Temporal Tendencies of River Discharge of Five Watersheds of Northern Mexico

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Abstract—*The watersheds of northern Mexico that encompasses the Rio San Pedro, Sinaloa, Nazas, Aguanaval, San Juan, and San Fernando-Soto La Marina are located within the main mountain ranges of northern Mexico and within the zone of large deserts of the boreal hemisphere. The hydro-climate variations, the management of forest soils and land use changes are shaping the supply and management of water resources. This research project aims to understand whether changes in discharge variables are present in time series data of 172 gauging stations of five watershed of northern Mexico. The Mann-Kendall test and the Sen's method were used to test for statistical changes in trends or tendencies and the magnitude of change of annual, monthly, monthly standard deviation, daily minimum (baseflow), and daily maximum (peakflow) discharge of the hydrometric stations mentioned above. Results showed that over 40 percent of the gauging stations had statistical significant tendencies in each of the five discharge variables analyzed. Most tendencies had a negative sign indicating a steady reduction of discharge in time. The reduction was, on the average over 5,000 m3 year-1 for annual discharge. Although further research is required to understand the potential sources of variation that explains the negative tendencies of discharge, it can be preliminary attributed to subtle climate changes, and management practices of water and other natural resources.*

Introduction

Conventional management of water resources cannot meet water supply for future development in arid, semi-arid, and subtropical countries (UNCED, 1992; Postel, 2000). Northern Mexico is placed within the arid, semi-arid zone belt of the northern hemisphere. In addition to highly erratic and variable water supply given by hydro-climate variations (Návar, 2001; Návar, 2004; Schmandt and others 2001); unsustainable practices of hydrologic resources are shaping new approaches to meet future demands. Unsustainable practices of water resources include high per capita water use, with a little over 300 l per day per person in several regions, and a high ratio of volume of irrigation to productivity, a common feature in several irrigation districts (Návar, 2004). High losses of water in the distribution systems of most cities (30-40 percent) (CNA, 2000), contamination of streams, reservoirs, and aquifers (De León Gomez y Medina Barrera, 2000; Flores-Laureano y Navar, 2002; Lizárraga, 2003), and abatement of reservoirs and river fragmentation (CONAFOR, 2004) are also indicators of unsustainable management practices of water resources. Other biological indicators are losses of species diversity in streams (Contreras and Lozano, 1994; Edwards and Contreras, 1997) and changes in species structure of plants in streams (Guerra, 1998). These are partially the result from several unsustainable management practices such as river contamination, drawdown of reservoirs, and river fragmentation.

Future conventional water supplies in the region are not warranted because of demographic growth and the presence of drought spells. In addition, Mulholand and others (1997) and the IPCC (2001) predicted using general circulation models that northern Mexico may receive 10 percent less rainfall and generate between 5-10 percent less streamflow with increasing temperatures by global warming. Návar (2001) observed that in the presence of worst drought episodes on record, several regions of northern Mexico receive 12 percent less rainfall and 27 percent less streamflow. Therefore, climate change is already or may magnify drought spells and reduce water supply in the region.

In this part of the Conafor project, we aim to address whether statistical changes in river discharge are taking place in several streams that drains northern Mexico.

A total of 172 hydrometric stations were statistically analyzed by trends and trend magnitude in five variables of river discharge in the hydrologic regions of Sinaloa (RH10), Presidio-San Pedro (RH 11), Nazas-Aguanaval (RH 36), San Juan (RH 37), and San Fernando-Soto La Marina (RH 25). The working hypothesis was that there is no change in any of the variables of river discharge in time and therefore the change in magnitude is equal to zero.

Materials and Methods

Location of the Study Area

The region under study comprises the hydrologic regions of Sinaloa, Presidio-San Pedro, Nazas-Aguanaval, and San Fernando-Soto La Marina and the Rio San Juan watershed located within the Mexican States of Sinaloa, Nayarit, Durango, Chihuahua, Zacatecas, Coahuila, Nuevo Leon, and Tamaulipas.

Population

Demographic information on each watershed is reported in table 1.

Climate

A diversity of climates is present in the studied watersheds (CAN, 1994; 2000). Cold climates are observed in the highest peaks of the mountain ranges; cold-temperate climates in the central valleys, at the piedmont of the Sierras; subtropical, and tropical climates in the low ranges of the Pacific Ocean and Gulf of Mexico piedmonts; to dry climates in the central Chihuahuan Desert.

Plant Cover

Extensive areas are covered by Pine, Oak, mixed Pine-oak forests in the eastern and western Sierras Madre mountain ranges. At the piedmont of the mountain ranges, submontane forests are characterized by thorny shrubs and broadleaved, low trees. In several places of the piedmont, tropical and subtropical flora dominates the landscape. Chaparral, dry, xerophitic plant cover is typical at the central Chihuahuan Desert. Tamaulipan thornscrub, acacia and mesquite forests extend in the lowlands of the Pacific Ocean, Gulf of Mexico, and Great Plains of North America.

Table 1. Population in five watersheds of northern Mexico.

