Modeling annual discharge of six Mexico's northern rivers

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ABSTRACT

The overall goal of this report was to understand river discharge variability to improve conventional water management practices of Mexico's northern subtropical rivers. This report addresses whether: a) river discharge tendencies, patterns and cycles can be detected with proxy and instrumental records; and b) annual discharge can be forecasted by stochastic models. Eleven gauging stations of six major rivers; three lowland rivers discharging into the Pacific Ocean (Rios Santa Cruz, Acaponeta, and San Pedro); five upland rivers draining into the Pacific Ocean (Rio San Pedro: Peña del Aguila, Refugio Salcido, San Felipe, Vicente Guerrero and Saltito), one river flowing across the interior Basin (Rio Nazas: Salomé Acosta) and two more rivers discharging into the Northern Gulf of Mexico (Rio San Juan: El Cuchillo and Rio Ramos: Pablillos) were statistically analyzed. Instrumental recorded daily discharge data (1940-1999) and reconstructed time series data (1860-1940) using dendrochronological analysis delivered annual discharge data to be modeled using autoregressive integrated moving average, ARIMA models. Spectral density analysis, autocorrelation functions and the standardized annual discharge data evaluated annual discharge frequency cycles. Results showed ARIMA models with two autoregressive and one moving average coefficient adequately project river discharge for all gauging stations with four of them showing significant declining patterns since 1860. ARIMA models in combination with autocorrelation and spectral density techniques as well as standardized departures, in agreement with present (2002-2010) observations, forecast a wet episode that may last between 9 and 12 years thereafter entering again into a dry episode. Three dry-wet spell cycles with different time scales (1-2 years; 4-7 years; 9-12 years) could be discerned from these analyses that are consistent for all three northern Mexico's river clusters that emerged from a multivariate analysis test.

Keywords: Cycles; patterns; tendencies; spectral density; drought and wet episodes.

Modelagem da vazão anual de seis rios do norte do México

RESUMO

O objetivo geral deste trabalho foi a modelagem da variabilidade da vazão de rios para melhorar a gestão convencional das águas dos rios subtropicais do norte do México. Este artigo abordou as seguintes hipóteses: a) tendências das vazões do rio, padrões e ciclos podem ser detectados com base em registros de dados simulados e de instrumentos, e b) vazão anual pode ser prevista por modelos estocásticos. Onze estações hidrométricas de seis grandes rios; três rios de planície que drenam diretamente para o Oceano Pacífico (Rios Santa Cruz, Acaponeta, e San Pedro), cinco localizados nos trechos superiores desses rios (Rio San Pedro: Peña del Aguila, Refugio Salcido, San Felipe, Vicente Guerrero e Saltito) que drenam para bacia interior (Río Nazas: Salomé Acosta) e os dois últimos que drenam para o norte do Golfo

México (Rio San Juan: El Cuchillo e Rio Ramos: Pablillos) foram analisadas estatisticamente. Dados armazenados de vazões diárias observadas (1940-1999) e dados reconstituídos a partir de série dendrocronológica histórica (1860-1940) resultou em dados de vazão anual a serem modelados usando médias móveis auto-regressivas integradas (modelos ARIMA). A análise de densidade espectral, funções de autocorrelação e os dados padronizados de vazão anual permitiram a avaliação dos ciclos de frequência anual de vazão. Os resultados mostraram que os modelos ARIMA com dois coeficientes e média móvel autorregressiva foram adequados para modelar a descarga do rio para todas as estações, em que quatro deles apresentaram tendências significativas de redução da vazão a partir de 1860. Modelos ARIMA em combinação com técnicas de autocorrelação e densidade espectral, bem como observações dos dados de vazão atuais (2002-2010), indicam que o norte do México está em um ciclo de cheias que pode durar de 9 a 12 anos antes de passar novamente por um período de seca. As estatísticas utilizadas mostraram a presença de três ciclos (anos 1-2, 4-6 e 9-12) consistentes para os três grupos de estações que surgiram a partir da análise multivariada.

Palavras-chave: ciclos; padrões; tendências; densidade espectral; episódios de seca e cheias**.**

1. INTRODUCTION

Mexico´s freshwater availability is high with an average of 474.9 Km^3 $year^{-1}$ that equates to 4,749 m^3 $inhabitant^{-1}$ $year^{-1}$ (México, 2005). Overall only 18% of water resources are pumped out from rivers and aquifers for consumptive use, totaling 78,000 M m^3 y^{-1}. This volume supplies agriculture (78%), urban-public (12%), industry (8%), and livestock (2%) (México, 2001). Mexico's irrigated area total 6.3 M ha, of which 3.4 M ha are irrigated with surface water and the remaining 2.9 M ha with primarily groundwater (México, 2005).

In Mexico, as in many other places, water resources are not evenly distributed in time neither in space. For example, per capita water availability is steadily declining since it was close to 18,000 m^3 $inhabitant^{-1}$ $year^{-1}$ in the 1950's (México, 2007). On the other side, the country's most productive central-northern portion has only 31% of renewable freshwater (México, 2009). Currently, several Mexico's northern watersheds already show signs of water scarcity to cope with increased conventional demands. For example, several over-stressed regions by persistent shortages have water pressure indices well above 100%.

