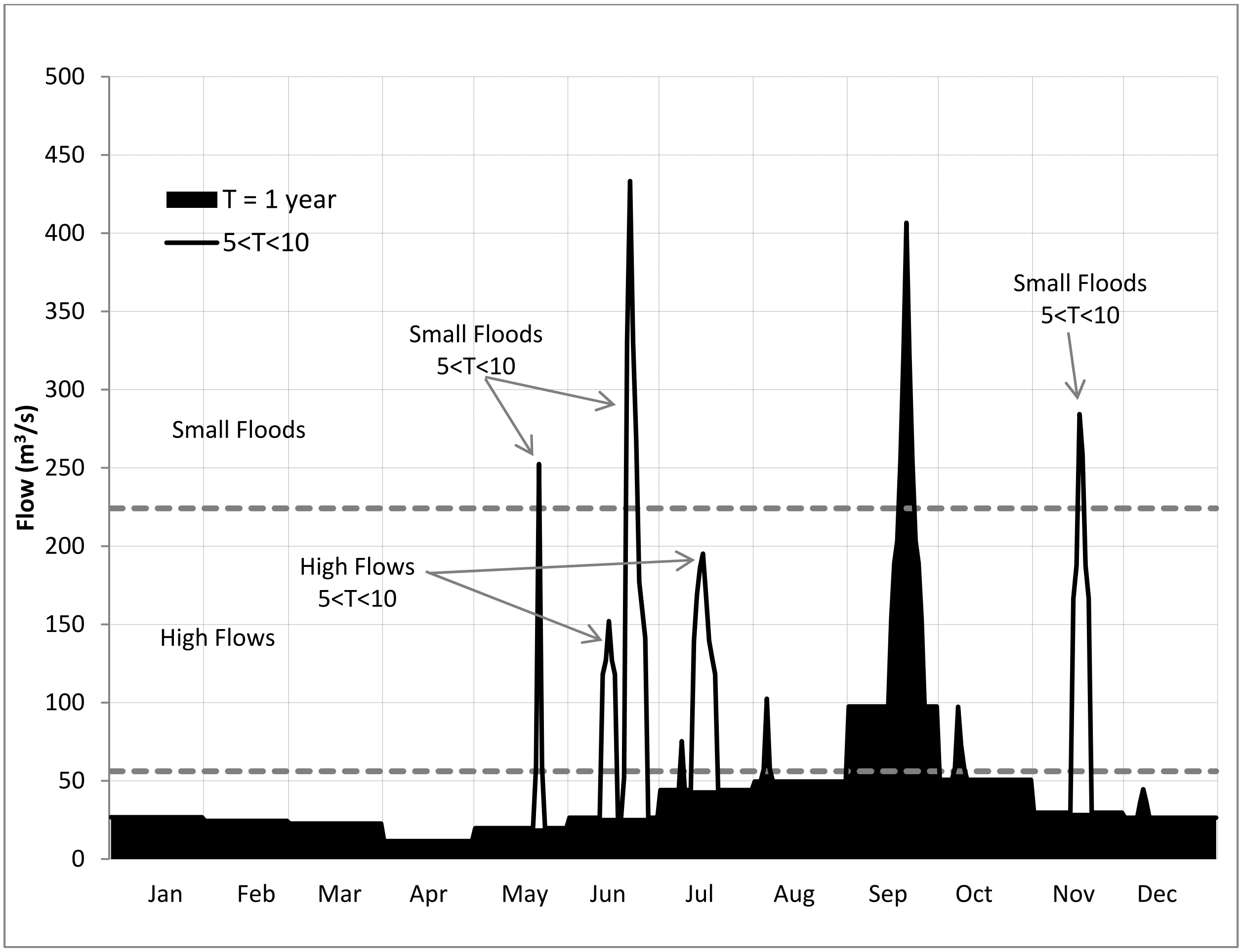

Figure 3-7: Annual Hydrograph, Return Period = 5-10 years, pre-1946 conditions

Figure 3-8 shows the annual hydrograph for flows with one and ten or more year return period in the pre-1946 conditions. Similarly that in the previous analysis, results show that small floods did not occur so frequently outside the monsoon season (June to October) nor large high flows (Peak flow > 125 m^3/s). Small floods and high flows showed in Figure 3-8 used to occur once every ten years or more.

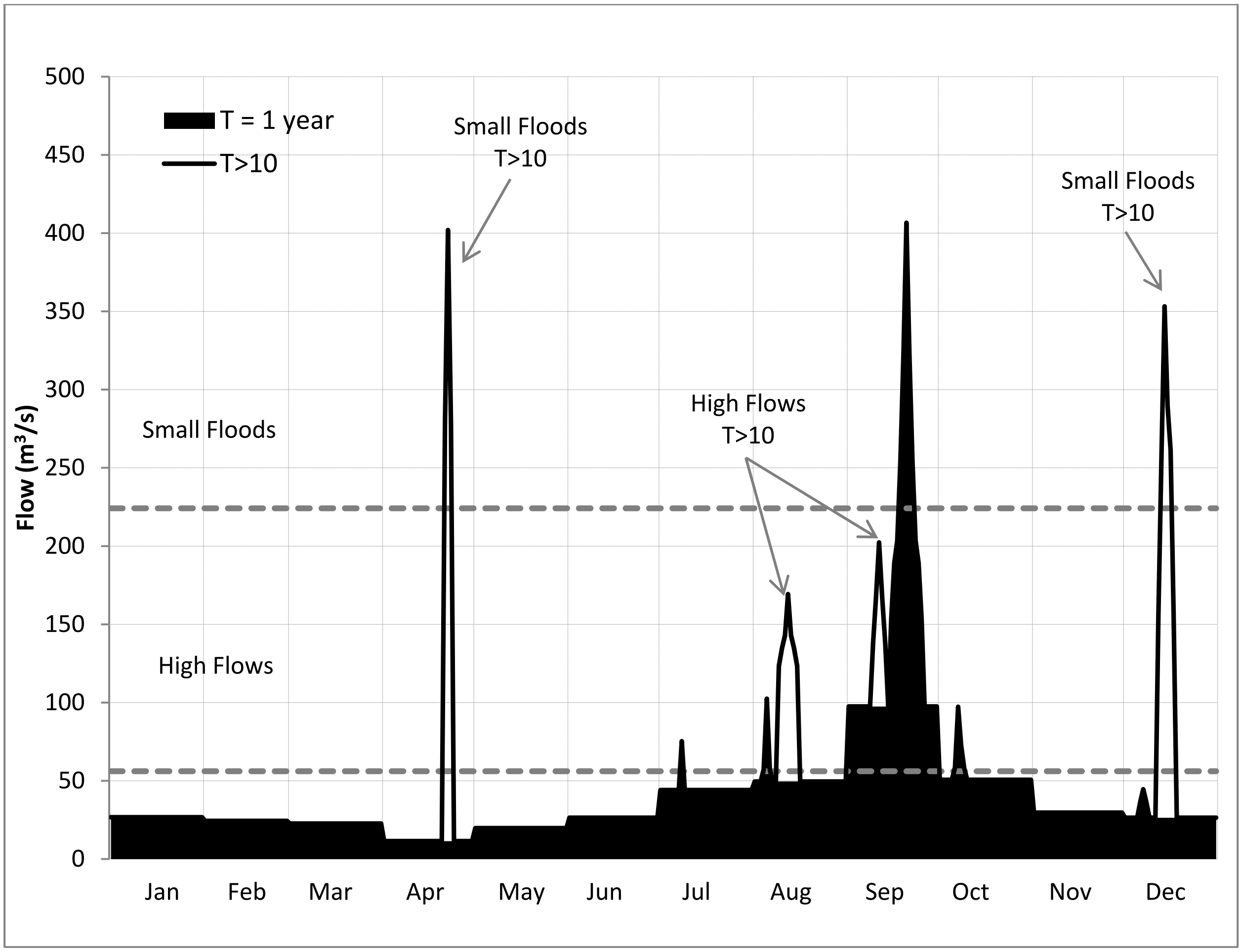

Figure 3-8: Annual Hydrograph, Return Period >10 years, pre-1946 conditions

3.4.2. AFTER 1946

Figure 3-9 shows the annual hydrograph for flows with one year return period in the post-1946 conditions. Table 3-14 shows the volume for each month according to the 1-year return period hydrograph; the total volume in the hydrograph is small (492X10^6 m^3/year) compared to the pre-1946 conditions (1,471X10^6 m^3/year). Every year only 4 high flows occur; these high flows can be the result of storage release from Luis L. Leon reservoir to be prepared for the monsoon season (in May and June) or to spill the water stored in the flooding storage capacity (in July and August). Notice that no small flood occurs every year in the post-1946 conditions. This might be the cause for the reduction in channel width in the post-1946 period.

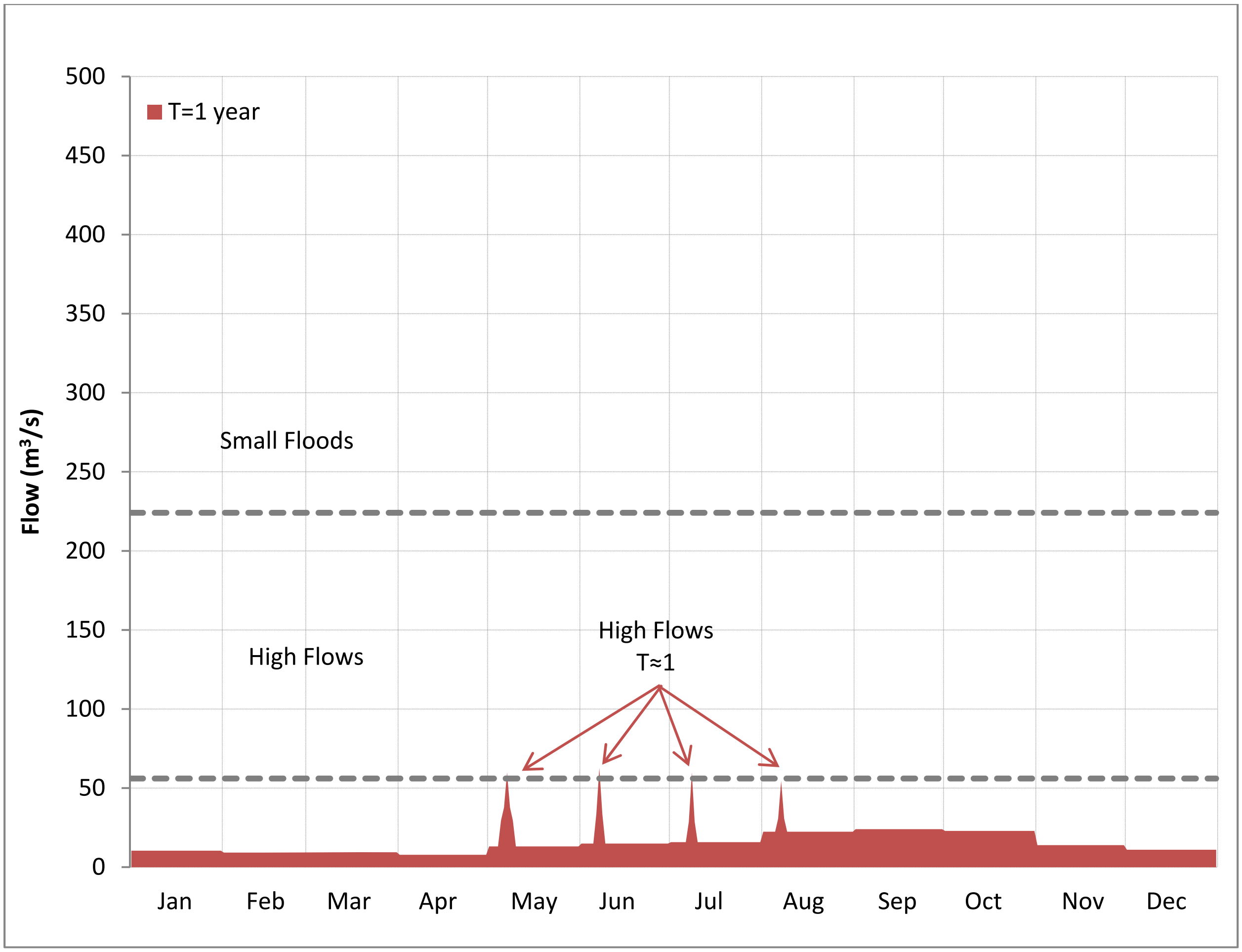

Figure 3-9: Annual Hydrograph, Return Period = 1 year, post-1946 conditions

Table 3-14: Annual hydrograph volume for 1 year return period flows, post-1946 conditions

	Volume (1X10⁶ m³)												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Sum
Median	28	23	25	21	35	39	43	60	62	61	36	30	463
High Flows	---	---	---	---	11	7	6	4	---	---	---	---	29
Small Floods	---	---	---	---	---	---	---	---	---	---	---	---	0
Total	28	23	25	21	46	46	49	64	62	61	36	30	**492**

Figure 3-10Figure 3-5 shows the annual hydrograph for flows with one and two to three year return period in the post-1946 conditions. Results show that small floods occur once every 2 or 3 years in June and September. This result combined with the 1 year return hydrograph mean that one year there may be no small flood such as in the 1 year return period hydrograph (Figure 3-9), the following year one small flood may occur in June with a peak of 265 m3/s and the next year one small flood may occur in September with a peak of 341 m3/s. Notice that the small flood that used to happened every year in September (407 m^3/s) for the pre-1946 conditions, now is happening once every 3 years with a smaller peak magnitude (342 m^3/s).

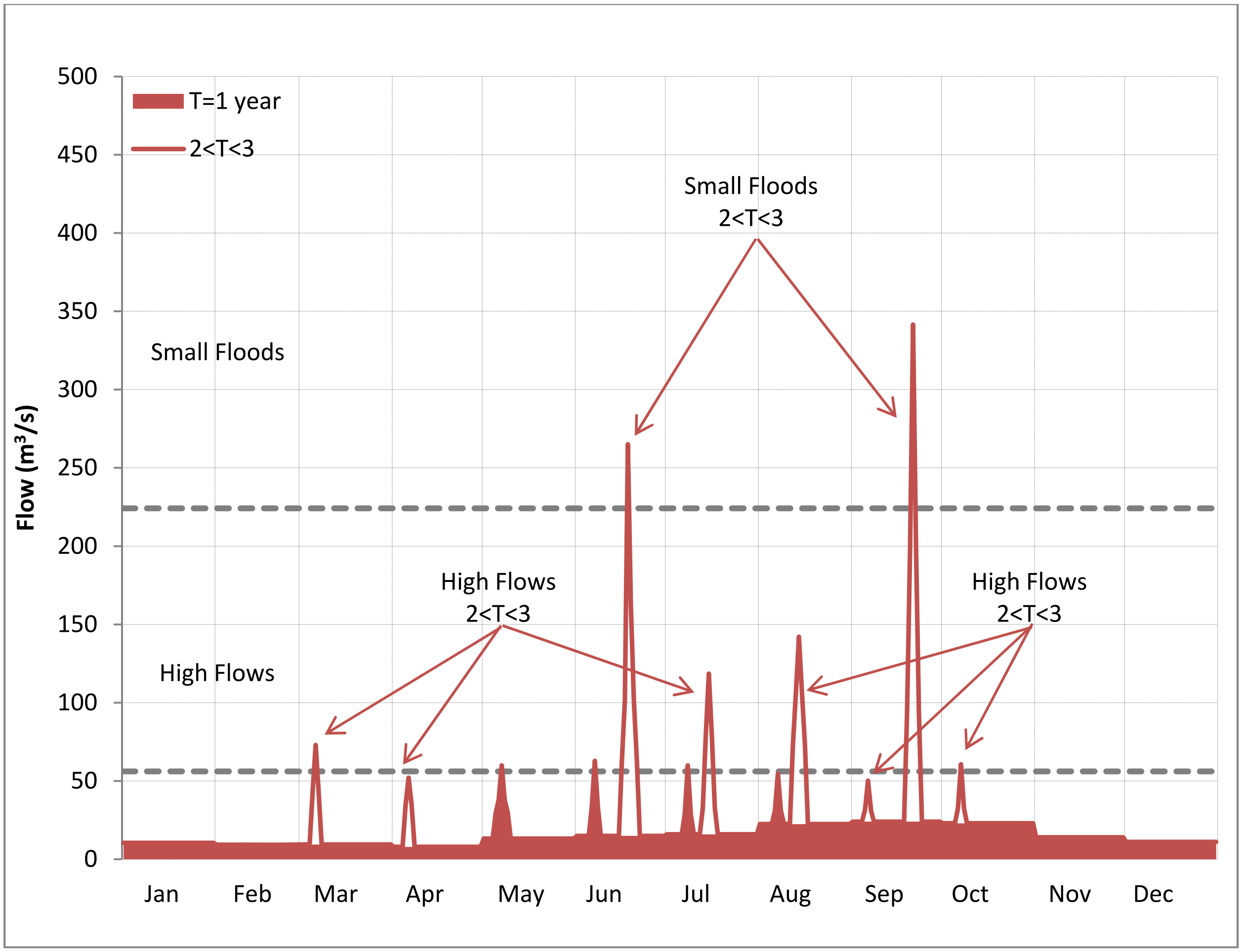

Figure 3-10: Annual Hydrograph, Return Period = 2-3 years, pre-1946 conditions

Figure 3-11Figure 3-5 shows the annual hydrograph for flows with one and five to ten year return period in the post-1946 conditions. Small floods occur once every 5 years in July, August and October. Notice that small floods that used to happen every 2-3 years in July August and October (405, 396 and 422 m^3/s) for the pre-1946 conditions, they are occurring in the double of time in the post-1946 period, every 5 years, with smaller peak magnitudes (293, 326 and 438 m^3/s) for July and August.

