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Hydrologic Model for the Rio Conchos Basin: Calibration and Validation

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Abstract

This report focuses on the hydrologic modeling of the Rio Conchos basin, a main Mexican tributary of the Binational Rio Grande basin. Located in the Mexican State of Chihuahua, the Rio Conchos basin provides about 55% of the water deliveries to the US under the 1944 water sharing treaty between Mexico and the US. However, during drought periods, for instance in 1990s, water deficit under the 1944 treaty can occur. In order to answer several pressing questions related to water availability under future climatic conditions, a hydrologic simulation model has been developed for the Rio Conchos basin using the Water Evaluation and Planning (WEAP) modeling software. This report provides a description of the hydrological modeling of the Rio Conchos basin using the soil moisture method incorporated in WEAP. The Rio Conchos hydrologic model reported here is an extension of the model previously reported in Amatto *et al*. (2006). In this research, the calibration period for the model has been extended from a one-year period (1980) to a ten-year period (1980-1989) with appropriate adjustments to the model parameters. In addition, a ten-year validation period (1990-1999) has also been added.

Contents

1. Introduction

Changes in temperature and precipitation patterns as a consequence of the increase in concentrations of greenhouse gases may affect the hydrologic processes, water resources availability, and water available for agriculture, population, mining, industry, aquatic life in rivers and lakes, and hydropower. Climate changes will accelerate the global hydrological cycle, with an increase in the surface temperature, changes in precipitation patterns, and evapotranspiration rates. The spatial change in amount, intensity and frequency of precipitation will affect the magnitude and frequency of stream flows; consequently, it will increase the intensity of floods and droughts, with substantial impacts on the water resources at local and regional levels. Global climate simulations indicate that precipitation will decrease in lower and mid latitudes and increase in high latitudes (IPCC, 2008). For instance, precipitation will decrease in part of North America (Mexico), central America and South America, Caribbean regions, sub tropical western coasts, and over the Mediterranean. Likewise, evaporation, soil moisture content, and groundwater recharge will also be affected. Consequently, drought conditions are projected in summer for sub-tropical regions, low and mid latitudes. These facts arouse the interest of many researchers to analyze these effects at the basin (local) scale. Additionally, at the local scale, to evaluate and quantify these impacts, technical procedures need be performed which include hydrological modeling, downscaling climate data, modeling water resources, and evaluating climate change scenarios to predict future water availability in the water system under study.

Several hydrologic and climate change studies have been carried out in different regions of the world, such as in the Nile basin (Yates and Kenneth, 1998) and the Sacramento basin in California (Joyce *et al*., 2006); however, there are few studies about the effect of climate change on transbounday water resources, such as the Rio Conchos basin. This paper focuses on the hydrologic modeling of the Rio Conchos basin, a main Mexican tributary of the Binational Rio Grande/Bravo basin. Located in the Mexican State of Chihuahua (Figure 1), the Rio Conchos basin has a surface area of 67,808 km^2. It provides about 55% of the water deliveries to the USA under the water sharing treaty signed between Mexico and the USA in 1944. This represents the highest amount of all the Mexican tributaries considered on the 1944 treaty. However, during drought periods, for instance in 1990s, there can arise conflict and competition for the water resources in this basin, as consequence Mexico can accumulate a water deficit under the 1944 treaty. In addition, the hydrological behavior of the basin indicates recurrent periods of water stress, problems with long drought periods, allocation and release, and water pollution. Thus, the following questions arise: What will happen to the availability of water resources in this basin over the next 50 to 100 years taking account of climate change impacts in the basin? How will this water availability affect the water agreements signed between Mexico and USA? How will organizations involved in water resources management face this problem? What water policies will need to be implemented in order to face drought periods?

To figure out the answers to these questions it is necessary to resort to models of planning and hydrologic simulation that can help us find answers to these questions. To this end, the Water Evaluation and Planning (WEAP) modeling software is used (SEI, 2006). WEAP has a hydrological module which is spatially continuous with areas configured as a set of sub-catchments that cover an entire river basin under study, considering them to be a complete network of rivers, reservoirs, channels, aquifers, demand points, etc. Likewise, this module includes a method to simulate catchment processes, such as evapotranspiration, runoff, and infiltration, as a dynamic integrated rainfall-runoff model including various components of hydrologic cycle.

This report provides a description of the hydrological modeling in the Rio Conchos basin to assess climate change impacts using the Soil Moisture Method incorporated in WEAP. The Rio Conchos hydrologic model reported here is an extension of the model previously reported in Amatto *et al*. (2006). In this research, the calibration period for the model has been extended from a one-year period (1980) to a ten-year period (1980-1989) with appropriate adjustments to the model parameters. In addition, a ten-year validation period (1990-1999) has also been added.

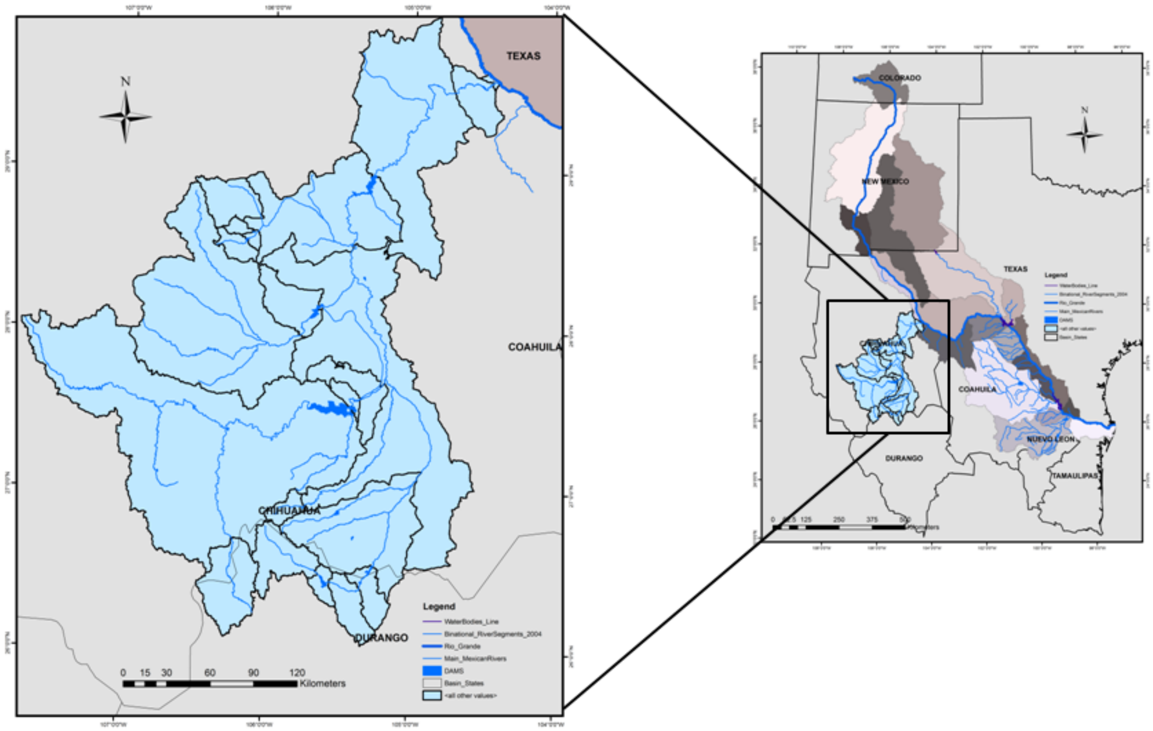


Figure 1. Location of the Rio Conchos Basin

1.1 Objectives

To answer the questions formulated above, the present research has the following main objectives:

- Model the hydrological behavior of the Rio Conchos basin (rainfall – runoff); to this end, the soil moisture method incorporated in WEAP model is used (described in this report);
- Downscale the climate data from 5 General Circulation Models (GCMs). Data from GCMs have coarse resolution; therefore, for increasing it, downscaling methods will be applied (in progress);
- Simulate climate change emission scenarios A2 and B1 on the water resources system in study (in progress);
- Assess climate change impacts on water resources in basin and their effects on 1944 Treaty between the United States and Mexico (in progress); and

- Simulate and evaluate water management scenarios that help to mitigate the climate change effects in the next 100 years (in progress)

2. Climate and Land Use Data

This sections discuss the monthly climate data used for 20 sub catchments located in the study basin (Figure 2); likewise, characterization and soil groups considered in the study are pointed..

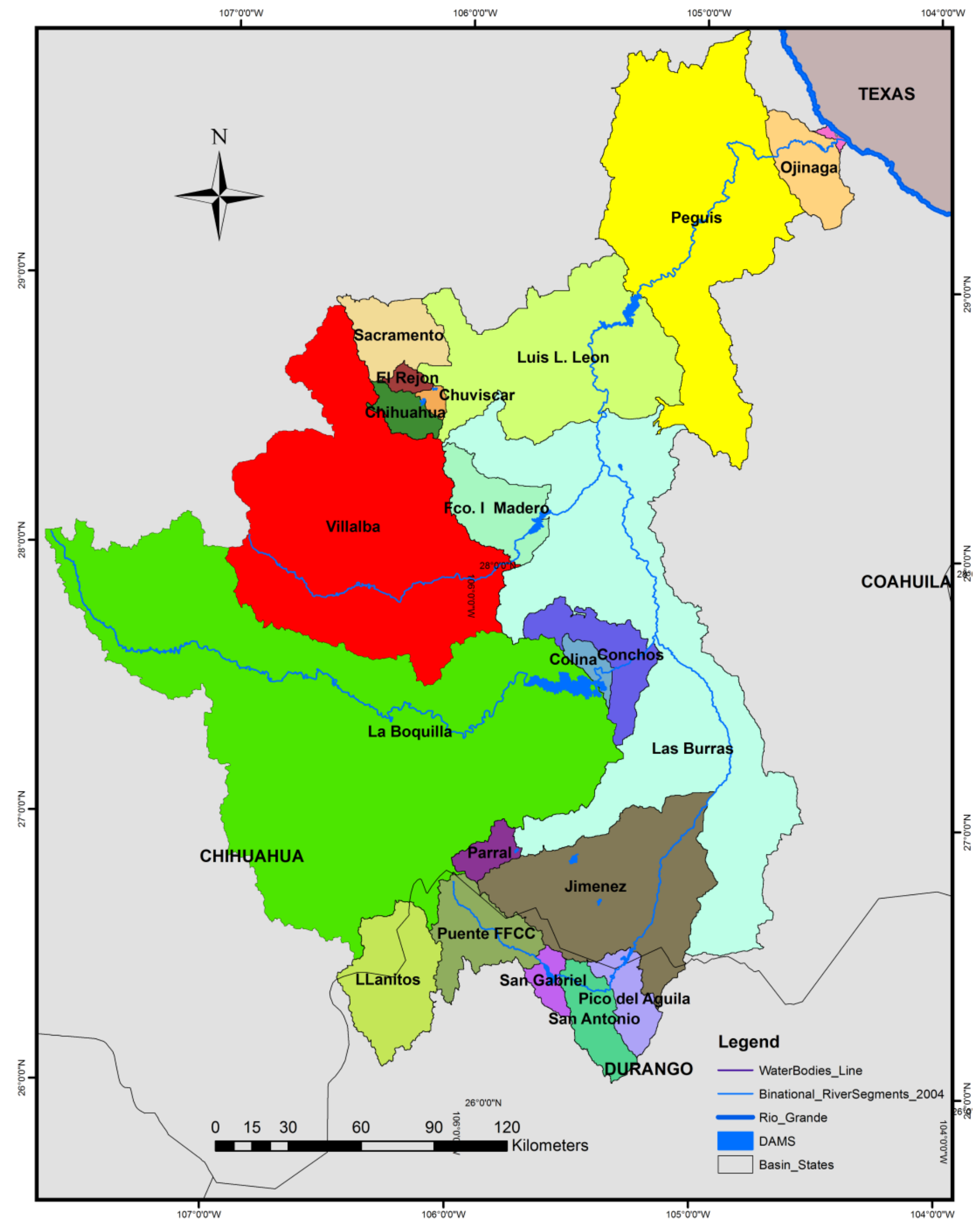


Figure 2. Location of Catchments in the Study Basin

2.1 Climate Data

2.1.1 Precipitation

Precipitation is one of the most important parameters in the hydrological simulation of a basin. In the Rio Conchos basin we can indentify three main areas: (1) A small region located about 2500 m above sea level composed by mountains with massive plateaus (Chihuahuan Sierra) in which the precipitation is around 1,000 mm per year on average; (2) A transition region, with an annual precipitation of about 450 mm per year, formed by valleys surrounded by mountainous areas; and (3) A desert zone at an altitude of about 1200 m with an annual precipitation of around 300 mm per year (Kim and Valdes, 2002).

For this study, daily precipitation from 1980 to 1999 (20 years) was used to calibrate and validate a hydrologic model of the basin in WEAP and to analyze its temporal behavior. These data were provided by the Mexican Institute of Water Technology (IMTA) for control stations in each sub catchment (Gomez, Mejia, and Gutierrez, 2005), and monthly cumulative values were calculated in order to carry out the hydrological modeling. The observed range of monthly maximum values was between 200 to 310 mm (Figure 3). Likewise, the annual average is about 425 mm/year with seasonal variation indicating that the wet period is from June to September (Figure 4). On the other hand, rainfall shows spatial variation with altitude, with higher values in the Llanitos sub basin, 740 mm/year on average, located in the upper basin. The lowest values are recorded in the Luis Leon and Peguis sub basins located in the lower basin, with annual averages of about 325 mm. In the middle basin, annual precipitation varies from 350 to 400 mm, with monthly averages ranging from 42.6 mm to 101.3 mm in June and August, respectively.

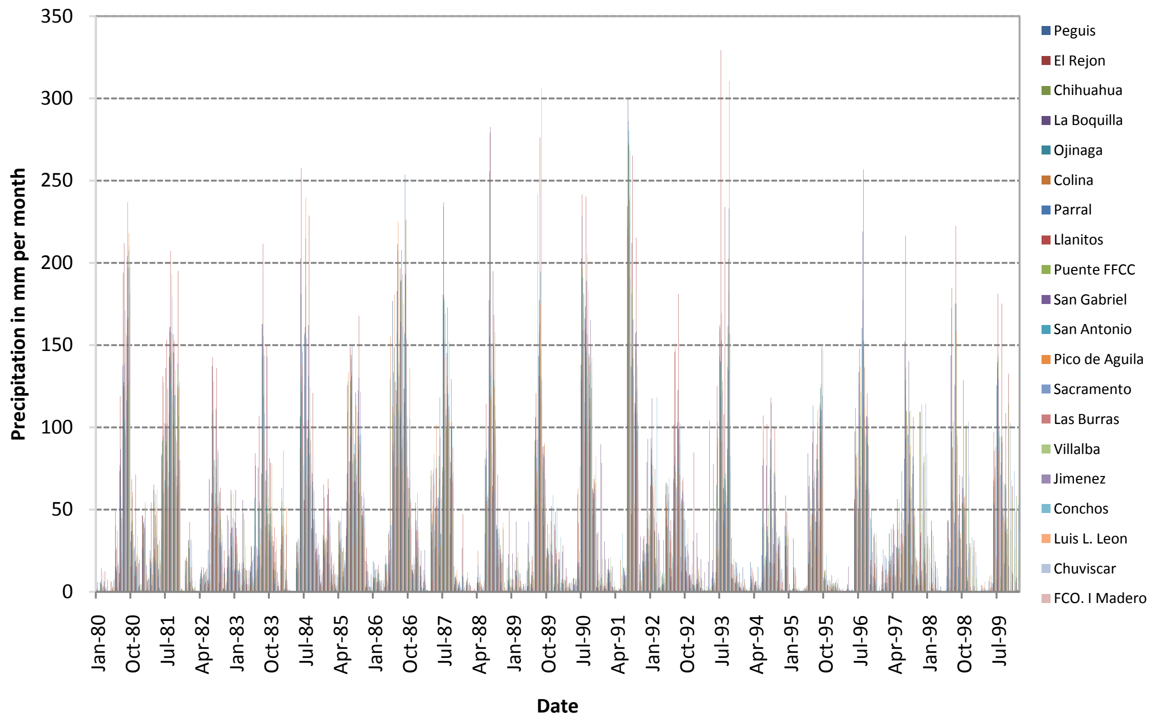


Figure 3. Monthly Precipitation in the Rio Conchos basin for the period, 1980-1999.