Watershed	Inhabitants
1. Sinaloa (RH 10)	2,279975
2. Presidio – San Pedro (RH 11)	1,465720
3. Nazas-Aguanaval (RH 36)	1,655910
4. Cuenca Rio San Juan (RH 37)	4,216607
5. San Fernando – Soto La Marina (RH 25)	682033
Total	10,300245

Sources: CONAPO, INEGI (2000).

Soils

Soils are characterized mainly by Litosols in the uplands of the major mountain ranges. Regosols and Xerosols dominate the landscape of the central Chihuahuan Desert. Vertisols are characteristic in the lowlands of the Pacific Ocean and Gulf of México.

Methods

A total of 172 gauging stations placed in five watersheds were selected for discharge analysis. The number of hydrometric stations analyzed is reported in table 2.

The Mann-Kendall nonparametric test was used for detecting statistical trends in discharge time-series data. The test reveals the presence or absence of monotonic increasing or decreasing trends. The mathematical formulation of the Mann-Kendall test is described in equations [1] - [3].

$$Z = \begin{cases} \dfrac{S-1}{\sqrt{VAR(S)}} & if \quad S>0 \\ \dfrac{S+1}{\sqrt{VAR(S)}} & if \quad S<0 \end{cases} \qquad [1]$$

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \operatorname{sgn}\left(x_j - x_k\right)$$

$$\operatorname{sgn}\left(s_j - x_k\right) \begin{cases} 1 \quad if \left(x_j - x_k\right) > 0 \\ -1 \quad if \left(x_j - x_k\right) < 0 \\ 0 \quad if \left(x_j - x_k\right) = 0 \end{cases} \qquad [2]$$

$$VAR(S) = \frac{1}{18}\left[n\left(n-1\right)\left(2n+5\right) - \sum_{p=1}^{q} t_p\left(t_p-1\right)\left(2t_p+5\right)\right]$$

[3]

where xj and xk are the annual values in j and k years, q= number of tied groups and tp= is the number of data values in the pth group. The presence-absence of a statistically significant trend is evaluated using the Z value, which is normally distributed.

Table 2. The number of hydrometric stations analyzed for trends and trend magnitude in five watersheds of northern Mexico.

Watershed	Hydrometric Stations	Average Discharge ($M\ m^3y^{-1}$)	Average Period
1. Sinaloa (RH 10)	58	7,970	1960-1999
2. Presidio – San Pedro (RH 11)	15	4,154	1970-1998
3. Nazas-Aguanaval (RH 36)	33	328	1940-1999
4. Cuenca Rio San Juan (RH 37)	30	1,260	1955-1999
5. San Fernando – Soto La Marina (RH 25)	36		1970-1999

Data source: CNA (2003).

A total of five discharge variables were tested by the sign test. Discharge variables are: (i) annual discharge, (ii) monthly discharge, (iii) the standard deviation of monthly discharge, (iv) minimum daily discharge, and (v) maximum daily discharge.

The non-parametric Sen's method was used to detect the magnitude of slope change in all five discharge variables. The slope is described as a change of the variable per unit time. The Sen's method was used assuming a linear trend in the short time series. Equation [4] describes the Sen's method.

$$Qi = \frac{x_j - x_k}{j - k} \qquad [4]$$

where j>k.

Equation [4] is the median slope of N=n(n-1)/2 slope estimates Qi.

Results and Discussion

Discharge is being modified in the five studied watersheds. Table 3 shows the number and percentage of gauging stations which had a statistically significant trend, with negative slope (-), and positive slope (+).

M.Std.Dev. = Standard deviation of monthly discharge. The ratio of last row was estimated from the number of gauging stations with statistical significance to the total number of gauging stations analyzed.

In general, over 40 percent of the gauging stations analyzed showed a statistical significant trend. Of these, on the average, 26 percent had a negative trend and the remaining 16 percent had a positive tendency. Annual and monthly discharge are steadily decreasing at the watersheds San Pedro, Nazas, San Juan, and San Fernando but increasing at the watershed Sinaloa. The former watersheds are characterized by having an important area within the interior valleys and the Chihuahuan Desert of northern Mexico, where erratic and infrequent rainfall and high evapo-transpiration losses control the hydrologic cycle. In the Sinaloa watershed, most gauging stations with positive trends in annual and monthly discharge are located in the lower parts of the watershed, below most irrigation districts, dams, and urban areas. Therefore, the increasing tendency is partially due to management of water resources, rather than to the steady changes in hydroclimate.

The monthly discharge variation is being reduced at all watersheds, partially indicating the influence of reservoirs, over-utilization of streamflow, and steady inputs of municipal and irrigation excess into streams.

Minimum daily discharge, which is a measurement of baseflow, is increasing at most gauging stations at the watersheds Sinaloa and San Pedro, but it is reducing at most gauging stations in the remaining watersheds (Nazas, San Juan, and San Fernando). Irrigation –excess and urban discharge partially explains baseflow increments and water withdrawals in excess from aquifers of the interior watersheds. Subtle changes in rainfall

Table 3. Number of gauging stations with statistical significance in discharge trend.