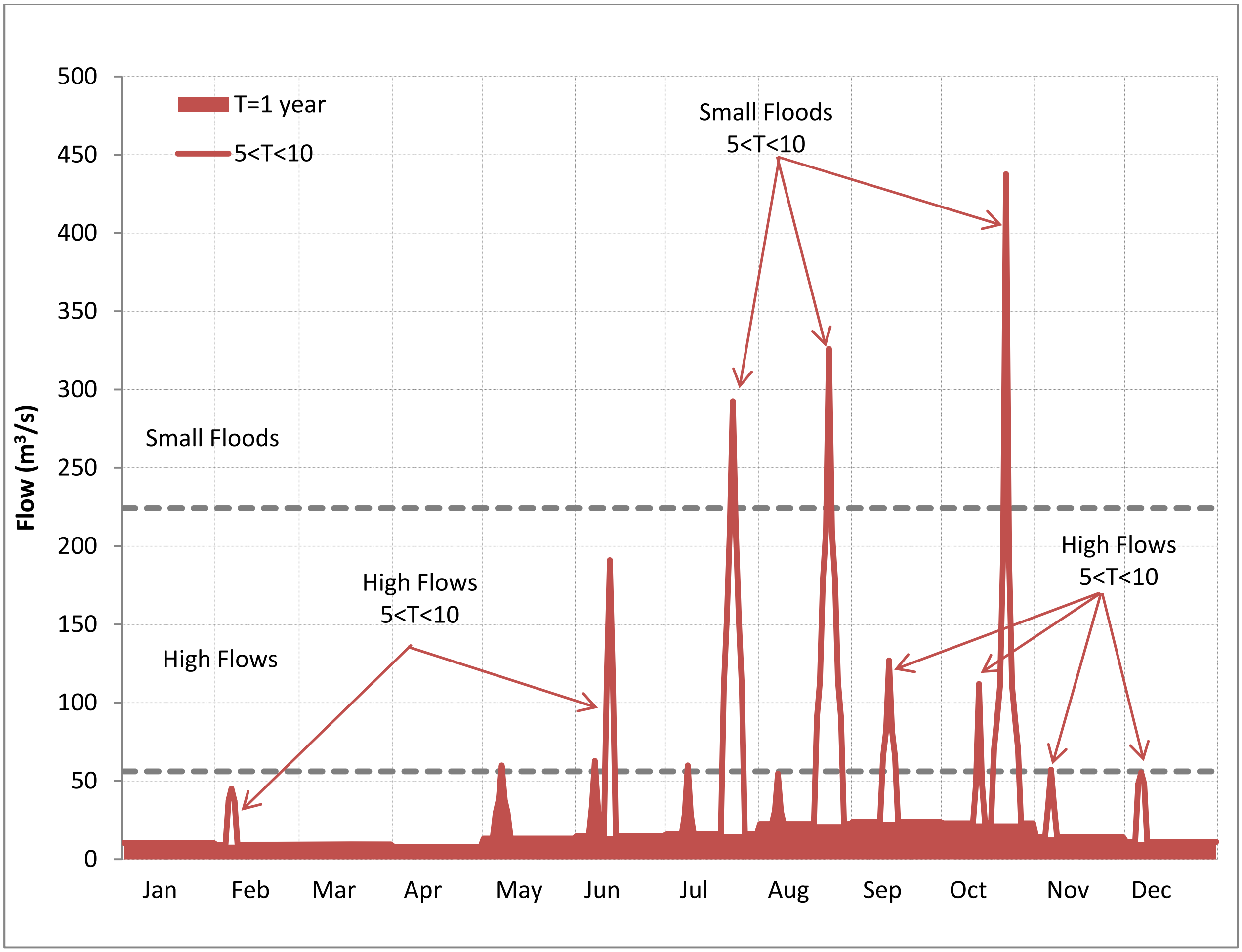

Figure 3-11: Annual Hydrograph, Return Period = 5-10 years, pre-1946 conditions

Figure 3-12Figure 3-5 shows the annual hydrograph for flows with one and ten year return period in the post-1946 conditions. Similarly to the pre-1946 period, small floods do not occur so frequently outside the monsoon season (June to October) nor high flows.

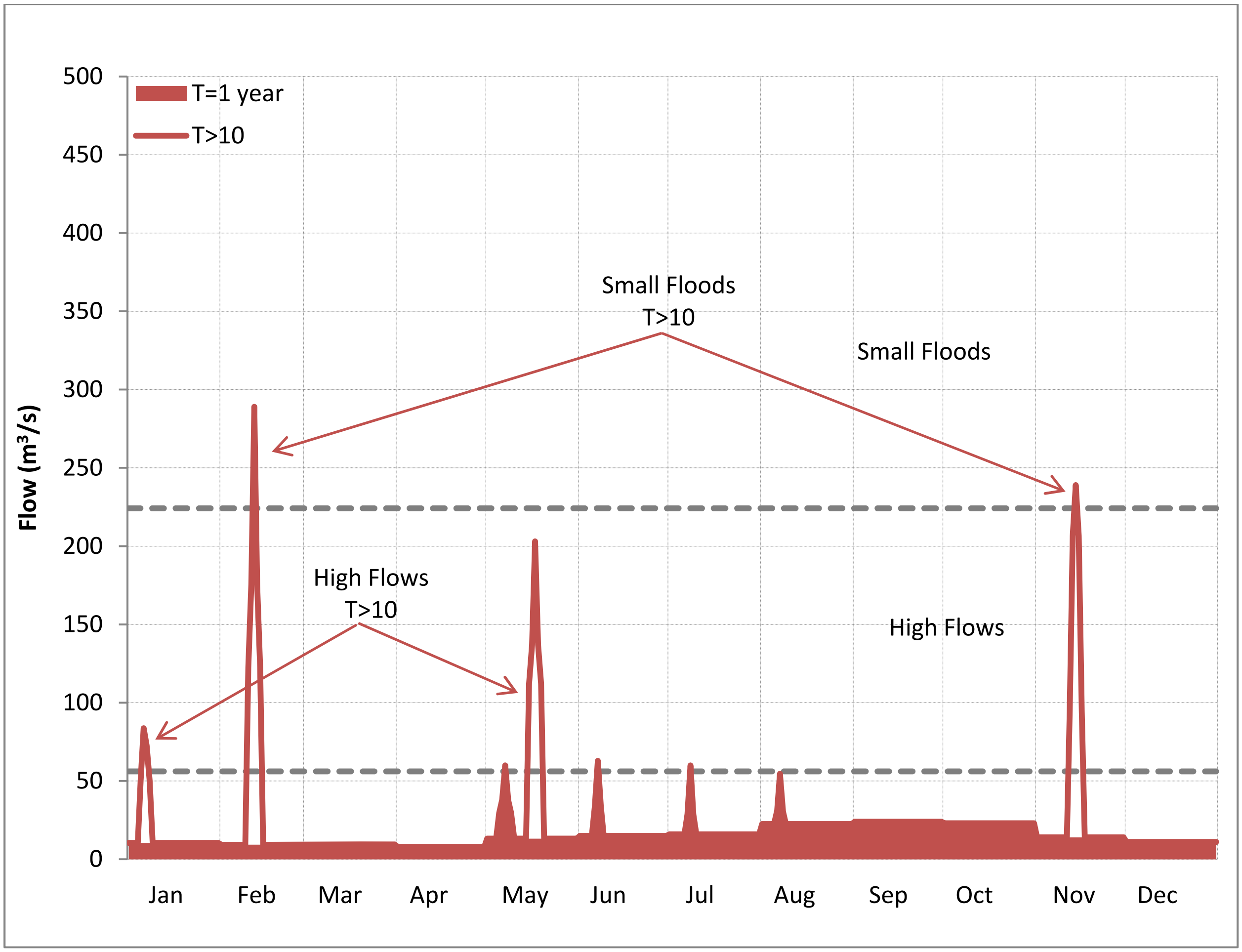

Figure 3-12: Annual Hydrograph, Return Period >10 years, pre-1946 conditions

3.4.3. Comparison

Figure 3-13 shows the annual hydrograph for flows with one year return period for the pre-1946 and post-1946 conditions. Even though there is the same number of high flows, there is different timing and magnitude of these. Most importantly, one small flood with a median peak of 407 m^3/s occurred every year in the pre-1946 conditions while in the post 1946 condition it does not occur. Also notice the big variability of median monthly flows in the pre-1946 conditions, the ratio of the maximum value (September=97 m^3/s) and the minimum value (April=11 m^3/s) 8.8 is times; meanwhile in the post-1946 conditions, the same ratio of maximum value (September=24 m^3/s) and the minimum value (April=88 m^3/s) is 3 times only.

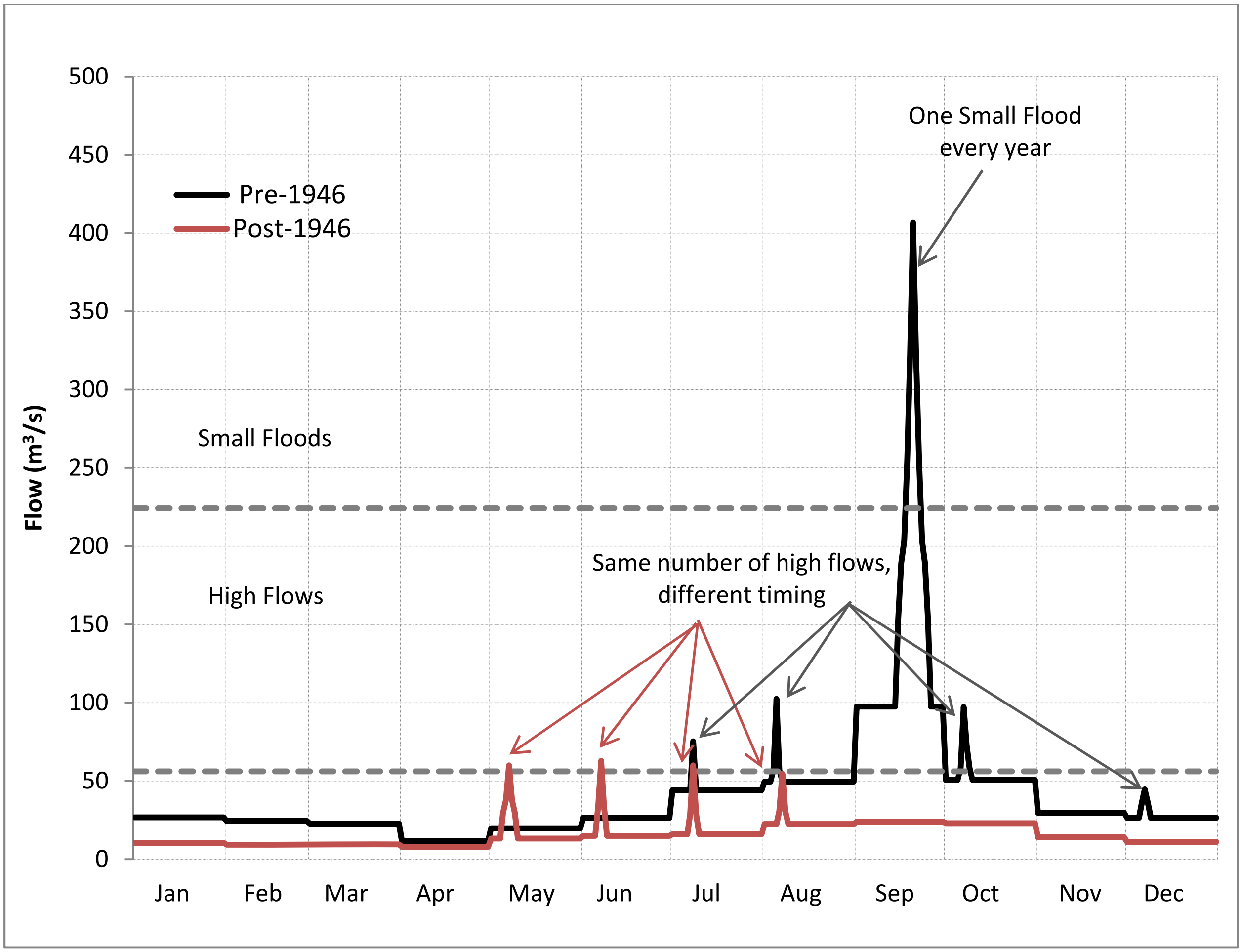

Figure 3-13: Annual Hydrograph, Return Period = 1 year, post and pre-1946 conditions

Figure 3-14 shows annual hydrograph for flows with one year return period for the pre-1946 and 2-3 year return period for the post-1946 conditions. The hydrograph for the pre-1946 condition considers that two small floods happened every year, the one fixed in September, and the one variable in time that this occasion occurred in July. For the post-1946 Hydrograph, it is considered that both small floods occurred that year, in June and September. High flows in May, June, July, August and October occur in both hydrographs. Figure 3-14 demonstrate how high flows and small floods that occurred every year in the pre-1946 conditions, they are occurring every 2-3 in the post-1946 conditions. Not only small floods do not occur so often in the post-1946 conditions, but also their magnitude (median peak) is smaller than in the pre-1946 conditions.

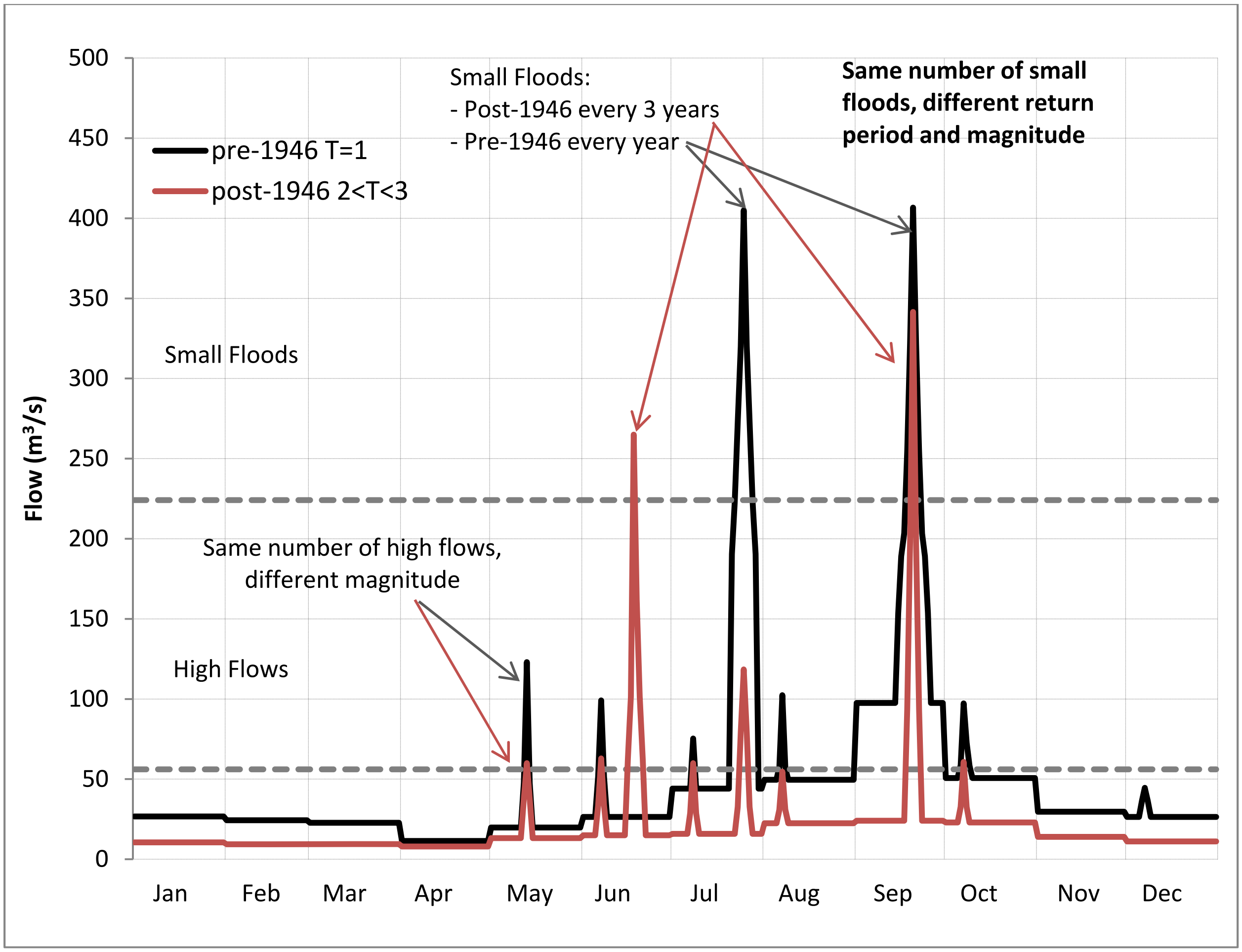

Figure 3-14: Comparison of annual hydrograph, Pre-1946 T=1 year Vs. Post -1946 2<T<3

Figure 3-15 shows annual hydrograph for flows with 2-3 year return period for the pre-1946 and 5-10 year return period for the post-1946 conditions. The hydrograph for the pre-1946 condition considers that three small floods happened, the one fixed in September, and two variables in time that this occasion occurred in August and October. For the post-1946 Hydrograph, it is considered that two small floods occurred that year, in August and October. High flows in February, May, June, July, August, October, November and December occur in both hydrographs. Figure 3-15 demonstrate how high flows and small floods that occurred every 2-3 years in the pre-1946 conditions, they are occurring every 5 in the post-1946 conditions. Same conclusion can be derived from these results, not only small floods do not occur so often in the post-1946 conditions, but also their magnitude (median peak) is smaller than in the pre-1946 conditions. Notice that the fixed small flood of September may not occur every year in the post-1946 conditions.

