Water supply and demand in the lower Río Bravo/Río Grande basin: The irrigated agriculture scenario

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RESUMEN

El manejo convencional de los recursos hidrológicos no puede sustentar el desarrollo en la cuenca baja del Río Bravo/Río Grande. Proyecciones a largo plazo del suministro y demanda del agua proveen información para planear el manejo sustentable de los recursos hidrológicos. Cuatro escenarios se estudiaron para proyectar la disponibilidad y el suministro del agua en la parte mexicana de la cuenca baja del Río Bravo/Río Grande: (i) desarrollo de la infraestructura para el aprovechamiento de las aguas del río Conchos, (ii) sequía histórica, (iii) hidrología normal y (iv) la presencia simultánea de (i) y (ii). El área agrícola de riego podría ser más variable, con pérdida de superficie agrícola irrigada en el distrito 025 de México de la cuenca baja del Río Bravo/Río Grande, por la creciente demanda del agua en los sectores doméstico, industria, municipal y comercial de los municipios fronterizos del Río Bravo/Río Grande, magnificado por la sequía y el desarrollo en infraestructura para el aprovechamiento de las aguas del río Conchos.

PALABRAS CLAVE: Agricultura irrigada, manejo sustentable de recursos hidrológicos, distrito de riego 025, sequía histórica registrada y desarrollo de infraestructura hidráulica en el río Conchos.

ABSTRACT

Conventional management of water resources cannot sustain development in the lower Río Bravo/Río Grande watershed. Long-term projections of water supply and demand provide information to plan for the sustainable management of water resources. Four scenarios were studied to project water availability and supply on the Mexican side of the Lower Río Bravo/Río Grande watershed: (i) water development of the Conchos River, (ii) drought spells on record, (iii) normal hydrological conditions, and (iv) the simultaneous presence of (i) and (ii). The size of agricultural lands could become more variable, with loss of irrigated agriculture in district 025 of the Mexican lower Río Bravo/Río Grande, due to increasing water demand from domestic, industrial, commercial, and municipal sectors in the municipalities bordering the Río Bravo/Río Grande, magnified by drought and the development of water demand of the Conchos river.

KEY WORDS: Irrigated agriculture, sustainable management of water resources, Irrigation District 025, drought on record and normal hydrological conditions.

INTRODUCTION

The lower watershed of the Río Bravo/Grande basin on the Mexican side, from Reynosa to the Gulf of Mexico at Matamoros, is facing a complex set of water supply and demand issues. Irrigation and domestic, industrial, municipal, and commercial water uses dominate in this area. Environmental concerns regarding streamflow shortages along the main course of the Río Bravo/Río Grande and severe contamination (Vogel and Armstrong, 1997) are important issues for the management of riparian ecosystems (Contreras and Lozano, 1994; Edwards and Contreras, 1997; CEFPRODHAC, 1997; Chapman, 2000).

The basin has been experiencing rapid economic, public, services and trade growth due to the North American Free Trade Agreement (NAFTA)(Aguilar and Chapa, 1998). Population and industry almost doubled from 1970 to 1995 (INEGI, 1995). Population growth in the bordering municipalities of the basin place considerable demand on water supply from yearly average of 74 Mm^3 in the 1970's to 193 Mm^3 in the 1990's (CNA, 1997). The basin has been experiencing recurrent drought spells contributing to surface water shortages and reduced agricultural areas in irrigation district 025 of Mexico.

The lower Río Bravo/Río Grande watershed contributes an average of 4.6% of the water supply in the region. (IBWC, 1994; SARH CNA, 1994). The remainder comes from the middle and upper watersheds of the Río Bravo/Río Grande basin through La Amistad and Falcón reservoirs (Chapman, 2000; Schmandt *et al.*, 2000). The Conchos is the main Mexican tributary of the Bravo/Río Grande and contributes to these reservoirs, at a larger rate than provided in the US/Mexico treaty of 1944 (IBWC data 1980-1994; Ward, 1998). The San Juan is the main tributary of the lower Río Bravo/Río Grande. It also discharged at an average rate higher than stipulated in the treaty (ERL, 1991; Návar, 2001). However, the current drought and the construction of El Cuchillo reservoir lowered the rate of discharge into the Río Bravo/Río Grande (Navar, 2001). Because of the drought, Mexico was unable to meet its obligations of the 1944 treaty in recent times.

Future increase in public water demands coupled with the presence of drought spells, and the likely full utilization of the Río Conchos headwaters could result in serious social, political, economical, and environmental concerns in the region. Under such scenarios, the Río Bravo/Río Grande may not meet water demand of the Mexican side of the lower Río Bravo/Río Grande. The objectives of this study are (1) to forecast future supplyes and demand under (a) normal hydrological conditions, (b) full development of the Mexican waters, (c) worst drought on record, and (d) full Mexican development of the Mexican waters coupled with a worst drought of record. We assess the impact of these scenarios on the size of irrigated land of irrigation district 025 for 1990-2005; 2010-2025; and 2030-2045. The worst drought of record was estimated as the critical draw-down or depletion period of La Amistad and Falcón reservoir in the 1945-1960. This interval extends from a local maximum (100% of storage conservation capacity) to the lowest subsequent minimum value before a large maximum. "Normal" hydrological conditions were assumed as the 15 year period where reservoir storage oscillates with the smallest variation. Full development of Mexican waters assumes that Mexico use all water left after complying with the 1944 treaty with the US.

METHODOLOGY

The Hydrologic Region of the Lower Río Bravo/ Río Grande/Río Conchos. The Lower Río Grande/Río Bravo watershed, LRGW, belongs to the Río Bravo/Río Conchos basin, which comprises a total area of 870 000 km^2, of which, approximately 400 000 km^2 drain into closed watersheds. According to IBWC (1993), the lower Río Bravo/ Río Grande watershed covers an area of 44 193 km^2, from Falcón reservoir to its outlet into the Gulf of Mexico, of which 92.9 % (41 065 km^2) belongs to Mexico and the remainder within the United States. The study area covers in Mexico the municipalities of Reynosa, Río Bravo/Río Grande, Valle Hermoso, and Matamoros of the State of Tamaulipas, Mexico.

