Water Scarcity and Degradation in the Rio San Juan Watershed of Northeastern Mexico

Escasez de agua y degradación en la cuenca del río San Juan del noreste de México

José de Jesús Návar Cháidez
Profesor del Centro Interdisciplinario de Investigación
para el Desarrollo Integral Regional (ciidir-ipn) Unidad Durango
Dirección electrónica: jnavar@ipn.mx

Abstract
Freshwater has become a limited resource for development in the Rio San Juan watershed, the major tributary of the Lower Rio Bravo, in northeastern Mexico. The results of unsustainable practices include: the inter-basin transfer of freshwater, groundwater depletion, low or non-existent river flows in several river segments, rising pollution levels, high per capita water use, low irrigation efficiency, the disturbance of riparian ecosystems, and social conflict between water uses and users, all exacerbated by recurrent drought episodes of several temporal scales. This report shows that improving sustainable management practices could make it possible to meet current conventional water demands for agriculture, population, industry, as well as for riparian environments and ease social tension but policies are required to increase water use efficiency in all economic sectors, together with new partnerships that cut across disciplinary and professional boundaries.

Keywords: 1. Municipal, agricultural, and industrial water use, 2. aquatic ecosystem deterioration, 3. sustainable use of freshwater resources, 4. northeastern Mexico, 5. Rio San Juan.

Resumen
El agua se ha convertido en un recurso limitante para el desarrollo en la cuenca del río San Juan, el mayor tributario del bajo Río Bravo, del noreste de México. Señales de manejo no sostenible incluyen: la transferencia del agua entre cuencas, la disminución del nivel del agua de los acuíferos, la presencia de caudales mínimos e inexistentes en varios segmentos de los ríos, aumento en los niveles de contaminación, altos consumos per cápita, baja eficiencia en la agricultura, el disturbio de los ecosistemas acuáticos y los problemas sociales entre usos e usuarios, todos estos magnificados por la presencia de sequías recurrentes de diferentes escalas temporales. En este reporte se muestra que el reforzamiento de las prácticas de manejo sostenible del agua podrían cumplir con las demandas para la agricultura, la población, la industria y el medio ambiente además de aliviar la inestabilidad social pero se requiere de políticas para aumentar la eficiencia en el uso en todos los sectores de la economía además de nuevas formas de integración que crucen las fronteras interdisciplinarias y profesionales.

Palabras clave: 1. Uso agrícola, municipal e industrial, 2. deterioro de ecosistemas acuáticos, 3. uso sostenible de los recursos hidrológicos, 4. noreste de México, 5. rio San Juan.

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INTRODUCTION

unesco listed 50 countries as having potential problems in meeting future water demands, including Mexico (1999). In general, freshwater is not evenly distributed in either time or space. Currently, Mexico has high water availability with 474.9 km^3 per year, which is equivalent to 4 749 m^3 per inhabitant per year (inegi-semarnap, 1997; cna, 2005a). Per capita water availability has steadily diminished from approximately 18 000 m^3 per inhabitant per year in the 1950's (inegi, 2007). The central-northern portion of the country, which produces 87 percent of the Gross Domestic Product (pib), has only 31 percent of renewable freshwater as opposed to the southern portion, which has the remaining 69 percent (cna, 2009). At present, several watersheds in northern Mexico are already showing signs of water shortage in their ability to cope with increased conventional and environmental demands.

The Rio San Juan watershed is the major tributary of the Lower Rio Bravo; the international boundary between the US and Mexico. The region is prone to erratic drought spells of several temporal and spatial dimensions; the drought episode of the 1990s being a good example of hydro-climate variation. In the presence of drought episodes of decadal scales, characteristically similar to that recorded in the 1950s, or the 1990s, the watershed would not be able to meet conventional water allocations for all conventional uses. Indeed, at present, agriculture is shrinking due to increased municipal and industrial water demands (Návar, 1999).

sarh-sep (1989), inegi (2007) and cna (2009) listed a complex set of issues regarding the management of water resources of the Rio San Juan watershed. The most acute problems addressed were: (1) its low, erratic availability, (2) its variable spatial distribution, and (3) its contamination. Environmental concerns regarding the health of aquatic ecosystems has evolved as an important issue because of the shrinkage of riparian plant communities (Guerra, 2000) and the disappearance of native freshwater fish species (Contreras and Lozano, 1994; Villarreal, 1983).

Postel (2000) stressed that extracting more fresh blue water for human uses is jeopardizing the health of aquatic ecosystems. The Rio San Juan watershed is already showing signs that severe diversions from several segments of major tributaries, the construction of large reservoirs, and headwater pollution are contributing to the reduction of the stream flow into the Lower Rio Bravo and the disappearance and disturbance of several aquatic communities and species. Guerra (2000); Contreras and Lozano (1994); Obregon (1987); Villarreal (1983) document the disappearance and disturbance of tree, fish and benthonic insect species that dwell along the tributaries of the Rio San Juan. If this state of affairs continues, the number of aquatic species under some form of threat would probably increase while restoration efforts would require considerable expenditure of resources.

The sustainable management of the Rio San Juan water resources is critical to meeting agriculture, industry and municipalities' freshwater demands, as well as to conserving the health of aquatic ecosystems and the life they support. This paper deals with the current state of water resources and aquatic ecosystems; future scenarios; and the potential implementation of practices dealing with sustainable water resource management for meeting conventional demands as well as for conserving and protecting riparian environments.

THE STUDY AREA

The Rio San Juan watershed covers an area of 34 000 km^2 within the Mexican States of Coahuila (40%), Nuevo Leon (57%), and Tamaulipas (3%). It is located between 25º45' and 27º30' NL and 98º30' and 102º00' WL in the northeastern portion of Mexico (Figure 1). The most important Rio San Juan tributaries rise in the Sierra Madre Oriental mountain range and flow through the Great Plains of North America and the plains of the northern Gulf of Mexico. Rio San Juan belongs to the Rio Bravo – Rio Conchos basin and drains into the Lower Rio Bravo near Camargo, Tamaulipas. The main stem is named Rio San Juan, but other smaller branches such as Rio Pilon, Rio Salinas, Rio Pesqueria, Rio Santa Catarina, and Rio Ramos are important tributaries. The Rio San Juan watershed borders the lower Rio Bravo basin to the northeast, the Rio Alamo watershed to the north, the Rio San Fernando watershed to the southwest and the Rio Salado watershed to the southwest and northwest.

