FRONTERA NORTE e-ISSN: 2594-0260

Revista internacional de fronteras, territorios y regiones / International Journal of Borders, Territories and Regions

FRONTERA NORTE VOL. 33, ART. 9, 2021

https://doi.org/10.33679/rfn.v1i1.2137

The Colorado River Damming Impact on the Shrimp Fishery in the Upper Gulf of California, Mexico

El impacto del represamiento del Río Colorado en la pesquería del camarón en el Alto Golfo de California, México

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ABSTRACT

The objective of this work is to demonstrate the relationship among the Colorado River flows and volumes of shrimp caught in the Upper Gulf of California (AGC). A correlation analysis was applied to historical series of data about landed shrimp catch, fishing effort and flow from the Colorado River towards the gulf. Dependence, proportionality, and linear relationship indicators were obtained. The main results showed that the interannual captures were lower in periods without water input from the river and higher with the water inputs to the estuary. In addition, the results showed that the contributions of nutrients carried in the river water to the estuary could increase the Carbon fixation. This study is important because it contributes to the discussion and strengthens the fact that this river is important in the environmental and fishing dynamics in the AGC.

Keywords: 1. Colorado River, 2. fisheries, 3. shrimp, 4. damming, 5. Upper Gulf of California.

RESUMEN

El objetivo de este trabajo es demostrar la relación entre los flujos del Río Colorado y los volúmenes de camarón capturados en el Alto Golfo de California (AGC). Se aplicó un análisis de correlación a series históricas de datos de captura del desembarque de camarón, el esfuerzo pesquero y el flujo del Río Colorado hacia el Delta. Se obtuvieron indicadores de dependencia, proporcionalidad y relación lineal. Los principales resultados mostraron que las capturas interanuales fueron menores en períodos sin aporte de agua del río y mayores con los aportes de agua al estuario. También mostraron que los aportes de nutrientes por el ingreso de agua dulce al estuario pudieron incrementar la fijación de carbono. Este estudio es relevante porque aporta a la discusión y fortalece el hecho de que este río binacional transfronterizo es importante en la dinámica ambiental y pesquera en el AGC.

Palabras clave: 1. Río Colorado, 2. pesca, 3. camarón, 4. represamiento, 5. Golfo de California.

Received: July 16, 2020
Approved: September 7, 2020
Online publication: May 15, 2021

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Frontera Norte Frontera Norte is a yearly digital journal published by El Colegio de la Frontera Norte. https://fronteranorte.colef.mx

INTRODUCTION

The objective of this work is to analyze the relation that has existed between the control on the Colorado River over the process of dam constructions throughout its course and shrimp catch in the region of the Upper Gulf of California (UGC). Shrimp catch has been the fundamental fishing activity in the region and one of the main factors for the growth and development of the communities whose history is strongly linked to this activity.

The damming process of this important transborder river is considered to have been disregarded or the delta of the river in the Gulf of California completely ignored, even today, when the academic debate has become polarized among those who recognize the importance of the freshwater flow to the delta to maintain and enrich biodiversity, and those who argue that the impact of damming is irrelevant in the Upper Gulf of California region.

Commercial shrimp catch in the Upper Gulf of California comes from the fishing ports of Puerto Peñasco and the Gulf of Santa Clara, in Sonora, and from San Felipe, in Baja California.

The present work is based on the research carried out by Galindo-Bect *et al.* (2000), in which they explain the variations in the shrimp catch reported by the fishing fleet in San Felipe, Baja California, on account of the freshwater discharges from the Colorado River in the marine ecosystem and conclude that this is explained by a meaningful relationship.

The difference between the research of the afore-mentioned authors and our article is that the historical catches by the three main UGC communities were included. That is, practically the total catch in the region was integrated, and the contribution of nutrients that the river adds to the marine system was incorporated into the analysis.

The reason to justify this research arises from the conclusion drawn by Bernacsek (2001), which refers to the need to generate accurate information for the management of fisheries affected by dams, and according to the afore-mentioned author, this information refers to changes in the flow and discharges of freshwater, and sediment and nutrients deposition that can affect fish and shrimp populations. In addition to conventional information for the management and evaluation of fisheries gathered from catch and effort data, the evaluation of biodiversity and fish population, environmental parameters and indicators of the impact of the dams that can be incorporated into dynamic multivariate models of fisheries to estimate the impact and damage that dams generate on populations.

Bernacsek's proposal (2001) was adopted, in such a way that this work analyzes catch and effort data, relating them to the historical freshwater flows from the river to the delta in the Gulf of California. The flow of the river is considered to be an important variable that affects the dynamics and exploitation of shrimp and it therefore influences the social and economic aspects of the coastal communities in the region.

The studies and analyzes that have been carried out examining the relationship between the flow of the Colorado River and the fishing dynamics are important, so they must be integrated into larger multidisciplinary studies in order to explain the current situation in the

https://doi.org/10.33679/rfn.v1i1.2137
region. Ideally, such studies can be adapted to dynamic models that include both environmental and socio-economic aspects to understand, for example, the crisis and the risk to endemic species, the impact that the change has in the ecosystem conditions of the Colorado River delta, the precarious conditions among the fishermen of the UGC, the binational management strategies of the river, among others.

FISHING IN THE REGION

The main economic activity in the UGC region is fishing. About 70 species are caught, such as blue shrimp, clam, brown shrimp, octopus, corvina, manta ray, shark, mullet, minor pelagic species, among others. Shrimp catch became the most important in the UGC region due to the volume of catch and the economic value it represents. Its course is decisive for the rest of the fishing activity in this region, since almost all the effort in the region was made by the industrial fleet and the smaller fleet of San Felipe, Puerto Peñasco and the Gulf of Santa Clara (Vázquez, Fermán, García, & Arredondo, 2012).

Fishing is most important in small communities where primary activities are the main economic activities. That is, small communities have greater economic dependence on fisheries, since the diversity of economic sectors is lower, compared to larger communities, where there is a greater diversity of economic activities, for example, Puerto Peñasco has a greater variety of activities of the tertiary sector, while in the Gulf of Santa Clara fishing is the main economic activity.

Fishing in the region has gone through periods of promotion and support by the government, under regional development considerations and arguments, which contributed to the development and growth of the cooperative sector. The above-mentioned contrasts with the current situation, in which environmental and socioeconomic deterioration prevails in the region.