Recurrent drought spells control water resources availability since northern Mexico is a climatically sensitive-prone area because of its subtropical location, a region susceptible to changes in precipitation at several temporal and spatial scales. Drought episodes have reliably been well documented by instrumental and reconstructed proxy rainfall and dendrochronological records (O'Hara and Metcalfe, 1997; Stahle et al., 1999; Diaz et al., 2002; Cleaveland et al., 2003; Návar, 2008). However, how reduced rainfall controls surface and groundwater resources is missing elsewhere. Any hydro-climatic model would predict that rainfall variation drives watershed discharge and aquifer recharge, although its magnitude requires further empirical quantification and evidence. Coupling physical modeling with measured rainfall-discharge data would eventually improve predictions. For instance, Návar (1999) proved the river discharge magnification effect by diminished rainfall; e.g., the Mexico's northeastern Rio San Juan discharge was reduced along the main stem by 52% during the 1950's drought spell on record although annual precipitation declined by only 20%.

Hydro-climate variability drives water availability, pressure and competition and modeling river discharge plays a key role in the decision-making process with the aim to properly manage water resources in places with scarce, erratic hydro-climatic conditions (Postel, 2000). However, discharge cycles, their magnitude and temporal duration must first be understood to be later coupled with reconstructed rainfall data to fit more physically-based

models. For instrumental records, Návar et al. (2006) for Mexico's northern rivers; Návar (2009) for rivers of Durango, Mexico; Hernández and Návar (2010) for rivers of Michoacán, Mexico found that approximately 40% of all gauging stations analyzed are presenting statistical oscillations and tendencies; of which approximately 26% show monotonic reduced annual discharge for the instrumental period of 1940-2000. However, modeling requires information on whether oscillations and tendencies are consistent over longer time series data that can be documented with proxy information to understand sources of inherent intrinsic climatic variability and potential subtle climate shifts.

In light of this information, this research addresses the question whether longer proxy and instrumental river discharge data can be stochastically modeled with the aim to derive oscillations and tendencies. Daily river discharge data for eleven sub-tropical gauging stations for six Mexico's northern large rivers (Acaponeta, San Pedro, San Juan, Nazas, Pablillos, and Santa Cruz) was available to fit ARIMA models; autocorrelation and spectral density analysis. In addition to a cumulative standardized departure aided to understand oscillations and tendencies with the aim to set up better river management guidelines.

2. MATERIAL AND METHODS

2.1. The study area.

The study area covers the basins of Sinaloa, Presidio-San Pedro, Nazas-Aguanaval, and San Fernando-Soto La Marina and the Rio San Juan. These watersheds are found within the Mexican northern States of Sinaloa, Nayarit, Durango, Chihuahua, Zacatecas, Coahuila, Nuevo Leon, and Tamaulipas. The hydrometric stations spans from $21^057'15''$ at the 'Río San Pedro' site to the $25^043'10''$ of North Latitude at the 'El Cuchillo' site and from $106^057'10''$ at the 'Santa Cruz' station in Sinaloa, to $99^033'20'$ of West Longitude at the 'Pablillo' site in Nuevo León, Mexico (Figure 1).

A diversity of climates characterizes Northern Mexico's landscapes (México, 2000). Cold climate typifies the highest peaks and uplands of the two main mountain ranges. The central valleys, and mesas of the Cordilleras feature cold-temperate climates. Subtropical and tropical climates are characteristic of the low ranges of the Pacific Ocean and Gulf of Mexico. Dry-warm climates are common in the central Chihuahuan Desert and the southern Great Plains of North America.

Pine, oak, and a mixture of pine-oak forests cover extensive upland areas of the eastern and western Sierras Madre mountain ranges. Montane forests, characterized by thorny shrubs and low, broadleaved trees, distribute widely on the piedmonts of the main mountain ranges. Tropical and subtropical flora dominates plant cover in the plains and low piedmont slopes facing the oceans. Chaparral, dry, xerophytic plant cover is typical at the central Chihuahuan Desert and the southern Great Plains of North America. Tamaulipan thornscrub, acacia and mesquite forests extend into the lowlands of the Pacific Ocean, northern Gulf of Mexico and at several places of the Great Plains of North America. Tropical dry forests are typical of the lowlands of the Pacific Ocean.

Shallow Litosols and Regosols are typical of the main mountain ranges. Deep Regosols, Xerosols, and Yermosols dominate the landscape of the central Chihuahuan Desert. Deep Vertisols characterizes the plains in the lowlands of the Pacific Ocean and the northern Gulf of México.

Figure 1. Location of the study area and the eleven hydrometric stations in northern Mexico.

2.2. Instrumental and reconstructed annual discharge data.

Annual instrumental discharge data (1940-2000) collected from official records for the gauging stations: Santa Cruz (RH 10); San Pedro (RH 11); Acaponeta (RH 11); Salomé Acosta (RH 36); San Felipe (RH 11); Refugio Salcido (RH 11); Peña del Águila (RH 11); Vicente Guerrero (RH 11); Saltito (RH 11); El Cuchillo (RH 37); Pablillo(RH 25) was reconstructed back to 1860 using dendrochronological analysis reported for the Sierra Madre Oriental and Occidental mountain ranges, SMO and SMW, respectively. A total of six dendrochronologies; three for the SMO (La Marta, El Potosí, and La Encantada) reported by Arreola-Ortiz and Návar-Cháidez (2010) and three for the SMW (El Gato, Banderas, and Las Bayas) reported by González-Elizondo et al. (2005) fitted regression equations with annual discharge as the dependent variable. It is highly likely annual baseflow correlates better with tree ring width since annual discharge is most of the time controlled by heavy downpours lasting a few days in semi-arid and subtropical landscapes. However baseflow information could not be derived at this time for these time series. In general, El Gato data predicted well annual river discharge for most SMW gauging stations and El Potosi dendrochronological data fitted better the El Cuchillo-Pablillos annual river discharge data. Regression equations were statistically significant, with coefficients of determination, r^2, between $0.10 \leq r^2 \leq 0.40$ and probabilities < 0.05.