Although the Rio San Juan watershed features a wide variety of climates, in general arid to semi-arid climates dominate the landscape of the eastern portion while a temperate climate characterizes the high elevations of the Sierra Madre Oriental mountain range, with most rainfall being delivered during the summer months (inegi, 1995). Average annual precipitation and temperatures, in the arid northwestern portion are 200-500 mm and 22ºC respectively. In the central and eastern areas of the watershed, a semi-arid climate characterizes the area, which

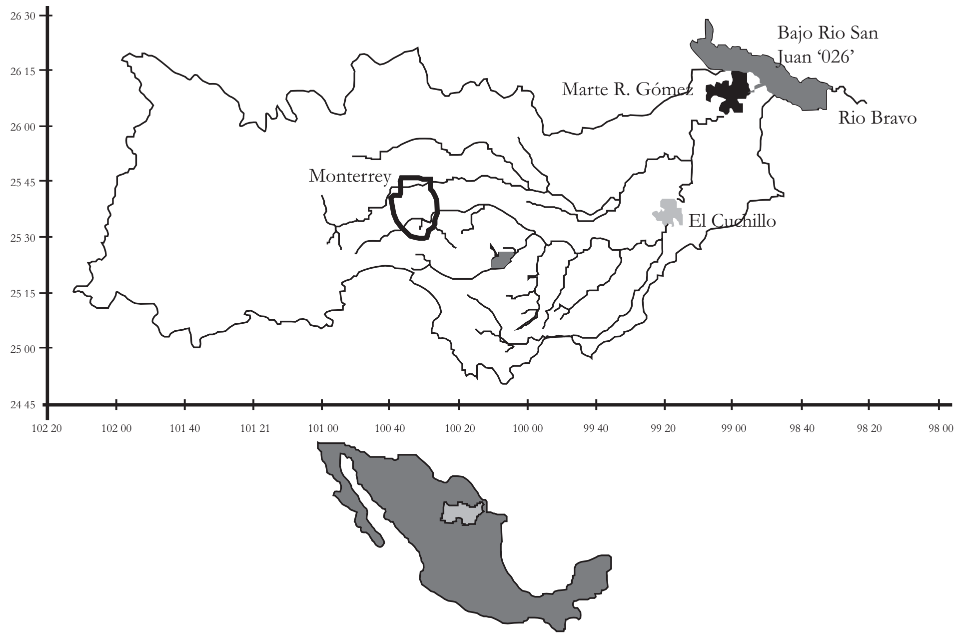

Figure 1. *Location of Río San Juan watershed in northeastern Mexico*

has an average annual temperature of 18-21°C and average annual precipitation of 500-700 mm. The Sierra Madre Oriental mountain range has a semi-arid to temperate climate with a mean annual temperature and precipitation of 12-16°C and 600-1500 mm (sarh-sep, 1989). This part of the watershed has a more positive water balance and is an aquifer recharge zone because it is where most tributaries rise (Návar *et al*., 1994).

Soils in the Rio San Juan watershed are characterized by: (a) Lithosols in the central and western portion of the watershed, (b) Yermosols in the eastern region, and (c) Xerosols, Vertisols and Rendzins in the northern part of the watershed. Primary land uses include: (1) native scrub forests (Tamaulipas thorny shrub, succulent, rosette shrub, sub-awnless shrub, sub-montane shrub and mesquital) covering 65 percent of the total area; (2) coniferous and broadleaf forests comprising 6.37 percent of the total area, (3) irrigated and dry land agriculture occupying 18 percent of the watershed and (4) other land uses (reservoirs, urban area, grassland, secondary native scrub forest) covering the rest of the watershed

(Aranda *et al.*, 1998; Návar and Rodríguez, 2002; Návar-Cháidez, 2008). Due to gas mining, the expansion of intensive agriculture, shifting conventional, intensive cultivation practices, coal production, and other activities, land use is rapidly changing in the watershed with annual deforestation rates varying between two percent and three percent (Treviño *et al.*, 1996; Návar-Cháidez, 2008).

The hydrology of the Rio San Juan watershed. Precipitation in the area originates from several sources: (1) the position of the inter-tropical convergence zone, itcz, (2) the location of high pressure cells in the Atlantic and Pacific oceans, (3) the evolution and circulation of global air masses, and (4) tropical cyclones (García, 1987; García and Mosiño, 1968; Wallen, 1955). The region has a bimodal type of rainfall, with the first peak in May-June and the second from late August to September. A seasonal dry spell in July and August characterizing the region appears to be related to the back and forth migration of the Bermuda High in the North Atlantic Ocean. Estimates of average long term (1940-2004) annual precipitation in the Rio San Juan watershed conducted by the author of this report concur with statistics reported by cna (2005) and imta (2001) for this basin and total approximately 504 mm (arithmetic average = 518 mm, Thiessen polygons = 502 mm, and isohyets = 492 mm). Sixty five percent of all storms have associated rainfall depths of less than 5 mm and account for 35 percent of annual precipitation and only 15 percent of all storms are capable of producing runoff (Návar and Synnott, 2000). Weighted rainfall interception loss is approximately 12.3 percent (Návar *et al.*, 1999; Návar *et al.*, 1999a) leaving only 438 mm for net precipitation. Average long term (1930-2004) annual discharge of the Rio San Juan at the 'El Cuchillo' gauging station is 757 mm^3 $year^{-1}$ and at 'Los Aldamas' (1967-2004) is 1 038 mm^3 $year.^{-1}$ The latter figure accounts for 34.25 mm that runs off the entire watershed. Groundwater recharge and evapo-transpiration account for approximately 24.5 mm and 318 mm, respectively. Consequently, gross evapo-transpiration (interception, evaporation and transpiration) controls the water balance with 88 percent of total precipitation because northern Mexico is located in the northern hemisphere's largest desert region (26º NL), receiving considerable solar radiation and low erratic rainfall. Hence, runoff accounts for only seven percent and groundwater recharge for five percent of the total average annual precipitation.