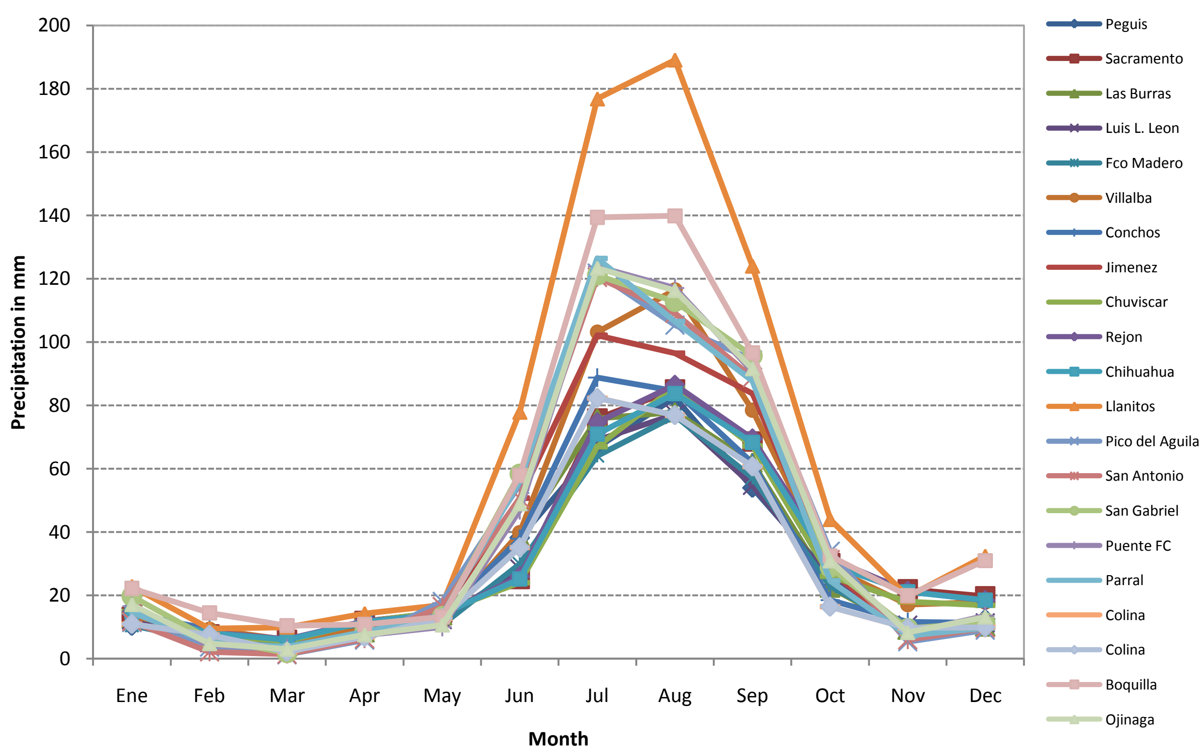


Figure 4. Monthly mean precipitation in the Rio Conchos basin, 1999-2000

2.1.2 Temperature

Similar to precipitation, temperature is another important parameter in assessing the climatic change impacts on water resource systems. According to climate model predictions, using several scenarios of greenhouse gas emissions, global mean temperature probably will increase from 1.1 to 6.4 ^{o}C in the next 100 years (IPCC, 2001), which means an increase of extreme weather events as well as important changes in the precipitation and atmospheric circulation patterns. For this study case, surface temperature was obtained from the North American Regional Reanalysis (NARR, http://nomads.ncdc.noaa.gov/thredds/catalog/narr/199107/19910731/catalog.html) for the period 1980 -1999. First, these data were processed using GIS tools to estimate monthly average temperature for each sub catchment in the Rio Conchos basin.

Maximum temperatures occur in the period from June to August and minimum from November to February (Figure 5, monthly average of 20 years). For the first period (June-August), the spatial variation indicates that high values occur in the lower basin (desert region), with values around 32 ^{o}C for the Ojinaga and Peguis sub basins, and 21 ^{o}C for the Llanitos and Puente FFCC sub basins. For the second period (November to February), the temperature varies from 7 – 11 ^{o}C and 12 - 16 ^{o}C for the lower and upper basin, respectively. On the other hand, temperature and precipitation show a negative correlation during the period of analysis, which means that the temperature tends to rise and rainfall to decrease, indicating very interesting climate change impacts in the basin during the last 20 years (Figure 6) and whose annual analysis indicates that the temperature is increased by one degree Celsius and the precipitation was reduced by 5% in average.

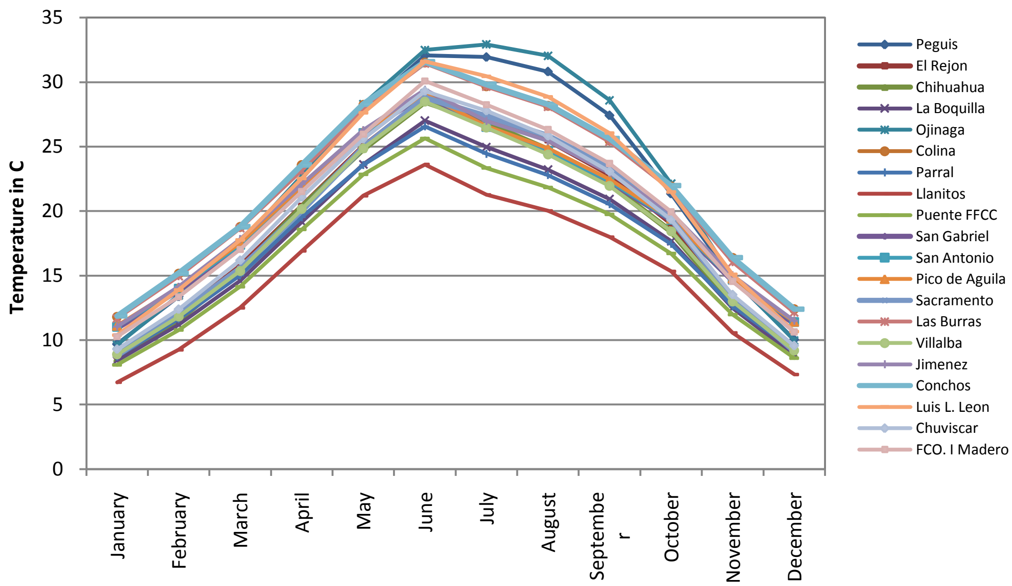


Figure 5. Monthly average temperatures in the Rio Conchos basin, 1980-1999

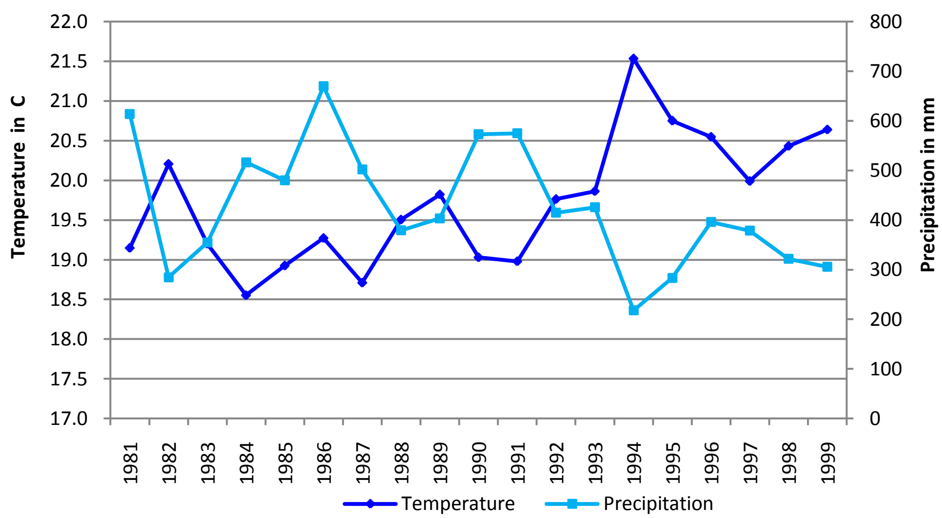


Figure 6. Annual variations of temperature and precipitation in the Rio Conchos basin.

2.1.3 Relative Humidity

Relative humidity data for 1980 to 1999 was obtained from NARR (http://nomads.ncdc.noaa.gov/thredds/catalog/narr/catalog.html). GIS tools were used to compute monthly averages for each sub catchment. Spatial variation indicates that lowest values of relative humidity occur in Fco Leon, Pegui, and Ojinaga catchments located in the lower basin, and the highest values occur in the upper basin. The average for the whole basin is around 42% and the temporal variation indicates that maximum values occur from July to September. On the other hand, the minimum values of relative humidity are observed from March to June.

2.1.4 Wind Velocity

In the Rio Conchos basin, the dominant winds come from Southwest to Northeast. Two components of velocity were obtained from the NARR (http://nomads.ncdc.noaa.gov/thredds/catalog/narr/catalog.html) for different sub catchments of the basin. Velocity vectors for East-West (U) and North-South (V) were processed in to get the wind velocity. The wind speed during the year indicates a seasonal variation with high values from November to April, with an average of 12 km/h for the whole basin. In general, in the upper basin (La Boquilla, Llanitos, Parral sub basins) the wind speed is greater than in the lower basin (Luis Leon, Peguis, Ojinaga sub basins), with 18 km/h and 6 km/h, respectively for the same period of time. On the other hand, the minimum wind speed is observed from May to October (6.1 km/h average) a period in which the maximum temperature occurs.

2.2 Land Use Data

The twenty sub-basins were sub-divided again by soil groups and land use categories (Amato *et al.*, 2006). The land use and soil coverage data from IMTA (Gomez, et al., 2005) were applied for the Soil Moisture Method in the WEAP model. Table 1 shows the soil groups considered in WEAP model. Also, in Figure 7 can be seen the spatial distribution of the land use in the study area.

Table 1. Land Use Groups Used in the Hydrologic Model

Land Use Code	Land Use Category
10	Forest
20	Forrest Grasses
30	Water Bodies
40	Irrigated Areas
50	Naturally Irrigated Areas
60	Small Pasture Grasses
70	High Grasses and Small Brush
75	Other Vegetation
80	Grazing Pastures
85	Urban Areas
90	Wetland Vegetation
95	Without Apparent Vegetation

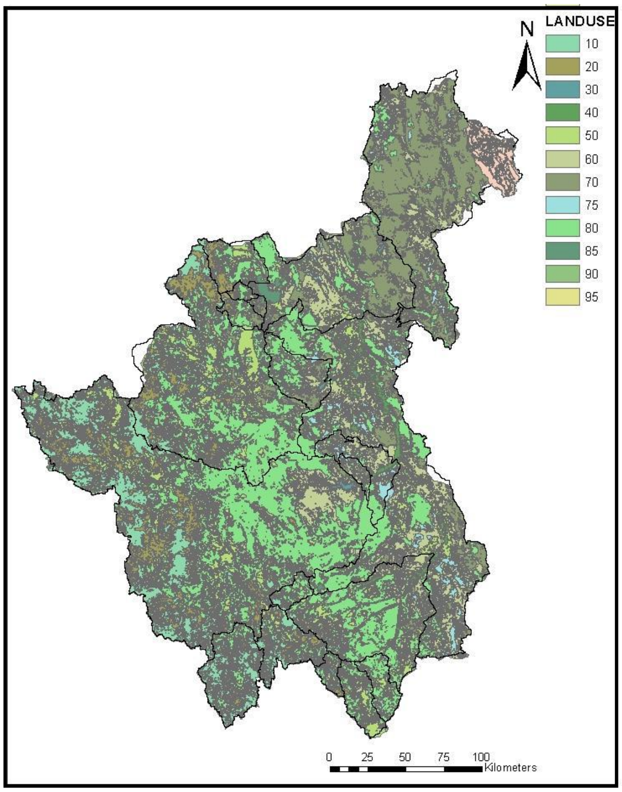


Figure 7. Soil Coverage in the Conchos Basin

3. Methodology

In this part, the methods and procedures are described in order to achieve the objectives of this investigation. First, to assess climate change impacts on water resources, a hydrological modeling of the study basin must be developed. For this purpose, climate data and historical flows in control stations were used. This section discusses the model calibration for naturalized flows as well as historical flows in which the hydraulic infrastructure is considered in the basin.

3.1 Model Calibration

The calibration process is carried out using historical observed data inputs such as precipitation, temperature, relative humidity, and wind velocity and stream flow outputs. Naturalized flows for a period of 10 years (1980 - 1989) from the Texas Commission on Environmental Quality (Brandes, 2003) were used to calibrate the Rio Conchos hydrologic model. The model was then run for a validated period of the ten years (1990-1999) to test the calibration. The calibration involved both quantitative and qualitative evaluation of the hydrologic response of each tributary in each sub basin. Soil parameters were adjusted in order to reproduce the naturalized monthly and annual stream flows. The soil moisture method in WEAP software was used and this methodology and required parameters are described below.

3.1.1 Soil Moisture Method

For hydrological modeling purposes in WEAP, the soil moisture method can be used which is based on empirical functions that describe the behavior of evapotranspiration, surface runoff, interflow, base flow, and deep percolation for a watershed or group of interconnected basins (SEI, 2007). The model considers the movement of water through the two soil layers (Figure 8). The first layer represents the water retained near the surface, which is available to plant roots; the second layer is deeper and water from this layer can be transmitted as base flow or groundwater recharge. The parameters of this model include the water holding capacity of the layers as well as the water movement between them. For a basin subdivided into a number of sub basins with different fractional land use or soil type areas, the mathematical expression used in this model is following (Yates et al., 2006):

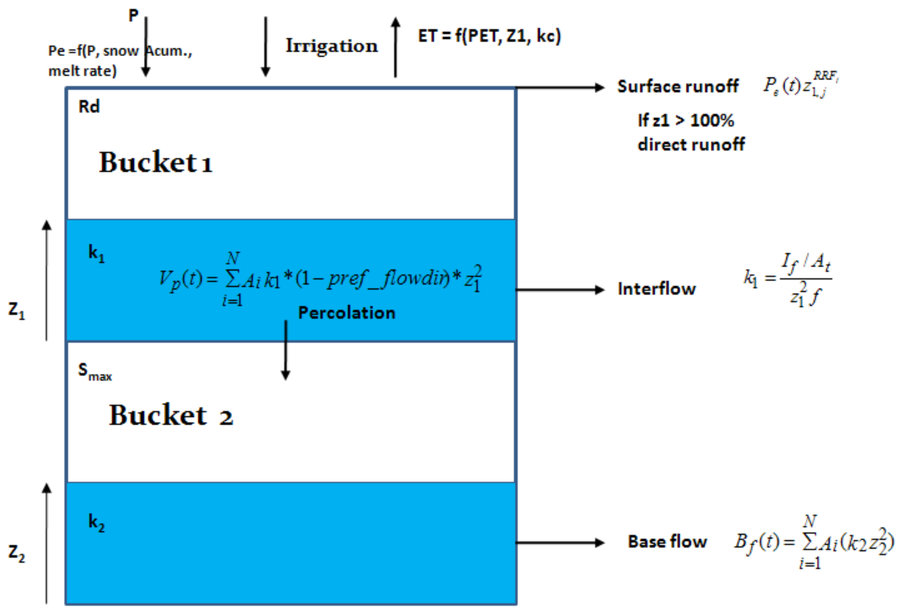


Figure 8. Two Buckets Hydrology in the Soil Moisture Method

$$Rd_j \frac{dz_{1,j}}{dt} = P_e(t) - PET(t)k_{c,j}(t)(\frac{5z_{1,j} - 2z_{1,j}^2}{3}) - P_e(t)z_{1,j}^{RRF_j} - f_j k_{s,j} z_{1,j}^2 - (1-f_j)k_{s,j} z_{1,j}^2 \quad (1)$$

where

$z_{1,j} \in [0,1]$	relative soil water storage, a fraction of the total effective water storage in the root zone layer in area *j* [dimensionless];
Rd_j	soil water holding capacity of area *j* [mm];
Pe	effective precipitation [mm];
$PET(t)$	reference potential evapotranspiration [mm/day];
$k_{c,j}$	crop coefficient for area *j*;
RRF_j	Runoff Resistance Factor for area *j* that depends of the land cover. Higher values of this factor result in higher evaporation and less runoff from the basin.
$P_e(t)z_{1,j}^{RRF_j}$	is the surface runoff
$f_j k_{s,j} z_{1,j}^2$	interflow from the first soil layer for area j

f_j partitioning coefficient related to the land cover type, soil, and topography for area *j*, that divides flow into horizontal f_j and vertical $(1-f_j)$ flows; and

$k_{s,j}$ saturated hydraulic conductivity of the root zone layer of area *j* [mm/time].

The change of storage in the second layer is computed by the following expression:

$$S_{\max}\frac{dz_2}{dt}=\left[\sum_{j=1}^{N}(1-f_j)k_{s,j}z_{1,j}^2\right]-k_{s2}z_2^2 \tag{2}$$

where S_{max} is the deep percolation from the upper layer storage and k_{s2} is the saturated hydraulic conductivity of the lower storage (mm/time)

3.1.2 Root zone water capacity

An initial value of 900 mm for root zone layer water capacity was used for irrigated areas, small pastures grasses, and cultivated grassland, and 2500 mm for forest areas. However, these values did not give good model performance. Adjustments of this parameter were made taking into account the depth of soils in the basin which range from 20 cm to 50 cm, on average (Pro Fauna, 2003). Table 2 shows the calibrated values for each sub basin, with 300 mm for La Boquilla (upper basin) and 400 - 600 mm for Luis Leon, Peguis and Ojinaga (lower basin). This pattern is due basically to the type and formation of soils in each zone; for instance, in La Boquilla the soil type is Podzols whose formation is situ and coluvial, except in the Zaragosa valley close to La Boquilla reservoir where the soils are of alluvial origin and are a little deeper. On the other hand, in Luis Leon, Peguis, and Ojinaga sub basins, the soils are of alluvial origin and deeper, more of 50 cm on average.