2.3. Fitting ARIMA models.

Autoregressive integrated moving average models, ARIMA, fitted proxy and instrumental time series data. The data was smoothed because of a lack of significant auto-correlation functions on the original discharge time series. Trend and de-trended auto-regressive, integrated moving average, ARIMA, models fitted smoothed annual reconstructed and instrumental time series data (1860-2000). Moving average statistic with a time t = 5 years smoothed data well. I searched for ARIMA models that produced unbiased annual discharge data; accounted for the largest variance (large coefficient of determination and small standard error), had uncorrelated AR or MA coefficients, and that projected consistent patterns and tendencies with the original data source. Autoregressive parameters explain the relationship between current and previous discharge while moving average parameters define better cycles within the time series. ARIMA models can be described as a combination of both parameters with or without a tendency or a seasonal component. A simple ARIMA model with an autoregressive and one moving average parameter with no seasonal pattern is (1,0,1) and explains that the previous discharge is well related to the current discharge and that the time series has one potential cycle. Parameters are often calculated using statistical software. For this analysis the Statistical Analysis System (Sas) was employed.

2.4. Classifying gauging stations.

Principal component analysis, a multivariate analysis statistic, classified and ordered all eleven gauging stations using instrumental annual discharge data. The statistical method was conducted on un-transformed data with the correlation option in SAS v 8.0 (Sas, 1997).

2.5. Magnifying and extracting dry-wet frequency cycles.

The time series discharge data augmented the resolution by calculating the cumulative standardized z coefficient value. The standardization procedure contrasts time series data since discharge values are transformed into a compatible Z statistic. The cumulative standardize Z coefficient was calculated as follows;

$$Z = \sum_{zi=1}^{Zn} z_i + z_{i+1} \therefore z_i = \frac{x_i - \bar{x}}{s} \therefore s = \sqrt{\frac{(x_i - \bar{x})^2}{n-1}}$$

When the Z coefficient value is plotted as a function of time, t, negative Z values produce downward tendencies indicating the presence of drought spells. In contrast when the cumulative Z coefficient value make upward tendencies it provides indications of wet cycles. Then, the Z coefficient value magnifies drought and wet patterns in the time series data.

2.6. Identifying wet and dry cycle periodicities.

Predicted discharge time series by the ARIMA models were statistically analyzed for frequency cycles using spectral density analysis. The autocorrelation, the partial autocorrelation and the inverse autocorrelation, as well as the spectral density functions fitted reconstructed and instrumental time series data. Confidence interval bands (α=0.05) on the correlation and spectral functions furnished preliminary statistical backgrounds on r values > than confidence interval bands. Spectral density analysis and the standardized cumulative Z index confirmed the cycle frequency as a function of peaks to noise ratios in a spectral band.

3. RESULTS AND DISCUSSION

3.1. Fitting ARIMA models

Autoregressive, integrated moving average models with a linear tendency fitted better than the autoregressive-moving average models proxy and instrumental data since the mean r^2

increased from mean values of 0.64 to 0.73 and the mean standard error was reduced on average from 92 to 82 Mm^3. An example of instrumentally-recorded, reconstructed, smoothed, modeled and projected flows for the Nayarit's gauging station 'San Pedro' is shown in Figure 2. In general, best prediction ARIMA models contain two auto-regressive and one moving average parameters with a linear tendency that adequately project annual discharge, with a coefficient of variation of 12% (08%) of the mean annual discharge (Table 1). Therefore, two previous discharge values are well related to the present discharge and the time series has on the average one cycle. The inter-annual cycle was the most statistically significant. For all ARIMA models, the linear tendency had a negative slope but only four (San Pedro, Upper Nazas or Salomé Acosta, Pablillos, and Santa Cruz) had statistical significance ($p \leq 0.05$). That is, in this report, the linear decreasing discharge tendency is accepted for four out of eleven studied gauging stations; in 36% of the studied rivers the downward tendency extends to the period of 1860-1940 (Table 1). Surprisingly these results are consistent with findings for other rivers of Mexico's northern and central watersheds. Most models predict well smoothed annual discharge since coefficients of determination, r^2, larger than 0.69 and standard errors of less than 40% were observed in these models. Most second order autoregressive parameters show negative signs stressing the stochasticity of these time series. The up and down tendencies can be noted in Figure 2 as well.