Dry spells. Northern Mexico is prone to precipitation changes on several temporal and spatial scales. Drought spells of different magnitudes are recurrent in the RioSan Juan watershed (Figure 2). The drought episode of the 1950s has been well documented in rainfall, discharge and dendro-chronological data and is con-

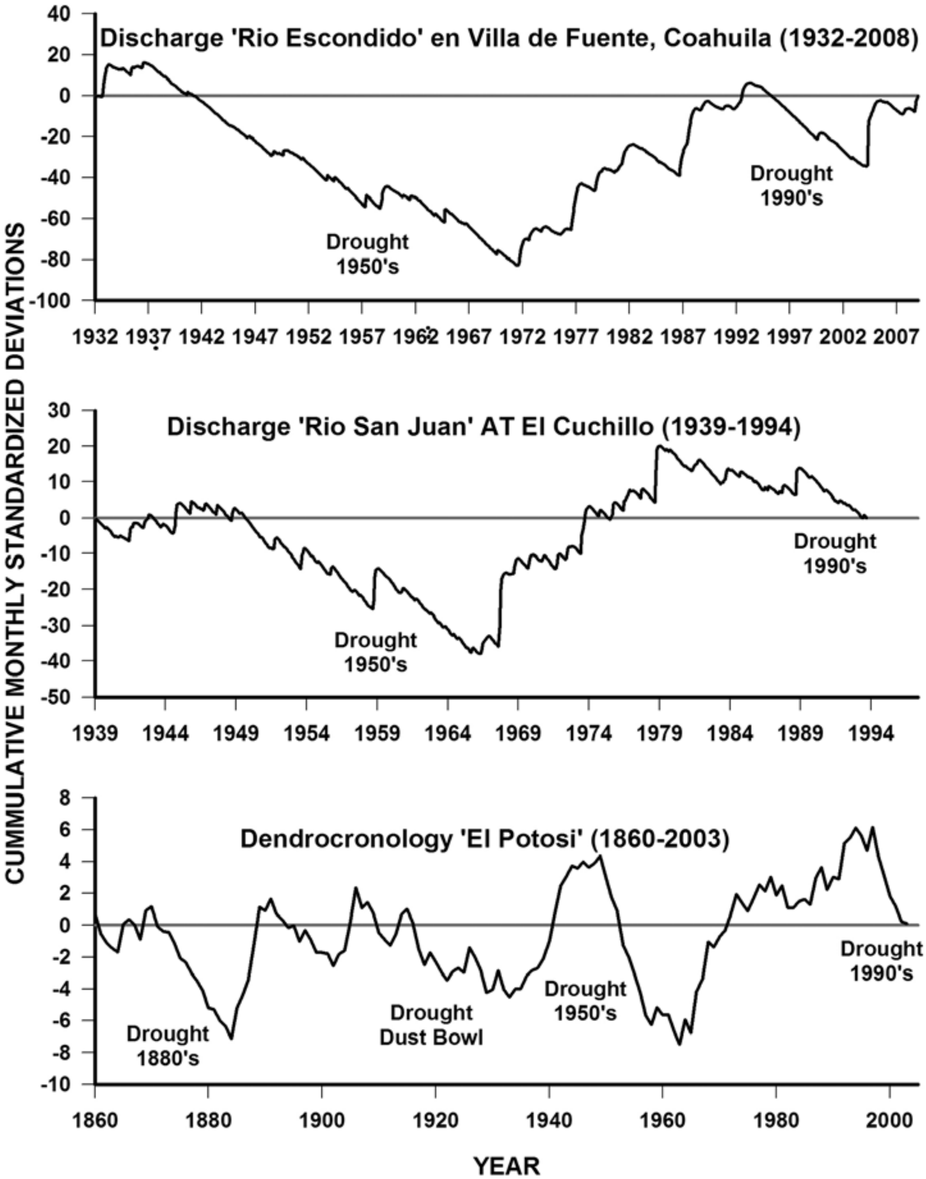

Figure 2. *Hydro-climate at two gauging stations and dendrochronology data at one gauging station for Pseudotsuga menziesii in northeastern Mexico. Drought spells are also depicted in each figure*

sistent with drought spells reported by Návar (2008) for northern Mexico. The Rio San Juan discharge along the major stem was reduced by 52 percent during the drought spell recorded in the 1950s (Návar, 1999a). At this time, discharge at 'El Cuchillo' was approximately 380 mm^3 a $year^{-1}$ and 546 mm^3 $year^{-1}$ at Los Aldamas Runoff therefore only accounted for 48 percent (16.5 mm) of the long-term runoff average. In the last drought episode of the 1990s, river discharge was zero on numerous occasions at several gauging stations along various perennial tributaries of the Rio San Juan.

Instrumental discharge records by Návar *et al.* (2006) for rivers in northern Mexico; Návar (2009) for rivers in Durango, Mexico; and Hernández and Návar (2010) for rivers in Michoacán, Mexico found that approximately 40 percent of all gauging stations analyzed display statistical oscillations and trends; of which approximately 26 percent saw reduced monotonic annual discharge for the period from 1940 to 2000. Návar (2010b) found that the downward tendency extends back to 1860, the earliest period for which when discharge data for eleven rivers of northern Mexico has been reconstructed.

Using stochastic models, Návar (2010b) projected annual discharge for eleven rivers in northern Mexico for the period from 1860 to 2000 and detected wet and dry spells, in keeping with the spectral density analysis of predicted discharge values. Drought spells were detected to last from 1-2; and 4-6 years; and longer periods of 9 to 11 years (1880s, 1900s, 1920s, 1950s, and 1990s). Inter-annual discharge variability does not have a simple explanation and is probably a function of a combination of the rainfall producing processes operating on several time and space scales. The second dry-wet cycle (4-6 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 of periods of approximately 4 years (Stahle *et al.*, 1999). The enso causes severe, prolonged summer droughts and wet winters with reduced total annual rainfall and as well as indirectly controlling river discharge. The third quasi decadal discharge dry-wet variability was evident in all stochastic models, spectral density analysis, as well as in Durango's reconstructed precipitation (Stahle *et al.*, 1999; Návar, 2008) and the reconstructed climate variability of Mexico based on historic sources (O'Hara and Metcalfe, 1997). 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 are repeated in the time series and stochastic models in the 1880s, 1900s, 1920s, 1930s, 1950s, 1980s, and 1990s. The cooling of the northeastern Pacific Ocean waters brings below average rainfall and discharge to northern Mexico.

