Hydroclimatology of the North American Monsoon

David J. Gochis[1] and Luis Brito-Castillo[2]

[1]NCAR/ASP/RAP (E-mail: gochis@rap.ucar.edu); Centro de Investigaciones Biologicas del Noroeste (CIBNOR), Guaymas, Sonora, Mexico

ABSTRACT

The North American Monsoon (NAM) system controls the warm season climate over much of southwestern North America. Characterized as a semi-arid environment, understanding the regional behavior of the hydroclimatology and its associated modes of variability is critically important to effectively predicting and managing perpetually-stressed regional water resources. This work explores the hydroclimatology of northwestern Mexico, i.e. the core region of the NAM, by developing a detailed hydroclimatology from 15 unregulated headwater basins along the Sierra Madre Occidental mountains in western Mexico. The present work is distinct from previous studies as it focuses on the intra-seasonal evolution of rainfall-runoff relationships and contrasts the sub-regional behavior of the rainfall-runoff response. It is found that there is substantial sub-regional coherence in the hydrological response to monsoon precipitation. Three physically-plausible regions emerge from a rotated Principal Components Analysis of streamflow and basin-averaged precipitation. Month-to-month streamflow persistence, rainfall-runoff correlation scores and runoff coefficient values demonstrate regional coherence and are generally consistent with what is currently known about sub-regional aspects of NAM precipitation character.

The North American Monsoon Region: Selected Test Basins

The core region of the North American Monsoon region is characterized by steep topographic and precipitation gradients, which, in turn, result in strong gradients in vegetation. For the streamflow analysis portion of this study we have selected 15 basins (Fig. 1) which drain the Sierra Madre Occidental mountains in western Mexico (3 of which drain to the east). Drainage areas range between 1,000 and 10,000 sq. km. All basins are unregulated by impoundments or large diversions to the best of the authors' knowledge. Other basin characteristics are provided in the Table 1.

Figure 1

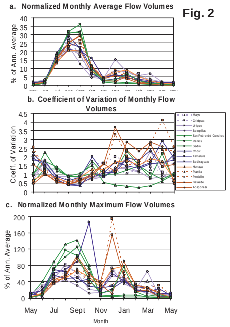
Table 1

Station	River	Drainage Basin	Drainage Area (sq. km)	Gage Location (deg)	Gage Location (deg)	Period of Record	Mean Annual Flow Volume (10^3 m3)	Annual Coefficient of Variation
1. Villalba*	San Pedro del Conchos	Conchos*	9405	-105 46 40	27 59 10	1938-90	411401	0.637
2. Chinipas	Chinipas/Oteros	Fuerte	5098	-108 32 30	27 25 00	1965-98	1023985	0.505
3. San Bernardo	Mayo	Mayo	7510	-108 52 55	27 24 45	1960-99	1003542	0.401
4. Urique	Urique	Fuerte	4000	-107 50 20	27 18 10	1968-99	439165	0.546
5. Batopilas	Batopilas	Fuerte	2033	-107 44 15	27 01 20	1982-97	372859	0.383
6. Choix	Choix	Fuerte	1403	-108 19 45	26 44 10	1955-98	295679	0.374
7. Sardinas*	Sextin or del Oro*	Aguanaval*	4911	-105 34 12	26 05 00	1970-94	524074	0.610
8. La Huerta	Humaya	Culiacan	6149	-106 42 00	25 22 10	1969-99	1120591	0.502
9. Badiraguato	Badiraguato	Culiacan	1018	-107 32 15	25 20 00	1959-99	252900	0.611
10. Tamazula	Tamazula	Culiacan	2241	-106 58 30	24 56 00	1962-99	648172	0.348
11. Salome Acosta*	Ramos*	Aguanaval*	7130	-105 24 52	25 16 06	1969-94	557191	0.474
12. Ixpalino	Piaxtla	Piaxtla	6166	-106 35 45	23 57 20	1952-99	1627005	0.359
13. Siquerios	Presidio	Presidio	5614	-106 15 00	23 00 30	1956-99	1044081	0.518
14. Baluarte II	Baluarte	Baluarte	4635	-105 50 30	22 59 00	1947-99	1774999	0.422
15. Acaponeta	Acaponeta	Acaponeta	5092	-105 20 30	22 29 00	1945-99	1362309	0.382

* Denotes basins which drains to the east of the SMO

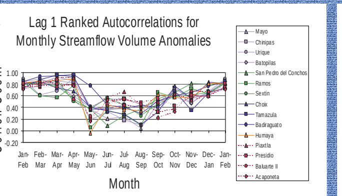
The Streamflow Regime in NW Mexico

Fig. 2



The streamflow regime in NW Mexico is dominated by a strong summertime signal concomitant with summer monsoon rains (Fig. 2a). All basins show a distinct summer maximum in monthly flow volume. Interannual monthly streamflow variability (quantified as the coefficient of variation of monthly flow volume, Fig. 2b) is lowest during the summer months indicating that the higher flows are a regular feature. There is marked flow variability in the low flow season in the spring and also in the fall. The increased variability in the late fall and early winter are likely due to land-falling tropical storms. In nearly all basins, the months with maximum flow volume are summer months.

