J6.7

HYDROCLIMATOLOGY OF THE NORTH AMERICAN MONSOON REGION IN NORTHWEST MEXICO

David J. Gochis
National Center for Atmospheric Research, Boulder, CO, USA

Luis Brito-Castillo
Centro de Investigaciones Biologicas del Noroeste (CIBNOR), Guaymas, Sonora, Mexico

W. James Shuttleworth
Department of Hydrology and Water Resourece, University of Arizona, Tucson, AZ, USA

1.1 INTRODUCTION

The region of northwest Mexico is generally semi-arid, with an annual precipitation regime dominated by warm-season convection that strongly interacts with the regional topography and surrounding bodies of water. The summertime monsoonal circulation, its onset, precipitation character, and the hydrological response to it, exhibit considerable spatial and temporal variability. This variability complicates diagnostic and predictive efforts and limits adaptive management of regional water resources. This work explores the complex relationship between precipitation and streamflow in the North American Monsoon (NAM) region by constructing a regional hydroclimatology from selected headwater catchments from northwest Mexico.

In this paper we extend several of the existing works from this region by analyzing observed streamflow and gridded precipitation records for 15 unregulated basins situated along the cordillera of the Sierra Madre Occidental (SMO) underlying the core of the NAM. As such, this work constitutes a regional hydroclimatology of basins draining the mountains in northwest Mexico based on currently available data (Note: See Gochis et al., 2004). The motivation for this effort is two-fold; the first is to create a comprehensive documentation of principal hydroclimatic features within the core region of the North American Monsoon. The second motivation is to elucidate the evolution of rainfall-runoff relationships throughout the monsoon season, which may have predictive value in the context of hydrological forecasts across a range of time-scales.

2. DATA AND METHODS

2.1. Data

Selected basins draining the SMO are shown in Figure 1. Monthly streamflow data were obtained from the BANDAS (Banco Nacional de Datos de Aguas Superficiales) data archive, BANDAS (1998). Streamflow periods of record vary for individual basins, but all basins possess a minimum of 10 years of data. The size of these catchments studied in the present analysis range from 1,000 – 10,000 km^2 and are unregulated. Thus, the results presented herein are constrained to focus on the "natural" hydrological response of typical SMO headwater catchments to monsoon rains. Three of the 15 basins studied (1. Rio San Pedro del Conchos, 7. Rio Sextin, and 11. Rio Ramos) drain to the east of the North American cordillera towards the Mexican Plateau. In the present work, emphasis is placed on examining the intraseasonal evolution of monthly streamflow, as opposed to strictly focusing on aspects of the interannual variability of streamflow. Given these differences, the present analysis should be viewed as a logical expansion of that given by Brito-Castillo et al. (2003), by extending depiction of the regional hydrological regime to the eastern SMO and to the intra-seasonal timescale.

Rainfall data used in these analyses were from the 1948-1998, daily, 1°, gridded precipitation dataset for Mexico, of Higgins et al. (1996). Basin average precipitation for each basin was calculated by averaging grid values contained within each individual basin using the ARC/INFO (ESRI, 2002) spatial statistics functions, as was done by Gochis et al. (2003).

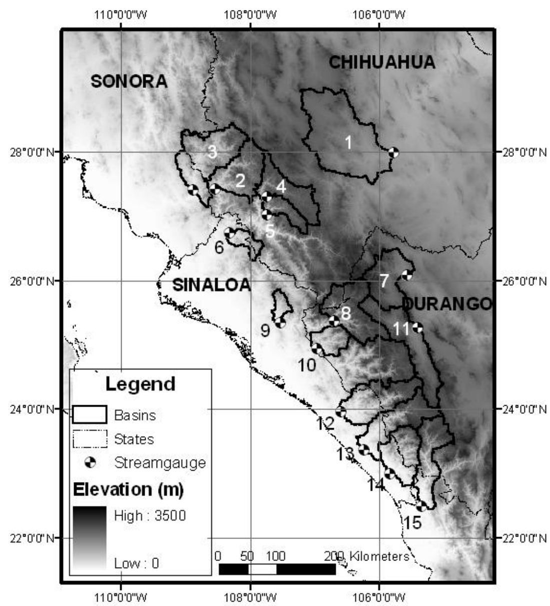

Figure 1. Map of selected headwater basins in northwest Mexico. Topography is in grey-shading.