Longer time cycles of approximately 300 years are recorded in O'Hara and Metcalfe's (1997) historical and Stahle *et al.*'s (1999) dendrochronological data sets. The period from 1345 to 1640 appears to have been relatively wet; the period from 1640 to 1915 relatively dry and since 1915 there has been a shift towards somewhat wetter conditions in Mexico. Due to the reconstructed short time series data used to build the stochastic models, these longer dry-wet sequences are absent from future projections. The 1640 to 1915 dry episode surfaces appear to have been dominated by the prolonged blocking of the monsoon and an increase in the frequency of the 'nortes' that coincides with the Little Ice Age, an anomaly that controlled the earth's climate (O'Hara and Metcalfe, 1997). The monsoon suppression, the Bermuda High lying well to the east and the southward displacement of the Intertropical Convergence Zone, itcz, control the dry period (Douglas, 1982); since two major features of atmospheric circulation, Trade winds and the sub-tropical high pressure belt influence Mexico's current precipitation.

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

Wet episodes. Discharge data at 'El Cuchillo' gauging station showswet episodes during the 1880s, 1900s, 1940s, 1970s, and 1990's as well as 1895, 1905, and 1995. Heavy rains concentrated in short time periods are responsible for high annual discharge in northern Mexico. The presence of hurricanes, cyclones or tropical depressions is of paramount importance for the availability of water resource in the region, although they also sometimes cause heavy losses of human lives and property. cna (2003) described five hurricanes (Allen, 1980; Barry, 1983; Gilbert, 1988; Dolly, 1996; and Keith, 2000) that swept through the state of Nuevo León and Návar (2003) and predicted that an average of two (between 1 and 4) more will hit the state between 2004 and 2013. This forecast has come true so far, since 'Emily' and 'Alex' caused heavy rains in Nuevo León in 2005 and 2010, respectively. Information is being analyzed with the aim of improving the understanding of and ability to forecast these climatic events in the near future. For heavy seasonal rains, a combination of the location of: a) Intertropical Convergence Zone, and b) high pressure cells in the North Atlantic Ocean with climatic events such as the enso or pdo may eventually yield more accurate predictions.

DIAGNOSIS AND FUTURE SCENARIOS

Three large reservoirs have been constructed so far in the Rio San Juan watershed. The Marte R. Gómez, 'El Azúcar', reservoir (ordinary storage capacity 1 000 mm^3) was built in the 1940s to permit agriculture in the 026 'Lower San Juan' irrigation district (80 000 ha). The Rodrigo Gómez, 'La Boca', reservoir (ordinary storage capacity 41 mm^3) was closed in the 1950s to provide domestic supplies to the Metropolitan Area of Monterrey (mam). The José López Portillo 'Cerro Prieto', reservoir (ordinary storage capacity 393 mm^3) was built in the early 1980s in the adjacent Rio San Fernando watershed to supply the domestic and industrial water demands of mam, and was the first case of inter-basin transfer of freshwater to cope with shortages in Mexico's northeast. 'El Cuchillo' reservoir (ordinary storage capacity 1 024 mm^3) was closed in 1993 with the sole objective of meeting mam's increasing domestic and industrial water supplies. Average runoff in the Rio San Juan watershed is approximately 1 130 mm^3 while total maximum ordinary storage capacity is approximately 2 065 mm^3; this reliance on fresh blue water resources is severely degrading vital aquatic ecosystems. Between the 'El Cuchillo' and 'Marte R. Gómez' reservoirs there are 59 km of streams with highly regulated discharge for most of the year. Deliveries from the 'El Cuchillo' to 'Marte R. Gómez' reservoirs are transferred annually in November or early December to plan for the next irrigation schedule of the 026 irrigation district. This policy leaves the channel with little discharge from Rio San Juan for 97 percent of the time. Major reservoirs' storage during the 1990s fell to the lowest levels since their construction, below a third of their ordinary maximum capacity.

Water quality. In 1988, the now-defunct Mexican Commission of Ecology of the Ministry for Urban Development and Ecology classified the Rio San Juan watershed as the 3rd most polluted of the country. Water quality studies showed high concentrations of heavy metals in several major tributaries (Kramar *et al.*, 1992; Vogel *et al.*, 1995). However, by 1994, the state government of Nuevo Leon had initiated the 'Plan Monterrey IV', which channeled most treated municipal and industrial raw sewage to the Ayancual stream and Rio Pesqueria. These tributaries drain the northern portion of the mam, bypass 'El Cuchillo' and discharge into the Marte R. Gómez reservoir. Before raw sewage discharges into these rivers, it is treated in three large first-degree plants. Studies conducted in 1996 on two major tributaries (Rio San Juan and Rio Santa Catarina) showed that pollution problems persisted because 18 percent of the stream water samples (from 8 gauging stations for 10 consecutive months) analyzed for chemical, physical, bacteriological and heavy metals exceeded set standards (Flores-Laureano and Návar, 2002). At times of low discharge, several pollutants, including various heavy metals, exceeded set concentrations reported in Mexican and international water quality standards. Mass flux was important during high discharge episodes that occur during the rainy season, stressing the potential water quality problems of heavy metals in major reservoirs.