Since the 1970s, fishing in this region has been strictly controlled and subject to management and handling policies with the main purpose of protecting two species: the vaquita (*Phocoena sinus*), an endemic mammal, and the totoaba fish (*Totoaba macdonaldi*). For this purpose, regulations have been implemented on fishing equipment and techniques; specific areas of prohibition of fishing have also been decreed, considering conservation a priority.

These regulatory policies have created a social and economic deterioration in coastal communities with greater dependence on fishing, since these policies have been dissociated from the precepts of sustainable development (Vázquez, 2019). Another factor is the fact that fishing in general has been managed as an activity disassociated from the general context of the Colorado River-Upper Gulf of California system, since the policies of distribution and allocation of water from the river flow have not considered the delta as part of the system. It additionally contributes elements to a complex estuarine ecosystem, in which there is dependence between the river system and biodiversity both in the delta and in the UGC.

The Colorado River has been drastically impacted by the damming and retention of water along its course, blocking the flow to the delta and affecting the environment in the UGC (Aragón, 2000). The retention of water, and therefore, the decrease in flow to the delta, has modified the environments that were previously brackish, transforming them into hypersaline environments, due to the contraction of the wetlands in the delta, which comprised a total area of 780,000 ha, and is currently reduced to 60,000 ha. The alteration of the river flow has caused an impacted environment, generating direct negative effects on riparian vegetation, affecting populations of migratory birds, altering spawning areas of marine species and significantly reducing the areas of refuge and breeding of the vaquita, and consequently it has generated collapse in some fisheries (UNEP, 2004).

The cross-border section of the river

The Colorado River is transnational, since it begins in the Rocky Mountains, in the state of Wyoming, and flows southwards along 2,300 km encompassing the states of Colorado, Utah, New Mexico, Nevada, Arizona and California, in the USA. When crossing the border into Mexico, it runs over the last 130 km stretch that serves as the dividing line between the states of Baja California and Sonora, to debouch into the Gulf of California.

For more than a hundred years this river has been the object of studies and analysis from different approaches and disciplines. It has been studied by geology and even the social sciences, and from predictive models of sediment flow and discharge to aspects of geopolitics have been developed. The dynamics and diversity of studies has generated abundant literature (for example Wilhite, 2005; Glenn *et al.*, 2001; Muehlmann, 2013; Robinson & Kenney, 2012), which have considered the river as an ecosystem service framed in a multi-regulated scheme immersed in a highly competitive water market, which also has direct and indirect effects in the Gulf of California.

As stated before, the river influences seven states in the United States and two in Mexico, providing water for 40 million people in total. California is the state with the largest allocation of water from the river flow, with a total of 5,427 mm^3, followed by Colorado with 4,755 mm^3, representing 26.6 and 23.3 % of the total, respectively. The Mexican section of the river represents an allocation of 9 % of the total flow, which means 1,850 mm^3 (Cortez, Castro, & Sánchez, 2019). Almost all of the river water is used for human benefit: 78 % is destined for agricultural activities and the rest is destined for municipal and industrial use, excluding the allocation of river water for environmental services (Boepple, 2011).

This current scheme for the allocation and use of river water could increase in the future, due to the increasing demand for water to sustain human activities. According to Kohlhoff and Roberts (2007), only in the state of Arizona has the demand for water exceeded the amount of groundwater available, since it is estimated that between 2020 and 2040 this demand will exceed the availability of renewable water. This scenario of water stress is enhanced by the predictions of population growth only in that state, without considering the conditions of the remaining six states and the demand for water in the Mexicali Valley. The circumstances described have prompted the search for options to increase water availability,

https://doi.org/10.33679/rfn.v1i1.2137

and have given rise to the Arizona-Mexico Water Augmentation Consortium proposal, which –without going into great detail– mentions that the state of Arizona, in collaboration with the United States and Mexico, would create infrastructure in Mexico to desalinate seawater from the Gulf of California and provide freshwater to Mexico in exchange for the allocation of water from the Colorado River (Kohlhoff & Roberts, 2007). This proposal does not include the effects on the delta or the impacts on the fisheries of the region.

Shrimp Fishery in the Upper Gulf of California

Shrimp catch in the UGC has been the main source of economic income for the fishing communities of San Felipe, in Baja California, and Puerto Peñasco and the Gulf of Santa Clara, in Sonora. Of the four shrimp species that are exploited in the Mexican Pacific, only the blue shrimp (*Penaeus stylirostris*) and the brown shrimp (*Penaeus californiensis*) are found in the UGC (Rodríguez de la Cruz, 1981), and represent approximately 90 % of the disembarked catches (Rosas, García, & González, 1996).

The blue shrimp fishing crisis in the UGC is a very complex problem that requires multidisciplinary analysis. Studies carried out in other regions mention that annual fluctuations are positively correlated with river discharges, rainfall and temperature, such is the case of rivers in Sinaloa, Mexico (Del Valle & Martin, 1995; Bect, 2000), in the Gulf of Mexico (Gracia, 1989), in Peru (Tadanobu & Rodríguez, 1990; Mendo & Tam, 1993), in Senegal, Mozambique and Cape Province, in Africa (Gammelsrod, 1992; Reddering, 1988). Morales (2001) applied an ecological model in the northern region of the Gulf of California and concluded that the behavior of shrimp catch responds favorably to the fluctuations of the Colorado River discharge.