In seven out of nine hydrometric stations analyzed, discharge monotonically reduces in northern Mexico (Návar, 2009). Hernández and Návar (2010) found that 24% of all Michoacan State's gauging stations analyzed also present discharge downward tendencies. Návar et al. (2006) calculated that 26% of Mexico's northern 175 gauging stations studied are also presenting reduced instrumental discharge. That is, between 20 and 40% of river discharge data analyzed for instrumental records show monotonically reduced discharge tendencies that are consistent with the percentage of proxy discharge tendencies as well.
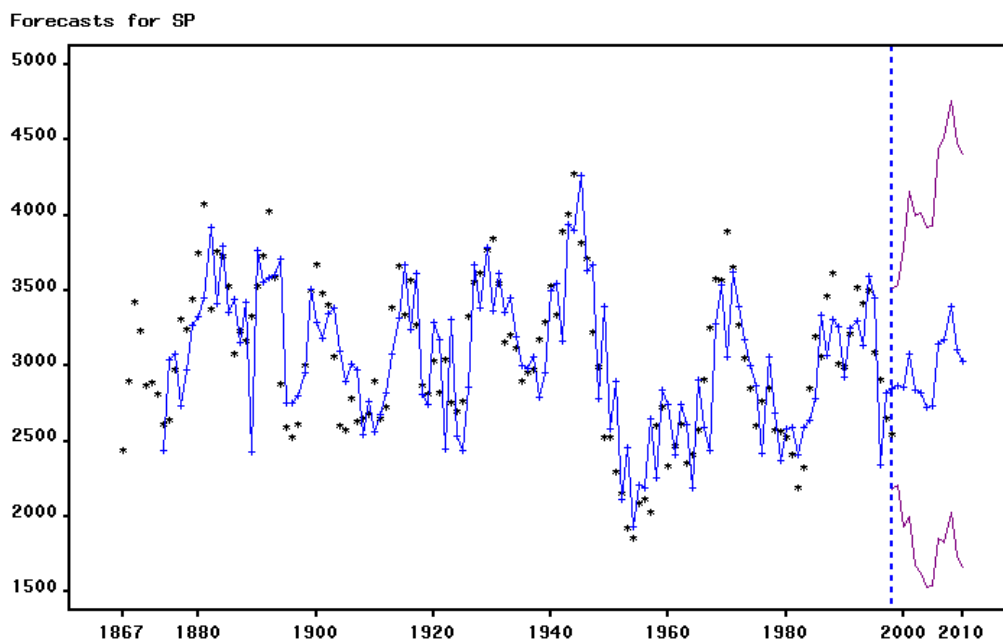
Figure 2. Smoothed annual instrumental and reconstructed discharge data fitted with an ARIMA model (2,0,1) with a linear tendency for the gauging station 'San Pedro' in Nayarit, Mexico.

All ARIMA models project consistently increased river flow for the period of 2002-2004 to 2010-2012 as it has been the case for instrumental and visual observations for all of these rivers for this time period. Unfortunately, discharge data is not yet publically available to

validate stochastic models for the last period (2000-2010) of instrumental records. Good correlations were found between discharge predictions by ARIMA models reported in Table 1 for all eleven gauging stations.

Table 1. ARIMA models for predicting annual smoothed discharge for Mexico's northern eleven gauging stations from six rivers.

Gauging Station	Model	MA(1)	MA(2)	AR(1)	AR(2)	Linear Trend	Sx	R^2
Acaponeta	(2,0,1)	0.63		1.60	-0.73	-2.20	142.63	0.71
San Pedro	(2,0,1)	0.48		1.51	-0.64	**-2.36**	262.31	0.73
El Cuchillo	(2,0,2)	0.65	-0.45	1.35	-0.62	-2.80	134.04	0.70
Salomé Acosta	(2,0,2)	-1.32	-0.44	-0.24	0.64	**-0.95**	84.59	0.69
Pablillos	(2,0,0)			1.04	-0.19	**-0.39**	22.99	0.79
Vicente Guerrero	(2,0,1)	0.41		1.42	-0.61	-0.10	7.02	0.70
San Felipe	(2,0,1)	0.36		1.47	-0.65	-0.36	18.81	0.75
Refugio Salcido	(2,0,0)			1.16	-0.39	-0.22	13.41	0.76
Peña del Aguila	(2,0,2)	0.56	-0.59	1.33	-0.62	-0.44	25.18	0.75
Saltito	(2,0,0)			1.05	-0.26	-1.01	56.91	0.73
Santa Cruz	(2,0,1)	0.50		1.50	-0.62	**-2.12**	186.69	0.72

Note: bold numbers are statistically significant ($p < 0.05$)

3.2. Classifying gauging stations.

Three principal components accounted for by 90% of the total annual discharge variance. The first two are graphed in Figure 3 and they accounted for by 75% of the total annual discharge variance. The first principal component divides data into large (Santa Cruz, Acaponeta, San Pedro and El Cuchillo) and small (R. Salcido, Pablillos, San Felipe, P. Águila, V. Guerrero, Salomé Acosta, Saltito) discharge station values. The second principal component dissects data into Pacific Ocean, the Interior basin draining- river and the upland-watershed gauging stations with intermediate northern Gulf of Mexico gauging stations. As expected, three main clusters emerged quite well from this multivariate analysis. The first one makes up by rivers that drain into the Pacific Ocean (San Pedro, Santa Cruz, and Acaponeta) with reported high internal series' correlation coefficients ($r > 0.87$). The second cluster separated well and conformed rivers draining into the northern Gulf of Mexico (El Cuchillo and Pablillos) that also reported high internal series' r values ($r > 0.67$). The third cluster contained rivers discharging into interior basins (Salome Acosta) together with upland-watershed rivers that drain into the Pacific Ocean (Vicente Guerrero, Peña del Aguila, R. Salcido, El Saltito), which reported also large internal correlation coefficient values ($r > 0.72$). However, small correlation values were found for any of these three river clusters.