Fresh water for municipal and industrial supply. Metro Monterrey is an industrial center, ranking 2^nd^ in Mexico in this sector. mam has been experiencing fast commercial, service, manufacturing and industrial growth over the past three decades. This trend was enhanced by the nafta trade agreement and it will probably continue its rising trend with the trade agreement signed between Mexico and the European Union. This economic boom has created annual population growth of 3.5 percent as a result of immigration from the interior of Mexico. The 1995 population of the watershed was 5 M inhabitants, of which approximately 4 M were housed in Metro Monterrey, and is expected to increase to 8.4 M inhabitants by the year 2020 (Conapo, 1996). Metro Monterrey houses this population within 360 km^2 in nine municipalities (Apodaca, Garcia, Escobedo, Guadalupe, Juarez, Monterrey, San Nicolas, Santa Catarina and San Pedro). Taking discharge and aquifer recharge, current population and average hydrology into account, the watershed possesses a water availability of 484 m^3 $inhabitant^{-1}$ $year^{-1}$ and would be reduced to 230 m^3 per inhabitant per year by the year 2020. These figures are lower than those recorded for the Lower Rio Bravo watershed (sarh-cna, 1994; Schmandt *et al*., 2000). The watershed therefore ranks amongst the poorest regions as regards per capita fresh blue water availability such as Syria, Israel, and Saudi Arabia. Per capita water use estimates, including domestic, commercial, municipal, and industrial supplies, approach 290 liters per day per inhabitant for mam. sadm (2002) estimated per capita domestic water consumption to be 130 l per day, down 18 percent from 1997 (Scott *et al*., 2007). Assuming that the per capita estimate of 290 liters per day per inhabitant is constant across spatial and temporal scales, water demand to meet municipal and industrial supplies is currently 415 mm^3 year 1, which would increase to 890 mm^3 $year^{-1}$ for the year 2020. In the event of drought episodes such as the one recorded in the 1990s or the 1950s, during the period from 2020 to 2030 the river would not be able to supply enough water of sufficient quality for domestic, industrial, dilution, or environmental use.

Freshwater for food security. Conventional irrigation has been practiced in the Rio San Juan basin since early last century. At present, the watershed has approximately 172 000 ha of irrigated agriculture located next to the major tributaries (Návar and Rodríguez, 2002). The most important irrigation districts are: (1) 'Lower San Juan' or 026 (80 000 ha), (2) 'Las Lajas' (15 000 ha), and (3) other smaller rural districts distributed along major tributaries, where corn, sorghum and oranges are the most important crops. Crop consumptive use estimates, weighted by precipitation, indicate that irrigated agriculture demands, an average of 1 200 mm^3 a $year^{-1}$ of fresh blue water but during drought spells, crops demand 1 700 mm^3 a $year^{-1}$ (Návar and Rodríguez, 2002). The 'Marte R. Gomez' and lately the 'El Cuchillo' reservoirs supply an average of 540 mm^3 a $year^{-1}$ to irrigation district 026 while the 'El Cuchillo' reservoir supplies 15 mm^3 a $year^{-1}$ to the 'Las Lajas' irrigation district 'Las Lajas'. The remaining volume is pumped directly from the phreatic zone of most tributaries or directly from streams. However, during the 1990s, irrigated land area in the 026 occupied a third of the total available land on average (Figure 3). The drought spell of the 1990s and the construction of 'El Cuchillo' reservoir are largely responsible for this shrinkage. Future scenarios project that the size of irrigated lands would contract between 55 percent and 66 percent for the year 2045 under normal hydrology and drought spells similar to those recorded in the 1950s in the Rio San Juan watershed (Návar, 2001). Irrigated land contraction is also a fact in the lower Rio Bravo watershed, on both sides of the border (Návar, 1999a; Návar, 2004). The major causes of this decline are: the transfer of water rights to meet increasing demand for municipal and industrial supplies, potential developments along the major stem, and the presence of drought spells (Návar, 1999). This trend is also common in the lower Rio Bravo/Grande watershed (Schmandt *et al.*, 2000), as well as in other regions of the semiarid world (Postel, 2000).

Social instability and conflicts. Mexico's Water Law stipulates that water is a property of the country, with the National Water Commission (cna) administering a system of certificates for water use. cna grants 25-year concessions for blue water surface irrigation. As from 1992, public irrigation districts were transferred to

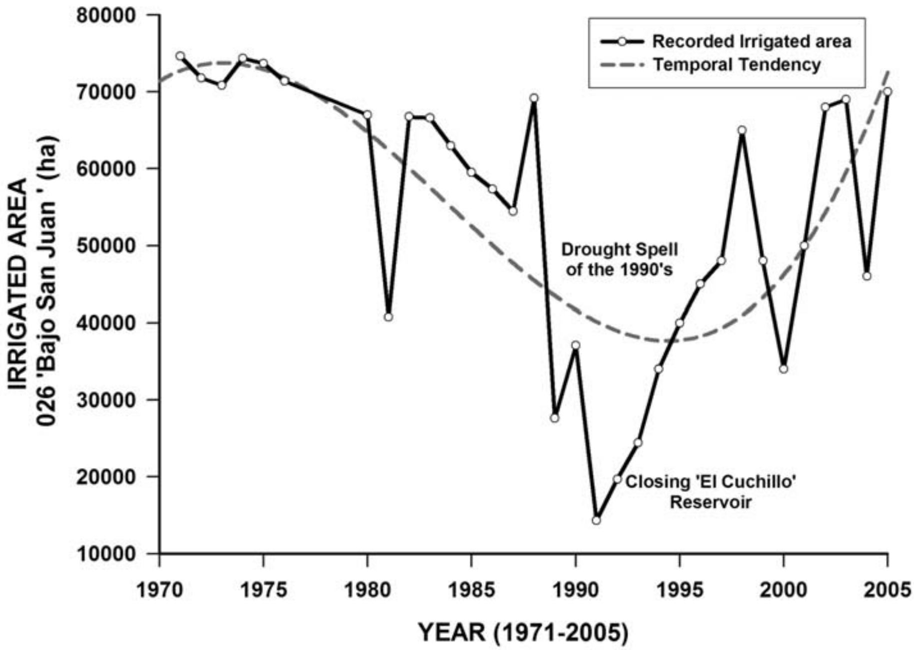

Figure 3. *Recorded and estimated irrigated area in the 026 District of Northwestern Tamaulipas, Mexico*

water users' associations called 'módulos'. The hydraulic committee headed by the cna district chief with the water users' association representation approves or modifies operations and maintenance plans.

