Research Report:

Effect of Extreme Storms on Treaty Obligations In the Rio Conchos

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Introduction

The Rio Conchos River, is the main tributary for the Rio Grande/Bravo. Its water revitalizes the Rio Grande/Bravo stream at his confluence, in the Ojinaga-Presidio area. The Rio Conchos, as well other 5 tributaries of the Rio Grande/Bravo (Figure 1), is listed in the treaty of 1944 between Mexico and the United States. The treaty of 1944 specifies that Mexico has the obligation to deliver to the U.S. one third of the waters coming from these 6 tributaries, providing that this one third shall not be less than 431.721 Million m^3/year in cycles of 5 consecutive years. Deficits in the treaty deliveries must be paid in the following treaty cycles. The treaty cycles may expire earlier than 5 years if the U.S. active storage in both international dams (Amistad and Falcon) is filled with US waters. In addition, all deficits are considered paid if the cycle expired earlier than 5 years. On average, the Rio Conchos delivers 740 Million m^3/year of water to the Rio Grande/Bravo. However, under wet periods, this river has delivered 2,661 Million m^3/year, contributing significantly to the earlier expiration of treaty cycles. Historically, under wet periods, water from the Conchos fills Amistad and Falcon dams; thus, delivery of treaty obligations from Mexico to the U.S. was set considering the frequent reset of treaty cycles due to wet conditions. Even though these wet conditions were considered for the management of treaty deliveries, nowadays there is no statistical description of the outflows from the Rio Conchos River, leaving the treaty deliveries very uncertain.

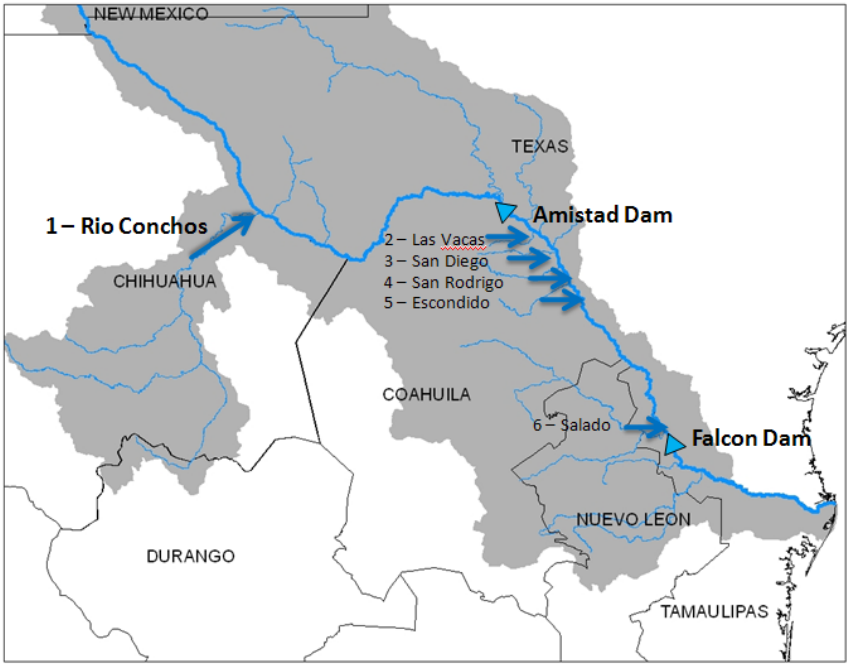


Figure 1 – Rio Grande/Bravo Basin.

Objective

The objectives of the term project are:

- Obtain a probability distribution function that properly describes the outflows from the Rio Conchos to the Rio Grande/Bravo.
- Evaluate how wet conditions in the Rio Conchos Basin are related with the occurrence of tropical storms, hurricanes, in the area.
- Besides, how the tropical storms have influenced the reset of treaty cycles
- Finally, evaluate how a change in the occurrence frequency of wet conditions will impact the reset of treaty cycles?

Rio Conchos Basin

The headwaters of the Conchos river are located in the Sierra Madre Oriental, at an altitude of 7,200 feet above sea level (2,200 meters above sea level), when it start its journey on the central plains of Chihuahua, flowing through the Chihuahuan Desert, where this river is a ribbon of life, until it reaches the Rio Grande/Bravo, when it revitalize the water of this stream (Figure 2).

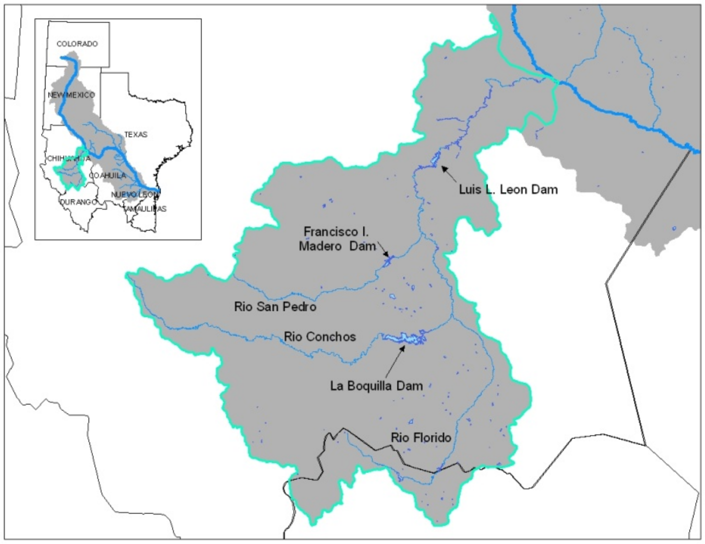


Figure 2 – Location of the Rio Conchos Sub-basin

The Rio Conchos is an important piece of the basin because it supplies the water for the agriculture requirements in Chihuahua and along the Rio Grande/Bravo from Presidio-Ojinaga to Laredo-Nuevo Laredo. Besides, its waters supply the environmental flows for the Big Bend area. Literally, the Rio Grande/Bravo comes back to life again because of the waters from the Rio Conchos.

Information Sources:

Streamflow data for the Rio Conchos was obtained from the International Boundary and Water Commission (IBWC 2008). Data related to the treaty cycles was obtained from the National Water Commission of Mexico (Comisión Nacional del Agua - CONAGUA 2004). Information related to hurricanes was obtained from the National Hurricane Center (NHC 2009a).

Geographic Information was obtained from the Geodatabase of the Rio Grande/Bravo (Patino 2004) and from the National Hurricane Center (NHC 2009b)

Outflow from the Rio Conchos

Because of the regional climate, its geographic position and the water management in the basin, the outflow from the Rio Conchos varies significantly from year to year. One of the objectives in this project is to obtain a probability distribution function that properly represents the Rio Conchos. Let's start our journey by taking a look to the descriptive statistics of the Rio Conchos. Table 1 shows the descriptive statistics of parametric and non-parametric measures of location, spread and symmetry for the annual outflow of the Rio Conchos.

Table 1. Parametric and Non-parametric measures of location, spread and symmetry for the Rio Conchos

Parametric		
Location		
Mean:	740	million m^3/year
Spread		
Std. Dev.:	536	million m^3/year
Symmetry		
Coef. Of Skewness:	1.260	

Non-Parametric		
Location		
Median	623	million m^3/year
Spread		
IQR =	624	million m^3/year
Symmetry		
Quartile Skew Coef.:	0.209	

In order to obtain the probability density function, the following steps were done: 1) the data was transformed using the cube root of the original data. This transformation was selected because it gives the skewness coefficient closest to zero. 2) As a first approach, the normal distribution function was selected to represent the distribution of the cube root data. 3) The normal distribution was tested through the goodness of fit procedure, where the calculated chi-square value of 14.4 is less than the theoretical value 15.5. Because of this, the function provided by the normal distribution function was selected to represent the probability and cumulative density function of the Rio Conchos. The probability and cumulative distribution function are the followings:

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{\left(-\frac{1}{2}\left(\frac{Q^{1/3}-\mu}{\sigma}\right)^2\right)} \qquad [1]$$

$$F(X) = \Phi\left(\frac{Q^{1/3}-\mu}{\sigma}\right) \qquad [2]$$

Where the mean μ=8.5, the standard deviation σ=2.2482 and Φ is the standard normal cumulative distribution function. Figure 3 is the comparison of the flow duration curve and the cumulative distribution function for the Rio Conchos outflow.