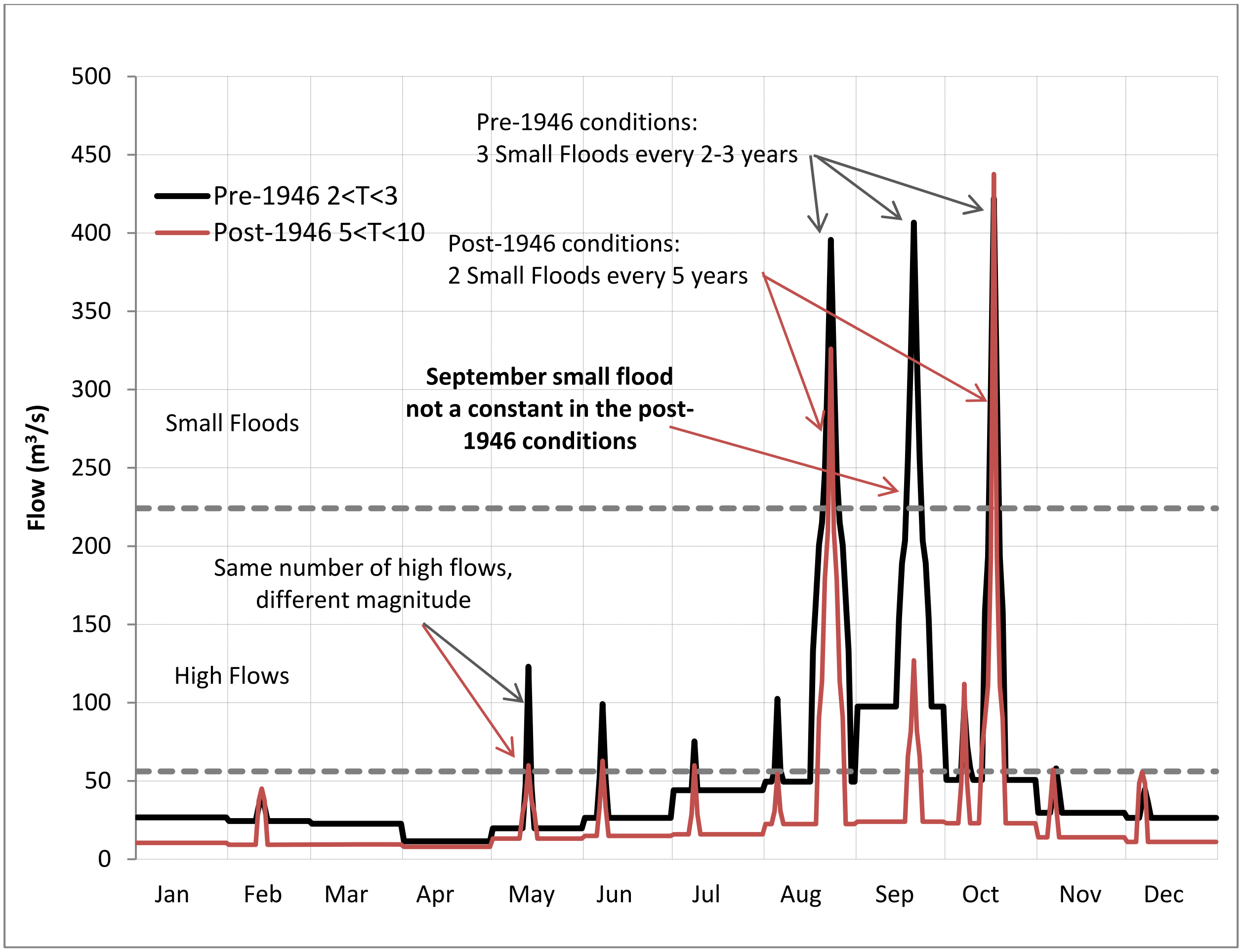

Figure 3-15: Comparison of annual hydrograph, Pre-1946 2<T<3 year Vs. Post -1946 5<T<10

3.5. CONCLUSIONS

From the previous analysis of the normal flows, it can be concluded that when comparing pre-1946 to post-1980:

- Pre-1946 conditions have more frequent small floods (median peak flow = 400 m^3/s), one fixed every year in September, and at least one small flood in one of the following months: July, August and October.
- High flows and small floods that occurred every year in the pre-1946 condition, they happened every 2-3 years in the post-1946 conditions.
- Similarly, high flows and small flows that occurred every 2-3 years in the pre-1946 condition, they happened every 5 years in the post-1946 conditions.
- Median annual flows decreased by 656.8 X10^6 m^3, or 59.0% of the pre-1946 annual quantity.

- September has the largest median monthly flows, while April has the lowest for both conditions
- Small flow pulse event decrease in magnitude for a majority of the year by an average of 34%. However, in the post-1980 winter months, there is an average increase of 61%. Events occur with roughly the same frequency for both periods (7.4 against 6.4 per year).
- Large high flow pulse events are four times more likely to occur in the post-1946 conditions but have an average 17% less flow.
- Small floods are two times less likely to occur in the post-1946 conditions and have a smaller median peak flow magnitude.

4. DROUGHT PERIODS

In this section are analyzed the daily mean flow values of drought years for both periods. Pre-1946 period include mean daily flow data for 29 years, from 1901 to 1913 and from 1931 to 1946. Post-1946 period include data for 30 years, from 1980 to 2009. Drought years are defined as those when the annual flow volume is smaller than the median annual volume for the period of analysis. Table 4-1 shows the median, mean and standard deviation for both periods. The median annual streamflow has been reduced by half, from 1,318X10^6 m^3 on the pre-1946 to 676X10^6 m^3 on the post-1946.

Table 4-1: Annual statistics, Pre-1946 and Post-1946

	Percentile (1X10^6 m^3/s)			Average	Std. Dev.
	0.75	0.5 (Median)	0.25	(1X10^6 m^3/s)	(1X10^6 m^3/s)
Pre-1946	2530	**1318**	1053	1892	1104
Post-1946	1157	**676**	404	1000	837
Deficit	1373 (54%)	**642 (49%)**	649 (62%)	892 (47%)	267 (24%)

Figure 4-1 and Figure 4-2 show the annual streamflow volume at Johnson Ranch for both periods. For the pre-1946 period, the daily mean flow of the following years is analyzed: 1901, 1903, 1910, 1913, 1931, 1934-1937, 1939-1940 and 1943-1946. For the post-1946 period, the daily mean flow of the following years is analyzed: 1983, 1994-2003, 2005-2007 and 2009.

A similar analysis has been done for mean daily flows during drought years. Flows have been categorized in: median flows, high flows, small floods and large floods using the same thresholds calculated in the previous section.

- A *median monthly flow* is the median value of all the daily mean flows for the month and the drought years of the hydrologic period analyzed.
- A *high flow* is a flow with a peak between the 75th (56 m^3/s) and the 95th (224 m^3/s) percentile of daily flows.
- A *small flood* is a flow with a peak between the 95th (224 m^3/s) and 1,100 m^3/s.
- A *large flood* is a flow with a peak larger than 1,100 m^3/s.

In this section the objective is to characterize these flows during drought years. The Indicators of Hydraulic Alteration (IHA) software is used to label the different flows along the periods of analysis. The frequency of each event (i.e. high flow, small and large floods) has been determined for each period of analysis. Return periods for each event have been calculated using the frequency of each event.

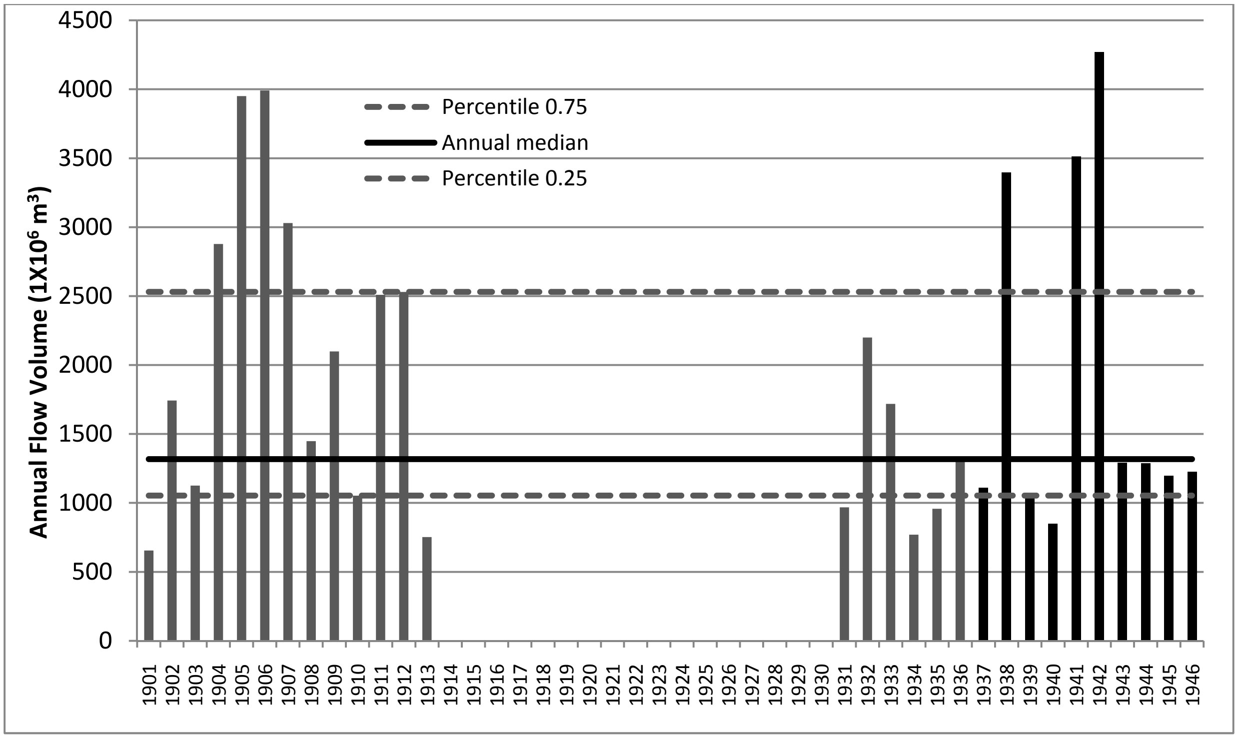

Figure 4-1: Johnson Ranch annual flow volume, pre-1946

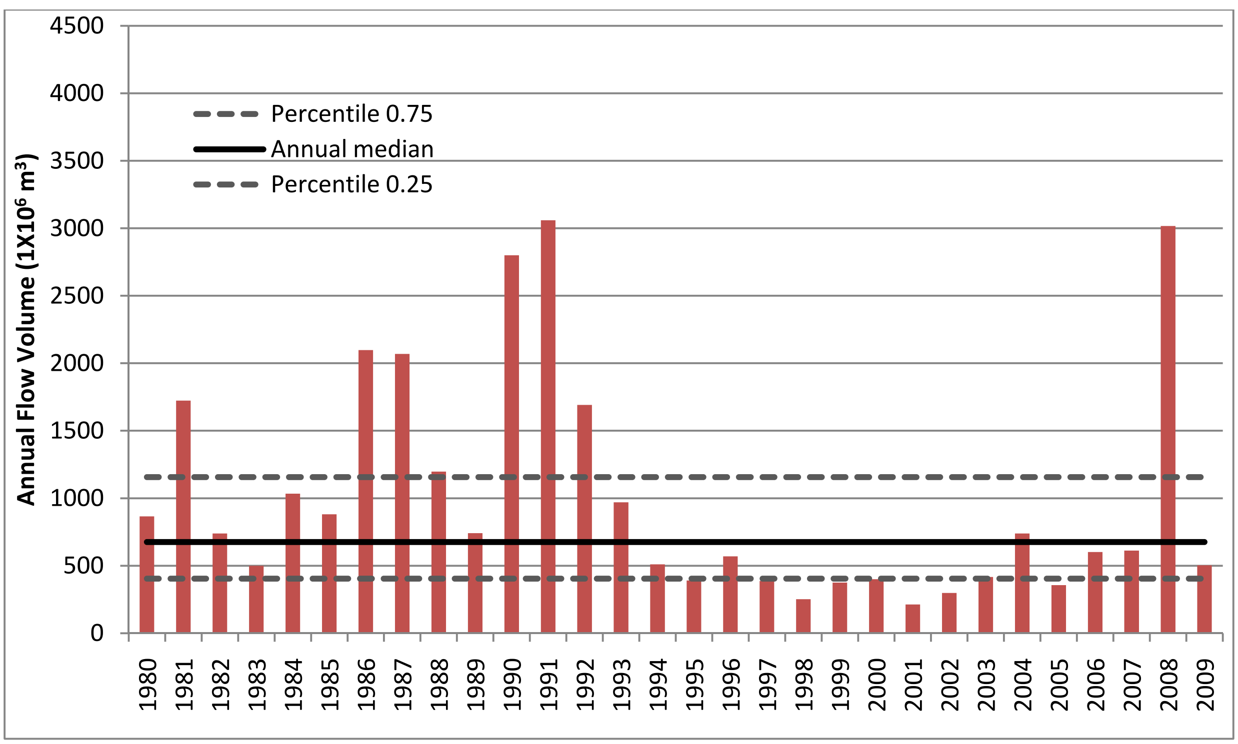

Figure 4-2: Johnson Ranch annual flow volume, post-1946

4.1. MONTHLY MEDIANS

The median monthly flow is the median value of the daily mean flows for each month of the selected drought years. One value for each month has been calculated for pre-1946 and post-1946 periods under drought conditions.

4.1.1. BEFORE 1946

Table 4-2 provides a summary of median monthly flows during drought years prior to 1946. The peak monthly median flow occurred in September at 45 m^3/s (1,590 cfs) and the minimum in April at 10 m^3/s (353 cfs). Figure 4-3 shows the median monthly flow under drought and normal conditions for the pre-1946 period. Main differences in the median flows are from June to November.

Table 4-2: Median monthly flows, pre-1946 period

	Pre 1946 Monthly Flows (m^3/s)			Median	Deficit	
	75th	Median	25th	Norm. Cond.	(m^3/s)	(%)
Jan	33	26	14	27	0	1
Feb	33	25	18	24	-1	---
Mar	33	24	16	23	-2	---
Apr	17	10	4	11	2	14
May	32	15	6	20	5	24
Jun	34	20	9	26	6	24
Jul	52	27	15	44	17	38
Aug	46	24	13	50	26	52
Sep	96	45	20	98	52	54
Oct	63	36	19	51	15	30
Nov	32	24	15	30	6	21
Dec	28	21	9	26	5	20

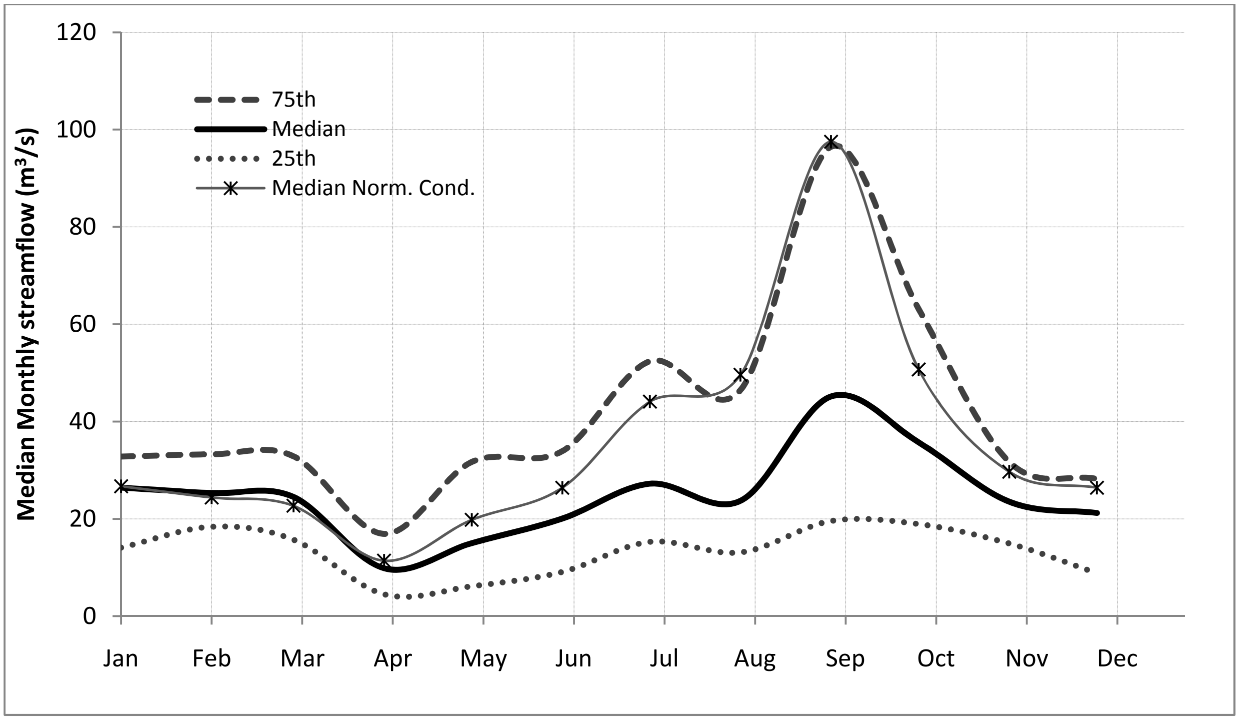

Figure 4-3: Median monthly flows under drought conditions, pre-1946

4.1.2. AFTER 1946

Table 4-3 provides a summary of median monthly flows during drought years after 1946 (1980-2009). The peak monthly median flow occurred in October at 13 m^3/s (460 cfs) and the minimum in April at 3 m^3/s (105 cfs). Figure 4-4 shows the median monthly flow under drought and normal conditions for the post-1946 period.