Rio San Juan crosses three Mexican States, which, in 1952, in coordination with Federal Government, signed a treaty on the use of the Rio San Juan headwaters and agreed to grant irrigation water rights to be used mostly to supply agriculture for the 026-irrigation district through the 'Marte R. Gomez' reservoir. The treaty was reviewed in the late 1980s and led to the construction of 'El Cuchillo' reservoir with the main objective of supplying domestic water to the city of Monterrey. An arrangement was made between farmers in the 026 irrigation District and the city of Monterrey, whereby farmers grant use of their water rights from the nearby 'Cuchillo' reservoir and the municipal water utility Servicios de Agua y Drenaje de Monterrey, sadm returns urban used and treated water to farmers for irrigation. This arrangement benefits both parties since sadm supplements its water supply with a high quality but intermittent supply from the 'Cuchillo' reservoir and farmers receive a constant supply of nutrient-filled water for irrigation. Due to the lack of sufficient water for meeting water rights obligations for irrigation and domestic use during the early 1990s, the treaty and its subsequent modifications created social conflicts between water users (farmers in the 026 and sadm officials) and stress between political boundaries (Nuevo Leon and Tamaulipas), which reached their peak during and immediately after the 'El Cuchillo' reservoir was closed. The long-term outlook is for urbanization to continue and water availability to decrease, particularly for irrigation. New water management strategies will therefore have to be created. None of these treaties has ever properly examined the ecological role stream freshwater plays in the health of riverine ecosystems and they must be modified accordingly.

Water for conserving the health of aquatic ecosystems. The Rio San Juan watershed has 5 900 ha of riparian vegetation (Guerra and Návar, 1999), characterized by 24 genera of shrubs and trees. Taking evapo-transpiration into account, this community requires an average of 120 mm^3 a $year^{-1}$ to fulfill transpiration demands. To function properly, the flow quantity, quality, frequency, and timing must be restored at several places along the Rio San Juan. The main riparian plant communities are characterized by *L. leucocephala - P. tremuloides - M. Azederach - Fraxinus spp; T. Mucronatum – P. occidentalis – S. laevigata; and the invasive species P. aculeata – P. laevigata – A. farnesiana – C. pallida.* The presence of exotic and xerophytic species and the disappearance of native phreatophytes are partial indicators of river discharge changes along the major tributaries. Other sources of disturbance include overgrazing and harvesting practices for firewood and charcoal production. During the drought spell of the 1990s several large trees of the species Taxodium mucronatum died along the upper side, just below the piedmont, of major tributaries. This species has considerably reduced its population in the major stem of the Rio San Juan below its junction with the Rio Santa Catarina, in contrast with its presence in other watersheds close to the Rio Bravo.

The fish community of the Rio San Juan contains 38 genera (Contreras and Lozano, 1994), of which 18 were monitored during 1999 (Guerra, 2000). Villarreal *et al.* (1983) noted the disappearance of four fish native species (*N. stramineus, N. amabilis, D. episcopa,* and *C. anomalum*) due to stream water pollution and reductions of discharge along the major tributaries. Contreras and Lozano (1994) noted that for northern Mexico there are approximately 200 species of freshwater fishes and that 120 are under some form of threat. These authors have attributed the disappearance of fish species to rising pollution levels as well as the introduction of exotic fish species. Other authors observed evidence of bio-accumulation of several heavy metals in several fish species (Obregon, 1987; Villarreal *et al.*, 1986) and Guerra (2000) linked the diversity-abundance of the fish community to water quality parameters along the Rio San Juan and noted that the diversity-abundance of the benthonic insects' community, which is characterized by 34 genera, was also dependent on water quality and quantity parameters as well as on physical characteristics of the main channel. Conserving the vital role of these communities require the restoration of flows, their timing, quantity, and quality. Therefore changes in the present treaty are required to enable major reservoirs to deliver water downstream with the sole aim of protecting river ecosystems. In other words, the environmental flow must be implemented in this river and its prescription requires further hydrologic studies on several spatial and temporal scales.

The Lower Rio Bravo. The Rio San Juan is the major tributary of the lower Rio Bravo although the treaty between Mexico and the US stipulates that all its headwaters belong to Mexico. However, by 1992, the Rio San Juan discharged into the Rio Bravo at a rate of 392 mm^3 $year^{-1}$ (1954-2008) and accounted for 40 percent of all gauged discharges of the Rio Bravo near Brownsville, TX (Návar, 1999a). However, because of the construction of 'El Cuchillo' reservoir and the drought episode of the 1990s, by 1993, discharge had dropped to 39 mm^3 $year^{-1}$ and most of this decade it was below 30 mm^3 (Figure 3). The drought episode of the 1950s is also present in this data series and for the period of 1950-1965, discharge into the lower Rio Bravo was less than 40 mm^3 for 10 out of 12 years. The tendency to reduce discharge to a minimum is underway because of: (a) increased developments leading to larger water diversions from streams and reservoirs to meet municipal and industrial supplies of major cities, (b) the occurrence of drought episodes, and (c) coping with irrigation demands (Návar 1999, 1999a).

Climate change. There is evidence that the earth's climate is probably changing due to the accumulation of greenhouse gases in the atmosphere (ipcc, 2007). Future scenarios for Mexico are quite vague at the present but preliminary climate model projections for the country's northern portion points to reduced annual precipitation (between 5 to 20%) and river discharge of less than 25 percent by the end of this century (ipcc, 2007). A steady decline in discharge has been recorded for approximately 40 percent of the 175 gauging stations analyzed for northern Mexico (Návar *et al.*, 2006; Návar, 2009) as well as for 40 percent of the 17 gauging stations in Michoacan, México (Hernández and Návar-Cháidez, 2010) for the

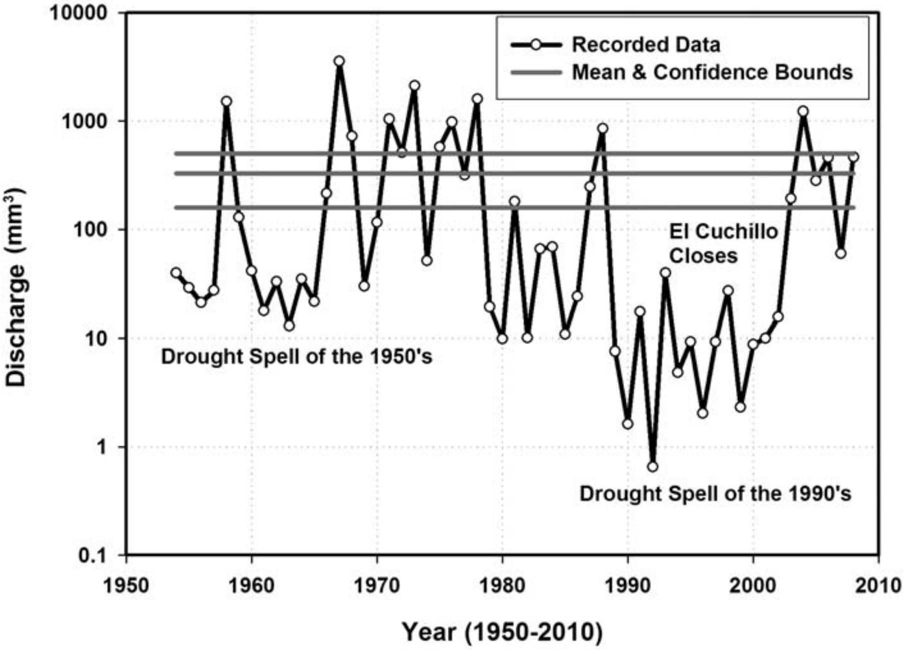

Figure 3. *Historical records and statistics of the RíoSan Juan discharge into the lower Río Bravo at Camargo, Tamaulipas, Mexico*