Climatically-driven rainfall patterns that produce river discharge; e.g., bimodal type of rainfall originated from easterlies of the Atlantic Ocean are typical of Mexico's northeastern watersheds (El Cuchillo and Pablillos). Monsoonal, uni-modal summer rainfalls originated from Pacific Ocean easterlies appear to feature basins RH 10; RH 11 and RH 36. Geology consisting on Shales and Limestones of Upper Cretacic origin along with recent sedimentary deposits dominate the landscape of the Sierra Madre Oriental mountain range that gives life to Rios San Juan and Pablillos as well as to many other smaller rivers. Volcanic rocks of the Cenozoic era characterize the geology of the Sierra Madre Occidental mountain range. Lower andesitic and upper rhyolitic units of different age composed the volcanic rocks.
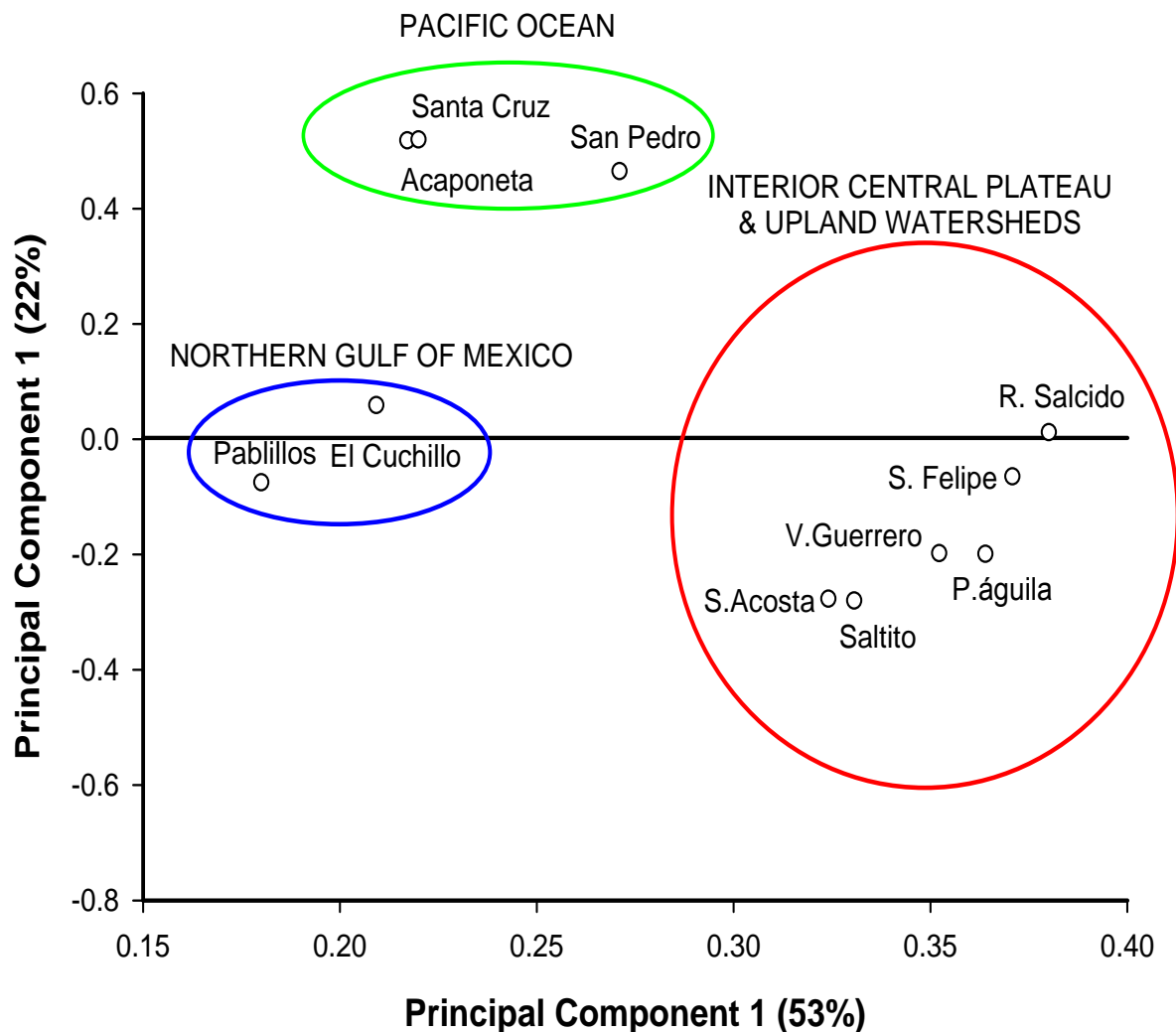

Figure 3. Principal component analysis for instrumental and reconstructed annual discharge data for eleven Mexico's northern rivers.