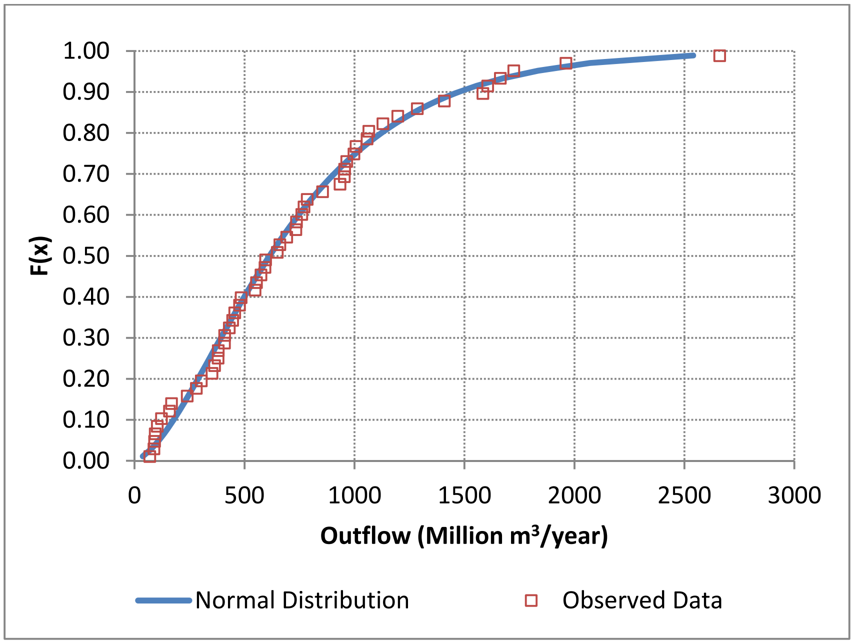
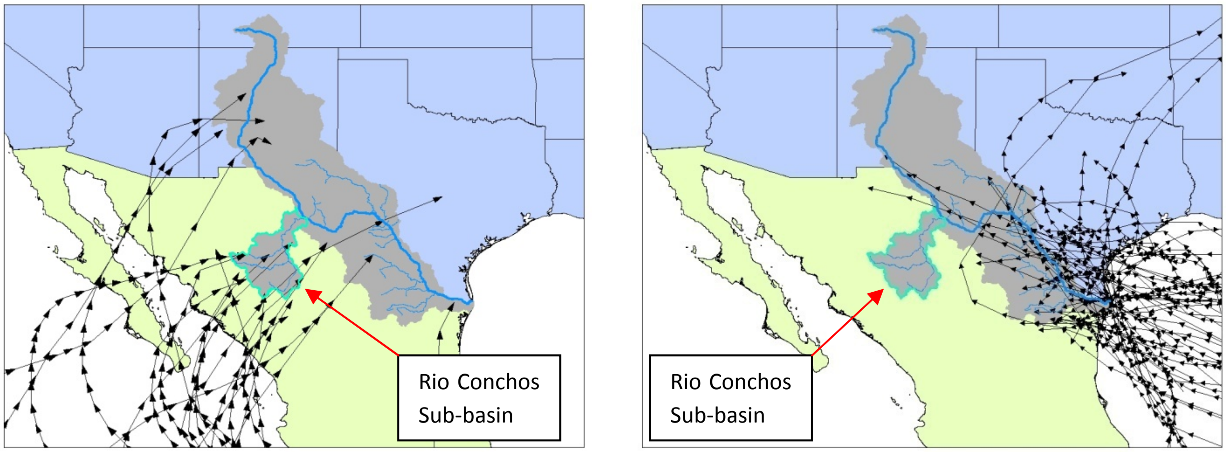


Figure 3 – Cumulative distribution function for the Rio Conchos Outflow.

Extreme Storms and Wet Conditions in the Conchos

Now, let's find out if the wet conditions that happen in the Rio Conchos are related with the occurrence of tropical storms in the area. Figure 4 shows the tracks of the Hurricanes/Tropical Storms/Tropical depression that have hit the Rio Grande/Bravo from the Pacific Ocean and the Gulf of Mexico. The correlation between the Pacific and the Gulf hurricanes with the outflow from the Rio Conchos is 0.058 and 0.0006. Even though this is not a strong correlation between the variables involved, these coefficients highlight that storms from the Pacific Ocean have more influence in the outflow from the Rio Conchos basin than the storms from the Gulf of Mexico.



a. Track of Hurricanes from the Pacific b. Track of Hurricanes from the Atlantic

Figure 4 – Track of Hurricanes that have hit the Rio Grande/Bravo Basin

Table 2 shows a list of sixteen hurricanes from the Pacific Ocean that have hit the Rio Grande/Bravo or their trajectory were at least 100 kilometers close to the basin. In Appendix A is shown the trajectory for each hurricane and the hydrograph for the outflow of the Rio Conchos basin.

Table 2. Hurricanes from the Pacific Ocean that have hit the Rio Conchos basin

Year	Date	Name	Category
1957	6-Oct	Notname	TD
1957	22-Oct	Notname	L
1962	4-Oct	Doreen	TS
1966	17-Sep	Helga	TD
1968	13-Sep	Naomi	TS
1969	12-Oct	Jennifer	TD
1973	26-Sep	Irah	TD
1973	27-Sep	Jennifer	TD
1974	24-Sep	Orlene	TD
1978	26-Sep	Paul	TD
1986	2-Oct	Paine	H
1990	2-Oct	Rachel	TS
1993	13-Sep	Lidia	TS
1994	14-Oct	Rosa	TS
1996	14-Sep	Fausto	TS
2008	12-Oct	Norbert	TS

* TD – Tropical Depression; TS – Tropical Storm; L – Low Pressure

Now, let's define the hydrologic conditions for the outflow. Normal conditions are considered those inside the Inter Quantile Range, this means the percentiles are higher than 0.25 but lower than 0.75 ($0.25<p<0.75$). Thus, Dry conditions are considered when the percentile is lower than 0.25 ($p<0.25$) and

Wet conditions are considered when the percentile is higher than 0.75 ($p>0.75$). Using the cumulative distribution function obtained in the previous section (Equation 2), $Q_{0.25}=340$ million m^3/year and $Q_{0.75}=1005$ million m^3/year. Figure 5 show the hydrologic conditions for the Rio Conchos. Table 3 shows the number of years, storms and the rate of extreme storm occurrence associated to each hydrologic condition.

Table 3. Number of storms associated to each hydrologic condition

Condition	Percentile	Annual Flow (million m^3/year)	# of Storms	# of years	Rate of Occurrence (Storms/year)
Dry	$p<0.25$	$Q_{annual}<340$	3	11	0.27
Normal	$0.25<p<0.75$	$340<Q_{annual}<1005$	7	30	0.23
Wet	$p>0.77$	$1005<Q_{annual}$	6	13	0.46
		Σ=	16	54	