past 50 years. Rivers in the state of Durango show similar tendencies for the past 200 years (Návar, 2009). Land-use changes are associated with steady discharge reductions but there are partial indications that subtle changes in rainfall parameters (number of rainy days, depth-frequency-duration, etc.) as climate change indicators may also be contributing to reduced discharge (Méndez-González *et al.*, 2008). Further information on this issue would be provided as long as new data is analyzed to understand and isolate the potential effect of climate change on water resources in the watershed.

Outlook for the future .The outlook for mid-term future projects is rather gloomy, assuming that this state of affairs will continue for the next 25 years. For example, Návar (2008) reconstructed decadal drought episodes for northern Mexico and advanced that the next drought spell would strike the region sometime between 2020 and 2030 if the climatic tendency continued as it has done during the last century. Five decadal drought episodes can be observed in the dendrochronology data for *P. menziesii* from 1860 to 2005. In other words, there is an average of one dry decadal spell for every 30 to 40 years, consistent with the work conducted for northern Mexico. Since the last one occurred in the 1990s, the next drought episode would be expected to occur in northern Mexico between the 2020s and 2030s. Under this dry set up, there would be a reduction of discharge into 'El Cuchillo' reservoir of less than 40 percent. In the watershed, steady population growth from approximately 5 M in the 1990s to 8.5 M in the 2020s would demand an increase in freshwater from 400 M in the 1990s to 850 M in the 2020s. Therefore, under these circumstances that mimic the climatic conditions of the 1950s and the 1990s, there would only be enough water storage in the 'El Cuchillo' reservoir to partially meet domestic supply demand in the basin and the area irrigated in the 026 would probably attain a value of close to 0 ha and agriculture would rely only on green water, taking a toll on crop productivity. Other irrigated land areas in the watershed would also suffer the consequences of this climatic event. There would not be enough fresh blue water in the river system to dilute local pollution, or other regional effluents, which in turn would increase pollution levels and make poor people suffer the health consequences of this new situation. Riparian ecosystems would also take their toll on this new environment. A new wave of large, dying ancient riparian trees thathave survived the drought spells of the past 500 years would probably succumb to this new climatic event, exacerbated by unsustainable practices. Other plant, fish, benthic insect and aquatic communities that dwell in blue water habitats would dramatically diminish the abundance of late-successional species, taking these communities back to earlier times, losing the goods and services they currently provide for both ecosystems and society. No discharge would be diverted into the lower Rio Bravo with dire consequences for the hydrology of this outlet into the Gulf of Mexico. More precise discharge projections under different scenarios are required in the Rio San Juan in order to plan for the future.

A need to strengthen the sustainable management practices of water resources. Current fresh blue and green water resource management practices are unsustainable in the Rio San Juan watershed, as borne out by the indicators of water quality, discharge disturbance, crop productivity, the disappearance of riverine species and the presence of social conflicts, although sustainable practices are being implemented in several places. The philosophical concept of sustainability must be swiftly enhanced in the integrated management of water resources in the entire Rio San Juan watershed. This holistic approach states that integrated water resource management is based on the perception of water as an integral part of the ecosystem, a natural resource, and a social and economic asset, whose quantity and quality determine the nature of its utilization. To this end, water resources must be protected, taking into account the functioning of aquatic ecosystems and the perenniality of the resource, in order to satisfy and reconcile the need for water for human activities. In developing and using water resources, priority must be given to the satisfaction of basic needs and the safeguarding of ecosystems. Beyond these requirements, however, water users should be charged appropriately. Action must be taken on four fronts.

The first front seeks to promote a dynamic, interactive, iterative, and multisectorial approach to water resource management, including the identification and protection of potential sources of water supply that integrates technological, socio-economic, environmental, and human health considerations. The National Water Commission is the organization that makes decisions regarding water resource allocation in Mexico. The water users' association (wua) holds water concession titles and proposes operation and maintenance plans for the irrigation district. The Water Consultancy Associations assist the wua. The water and sewer services institution is an autonomous public utility within the state government that supplies water to cities. The farmers' association oversees the organization. Sagarpa is the Undersecretariat of Agriculture, Livestock and Fisheries. Procampo is an agriculture-funding subsidies institution that ispart of Sagarpa. Semarnat is the head office of cna. Environmentalist groups address issues related to the protection and conservation of riparian species, plant communities and ecosystems. Research institutions focus on key issues such as cost-effective irrigation technologies, improved agricultural crop species adapted to droughts that rely on reduced green water, water management issues regarding rivers and reservoirs under different water availability scenarios, reduction of evapo-transpiration on farms, the environmental flow, etcetera. Universities and higher education institutions undertake local and regional studies on society, natural resources, economics, and the environment. They also examine how they change under different scenarios and how they can be protected, conserved or enhanced for the use of future generations. There must be close, interactive links between all these institutions, which must meet periodically in order to be dynamic and iterative to adapt new management strategies for upcoming scenarios.