3.3. Dry-wet cycles

The time series data, the ARIMA models and the standardized cumulative departures show well dry and wet cycles. Below-average river discharge for several time periods indicates dry spells and above-average river discharge annual values are classified as wet episodes. Dry and wet spells can be noted for each river cluster in Figures (4 and 5), respectively.
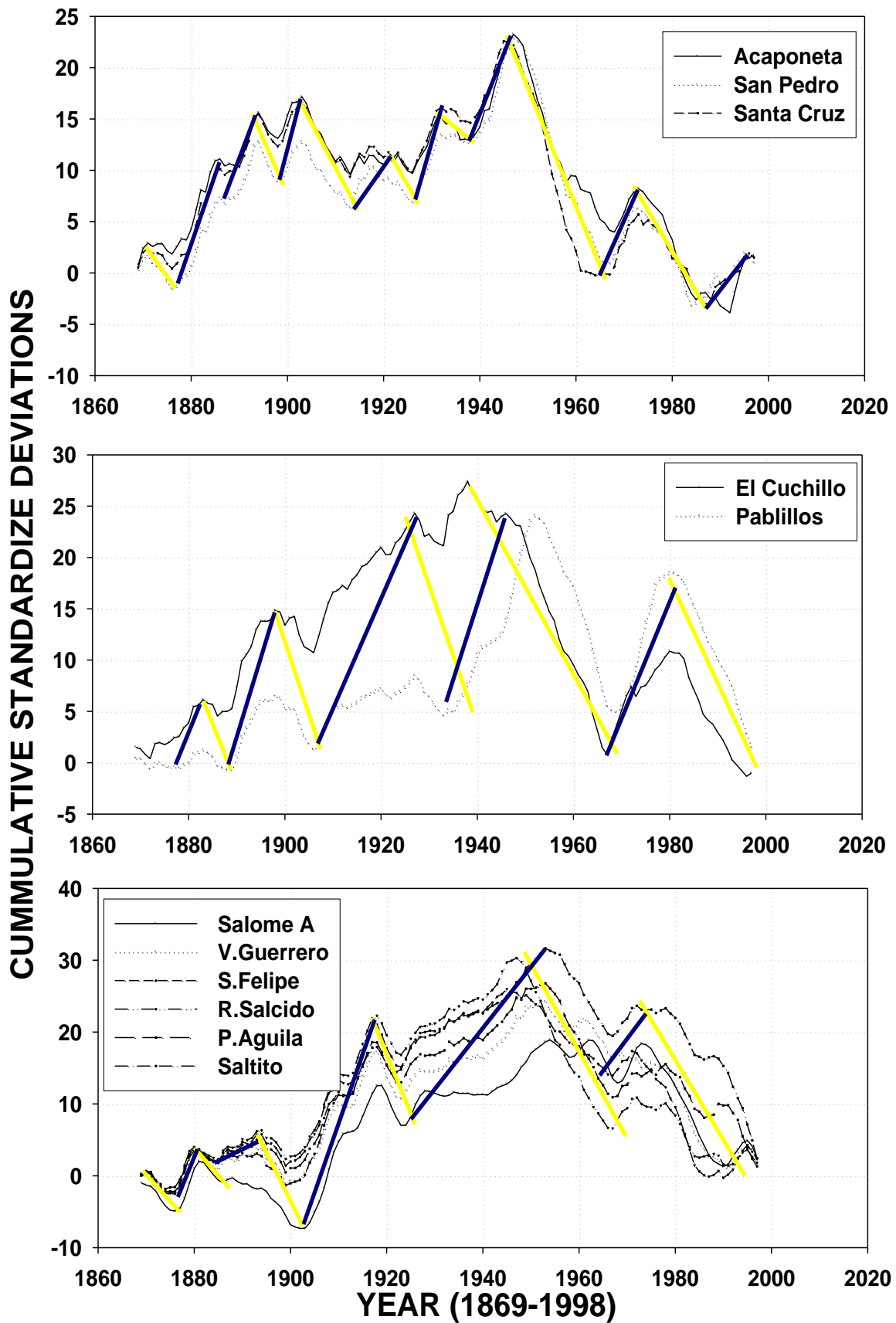
Figure 4. Dry-wet (yellow-blue lines) cycles depicted in standardized annual discharge deviations for all reconstructed and instrumental records for each Physiographic Region.