Table 4-3: Median monthly flows, post-1946 period

	Post-1946 Monthly Flows (m^3/s)			Median
	75th	Median	25th	Norm. Cond.
Jan	11	8	7	11
Feb	8	6	5	9
Mar	7	5	3	10
Apr	6	3	2	8
May	16	4	2	13
Jun	17	9	2	15
Jul	17	10	4	16
Aug	23	12	7	23
Sep	16	8	3	24
Oct	24	13	6	23
Nov	12	9	6	14
Dec	9	8	6	11

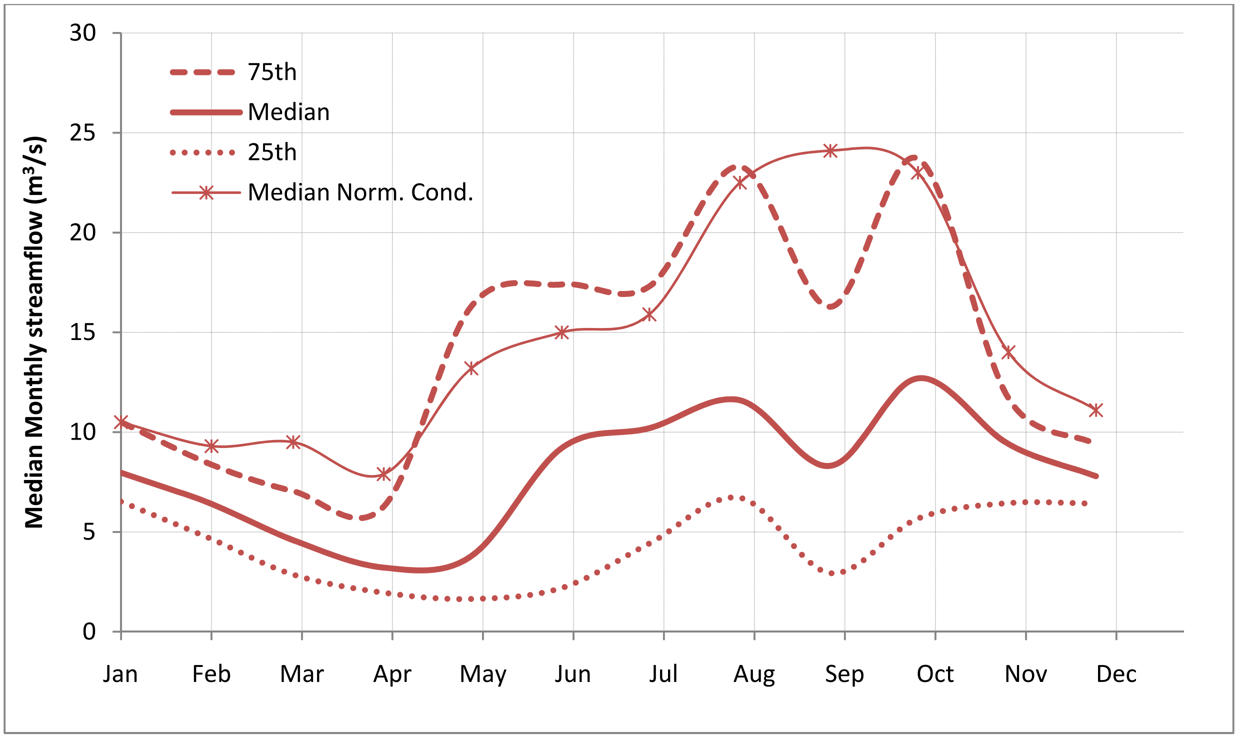

Figure 4-4: Median monthly flows under drought conditions, post-1946

4.1.3. COMPARISON

Figure 4-5 shows monthly medians, 25th and 75th percentile flows for pre-1946 and the post-1946 (1980-2009). Median values are compared in Table 4-4. During droughts, there is a significant difference between pre-1946 and post 1946 conditions. The annual median flow volume for the pre-1946 and post-1946 are $782X10^6$ m^3 and $251X10^6$ m^3, respectively. Comparing these annual volumes of the periods, the resulting deficit is $531X10^6$ m^3 of water, or 68% of the pre-1946 quantity. Much of this deficit (65%) comes from high flow months June through November. Notice that in the pre-1946 conditions, the median monthly values preserve the seasonal shape, with high values during monsoon season (June to October) and low values during winter and spring. On the contrary, in the post-1946 conditions, the annual hydrograph is completely distorted. The peak monthly flow has shifted to October, and there is a decrease in the median monthly flow in September, that used to be the month with the highest median monthly value.

Table 4-4: Comparison of monthly median flows

	Monthly Median Flows during droughts (m³/s)			
	Pre 1946	Post 1980	Deficit	% Deficit
Jan	26	8	18	70
Feb	25	6	19	75
Mar	24	5	20	81
Apr	10	3	7	67
May	15	4	11	75
Jun	20	9	11	54
Jul	27	10	17	63
Aug	24	12	12	51
Sep	45	8	37	82
Oct	36	13	23	64
Nov	24	9	14	60
Dec	21	8	13	63

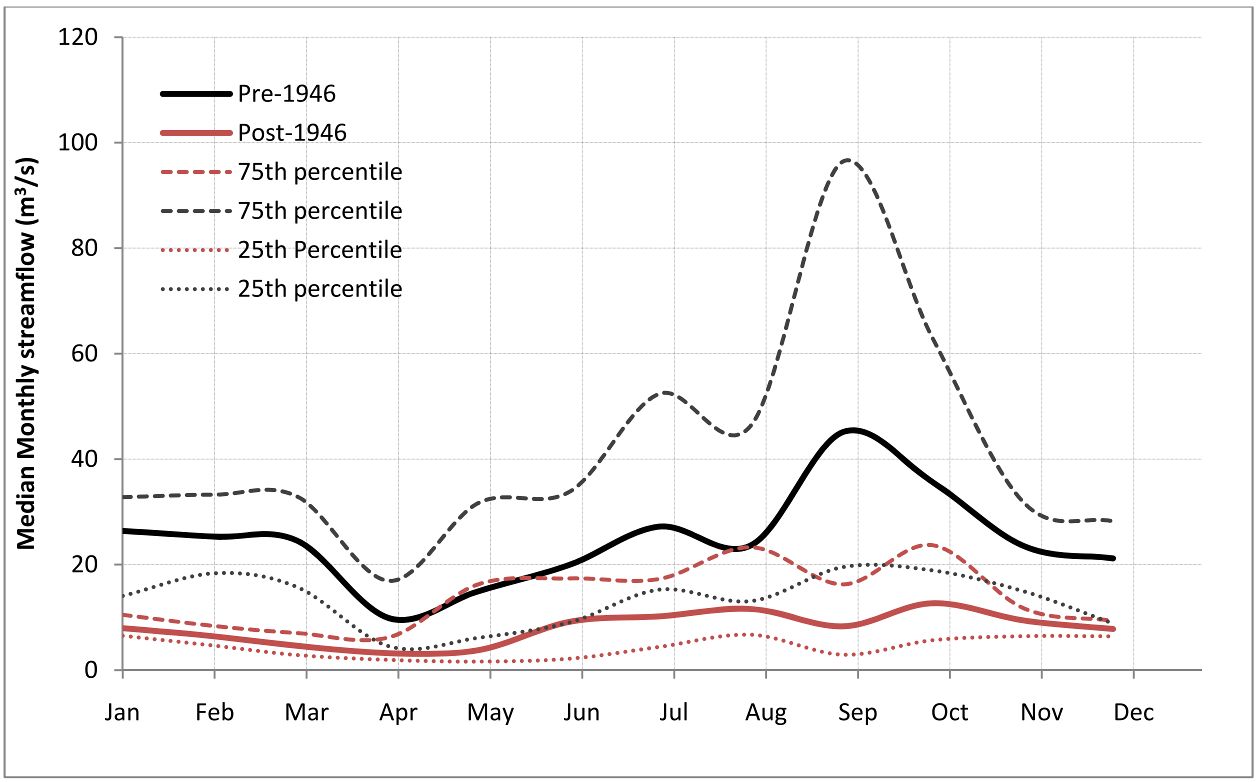

Figure 4-5: Comparison of median monthly flows under drought conditions

4.2. HIGH FLOWS

High flows are defined as those whose peak flow exceed the 75 percentile (56 m^3/s) but are lower than the 95th percentile (224 m^3/s) of daily flows for the whole period. These thresholds already established in the normal conditions section are used in order to evaluate how frequently high flows occurred during drought in the pre-1946 and post-1946 periods.

Similar to the previous section, each high flow have been identified, selected and analyzed individually by month and period of analysis (pre1946 or post-1946).

In this section is presented the characteristics high flows during drought years for each month, period (pre-1946 or post-1946) and type of high flow (small or large). For the pre-1946 the small high flows have a peak lower than 125 m^3/s; meanwhile for the post-1946, small flows have a peak lower than 100 m^3/s.

4.2.1. BEFORE 1946

Table 4-5 shows the high flow pulses with peaks lower than 125 m^3/s (4,414 cfs) for drought years prior 1946 for different return periods (T). Small high flow pulses that happen:

- Every year (T<1.5 years) occur July, August, September and December with a duration of 3 days and peak flows of 71, 102, 91 and 40 m^3/s, respectively.
- Every 2 to 3 years (1.5 years < T < 3.5 years) occur in the rest of the months (January, February, March, April, May, June, October and November), with a duration of 3, 3, 3, 3, 3, 3, 4, and 3, days and peak flows of 36, 40, 38, 61, 116, 98, 84 and 42 m^3/s, respectively.

Table 4-5: High flow pulses during drought years lower than 125 m^3/s, Pre-1946 period

	Small high flow pulses during drought years (m^3/s)											
Day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	31	28	31	53	38	53	41	55	50	58	34	30
2	36	40	38	61	116	98	70.5	102	91	84	42	40
3	31	28	31	53	38	53	41	55	50	64	34	30
4	---	---	---	---	---	---	---	---	---	58	---	---
5	---	---	---	---	---	---	---	---	---	---	---	---
6	---	---	---	---	---	---	---	---	---	---	---	---
Duration (days)	3	3	3	3	3	3	3	3	3	4	3	3
Peak (m^3/s)	36	40	38	61	116	98	71	102	91	84	42	40
Frequency	0.40	0.47	0.47	0.33	0.53	0.60	0.76	1.00	1.13	0.60	0.47	0.73
T (years)	2.5	2.1	2.1	3.0	1.9	1.7	1.3	1.0	0.9	1.7	2.1	1.4

Table 4-6 shows the high flow pulses with peaks larger than 125 m³/s (4,414 cfs) for the prior 1946 period for different return periods (T). Large high flow pulses that happen:

- Every 5 to 10 years (3.5 years < T < 10) occur in July with a duration of 8 days and a peak flow of 188 m³/s.

Table 4-6: High flow pulses during drought year larger than 125 m³/s, Pre-1946 period

	Large high flow pulses during drought years (m³/s)											
Day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	---	---	---	---	---	---	139	---	---	---	---	---
2	---	---	---	---	---	---	166	---	---	---	---	---
3	---	---	---	---	---	---	180	---	---	---	---	---
4	---	---	---	---	---	---	188	---	---	---	---	---
5	---	---	---	---	---	---	166	---	---	---	---	---
6	---	---	---	---	---	---	139	---	---	---	---	---
7	---	---	---	---	---	---	124	---	---	---	---	---
8	---	---	---	---	---	---	109	---	---	---	---	---
Duration (days)	---	---	---	---	---	---	8	---	---	---	---	---
Peak (m³/s)	---	---	---	---	---	---	188	---	---	---	---	---
Frequency	---	---	---	---	---	---	0.10	---	---	---	---	---
T (years)	---	---	---	---	---	---	9.7	---	---	---	---	---

4.2.2. After 1946

Table 4-7 shows the high flow pulses lower than 100 m³/s (3,531 cfs) for the after 1946 period for different return periods (T). High flow pulses that happen:

- Every year (T<1.5 years) occur May, June, July and August, with a duration of 5, 3, 3, and 3 days and peak flows of 57, 54, 60 and 53 m³/s, respectively.
- Every 2 to 3 years (1.5 years < T < 3.5 years) occur in September and October with a duration of 3 days and peak flows of 47 and 63 m³/s, respectively.
- Every 5 to 10 years (3.5 years < T < 10) occur in March, April and November with a duration of 3 days and peak flows of 69, 32 and 62 m³/s, respectively.
- Every 10 years or more (T > 10 years) occur in February with duration of 3 days and a peak flow of 46 m³/s.

Table 4-7: High flow pulses during drought years lower than 100 m³/s, Post-1946 period

Day	Small high flow pulses during drought years (m³/s)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	---	10	33	13	14	26	25	29	24	25	20	---
2	---	46	69	32	32	54	60	53	47	63	62	---
3	---	10	33	13	57	26	25	29	24	25	20	---
4	---	---	---	---	32	---	---	---	---	---	---	---
5	---	---	---	---	14	---	---	---	---	---	---	---
6	---	---	---	---	---	---	---	---	---	---	---	---
Duration (days)	---	3	3	3	5	3	3	3	3	3	3	---
Peak (m³/s)	---	46	69	32	57	54	60	53	47	63	62	---
Frequency	---	0.07	0.20	0.20	1.07	1.13	1.20	1.13	0.47	0.53	0.20	---
T (years)	---	15.0	5.0	5.0	0.9	0.9	0.8	0.9	2.1	1.9	5.0	---

Table 4-8 shows the high flow pulses larger than 100 m³/s (3,531 cfs) for the after 1946 period for different return periods (T). High flow pulses that happen:

- Every 2 to 3 years (1.5 years < T < 3.5 years) occur in July and October with a duration of 3 days and peak flows of 111 and 117 m³/s, respectively.
- Every 5 to 10 years (3.5 years < T < 10) occur in June, August and September with a duration of 3, 5 and 5 days and peak flows of 174, 173 and 127 m³/s, respectively.

Table 4-8: High flow pulses during drought years larger than 100 m³/s, Post-1946 period

Day	Large high flow pulses during drought years (m³/s)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	---	---	---	---	---	77	60	57	102	46	---	---
2	---	---	---	---	---	174	111	104	114	117	---	---
3	---	---	---	---	---	77	60	173	127	46	---	---
4	---	---	---	---	---	---	---	104	114	---	---	---
5	---	---	---	---	---	---	---	57	102	---	---	---
6	---	---	---	---	---	---	---	---	---	---	---	---
Duration (days)	---	---	---	---	---	3	3	5	5	3	---	---
Peak (m³/s)	---	---	---	---	---	174	111	173	127	117	---	---
Frequency	---	---	---	---	---	0.27	0.33	0.20	0.20	0.40	---	---
T (years)	---	---	---	---	---	3.8	3.0	5.0	5.0	2.5	---	---

4.2.3. Comparison

Table 4-9 and Figure 4-6 show a comparison of small high flows (peak flow < 125 m3/s). The majority of months see reductions up to 51% (in May) with a few notable exceptions. For the period of Nov-Mar, the intensity of flow pulses actually increased, up to 81% in March, probably caused by dam releases. Prior to 1946, there was an average of 8.3 small high flow pulse events per year. Post 1980, the frequency dropped to 6.1 per year.

Table 4-9: Magnitude and frequency of high flow pulses during drought years smaller than 125 m3/s

	Small high flow pulses during drought years				
	Peak Flow (m^3/s)			Return Period (years)	
	Pre 1946	Post 1946	% Reduction	Pre 1946	Post 1980
Jan	36	---	---	2.5	---
Feb	40	46	-15%	2.1	15.0
Mar	38	69	-81%	2.1	5.0
Apr	61	32	48%	3.0	5.0
May	116	57	51%	1.9	0.9
Jun	98	54	45%	1.7	0.9
Jul	71	60	15%	1.3	0.8
Aug	102	53	49%	1.0	0.9
Sep	91	47	48%	0.9	2.1
Oct	84	63	25%	1.7	1.9
Nov	42	62	-46%	2.1	5.0
Dec	40	---	---	1.4	---

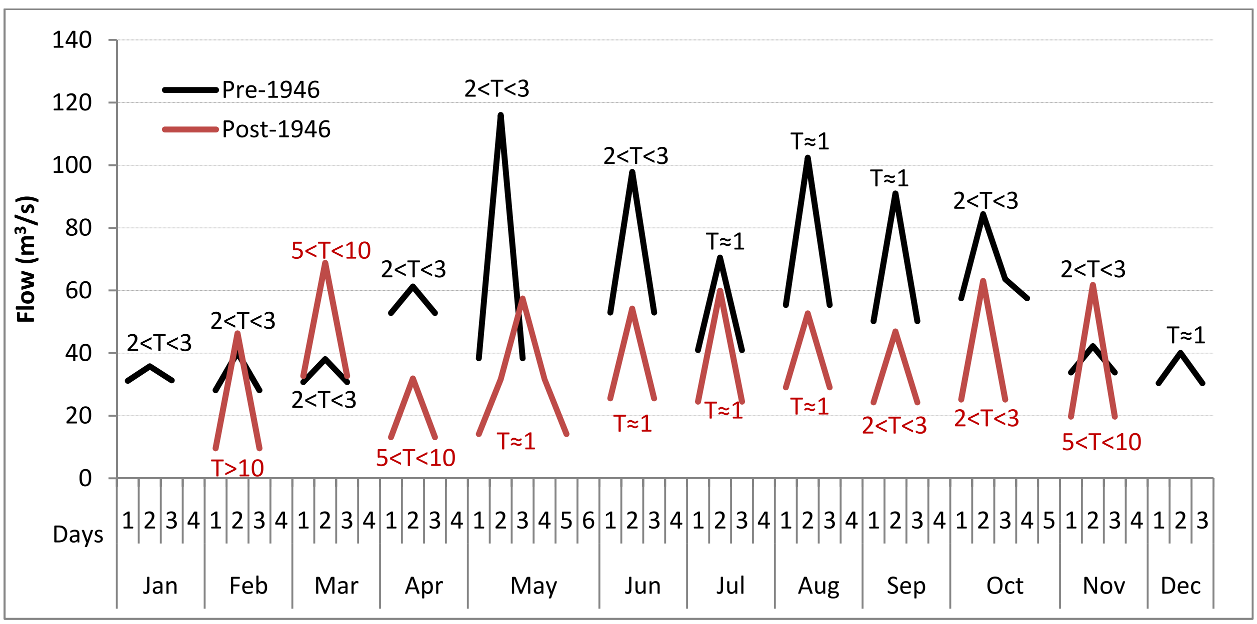

Figure 4-6: Duration, magnitude and frequency of high flow pulses during drought years smaller than 125 m³/s

A summary of large high flow pulses (peak flow> than 100 m3/s) is shown below in Table 4-10 and Figure 4-7. In the pre-1946 period, only large high flows occurred in July. On the contrary, in the post-1946 period large high flows occurred from June to October. This means that large high flow pulses (peak flow > 100 m3/s) were not very common in the pre-1946 conditions as they are now in the post-1946 conditions; this may be as a consequence of reservoir releases upstream.For instance, in July large high flow pulses occurred once every 3 years in the post-1946 period, meanwhile they occurred once every 10 years in the pre-1946 periods.