The second front addresses several areas of sustainable water resource management. Conserving water in the agricultural, municipal, and industrial sectors is one of the major issues of the Rio San Juan watershed. Productivity in the 026 irrigation district is low, between 30 percent and 44 percent of the productivity of most Mexican irrigation districts (sarh, 1981; cna, 2005b; Scott *et al.*, 2007). It takes 2 800 mg of green water in the form of soil moisture to grow 1 mg of grain (sorghum and corn) when the worldwide average is 1 000:1 (Doorenbos and Kassam, 1979). The irrigation efficiency given by: (1) water conveyance, (2) water application efficiency, and (3) water use efficiency is critical to conserving stream water for other uses. In the 026-irrigation district, the efficiency of the water conveyance system is 71 percent, of the secondary drain system is 75-80 percent, and of individual farms is 65 percent (sarh, 1981; cna, 2005b). The overall estimated conveyance efficiency lies within the range of 32-36 percent and by increasing it to a feasible range of 60 percent, a volume of 200 mm3 would be annually conserved. Surface irrigation is common in the watershed and this method has an efficiency of 70 percent (Schwab *et al.*, 1981; cna, 2007). Water use efficiency by crops also lies within the range of 60 percent. Other technologies such as drip irrigation would improve green water use and application efficiency by 95 percent and conserve an additional 120 mm^3 $year^{-1}$ in the 026-irrigation district. New irrigation technologies such as pressurized irrigation have been introduced in the brsj and there are currently approximately 1 700 ha being treated in this way (cna, 2005b). This area must obviously be further increased. Efficiency must also be improved by rehabilitating the irrigation district to reduce losses in the conveyance system as well as in the distribution infrastructure (Návar, 1999; cna, 2005b; Scott *et al.*, 2007).

The municipal and industrial sectors must be more efficient in the channeling and distribution system. Volume losses in the distribution system of most Mexican large cities are approximately 30 percent (cna, 2000; 2005b). Eliminating these leaks would therefore conserve 124 mm^3 $year^{-1}$. Per-capita water use is also high for a city located within a semi-arid environment, given that the average in the US is 300 liters per day per inhabitant (Soley *et al.*, 1998). By reducing it to a feasible 200 liters per day per inhabitant, municipalities would conserve an additional volume of 120 mm^3 $year^{-1}$. This reduction is underway since domestic water use per capita alone was reduced by 18 percent from 1997 to 2002 (Scott *et al.*, 2007). It is quite possible to reduce it even further since cities such as Aman and Lalitpur have per-capita water uses of 40 liters per day per inhabitant (Schmitt, 1997).

There is an urgent need to improve the quality of most effluents diverted into streams since pollution problems persist in most tributaries (Flores-Laureano and

Návar, 2002). Using other environmental methodologies or living filters in the form of aquatic plants, conserving wetlands and riparian communities, and recycling this water to meet agricultural demands could be another way of improving effluent water quality and of doubling productivity for every drop of fresh blue water extracted from reservoirs, rivers and aquifers, as stressed by Postel (2000). This is another example of ways of preparing for the enforcement and strengthening of sustainable water resource management. In the area of reservoirs, there is an urgent need to modify their management towards an optimization procedure whereby evaporation is minimized while at the same time maintaining enough storage to secure strategic supplies. Considerationmust be given to water stream delivery streams according to the timing and quantity required exclusively for protecting aquatic ecosystems and the life they support. The environmental flow must be predominantly implemented in the San Juan River between the 'El Cuchillo' and 'El Azúcar' reservoirs and between 'El Azúcar' and the lower Rio Bravo as well. Hydrologic examples of the environmental flow can be found in Návar (2010a) and a norm is under development by the Undersecretariat for Natural Resources and Environment of Mexico.

There is therefore an urgent need to promote action on this front. Having users, environmental groups, government, research and educational institutions in the Rio San Juan watershed and lower Rio Bravo area address these issues could be one of the best ways to continue preparing for sustainable development (Schmandt *et al.*, 2000).

The third front seeks to design, implement and evaluate projects and programs that are both economically efficient and socially appropriate within clearly defined strategies, based on an approach of full public participation, including that of women, youth, indigenous people, and local communities, in water management policy and decision-making. The El Cuchillo reservoir project is an example of how to strengthen arrangements that are working today such as the agreement between sadm and farmers in the brsj irrigation district on: a) the rehabilitation of the pumping stations, b) the relocation of domestic and industrial water supply sources, c) allocations of treated effluents, and d) others. An agenda on environmental hydrologic services is being implemented at this time with the aim of: a) making people aware of the major Rio San Juan issues, b) projecting the feasibility of implementing water conservation programs along major tributaries, c) public funding of most programs and projects, d) others. These programs must be iterative (continuously reviewed and modified according to the new scenarios) bearing in mind the presence of drought episodes in order to avoid future social conflicts and be socially acceptable. In addition to the compensation paid to farmers when there is insufficient water in the reservoir for irrigation, research studies must focus on how to buffer economic local impacts caused by reduced irrigation land in order to be economically feasible.

The fourth front of action seeks to identify and strengthen or develop the appropriate institutional, legal, and financial mechanisms to ensure that water policy and its implementation are a catalyst for sustainable social progress and economic growth. Mexico has the appropriate institutional (cna, Semarnat, Sagarpa, research institutions, universities, environmental groups, farmers' associations, módulos and watershed councils, watershed committees, technical consultancy groups), legal (the Forestry Law, the Environmental Law, the Water Law, all of within the framework of the Mexican Constitution) and financial mechanisms (banks, other financing institutions, Procampo, Proárbol, etc.) to ensure that water policy and its implementation are a catalyst for sustainable social progress and economic growth. However, knowing how to strengthen and link them in order to reduce the unsustainable practices described above should be an object of further study. Issues such as the right price of water and the conservation or transfer of water rights must be addressed accordingly.

CONCLUSIONS

The Rio San Juan watershed is already showing signs of unsustainable practices of water resource management because of the heavy reliance on water resources. These include the overuse of surface water and the depletion of groundwater resources and the emergence of social conflict between water users and political entities. At the same time aquatic communities are shrinking and riparian species are disappearing. Increased future water demands in the municipal and industrial sectors coupled with drought episodes would stress human tensions even more in the near future. Future scenarios envisage the acceleration of the disappearance of aquatic communities and the increasing number of riverine species listed in the red books. Sustainable water resource management practices are underway in the watershed but must be strengthened and fully enforced in order to boost this trend. This paper addresses issues to meet conventional demands and protect aquatic environments by implementing several practices in every sector of the economy. There is therefore an urgent need to promote these practices in the municipal, industrial, and agricultural sectors in order to satisfy the needs of a growing population, agriculture and industry while at the same time maintaining the health and productivity of riparian ecosystems.

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