All reconstructed and instrumental time series are intrinsically and consistently synchronized due to the large internal correlation coefficients and dry and wet cycles are also consistent between hydrometric stations and therefore between physiographic regions. Dry-wet cycles randomly oscillate with different durations and magnitudes; e.g., quasi-decadal dry cycles are noted for the 1870's; early 1900's; the 1930's; the 1950's; the 1980's and the 1990's. Wet quasi-decadal cycles were present during the 1880's; peaking during the 1920's; peaking between the 1940 and 1950's and the last important one peaking in the 1970's. These cycles are also consistent with those reported earlier by Díaz et al. (2002) for Chihuahua, Mexico; by Cook et al. (1999) for the southern portion of the US and by Cleaveland et al. (2003) and Stahle et al. (1999) for Durango, México. Rainfall and discharge patterns for the last century for Puerto Rico reported by Larsen (2000) also show some consistency with dry-wet cycles detected in this study.
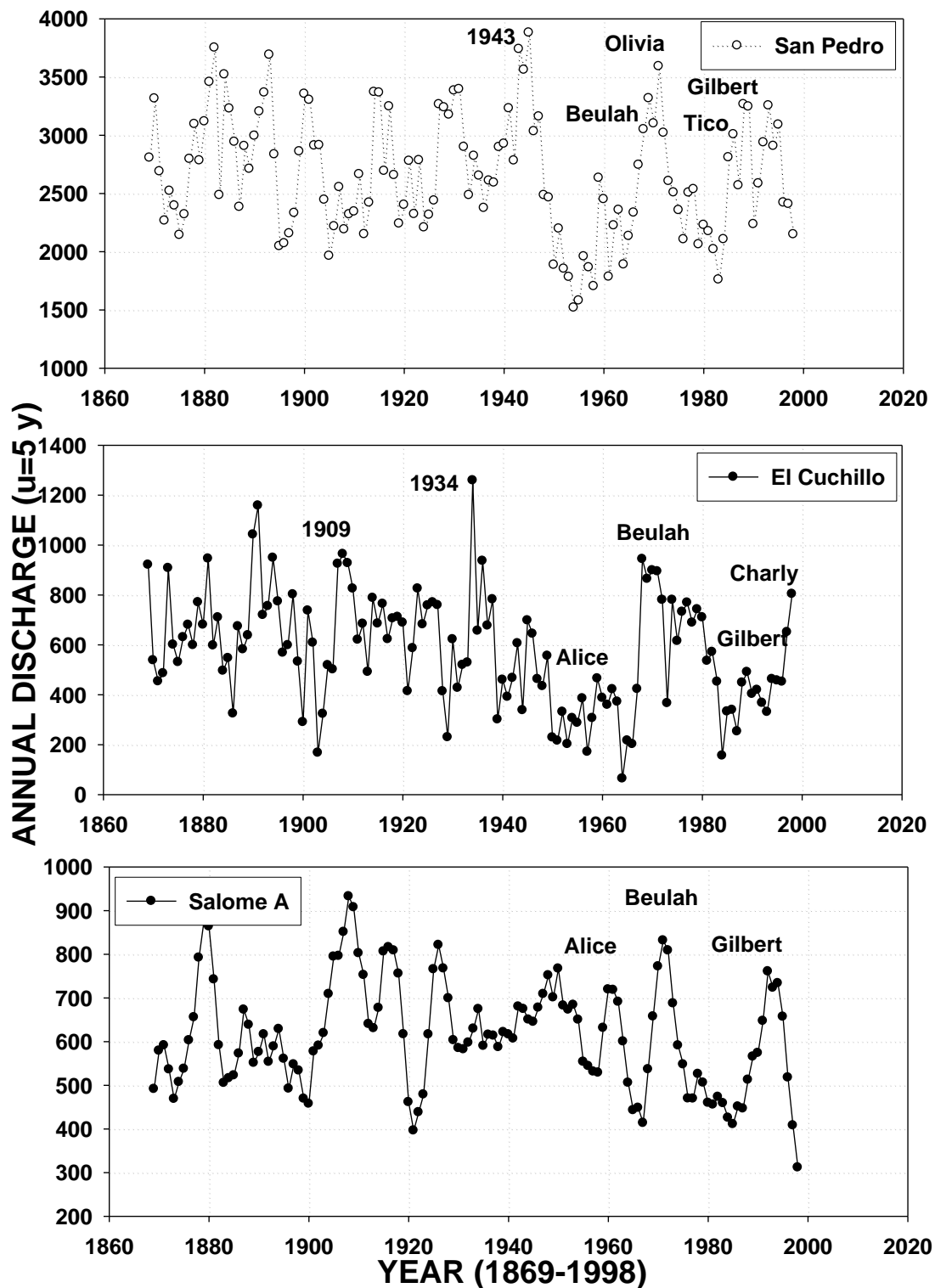
Cyclones, hurricanes or tropical depressions notably increase annual discharge for Mexico's northern rivers. Discharge caused by these climatic phenomena may account for up to four times the long-term annual discharge average. For rivers of the Mexican State of Nuevo Leon, Návar (2003) projected the presence of an average of 2 (with confidence bounds of between 1 and 4) cyclones moving into the State for the period of 2004-2013. This prediction has come true so far since 'Emily' and 'Alex' swept across the State pouring heavy rains with consequently heavy discharge rates for most northeastern rivers during 2005 and 2010, respectively. For proxy discharge data, the 1909 hurricane has been well documented for northeastern Mexico. There is also information on heavy rains producing notable discharge rates across northern Mexico in the 1880's and during the 1890's. These wet episodes must be confirmed with other sources of information to be reliable documented.

Dry-wet episodes present frequencies with different time periods. However, in general, three major cycles could be consistently detected in the spectral density analysis. These findings are consistent with the magnified standardized cumulative Z coefficients and the autocorrelation functions for all time series; these cycles are: (i) 1-2 years; (ii) 4-7 years; and (iii) 9-11 years. The last quasi-decadal cycle does have statistical significance but only at $p=0.10$. The small number of decadal cycles in the time series may explain the lack of potential statistical significance. ARIMA models also project dry and wet spells, in agreement with the spectral density analysis on predicted discharge values, lasting from 1-2; 4-7; and longer periods that last between 9 to 11 years that are consistent in time (1880's, 1900's, 1920's, 1950's, and 1990's).

O'Hara and Metcalfe (1997); Stahle et al. (1999) and Návar (2008), using primary and secondary historical sources of information and dendrochronological data coupled with instrumental records reconstructed Mexico's northern seasonal precipitation. These authors found quasi decadal drought spells during 1450-1500; 1550's, 1600's, 1695-1720, 1750-1820; 1870-1880, 1895-1910; 1930's, 1950's, 1990's. For the study period in this report, both sources of hydro-climatic data matches well drought episodes and show the 1950's and 1990s' dry oscillations are the worst on record for this part of the country since late 1880's.

The inter-annual discharge variability requires additional sources of information in order to be more explicitly described. The annual migration of the Bermuda High in the North Atlantic Ocean combined with the seasonal displacement of the Inter-tropical Convergence Zone, ITCZ may partially explain the inter-annual variability. The second dry-wet cycle (4-7 years) correlates well with indices of El Niño/Southern Oscillation, ENSO (Cavazos and Hastenrath, 1990; Stahle et al., 1999; Méndez-González et al., 2008) that exhibit statistically significant spectral peaks in the ENSO frequency band near periods of 4 years (Stahle et al., 1999). The ENSO causes severe and prolonged summer droughts and wet winters in northern Mexico (González-Elizondo et al., 2005) with total reduced annual rainfall and it has an indirect control on river discharge as well. The third quasi decadal discharge dry-wet variability is evident in all ARIMA models, spectral density analysis, as well as in

reconstructed Durango's seasonal precipitation (Stahle et al., 1999; Návar, 2008). The reconstructed Mexico's climate variability using historic sources also shows this variability (O'Hara and Metcalfe, 1997).