Fig. 3

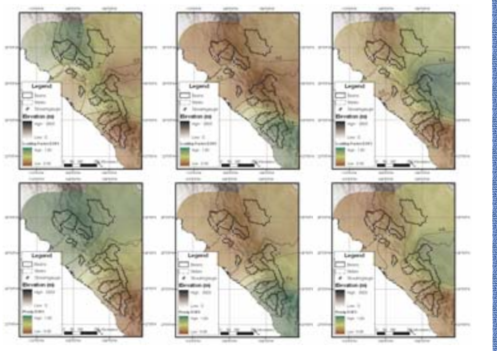


The clear signal in the annual cycle of streamflow does not necessarily imply increased predictability in summertime streamflows. Figure 3 shows the 1 month lag autocorrelation values for the 15 test basins. While low flow months tend to have a strong serial correlation the transitional months of May and Jun and the summer months of June, July, August, and Sept. each possess comparatively low correlation values with the respective preceding month's streamflow.

Principal Components Analysis (PCA)

A principal components analysis was performed on both the JAS streamflow volumes and basin averaged precipitation. Loading factors were then spatially interpolated to reveal regions of coherent variability. Both streamflow and precipitation exhibit a N-S dipole structure in the first two components. This feature has been found by Brito-Castillo et al. (2002) in their analysis of reservoir inflow volumes in the same region. These features suggest there are at least two distinct modes which influence the precipitation and runoff regime in the NAM region. The third principal component of streamflow and precipitation variability also suggests that basins on the east-side of the SMO differ from the basins on the west.

Fig. 4



Runoff Coefficient Analysis

To obtain an understanding of the rainfall runoff relationship in the NAM region we calculate the runoff coefficient (Qr=discharge/precipitation) for the 15 test basins. Lacking a long time series of the event data we used the 1 degree CPC gridded daily precipitation product (Higgins et al. 1996). This product is gridded from available historical gage precipitation measurements from the climate observing network across Mexico. Basin average precipitation values were calculated for each basin and used in calculation of the runoff coefficient. We used JAS (July-August-September) and monthly values of both precipitation and streamflow. Various combinations of months and monthly lag periods were also calculated but the results changed little. As can be seen from Table 3, mean values of the seasonal (JAS) runoff coefficient varied from 9-43%. Smaller values of the runoff coefficient (between 9 and 20%) appear to be confined to the northernmost basins. Fig. 5 shows a broad but noisy inverse correlation between JAS Qr and basin area. Most notable in Table 3 and Fig. 6 is the seasonal evolution of the Qr towards higher values as the summer progresses. This evolution indicates that the basins are becoming "hydrologically-conditioned" by the summer rains. Bold values indicate that runoff coefficients for some periods exceeded 1.0. This occurred exclusively during the month of October, after the cessation of most monsoon rains.

Table 3

Runoff Coefficient Table

Basin	Area	JAS (Qr=Q/P)	Jul	Aug	Sep	Oct
1. San Pedro del Conchos	9405	0.09	0.06	0.10	0.13	0.18
2. Chinipas	5098	0.27	0.19	0.30	0.35	0.75
3. Mayo	7510	0.18	0.12	0.22	0.26	0.55
4. Urique	4000	0.13	0.09	0.15	0.18	0.33
5. Batopilas	2033	0.22	0.18	0.25	0.22	0.43
6. Choix	1403	0.34	0.25	0.36	0.43	0.87
7. Sextin	4911	0.21	0.10	0.21	0.31	0.27
8. Humaya	6149	0.23	0.15	0.24	0.32	0.45
9. Badiraguato	1018	0.30	0.19	0.27	0.41	**1.18**
10. Tamazula	2241	0.40	0.32	0.42	0.53	**1.32**
11. Ramos	7130	0.15	0.08	0.16	0.19	0.26
12. Piaxtla	6166	0.33	0.21	0.34	0.47	**1.40**
13. Presidio	5614	0.24	0.15	0.23	0.36	0.63
14. Baluarte	4635	0.43	0.28	0.43	0.64	**1.23**
15. Acaponeta	5092	0.34	0.22	0.32	0.48	0.81
EOF1 (North)		0.21	0.14	0.23	0.29	0.52
EOF2 (South)		0.34	0.22	0.33	0.49	**1.02**
EOF3 (East)		0.19	0.11	0.20	0.25	0.32

Fig. 5

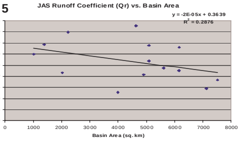
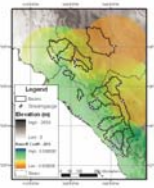
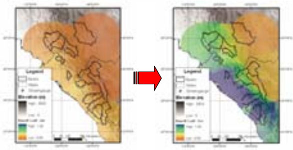