3.1.3 Root zone hydraulic conductivity k_1

The root zone hydraulic conductivity, k_1, is a very important parameter in the calibration process, which controls the flow of water from the upper layer to the lower soil layer as well as the interflow. The interflow depends of the preferred flow direction; for the Rio Conchos basin this values from 0.05 to 0.20 were used for some sub catchments in the upper and middle basin such as La Boquilla, Villaba, and Las Burras. On the other hand, for Luis Leon, Peguis, and Ojinaga, located in the lower basin, the flow direction was assumed to be equal to zero, indicating vertical flow in those areas.

To estimate k_1, first, the average interflow contribution was estimated from the difference between the 30% and 90% exceedance flows for each station using the following expression:

$$k_1 = \frac{I_f \;/\; A_t}{z_1^2 f} \tag{3}$$

where I_f is the interflow; for instance, in the La Boquilla sub basin, the 30% and 90% exceedance flows are 89 million m^3 and 6 million m^3, respectively. The difference between them is assumed to be the interflow; which is about 83 million m^3. For the sub basin area of 20761.89 km^2 (including Llanitos sub basin), assuming $z_1 = 30\%$ and flow direction f = 0.3, k_1 = 148 mm/month. However, to improve the results k_1 was adjusted to 120 mm/month, and a temporal variation of flow direction was assumed with 0.15 as the average value. A similar procedure was used for the other sub basins whose calibrated results are shown in Table 2.

In each catchment, the flow from the upper layer to the lower layer (percolation) is estimated with a simple expression of its relative storage

$$V_p(t) = \sum_{i=1}^{N} A_i k_1 * (1 - pref\_flowdir) * z_1^2 \qquad (4)$$

Using the values found for the Villalba sub basin (see Table 1) in the expression above, the average volume of percolation is 190.6 million m^3/month. If this parameter is reduced, the stream flow is increased and flow to the lower layer is also reduced.

3.1.4 Initial root zone water capacity z_1

The Initial root zone water capacity, z_1, value at the beginning of the simulation was estimated for each sub basin. Values ranged from 5 to 30% in some sub basins. Lower calibrated values were found for the sub catchments Luis L. Leon, Peguis, and Ojinaga in the lower basin where less relative storage of water exists in the top layer (desert area). Surface runoff is directly correlated with the initial storage, z_1; if z_1 is increased, the runoff is also increased. The values for this parameter are shown in Table 2.

Table 2. Upper Layer Soil Parameters for the Rio Conchos Basin.

Sub Basin	Drainage Area km^2	Layer 1 (upper)		
		Root Zone Capacity mm	Root Zone Conductivity mm/month	Initial z_1 %
Peguis	7999.2972	400	120	5
Sacramento	1042.6059	280	60	10
Las Burras	11309.4666	350	180	20
Luis L. Leon	5085.5131	400	60	5
FCO. I Madero	1211.3488	280	60	20
Villalba	9556.8624	250	100	30
Conchos	1114.3944	250	45	25
Jimenez	4422.9591	350	60	20
Chuviscar	106.0884	280	70	10
El Rejon	146.8494	280	70	10
Chihuahua	399.9897	280	70	10
Llanitos	1829.9295	400	100	30
Pico de Aguila	647.6067	350	60	20
San Antonio	821.1609	350	60	20
San Gabriel	305.8525	350	60	20
Puente FFCC	1270.6609	250	60	20
Parral	363.7890	275	60	20
Colina	259.0569	280	60	25
La Boquilla	18931.9788	300	120	30
Ojinaga	983.4705	600	80	5

3.1.5 Lower zone water capacity

Calibrated values of lower zone water capacity are shown in Table 3. It is likely that the high values found in some sub basins show the existence of deep aquifers. Initially, values between 2000 mm to 3000 mm were assumed; however, this resulted in high values of accumulated base flow in the rivers. Therefore, they did not represent the hydrogeology response of the basin. This behavior was observed from the second year of simulation, with extraordinarily large base flow volumes in the last year; in some cases above the normal flow. For this reason, lower zone capacity values higher than 12000 mm were evaluated.

3.1.6 Lower zone deep conductivity k_2

The deep conductivity controls the transmission of base flow in each sub basin. This parameter, together with lower zone deep water capacity, is essential to obtaining an acceptable accuracy of base flow in the river. It can be estimated with the following expression:

$$B_f(t) = \sum_{i=1}^{N} A_i (k_2 z_2^2) \tag{5}$$

where A_i is the area of the land use cover fraction, i, k_2 is the conductivity of the lower layer at full saturation ($z_2 = 1.00$) in mm/month, and z_2 is the relative storage given as a percentage of the effective storage of the lower soil layer. From the expression above, initial hydraulic conductivity was estimated as:

$$k_2 = \frac{(B_f / A_i)}{z_2^2} \tag{6}$$

The base flow (B_f) can be estimated with different methods depending of hydrologic behavior of basin in study. Considering the limited information, it is possible to make rough calculations of base flow using the straight line method (Chow *et al.*, 1988); as well as assuming that most base flow in the basin is produced within the range of 90% exceedance flow. For instance, for the Villalba sub basin with a drainage area of 9,557 km^2, the assumed base flow was 2.3 million m^3/month (90% exeedance value), and an assumed average initial storage value of $z_2 = 20\%$ for all fractions *j*, the hydraulic conductivity is k_2 = 6 mm/month. This value was adjusted to 5 mm/month to improve the calibration. The calibrated k_2 for each sub basin is shown in Table 3.

3.1.7 Initial lower layer storage z_2

Different values of initial storage in the lower soil layer were assumed in the hydrologic simulation. At the beginning of the simulation, percentages around 40 – 50 % were used. In many cases, the resulting base flow was more than 50% of the stream flow. For example, in the Villalba sub basin, the base flow was more than 70%; for this reason, the initial storage in the deep layer was reduced in most cases to no more than 50%. The calibrated values z_2 for each sub basin can be seen in Table 3 and they range from 5% to 20%. The lower values were found in the Peguis and Ojinaga sub basins located in the lower basin.

Table 3. Calibrated Lower Layer Soil Parameters for Rio Conchos basin Hydrologic Model

Sub Basin	Drainage Area km^2	Bucket 2		
		Deep Water Capacity mm	Deep Water Conductivity mm/month	Initial z_2 %
Peguis	7999.30	150000	25	5
Sacramento	1042.61	64000	6	20
Las Burras	11309.47	185000	45	20
Luis L. Leon	5085.51	120000	6	20
FCO. I Madero	1211.35	20000	45	20
Villalba	9556.86	200000	5	20
Conchos	1114.39	18000	45	20
Jimenez	4422.96	150000	5	10
Chuviscar	106.09	36000	10	20
El Rejon	146.85	36000	10	20
Chihuahua	399.99	60000	12	15
Llanitos	1829.93	250000	7	20
Pico de Aguila	647.61	13500	3	10
San Antonio	821.16	12000	3	10
San Gabriel	305.85	12000	3	10
Puente FFCC	1270.66	15000	3	10
Parral	363.79	40000	45	20
Colina	259.06	24000	45	20
La Boquilla	18931.98	300000	10	15
Ojinaga	983.47	150000	25	5

3.2 Stream flows

Naturalized and historical stream flows from Jimenez, La Boquilla, Villalba, Las Burras, el Granero, and Ojinaga control stations (Table 4) are used to calibrate and validate the model. Figure 9 shows the physical location of the stations mentioned above as well as the main rivers in the Conchos river basin.

Table 4. Rio Conchos Gage Stations and Drainage Area

Name	CRWR_ID	X_COORD	Y_COORD	Drainage Area (Km2)
Rio San Pedro at Villalba	FM4000PCP400	-105.77663	27.98457	9556.219
Rio Florido at Cd. Jimenez	FM5000PCP410	-104.91789	27.14191	7468.240
Rio Conchos at Las Burras	FM3000PCP390	-105.42108	28.53880	52045.066
Rio Conchos at El Granero	FM2000PCP380	-105.27088	29.00908	58679.263
Rio Conchos at Presa La Boquilla	FM6000PCP420	-105.41261	27.54562	20761.908
Rio Conchos at Ojinaga	FM1000PCP370	-104.44049	29.57854	67808.880

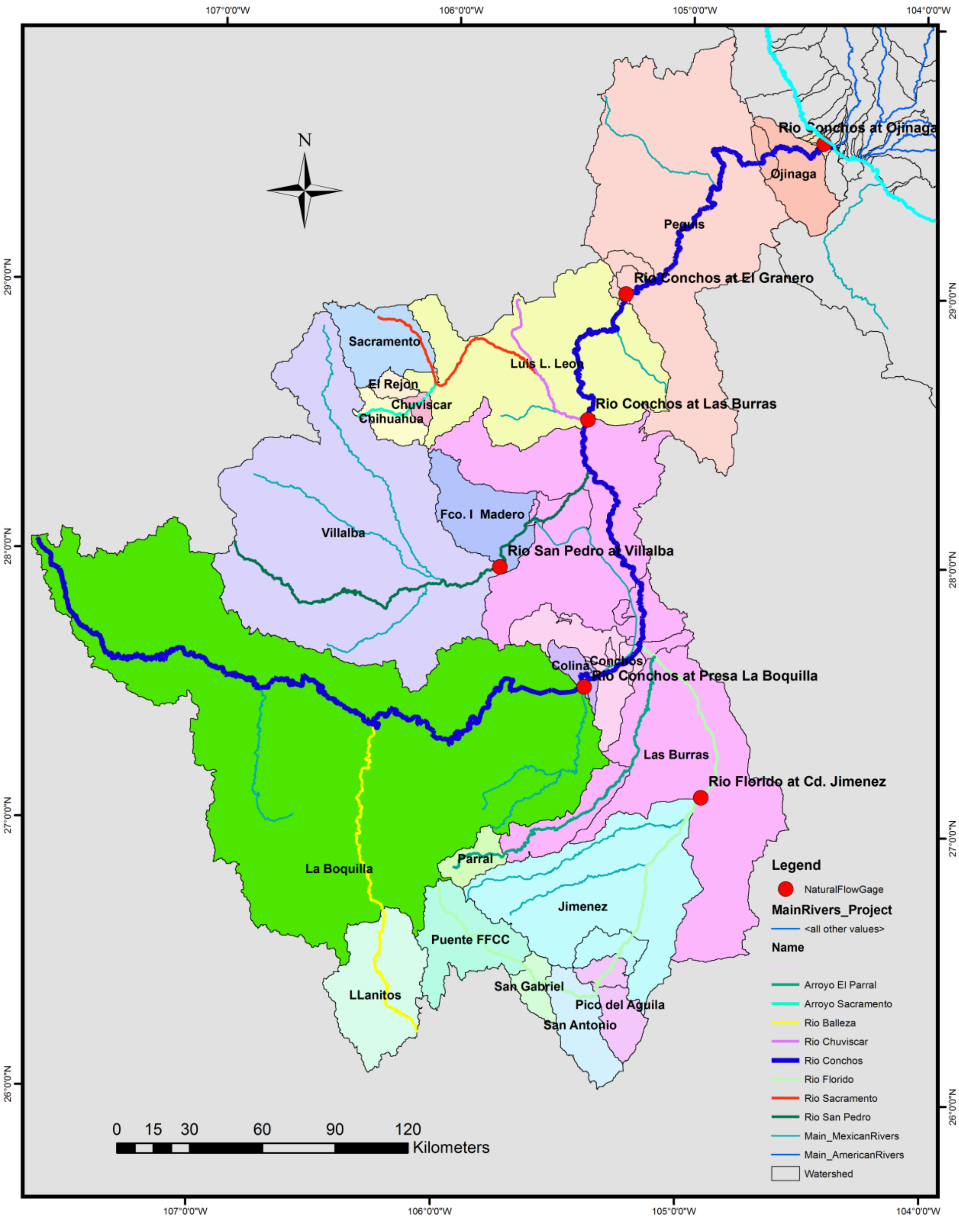


Figure 9. Location of control Stations (red circles) in the Rio Conchos basin.

3.3 Statistical Computations

The results of the hydrologic model performance are compared using several statistical parameters which include the observed and simulated mean flows, standard deviation the Root Mean Square Error (RMSE), the Mean Absolute Error (MAE), error in volume in percentage (VE), Coefficient of determination and Correlation. As it is noted in equations 9 and 10, the MAE and RMSE are used to measure the deviation between the observed and simulated stream flows values. On the other hand, the VE is defined as the ratio of the volume error to the observed streamflow volume expressed as percentage. Additionally, this analysis includes the Nash-Sutcliffe Coefficient(R) and Index of Agreement (IA) which are common parameters to evaluate the goodness-of-fit measure of the performance of hydrological models. All these indicators have been used for several hydrologic researchers, e.g., Legates and McCabe (1999), Fleming and Neary (2004), and Barbaro and Zerriello (2006) in whose studies, the statistical analysis was vital to assess the model performance. The mathematical expressions to compute the parameters mentioned above are:

Mean

$$\bar{Q} = \frac{1}{N}\sum_{i=1}^{N} Qo_i \tag{7}$$

Standard Deviation (STDEV)

$$STDEV = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(Qo_i - \bar{Q})^2} \tag{8}$$

Mean Absolute Error (MAE)

$$MAE = \frac{1}{N}\sum_{i=1}^{N}\left|Qo_i - Qs_i\right| \tag{9}$$

Root Mean Square Error (RMSE)

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(Qo_i - Qs_i)^2}{N}} \tag{10}$$

Error in Volume (VE in %)

$$VE = \frac{(V_o - V_s)}{V_o} x100 \tag{11}$$

Nash-Sutcliffe Coefficient(R)

$$E = 1.0 - \frac{\sum_{i=1}^{N}(Qo_i - Qs_i)^2}{\sum_{i=1}^{N}(Qo_i - \bar{Q})^2} \tag{12}$$

This coefficient of efficiency ranges from minus infinity to 1.0, with high values indicating better agreement. Physically, it can be interpreted as the ratio of the mean square error to the variance in the observed values, differenced from unity. If E is equal to zero, the observed mean is as good predictor as the model, and if the E <0 (negative values), the observed mean is a better predictor than the model (Legates and McCabe, 1999).

Index of Agreement (IA)

$$IA = 1.0 - \frac{\sum_{i=1}^{N}(Qo_i - Qs_i)^2}{\sum_{i=1}^{N}\left(\left|Qs_i - \bar{Q}\right| - \left|Qo_i - \bar{Q}\right|\right)^2} \tag{13}$$

where

Qo_i is the observed streamflow (m^3/s)

Qs_i is the simulated streamflow (m^3/s)

Vo is the observed streamflow volume (million m^3/month)

Vo is the simulated streamflow volume (million m^3/month)

$\bar{Q}$ is the average streamflow (m^3/s)

The index of agreement varies from 0 to 1, high values indicates a better agreement between modeled and observed streamflows.

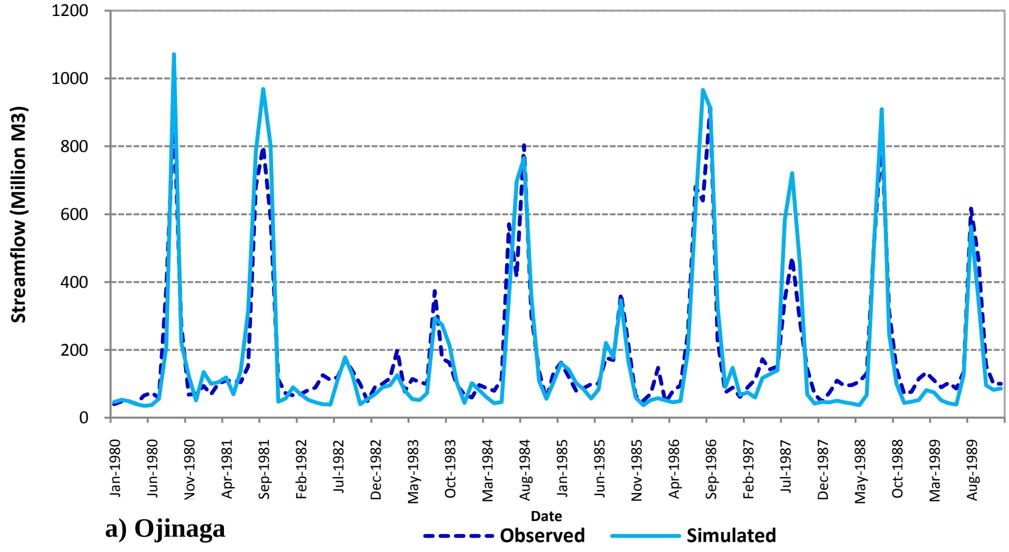
4. Calibration and Validation Results

In this section, simulated results are compared with the naturalized flows for each control station. These comparisons area carried out taking account the statistical parameters mentioned in previous sections. For this research, naturalized stream flows (Brandes, 2003) from 6 stations located along the basin were compared to the results of the model. In general, the results indicate that the model built in WEAP can be able to reproduce the hydrological dynamic of basin as is shown in the calibration and validation processes. Table 2 and 3 show the soil parameter values calibrated for the period from 1980 to 1989 whose stream flow results were validated with the period 1990 to 1999 (10 years), noting that in the validation process, some adjustments have been carried out basically in the second layer. Small depths proposed for this layer reproduced high base flows at the end of the simulation period.

