The Impacts of Climate Change and Variability on Water Resources in a Semi Arid Region in Mexico: The Rio Yaqui-Basin.

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BACKGROUND

This work consists of determining the impacts of climate change and variability on precipitation and reservoir storage in the Yaqui Basin. The Yaqui basin is classified as an arid to semi-arid climate with an average rainfall of 527 mm and a mean annual temperature above 22°C.The basin consists of roughly 72,000 square kilometers of land located mainly in Northwest Mexico (Figure 1).

Figure 1. Location Map

The Yaqui River Basin includes one of the most important agricultural regions in Mexico, known as the Yaqui Valley (roughly 225,000 hectares). The Valley is the main user of water and is a vital source of economic activity. Other water users besides the farmers include rural and urban municipalities, industries, and mines. The water stored to satisfy the user demands comes from a series of three reservoirs constructed along the river.

Every water user within the basin holds water rights. The agricultural users in the Yaqui Valley hold the largest water rights for of 2500 million cubic meters (MCM) per year of surface water and up to 600 MCM of groundwater per year. The yearly acreage and type of crops planted is determined partially the surface water storage available on October 1st each year.

TASKS

The overall objective of this project is to develop an Integrated Hydrologic-Economic-Quality Water Model for the Yaqui River Basin. It will be designed as a tool to support decision-makers that manage water supplies while minimizing impacts to the environment. The specific tasks related to the current work are as follows.

- Develop a water balance model to determine storage in the reservoirs on a monthly basis.
- Create and calibrate a seasonal rainfall-runoff model using by calibrating predicted runoff against measured flows .
- Estimate the uncertainty of the rainfall-runoff model using a Monte Carlo approach.
- Incorporate climate change into the water balance model based on estimated changes in precipitation estimates from a Regional Climate Model.
- Develop a temporally-correlated precipitation model to account for year-to-year variability

WATER BALANCE MODEL

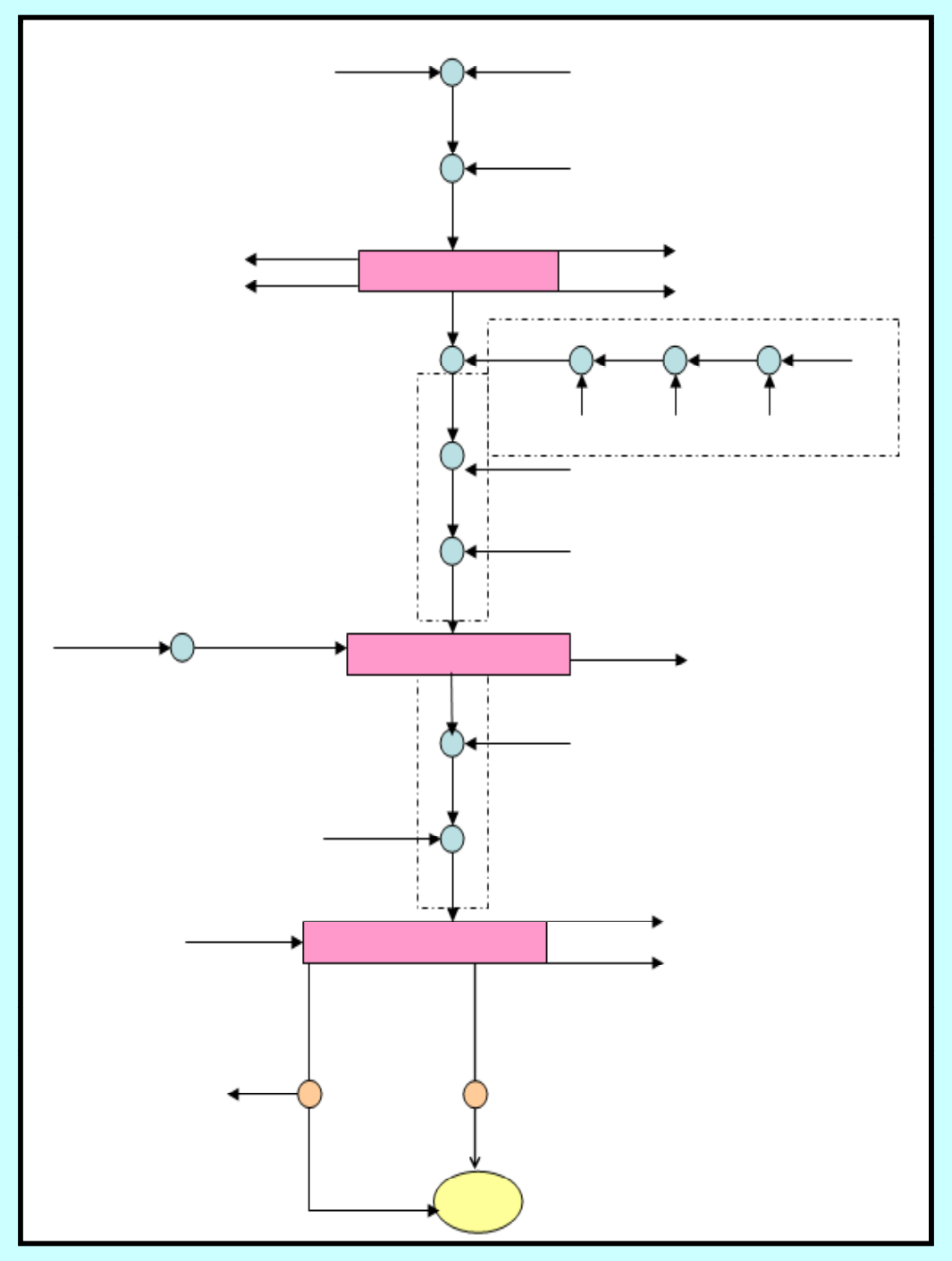


Figure 2.Node-link network model

The first step of the water balance model was to create a node-link network of the Rio Yaqui Basin, which is the conceptual basis for the surface water model (Figure 2).