	Discharge				
	Annual	Monthly	M.Std.Dev.	Minimum	Maximum
Sinaloa	25(-4,+21)	26(-5,+21)	28(-17,+11)	28(-3,+25)	27(-16,+11)
San Pedro	6(-4,+2)	5(-3,+2)	6(-6,+0)	2(-0,+2)	6(-6,+0)
Nazas	18 (-15,+3)	18 (-15,+3)	19 (-16,+3)	11 (-7,+4)	18 (-15,+3)
San Juan	13(-11,+2)	14(-12,+2)	12(-9,+3)	12(-8,+4)	12(-8,+4)
San Fernando	12(-9,+3)	12(-9,+3)	8(-7,+1)	18(-14,+4)	8(-7,+1)
Total	74(-43,+31)	75(-44,+31)	73(-55,+18)	71(-32,+39)	71(-52,+19)
Ratio (%)	43(25,18)	44(26,18)	42(32,10)	41(19,22)	41(30,11)

Table 4. The median slope (and confidence intervals) for five variables of discharge with negative tendency of 172 gauging stations in five watersheds of northern Mexico.

	Discharge				
	Annual	**Monthly**	**M.Std.Dev.**	**Minimum**	**Maximum**
Sinaloa	-3.66(2.19)	-0.82(1.06)	-0.32(0.41)	-1.91(0.51)	-9.69(6.25)
San Pedro	-0.11(0.12)	-2.05(0.94)	-2.52(4.89)	-1.02(0.77)	0(0)
Nazas	-4.74(3.98)	-0.40(0.31)	-0.50(0.28)	-1.31(0.92)	-1.28(0.80)
San Juan	-0.84(1.11)	-2.10(0.92)	-0.01(0.01)	-1.58(0.61)	-2.73(3.30)
San Fernando	-16.47(8.17)	-2.56(2.03)	-2.53(1.02)	-0.12(0.10)	-10.01(2.61)
Average	-5.16(3.11)	-1.59(1.05)	-1.18(1.32)	-1.19(0.58)	-4.74(2.59)

M.Std.Dev. = Standard deviation of monthly discharge.

frequency, depth, and intensity may also be contributing to changes in baseflow.

Maximum daily discharge is being reduced at most gauging stations in all watersheds. Increasing storage in arid, semi-arid, and subtropical reservoirs is reducing peakflows in most gauging stations.

The rate of change of discharge is reported in table 4.

Reductions in annual discharge are noticed in the San Fernando – Soto La Marina, Nazas, and Sinaloa watersheds. The San Juan and San Pedro watersheds have annual discharge reduced in less than 10,000 m3 y-1 and appear to be independent of management practices of water resources. For monthly discharge, the variation between watersheds diminishes.

Peakflows are most dramatically modified than baseflows. Sinaloa and San Fernando watersheds appear to have largest control on streamflow and therefore on peakflows. Baseflow is least modified in the San Fernando watershed.

Causes of shifts in river discharge are management practices of water and natural resources and subtle climatic changes. Conventional management practices must address new approaches to sustainable manage water resources, with special emphasis on critical times. River discharge must partially supply the domestic, agricultural, and industrial sectors (Doorenbos and Kassam, 1979; UNCED, 1992; Soley and others 1998). River discharge must also be protected with the aim to conserve landscapes, riparian ecosystems, species, and genes; as well as the goods and services they provide to society (UNCED, 1992; Postel, 2000). In arid, semi arid, and subtropical regions, prone to erratic, infrequent, and scarce rainfall and streamflow; with steady growing population searching for development, the conservation of streams with running water becomes a difficult task (Kleeberg and Weissberger, 1996; Schmitt, 1997). Therefore, every drop of water withdraw from reservoirs and rivers must double productivity in order to conserve water resources with the aim to sustainable manage water (Postel, 2000). The present and likely future scenarios suggest the need of: (a) reducing per capita water use, (b) increasing the efficiency of water use in the municipal, industrial, and above all in the agricultural sector, (c) treating all water diverted to streams and reservoirs, etc. These practices require the promotion of interactive, iterative, and multisectorial approaches; the planning for the rational utilization, protection, conservation, and management of water resources; the design, implementation, and evaluation of programs and projects that are economically efficient, socially acceptable, and environmentally compatible; and the identification and strengthening of appropriate institutional, legal, and financial mechanisms (UNCED, 1992; Schmandt and others (1998; 2000).

Conclusions

Discharge is being temporally and spatially modified in northern Mexico. A little over 40 percent of gauging stations analyzed showed changes of five discharge variables in time. Most gauging stations showed a negative tendency for most discharge variables for most watersheds indicating a reduction of annual, monthly, monthly deviation, daily minimum, and daily maximum flows. These changes appear to be the result of subtle climatic shifts, management practices of water and natural resources, the presence of reservoirs, irrigation districts, and metropolis within the watersheds. Further research is required for understanding the sources of variation of discharge within each watershed.

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