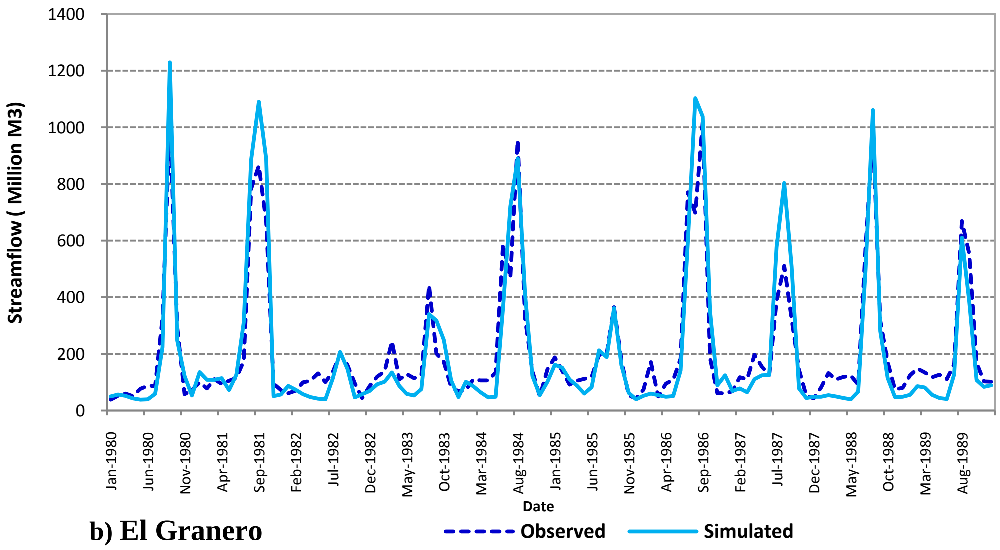
4.1 Calibration

Monthly simulated and observed stream flows for the calibration period (1980 - 1989) can be seen in Figures 10a-d for the control stations Ojinaga, El Granero, Las Burras, and la Boquilla, respectively. In most months, the simulated and observed flows are close, with a error in volume ranging from 2 - 19% for simulation period, for Ojinaga (lower basin) and La Boquilla (middle basin), respectively. The larger errors produced in the upper basin are due to the differences between simulated and observed base flows. For instance, for the La Boquilla station, simulated base flows are generally lower than the observed values from January to May. Probably, the uncertainties in naturalized flow calculations and a more accurate representation of the groundwater system in the middle and upper basin are affecting the estimations. The model reproduces fairly well the hydrological response of the basin in average terms; simulated stream flows represent between 85 to 95% of the naturalized flow.

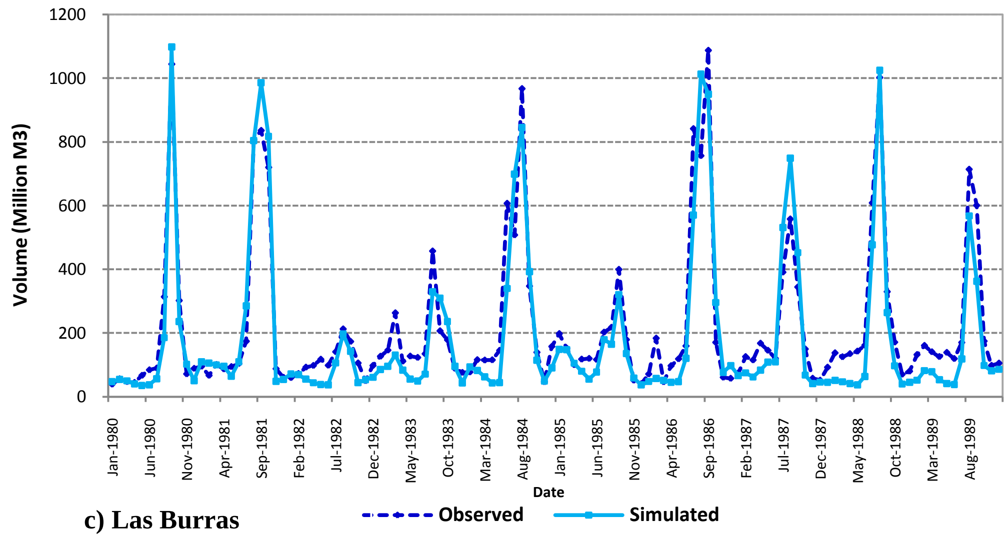
The trend of the model to reproduce the observed values is also seen in Figures 11a-d. Relationships between monthly simulated and observed flows indicate a high correlation whose coefficients vary from 0.91 to 0.95 for La Boquilla and Ojinaga, respectively. These statistical results indicate good model performance in reproducing the stream flows trend. The spatial variation indicates that the model is more accurate in reproducing the flows in the lower basin. The topography in the middle and upper basin (high slope), the size of the catchments (for instance La Boquilla), and other factors could be influencing in this behavior. The monthly simulated and observed flows for Villaba and Jimenez are presented in the Annex. Similarly, calibrated annual flows show slight differences from the annual naturalized flows. The error in volume is about 10% on average. The largest error is for Jimenez in the upper basin. Comparisons between annual simulated and observed flows are shows in the Annex.



a) Ojinaga



b) El Granero



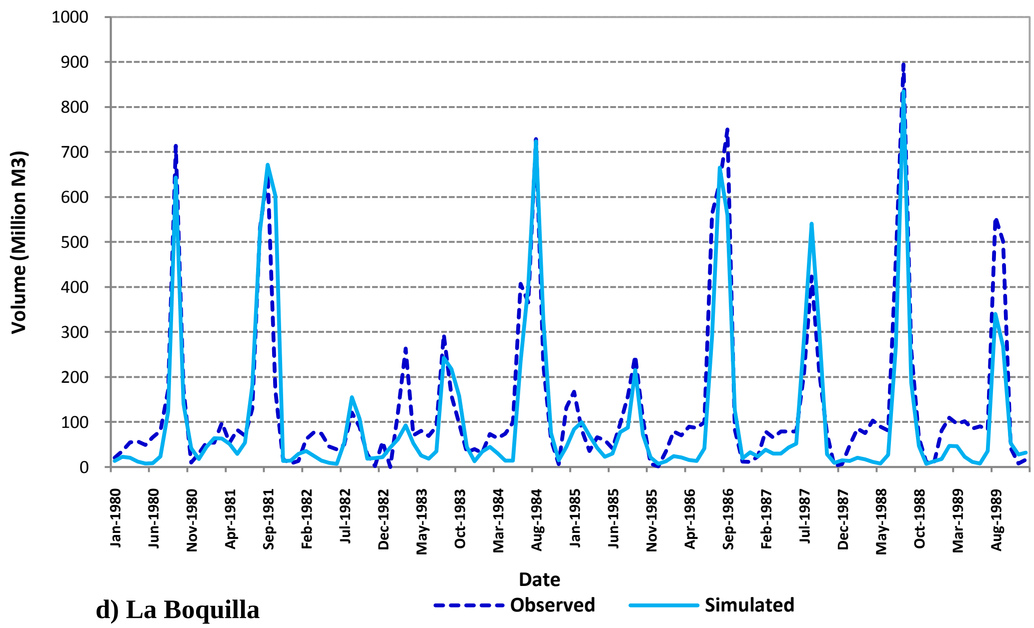


Figure 10. Monthly observed and simulated streamflows at selected stations in the Rio Conchos basin. (a) Ojinaga, (b) El Granero, (c) Las Burras, and (d) La Boquilla.

Figures 11a-d show the relationship between the monthly simulated and observed flows for the calibration period.

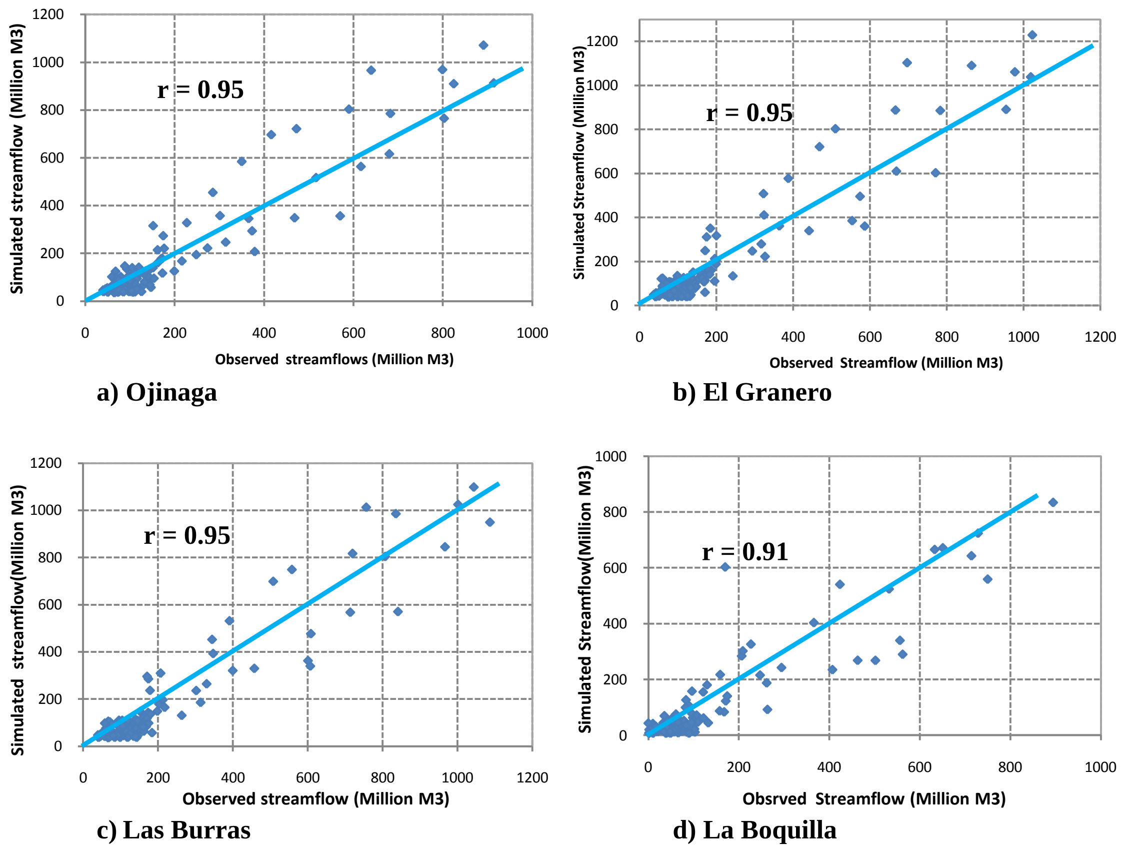
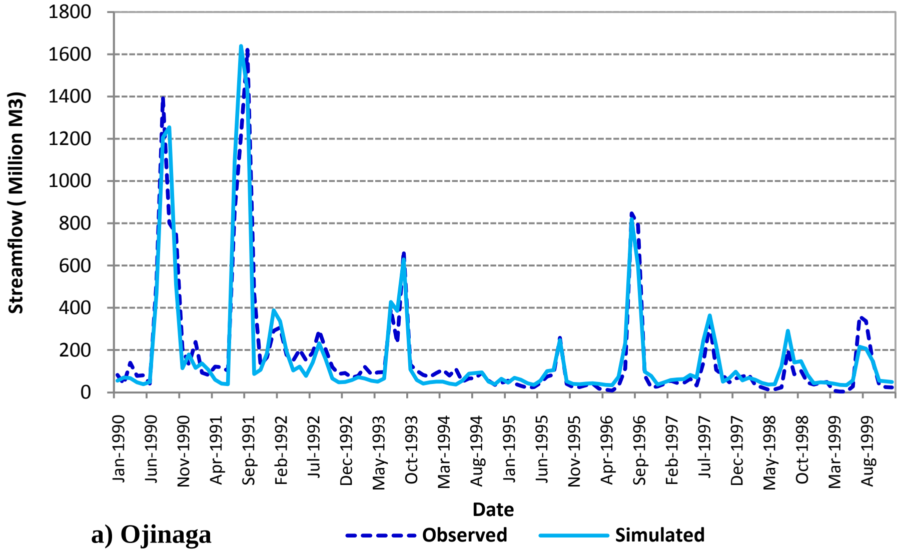


Figure 11. Relationship between monthly observed and simulated streamflows in control stations: (a) Ojinaga, (b) El Granero, (c) Las Burras, and (d) La Boquilla.

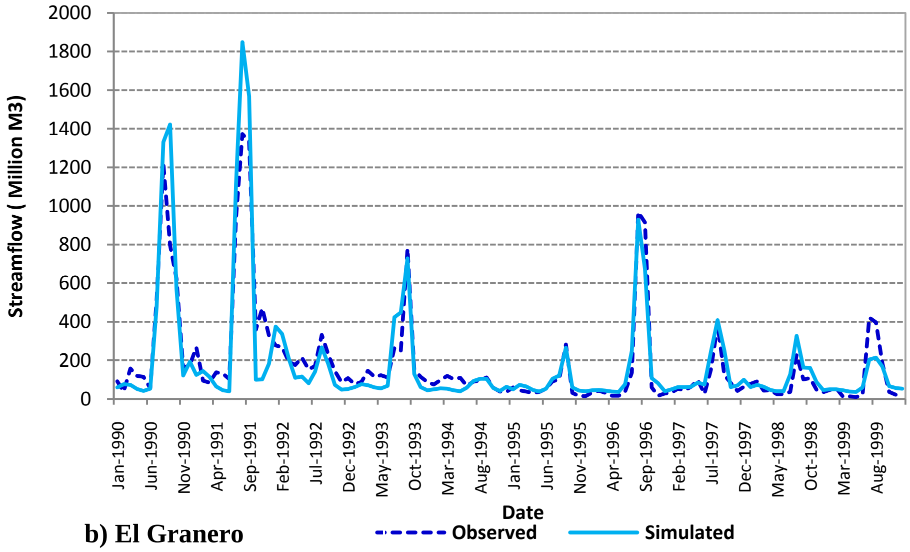
4.2 Validation

In order to validate the calibration of the hydrological model, it was run for a time period out of the calibration period, 1990 - 1999. Moreover, this time period presents drought conditions which are very important to assess the model performance since the calibration period was performed in normal hydrologic conditions. The results of the model validation are presented in Figures 12a-d. For all the selected stations, simulated monthly flows are close to the naturalized flows. On the other hand, the relationship between these flows indicates a high correlation for the Ojinaga, Granero, and Granero stations, with correlation rates higher than 0.94 (Figures 13a-c). The model shows good performance in reproducing the flows in the La Boquiilla, Villalba, and Jimenez stations.

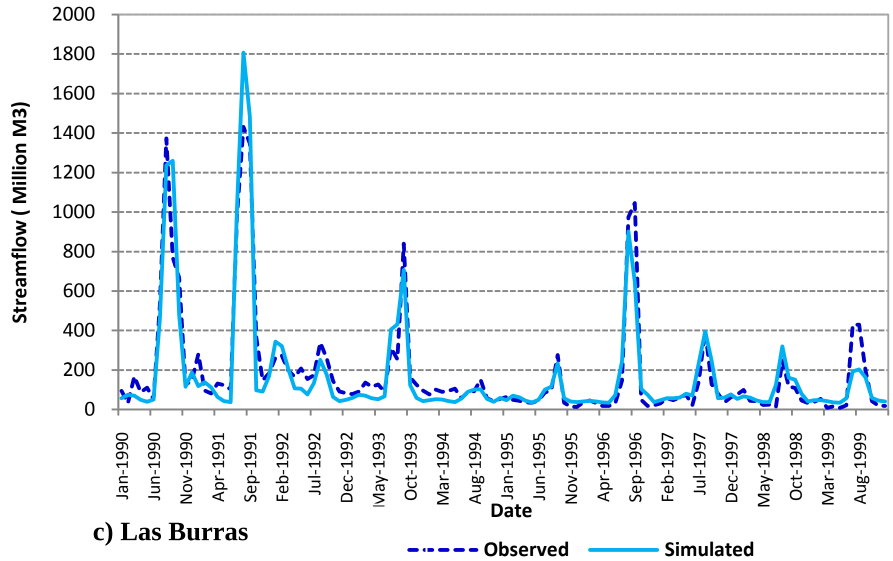
The model calculates accurately the peak and base flows. On a seasonal basis, the model tends to do better for summer and fall flows.