This node-link network includes the primary reservoirs within the basin which are La Angostura, El Novillo, and El Oviachic. It also includes the river reaches, and locations of water demand. The total water rights allocated to the basin are approximately 3000 MCM (Minjares, 2004) as shown in Table 1 .

Table1. Rio Yaqui Basin Reservoirs

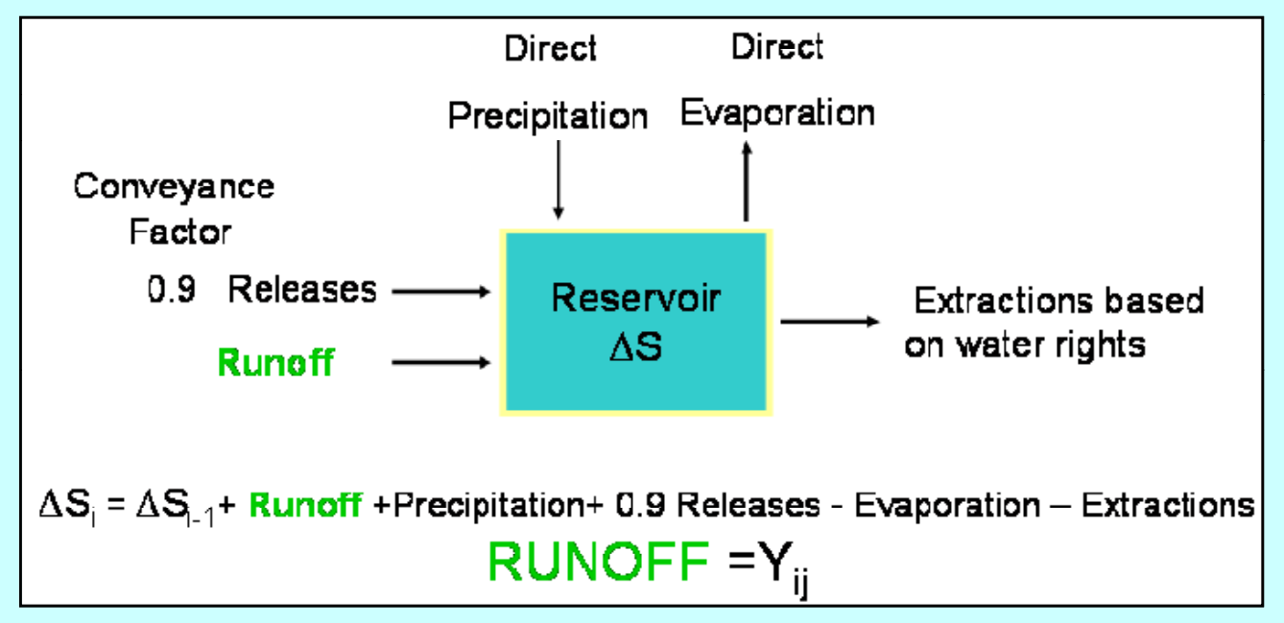
Reservoir	Capacity* (MCM)	Water Rights (MCM/yr)
La Angostura	880	57
El Novillo	2,799	NA
El Oviachic	2,782	2,800
Total	6,462	2,857

*less dead storage

A MATLAB code was developed in order to estimate the monthly storage of the main reservoirs for a period of thirty years. The model considers each surface water rights holder within the basin and takes into account priorities in allocating the water. The model also includes the maximum groundwater usage allowed to the Yaqui Valley farmers by their water rights, since farmers, are planning to be less dependent on surface water for irrigation.

The model solves a water balance on a monthly step (Figure 3). The input data such as direct precipitation, direct evaporation, and extractions comes from historical data. The runoff was obtained from a rainfall-runoff model developed in GIS.

Although the storage of the reservoirs is estimated on a monthly basis, the main objective was to determine the storage in the reservoirs in October of every year, when cropping decisions are made.



$\Delta S_i = \Delta S_{i-1} + \text{Runoff} + \text{Precipitation} + 0.9\ \text{Releases} - \text{Evaporation} - \text{Extractions}$