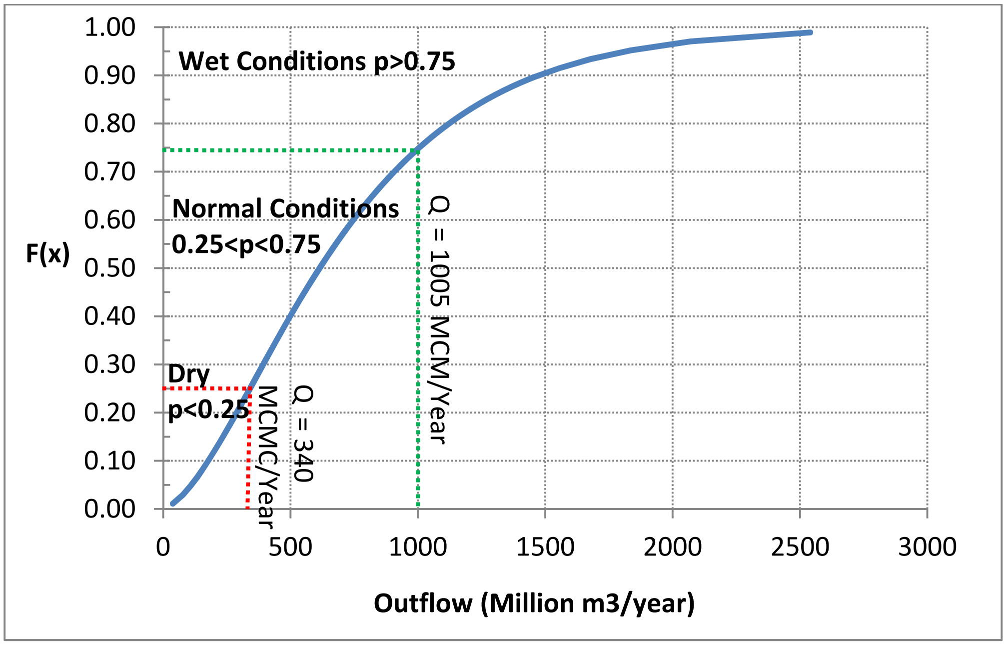


Figure 5 – Hydrologic Conditions for the Rio Conchos Basin

Two important conclusions can be derived from the previous results. First, extreme storms happened in dry years; which means that the occurrence of an extreme storm is not a liability of wet conditions. Second, even though it is more likely that extreme storms occur in wet periods, they are not the only cause of big outflows from the basin. Wet periods happened with and without the occurrence of extreme storms, meaning that extreme storms may increase the annual outflow from the basin, but they are not the only cause for big annual outflows coming from the Conchos basin.

Extreme Storms and Reset of Treaty Cycles

In order to evaluate the influence of extreme storms in the reset of treaty cycles, the following considerations were assumed:

- The period of time considered for this analysis is 40 years, from 01/Oct/1968 to 08/Oct/2008. This period is selected because since 1968 both international dams were operating and thus, the reset of treaty cycles is possible.
- Eleven extreme storms are considered, since these storms happened in the period of time defined.

A Poisson distribution was used to determine the probability mass function and probability density function for the occurrence of extreme storms (Eq. 3).

$$f(x,\lambda) = \frac{\lambda^{x}}{e^{\ln(\Gamma(x+1))}} e^{-\lambda} \qquad [3]$$

Appendix B shows the extreme storms associated to each treaty cycle. In summary, 3 out of 11 extreme storms provoked the reset of treaty cycles, so, the probability that a extreme storms provokes the .reset of a treaty cycle is P(Reset|Storm)= 0.2727. This probability was combined with the Poisson distribution to obtain the probability of Reset - No Reset given the occurrence of at least 1 storm. Appendix C shows the calculation of these probabilities. Table 4 shows the summary of probabilities for the combined analysis of the Poisson distribution and the Reset of treaty cycles due to extreme storms.

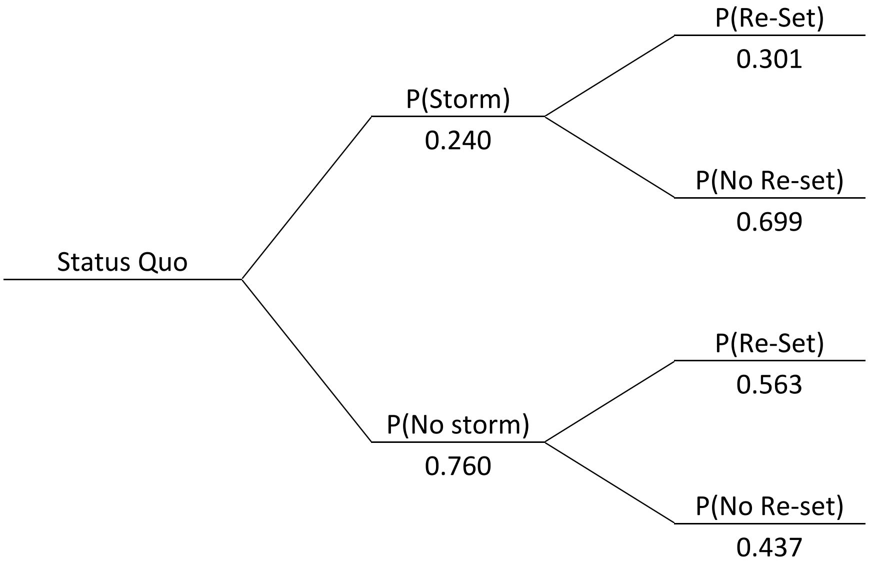


Figure 6 – Decision Tree for the Status Quo

Figure 6 shows the decision tree for the occurrence of extreme storms in the Rio Conchos basin. First, notice there is a 0.240 probability an extreme storm hit the Rio Grande/Bravo from the Pacific Ocean each year. Second, given that an extreme storm occurs, there is only a 0.301 probability the treaty cycle is reset due to the extreme storm. This means the occurrence of extreme storm is not the driving factor for the reset of treaty cycles. Historically, only 3 out of 11 extreme storms have re-set the treaty cycles, or comparing this value with the total number of short treaty cycles, 3 out of 21 short treaty cycles has been reset due to the occurrence of an extreme storm. Third, given that there is no extreme storm, there is a 0.563 probability the treaty is reset. This probability is higher than when extreme storms occur because several treaty cycles have been reset without the occurrence of any extreme storm (18 out of 21 short treaty cycles).

Table 4. Probability of Reset – No Reset due to the occurrence of Extreme Storms

P(Reset|No Storm)=	0.5631	P(Reset|Storm>=1)=	0.3005
P(No Reset|No Storm)=	0.4369	P(No Reset|Storm>=1)=	0.6995
	1.0000		1.0000
P(# of Stroms>=1)=	0.2404	P(Reset)=	0.49996
P(No Storms)=	0.7596	P(No Reset)=	0.50004
	1.0000		1.0000

The probability of Reset is obtained through the total probability theorem (Eq. 4).

$$P(Reset) = P(Reset|Storm) * P(Storm) + P(Reset|No\ Storm) * P(No\ Storm) \qquad [4]$$

$$P(Reset) = 0.0723 + 0.4277 = 0.49996$$

The term “$P(Reset|Storm) * P(Storm)$”, in the first equation shows that at the beginning of each year, **<u>there is a 7.23% chance the treaty cycle is reset due to an extreme storms</u>**. The second term in the Eq. 4 shows that at the beginning of the year, there is a 42.77% chance the treaty cycle is reset because wet conditions in the basin not directly associated with extreme storms.

The probability of No-Reset is obtained through the total probability theorem (Eq. 5). The first term in Eq. 5 expresses the probability the treaty cycles are not reset even though an extreme storm occurs. The second term of Eq. 5 accounts for the part of No-Reset probability when extreme storms do not happen.

$$P(No - Reset) = P(No - Reset|Storm) * P(Storm) + P(No - Reset|No\ Storm) * P(No\ Storm) \qquad [5]$$
$$P(No - Reset) = 0.1682 + 0.3319 = 0.50004$$

Notice the probability of Reset and No-Reset are about the same, P(Reset)=0.49996 and P(No-Reset)=0.50004. These results matches with the period of time since 1968 the basin has been in 5 year cycles (20 years) compared with the period time the basin has been reset in short treaty cycles (19.997 years). The previous results shows how uncertain is the delivery of treaty obligation from Mexico to the U.S; half of the time is expected to have plenty of water meanwhile the other half of the time is expected to deliver the water along a five year cycle.

How a change in the extreme storm occurrence may affect the reset of treaty cycle

Now let's suppose there is an increase in the occurrence of extremes storms in 20%. This value was selected arbitrary, just to evaluate the impact of an increase in the occurrence of extreme storms in the reset of treaty cycles. Besides, a 0.5 probability was proposed for the alternative climate condition. Figure 7 shows the decision tree for the alternative climate conditions.