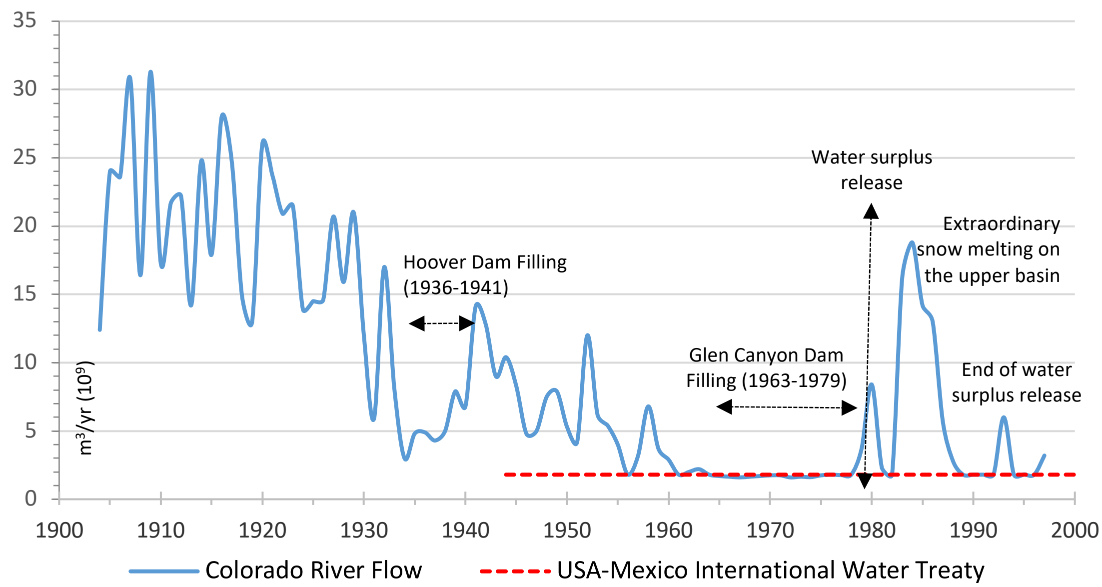
By applying an ecological model, Morales (2001) found that the behavior of shrimp catch responded favorably to the fluctuations of river flow in the Northern region of the Gulf of California.

Among the effects of rivers on estuarine and marine systems, one is related to the availability of nutrients and the increase in primary organic productivity (Snow, Adams, & Bate, 2000; Rodríguez, Flessa, & Dettman, 2001; Schöne, Flessa, Dettman, & Goodwin, 2003), present firstly in the species that are estuarine-dependent at a stage of their development, and secondly, in the reduction of fishery production in the region (Mann & Lazier, 1996; Ardisson & Bourget, 1997).

The volume of water from the Colorado River that entered the estuary in the UGC has been drastically reduced, since at the beginning of the last century the flow of the river on the US-Mexico border has decreased from $21,370x10^{6}$ $m^{3}/year^{-1}$ in the period prior to the construction of the Hoover Dam to low values of 1780x106 $m^{3}/year^{-1}$ during the filling period of the Hoover Dam in 1935-1941 and the Glen Canyon Dam in 1963-1979 (Fradkin, 1996; Samaniego, 2008). In the 1944 International Water Treaty between Mexico and the United States of America, the volume was limited to occasional flows due to surpluses of

1,850 x 106 $m^3/year^{-1}$ (graph 1), which represents 9.09 % of the total average river flow, while California gets 26.6 % and Colorado 23.3 % (Cortez Lara, 1999).

Graph. 1. Historical annual flow of the Colorado River on the US-Mexico border



Source: Váldez *et al.* (2013).

This allocation of water to Mexico is not enough to flood the estuary because it is fully used for agricultural and urban needs, without considering the ecological changes that would be induced by the restriction of freshwater to the estuary. Following the filling of the Glen Canyon Dam, global climatic changes caused anomalous rainfall and thaws that in turn led to extraordinary river flows of up to ~18,000x10^6 $m^3/year^{-1}$ in the 1979-1988 period (graph 1). During this period in Mexico, large areas of wetlands near the Colorado River were flooded, such as the *Laguna Salada*, the Hardy River and the *Cienaga de Santa Clara*, thereby increasing the area of protection and breeding of dependent estuarine species. This is shown in maps 1 and 2, which correspond to Landsat 7 TM satellite images, contrasting the flooded area with input from the river on June 9, 1984 and without input from the river in 1990.

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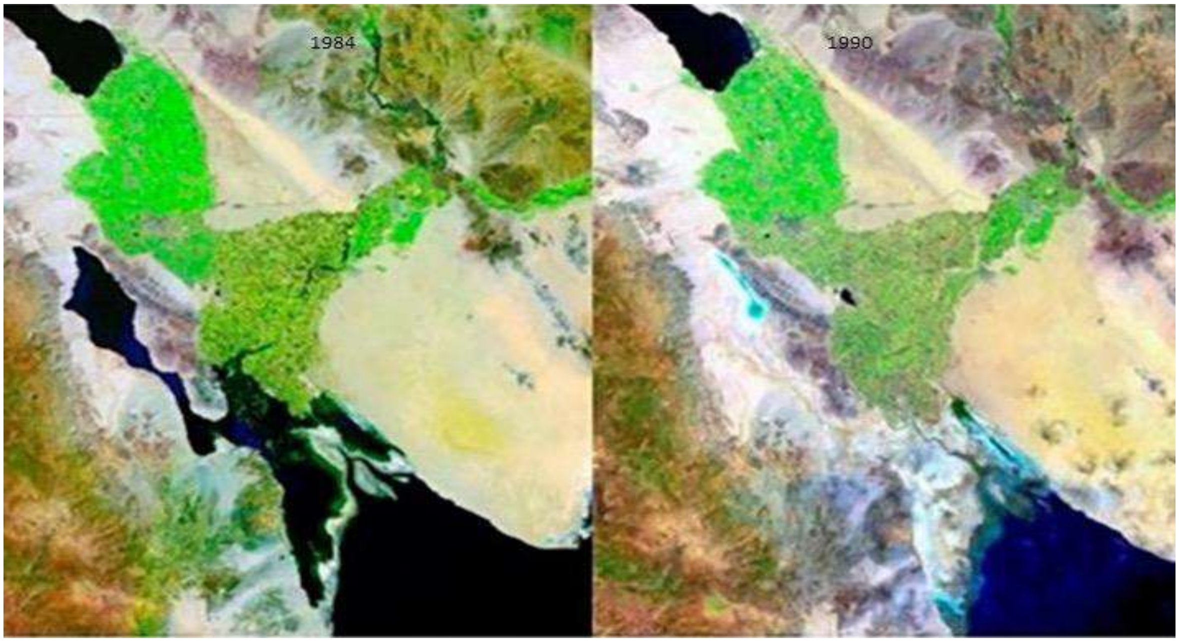
Maps 1 and 2. Area influenced by the flow of the Colorado River in the Delta of the Upper Gulf of California



Source: Adapted from Brusca, Alvarez, Hastings and Findley (2017).

It is for this reason that this study proposes to examine the interannual fluctuations of the shrimp catches disembarked in the UGC and analyze them considering the environmental impact due to the damming of the Colorado River.