Table 4-10: Magnitude and frequency of high flow pulses during drought years larger than 100 m^3/s

	Large high flow pulses during drought years				
	Peak Flow (m^3/s)			Return Period (years)	
	Pre 1946	Post 1980	% Reduction	Pre 1946	Post 1980
Jan	---	---	---	---	---
Feb	---	---	---	---	---
Mar	---	---	---	---	---
Apr	---	---	---	---	---
May	---	---	---	---	---
Jun	---	174	---	---	3.8
Jul	188	111	41%	9.7	3.0
Aug	---	173	---	---	5.0
Sep	---	127	---	---	5.0
Oct	---	117	---	---	2.5
Nov	---	---	---	---	---
Dec	---	---	---	---	---

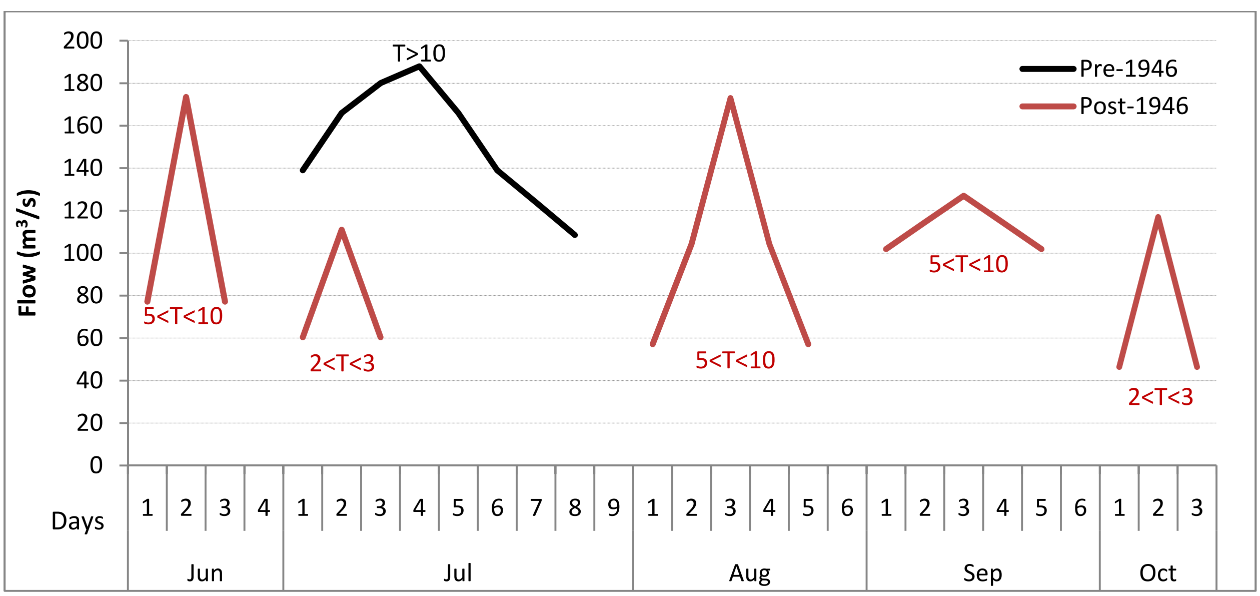

Figure 4-7: Duration, magnitude and frequency of high flow pulses during drought years larger than 125 m^3/s

4.3. Small Floods

Small Floods are those that have a peak flow greater than the 95 percentile (224 m^3/s) but smaller than 1,100 m^3/s (38,846 cfs), which is a below the Presidio/Ojinaga levees flow design, 1,190 m^3/s (42,000 cfs). The 95th percentile flow, 224 m^3/s (7,910 cfs), has been determined using the date of the pre-1946 period. This thresholds are used in both periods to evaluate the how frequently high flows occurred in drought years. Flows that satisfy the previous thresholds have been identified, selected and analyzed individually by month and period of analysis (pre1946 or post-1946) during drought years. For each month, the median of the flows was estimated in order to obtain a characteristic small flood. This section presents the characteristics small floods for each month and period of analysis (pre-1946 or post-1946) during drought years.

4.3.1. Before 1946

Table 4-11 shows the small floods for drought years of pre 1946 period and for different return periods (T). Small floods that happen:

- Every year (T<1.5 years) occur in September with a duration of 11 days and a median peak flow of 380 m^3/s.
- Every 2 to 3 years (1.5 years < T < 3.5 years) occur in October with durations of 7days and a median peak flow of 422 m^3/s, respectively.
- Every 5 to 10 years (3.5 years < T < 10) occur in June, July and August with a duration of 8, 7 and 11 days and median peak flows of 632, 323, and 270 m^3/s, respectively.
- Every 10 years or more (T > 10 years) occur in May with duration of 3 and a median peak flow of 247 m^3/s.

4.3.2. After 1946

Table 4-12 shows the small floods for drought years of post 1946 period and for different return periods (T). Small floods that happen:

- Every 5 to 10 years (3.5 years < T < 10) occur in June with a duration of 6 days and a median peak flow of 310 m^3/s.
- Every 10 years or more (T > 10 years) occur in August, September and October with durations of 9, 5 and 7 days and median peak flows of 402, 352, and 599 m^3/s respectively.

Table 4-11: Small floods (224 m^3/s <flow<1,100 m^3/s) during drought years, Pre-1946 period

	Small floods during drought years(m^3/s)											
Day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	---	---	---	---	49	49	78	90	113	66.3	---	---
2	---	---	---	---	247	339	175	129	139	140	---	---
3	---	---	---	---	49	632	258	172	150	229	---	---
4	---	---	---	---	---	339	323	193	204	422	---	---
5	---	---	---	---	---	265	258	215	262	229	---	---
6	---	---	---	---	---	136	175	270	380	140	---	---
7	---	---	---	---	---	121	78	215	262	66.3	---	---
8	---	---	---	---	---	105	---	193	204	---	---	---
9	---	---	---	---	---	---	---	172	150	---	---	---
10	---	---	---	---	---	---	---	129	139	---	---	---
11	---	---	---	---	---	---	---	90	113	---	---	---
12	---	---	---	---	---	---	---	---	---	---	---	---
13	---	---	---	---	---	---	---	---	---	---	---	---
Duration (days)	---	---	---	---	3	8	7	11	11	7	---	---
Peak (m^3/s)	**---**	**---**	**---**	**---**	**247**	**632**	**323**	**270**	**380**	**422**	**---**	**---**
Frequency	---	---	---	---	0.07	0.13	0.13	0.20	0.87	0.33	---	---
T (years)	**---**	**---**	**---**	**---**	**15.0**	**7.5**	**7.5**	**5.0**	**1.2**	**3.0**	**---**	**---**

Table 4-12: Small floods (224 m^3/s <flow<1,100 m^3/s) during drought years, Post-1946 period

	Small floods during drought years (m^3/s)											
Day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	---	---	---	---	---	25	---	62	197	38	---	---
2	---	---	---	---	---	37	---	164	274	168	---	---
3	---	---	---	---	---	310	---	232	352	388	---	---
4	---	---	---	---	---	130	---	404	274	599	---	---
5	---	---	---	---	---	37	---	232	197	388	---	---
6	---	---	---	---	---	25	---	164	---	168	---	---
7	---	---	---	---	---	---	---	62	---	38	---	---
8	---	---	---	---	---	---	---	---	---	---	---	---
9	---	---	---	---	---	---	---	---	---	---	---	---
10	---	---	---	---	---	---	---	---	---	---	---	---
Duration (days)	---	---	---	---	---	6	---	9	5	7	---	---
Peak (m^3/s)	**---**	**---**	**---**	**---**	**---**	**310**	**---**	**404**	**352**	**599**	**---**	**---**
Frequency	---	---	---	---	---	0.27	---	0.07	0.07	0.07	---	---
T (years)	**---**	**---**	**---**	**---**	**---**	**3.8**	**---**	**15.0**	**15.0**	**15.0**	**---**	**---**

4.3.3. COMPARISON

A summary of small flooding events is show below in Table 4-13 and Figure 4-8. The maximum flows for each period are similar with a pre-1946 of 632 m3/s and a post-1980 of 599 m3/s; however, the pre-1946 maximum value occurs in June, while the post-1980 occurs in October. Also notice that during drought conditions one small flood in the pre-1946 occurred every September (380 m^3/s), meanwhile in the post-1946 conditions it occurs once every 15 years. There is a decrease in 2 months, up to 50%, where small floods are present in both. During drought periods, prior to 1946 there was an average of 1.7 small flood events per year meanwhile in the post 1980, the frequency drops by more than half to 0.5 per year.

Table 4-13: Peak flows and frequency of small floods during drought years

	Small High Flow Pulses				
	Peak Flow (m^3/s)			Return Period (years)	
	Pre 1946	Post 1980	% Reduction	Pre 1946	Post 1980
Jan	---	---	---	---	---
Feb	---	---	---	---	---
Mar	---	---	---	---	---
Apr	---	---	---	---	---
May	247	---	---	15.0	---
Jun	632	310	51%	7.5	3.8
Jul	323	---	---	7.5	---
Aug	270	404	-50%	5.0	15.0
Sep	380	352	7%	1.2	15.0
Oct	422	599	-42%	3.0	15.0
Nov	---	---	---	---	---
Dec	---	---	---	---	---

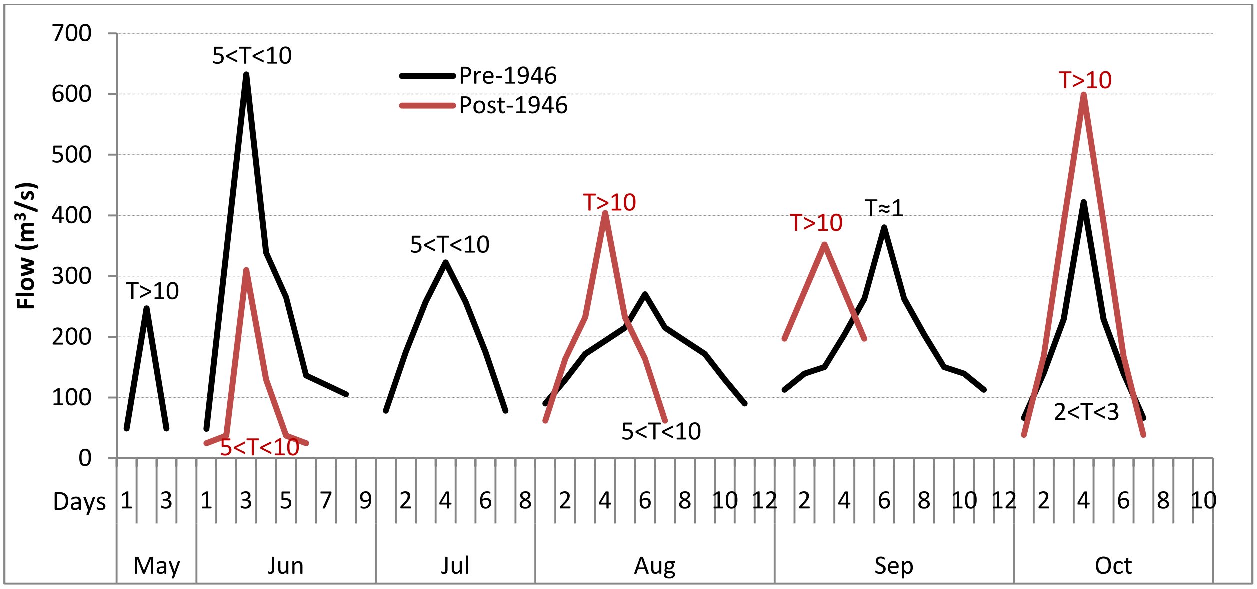

Figure 4-8: Duration, magnitude and frequency of small floods during drought years

4.4. Integration of Results

This section integrates the results of median monthly flows, high flows and small flood for the pre-1946 and post-1946 conditions during drought conditions.

4.4.1. Before 1946

Figure 4-9 shows the annual hydrograph for flows with one year return period during drought years in the pre-1946 conditions. Table 4-14 shows the volume necessary to satisfy the annual hydrograph. These results show that in order to satisfy the pre-1946 annual conditions, it is necessary a volume of 954X10^6 m^3 per year.

Table 4-14: Annual hydrograph volume for T = 1 year during drought conditions, pre-1946

	Volume (1X10^6 m^3)												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Sum
Median	71	61	66	25	40	52	73	63	117	96	61	57	782
High Flows	---	---	---	---	---	---	6	12	5	---	---	9	32
Small Floods	---	---	---	---	---	---	---	---	140	---	---	---	140
Total	71	61	66	25	40	52	79	76	262	96	61	65	**954**

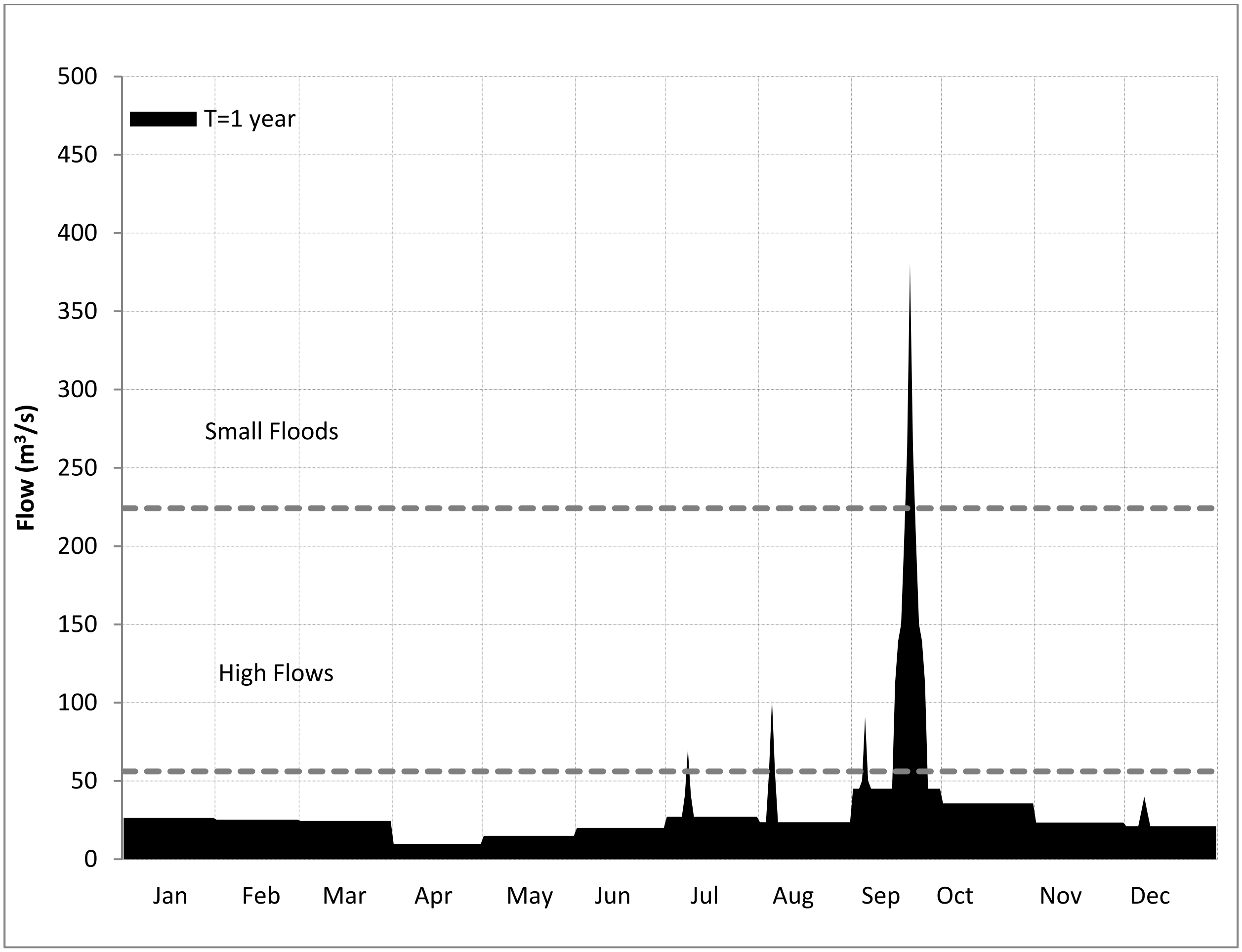

Figure 4-9: Annual Hydrograph for T = 1 year in drought years, pre-1946 conditions

There are several similarities with the hydrograph for normal conditions (Figure 3-5): 1) one small flood occurs in September of about the same size, the peaks flows are 380 m^3/s during drought years and 407m^3/s during normal conditions; 2) four high flow pulses practically in the same months, July, August and December for both conditions (Normal and droughts), October during normal conditions and September during drought conditions. The main difference between both hydrographs is in the median flows, mostly in four months, from July to October. The annual median flow volume for normal and drought conditions are 1,130X10^6 m^3 and 782X10^6 m^3, respectively. Comparing these annual volumes, the resulting deficit is 348X10^6 m^3 of water, or 31% less than volume during normal conditions.

Figure 4-10Figure 3-5 shows the annual hydrograph for flows with one and two to three years return period in the pre-1946 conditions during drought years. Results are consistent with the hydrograph of normal conditions (Figure 3-6), high flows start happening in all months. In addition, during drought years a small flood may occur in October with a bigger peak that the fixed small flood of September. Even though the overall year might be catalogued as a drought year, it was possible to have two small floods during drought years. The occurrence of small flood even in drought years may have contributed to maintaining the Rio Grande/Bravo as a wide sandy multi-threaded river.