$\text{RUNOFF} = Y_{ij}$

Figure 3. Water Balance

CREATION AND CALIBRATION OF THE RAINFALL-RUNOFF MODEL

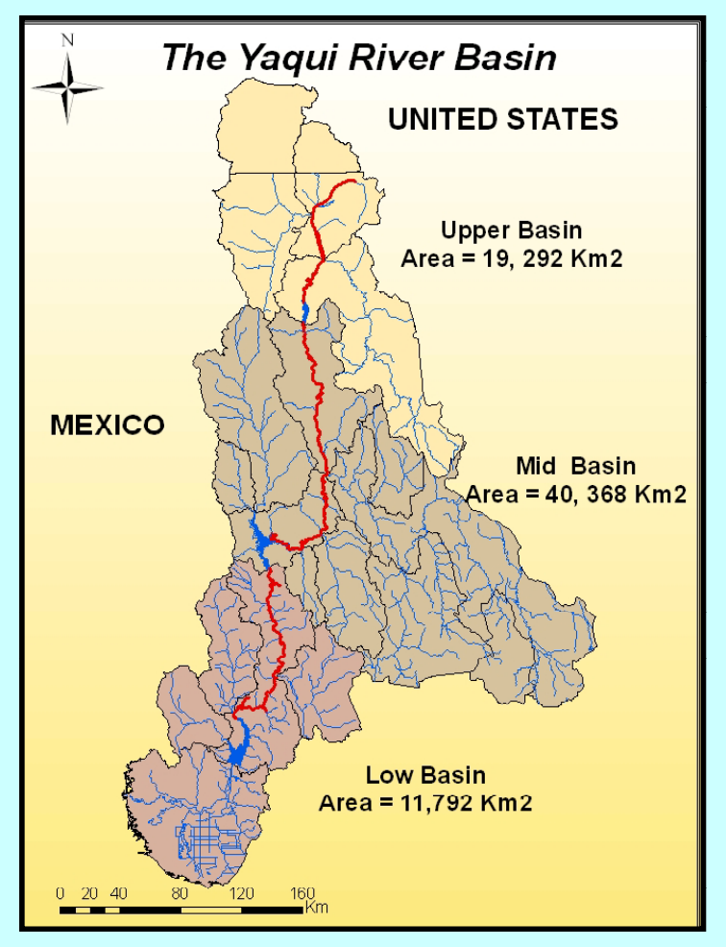


Figure 4. Sub-basins in the Rio Yaqui Basin

Sub-watersheds were delineated using DEM data and were aggregated into Upper, Middle, and Lower sub-basins, each with a single outflow. (Figure 4)

Precipitation data was interpolated on a monthly basis over a 33-year time span using GIS. The precipitation data was merged into three climatic seasons, based on consistent temporal patterns the reservoir operation rules:

- dry season: February-May
- summer season: June-September
- winter precipitation: October-January

A static runoff coefficient map was produced based on published data. Static runoff coefficients varied as a function of topography, vegetation, land use and precipitation. Runoff was estimated monthly on a pixel by pixel basis by multiplying the precipitation by the static runoff coefficient.

A simple linear model of the form $Y = \beta X + \alpha$ was used predict seasonal runoff (Y) as a function of runoff predicted using the static runoff coefficients (X). Values of α and β were found minimizing the sum of the squares of errors between the historically observed flows from each sub-basin and the model output.

RESULTS

Table 2. Parameters fitted with the linear model

Sub-Basin	Season	β	α (MCM/ month)	R^2
Upper	Dry	3.28	-58	0.73
	Summer	1.05	-122	0.65
	Winter	2.45	-108	0.82
Middle	Dry	2.88	-60	0.74
	Summer	2.48	-893	0.74
	Winter	2.53	-183	0.79
Lower	Dry	1.03	141	0.53
	Summer	0.97	42	0.45
	Winter	0.23	137	0.41

Table 2 shows each parameter fitted with the linear model and corresponding R^2 values. In most cases, the R^2 values indicate reasonable fits. Negative values of the intercepts (α) imply that a substantial amount of rainfall is necessary to produce any runoff.

For the upper and middle sub-basins, β is generally greater than one. These sub-basins are mainly located in higher regions with more frequent precipitation, implying that antecedent soil moisture may produce more runoff . lower basin, the values of β are smaller. The lower basin corresponds to a very arid area, so that we would expect to have lower antecedent soil moisture conditions and correspondingly less runoff.