Irrigation water demands. Agriculture has dominated water use in the lower Río Bravo/Río Grande because of the size of irrigated lands. The irrigation districts of the Mexican portion of the watershed are: the 026 or Bajo San Juan and the 025 or Bajo Río Bravo/Río Grande districts (Figure 1). Within the American portion of the watershed, there are currently 29 irrigation districts of 33 originally established (Schmandt *et al.*, 1998). Total irrigated areas accounts for 620 483 ha, of which 53.8% (333 615 ha) lies within Mexico and the remaining 46.2% (286 468 ha) lies within the USA (IBWC, 1993). Total irrigated area in Mexico (226 000 ha) utilizes discharge from the main stem of the Río Bravo/Río Grande because the lower 026 or Bajo San Juan district irrigates agriculture from the complex Marte R. Gómez-El Cuchillo reservoirs, which were built along the headwaters of the Río San Juan.

METHODS

To forecast future supply and demands on the Mexican Bajo Río Bravo/Río Grande watershed, a water balance was conducted on the main stem of the Río Bravo/Río Grande. The balance employed the following inflows and outflows. Inflows: i) releases from the Falcón reservoir, gauged immediately below the reservoir, ii) discharges from the Río Alamo and Río San Juan and iii) irrigation excess from district 026. Outflows: i) water diversions from the Río Bravo/Río Grande for the American and Mexican sides of the watershed for agriculture, and ii) water diverted by several cities for municipal use. The outlet was considered to be the river reach at Brownsville, TX. The water balance is closed and four scenarios were imposed on releases from Falcón reservoir: (a) normal hydrological conditions, (b) full development of the Mexican waters, (c) worst drought of record, and (d) full Mexican development of the Mexican waters coupled with a worst drought of record. The volume of discharge allotted for Mexico at Anzaldúas was estimated using regression equations derived from IBWC data for the period of 1980-1994. It was assumed that discharge delivered for Mexico supplied first municipalities and industry and the volume left was allotted for irrigation of the 025 district. Volume divided by irrigation depth results in irrigated land. The irrigation depth was estimated by using the consumptive use for two of the most common crops (maize and sorghum) after average monthly precipitation was subtracted. Population and industry water demands increase in time while irrigation depth remains nearly fixed in time of simulation. Given business as usual scenarios, the size of irrigated agriculture is dependent on the volume of discharge and on public and industrial demands. The volume of discharge in the future is dependent also on the hydroclimatic conditions and further developments of water use along the main tributaries of the Río Bravo/Río Grande.

The size of irrigated lands in the lower Río Bravo and water demands. Historic irrigated lands in the US and Mexican sides of the lower watershed are variable in size

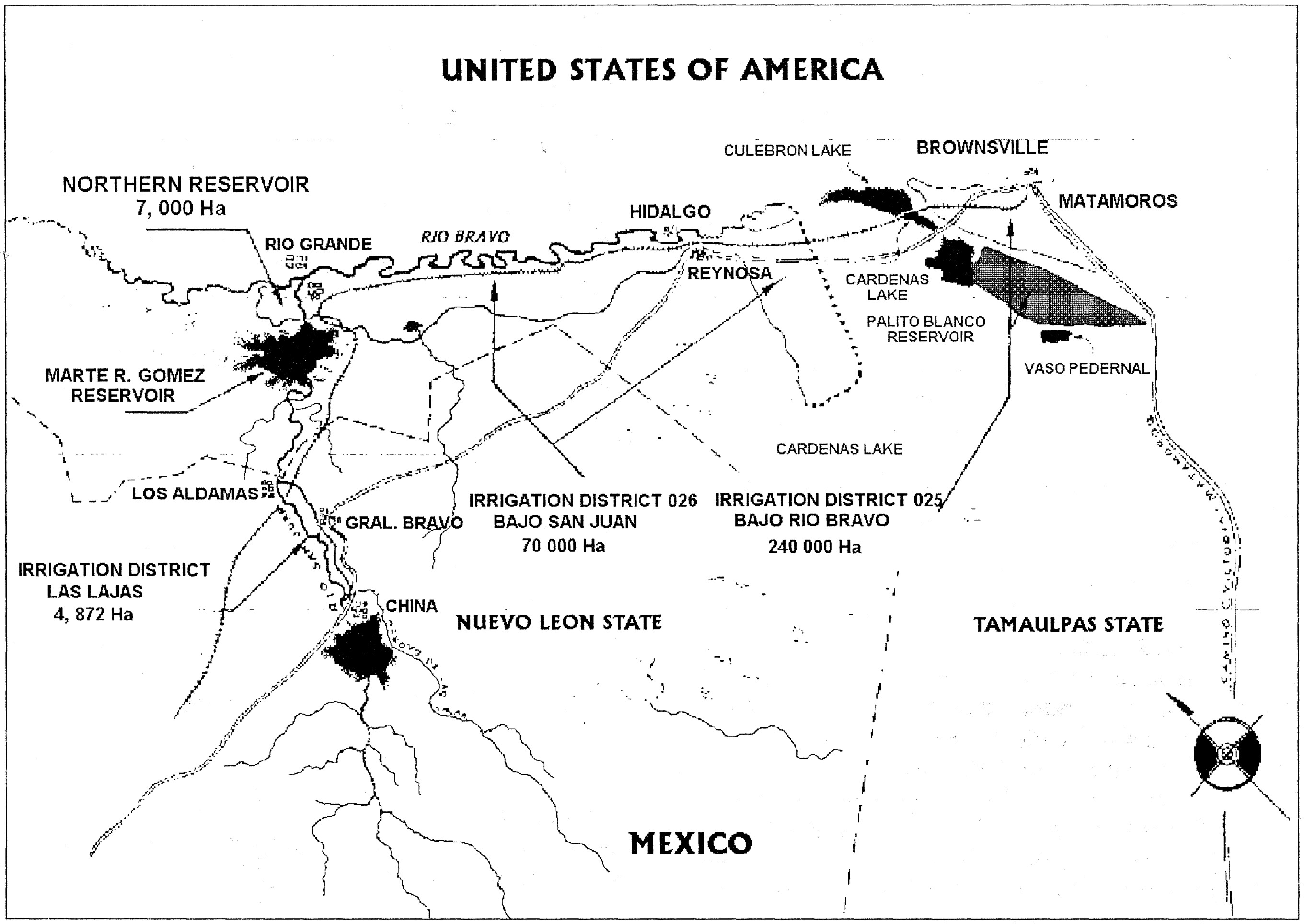

Fig. 1. Several features of the lower Río Bravo/Río Grande watershed in the Mexican portion of the Basin.