METHODOLOGY

Historical data from 1900-1998 on the flow of the Colorado River on the US-Mexico international border were used (personal communication with Bernal Rodríguez, September 24, 2003). The fishing statistics of the annual shrimp catches disembarked in Puerto Peñasco, San Felipe and the Gulf de Santa Clara from 1950-1999 were used, considering that the sum of them is representative of the UGC (National Fisheries Institute, n.d.). From these catch statistics, the Catch per Unit Effort (CPUE) was obtained, dividing the annual tons of shrimp caught by the number of boats per season. This was done taking into account that the statistics consider the number of vessels and the volume of catch disembarked. There are no records of the number of trips and the fishing time spent per boat, so this limitation impedes obtaining a refined version of the yield per boat (Pérez, Aragón, & Espinosa, 2009).

In order to inquire about the years with and without contributions of river water to the estuary, the 1,850 x 10^6 m^3/year^{-1} of the International Treaty of Boundary and Waters with the United States was subtracted from each year. With these values and the captures of shrimp landed in the UGC, the coefficients of determination (r^2) were determined, with a one-year and two-year lag, from a simple linear regression analysis for the period 1959-1999. The one-year lag is due to the fact that the river water that entered in one year influenced the shrimp catch of the subsequent fishing season. The two-year lag is due to the fact that the water accumulated in the basins of the Laguna Salada, the Hardy River and the Cienega de Santa Clara (maps 1 and 2) influenced the shrimp catch up to two years after the termination of the shipment of surpluses from the Colorado River to Mexico.

The tons of nitrogen and phosphorus that could reach the estuary with the surpluses of the river in the period 1979-1988 were calculated considering a concentration of 30 μM of nitrates and 2 μM of phosphates dissolved in the water reported by Cupul (1994). With this information, the possible carbon fixation in the form of primary production was calculated at a ratio of 106C:16N:1P according to Richards, Ketchum and Richards (1963). The tons of shrimp that could be stimulated with the surpluses of the Colorado River were calculated considering that 10 % of the fixated carbon is transferred from one trophic level to another.

RESULTS

Relation of the Colorado River flow and fishing effort

The shrimp trawling fleet or larger vessels (boats) increased significantly in the 1970-1980 period as a result of the National Fisheries Development Plan (López, 1997) that allowed financing for the development of the project, substantially increasing the number of larger vessels. However, in the early 1980s the growth of the shrimp fleet was limited, since the cooperatives that had acquired larger vessels suffered economic crises due to factors related to the levels of financing debt and the uncertainty in the recovery of investment, which was made worse by the recurring long-term macroeconomic crises in the country.

This was reflected in the seizure processes of vessels, and therefore, in the decrease in fishing effort. Greenberg (1993) mentions that in 1990 there were 226 boats in Puerto Peñasco, 40 in San Felipe, and 15 in the Gulf of Santa Clara. This number of vessels decreased to less than half in the following years (graph 2). On the other hand, the fishing effort represented by smaller vessels (skiffs) increased significantly from 1980, so the fishing effort exerted by this fleet is unknown.

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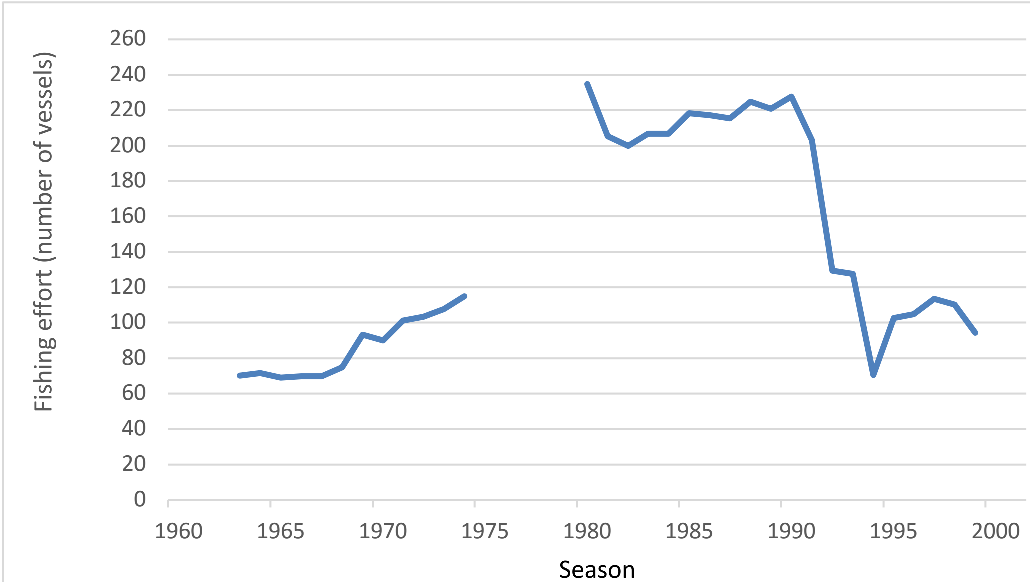
Graph 2. Variation in the number of shrimp boats in Puerto Peñasco in the period 1962-1999

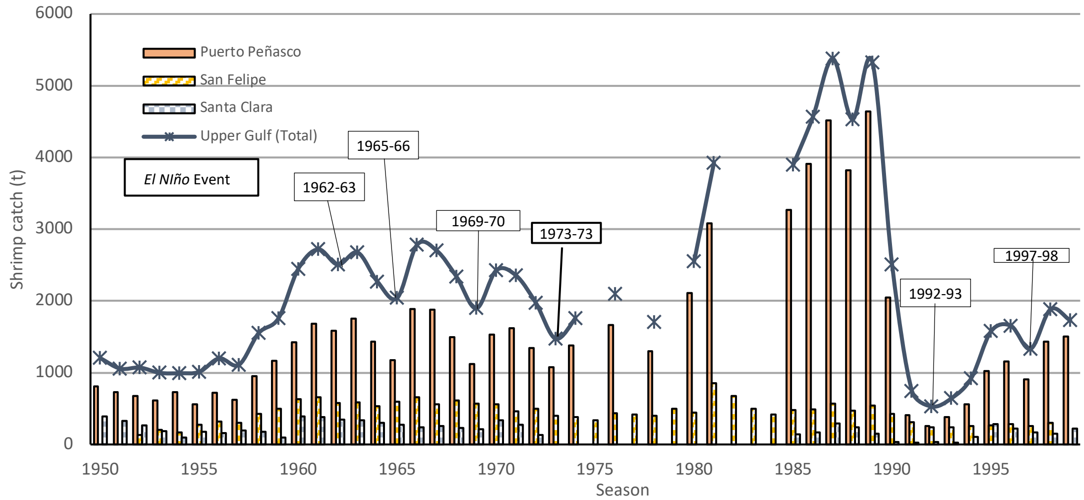


Source: Prepared by the authors based on data provided by the National Fisheries Institute (n.d.).