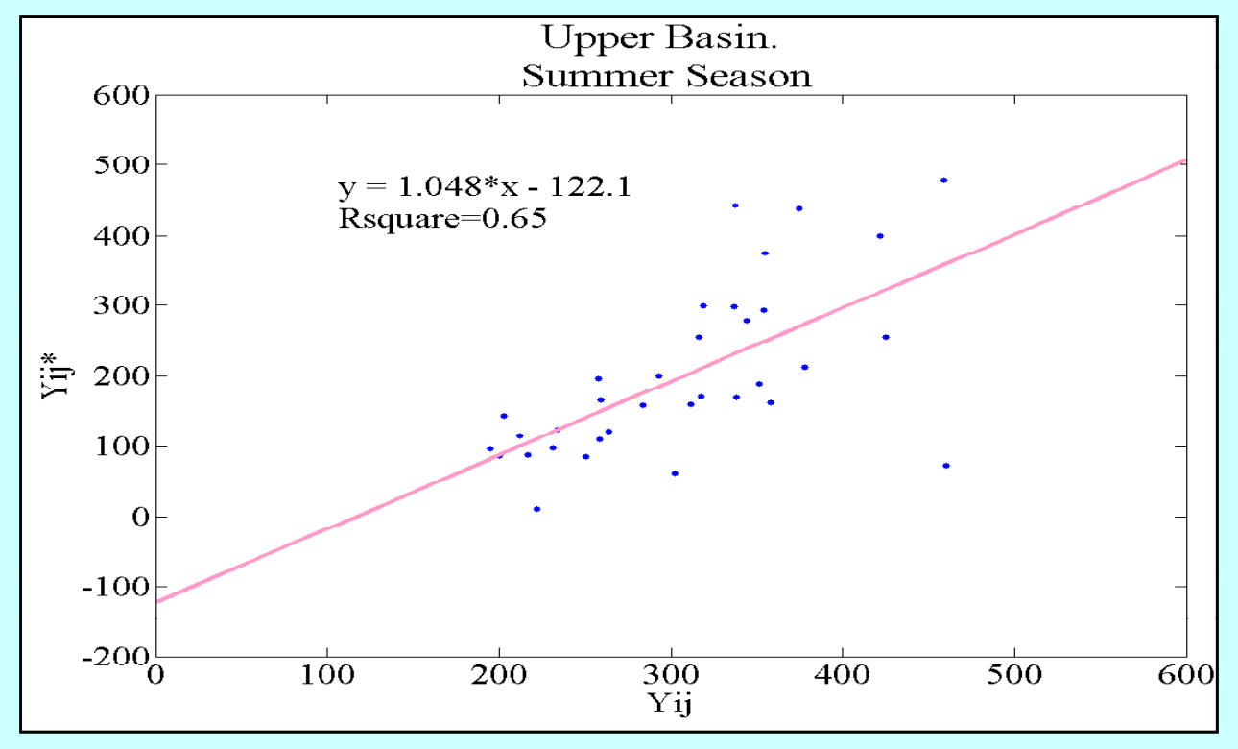


Figure 6. Fit of linear model

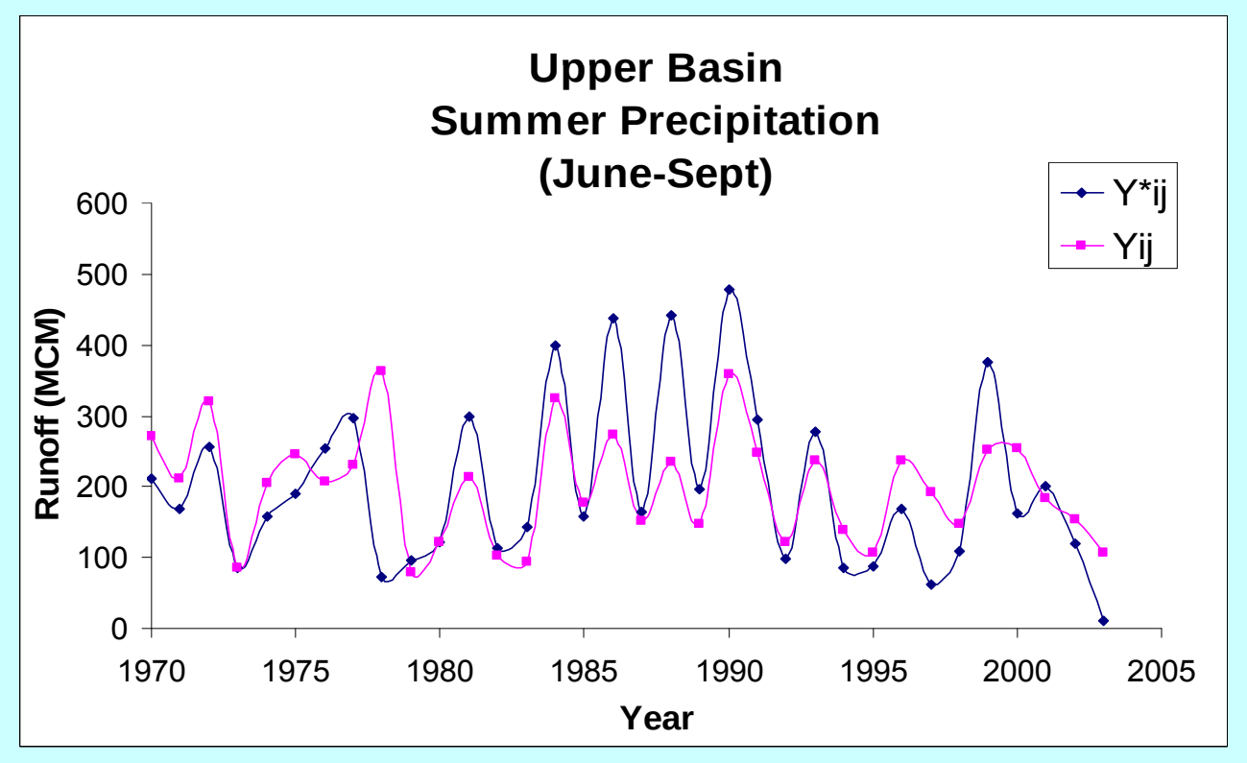


Figure 7. Historical vs. estimated run-off

Figure 6 shows a typical fit of predicted (Y) vs. measured (Y^*) runoff. The historical runoff values are compared with the estimates from the calibrated rainfall-runoff model in Figure 7 for the Upper sub-basin in the summer season over the 33-year calibration period. The timing of the peak matches reasonably well, but the model tends to under predict runoff during wetter years.

UNCERTAINTY ANALYSIS: A MONTE CARLO APPROACH

Uncertainty in the rainfall-runoff model predictions were assessed using a Monte Carlo simulation approach, assuming that model errors are normally distributed. Runoff was calculated using the relationship

$$Y = \hat{\alpha} + \hat{\beta} X \pm t_{n-2,1-\alpha/2} S_{\hat{Y}X_0}$$

where $\hat{\alpha}$ and $\hat{\beta}$ are best estimates, $t_{n-2,1-\alpha/2}$ is the t statistic, and $S_{\hat{Y}X_0}$ is the standard error of the estimate. In the Monte Carlo simulations, 100 values of $1-\alpha/2$ were randomly generated from a uniform distribution.

RESULTS

Figure 8 shows the best estimates and 10% and 90% confidence intervals for total storage in the basin at the beginning of every October. For this case, the precipitation values used to generate the storage come from historical data over the period 1970-2000.

The red line in Figure 8 indicates the amount of water that is needed to satisfy all water rights within the basin.