2.2 Methods

Various analyses were constructed in order to define the regional hydroclimatological response to precipitation along the SMO in northwest Mexico. The annual cycle of the streamflow regime for all the test basins is described below in terms of the monthly percentages of annual flow volumes. Interannual variability in monthly streamflow is shown by annual plots of the monthly coefficients of variation[*]. Monthly maximum flow volumes are also plotted in order to illustrate and discuss the annual cycle of maximum flows as well as some mechanistic causes for extreme events.

To examine regional coherence of streamflow and precipitation in the core NAM region, an empirical orthogonal function (EOF) analysis, similar to that of Brito-Castillo et al. (2002 and 2003). Seasonal time series of streamflow and precipitation anomalies for July-August-September (JAS) were constructed. Due to differing periods of record, the streamflow time series were not strictly overlapping, and possessed occurrences of missing data. Data from all basins were then applied in an EOF analysis using pairwise deletion of the correlation matrix and Varimax rotation (where, gamma =1.0). The degeneracy criteria of North et al. (1982) were applied in an attempt to determine which of the leading EOFs to retain for analysis. For the present analysis, only the top three principal components of streamflow variability were retained. (Further details on the EOF analyses and the delineation and plotting of leading components is available in Gochis et al., 2004).

The relationship between monthly and seasonal rainfall and runoff is evaluated by means of the lag 0 precipitation (P)-streamflow (Q) correlation value and runoff coefficient (Q_r). Spearman rank correlation values were used, as opposed to Pearson values, because the Spearman rank value is less influenced by outliers than is the Pearson value. Here, Q_r is expressed as streamflow volume divided by total precipitation [i.e.. $Q_r = Q / P$]. Effectively, Qr describes the bulk fraction of rainfall that ends up as streamflow.

3. RESULTS

The principal findings from this study can be summarized as follows:

- Across northwestern Mexico, the natural streamflow regime is dominated by warm season rainfall associated with the NAM system (Figure 2a). In the 15 headwater catchments studied, streamflow volume during July, August and September constituted between 50% and 85% of the total annual streamflow. A secondary, though much smaller, maximum in monthly streamflow values was observed in the early winter along catchments draining the western slope of the Sierra Madre. This secondary maximum is likely due to infrequent baroclininc disturbances or, possibly, late-season land falling tropical storms.

---

[*] The 'coefficient of variation' is defined here as the long term standard deviation of monthly streamflow volume divided by the long term monthly mean streamflow volume.

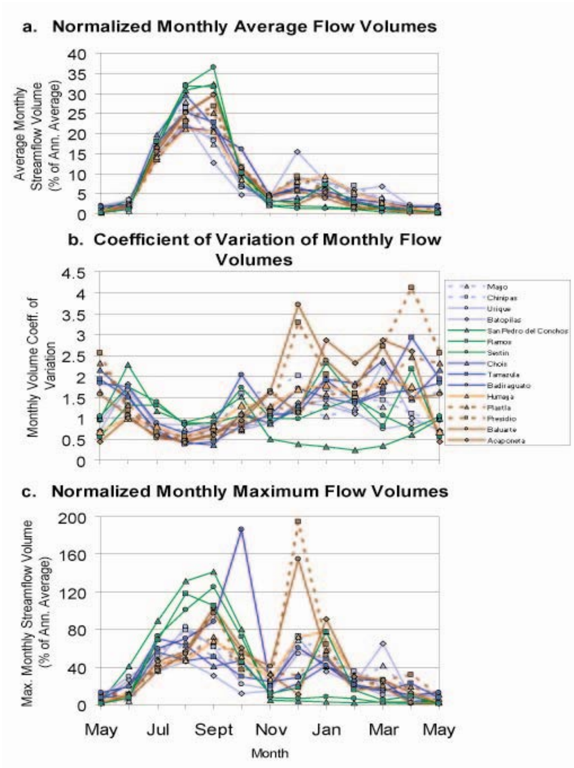

Figure 2. a) Normalized monthly average streamflow volumes, b) coefficient of variation of monthly flow volumes, c) normalized monthly maximum flow volumes.

- Monthly coefficients of streamflow variability (Fig. 2b) are lowest during the peak streamflow months of JAS and range between 40-150% for all basins. While this implies that standard deviations in monthly streamflow are low compared to the mean values, the magnitude of these deviations can be substantial fractions of the mean annual flow volume and, thus, can be critically important for the management of regional water resources. Monthly coefficients of variation in all other months range between 75-350% of monthly mean values. The importance of this higher degree of variability in non-peak months may appear to be diminished by the values of the standard deviations in these months comprising much smaller fractions of mean annual streamflow. However, winter precipitation can be critical for averting water shortages during the late winter and spring irrigation seasons across northwest Mexico.