because of uncertainties in water supplies for irrigation regardless of the storage management of reservoirs 'La Amistad', 'Falcón' and 'Marte R. Gómez'. In the 025 district, average irrigated lands (1978-1997) sized 188 000 ha year^{-1}. However irrigated lands are contracting with time. The volume of water used for irrigation within the 025 district is also variable and it is dependent on the volume of water storage in the reservoirs mentioned above and the operation of reservoirs. Annual average and standard deviations of volume of water used for irrigation are 737 and 356 Mm^3 year^{-1} (CNA, 1998).

Population of the lower Río Bravo/Río Grande watershed. Population in the lower watershed is steadily increasing (Aguilar and Chapar, 1998; Schmandt *et al.*, 1998; Schmandt *et al.*, 2000). In the Mexican side, the increment rate for the 1990's was approximately 3.9% and it is expected to decline to 2.5% for the year 2010 (CONAPO, 1996). This rate represents approximately 32 000 new inhabitant year^{-1} for the 4 municipalities bordering the lower Río Bravo/Río Grande watershed.

Total population for the municipalities of the lower Río Bravo/Río Grande was obtained from INEGI sources for the period of 1960 to 1995 and predicted from CONAPO sources for the years 2000 to 2010. A linear trend was fitted to predict future population up to the year 2045. Three scenarios of population growth had been proposed and described by CONAPO (INEGI 1995) (Figure 2).

Observed population increased 2.3 times from 1960 (0.32 M) to 1990 (0.73 M). Conapo (1996) reports increases of 1.5 times for the year 2010 (1.29 M) in comparison to the 1995 population. Predicted population for the years 2030 and 2045 would be 1.99 and 2.44 M, respectively, representing increments of 235 and 288% of the population reported for the year 1995.

Public water demands in the lower Río Bravo/Río Grande watershed. The main stem of the Río Bravo/Río Grande supplies water for public (domestic, municipal, and commercial use) use, through releases from La Amistad-Falcón reservoirs, for 8 out of the 10 Mexican municipali-

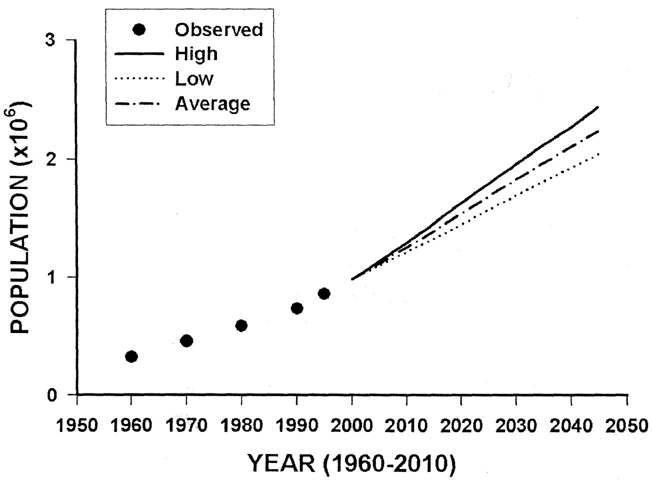

Fig. 2. Population trends in the Mexican portion of the lower Río Bravo/Río Grande watershed, from Reynosa to Matamoros, Tamaulipas, Mexico (Source: INEGI 1950-1990 and CONAPO 1996).

ties of the lower Río Bravo/Río Grande watershed. Marte R. Gómez reservoir supplies water to the remaining other two municipalities. Total public water demand for the 8 municipalities was estimated with information provided by several sources for several time periods. For six municipalities in 1995, total public water supply was approximately 115 Mm^3 $year^{-1}$. A similar figure has been reported on water diversions from the Río Bravo/Río Grande at Anzaldúas for municipal water use for the period of 1960 to 1997 (114 Mm^3 $year^{-1}$ with a standard deviation of 64 Mm^3 $year^{-1}$). For the period of 1990 1998, average water diversions from the Río Bravo/ Río Grande for public water supply was 199 Mm^3 $year^{-1}$ with a standard deviation of 66 Mm^3 $year^{-1}$. Therefore, diversions from Anzaldúas for public water supply and population estimates provided by INEGI (1998) were plotted to estimate the average *per capita* water supply.

The *per capita* public water supply steadily increased when projected in time. Therefore, a maximum *per capita* water use had to be proposed. The maximum constant *per capita* water supply was 405 liters per person per day after 1995. This figure appears to be quite large. However, it accounts for domestic, residential, commercial, and public supply (Figure 3). On the other hand, this constant *per capita* water use was recorded for 1995 during the middle of the drought episode of the last decade.