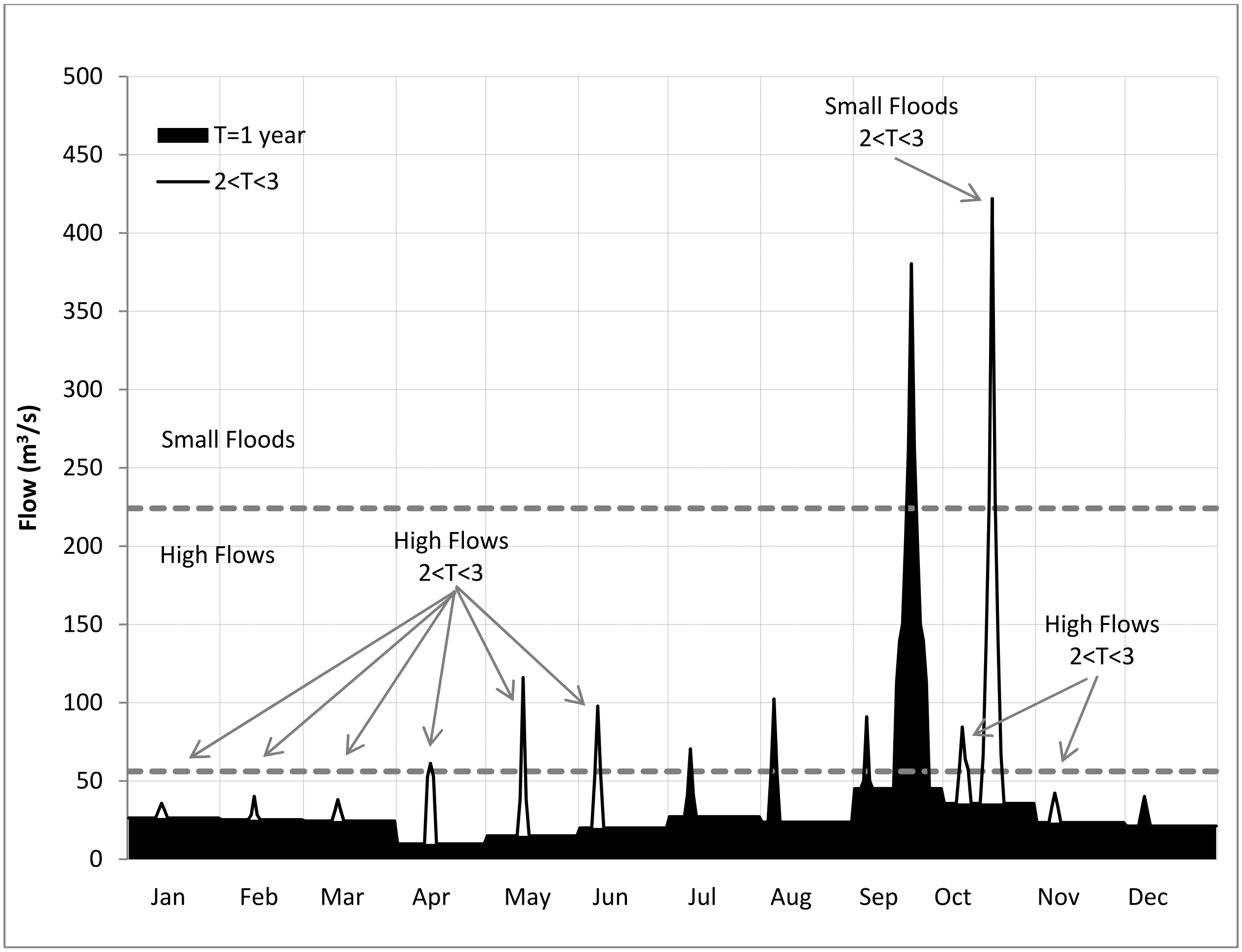

Figure 4-10: Annual Hydrograph during drought years, Return Period = 2-3 years, pre-1946 conditions

Figure 4-11Figure 3-5 shows the annual hydrograph for flows with one and five to ten year return period in the pre-1946 conditions during drought years. Similarly to normal conditions (Figure 3-7), small floods start appearing outside the monsoon season, in this case in May.

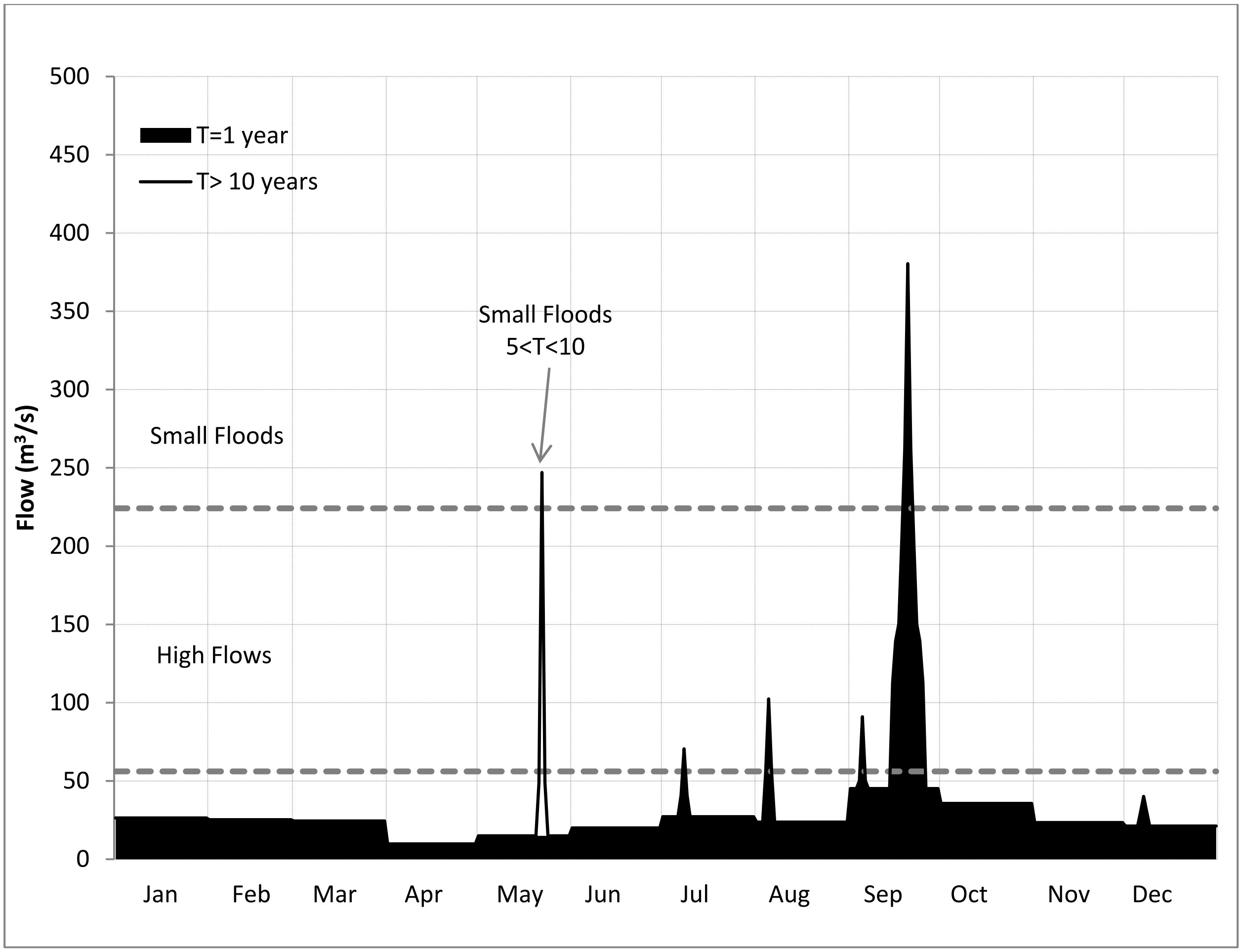

Figure 4-11: Annual Hydrograph, Return Period = 5-10 years, pre-1946 conditions

Figure 4-12Figure 3-5 shows the annual hydrograph for flows with one and five to ten year return period in the pre-1946 conditions during drought years. Similarly to normal conditions (Figure 3-8), small floods and high flows start occurring outside the monsoon season. Notice that small floods used to even during drought years.

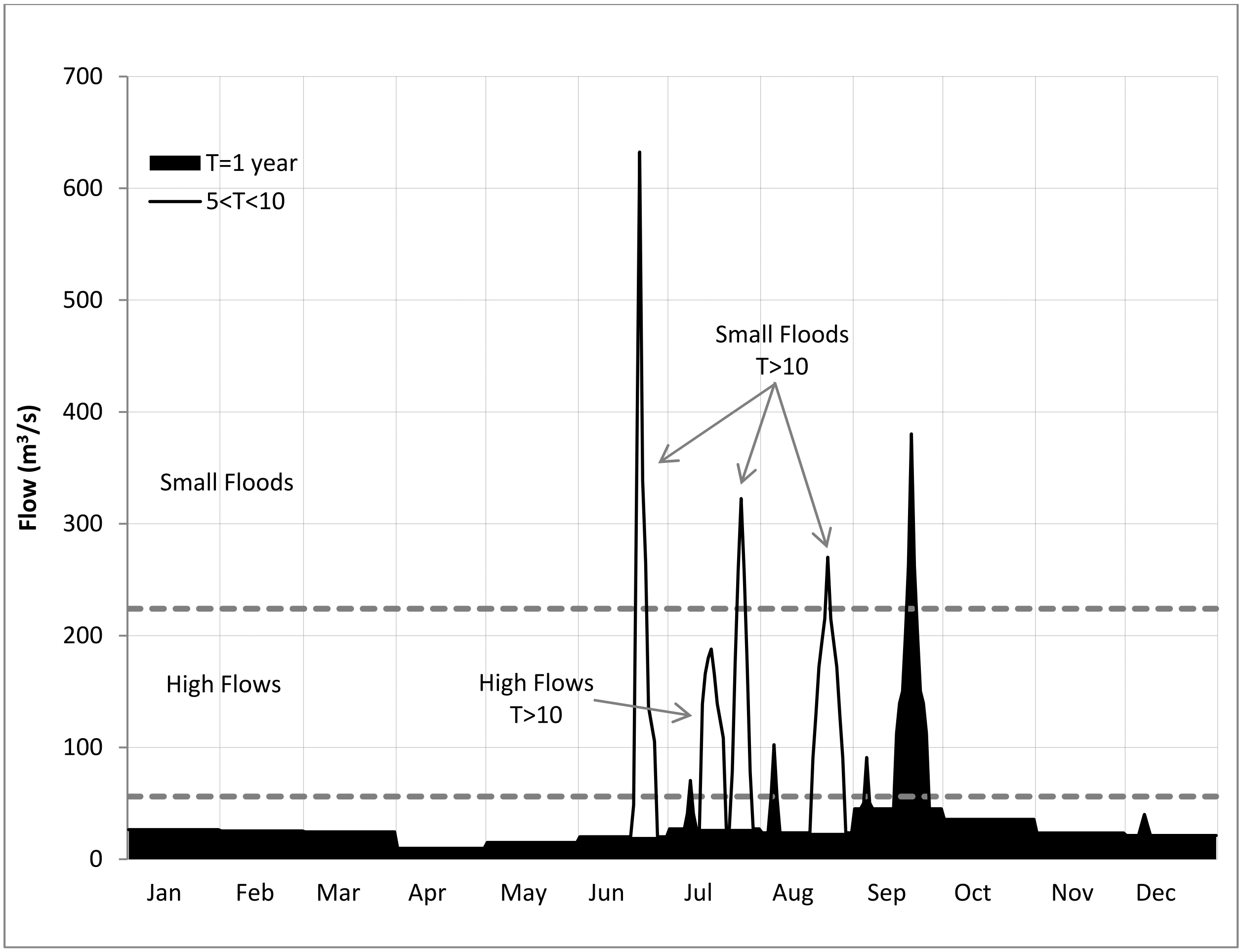

Figure 4-12: Annual Hydrograph, Return Period >10 years, pre-1946 conditions

4.4.2. After 1946

Figure 4-13 shows the annual hydrograph during drought years for flows with one year return period in the post-1946 conditions. **Error! Reference source not found.** shows the volume for each month according to the 1-year return period hydrograph; the total volume in the hydrograph is very small (390X10^6 m^3/year) compared to the pre-1946 conditions (954X10^6 m^3/year). Every year only 4 high flows occur, similarly as what happens during normal conditions. <u>Notice that no small flood occurs during drought years in the post-1946 conditions.</u> The absence of this small flood might be one of the causes for the reduction in channel width in the post-1946 period.

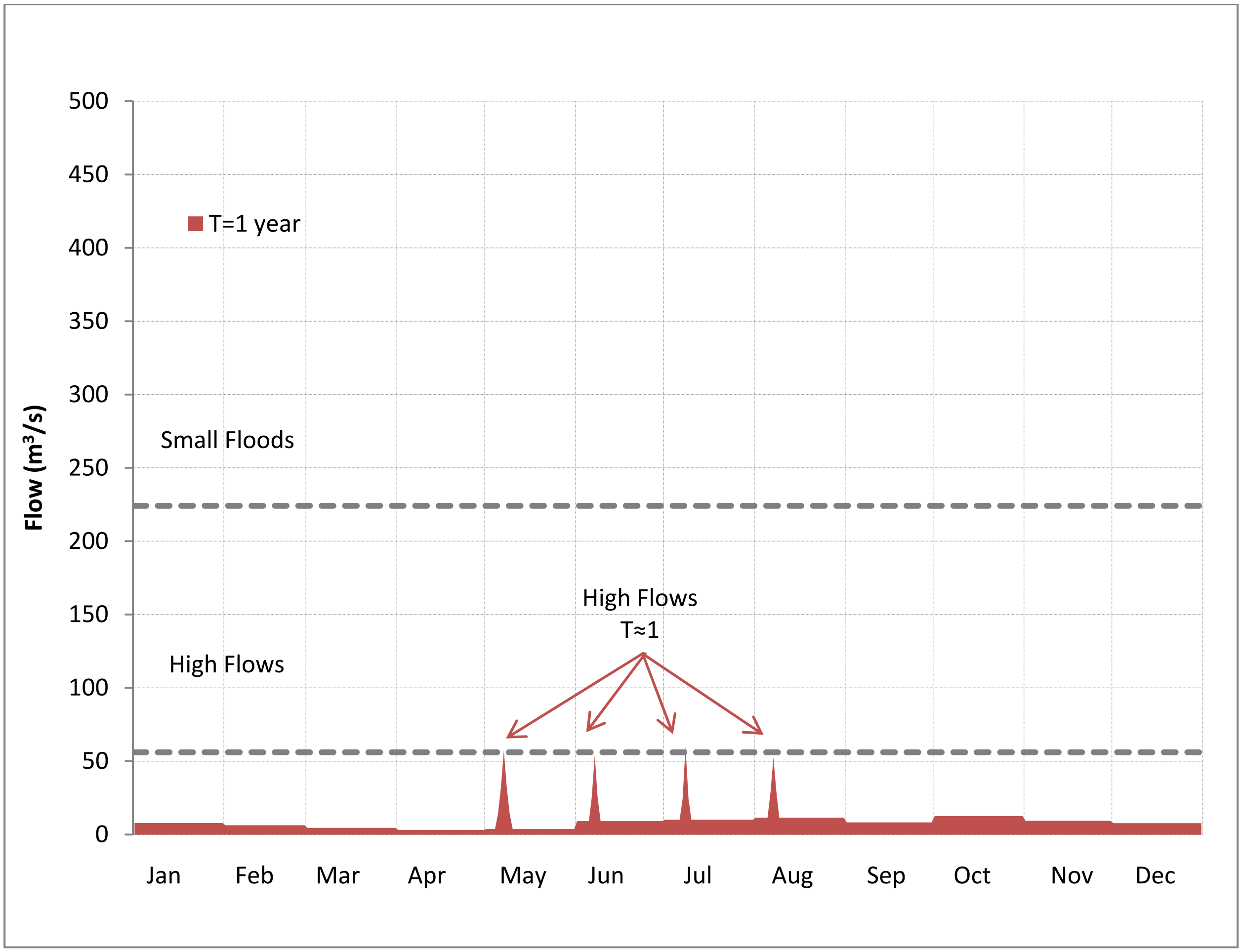

Figure 4-13: Annual Hydrograph during drought years, Return Period = 1 year, post-1946 conditions

Table 4-15: Annual hydrograph volume for T = 1 year during drought years, post-1946

	Volume ($1X10^6$ m^3)												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Sum
Median	21	15	12	8	10	24	27	31	22	34	24	21	251
High Flows	---	---	---	---	11	7	7	7	---	---	---	---	31
Small Floods	---	---	---	---	---	---	---	---	108	---	---	---	108
Total	21	15	12	8	21	31	34	38	130	34	24	21	**390**

Figure 4-14Figure 3-5 shows the annual hydrograph during drought years for flows with one and two to three year return period in the post-1946 conditions. Results show that more high flows occur during drought years but no small flood is happening in this return period.