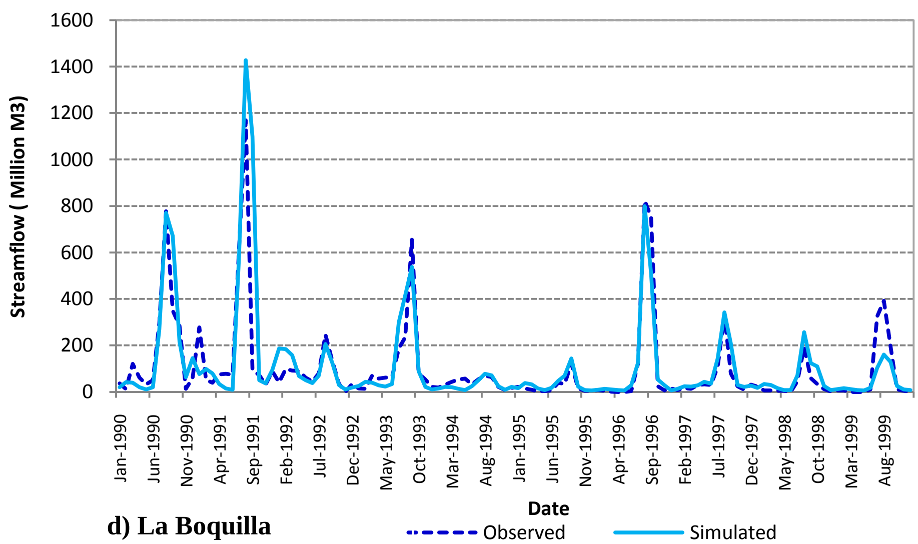
a) Ojinaga



b) El Granero

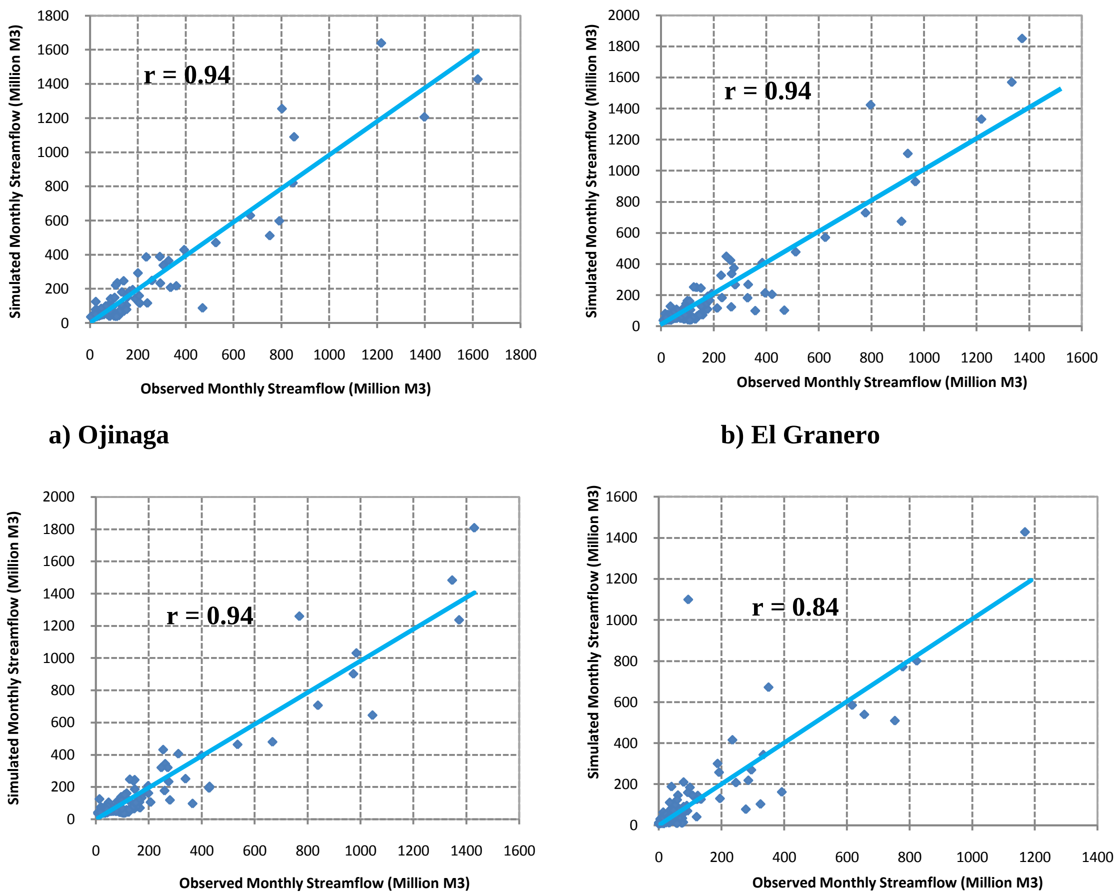


c) Las Burras



d) La Boquilla

Figure 12. Monthly variation of observed and simulated stream flows for the validation period; (a) Ojinaga, (b) El Granero, (c) Las Burras, and (d) La Boquilla.



a) Ojinaga **b) El Granero**

c) Las Burras **d) La Boquilla**

Figure 13. Relationship between monthly observed and simulated streamflows for the validation period for the stations: (a) Ojinaga, (b) El Granero, (c) Las Burras, and (d) La Boquilla.

4.3 Statistical Analysis

Table 5 shows the statistical summary of the comparison between simulated and observed streamflow values for the calibration period. Big differences on the mean flows are presented in the La Boquilla and Las Burras stations. Likewise, as it was mentioned above, the mean absolute error (MAE) and root mean square error (RMSE) are used to measure the deviation between the model outputs and the observed flows; it is noted that MAE shows smaller deviation than the RMSE (RMSE > MAE), with slight differences for the annual stream flows. In addition, for annual flows, the deviations computed with both statistical parameters are smaller than the monthly streamflows. This behavior shows that the largest variance in the differences between simulated and observed values are found in the monthly streamflows. In terms of volume errors, small differences for monthly and annual mean streamflow are found in Villalba, El Granero, and Ojinaga stations, with errors less of 3 %. In hydrologic modeling for water resources management, errors less than 10 % can be considered as very good, when the errors are within 10 and 20 % as good, and fair performance of the model when the error are 20 and 30 %. In Table 3, 3 of 5 control stations considered, the mean monthly and annual error were within 10 % (very good), 1 control station was within 10 and 20 % (good), and only one station was in the fair performance range (Rio Florido at CD Jimenez, see Table 5). Also, the biggest differences between the naturalized and simulated flows are in La Boquilla, Jimenez, and Las Burras stations, with errors of 19.5 %, -33.44%, and 14.12%, respectively; however, for the validation period the errors are lower than those listed above (see Table 6). The negative error indicates the model overestimates the flows in that station.

Moreover, Table 5 presents the Nash coefficients for monthly and annual values. It ranges from -0.12 to 0.87. A negative value was computed for annual streamflows at the Jimenez station meaning in this case that the square of the differences between observed and simulated values is larger than the variability of the observed values; therefore the mean observed is a better indicator that the simulated. In Table 6, for the validation period, the Nash coefficient ranges from 0.60 to 0.97 indicating a very good agreement between modeled and observed flows. On the other hand, the index of agreement ranges from 0.81 to 0.97 and from 0.91 to 0.99 for the calibration and validation period, respectively (Tables 5 and 6), showing similarly as Nash coefficient, a high agreement between simulated and observed. Additionally, the overall correlation coefficient varies from 0.88 to 0.95, indicating a strong relationship between simulated and observed flows. Larger correlation coefficients exist in the lower basin stations located, such as Las Burras, El Granero, and Ojinaga. Uncertainties in the measured data, and the average climatology data used for each sub catchment, as well as the complex hydrological characteristics of the upper basin, influence this behavior.

Table 5. Summary of Annual and Monthly Fit Statistics for Simulated by WEAP and Observed Stream Flows at 5 gage Stations in the Conchos River Basin, January 1980 through December 1989. Calibration Period

Statistics	Rio San Pedro at Villaba		Rio Conchos at Presa La Boquilla		Rio Florido at CD. Jimenez		Rio Conchos at Las Burras		Rio Conchos at Granero		Rio Conchos at Ojinaga	
	Monthly	Annual	Monthly	Annual	Monthly	Annual	Monthly	Annual	Monthly	Annual	Monthly	Annual
Number of Months/years	120	10	120	10	120	10	120	10	120	10	120	10
Mean Observed Flow (m^3/s)	11.45	11.50	52.13	52.26	5.46	5.50	81.45	81.66	78.23	78.43	71.66	71.85
Mean Simulated Flow (m^3/s)	11.31	11.36	41.87	42.04	7.28	7.34	69.86	70.13	75.52	75.81	70.36	70.63
STDEV Observed	22.19	6.82	67.90	18.52	12.15	3.95	88.80	23.46	85.09	22.58	75.17	20.90
Median observed (m^3/s)	2.54	9.80	30.13	51.25	0.60	5.14	47.70	78.94	45.51	75.19	40.83	68.29
Median simulated (m^3/s)	2.32	9.03	13.96	39.18	0.87	5.76	32.11	67.08	34.04	72.19	33.42	65.64
STDEV Simulated	24.10	7.46	65.73	18.06	14.73	6.00	93.21	27.09	100.91	30.00	89.80	28.05
Mean Absolute Error (m^3/s)	5.55	3.05	19.79	13.16	3.04	2.35	23.43	14.34	22.92	11.03	19.86	9.21
Root Mean Square Error (m3/s)	12.57	4.23	29.72	15.32	7.15	3.96	31.54	16.54	33.70	13.18	30.07	11.22
Error in Volume (%)	1.19	1.19	19.55	19.55	-33.44	-33.44	14.12	14.12	3.34	3.34	1.70	1.70
Nash-Sutcliffe Coefficient(E)	0.68	0.57	0.81	0.24	0.65	-0.12	0.87	0.45	0.84	0.62	0.84	0.68
Index of Agreement(IA)	**0.92**	**0.90**	**0.95**	**0.81**	**0.93**	**0.81**	**0.97**	**0.89**	**0.97**	**0.93**	**0.97**	**0.94**
Coefficient of Determination (r2)	0.73	-	0.83	-	0.78	-	0.90	-	0.90	-	0.90	-
Coefficient of Correlation (r)	0.85	-	0.91	-	0.88	-	0.95	-	0.95	-	0.95	-

Table 6. Summary of Annual and Monthly Fit Statistics for Simulated by WEAP and Observed Stream Flows at 5 gage Stations in the Conchos River Basin, January 1990 through December 1999. Validation Period

Statistics	Rio San Pedro at Villaba		Rio Conchos at Presa La Boquilla		Rio Florido at CD. Jimenez		Rio Conchos at Las Burras		Rio Conchos at Granero		Rio Conchos at Ojinaga	
	Monthly	**Annual**	**Monthly**	**Annual**	**Monthly**	**Annual**	**Monthly**	**Annual**	**Monthly**	**Annual**	**Monthly**	**Annual**
Number of Months/years	120	10	120	10	120	10	120	10	120	10	120	10
Mean Observed Flow (m^3/s)	12.48	12.45	37.17	37.44	5.81	5.85	68.83	69.08	68.61	68.86	64.53	64.75
Mean Simulated Flow (m^3/s)	11.71	12.03	41.53	41.69	4.61	4.63	65.85	66.05	69.62	69.84	64.32	64.52
Median observed (m^3/s)	2.25	7.23	13.00	30.25	0.44	2.20	34.93	57.69	37.30	56.06	30.96	49.20
Median simulated (m^3/s)	2.42	6.74	11.22	33.15	0.35	2.68	25.85	52.85	26.88	55.83	25.26	53.12
STDEV Observed	29.23	12.37	69.59	25.34	15.13	6.87	104.23	47.89	99.07	50.01	101.56	49.41
STDEV Simulated	29.52	12.30	80.64	32.12	11.78	4.46	109.87	46.57	116.57	49.66	105.17	45.41
Mean Absolute Error (m^3/s)	4.99	1.63	17.44	8.83	2.32	1.91	21.89	7.57	23.66	7.66	20.72	6.91
Root Mean Square Error (m3/s)	11.38	2.15	43.96	11.70	5.72	2.97	36.46	8.49	40.99	8.56	34.98	7.74
Error in Volume (%)	6.18	3.36	-11.34	-11.34	20.84	20.84	4.39	4.39	-1.42	-1.42	0.37	0.37
Nash-Sutcliffe Coefficient(E)	0.85	0.97	0.60	0.76	0.86	0.79	0.88	0.97	0.83	0.97	0.88	0.97
Index of Agreement(IA)	**0.96**	**0.99**	**0.91**	**0.95**	**0.95**	**0.92**	**0.97**	**0.99**	**0.96**	**0.99**	**0.97**	**0.99**
Coeficient of Determination (r2)	0.86	-	0.71	-	0.89	-	0.89	-	0.88	-	0.89	-
Coeficient of Correlation (r)	0.92	-	0.84	-	0.94	-	0.94	-	0.94	-	0.94	-

5. Conclusions

The hydrological model constructed in WEAP reproduces well the response of the basin. Comparisons carried out between simulated and naturalized stream flows, for both monthly and annual; indicate that is possible represent the dynamics of flow in the basin to assess climate change impacts under different climate change scenarios. However, it is necessary take into account uncertainties propagated in the hydrological modeling process which may have serious impacts on water resources management and on water supply forecasts. Relationships between naturalized and simulated values show a high correlation, meaning good model performance in reproducing the stream flows trend.

Nash coefficient and Index of Agreement were used to evaluate the performance of hydrologic model. The results indicate a high agreement between simulated and observed streamflows.

References

Amato, C. C., D. C. McKinney, E. Ingol-Blanco, and R. L. Teasley. 2006. WEAP Hydrology Model Applied: The Rio Conchos Basin, CRWR Online Report 06-12, Center for Research in Water Resources, University of Texas at Austin

Barbaro, J., and P. Zarriello. 2006. A precipitation –Runoff Model for the Blackstone River Basin, Massachusetts and Rhode Island. Scientific Investigations Report 2006-5213. U.S. Department of the Interior, U.S Geological Survey.

Brandes, R.J. 2003. Water Availability Modeling for the Rio Grande Basin, Naturalized Streamflow Data. Texas Commission on Environmental Quality. Final Report

Chow, V., D. Maidment, L. Mays, Applied Hydrology, McGraw-Hill, 1988.

Fleming, M., and V. Neary. 2004. Continuous Modeling Study with the Hydrologic Modeling System. Journal of Hydrologic Engineering. ASCE, 175-183.

Gomez, J., Mejia R., and A. Gutierrez. 2005. Study of Distributed Models for the Simulation of basin runoff: Application to the Conchos River Basin, Tributary of Bravo River. Mexican Institute of Water Technology (IMTA). SEMARNAT-2002-C01-0569.A3. Final Report.

Intergovernmental Panel on Climate Change (IPCC), 2008: Climate Change and Water. IPCC technical paper VI. http://www.ipcc.ch/ipccreports/tp-climate-change-water.htm

Intergovernmental Panel on Climate Change (IPCC), 2001: The Scientific Basis. "Regional Climate Information – Evaluation and Projections" http://www.ipcc.ch/ipccreports/tar/wg1/index.htm

Joyce, B., S. Vicuna, L. Dale, D. Purkey, and D. Yates. 2006. Climate Change Impacts on Water for Agriculture in California: A case Study in the Sacrament Valley. California Energy Commission and the California Environmental Protection Agency.

Kim, T.W. and J., Valdes. 2005. Synthetic Generation of Hydrology Time Series Based on Nonparmetric Random Generation. Journal of Hydrologic Engineering. ASCE, 10(5), 395-404.

Kim, T.W., J. Valdés, and J. Aparicio. 2002. Frequency and Spatial Characteristics of Droughts in the Conchos River Basin, Mexico. Water International. International Water Resources Association. 27(3), 420-430.

Legates, D.R., and Jr. McCabe. 1999. Evaluating the Use of "Goodness-of-Fit" Measures in Hydrologic and Hydroclimatic Model Validation. Water Resources Res; 35, 233-241.