Observed *per capita* public water use for 1960 and 1995 was 246 and 326 liters day^{-1} $inhabitant^{-1}$. These figures would increase for the years 2010, 2030, and 2045 to 352, 384, and 405 liters day^{-1} $inhabitant^{-1}$, respectively. This estimate is slightly larger than the figure estimated by Soley *et al.*, (1998) for domestic water use alone for the entire United States. As stated above, our estimation comprises also municipal, commercial and public water use and is consistent with figures

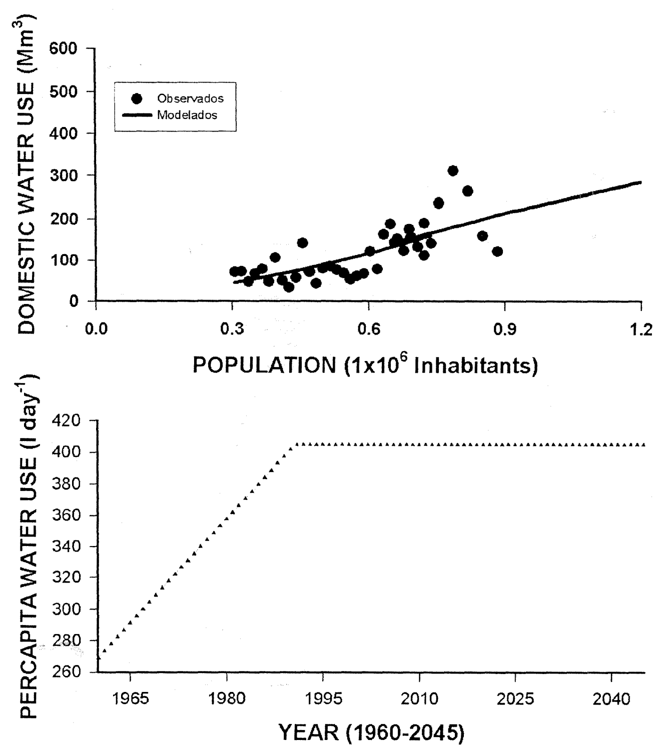

Fig. 3. Observed and predicted *per capita* domestic and municipal water use in the Mexican portion of the lower Río Bravo/Río Grande watershed (Source CNA 1998). The *per capita* water use had to be assumed to be a constant of 405 l per day per person, the maximum recorded for the Mexican Bajo Río Bravo/Río Grande.

reported for other modern societies. Several semi-arid cities such as Amman and Lalitpur (40 liters day^{-1} $inhabitant^{-1}$) (Schmitt, 1997) are the exception to the high *per capita* water supply.

Public water demand for the years 1960 and 1995 had an average of 26 and 101 Mm^3 $year^{-1}$, respectively. These figures would increase for the years 2010, 2030, and 2045 to 206, 309, and 386 Mm^3 $year^{-1}$, respectively.

Industrial water use. Temporal trends in industrial water use for the municipalities included in this study fitted a linear regression equation. Observed industrial water use for the years 1975, 1980, 1990 and 1995 were: 5.2, 1.2, 15.8, and 11.3 Mm^3 $year^{-1}$, respectively. For the years 2010, 2030, and 2045 these figures are expected to increase to: 40, 63, and 77 Mm^3 $year^{-1}$, respectively. These figures are in the range of 20% of the volume of water predicted for public water supply and it is consistent for several industrial centers such as the Monterrey Metropolitan Area (Návar, 2001).

Hydrometric information reviewed and analyzed

Hydrological data for the lower Río Bravo/Río Grande was obtained from the hydrologic bulletins annually published by IBWC. For this project, monthly data from 1980-1994 were employed. The gauging stations studied were:

- Streamflow gauged at 5 hydrometric stations along the Río Bravo/Río Grande, below Falcón reservoir.

- Inflows gauged in 4 hydrometric stations along Río Bravo/ Río Grande: from the Mexican tributaries Río Alamo and Río San Juan and irrigation-excess flows from District 025.

- Diversions gauged at 7 hydrometric stations along the Río Bravo/Río Grande; 6 in the USA and 1 in Mexico.

- Diversions for municipal use gauged in 5 hydrometric stations along the Río Bravo/Río Grande.

- Irrigated land areas of District 025.

Outflows. Outflows from the Río Bravo/Río Grande are gauged in 7 hydrometric stations:

Diversions for Municipal Use. Outflows from the Río Bravo/Río Grande for municipal use are being gauged by IBWC at 5 hydrometric stations:

Regression equations were used to estimate monthly discharges at each hydrometric station because of the high variability associated with discharge, diversions and inflows. The gauging stations immediately above the gauging station in study were considered the independent variables. The subtraction of discharges between hydrometric stations resulted in estimate of the diversions between gauging stations. This approach accurately fitted water budgets along the Río Bravo/ Río Grande and comprises several sources of variation such as losses in the main stem and resacas (ponds remaining after releases drains along the Río Bravo/Río Grande channel), withdrawals from the main stem during releases, errors in gauging, unaccounted diversions, etc. The equations employed are described below:

$$QRB_{Río\ Grande}=337.02+0.9207\ QRB_{Falcón};\ r^2=0.91,\ Sx=0.665\ Mm^3$$
$$QRB_{Anzaldúas}=200.64+0.459\ QRB_{Río\ Grande};\ r^2=0.56,\ Sx=0.934\ Mm^3$$
$$QRB_{San\ Benito}=-315.6+0.615\ QRB_{Anzaldúas};\ r^2=0.66,\ Sx=0.623\ Mm^3$$
$$QRB_{Brownsville}=-25.01+0.96\ QRB_{San\ Benito};\ r^2=0.82,\ Sx=0.462\ Mm^3$$

Where: Q = Monthly discharge (x1000 m^3);

Falcón, Río Grande, Anzaldúas, San Benito, and Brownsville are the IBWC gauging stations along the Río Bravo/Río Grande.

Hydrological Scenarios on the main stem of the LRB. The water balance of La Amistad-Falcón reservoirs, calculated for the period of 1945 to 1990 by Ward (1998) under the four scenarios employed in this study, was used as input data into the Lower Río Bravo/Río Grande. Monthly discharge below Falcón reservoir varied according the projected scenarios; a) normal hydrological conditions, NH, b) full development of Mexican waters, MD, c) drought of record or super-drought, SD, and d) full development of Mexican waters and super-drought, MDSD. Normal hydrological conditions and drought of record was estimated as the monthly discharge for 15 years. The drought of record or super-drought was defined as the highest draw-down 15-year period of La Amistad-Falcón reservoirs from 1945 1960. This dry episode is coincident with the worst drought of record estimated for the Río San Juan watershed, which lasted from 1949 to 1964 (Navar, 2001). Data consisting on releases from the complex La Amistad-Falcón were estimated by Ward (1998) for these four scenarios and provided for this report.