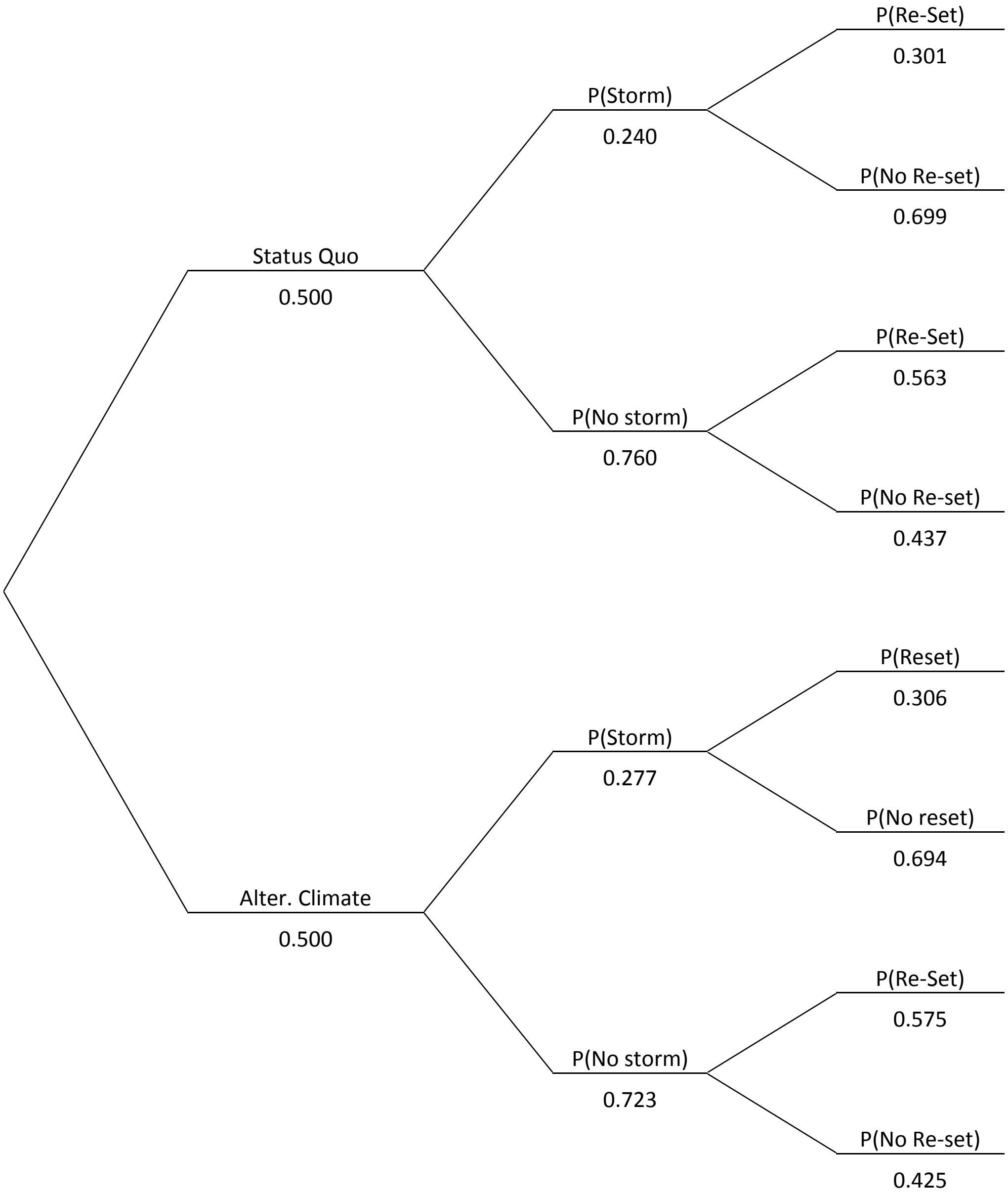


Figure 7 – Decision Tree for the Alternative Climate conditions.

Considering both, the Status Quo and the Alternative Climate condition, there is a 7.85% chance the treaty cycle is reset due to an extreme storm. This chance almost do not increase compared with the same probability calculated considering only the Status Quo conditions (7.23%).

Conclusions

An analysis of the annual outflow from the Rio Conchos to the Rio Grande/Bravo was done in this project to obtain the probability (PDF) and cumulative (CDF) distribution function for the outflow of the basin. Fifty three years of historical data was used for this purpose (from 1955 to 2008). In order to use the normal distribution function, the original data was transformed using the cube root of the original data. The Chi-Square test proved that the function proposed properly represents the PDF and CDF of the basin outflow.

Also, an analysis for the occurrence of extreme storms and their relationship with wet periods was overtaken in this project. First, the analysis of extreme storms showed that storms coming from the Pacific have more influence in the outflow of the Conchos basin than storms coming from the Gulf of Mexico. Historically, 16 storms have hit the Rio Grande/Bravo from the Pacific Ocean. Hydrologic conditions were defined using the CDF obtained in the first part of this project as follows: Normal conditions those were the outflow is between the Inter Quantile Range (IQR) ($0.25<p<0.75$), Wet conditions for outflows above the IQR ($p>0.75$) and Dry conditions for outflows below the IQR ($p<0.25$). Results showed that the occurrence of extreme storms is not exclusive of wet years; in fact, extreme storms occurred also during dry years; so the occurrence of an extreme storm is not a liability of wet conditions. Besides, even though it is more likely that extreme storms occur in wet periods, they are not the only cause of big outflows from the basin. Wet periods happened with and without the occurrence of extreme storms.

In addition the influence of extreme storms and the reset of treaty cycles were evaluated in this research. For this purpose the period of analysis was reduced to 40 years (from 01/Oct/1968 to 08/Oct/2008). A Poisson distribution was used to simulate the PDF and CDF of extreme storms in the basin. For the reset of treaty cycles, historical data was used to identify which treaty cycles were reset due to the occurrence of extreme storms. Historical data showed only three extreme storms, out of eleven, were able to reset the treaty cycles. Considering the historical data of the treaty cycles and the Poisson distribution of the extreme storms, at the begging of each year there is a 7.2% chance that the treaty cycles might be reset due to the occurrence of an extreme storm. Results showed that the occurrence of extreme storms is not a definitive factor for the reset of treaty cycles. In fact, more cycles has been reset without the occurrence of any extreme storm (18 out of 21 treaty cycles). If the frequency of occurrence of extreme storms is increased by 20%, the chance that the treaty cycles are reset due to extreme storm increases from 7.2% to 7.8%. In conclusion, extreme storms are not the main factor driving the reset of treaty cycles; eventually they will help, but they are not the main cause for the reset of treaty cycles.

References

IBWC - International Boundary and Water Commission (2008). Rio Grande historical Mean Daily Discharge Data. December 31st, 2008. <http://www.ibwc.state.gov/Water_Data/histflo1.htm>.

NHC – National Hurricane Center (2009a) – “Archive of Hurricane Seasons: Atlantic, Caribbean and the Golf and Eastern Pacific”. <http://www.nhc.noaa.gov/pastall.shtml>

NHC – National Hurricane Center (2009b) – “Historical Hurricane Tracks”. <http://maps.csc.noaa.gov/hurricanes/download.jsp>.

SEMARNAT - Secretaria de Medio Ambiente y Recursos Naturales (2004). “Estadísticas del Agua en México” Comisión Nacional del Agua. Sistema Unificado de Información Básica del Agua.

Appendix A

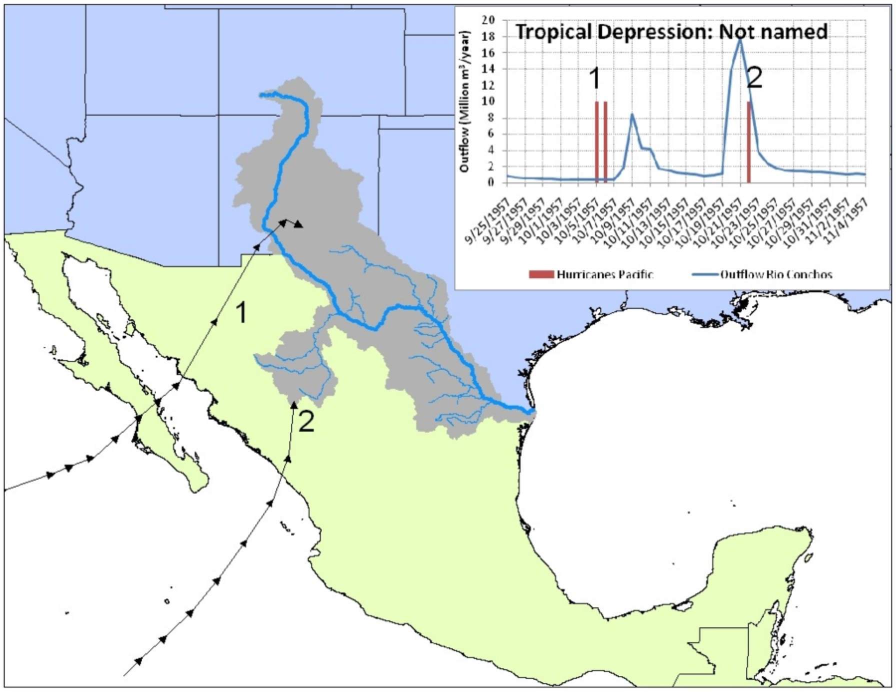


Figure A.1 – Hurricanes of 1957, Oct 1 – 6 and Oct 20-22.