Shrimp Catches in the UGC

The vessels from Puerto Peñasco contributed more than double the commercial shrimp catch disembarked in the UGC (graph 3). In general, three periods were observed with different catch proportions: the first, without the influence of river water in the period 1950-1979, where shrimp catches fluctuated between 1,998 and 2,783 tons per year (t/year^{-1}). The second, with the influence of the river in the period 1980-1990, with values between 2,504 t/year^{-1} and 5,375 t/year^{-1}. The third, in the period 1991-1999 with and without the influence of river water, with values significantly lower than the previous ones, between 529 t/year^{-1} and 1,883 t/year^{-1} (see map 1, 2 and graph 3). Interannual fluctuations were also observed with small increases in catches corresponding to a year after the El Niño events 1962-1963, 1965-1966, 1969-1970 and 1972-1973 (graph 3).

Graph 3. Commercial catch of shrimp disembarked in the Upper Gulf of California

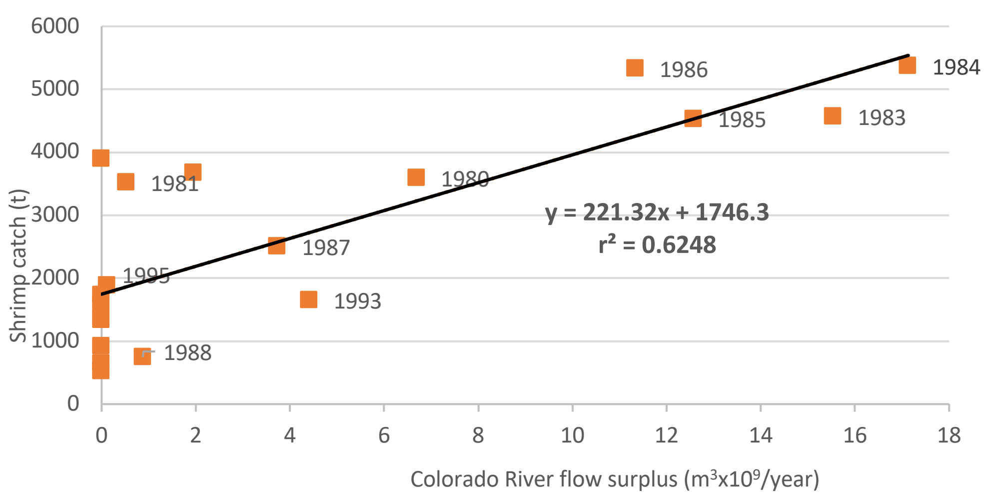


Source: Prepared by the authors based on data provided by the National Fisheries Institute (n.d.).

Relation Colorado River Flow-Shrimp Catch

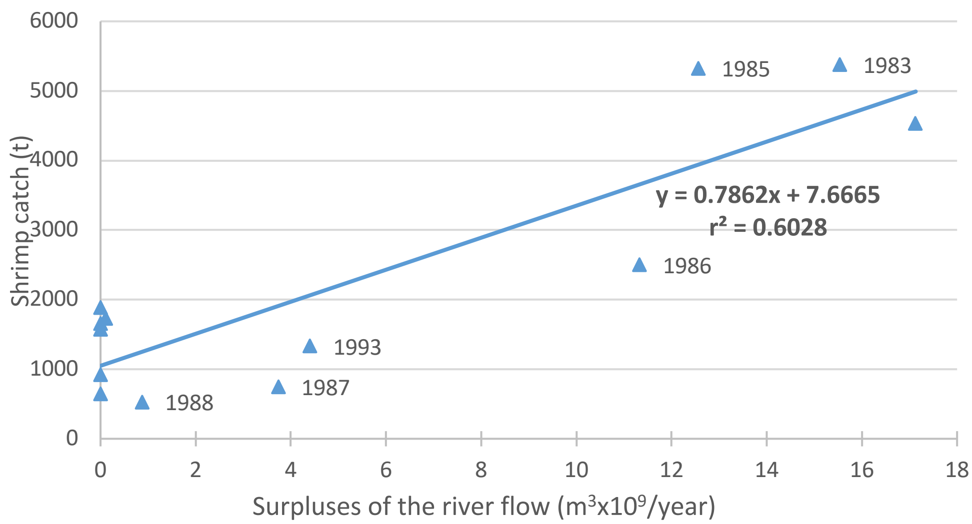
The coefficients of determination with a one-year lag ($r^2 = 0.624$) and two-year lag (0.602) show a direct correlation between the behavior of the river and the catch of shrimp disembarked in the UGC, with the highest catches in the eighties that are related to the greater surpluses of river water (graphs 4 and 5). This relationship is also evidenced when comparing CPUE and the shrimp catches disembarked in the UGC (graph 6).

Graph 4. Relationship between the catch of shrimp disembarked in the UGC and the surpluses of the Colorado River, considering a one-year lag



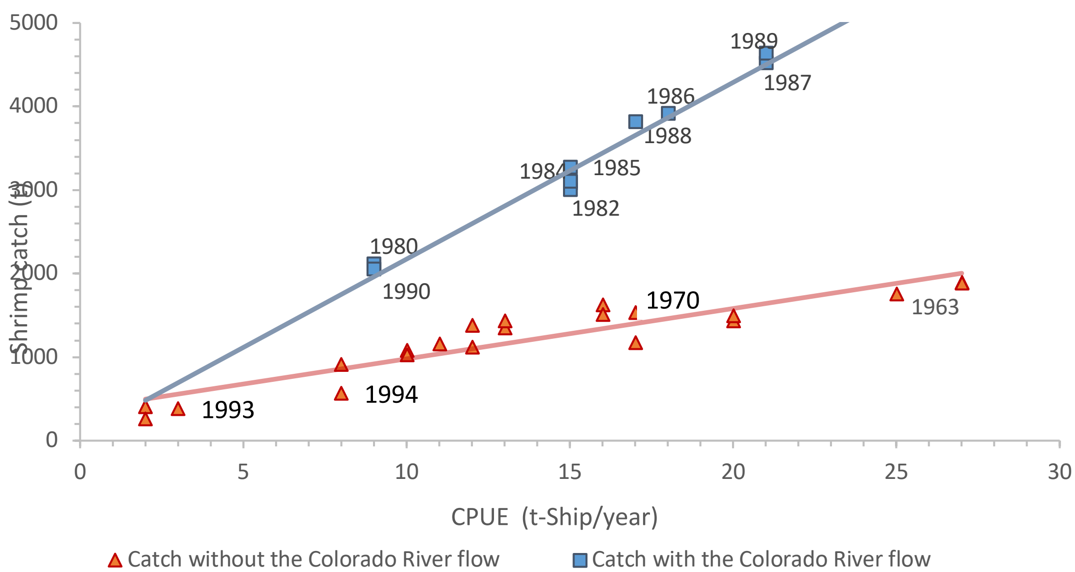
Source: Prepared by the authors based on data provided by the National Fisheries Institute (n.d.).