The irrigation depth was approximated using the crop consumption approach of Blaney and Criddle (Withers and Vipond, 1986). This approach was employed for irrigating the most popular crops: maize and sorghum for two consecutive growing seasons. Estimated consumptive water use for these crops was subtracted from monthly precipitation to determine the irrigation depth required for these two crops and the results are presented in Table 1.

The full water balance can define in a monthly temporal scale (i) discharge along the main stem of the Río Bravo/ Río Grande, (ii) water diversions between hydrometric stations, (iii) public and industrial water demand, (iv) volume of water left for irrigation, (iv) consumptive water demands for irrigation, and (v) the area to be irrigated for the volume of water remaining after the municipal and industrial uses have been satisfied.

RESULTS

Discharge along the Río Bravo/Río Grande, below Falcón reservoir. For the 1980-1994 period, observed average annual streamflow approximates 111.15, 115.32, 57.83, 26.98, and 21.27 $m^3\ sec^{-1}$ for the gauging stations of: i) below Falcón reservoir, ii) at Camargo, Tamps., iii) below Anzaldúas, iv) at San Benito, TX. and (v) at Brownsville, TX, respectively. Annual average streamflows progressively diminish from below Falcón reservoir to the Gulf of Mexico, with the exception of the hydrometric station located at Camargo, Tamaulipas, Mexico, where it increases by approximately 4% because of the inflows of the Río Alamo and Río San Juan, as well as the irrigation excess of the 026 irrigation district. Of the 100 % annual streamflow gauged below Falcón, only 19 % is recorded below Brownsville, TX. The sources of this reduction are the diversions for agricultural and municipal use and the likely aquifer recharge along the main stem of the Río Bravo/Río Grande.

Table 1

Estimations of irrigation depth by the consumptive water approach for maize and sorghum in the irrigation district 025 of the lower Río Bravo/Río Grande watershed of northeastern, Mexico

	MONTHS											
	J	**F**	**M**	**A**	**M**	**J**	**J**	**A**	**S**	**O**	**N**	**D**
Factor	0.92	0.88	1.03	1.06	1.15	1.14	1.17	1.12	1.02	0.99	0.91	0.91
Light (h)	7.60	7.27	8.45	8.71	9.45	9.41	9.61	9.21	8.38	8.13	7.48	7.48
Temperature 0F	14.2	17.1	19.9	23.7	27.5	29.4	31.3	31.3	27.5	23.7	18.0	15.2
I.D. Maize (mm)	85.44	89.1	112	127	151	157	167	160	134	119	94	86
I.D. Sorghum (mm)	79.74	83.2	105	119	141	146	156	149	125	111	88	80
Precipitation (mm)	40	36	14	38	88	67	61	61	94	61	27	32
Pan Evaporation (mm)	81.0	97.0	158	169	173	204	229	220	170	140	106	87
Consumptive use Maize					34.21 cm				26.53 cm			
Sorghum				35.27 cm					32.64 cm			

Total Maize= 60.74 cm, Total Sorghum=67.91 cm; Light Hours= Light (h), Factor which considers latitude, 25°30'.

Average annual streamflows also diminish along the main stem of the Bajo Río Bravo/Río Grande for all scenarios (Figure 4) from Falcón reservoir to its outlet into the Gulf of Mexico. That is, average monthly streamflows decrease about 50% from gauging station Camargo (378.1 Km from its outlet) to Anzaldúas (273.3 Km from its outlet) and it diminishes about 50% from below Anzaldúas to San Benito, TX (155.8 km from the Gulf of Mexico).

Estimated discharge is on the average 95, 99, 51, 25, and 20 m^3 sec^{-1}, for the gauging stations described for the normal hydrological conditions scenario. These estimates are reduced by 37%, 25%, and 11% in the MDSD, MD, and SD scenarios, respectively in comparison to estimates for the normal hydrological conditions scenario (Figure 4).

Diversions from the Río Bravo/Río Grande at Anzaldúas. For the period of 1980 1994, average annual diversions for the Mexican side of the Lower Río Bravo/Río Grande, between Río Grande city and Anzaldúas, was 1376 Mm^3 $year^{-1}$, with a standard deviation of 310 Mm^3 $year^{-1}$. For the proposed scenarios, the annual diversions would diminish by 34%, 27%, and 8% for the MDSD, MD, and SD, in comparison to the normal hydrological conditions scenario, respectively. That is, the average discharge rate to the Mexican side would be 47, 38, 43, 34 m^3 sec^{-1} for the NH, MD, SD, and MDSD scenarios, respectively (Figure 5).

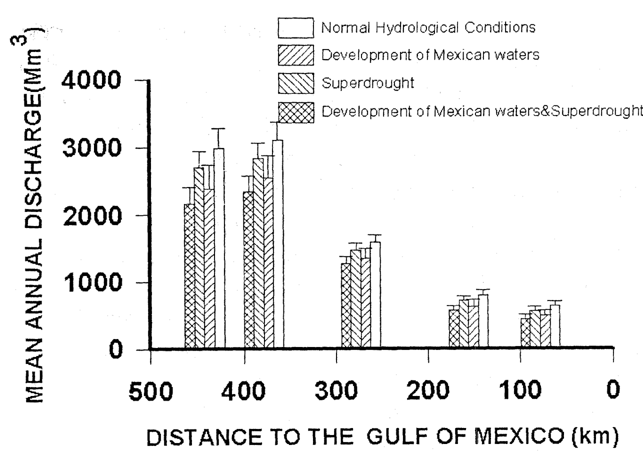

Fig. 4. Average annual streamflow estimated at five hydrometric stations along the Río Bravo/Río Grande for four scenarios.