- Streamflow maxima (Fig. 2c) for the periods of record appear to show some regional dependence. Basins draining the eastern slope of the SMO uniformly have their record streamflow months during either August or September. Basins draining the western SMO tend to receive their record streamflow months either during August-September or December-January.

- A Varimax Rotated EOF analysis of seasonal (JAS) streamflow revealed three distinct regions of coherent streamflow variability (Fig. 3): a northern region (EOF1), a southern region (EOF2), and an eastern region (EOF3). The three EOF's explain approximately 71% of the JAS inter-annual streamflow variability. An identical analysis performed on a long-term gridded precipitation data (not shown) set revealed a similar set of three regions of coherent precipitation variability, which explained approximately 86% of the JAS precipitation variability.

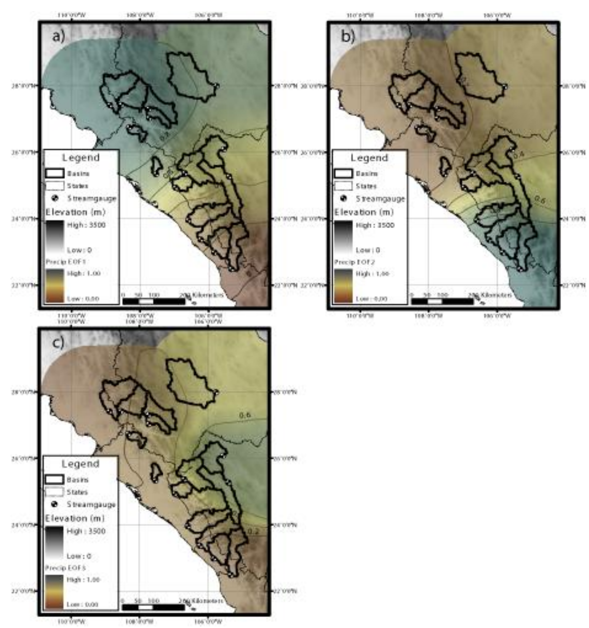

Figure 3. Interpolated loading factors from PCA analysis of JAS streamflow for: a) EOF1, b) EOF2, and c) EOF3. Contour interval is 0.2.

- The time series of regionally averaged JAS streamflow (Fig. 4) reveal a regime possessing significant interannual variability. Climatological aspects of this interannual variability have been discussed in Brito-Castillo et al., 2002 and later works. It is interesting to note, however, that there appear to be multi-year periods where *inter-basin* variability is enhanced or diminished. Enhanced (diminished) periods (red-shading (blue-shading)) are periods when there are appreciable difference (similarities) between north, south and central region streamflow. It is hypothesized that during periods when there is regional coherence (blue-shading) certain large-scale or teleconnective forcing mechanisms may be exerting significant influence across the entire NAM region.

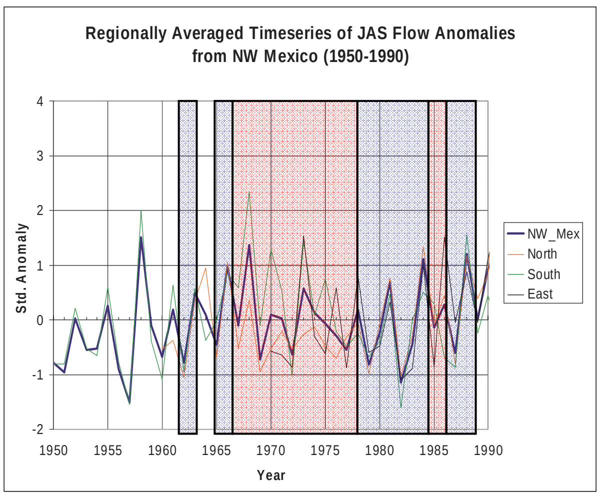

Figure 4. Time series of regionally averaged Jul-Aug-September streamflow. Red(blue) shading indicates periods of enhanced(reduced) Inter-basin variability.

- Precipitation-streamflow (*P-Q*) relationships as diagnosed by both rank correlation scores between monthly and seasonal precipitation and streamflow as well as monthly and seasonal runoff coefficients showed a strong regional behavior that corresponded well to the three regions defined by the EOF analyses. Seasonal *P-Q* correlations (not shown) tended to be highest for eastern-slope basins, followed by basins in the southwestern SMO, then by those draining the northwestern SMO. Regional composites and individual basin *P-Q* values tended to increase from July through October. Basins along the eastern SMO did not clearly exhibit this seasonal increase. Smaller catchments along the western slope of the SMO generally did not possess statistically significant correlation values until September or October.