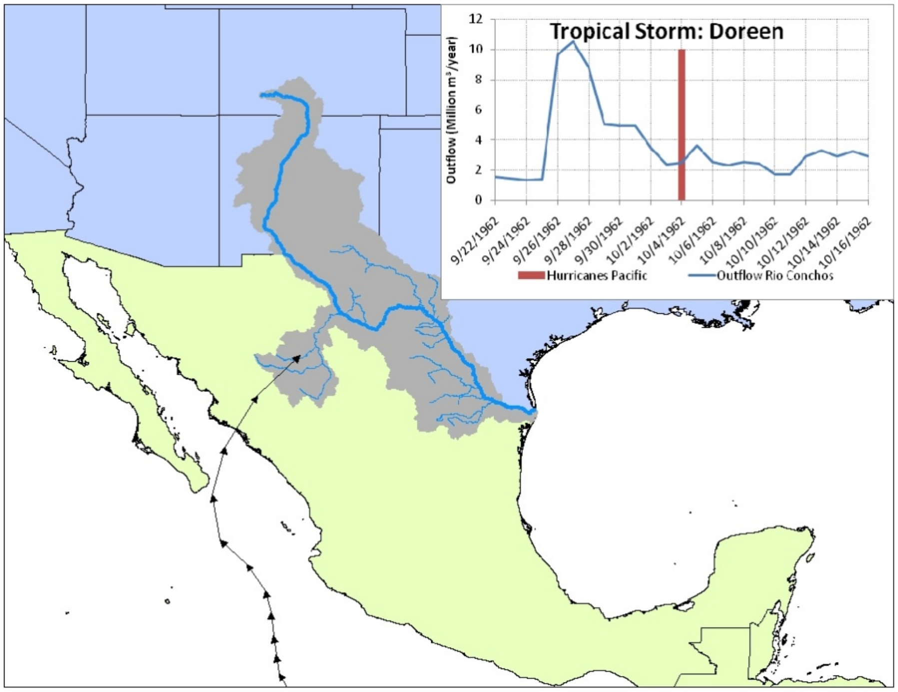


Figure A.2 – Hurricane Doreen, 1-4 Oct, 1962

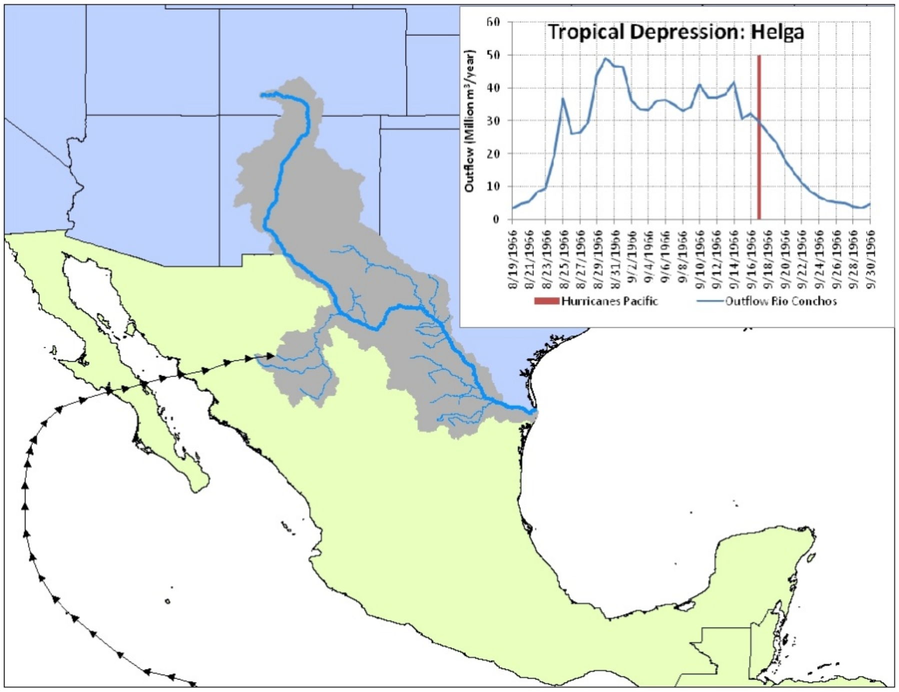


Figure A.3 – Tropical depression Helga, 9-17 Sep, 1966

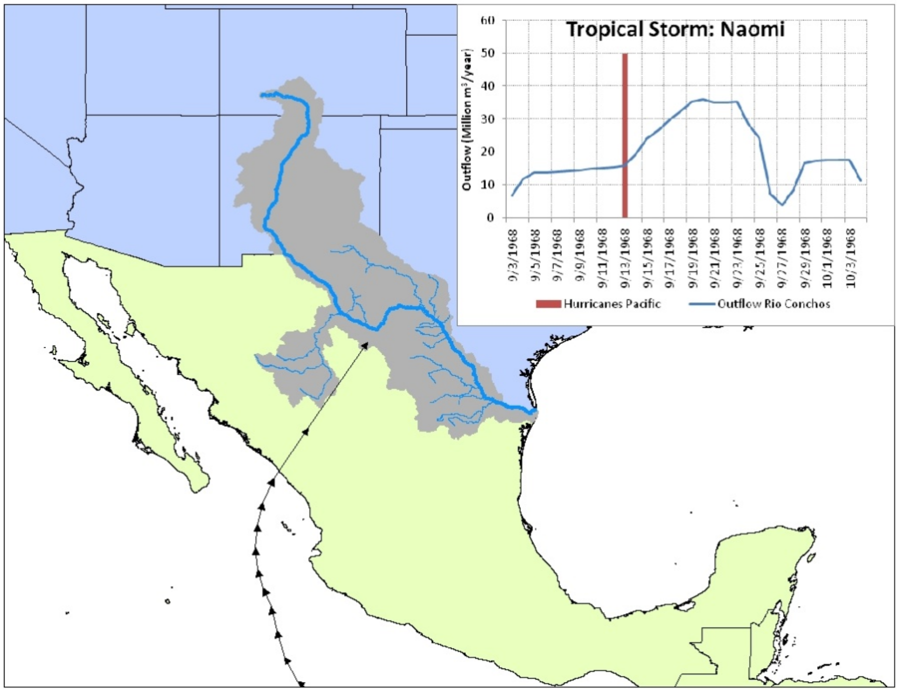


Figure A.4 – Hurricane Naomi, 9-13 Sep, 1968

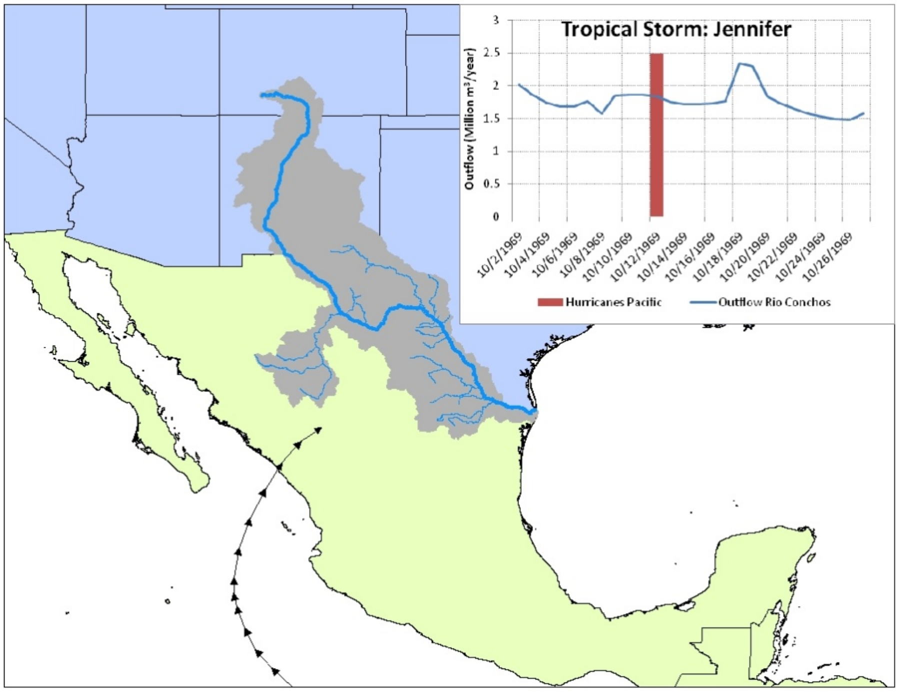


Figure A.5 – Hurricane Jennifer, 9-12 Oct, 1969

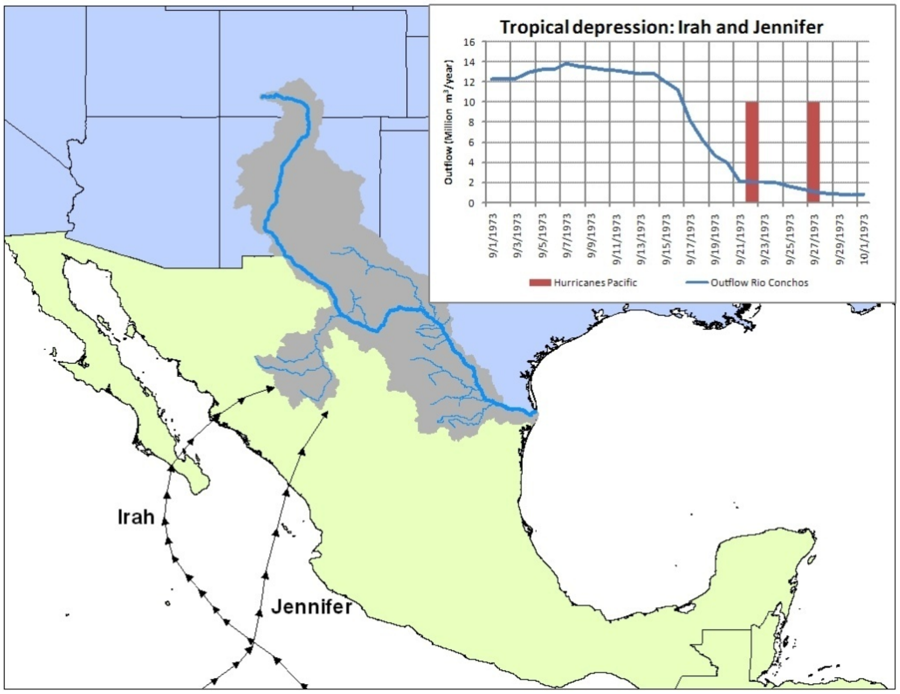


Figure A.6 – Hurricane Irah, 22-26 Sep; and Jennifer 23-27 Sep, 1973

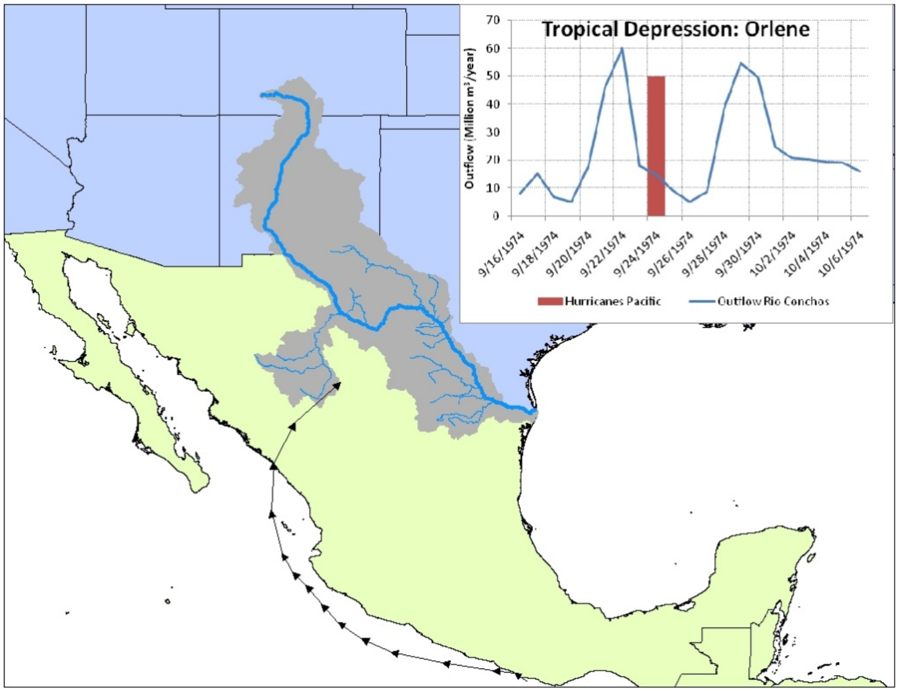


Figure A.7 – Hurricane Orlene, 21-24 Sep, 1974

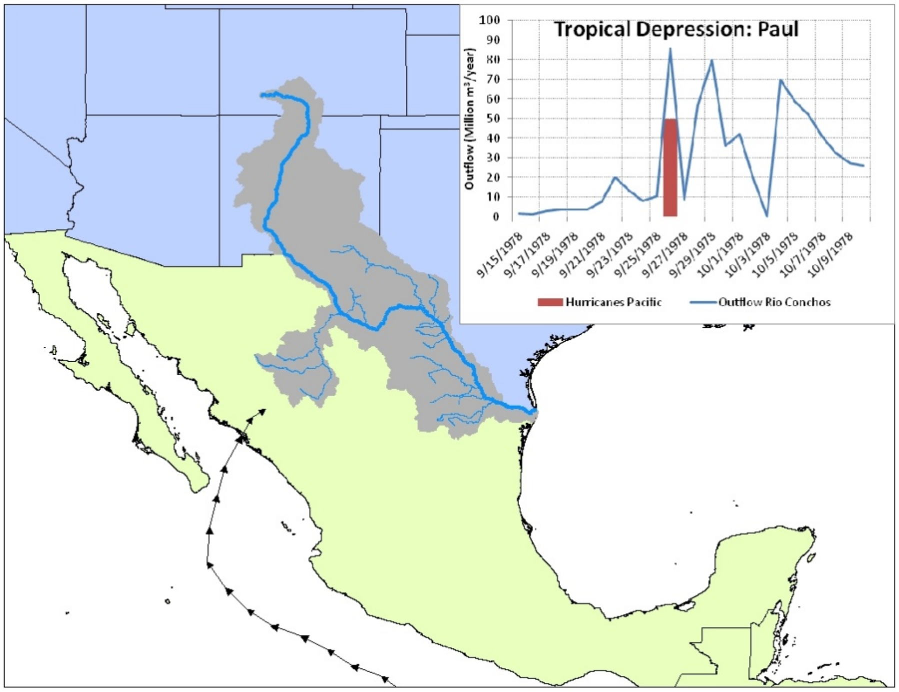


Figure A.8 – Hurricane Paul, 23-26 Sep, 1978

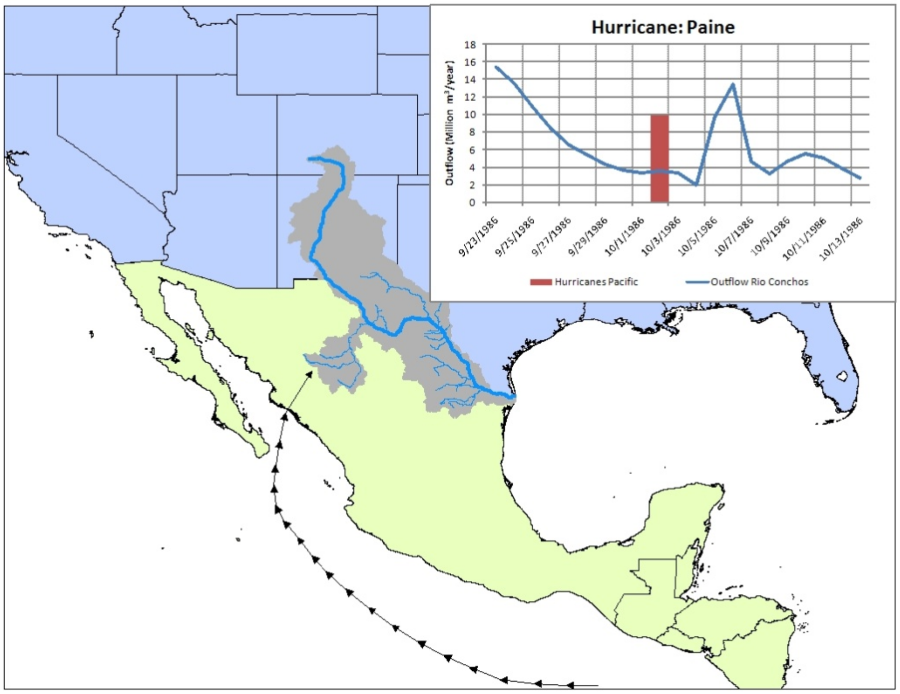


Figure A.9 – Hurricane Paine, 28 Sep - 2 Oct, 1986

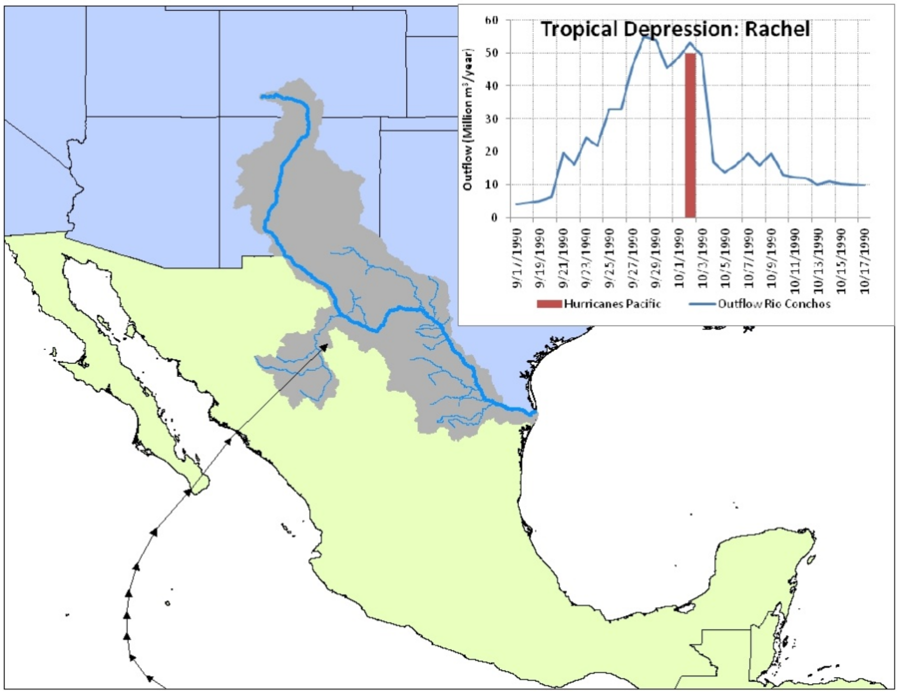


Figure A.10 – Hurricane Rachel, 27 Sep - 2 Oct, 1990

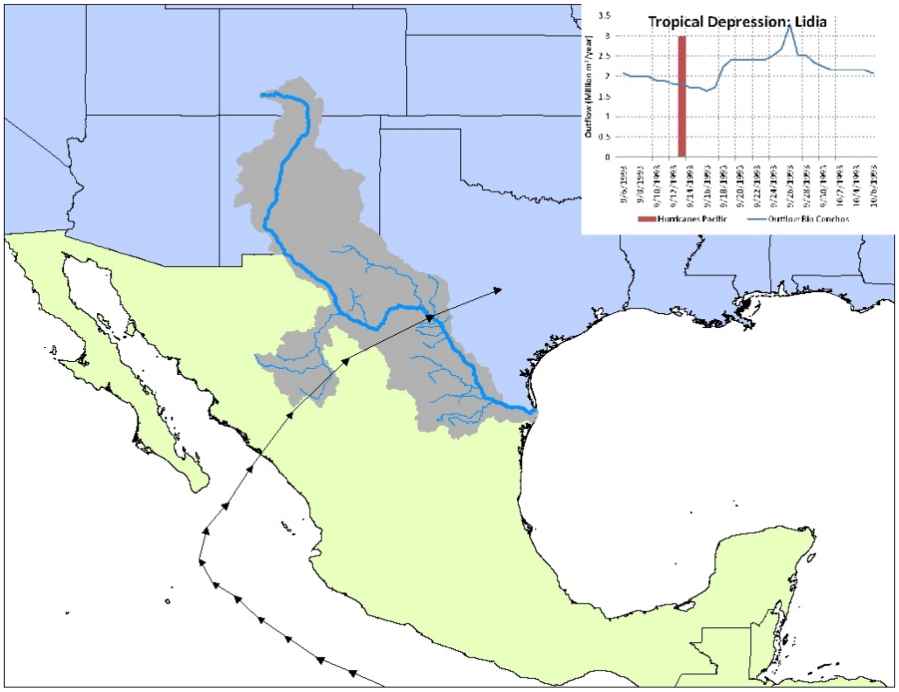


Figure A.11 – Hurricane Lidia, 8-14 Sep, 1993

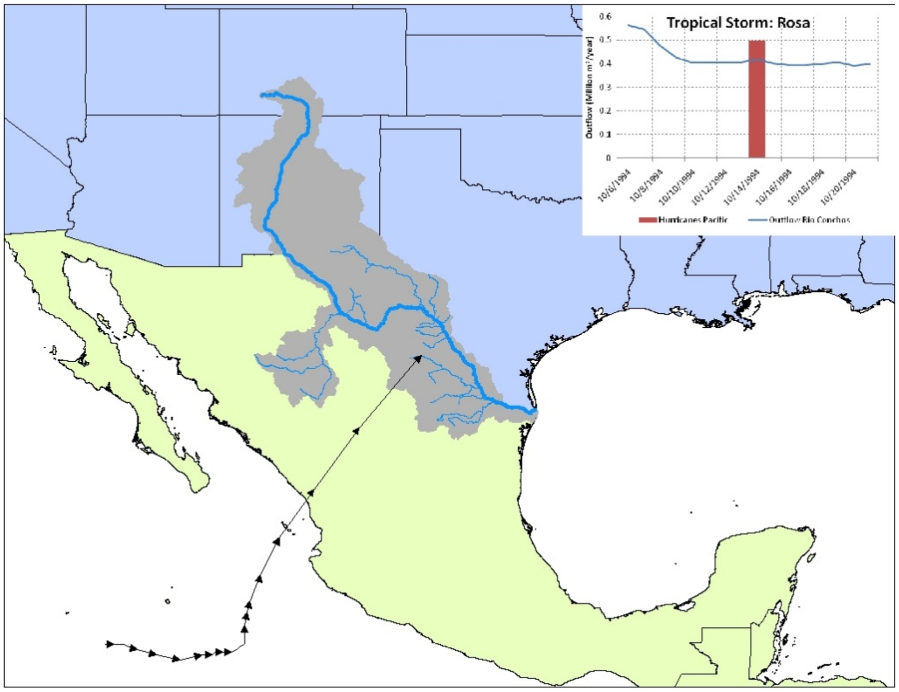


Figure A.12 – Hurricane Rosa, 8-14 Oct, 1994

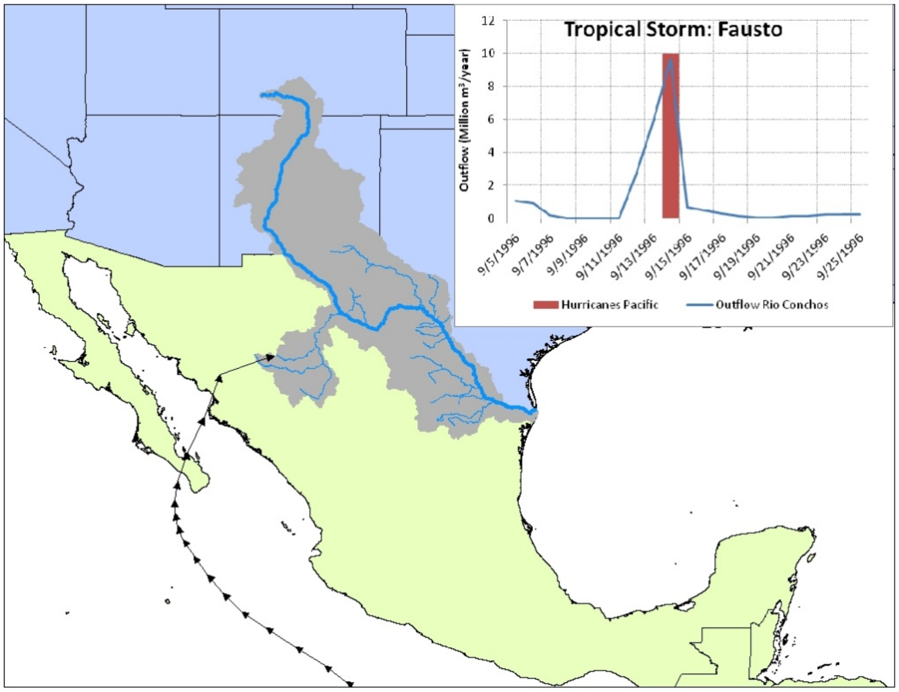