Fig. 6. Qr Jul-Aug-Sep





Rainfall Runoff Correlation Structure

The similar patterns revealed from the PC analysis above suggest that there is some correlation between JAS precipitation (P) and streamflow (Q). Spearman correlation coefficients for all 15 basins are given in Table 4. Statistically significant correlations are present in 9 out of 15 basins. It is noticed that all of the southern basins and those that drain to the east are significantly correlated while only 2 basins from the northwestern part of the domain are. Also shown in Table 4 are correlation coefficients for each of the individual months of the warm season. As with Qr, P-Q correlation values increase from Jul-Oct further illustrating the process of hydrological-conditioning. Essentially, as the summer evolves in-basin storage reservoirs such as soil moisture, rock fissures and surface depressions become filled. Subsequent rains are then more likely to runoff.

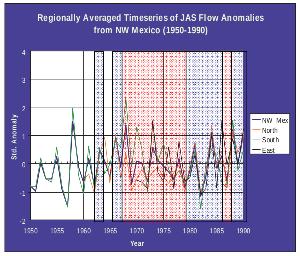
Table 4

Basin	Area	N-pairs	JAS	Jul	Aug	Sep	Oct
1. San Pedro del Conchos	9405	41	**0.58**	0.35	**0.56**	**0.75**	0.32
2. Chinipas	5098	29	**0.49**	0.39	0.42	**0.69**	**0.70**
3. Mayo	7510	36	0.31	0.36	0.37	**0.55**	**0.68**
4. Urique	4000	27	0.37	0.06	0.27	**0.66**	**0.59**
5. Batopilas	2033	16	0.42	0.06	0.50	0.38	0.59
6. Choix	1403	39	**0.45**	0.31	0.34	**0.58**	**0.61**
7. Sextin	4911	21	**0.87**	**0.83**	0.50	**0.81**	0.38
8. Humaya	6149	29	0.42	0.28	**0.48**	**0.66**	**0.67**
9. Badiraguato	1018	40	0.23	0.23	0.24	**0.56**	**0.67**
10. Tamazula	2241	33	0.27	0.37	0.19	0.38	**0.57**
11. Ramos	7130	23	**0.92**	**0.70**	**0.60**	**0.85**	**0.53**
12. Piaxtla	6166	44	**0.42**	0.26	0.30	**0.59**	**0.49**
13. Presidio	5614	40	**0.56**	0.25	**0.45**	**0.73**	**0.60**
14. Baluarte	4635	48	**0.52**	**0.45**	**0.44**	**0.54**	**0.66**
15. Acaponeta	5092	49	**0.36**	**0.42**	**0.37**	**0.50**	**0.59**
EOF1 (North)		39	**0.56**	0.38	**0.51**	**0.64**	**0.70**
EOF2 (South)		50	**0.52**	0.28	**0.42**	**0.69**	**0.64**
EOF3 (East)		28	**0.79**	**0.56**	0.46	**0.71**	**0.65**

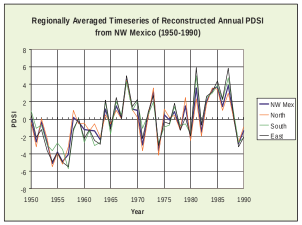
Boldface indicates correlation significant at 95% level.

Interannual Variability of NAM Streamflow

The time series of regionally averaged JAS streamflow 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.



As an exercise we have also plotted the timeseries of reconstructed annual Palmer Drought Severity Index (http://www.ngdc.noaa.gov/paleo/newpdsi.html) for NW Mexico. The PDSI appears to show more year to year persistence than does JAS streamflow. It should be noted that the PDSI reconstruction is based on tree-ring data and therefore is an integrated drought measure across warm and cool seasons. Combined with the noted lack of inter-basin spread in PDSI and its coarse resolution (2.5 deg) this annual PDSI reconstruction may be only marginally useful for diagnosing NAM streamflow variability.



References and Publications

Brito-Castillo, L., A. Leyva-Contreras, A.V. Douglas, 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.

Gochis, D.J. and Brito-Castillo, L, 2004: Hydroclimatology of the North American Monsoon. To be submitted to *J. of Hydrology.*

Gochis, D.J., J.-C. Leal, C.J. Watts, and W.J. Shuttleworth, 2004: Diagnostic analysis of 2002 and 2003 warm season precipitation from the NAME Event Raingage Network (NERN). In Press, *MWR* (pdf available by request).

Acknowledgements

Support for this work was provided in part by the NOAA Joint CLIVAR/PACS-GEWEX/GAPP North American Warm Season Precipitation Initiative: Contract No. NA16GP2002 and by the Advanced Study Program at the National Center for Atmospheric Research.