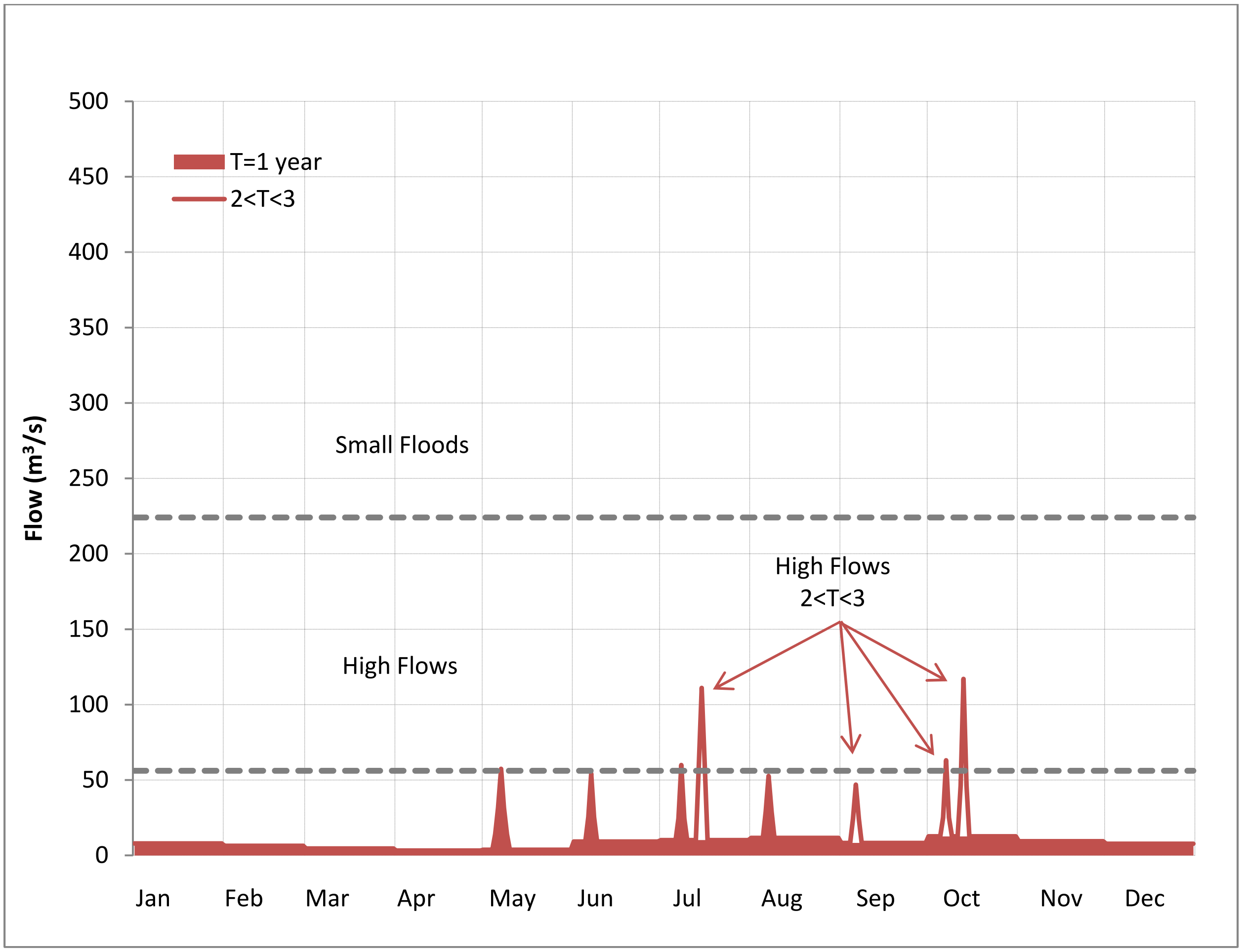

Figure 4-14: Annual hydrograph during drought years, Return Period = 2-3 years, pre-1946

Figure 4-15Figure 3-5 shows the annual hydrograph during drought years for flows with one and five to ten year return period in the post-1946 conditions. Up to this point, one small flood occurs in June with a peak flow of 310 m^3/s and a return period of 4 years. This result is very alarming; basically it is necessary to wait 3 year for a small flood under normal conditions and up to 4 years under drought conditions in the post-1946 period.

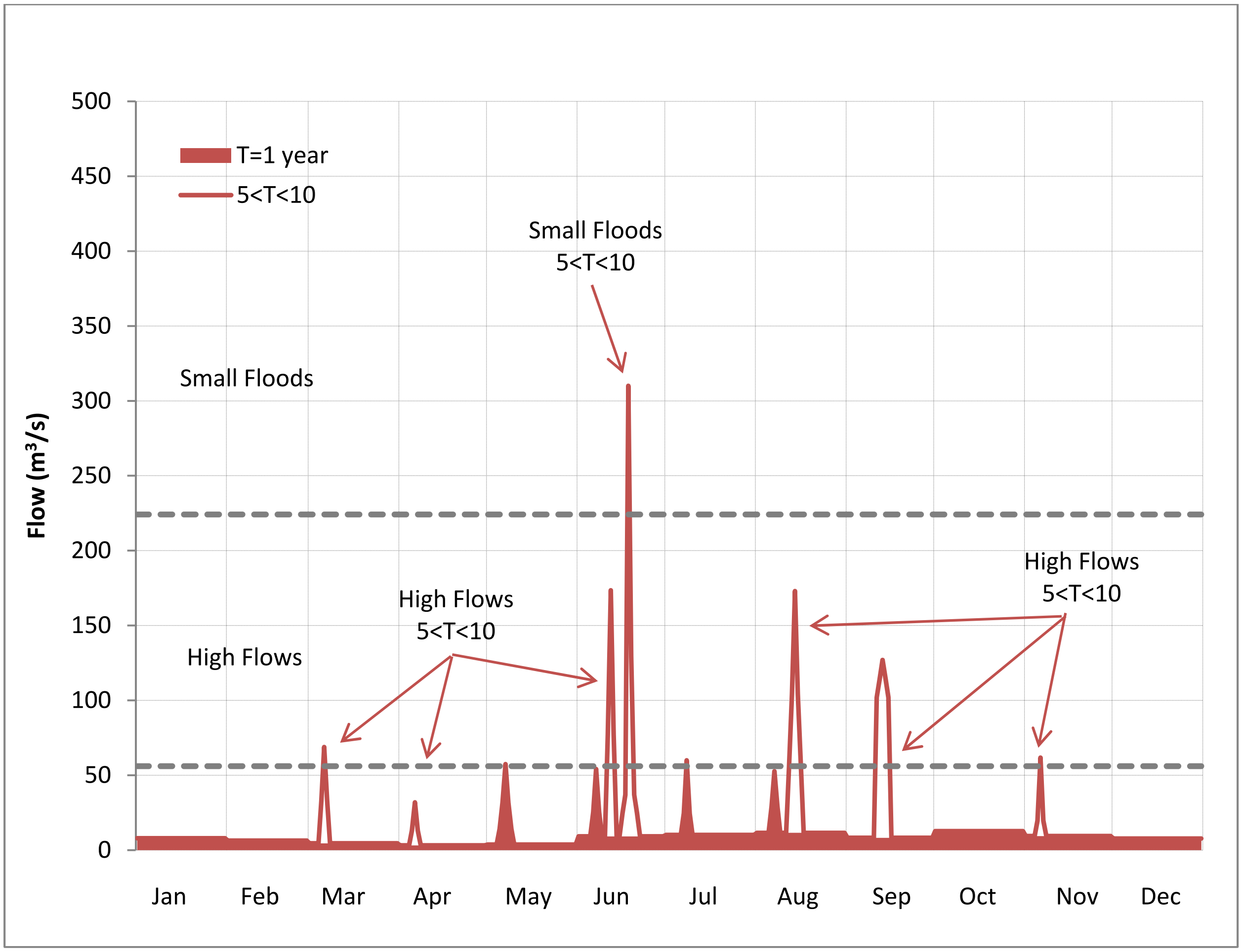

Figure 4-15: Annual hydrograph during drought years, Return Period = 5-10 years, pre-1946

Figure 4-16Figure 3-5 shows the annual hydrograph during drought years for flows with one and ten year return period in the post-1946 conditions. This Figure show that eventually, small floods will occur in their natural pattern, in August, September and October. Floods that used to happen every year (T=1 year) or once every 2-3 years in the pre-1946 conditions, now are happening every ten years or more, during drought years.

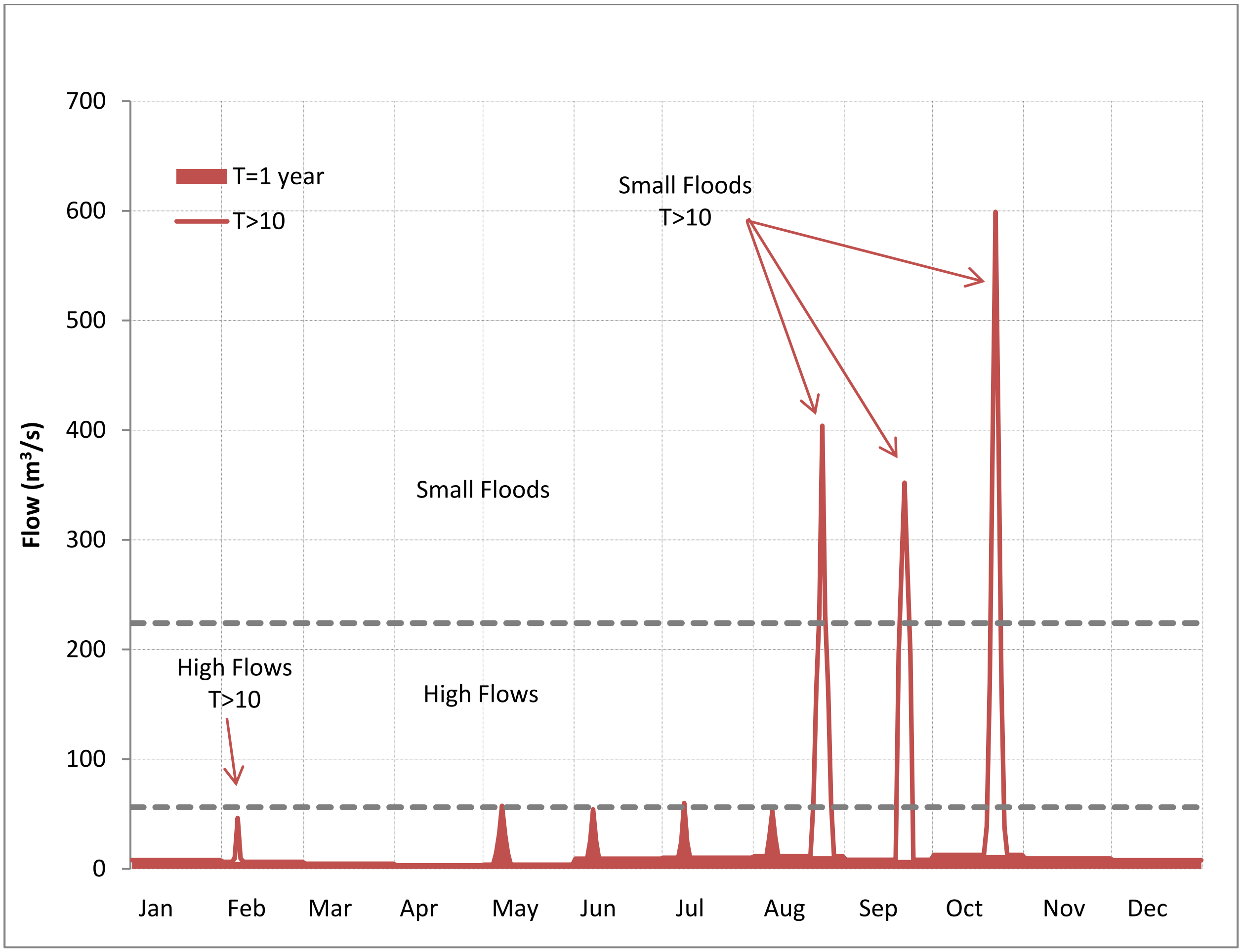

Figure 4-16: Annual hydrograph during drought years, Return Period >10 years, pre-1946

4.4.3. COMPARISON

Figure 4-17 shows the annual hydrograph during drought years for flows with one year return period for the pre-1946 and post-1946 conditions.

Even though the analysis is done during drought years, conclusions are the same as during normal conditions, there is the same number of high flows but smaller magnitude and different timing. Most importantly, one small flood with a median peak of 380 m^3/s occurred every year in the pre-1946 conditions while in the post 1946 condition it does not occur. Also, the distribution of the medians flows is altered; meanwhile in the pre-1946 September has the largest median flow (45 m^3/s), in the post-1946 October has the largest median flow (13 m^3/s).

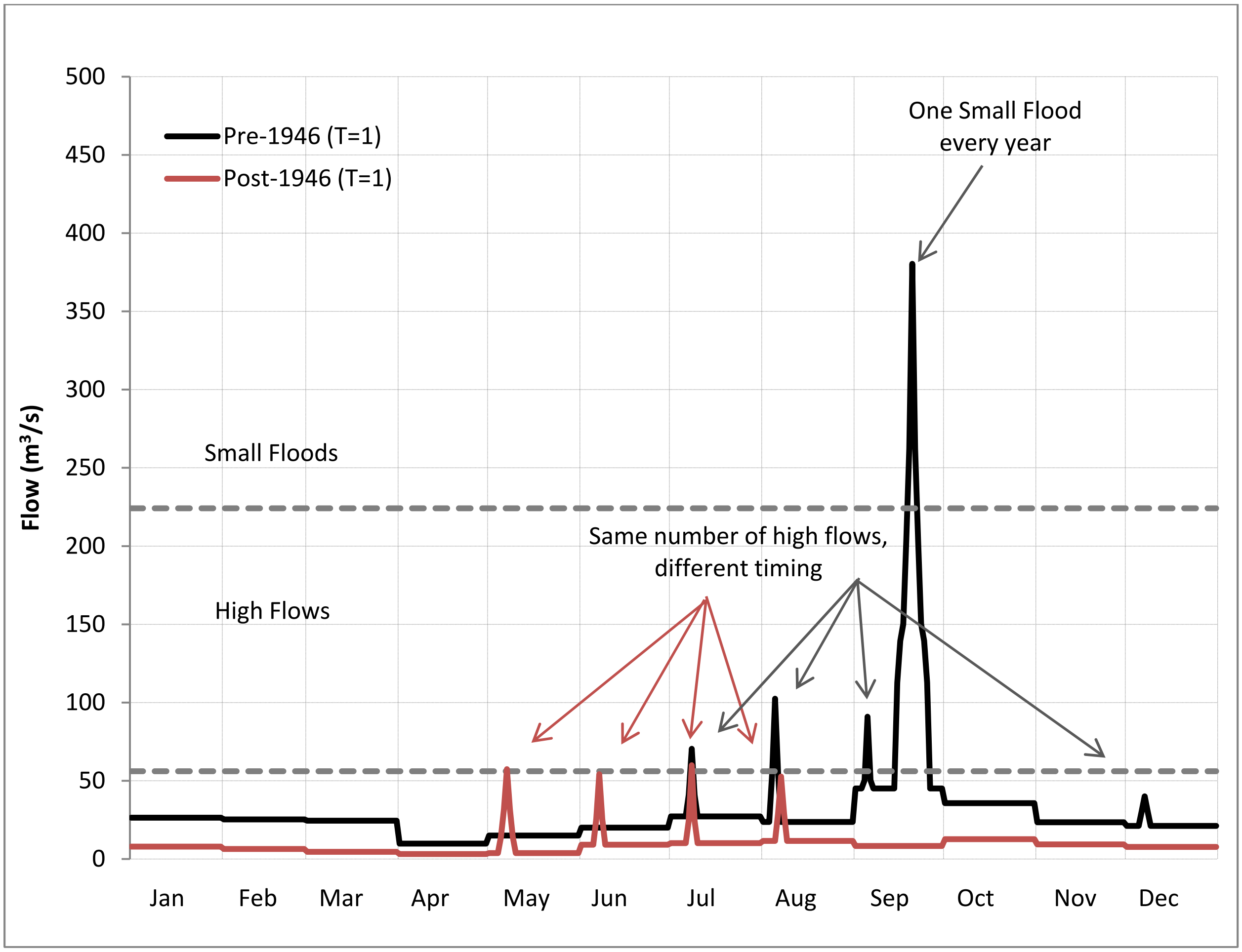

Figure 4-17: Annual hydrograph during drought years, T = 1 year, post and pre-1946

Figure 4-18 shows annual hydrograph during drought years for flows with one year return period for the pre-1946 and ten years or more return period for the post-1946 conditions. The hydrograph for the pre-1946 condition considers that two small floods happened every two-three years, the one fixed in September, and another occurred in October. For the post-1946 hydrograph, it is considered two small floods occurred that year, in September and October. High flows in February, May, June, July and August occur in both hydrographs. Figure 4-18 demonstrate how high flows and small floods that occurred during drought years every two-three years in the pre-1946 conditions, they are occurring every ten years or more in the post-1946 conditions; small floods barely occur in the post-1946 conditions during drought years.

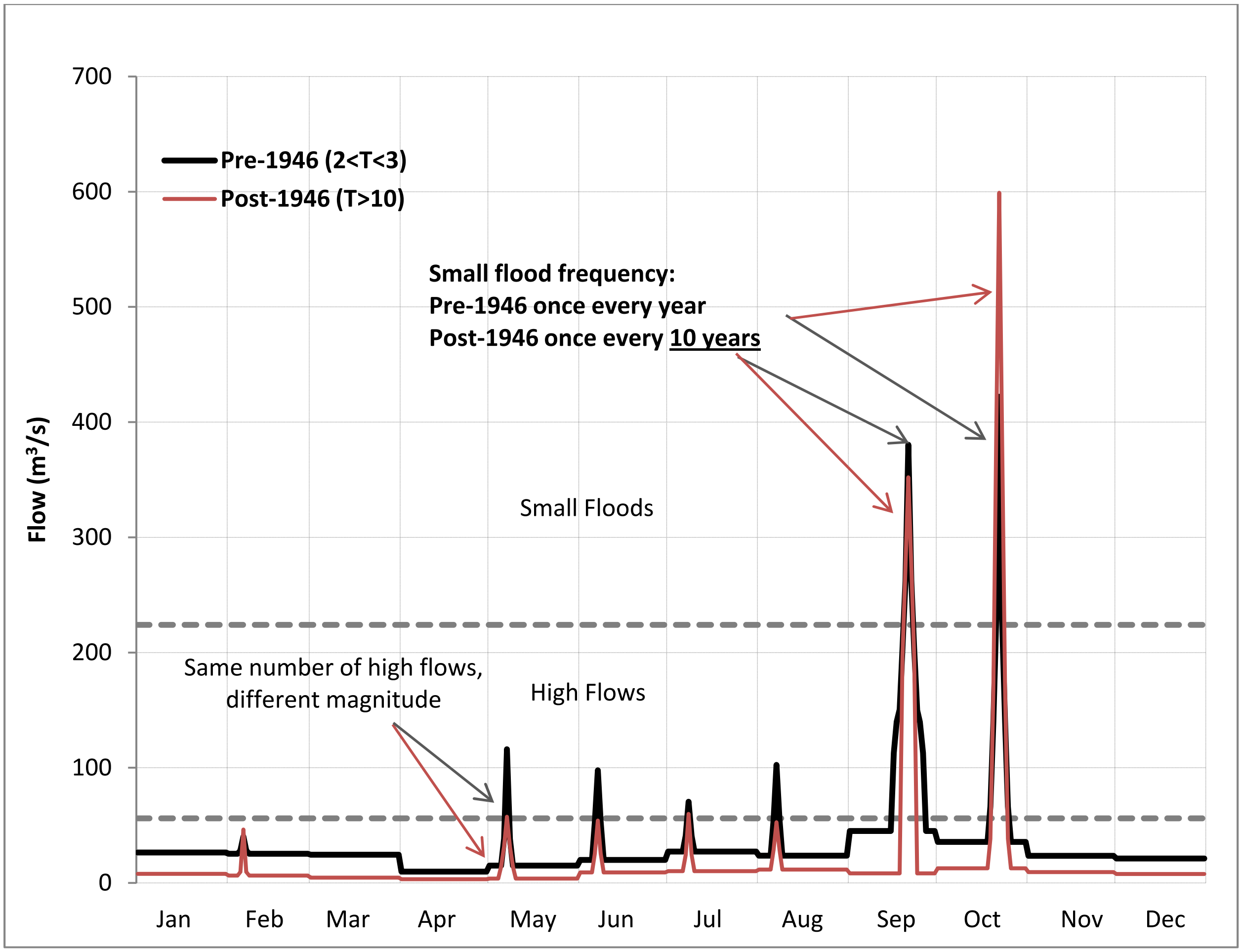

Figure 4-18: Comparison of annual hydrograph during drought years, Pre-1946 T=1 year Vs. Post - 1946 T>10 years

4.5. Conclusions

From the previous analysis of the drought years, it can be concluded that when comparing pre-1946 to post-1980:

- Small floods do occur during drought years in the pre-1946 conditions, they were a characteristic flow event during drought years. In the pre-1946 conditions, the fixed small flood of September (Flow peak = 380 m^3/s) still occurs during drought years preventing from agradation and channel reduction.
- Median monthly flows decreased significantly, by 531X10^6 m^3, or 68% of the pre-1946 annual volume. In addition, the shape of the median values is altered. During drought years the pre-1946 median values follow the normal condition pattern; in contrast. the post-1946 the highest median values has shifted from September to October.