Figure A.13 – Hurricane Fausto, 10-14 Sep, 1996

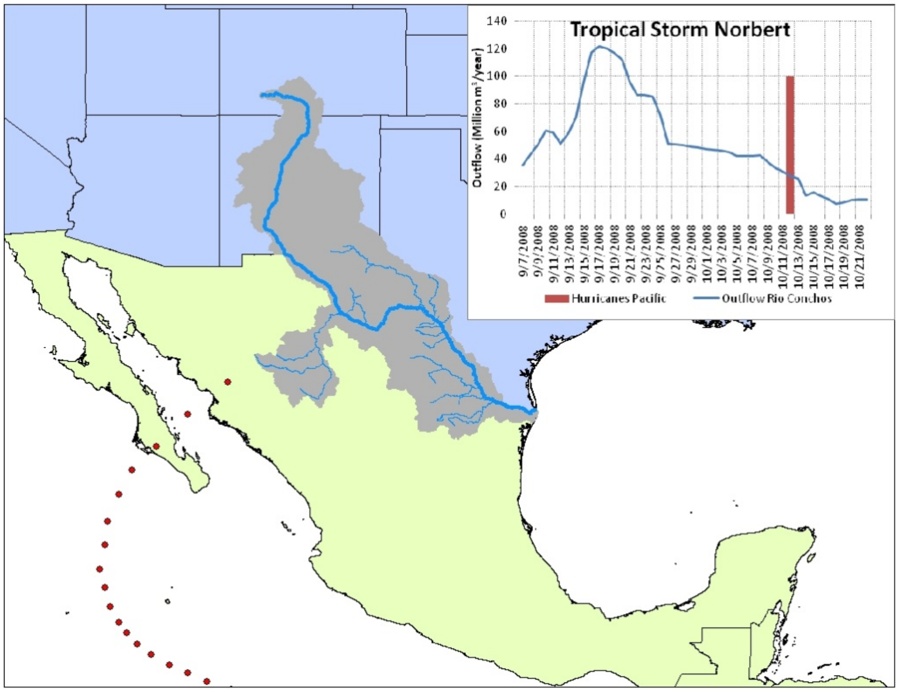


Figure A.14 – Hurricane Norbert, 4-12 Oct, 2008

Appendix B

Cycle	Date		Duration (years)	# of Hurricanes	Hurricane #1			Hurricane #2			Hurricane #3		
	Beginning	Ending			Name	Date	Reset the cycle?	Name	Date	Reset the cycle?	Name	Date	Reset the cycle?
1	01-Oct-1953	30-Sep-1958	5	2	Notname	06-Oct-1957	No	Notname	22-Oct-1957	No			
2	01-Oct-1958	30-Sep-1963	5	1	Doren	04-Oct-1962	No						
3	01-Oct-1963	30-Sep-1968	5	2	Helga	17-Sep-1966	No	Naomi	13-Sep-1968	No			
4	01-Oct-1968	21-Aug-1972	3.89	1	Jennifer	12-Oct-1969	No						
5	22-Aug-1972	15-Feb-1973	0.485	0									
6	16-Feb-1973	16-Oct-1974	1.666	3	Irah	26-Sep-1973	No	Jennifer	27-Sep-1973	No	**Orlene**	**24-Sep-1974**	**Yes**
7	17-Oct-1974	08-Dec-1976	2.145	0									
8	09-Dec-1976	06-Nov-1978	1.91	1	**Paul**	**26-Sep-1978**	**Yes**						
9	07-Nov-1978	16-Nov-1978	0.027	0									
10	17-Nov-1978	07-Sep-1979	0.808	0									
11	08-Sep-1979	11-Jun-1981	1.756	0									