Graph 5. Relationship between shrimp catch disembarked in the UGC and the surpluses of the Colorado River, considering a two-years lag



Source: Prepared by the authors based on data provided by the National Fisheries Institute (n.d.).

Graph 6. Relationship between the catch per unit of effort and the catch of shrimp disembarked in Puerto Peñasco during the period 1962-1999



Source: Prepared by the authors based on data provided by the National Fisheries Institute (n.d.).

Nitrogen, phosphorus, and carbon balance

The calculation of nitrate and phosphate flows in Colorado River estuary from 1979-1989, showed that the river distributed significant amounts of these nutrients due to surpluses of 1,850 10^6 $m^3/year^{-1}$, reaching maximum values of 7,101 t $N/year^{-1}$ and 1,047 t $P/year^{-1}$ in 1984 (Table 1). Carbon fixation as a result of primary production according to the ratio 106C:16N:1P of Richards, Ketchum and Richards (1963) may have reached a maximum value of 40,344 t $C/year^{-1}$ in 1984 from the nitrates, or 43,034 t $C/year^{-1}$ from the phosphates, of which, if considered that a 10 % may have been transferred from the shrimp trophic level, then the shrimp catches may have increased to 4,000 $t/year^{-1}$ approximately above the usual catch in periods without water input (table 1 and graph 7).

Table 1. Carbon fixation estimates in the UGC from 30 µM of nitrate concentrates and 2 µM of phosphates diluted in the Colorado River surpluses (1979-1988)

Years	River flow m^3 /year (10^9)	Nitrate flow t/year	Phosphate flow t/year	Carbon t/year from nitrates	Carbon t/year from phosphates	10% Carbon t/year from nitrates	10% Carbon t/year from phosphates
1979	1.88	790	116	4,488	4,787	449	479
1980	6.55	2,752	406	15,636	16,679	1,563	1,668
1981	0.48	202	30	1,146	1,222	115	122
1982	0	0	0	0	0	0	0
1983	15.22	6387	941	36,286	38,705	3,629	3,871
1984	16.9	7,101	1,047	40,344	43,034	4,034	4,303
1985	12.4	5,210	768	29,601	31,575	2,960	3,158
1986	11.1	4,664	688	26,498	28,265	2,650	2,827
1987	3.69	1,551	229	8,809	9,396	881	940
1988	0.84	353	52	2,005	2,139	201	214

Source: Prepared by the authors based on field work and Cupul data (1994).

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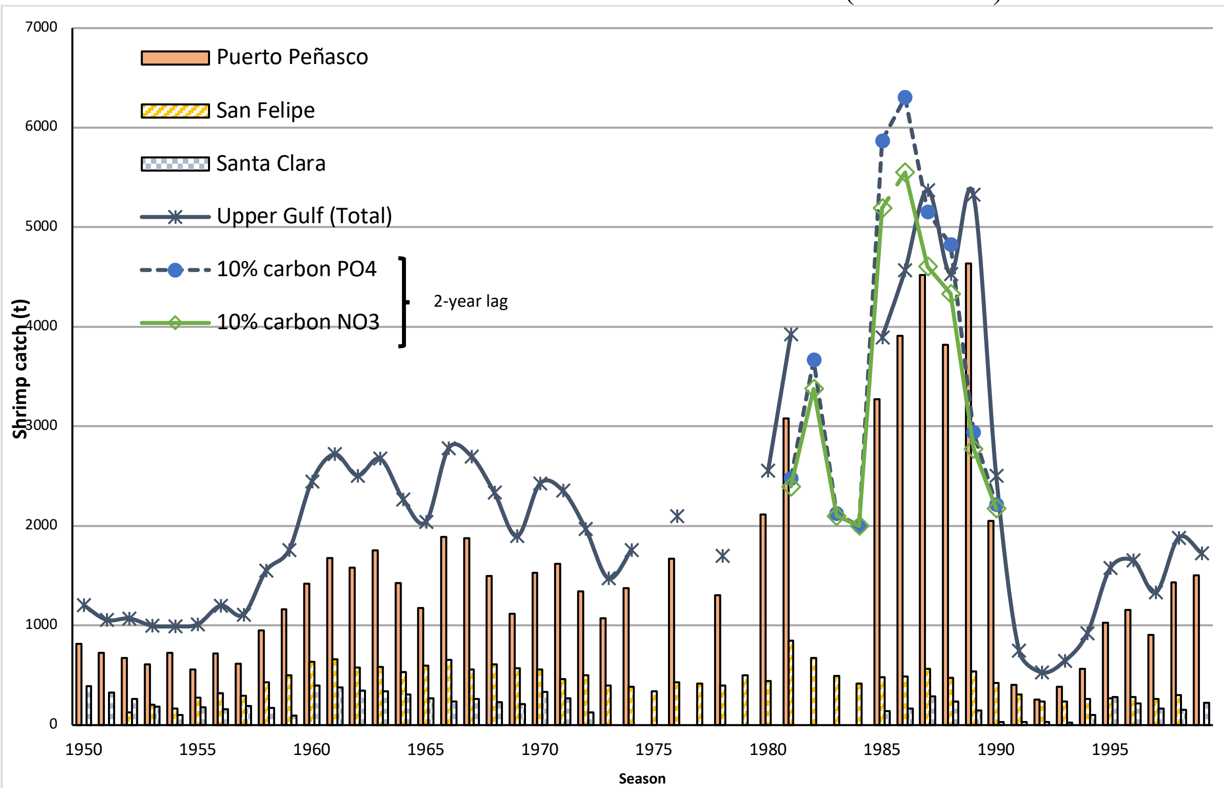
Graph 7. Comparison between the disembarked shrimp catch in the UGC and the estimated based on the Colorado River flow (1979-1988)



Source: Prepared by the authors based on field work and Cupul data (1994).