Figure 5. Cyclones, hurricanes, and tropical depressions causing floods and increasing annual flow for three Mexico's northern Rivers.

The northeastern Pacific Ocean cooling - warming cycle, called the Pacific Decadal Oscillation, PDO, appears to be related to this phase for northern Mexico (Jones, 2003). Quasi-decadal sequences repeated in the time series and ARIMA models during the 1880's, 1900's, 1920's, 1930's, 1950's, 1980's and 1990's. The cooling of the northeastern Pacific Ocean surface waters brings below average rainfall and discharge to northern Mexico. The PDO effect has also been related to surface runoff in Utah although its control is not consistent over time and appears insignificant during periods of instrumental recorded data (Tingstad and MacDonald, 2010). Weak associations between annual discharge and PDO variability can be explained since the latter manifests mostly in the North Pacific region and can persist over several decades. Mantua et al. (1997) described periods of 15-25 years and 50-70 years and dry spells last at the most 15 years (1950's) for this time series data.

The Atlantic Multidecadal Oscillation, AMO, is a recurring pattern of SST anomalies in the North Atlantic with a recurring period of 65-80 years (Knight et al., 2006). Positive AMO index values have been associated with drought in the continental U.S. during the 20th Century (Enfield et al., 2001). This cycle appears to control river discharge when looking at the cumulative Z index time series data (Figure 4). For rivers draining into the northern Gulf of Mexico, this cycle started, peaked and ended in the 1880's, the late 1940´s and the early 1960's, respectively. For rivers draining into the Pacific Ocean, this cycle started, peaked and ended during the 1990's, the 1950's and the late 1990's, respectively. However, proxy and instrumental discharge data is not sufficient to statistically correlate this tendency.

Longer time cycles of close to 300 years are discussed in O'Hara and Metcalfe's (1997) historical and Stahle's et al. (1999) dendrochronological datasets. The period 1345-1640 appeared to have been relatively wet; the period of 1640-1915 appeared to be relatively dry and since 1915 there has been a shift towards somewhat wetter conditions in Mexico. Due to the reconstructed short time series data to build the ARIMA models, the AMO and Little Ice Age dry-wet sequences are absent in future projections. The 1640-1915 dry episode appeared to have been dominated by the prolonged blocking of the monsoon and an increase of the 'nortes' frequency that coincides with the Little Ice Age (O'Hara and Metcalfe, 1997). The monsoon suppression, the Bermuda High lying well to the east and the southwards displacement of the Intertropical Convergence Zone, ITCZ, appear to control dry periods (Jauregi and Klaus, 1976; Jauregi, 1979); since two major features of atmospheric circulation the Trade winds and the sub-tropical high pressure belt influence Mexico's present day precipitation.

The reported longest dry-wet cycles (300 years) would point at a monotonic increasing discharge trend for all studied river gauging stations, since it appears it started during early the 20th century. Likewise the smaller, quasi decadal discharge tendencies would also tip at an increasing pattern unlike the ENSO cycle that was hitting northern Mexico in 2009. Since a negative discharge pattern is common in all ARIMA models as well as for other studied rivers, discharge variation must be controlled by other sources of perturbation that should be observed, measured, modeled and projected.

The potential climate change effect on annual river discharge cannot be derived by this statistical analysis. Cycles and tendencies are consistent for both proxy and instrumental discharge data. The declining river discharge pattern noted in all ARIMA models is probably associated to an increase of human control over water resources. Although, Mulholland et al. (1997) projected using climate change models that river discharge would diminish between 5 to 20% in semi-arid, subtropical Mexican eco-regions by climate change; climate variability appears to govern river discharge over other human-induced perturbations such as land use change, increased water demands from rivers and aquifers, and potential climate change. However, the latter control deserves more attention. By looking into the rainfall patterns, depth, duration, intensity parameters that drive river discharge may offer some insights into the climate change phenomenon. This is also a matter of further studies.

4. CONCLUSIONS

This research shows that variability of river discharge could be detected in proxy and instrumental discharge records as well as that ARIMA models with a linear tendency predicted well the reconstructed and instrumental time series data. Therefore, discharge variability is under the influence of synoptic climatic events of several temporal scales. Inter-annual, ENSO, PDO, AMO, and Little Ice Ages control individually or in combination Mexico's northern discharge patterns and tendencies. Monotonic reduced discharge for four hydrometric stations partially stresses the indirect evidence of human control over surface water resources. Therefore, this study calls for: a) extending and modeling discharge time series to explore the time cycles controlled by longer climate variability patterns; b) further understanding other major sources of variation that would better explain the downward river discharge trend; and c) combining AMO, PDO, ENSO, Little Ice Age climate events to better understand discharge variability across Mexico's northern watersheds with the aim to sustainable manage water resources in the region. Land-use changes, increasing irrigated area, human and industrial demands over time, as well as potential, temporal subtle climate changes could also explain discharge drifts. This is a matter of further studies.

5. ACNOWLEDGEMENTS

6. REFERENCE

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