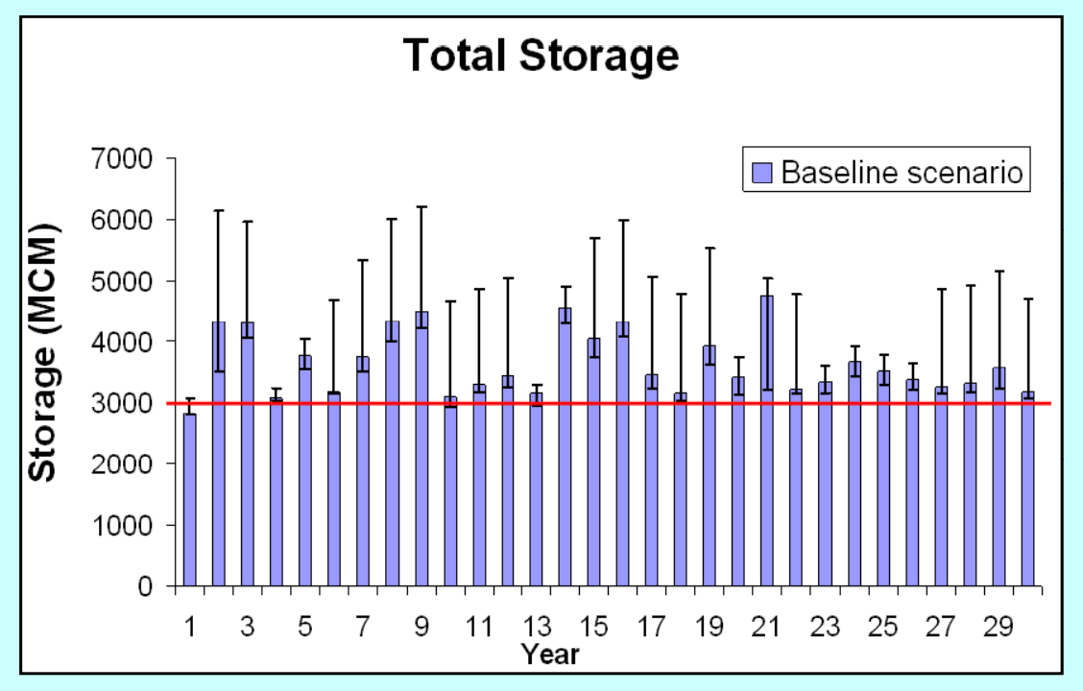


Figure 8. Total storage: best estimates and confidence Intervals

Based on the results in Figure 8, there is enough surface water to satisfy current water rights every year for the best estimates and, in most cases, for the 10% confidence interval. However, it was assumed in these simulations that all of the groundwater rights in the basin would be exploited, a situation that may not always be desirable.

The confidence intervals in Figure 8 appear to be truncated with respect to the lower confidence interval. This occurs because, when the runoff generation is low, the reservoirs approach the dead storage level, which cannot be exceeded. Figure 9 shows a cumulative frequency distribution (cdf) for storage in a particularly dry year, indicating that the cdf is “cut off” at the lower end because the storage cannot decrease below the level associated with dead storage.

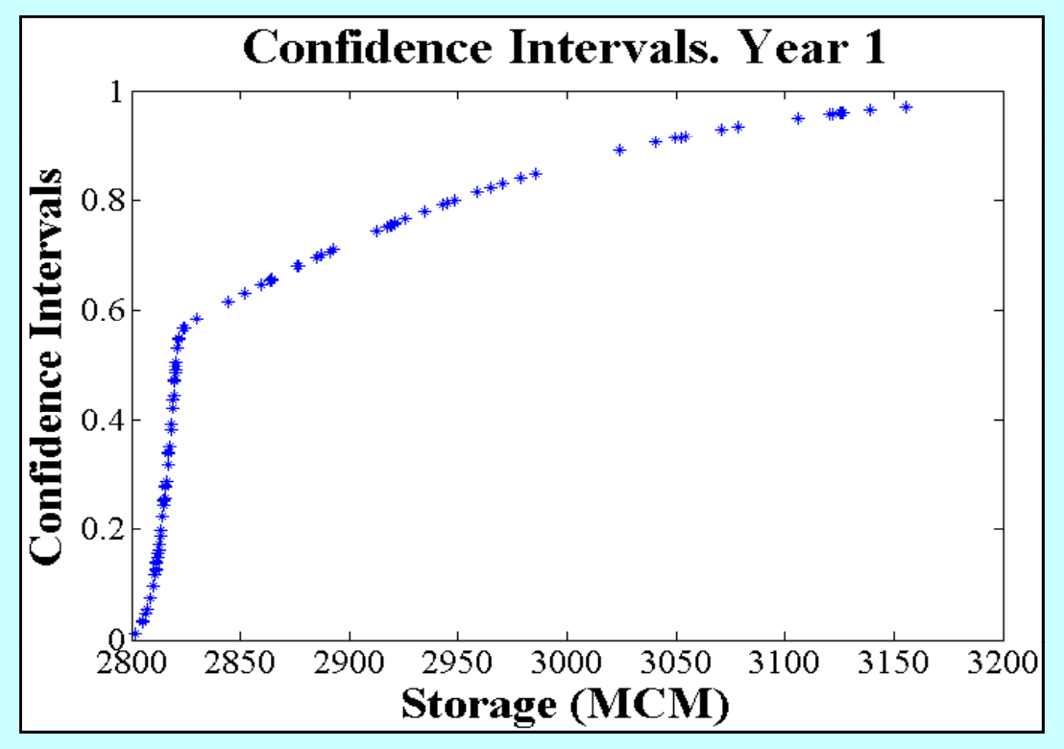


Figure 9. Cumulative frequency distribution for storage.

EFFECTS OF CLIMATE CHANGE ON RESERVOIR STORAGE

The PRECIS (Providing Regional Climates for Impacts Studies) model, which is based on the third generation of the Hadley Regional Climate Model (HADAM3P) was used to generate changes in precipitation over the period 2011 to 2041. Two SRES (Special Report on Emissions Scenarios) scenarios were used: A2 (high emission) and B1(low emission). These SRES scenarios are the most commonly applied in Latin American assessments of climate change impacts.