- During drought years, small high flow pulse occurred more frequently in the pre-1946 conditions, a median of 8 small high flow pulse per year, compare to 6 events per year in the post-1946 conditions.
- During drought years, large high flow pulse were not common in the pre-1946 conditions, it only happened once in the pre-1946 period, meanwhile large flow pulses happened once every two years in the post-1946 conditions.
- During drought years, small floods occurred more frequently in the pre-1946 conditions, a median of 2 events per year, meanwhile in the post-1946 conditions the median dropped to 0 events per year.

5. CONCLUSIONS

5.1. EXTREME FLOOD EVENTS

From analysis of extreme flood events, it can be concluded that:

- The characteristics of extreme flood events that re-widen the channel are: a) a peak flow larger than 1,400 m^3/s and b) a total flow of 1,000X10^6 m^3 for the whole flooding event.
- For the same storm frequency (return period), the magnitude of the flow has decreased by 50%
- Return periods for extreme events have doubled

  Pre-1946 : one event every 7~8 years

  Post-1946: one event every 15~16 years
- Flooding events occur on average two to three weeks later in the post-1946 conditions, from October 1-7th in the pre-1946 to October 21-28th in the post-1946.
- Pre-1946 events have greater variation; durations range from 8 to 30 days and peak flows from 1560 to 3851 m^3/s
- Post-1946 events are more uniform; durations are typically 3 weeks and peak flows range from 1030 to 1850 m^3/s

5.2. NORMAL HYDROLOGIC CONDITIONS

From analysis of mean daily flow at Johnson Ranch gage station in both periods of analysis, it can be concluded that:

- The volume of the median monthly flow for the pre-1946 and post-1946 are 1130X10^6 m^3/year and 464X10^6 m^3/year, respectively
- The annual deficit is 666X10^6 m^3 of water, or 59% of the pre-1946 quantity. The majority of the deficit comes from the high flow months of August, September, and October
- Pre-1946 conditions have more frequent small floods (median peak flow = 400 m3/s), one fixed every year in September, and at least one small flood in one of the following months: July, August and October.

- High flows and small floods that occurred every year in the pre-1946 condition, they happened every 2-3 years in the post-1946 conditions.
- Similarly, high flows and small flows that occurred every 2-3 years in the pre-1946 condition, they happened every 5 years in the post-1946 conditions.

Pre 1946

- A small flood occurs every year (T<1.5) in September
- Every 2 to 3 years (1.5 years < T < 3.5 years) small floods occur in July, August, and October
- Every 5 to 10 years (3.5 years < T < 10) small floods occur in May, June, and November

Post 1980

- There are no expected annual (T<1.5 years) small floods
- Every 2 to 3 years (1.5 years < T < 3.5 years) a small flood occurs in September
- Every 5 to 10 years (3.5 years < T < 10) small floods occur in June, July, August, and October

5.3. DROUGHT PERIODS

From analysis of mean daily flow during drought years at Johnson Ranch gage station in both periods of analysis, it can be concluded that:

- The volume of the median monthly flow during drought years for the pre-1946 and post-1946 are $782X10^6$ m^3/year and $251X10^6$ m^3/year, respectively. The annual deficit is $531X10^6$ m^3 of water, or 68% of the pre-1946 quantity. In addition, the shape of the median values is altered; in the post-1946 the highest median value has shifted from September to October.
- Small floods do occur during drought years in the pre-1946 conditions, the fixed small flood of September (Flow peak = 380 m^3/s) still occurs during drought years. Small floods occurred more frequently in the pre-1946 conditions, a median of 2 events per year, meanwhile in the post-1946 conditions the median dropped to 0 events per year.

Pre 1946

- A small flood occurs every year (T<1.5) in September
- Every 2 to 3 years (1.5 years < T < 3.5 years) small floods occur in October
- Every 5 to 10 years (3.5 years < T < 10) small floods occur in June, July and August

Post 1980

- There are no expected annual (T<1.5 years) small floods
- Every 2 to 3 years (1.5 years < T < 3.5 years) a small flood occurs in June
- Every 10 years or more (T > 10 years) small floods occur in August, September and October

6. PRESCRIBED ANNUAL HYDROGRAPH

After the extensive analysis done at Johnson Ranch gage station, these are the essential characteristics for a prescribed hydrograph:

- Median monthly flows with a distribution similar to the pre-1946 period. These values might be scaled, as it happens during drought years; however, the distribution must be similar to the one found in the pre-1946.
- Two small floods. One small flood fixed in September and another small flood in July, August, or October. The peak flow of these floods must be of 400 m^3/s.
- Four high flow pulses; one in each of the following months: July, August, October and December.

In order to propose an annual volume for the proposed hydrograph, first, it is necessary to analyze the annual volumes in the Rio Grande/Bravo at Johnson Ranch and in the Rio Conchos at Ojinaga.

Figure 6-1 shows the annual flow volume at Johnson Ranch and Rio Conchos at Ojinaga. Values for the Rio Conchos start in 1955 because data is available since that year. Notice that the Rio Conchos contributes with a significant amount of water at Johnson Ranch. A median value 78% of the flow at Johnson Ranch comes from the Rio Conchos. Table 6-1 shows the annual statistics for both sites.

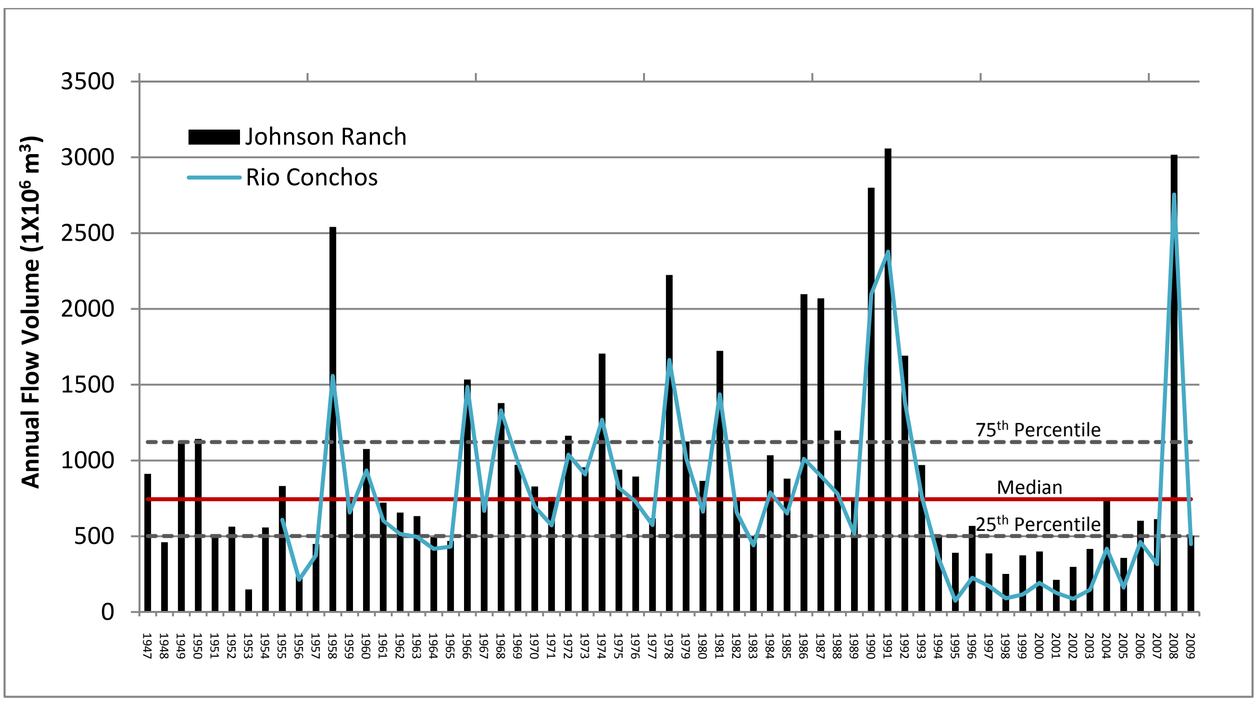

Figure 6-1: Annual flow of Rio Grande/Bravo at Johnson Ranch and Rio Conchos at Ojinaga

Table 6-1: Annual hydrograph volume during drought years for a 1 year return period, post-1946

	Period	Percentile ($1X10^6$ m^3/s) 0.75	0.5 (Median)	0.25	Average ($1X10^6$ m^3/s)	Std. Dev. ($1X10^6$ m^3/s)
Johnson Ranch	1947-2009	1121	**744**	501	954	682
Rio Conchos	1955-2009	962	**650**	396	749	574

Figure 6-1 shows several hydrologic periods, the extended drought of the 50's (1947 to 1957), the short drought of the 60's (1961 to 1965), the wet period of the 70's (1968 to 1981), 80's and early 90's (1984 to 1993), and the severe and extended drought of the 09's (1994 to 2007). The median annual flow at Johnson Ranch is $744X10^6$ m^3. Given that half of the years the annual volume is larger than the median, an annual volume of $1{,}000X10^6$ m^3 is proposed as an initial value.

For the pre-1946 hydrographs shown in the Executive Summary section (Figure ES-2 and Figure ES-4), approximately 75% of the annual volume is used to supply the median monthly flows, and 25% to supply high flows and small floods. Table 6-2 show the distribution median monthly flows of the pre-1946 period

Table 6-2: Median monthly flow distribution, prescribed hydrograph

	Median monthly flow distribution (%) Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Sum
Median	6	5	5	3	5	6	10	12	22	12	7	6	100

Table 6-3 show the daily flows for the small floods considered: a) one in September with duration of 11 days and a peak of 407 m^3/s; and b) another flood that varies in time, with duration of 9 days and a peak flow of 405 m^3/s. These small floods have been extracted from the pre-1946 period.

Table 6-3: Small floods, prescribed hydrograph

Day	September (m^3/s)	Variable (m^3/s)
1	154	190
2	189	223
3	203	273
4	255	320
5	322	405
6	407	320
7	322	273
8	255	223
9	203	190
10	189	---
11	154	---

Table 6-4 show the daily flows for the high flows considered in July, August, October and December. Only this 4 high flows will be considered initially, the rest of the high floods are expected to be meet by the system.

Table 6-4: Small floods, prescribed hydrograph

Day	July (m^3/s)	August (m^3/s)	October (m^3/s)	December (m^3/s)
1	75	57	58	36
2	---	102	97	45
3	---	57	73	36
4	---	---	58	---
5	---	---	---	---
6	---	---	---	---

Figure 6-2 show the proposed hydrograph for the Rio Grande/Bravo at Johnson Ranch. Table 6-5 shows the volume of water to supply the median monthly flow, high flows and small floods. Table 6-6 shows the median monthly flows of the hydrograph proposed.

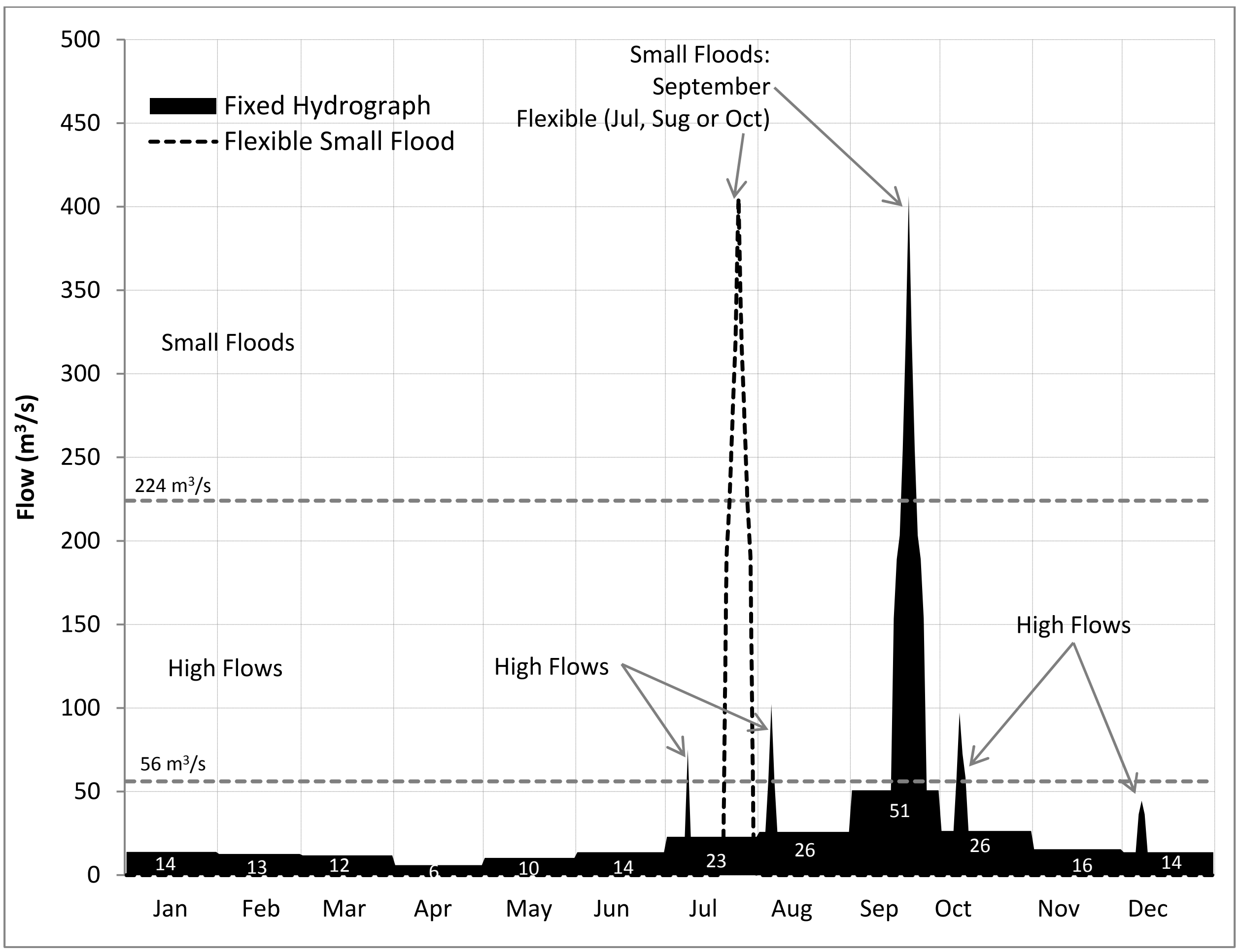

Figure 6-2: Annual hydrograph proposed in the Rio Grande/Bravo at Johnson Ranch

Table 6-5: Monthly volume, prescribed hydrograph

	Volume (1X106 m3)												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Sum
Median	37	31	32	15	28	36	62	69	132	71	40	37	589
High Flows	---	---	---	---	---	---	5	12	---	16	---	7	39
Small Floods	---	---	---	---	---	---	191	---	181	---	---	---	372
Total	37	31	32	15	28	36	257	81	313	86	40	43	**1000**

Table 6-6: Median monthly flows, prescribed hydrograph

	Median Monthly Flows (m^3/s)
Jan	14
Feb	13
Mar	12
Apr	6
May	10
Jun	14
Jul	23
Aug	26
Sep	51
Oct	26
Nov	15
Dec	14

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Appendix A. RIO GRANDE/BRAVO AT JOHNSON RANCH STREAMFLOW

A simple linear regression has been used to estimate the mean daily flow at Johnson Ranch from May 1st 1900 to March 31st 1913 and from January 1st 1931 to December 31st 1935. The software HEC-DSSVue was used to calculate the intercept B_0 and the slope B_1 used in the linear regression equation. Records from the gage station Rio Grande Below Ojinaga are used to estimate the flow at Johnson Ranch for every day *t*.

$$Johnson_t = B_0 + B_1 * Grande\ Below\ Ojinaga_t$$

Where:

B_0 = 0.57597

B_1 = 0.91238

Due to space limitations, raw data is excluded from the report. Data for Rio Grande/Bravo at Johnson Ranch can be found on the IBWC website at http://www.ibwc.gov/wad/DDQJOHNS.htm.