- Over the course of a warm season (JAS), approximately 21%, 34% and 19% of rainfall was converted to streamflow for the northern, southern and eastern regions, respectively. Early season (July) values of the runoff coefficient ranged from 6-32%. By October, values ranged between 18-140%. Runoff coefficients were highest in the southern region where rainfall was highest. In nearly all basins and composite regions, runoff coefficient values increased from July through October, indicating the process of hydrological conditioning. Runoff coefficient values exceeding 100% occurred in 4 of the 15 basins during October, which indicates basin discharge exceeding rainfall as summer rains decrease.

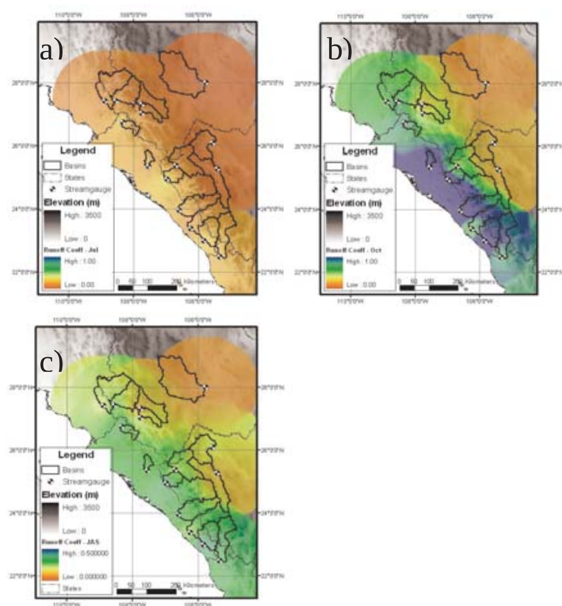

Figure 5. Spatially-interpolated plots of basin runoff coefficients for a) July, b) October, c) Jul-Aug-Sep.

4. CONCLUSIONS

This study shows the strong dependence of streamflow and, therefore, water resources, on monsoon rains. While the monsoon rains are, generally, a stable feature of the warm season climate in western Mexico, variability in the onset and total amounts of rainfall can have a significant impact on the annual water resource budget. There exists significant subregional coherence in streamflow throughout the monsoon season which likely reflects the different precipitation and physiographic regimes in Northwest Mexico. In addition to the peak streamflow generation period between July and October, autumnal land-falling tropical storms and early winter baroclinic disturbances can generate significant amounts of streamflow. As evidenced by high coefficients of variation outside the peak monsoon season, these events tend to be infrequent and therefore not particularly dependable for water resources planning.

5. REFERENCES

BANDAS, 1998: Bancos Nacional de Datos de Aguas Superficiales, Comission Nacional del Agua (CNA) y Instituto Mexicano de Tecnologia del Agua (IMTA), CD-ROM.

Brito-Castillo, L., A. Leyva-Contreras, A.V. Douglas, and D. Lluch-Belda, 2002: Pacific-Decadal Oscillation and the filled capacity of dams on the rivers of the Gulf of California continental watershed. *Atmosfera*, 15, 121-138.

Brito-Castillo, L., A.V. Douglas, A. Layva-Contreras, and D. Lluch-Belda, 2003: The effect of large-scale circulation on precipitation and streamflow in the Gulf of California continental watershed. *Int. J. Climatology*, 23, 751-768.

ESRI, 2003: ArcMap Version 8.2. Environmental Systems Research Institute, Inc.

Gochis, D.J., W.J. Shuttleworth and Z.-L. Yang, 2003: The hydrometeorological response of the modeled North American Monsoon to convective parameterization. *J. Hydromet.*, 4, 235-250.

Gochis, D.J., L. Brito-Castillo and W. J. Shuttleworth, 2004: Hydroclimatology of the North American Monsoon Region in Northwest Mexico. Submitted to *J. Hydrology*.

Higgins, R.W., J.E. Janowiak, and Y. Yao, 1996: A gridded hourly precipitation data base for the United States (1963-1993). NCEP/Climate Prediction Center ATLAS 1, 47 pp.

North, G.R., T.L. Bell, and R.F. Cahalan, 1982: Sampling errors in the estimation of empirical orthogonal functions. *Mon. Wea. Rev.*, 110, 699-706.