North American Regional Reanalysis, NARR. 1980 -1999
http://nomads.ncdc.noaa.gov/thredds/catalog/narr/catalog.html

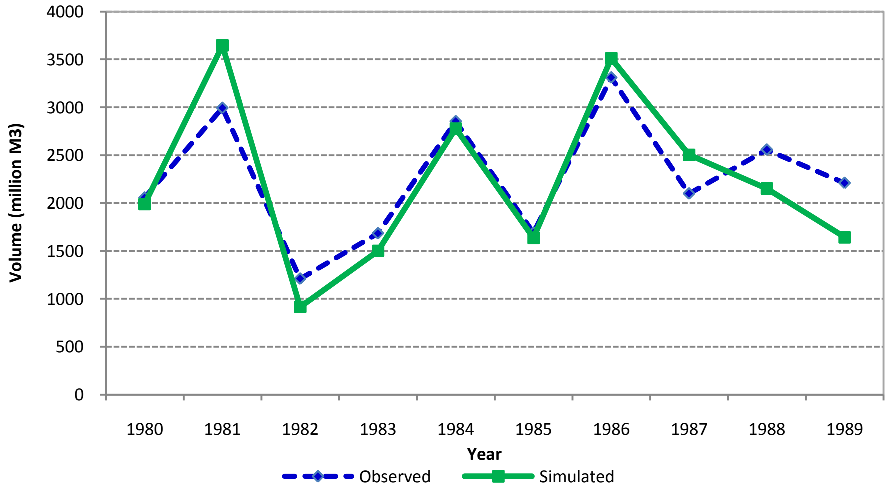
Pro Fauna. 2003. Physical and Hydrological Condition Indicators of the Rio Conchos, Chihuahua. Mexico

Stockholm Environment Institute, 2007. Water Evaluation and Planning System, WEAP. Boston.

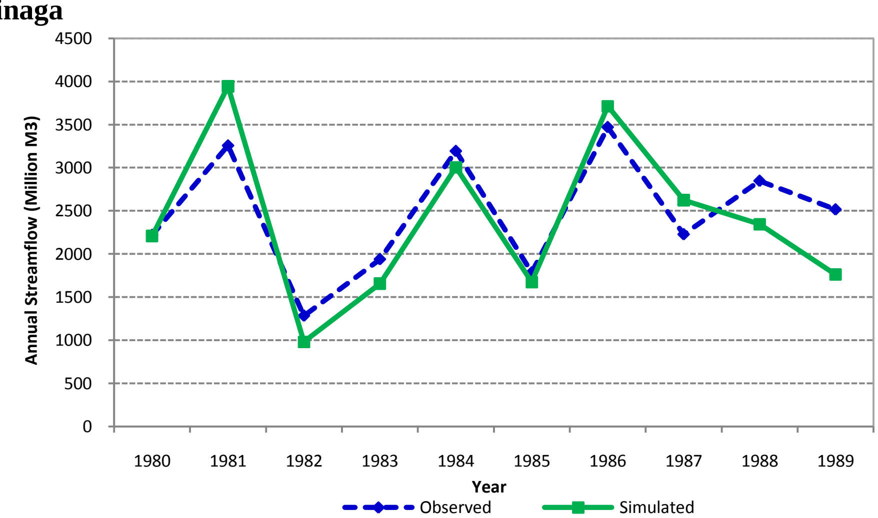
Yates, D., D. Purkey, J. Sieber, A. Huber-Lee, J. West, and H. Galbraith. 2006. A Physically-based, Water Resources Planning Model of the Sacrament Basin, California. J. of Water Resources Planning and Management.

Yates, D., and K. Strzepek. 1998. Modeling the Nile Basin under Climate Change. Journal of Hydrologic Engineering. ASCE, 20(3), 98-108.

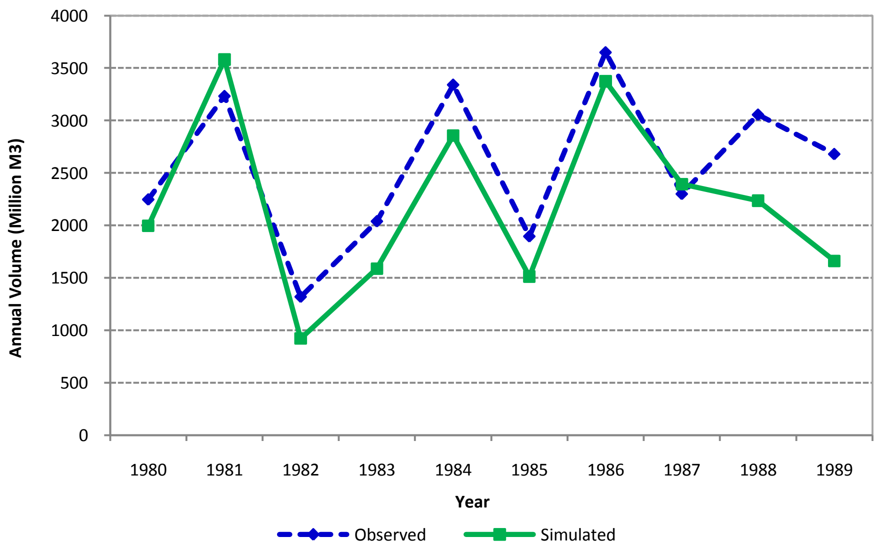
Annex A Calibration Period 1980-1989



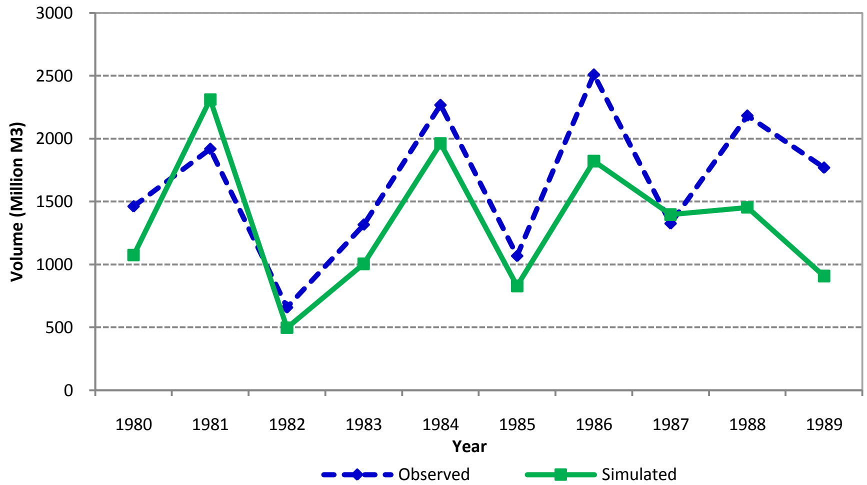
a) **Ojinaga**



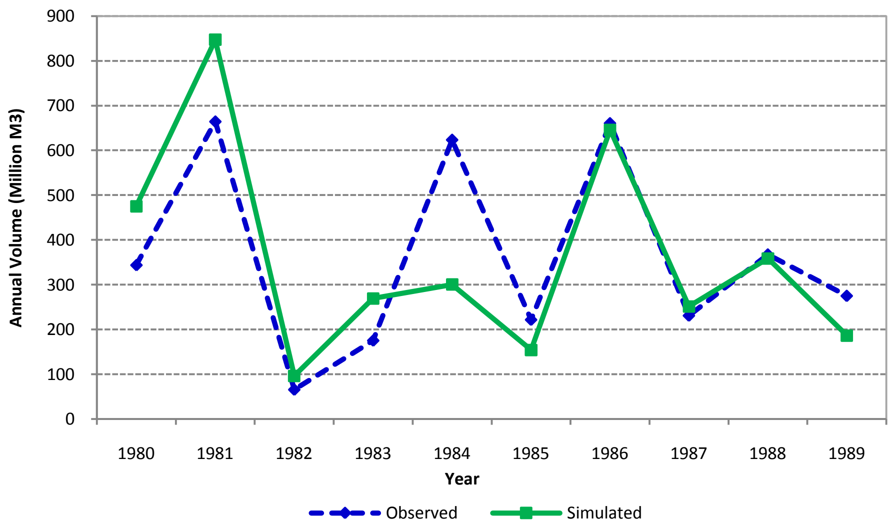
b) **Granero**



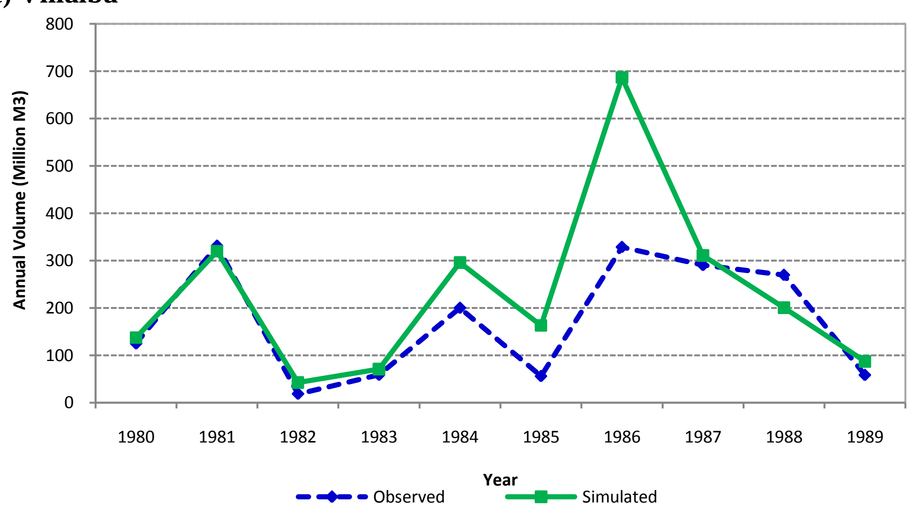
c) **Las Burras**



d) La Boquiilla

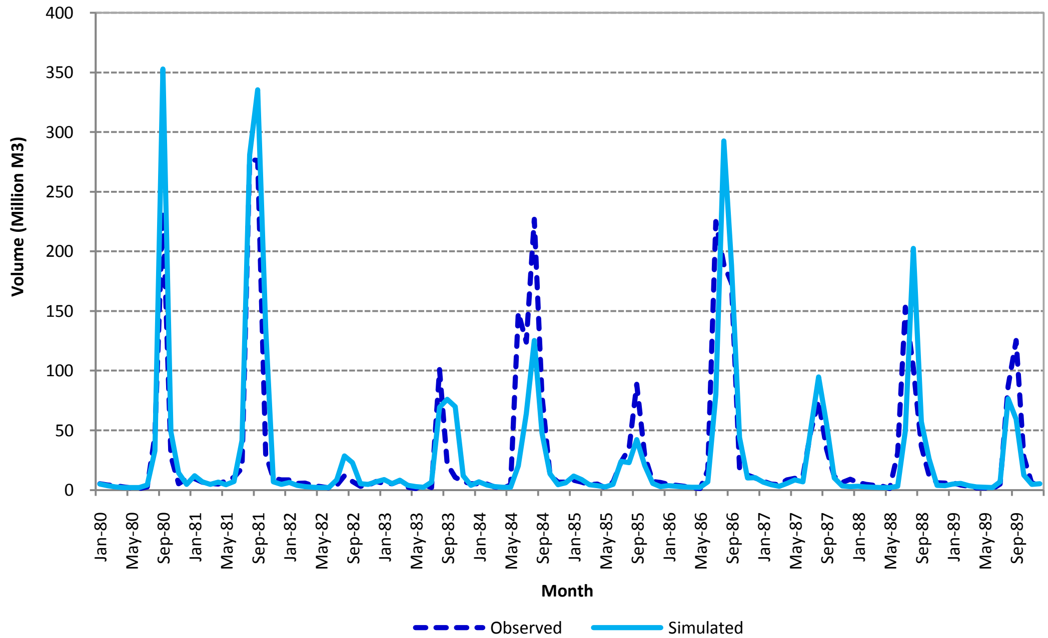


e) Villalba

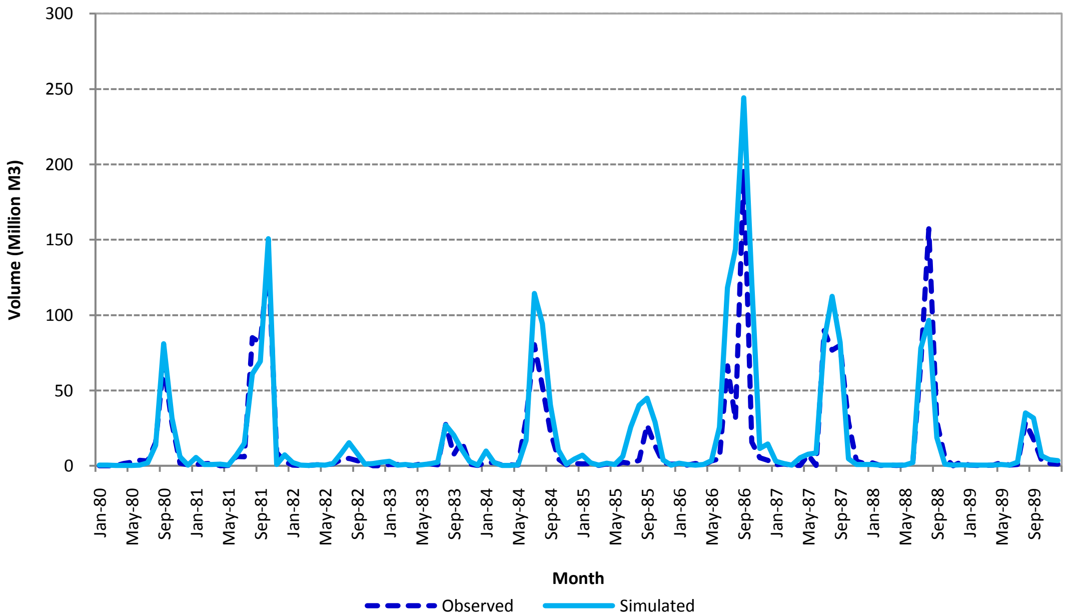


f) Jimenez

Figure A1. Annual simulated and observed streamflows (1980-1989) in calibration period (1980-1989): (a) Ojinaga, (b) El Granero, (c) Las Burras, (d) La Boquilla, (e) Villalba, and (f) Jimenez

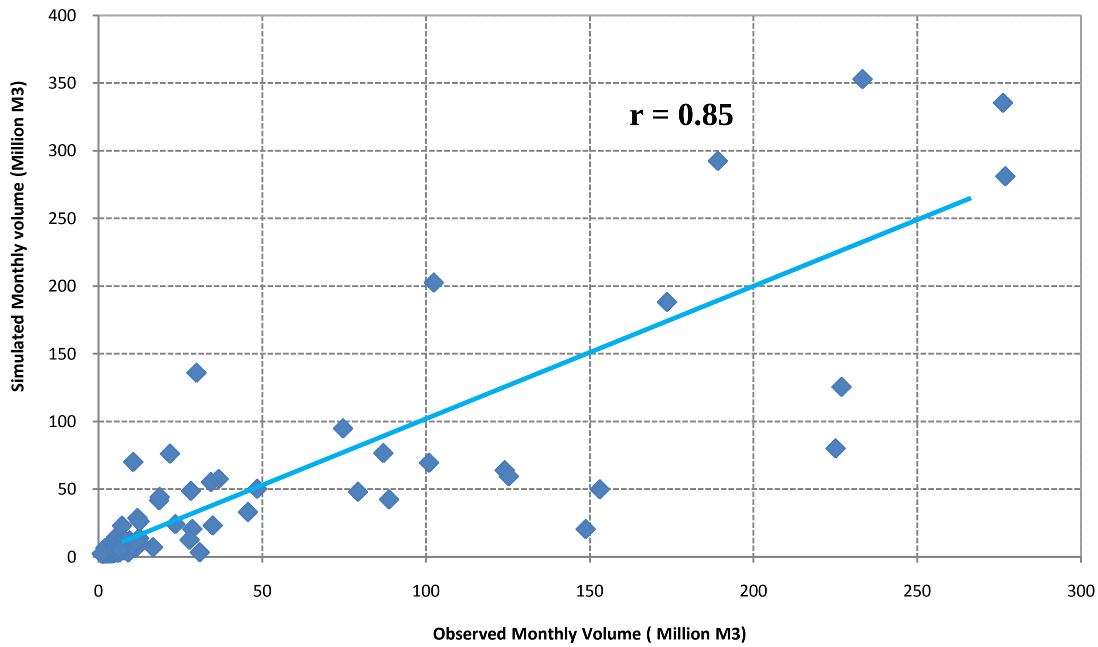


a) **Villaba**

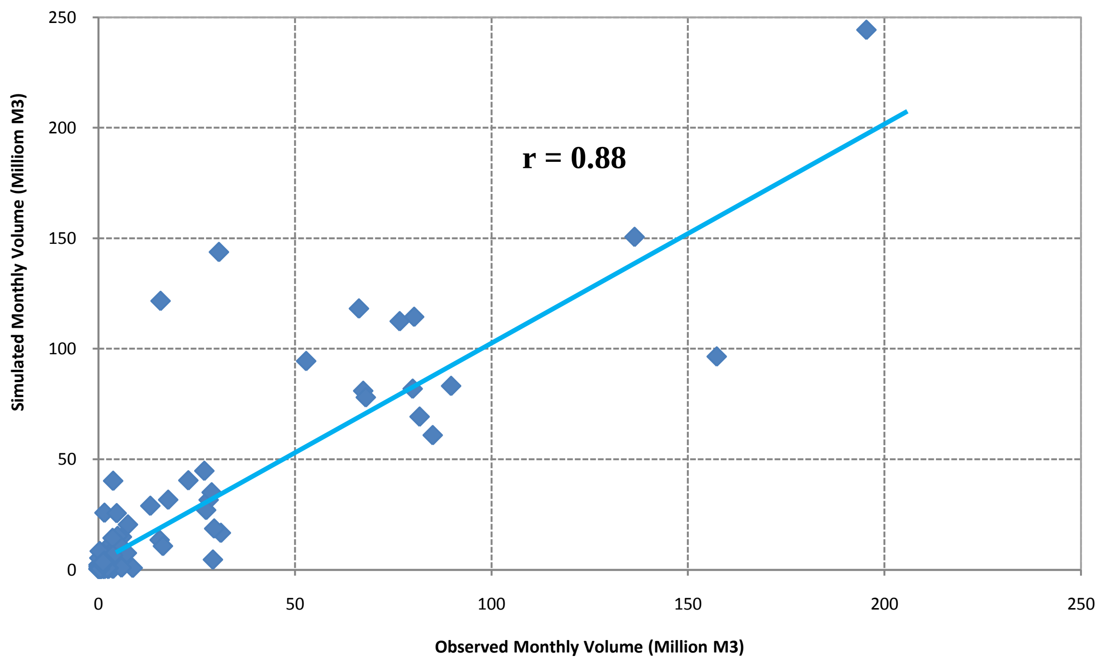


a) **Jimenez**

Figure A2. Monthly Simulated and observed streamflows in calibration period (1980-1989): (a) Villalba and (b) Jimenez stations.