Meeting water demands in the Mexican side of the lower Río Bravo/Río Grande

Public and industrial demands. The rate of discharge required to meet the public and industrial demands on the Mexican side of the lower Río Bravo/Río Grande basin increases linearly 147 215 283 Mm^3 $year^{-1}$ for the periods of simulation: 1990-2004, 2010-2024, and 2030-2045, respectively. The growth rate is approximately 46% at each time period (Figure 6).

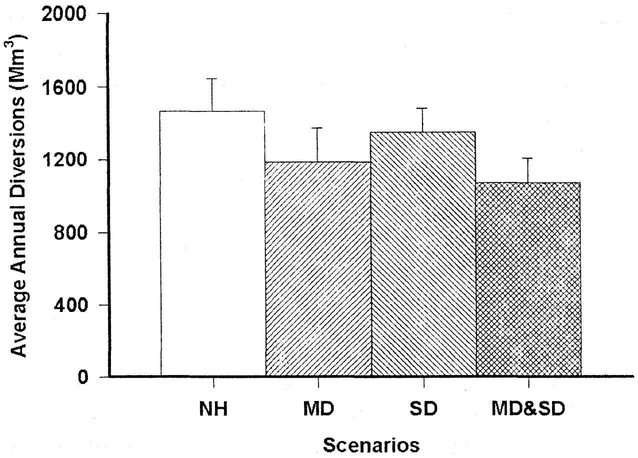

Fig. 5. Estimated water diversions for the Mexican side of the Bajo Río Bravo/Río Grande between Río Grande city and Anzaldúas under four scenarios. NH= Normal hydrological conditions, MD= Mexican use of water accorded in the 1944 treaty with the US, SD= Drought on record, MDSD= The simultaneous presence of a drought on record and the Mexican use of water accorded in the 1944 treaty with the US.

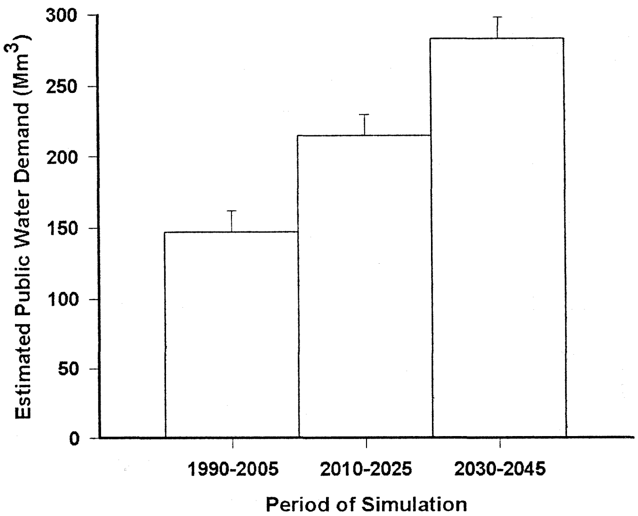

Fig. 6. Estimated water demands for public and industrial use for average population growth with drought awareness demands and average industrial use for four scenarios.

The volume of water allotted for irrigation remaining after public and industrial demands have been met. The remaining volume of water for irrigation after public and industrial water demands had been met diminishes with time of simulation because of increased demand placed on water supplies for public and industrial uses. Among time periods the maximum difference between the maximum and the minimum volume of water for irrigation is 15%, while among scenarios this percentage increases to 47%. Thus, the full development of the Mexican waters coupled with the worst drought spell of record would reduce significantly the volume of water for irrigation in the 025 district (Figure 7).

The size of irrigated land areas. The area of irrigated agriculture would contract on the average to 200676, 181032, 153112, and 133980 ha year^{-1}, under the NH, MD, SD, and MDSD scenarios, respectively if maize was cultivated in the area. For sorghum, average irrigated land areas would be reduced to 179710, 162118, 137115, and 119982 ha year^{-1}, respectively (Figure 7). Minimum estimates fall below 100 000 ha year^{-1}, which were never recorded in the 025-irrigation district in the last century.

DISCUSSION

These scenarios indicate a potential reduction of irrigated lands, on the average by the middle of this century by an average of 56%. Note that this estimate is quite conservative when compared to the already observed variations in irrigated agriculture in the last two years. These estimates are in agreement when compared with other approximations derived from regression analysis and the ratio of supplied irrigation volume to the irrigated area for recorded drought episodes. These comparisons are reported in Table 2.

Table 2

Estimated average irrigated land areas (x1000 ha) for the time periods of 1990-2005; 2010-2025; and 2030-2045 for the 025 irrigation district.

Time Periods	Statistical Forecasting	Third Drought of Record	Crop consumptive Use Approach			
			NH	MD	SD	MDSD
1990-2005	163	134	213	163	188	144
2010-2025	135	118	182	150	167	132
2030-2045	106	108	189	139	174	121

Statistical forecasting uses a simple regression between irrigated land area and time for information historically recorded. The third drought approach was worked out by interpolating the ratio between volume diverted and irrigated land area for the 3rd historic recorded drought spell. The worst historic recorded drought scenario includes only (1) drought *per capita* public demand, (2) average industrial water demand for the average population scenario.

The size of irrigated lands somewhat converge for the first two approaches and the scenario for the full development of the Mexican waters coupled with the presence of the worst drought of record. However, the last approach is quite conservative and the statistical forecasting and third drought approach converge nicely in the last period of simulation.

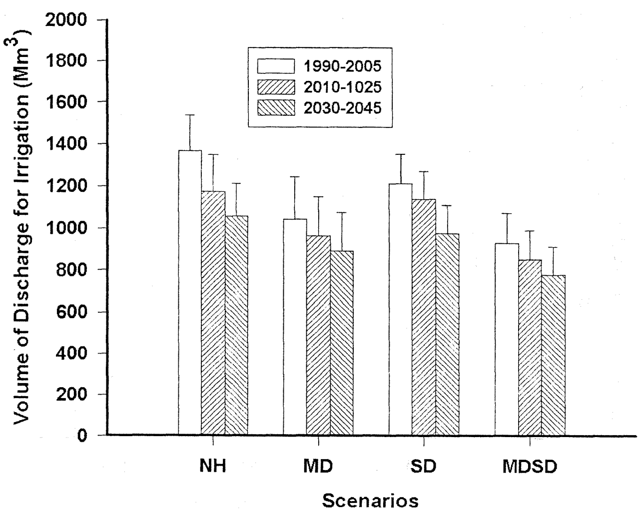

Fig. 7. The estimated average volume of water allotted for irrigation within the 025 irrigation district under the four scenarios.