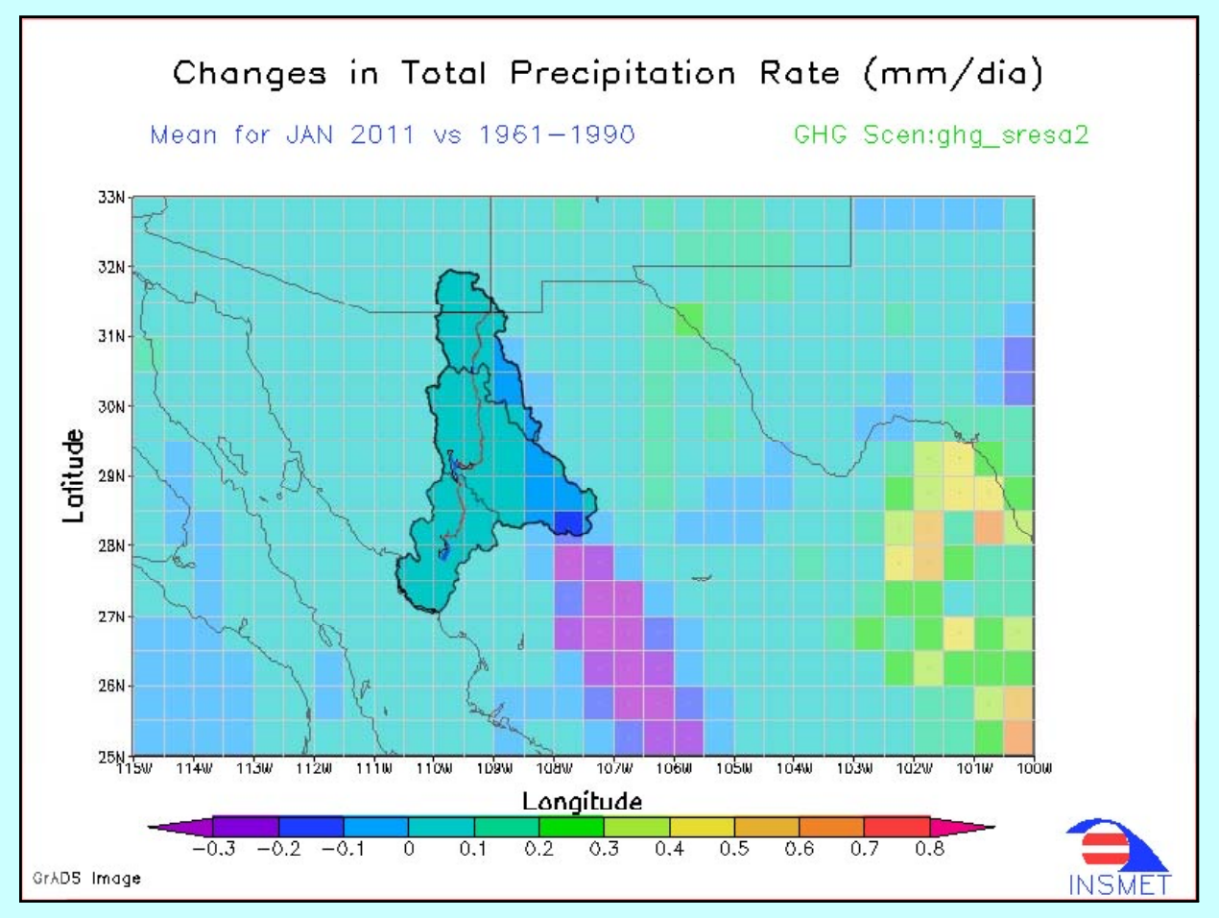


Figure 10. Changes in Total Precipitation Rate

Figure 10 shows a typical precipitation change map. Monthly percentage changes based in the 1961-1990 record (the baseline period used in PRECIS) were calculated for the Upper, Middle and Lower sub-basins, on a monthly basis. These percentage changes were then applied to the baseline precipitation record used in this work (1970-2000), assuming that this record would be repeated over the 2011 to 2041 period.

RESULTS

Figure 11 shows yearly reservoir storage on October 1st for both scenarios and the baseline scenario. The forecasted precipitation changes from PRECIS are very small and similar for both scenarios, producing results almost identical to the base line scenario. However, it is understood that typical climate models are not especially good at predicting the effects of climate cycles such as ENSO, which almost certainly affect the precipitation extremes in this region.