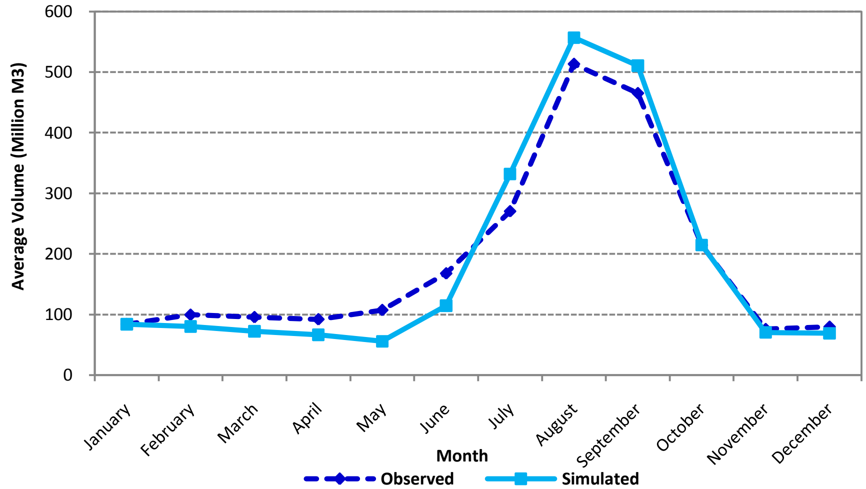


a) Villalba

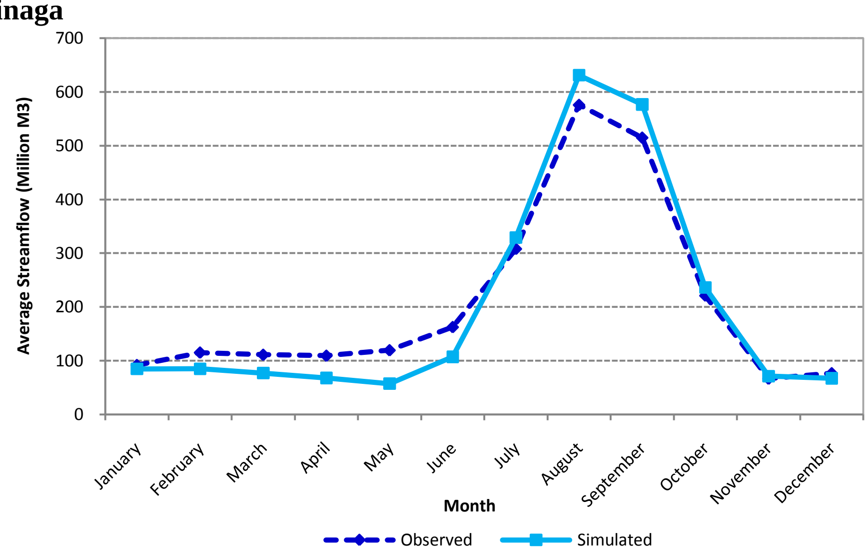


a) Jimenez

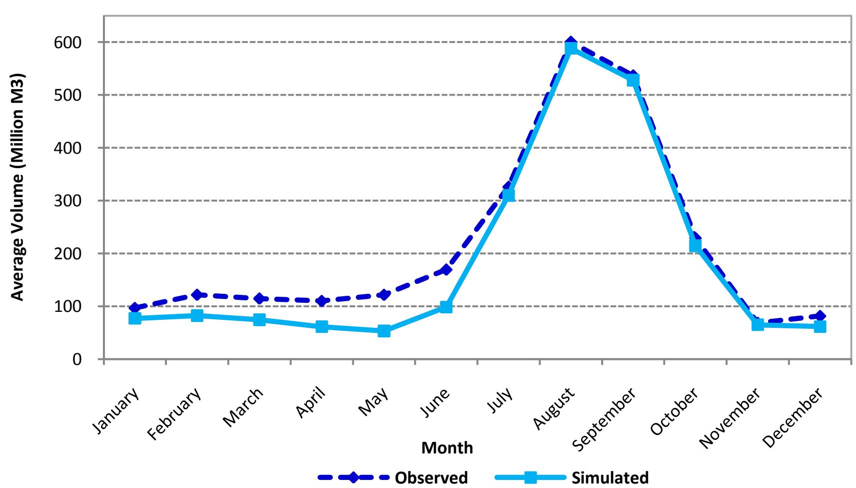
Figure A3. Relationship between monthly observed and simulated streamflows in calibration period (1980-1989): (a) Villaba, and (b) Jimenez.



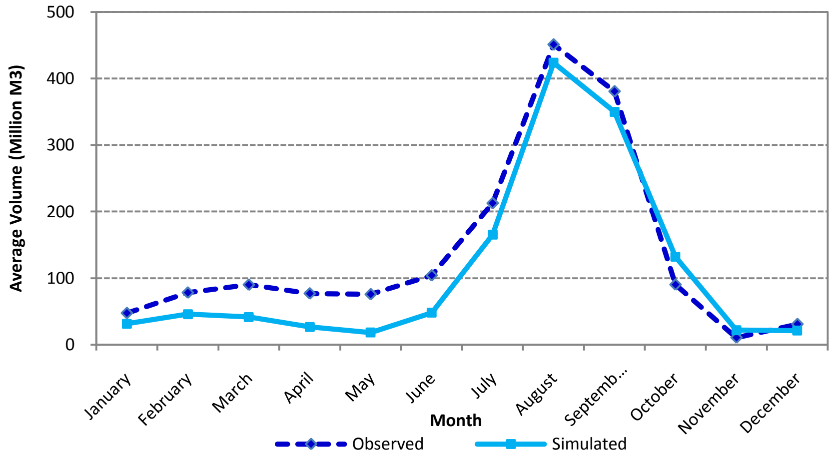
a) Ojinaga



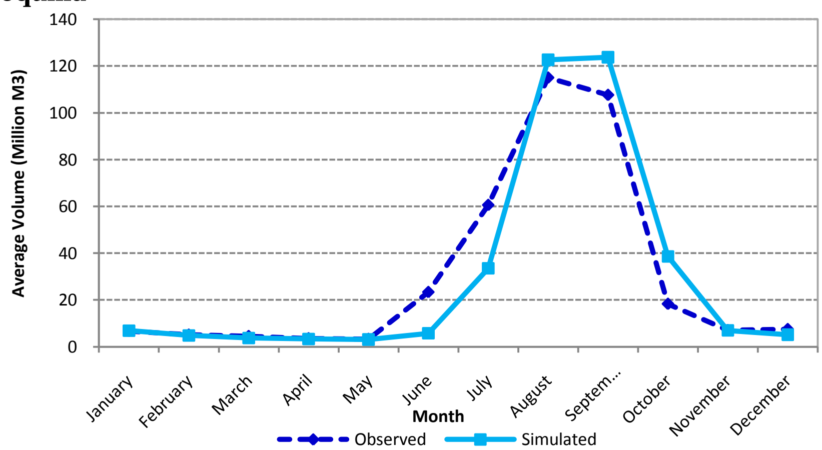
b) El Granero



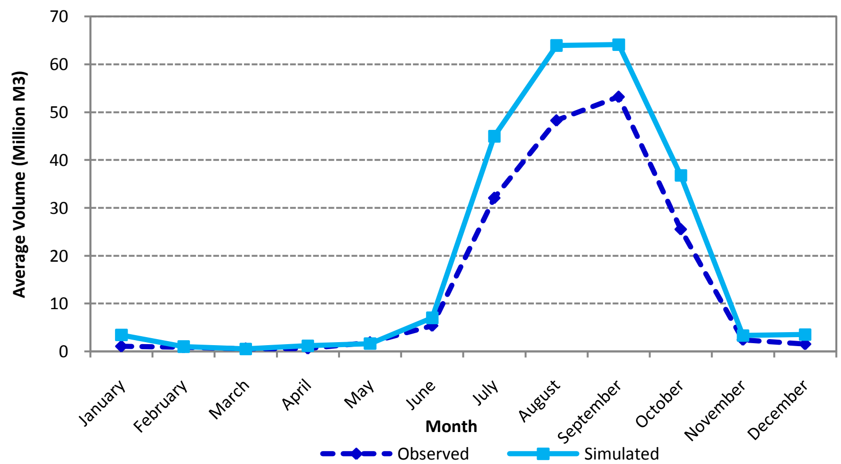
c) Las Burras



d) La Boquilla



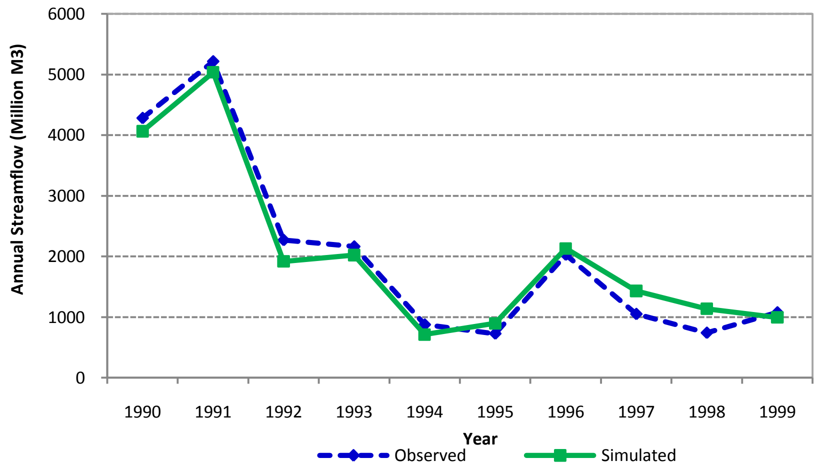
e) Villalba



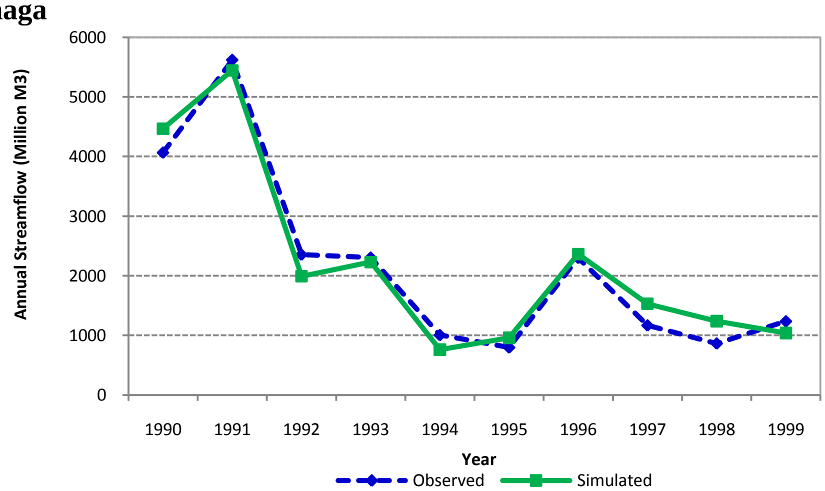
f) Jimenez

Figure A4. Simulated and observed monthly average streamflows calibration period (1980-1989)