12	12-Jun-1981	03-Sep-1981	0.23	0									
13	04-Sep-1981	11-Oct-1981	0.104	0									
14	12-Oct-1981	26-Oct-1981	0.041	0									
15	27-Oct-1981	01-Jun-1982	0.597	0									
16	02-Jun-1982	01-Jun-1987	5	1	Paine	02-Oct-1986	No						
17	02-Jun-1987	23-Jun-1987	0.06	0									
18	24-Jun-1987	02-Aug-1987	0.11	0									
19	03-Aug-1987	31-Aug-1987	0.079	0									
20	01-Sep-1987	29-Sep-1988	1.079	0									
21	30-Sep-1988	02-Nov-1991	3.093	1	Rachel	02-Oct-1990	No						
22	03-Nov-1991	17-Dec-1991	0.123	0									
23	18-Dec-1991	23-Jul-1992	0.597	0									
24	24-Jul-1992	26-Sep-1992	0.178	0									
25	27-Sep-1992	26-Sep-1997	5	3	Lidia	13-Sep-1993	No	Rosa	14-Oct-1994	No	Fausto	14-Sep-1996	No
26	27-Sep-1997	30-Sep-2002	5	0									
27	01-Oct-2002	30-Sep-2007	5	0									
28	01-Oct-2007	08-Oct-2008	1.019	1	**Norbert**	**12-Oct-2008**	**Yes**						

🟫	Cycles with no hurricanes
⬜	Hurricanes that reset the treaty cycles

Appendix C

Poisson Distribution

Historic Data

# of Storms = 11

# of Years = 40

Moments

Mean (x)= 0.275

Variance (x^2)= 0.275

Std. Dev. (x)= 0.524