DISCUSSION

It has been commonly stipulated that the decrease in shrimp catching by the ships in the UGC are due to a problem of overfishing. However, this paper shows that the lack of freshwater in the Colorado River delta system is also a key factor which influences the marginal return on effort, since its damming has modified the estuarine conditions of the UGC.

The CPUE was established as a performance indicator of fishing input, in this case, the boats. This calculation is deemed adequate as it explains the proportionality between shrimp catch in the UGC based on the catches and the annual effort, considering a potential variability in the catchability factor due to technological changes of the period (Petrere, Giacomini, & de Marco Júnior, 2010).

The historical behavior of shrimp catches in the UGC showed fluctuations related to the periods with or without freshwater input from the river. In a descriptive analysis in the data set that comprises the time between the CPUE and the effort, we can observe two periods with different trends in terms of proportionality. Between 1950-1979, without freshwater input, the fishing effort showed a linear increase with 86 ships on average, by a range of 70 to 115 vessels, but the catch produced marginal to negative returns with an average volume of 1,856 t/year^{-1}. This indicates that in said period the CPUE and the effort are inversely proportional.

In the period from 1980-1989, there was freshwater input from the river to the estuary. The catches showed a linear increase beyond the 5,000 t/year^{-1} over the course of several years, while the number of ships remained stable and the CPUE increased.

In the following years, the situation changed drastically. In 1992 there was no flow of freshwater, having a direct impact upon the fishing industry and resulting in low yields in catches and the rapid decrease in the number of ships (effort) as a response to the drastic decrease in shrimp catch up to 529 tons per year. This is a relevant condition because of the direct and proportional relationship, which can be explained by considering that catches are directly related to effort, and effort is a main factor that reacts to yields. Therefore, when yields (CPUE) drop, effort tends to drop, and vice versa. This situation also reacts to the linear function correlation of costs and effort (Cunningham, Dunn, & Whithmarsh, 1985).

In analyzing the shrimp catch performance in a period without freshwater input from the river (1960-1979), increases in shrimp catch were observed two years after El Niño (ENSO) events from 1962-1963, 1965-1966, 1969-1970, 1972-1973 and 1997-1998, it is then likely that these increases are linked to freshwater input to the estuary due to high rainfall brought by the ENSO events and described by Pavía and Badán (1998). The biological response on the freshwater input from the rivers and ENSO events has also been applied in other places (Childers, Day Jr., & Muller, 1990; Del Valle & Martin, 1995; Mann & Lazier, 1996; Bect, 2000), which strengthened this study's hypothesis on the paramount importance of the Colorado River and the ENSO events on recruiting for shrimp farming and shrimp survival on its early stages, for them to be part of the adult shrimp population available for fishery.

The coefficients of determination $r^2 = 0.624$ ($p<0.05$) and $r^2 = 0.602$ ($p<0.05$) with a one-year and two-year lag between shrimp catches and the surpluses of the river from 1960-1999, showed that apparently the increase in the shrimp catches disembarked in the UGC from 1979-1988 was associated with the freshwater input to the estuary. However, the available information is very limited, since during the eighties, the input only lasted nine years, and in three of these years (from 1982 to 1984) there are no records of shrimp catch. For this reason, the obtained coefficients of determination are only limited to six figures. In other words, most of the data regarding shrimp catch has been obtained in the years without freshwater input from the river.

The biological response to the influence of the river up to a one-year or a two-year lag is explained by water accumulation in the Hardy River, the Laguna Salada and the Ciénaga de Santa Clara wetlands, filled with the sustained input of the river surpluses during nine years in the eighties. The freshwater accumulated in these wetlands and the large amount of particulate organic matter that should have reached the estuary in this period, improved the conditions in the farming area for at least two years after the completion of the surplus delivery. During these years, large stretches of wetlands were recovered, from 5,800 to over

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63,000 ha (Glenn, Lee, Felger, & Zengel, 1996), with its highest in 1983, when river surpluses were released 10 times more than the quota established through the International Treaty of Boundary and Waters in Mexico and the United States (equal to the average natural Flow of the river).

Browder, May, Rosenthal, Gosselink and Baumann (1989) applied a numerical model through satellite images to explain the decrease in brown shrimp catch disembarked in the Louisiana coast, directly connected to wetland loss. It is likely that, although shrimp catch behavior is related to the size of the farming area due to wetland loss, in reality, the explanation is much more complex and related to environmental factors like food supply, predation, osmotic transport and interchange as a result of temperature and salinity in the early stages of development. (Jian-Chu, Jin-Nien, Chung-Tin, & Min-Nan, 1996; Jian-Chu, & Jin-Nien, 1998).

The estuaries are identified as major trails of particulate and dissolved matter of continental origin entering the oceans (Pritchard & Schubel, 1981). River have been traditionally considered as an external source of inorganic nutrients dissolved in the coastal zone (Meybeck, 1982; Chester, 1990; Milliman, 1991). Nutrient concentrations dissolved in the marine environment is one of the key factors for phytoplankton production as a food source (Dugdale, Morel, Bricaud, & Wilkerson, 1989; Riley & Chester, 1989; Nixon, 1992; Snow, Adams, & Bate, 2000) and fishery production from estuaries is related to this primary production (Houde & Rutherford, 1993).

Hernández, Galindo, Flores and Alvarez (1993) reported nitrate concentrations up to 50µM in the Rio Colorado riverbed (20 km from the mouth) in a period without freshwater input (1989-1990). In addition, Cupul (1994), when studying nutrients from the estuary with freshwater input from the river in 1993, reported nitrate values at between 20 and 30µM to the north of Montague Island. Furthermore, he stated that the freshwater input led to a dilution in the nutrient concentration of the estuary, with the calculation of the net nutrient input in relation to the ebb and flow of the tides, nutrient concentrations in the estuary, the nutrient exportation during the period without freshwater input was significantly higher (7.9 times for NO_3+NO_2 and 1.9 times PO_4).