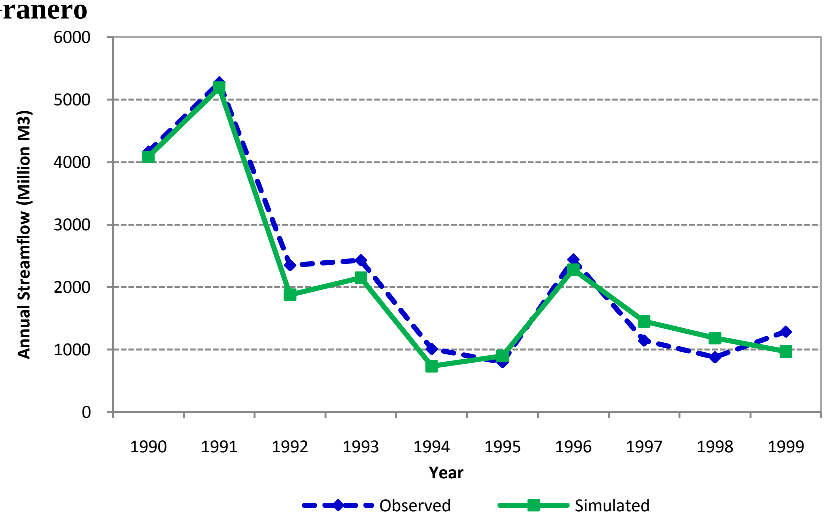
Annex B Validation Period 1990-1999



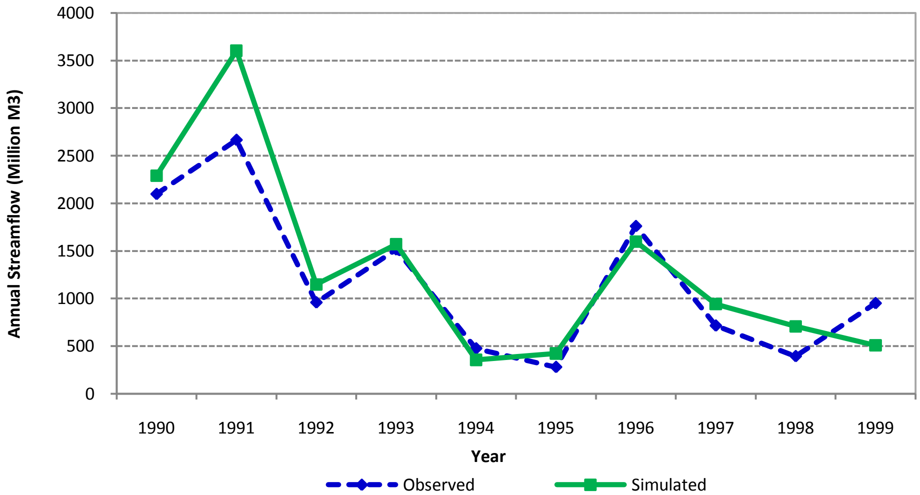
a) Ojinaga



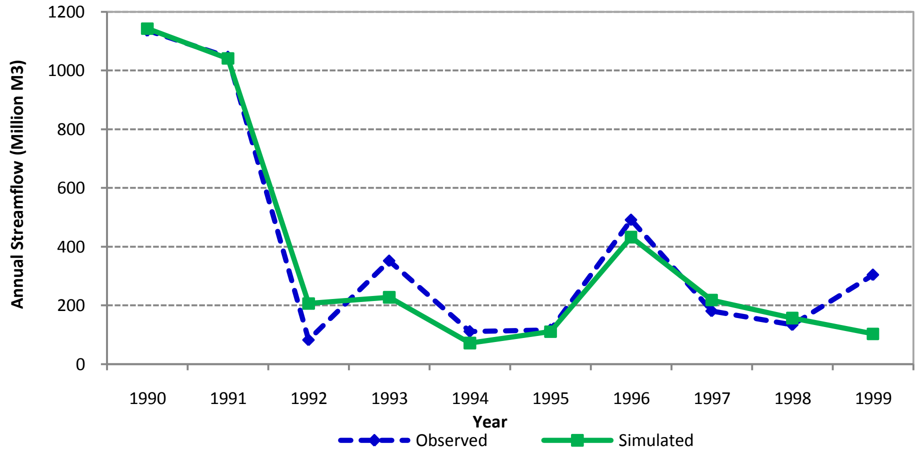
b) El Granero



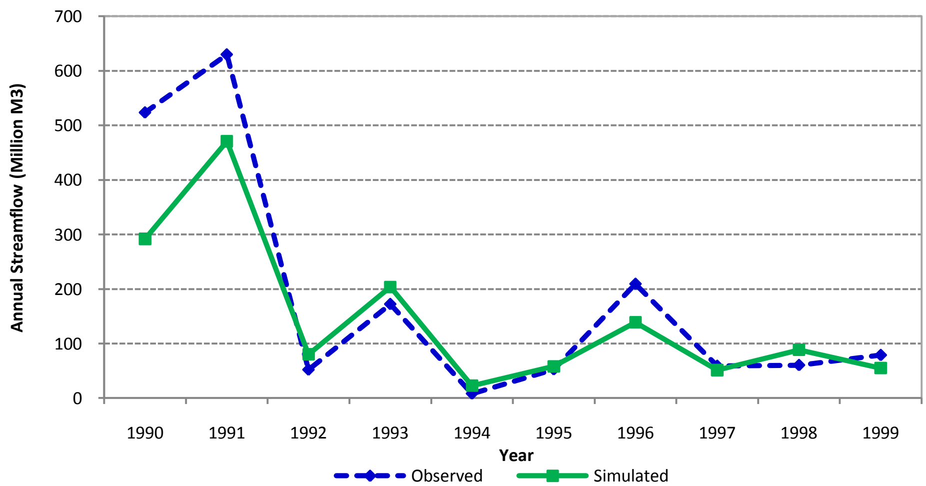
c) Las Burras



d) La Boquilla

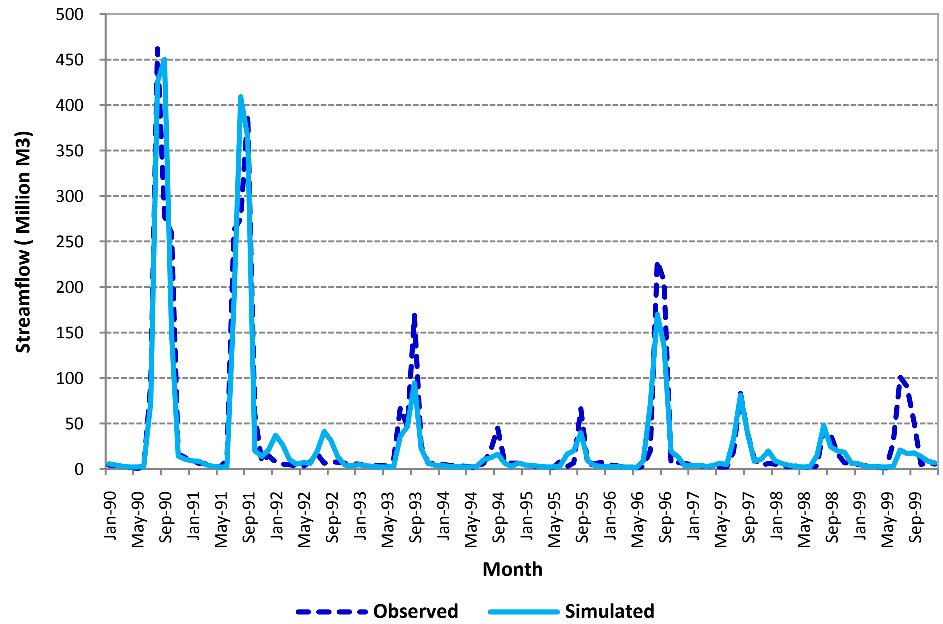


e) Villalba

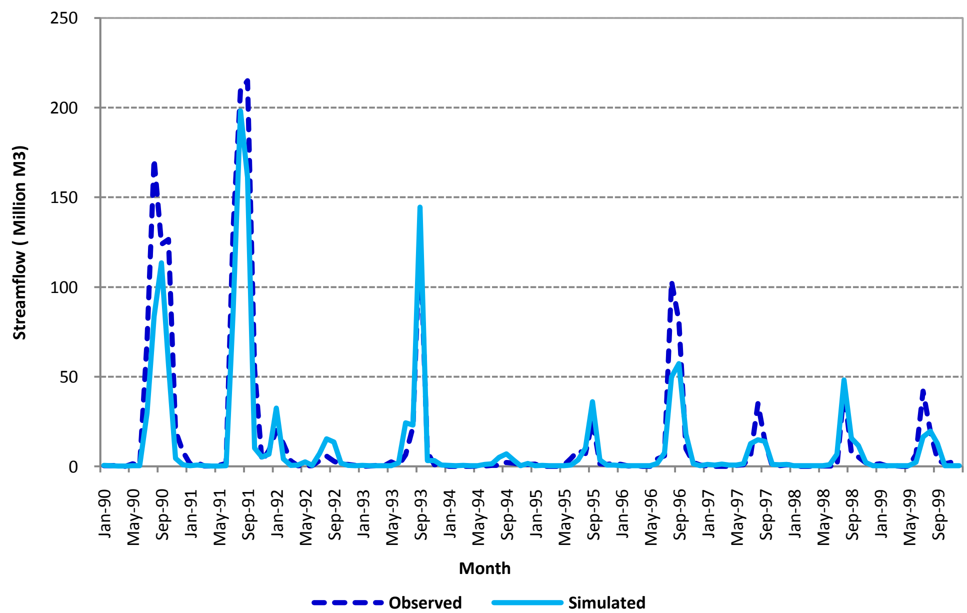


f) Jimenez

Figure B1. Annual simulated and observed streamflows for the validation period (1990-1999): (a) Ojinaga, (b) El Granero, (c) Las Burras, (d) La Boquilla, (e) Villalba, and (f) Jimenez



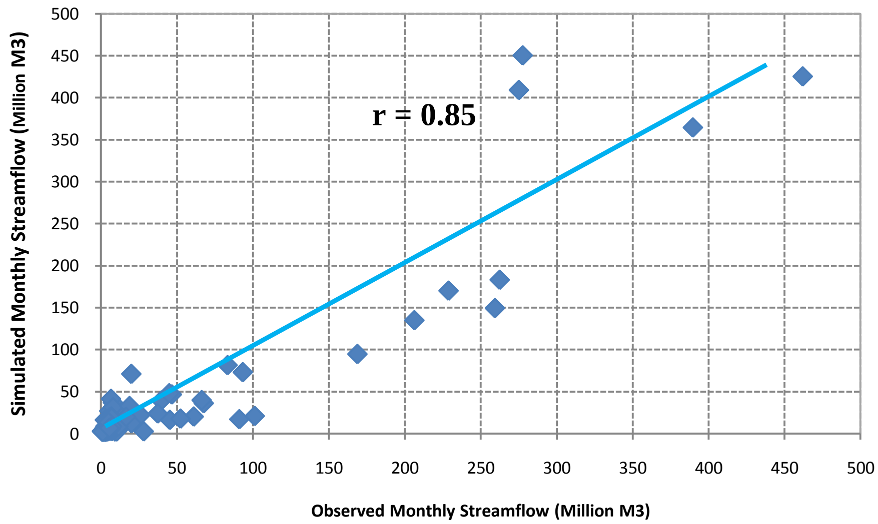
a) Villalba



b) Jimenez

Figure B2. Monthly simulated and observed streamflows for the validation period (1990-1999): (a) Villalba and (b) Jimenez stations.

a) Villalba



b) Jimenez

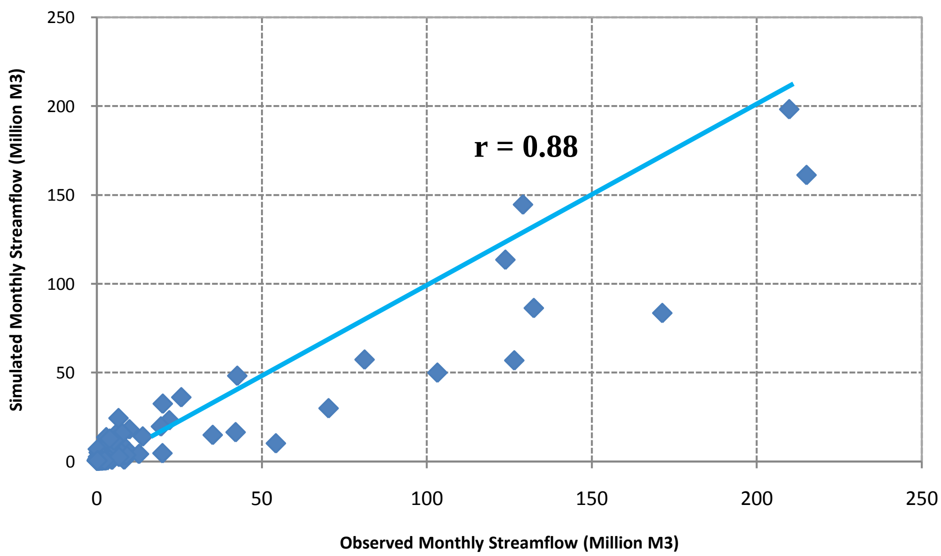
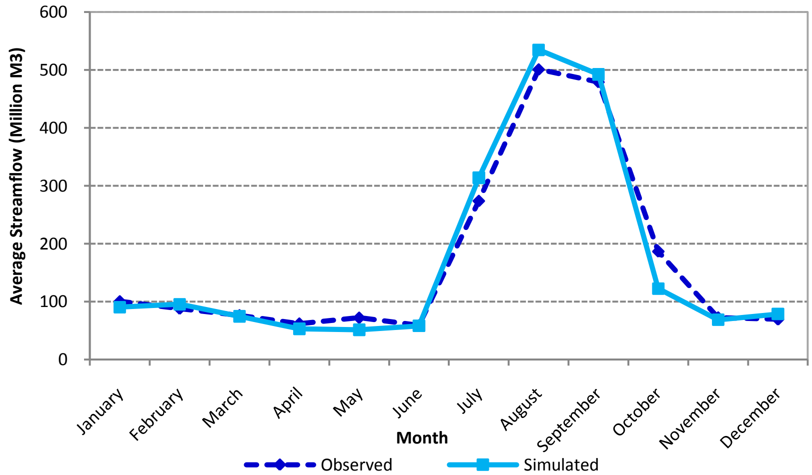
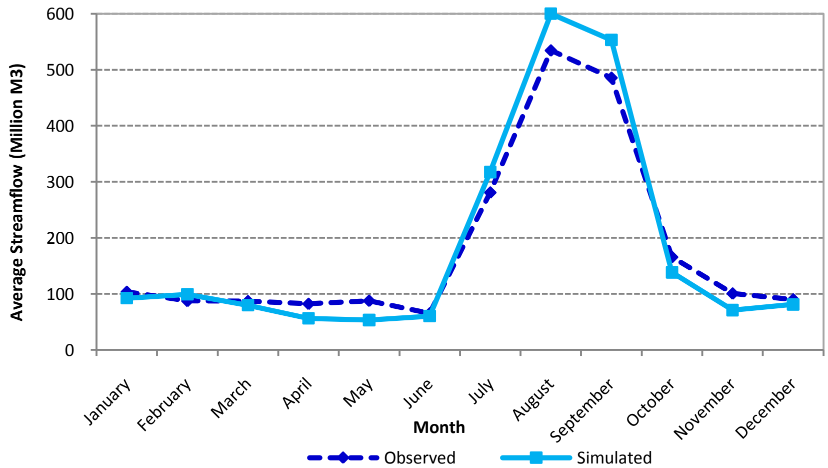


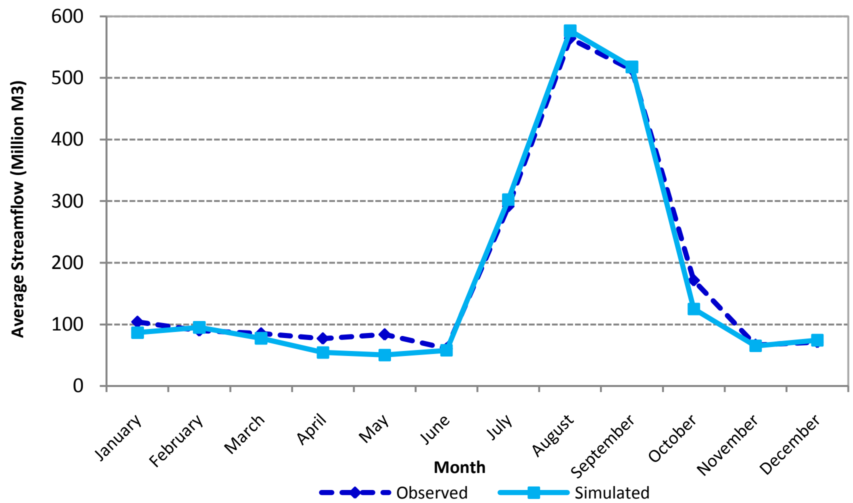
Figure B3. Relationship between monthly observed and simulated streamflows in validation period (1990-1999): (a) Villaba, and (b) Jimenez.



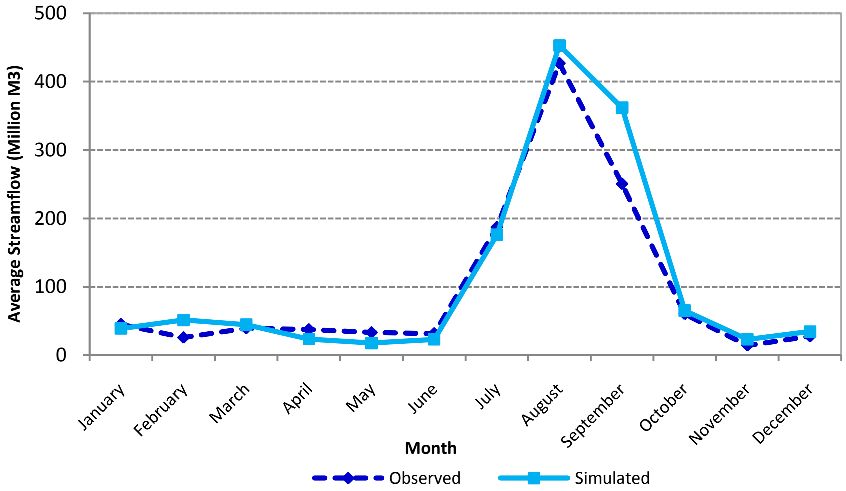
a) Ojinaga



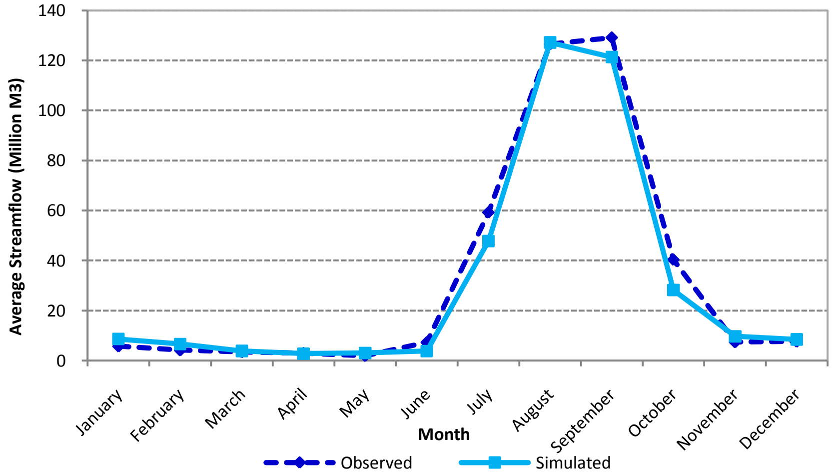
b) El Granero



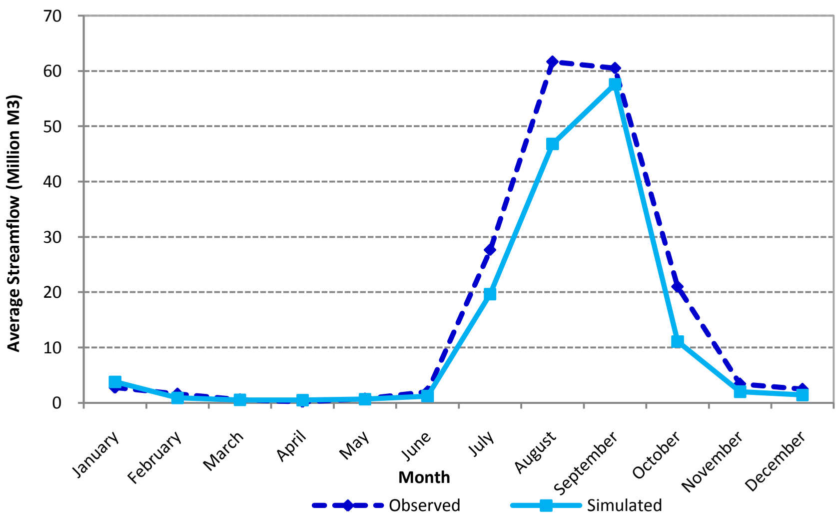
c) Las Burras



d) La Boquilla



e) Villalba



f) Jimenez

Figure B4. Simulated and observed monthly average streamflows in validation period (1990-1999)