Parameters

nu (1/t) = 0.275

t (t) = 1 year

Input data

λ= 0.2750

P(Reset)= 0.2727

P(No Reset)= 0.7273

$$f(x,\lambda)=\frac{\lambda^{x}}{e^{\ln\left(\Gamma(x+1)\right)}}e^{-\lambda x}$$

# of Storms	PMF	CDF	P(No-Reset|x)=	P(Reset|x)=	P(Reset)
(x)	$p_X(x)$	$F_X(x)$	P(No Re-Set)^x	1-P(No-Reset|x)	
0	0.7596	0.7596	0.43691	0.56309	0.4277
1	0.2089	0.9685	0.72727	0.27273	0.0570
2	0.0287	0.9972	0.52893	0.47107	0.0135
3	0.0026	0.9998	0.38467	0.61533	0.0016
4	0.0002	1.0000	0.27976	0.72024	0.0001
5	9.96E-06	1	0.20346	0.79654	7.93E-06
6	4.56E-07	1	0.14797	0.85203	3.89E-07
7	1.79E-08	1	0.10762	0.89238	1.6E-08
8	6.16E-10	1	0.07827	0.92173	5.68E-10
9	1.88E-11	1	0.05692	0.94308	1.78E-11
10	5.18E-13	1	0.04140	0.95860	4.96E-13

P(Reset)= **0.5000**

$$\sum_{x=1}^{x=10} P(Storm \geq x) * P(\mathrm{Re}\,set \mid x)) =$$ **0.0723**

Results

P(# of Stroms>=1)= 0.2404

P(No Storms)= 0.7596

P(Re-Set|Storm>=1)= 0.3005

P(No Re-Set|Storm>=1)= 0.6995

P(Re-Set|No Storm)= 0.5631

P(No Re-Set|No Storm)= 0.4369

P(Re-Set)= 0.5000

P(No Re-Set)= 0.5000