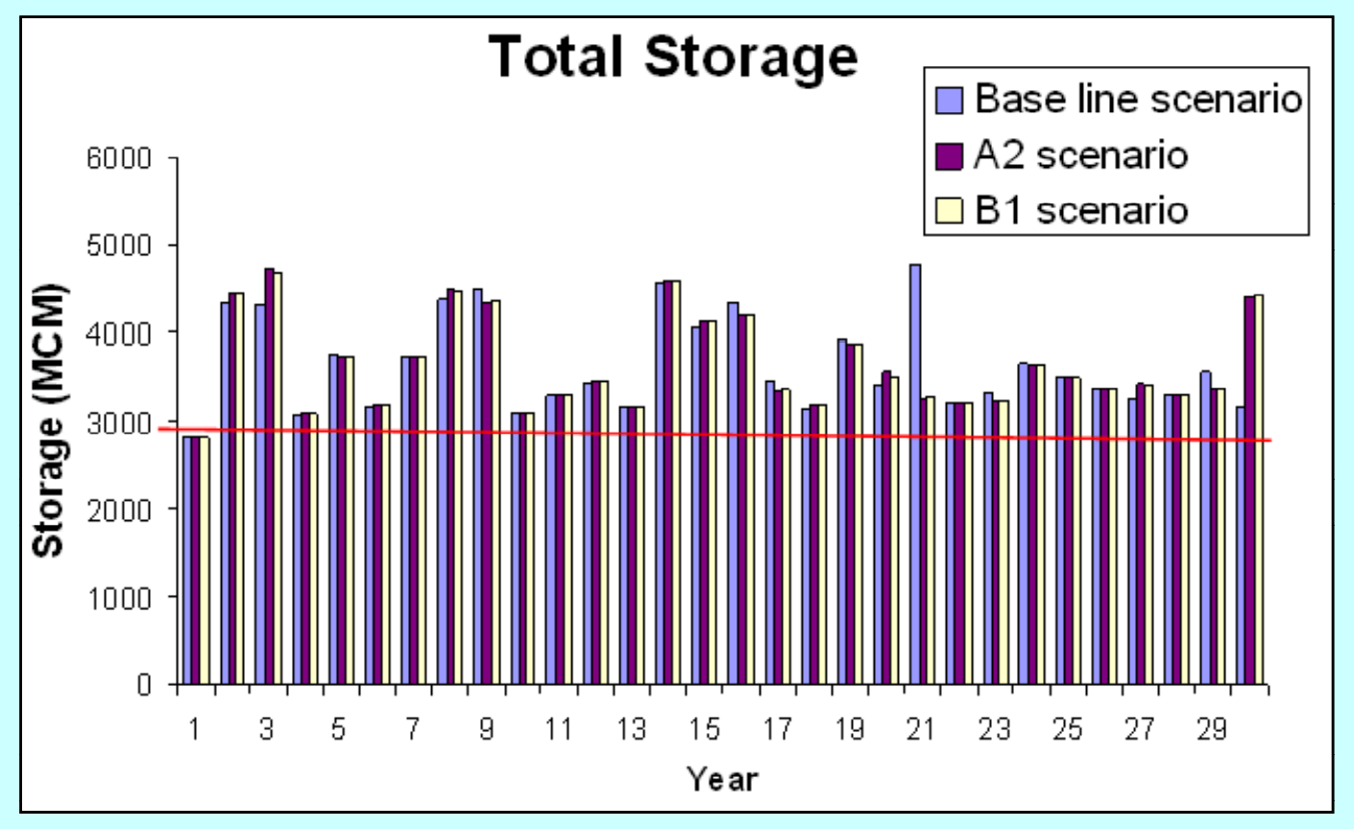


Figure 11. A2 and B1 scenario results.

CLIMATE VARIABILITY

To assess the effects of year-to-year correlations in precipitation (e.g. successive dry or wet years), a longer precipitation data set (104 years) was used (Nicholas et al, 2007). The precipitation data was grouped into five discrete precipitation classes: normal ($\mu-\sigma<P<\mu+\sigma$), wet ($\mu+\sigma<P<\mu+2\sigma$), very wet ($P>\mu+2\sigma$), dry ($\mu-2\sigma<P<\mu-\sigma$), and very dry ($P<\mu-2\sigma$). Transition probabilities (e.g. the probability of having successive dry or wet years) were determined on a season by season basis. Correlation between seasons was not considered at this time.

Once the transition probabilities were obtained, a Markov Chain - Monte Carlo approach was used to generate, on a monthly basis, precipitation for a period of thirty years. One hundred realizations were generated and simulated with the water balance model.