The contraction-expansion of agricultural lands has also been reported in other semi-arid ecosystems (Kleeberg and Weissgerber, 1996; Postel, 2000) and it has been attributed to erratic and infrequent dry and wet periods, characteristic of semi-arid ecosystems (Hare, 1983). During wet years none of the economic sectors would suffer from a lack of water resources but in dry spells the volume of water allotted for irrigation would be transferred to other primary uses (i.e., the examples of several arid and semi-arid countries) increasing pressure on the size of the irrigated agriculture. In the irrigation district 025, the size of agricultural lands has historically varied from 140 000 ha in the early 1980's to 220 000 in the wet years, with an average and standard deviation of 188,068 ha and 17 591 ha year^{-1}, respectively (SARH, 1981 and IBWC, 1980-1994). This represents a reduction of 37% and is smaller than that reported for irrigation district 026 or lower Río San Juan, located in northeastern Mexico, in which the irrigated area was reduced by 46% in 1997 (CNA, 1997; Navar, 1999, 2001). The reduction is largest under the potential developments of the Mexican waters in the presence of a super-drought. In contrast to the area irrigated under normal years (189 000 ha), 36% less area (121 000 ha) will be irrigated for the period of 2030-2045. That is, conserving water in the upper Río Bravo/Río Grande basin in the Mexican side will diminish irrigation area in the lower side of the Mexican Río Bravo/Río Grande watershed.

At the present time, in a drought of record situation, Mexico cannot meet its obligations of the 1944 treaty, entitling the United States of America to 350 000 acre-feet year^{-1} (432 Mm^3 year^{-1}) over a five-year average under normal climatic conditions from the Río Conchos, Río San Diego, Río San Rodrigo, Río Escondido, and Río Salado (Article 4 of the 1944 Treaty). Although full development of the Mexican waters has net been taken place yet, the current dry spell affecting northern Mexico has also reduced the size of agricultural lands. For the 2001, 0 ha were irrigated in the 025-irrigation district (El Norte, 2001). Heavy economic losses, social disruptions, and environmental degradation of aquatic ecosystems are becoming major issues of concern in the watershed and they will be magnified in the near future.

The future does not look promising either since Mulholand *et al.*, (1997) and the IPCC (2001), using general circulation models, predicted that northern Mexico, and specifically, the Río Bravo/Río Grande belt may receive 10% less rainfall and generate between 5 to 10 % less streamflow with increasing temperatures by global warming. Therefore, climate change may or probably is already magnifying drought in northern Mexico.

The present and likely future scenarios discussed above suggest the need for the sustainable management of water resources in all sectors of the economy of the Mexican lower Río Bravo watershed. High estimated *per capita* supply (405 l per inhabitant per day) has to be diminished. In this line of thought, the public sector must become more efficient in channeling, distributing, and treating domestic, industrial, commercial, municipal, and public water supplies. There is increasing evidence that volume loses in the water distribution system of most cities can be as high as 30% (Data from the city of Reynosa, Mexico). Therefore, by tapping all losses in the water distribution system of all cities of the Mexican lower watershed, the area of irrigated lands would increase an additional average of 5, 8, and 11% for the time periods of 1990-2004; 2010-2024; and 203-2044, respectively.

The use of treated municipal water for irrigation could offset any reduction of irrigated lands. This is a common practice in several semi-arid regions (i.e., the local plan of the San Juan watershed in northeastern Mexico). The full utilization of treated municipal wastewater for irrigation would account for an additional 32 000, 48 000, and 62 000 ha year^{-1} for the time periods of 1990-2004; 2010-2024; 2030-2044, respectively. These additional irrigated areas would bring agricultural lands into the long-term annual average size. Several programs are underway in a joint venture between United States and Mexico in the lower Río Bravo/Río Grande basin. A joint agreement between USA and Mexico is already funding several projects in this line of recycling water or doubling productivity as stated by Postel (2000).

Agriculture has to become more efficient to reduce the volume for irrigation when pursuing the sustainable management of water resources in the Mexican Bajo Río Bravo/ Río Grande. Irrigation is inefficient since it requires 2800 m^3 to produce 1 Mg of crop (Návar and Rodríguez-Téllez,