Considering the above, the estimate of nitrates and phosphates that may have reached the Colorado River delta from 1979 to 1989 (Table 1) shows that substantial amounts of these two nutrients that entered the estuary could increase the primary organic production through carbon fixation, according to the ratio 106C:16N:1P of Richards, Ketchum, and Richards (1963). This may have influenced the increase in the estuary's production capacity, as Houde and Rutherford (1993) mention when comparing the fish production in relation to primary organic productivity in ocean areas, coastal upwellings and estuaries in the US. These authors show that 10 % of primary organic productivity transfers to fish production. In consequence and considering this percentage, this research introduces the basis that 10 % of the estimated carbon transfers to the shrimp trophic level, therefore, we found that the tons of shrimp estimated in this research behave in a similar manner to the average catches during years without input from the river, so the freshwater input from the Colorado River from 1979 to 1988 ensured favorable conditions for the recovery of this fishery source (Graph 7).

Muñoz, Carriquiry, Nieto and Hernández (1999) measured the net metabolism of the Colorado River using data from the periods with input from the river in April 1993 and without input from the river in April of 1996. The reported nutrient flows were similar to those calculated in this research (Table 1). The authors estimated that the residence time of water in the delta decreases from 31 to 15 days with and without the river's flow respectively, which favors the nutrients advection and interchange to the UGC. Additionally, they say that the system salinity decreases from 36.65 psu to 22.8 psu with and without the river's flow respectively, which favors the ecological functioning of the delta by restoring the estuarine conditions, increasing the primary organic productivity, and favoring the formation of a saline barrier that prevents the entrance of oceanic predators. These conditions increase the shrimp survival in early stages of development and other ecologically and commercially important species, which is reflected in the recovery of fishery activities.

Millán, Santamaría del Ángel, Cajal and Barocio (1999) mentioned significant differences in the primary organic productivity in the Colorado River estuary over the annual cycle August 1989 to June 1990, with decreasing levels: from 14 $mgCm^{-3}h^{-1}$ in August 1989 to 6.4 $mgCm^{-3}h^{-1}$ in February 1990, 3.2 $mgCm^{-3}h^{-1}$ in April 1990 and 0.5 $mgCm^{-3}h^{-1}$ in June 1990. The decrease in productivity values is evident from summer 1989 to summer 1990 (14 to 0.5 $mgCm^{-3}h^{-1}$ respectively). This kind of variations in food supply is probably part of the mechanisms that support the shrimp biomass, and it is reflected in the disembarked commercial catch in the UGC. By comparing shrimp catches from 1989 and 1990, the highest and the lowest catches respectively in the history of this fishery could be observed. This slump is in line with the primary organic productivity decrease mentioned by the aforementioned authors.

While in 1993 surpluses of water from the river entered similarly to those in 1980 ($>5,000x10^6\ m^3/year^{-1}$), the impact in commercial shrimp catch was not reflected in the same way in both years. The factor associated with shrimp catch decrease after 1990 may be linked to the shrimp population health since in 1990 the presence of IHHNV (Infectious Hypodermal and Hematopoietic Necrosis Virus) was registered in wild populations of the UGC (Lightner, Williams, Bell, Redman, & Perez, 1992; Pantoja, 1993). However, the virus impact on the ocean's food chain is unknown since, although nutrients availability is not limiting in the UGC and the Colorado River estuary, the primary organic productivity decrease noted by Millán, Santamaría del Ángel, Cajal and Barocio (1999) may be related to this problem.

The viral illnesses in shrimp farms along Sonora and Sinaloa coasts is a widely known issue, yet poorly documented. Until 1987 the northwest shrimp farming areas were free of IHHNV, but in that same year, white shrimp post larvae (*Penaesu vannamei*) were carried

https://doi.org/10.33679/rfn.v1i1.2137

from the United States to Mexico, specifically to the states of Baja California Sur and Sinaloa, for the purpose of scientific experimentation. Three years later, in 1990, all farms and laboratories in the coast of Sonora were infected with IHHNV.

The virus that infects farms is likely to be released to the natural environment during the daily water replacement, being this the infection channel in wild shrimp populations. The presence and distribution of this virus in wild populations of the UGC has not been well documented since there are records only of some isolated samples in the northern and central parts of the Gulf of California (Unzueta, Holtschmit, Olivas, Martínez, Porchas, & Lizárraga, 1998).

Pantoja (1993) collected shrimp samples from 39 localities along the Gulf of California, six of these from the UGC: 15 in the north Gulf but south from Puerto Peñasco, and 18 in the south Gulf. The results showed a widespread distribution of the virus, with an infection rate ranging between 23 and 100 per cent of the analyzed samples for the UGC.

CONCLUSIONS

Freshwater flow restrictions from the Colorado River to the delta in the Gulf of California were shown to impact shrimp catch volumes. With the stimulus produced by the freshwater input to the Colorado River estuary, the shrimp catch disembarked in the UGC more than doubled in the 1979-1988 period.

River water flow has also been shown to provide nutrients to the delta, representing food availability and contributions to trophic chains.

The more than double increase in shrimp production in the 1979-1988 period was favored by the contributions of nutrients, the formation of estuarine conditions to protect against predation and by the increase in the size of the nursery area during the flooding of the wetlands of the Hardy river, the Laguna Salada and the Ciénega de Santa Clara. This further indicates the possible relationship between water flows and biodiversity in wetlands and estuaries.

Starting in 1989, freshwater flows were restricted to the Colorado River delta, which influenced the catch volumes in the period 1990-1993. This impacted the fishing effort, which decreased notably from 1992 to 1994.

The historical behavior of the shrimp catches in the UGC resulted mainly from the periods with and without freshwater input, rather than the behavior of the fishing effort. The shrimp catch increased the year after the El Niño events, except for the one that occurred in 1972-1973; however, all of them resulted from the behavior of rainfall. The modifications and alterations in the delta have in turn altered the salinity conditions, impacting the spawning and breeding areas of species, in addition to generating conditions that favor the introduction of marine species that act as predators.

The transborder river context and the pattern of water demand for human activities in the border states in Mexico and the United States indicate that the pressure for the use of water from the Colorado River in the future will increase and complex water management and allocation systems will be created. Unfortunately, there is no evidence that the river delta ecosystem is considered in these future management schemes and therefore the environmental and socioeconomic prospects in the UGC region are not favorable.

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