RESULTS

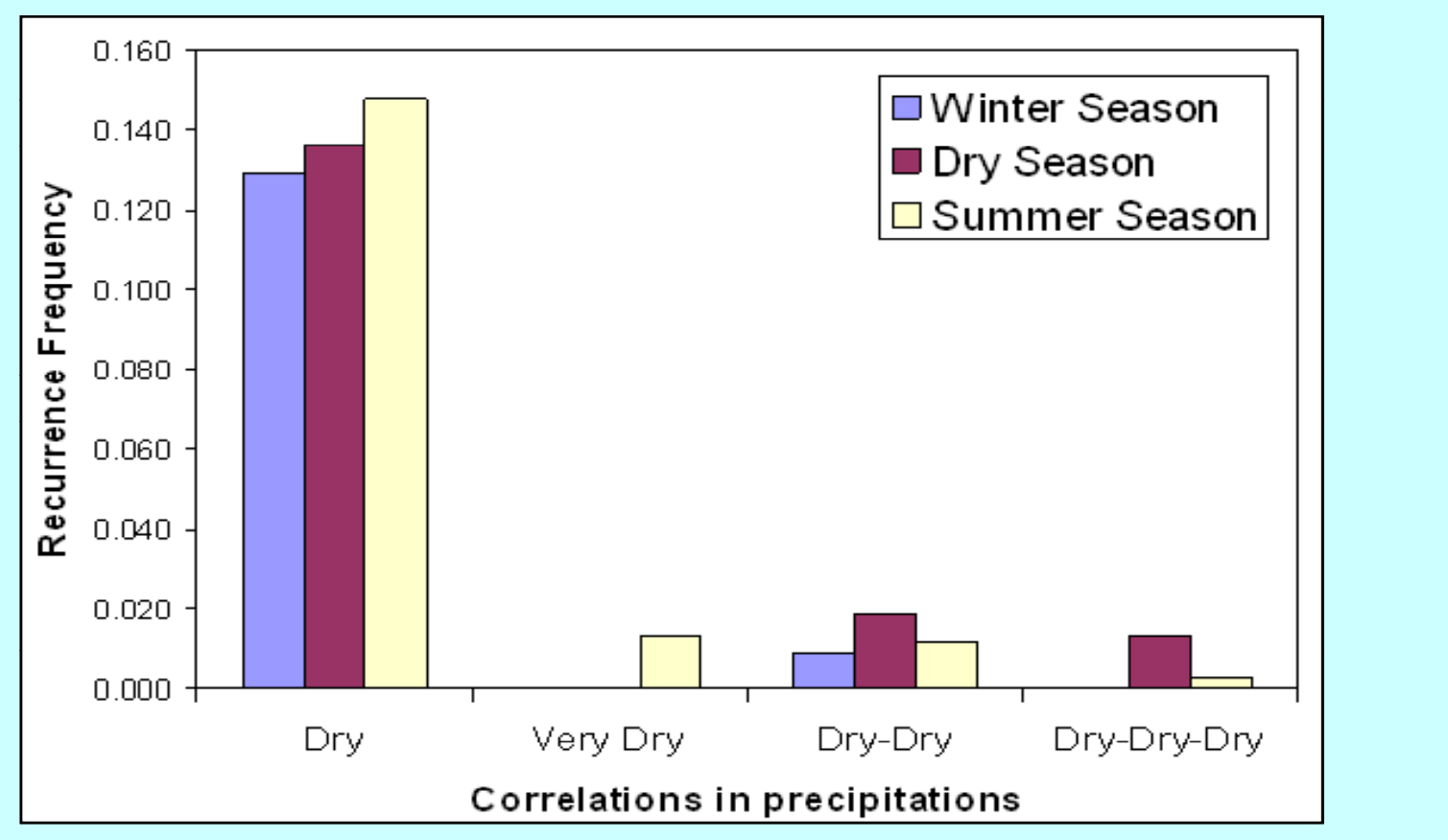


Figure 12. Precipitation correlation for dry conditions

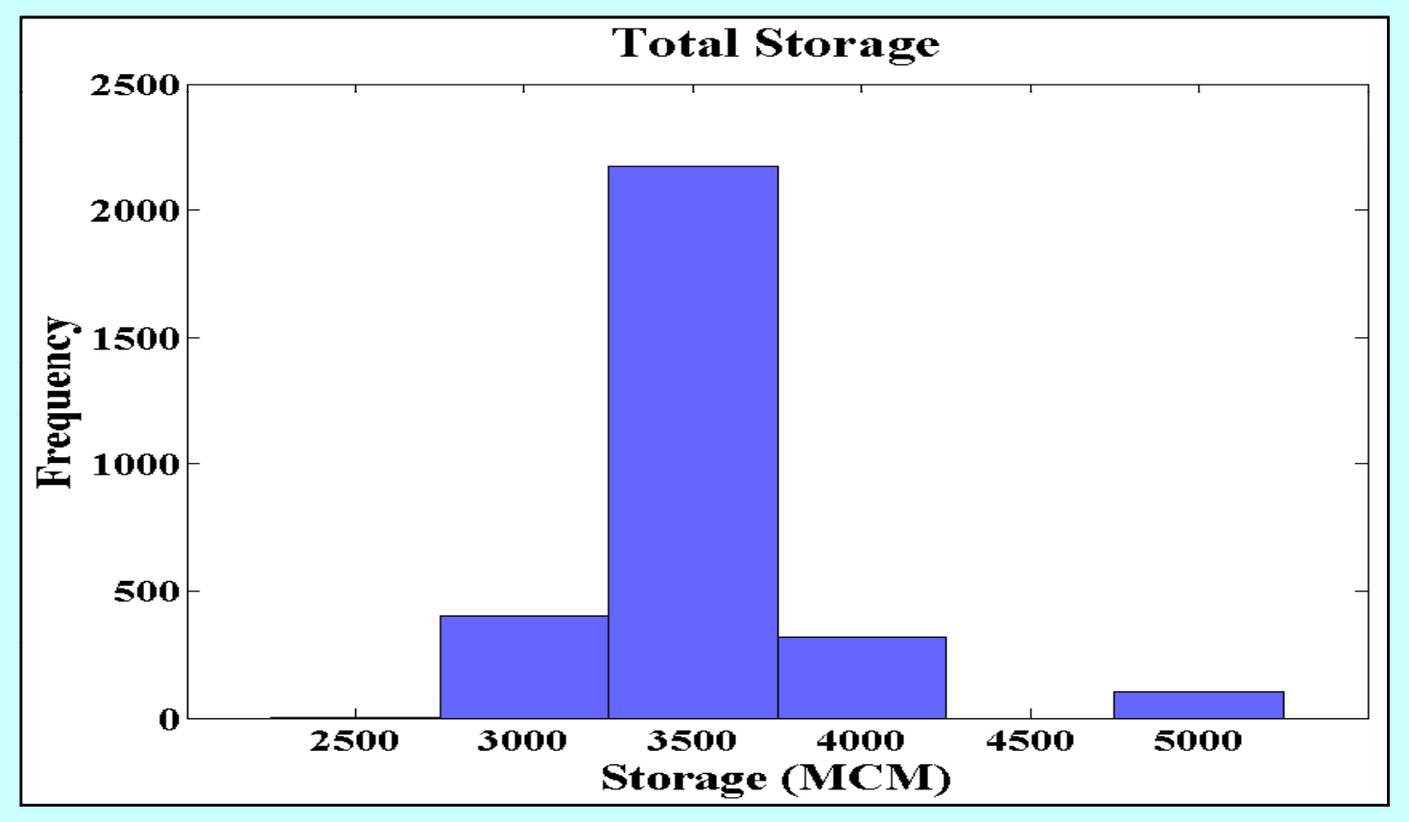


Figure 13. Frequency of occurrence for total storage.

Figure 12 shows that there is a small, but significant probability that two or three dry seasons can occur successively. However, Figure 13, which shows frequency of total reservoir storage on October 1st , indicates that users will have enough water to meet their needs every year (approximately 3000 MCM).

CONCLUSIONS

- The results show that there is sufficient surface water to meet users’ needs for a wide range of conditions (uncertainty, climate change, and climate variability). However, all of the simulations were run under the assumption that high groundwater extraction rates could supplement surface water supplies.
- The rainfall-runoff model produces acceptable results when compared with historical data. The best and worst matches are obtained in the middle and lower basin, respectively. We suspect that the poor fits are due to merging infrequent, short-duration, and intense precipitation-runoff events. However, the historical flow data in the lower basin may be unreliable.
- The impact of uncertainty in the rainfall-runoff model predictions were assessed using a Monte Carlo approach. One hundred numbers randomly generated give a good estimation of the uncertainty related to the rainfall-runoff model. In order to have better insight more random numbers should be generated.
- The storage estimates obtained from the incorporation of climate change into the water model are very similar to the ones obtained using the base line scenario. The use of more climate models or different SRES scenarios that are more optimistic or pessimistic might produce different results.
- Future assessments of climate variability should consider season to season correlation and different ways of classifying precipitation levels and corresponding probabilities.

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3. PRECIS http://precis.insmet.cu/menu_page.htm