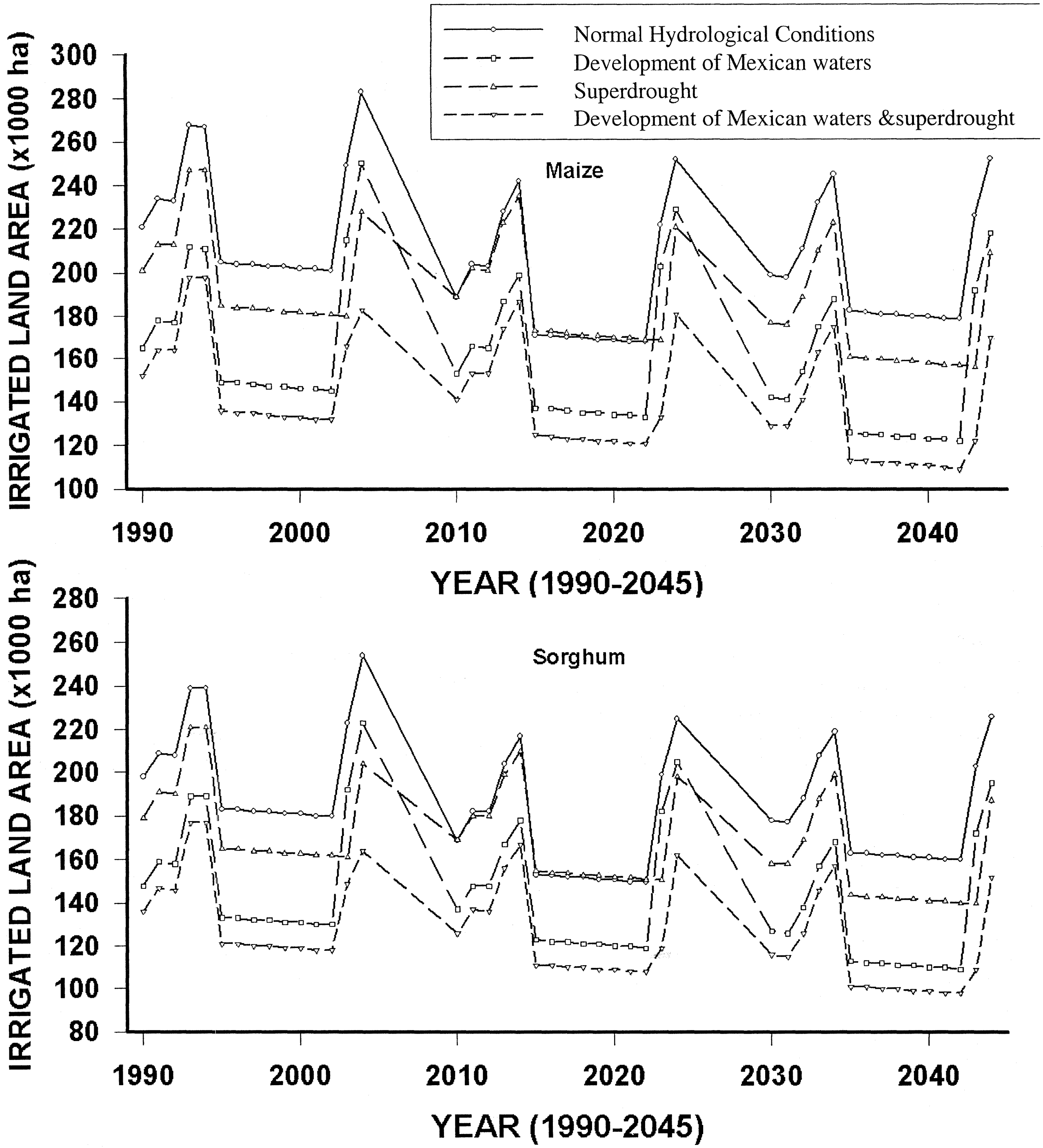

Fig. 8. Estimated irrigated land areas for maize and sorghum for four scenarios for average population growth, drought awareness public demand, and average industrial water use on the 025-irrigation district.

2002). It reflects heavy water losses in the conveyance system, application efficiency, and water use efficiency. Addressing crop water requirements is critical in order to increase water savings and irrigated land area (i.e., planting alfalfa or cotton would require 56 and 14% more volume of water than planting maize). Thus, by using the same volume of water, 56 and 14% more area would be planted with corn than by planting alfalfa or cotton. Sorghum, a less water demanding crop (10 and 25% less irrigated volume used than corn and cotton, respectively) is being preferentially planted in the lower Río Bravo/Río Grande irrigation district because of the water shortages allotted for irrigation, resulting from the present drought spell. Other economic considerations must be considered when shifting crops in the 025-irrigation district.

The irrigation efficiency is classified in: (1) water conveyance, (2) water application efficiency, and (3) water use efficiency. The main conveyance system has an efficiency of 71%, the secondary drain system between 75-80%, and at the individual farms level the efficiency is 65% (SARH, 1981). The overall estimated efficiency lies in the range of 32 to 36% and by increasing it to a feasible range of 60%, the total irrigated land area would increase from 24 to 28%. The water application system in the irrigation district 025 is conducted mainly by surface irrigation which has an average efficiency of 70% (Schwab *et al.*, 1981). The water use efficiency is also in the range of 60% because of the high water table (Reyes, 1986), with irrigation-excess drained into the Río Bravo/Río Grande, as well as into the Gulf of Mexico (CNA, 1998). Therefore, other irrigation technologies may also improve the water application efficiency and increase the area of irrigated lands.

The environmental services provided by streamflow of sufficient quality must be also addressed when allocating water to other uses. The aquatic communities of plants, fish, insects and other organisms are already under stress in the Río Bravo/Río Grande (Contreras and Lozano, 1994; Contreras and Edwards, 1998). Extinction of fish species has occurred in several tributaries of the Río Bravo/Río Grande. Villareal (1983) pointed out that four fish species (*Notropis stramineus*, *Notropis amabilis*, *Dionda episcopa*, and *Campostoma anomalum*) had become extinct due to dramatic increases in the salinity and alkalinity of the river. Villareal *et al.*, (1986) and Obregón (1987) also reported the bio-accumulation of Zn and Fe in two fish species (*Poecilia formosa* and *Cichalosoma cyanoguttatum*) in the Río Santa Catarina, and bio-accumulation of Pb, Fe and Cu in four fish species (*Astyanax mexicanus*, *Notropis braytoni*, *Notropis jemezanus*, and *Cichlasoma cianoguttatum*). Guerra (2000) found evidence that the diversity–abundance of the fish community is sensitive to pollution of the Río San Juan of Nuevo León, Mexico.

The benefits of conducting sustainable management of water resources in the Mexican Bajo Río Bravo/Río Grande watershed comply with the expectations of society. However, several aspects of sustainability must be considered. The UNCED (1992) and Schmandt *et al.*, (1998; 2000) discussed the need of the promotion of an interactive, iterative and multisectorial approach, the planning for the rational utilization, protection, conservation, and management of water resources, the design, implementation and evaluation of projects and programs that are economically efficient and socially appropriate, and (4) the identification and strengthening or development the appropriate institutional, legal and financial mechanisms. These are some issues that must be explored in coming research papers on water and sustainable development in the Bajo Río Bravo/Río Grande.

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