RESPONSE OF THE SHRIMP POPULATION IN THE UPPER GULF OF CALIFORNIA TO FLUCTUATIONS IN DISCHARGES OF THE COLORADO RIVER

BY

ESTEBAN M. PÉREZ-ARVIZU[1]), E. ALBERTO ARAGÓN-NORIEGA[2,3]) and LETICIA ESPINOSA CARREON[1])

[1]) Centro Interdisciplinario de Investigación para el Desarrollo Integral Regional, Unidad Sinaloa, Blvd Juan de Dios Batiz Paredes # 250, Guasave, Sinaloa 81101, Mexico

[2]) Centro de Investigaciones Biológicas del Noroeste, Unidad Sonora, Km 2.35 Camino al Tular, Estero de Bacochibampo, Guaymas, Sonora 85454, Mexico

ABSTRACT

Since 1935, the freshwater discharge from the Colorado River into the Gulf of California has decreased drastically, affecting the biological cycles of endemic species and other endangered species. In this study, a relationship was determined between the Colorado River freshwater discharge, the abundance of blue shrimp, *Litopenaeus stylirostris* (Stimpson, 1874) postlarvae, and the density of adult shrimp in the Upper Gulf of California (UGC). Data on Colorado River flow from 1904 to 2002, blue shrimp postlarvae from 1993 to 1997, and records of daily catches from pangas (small boats) of the commercial fleet operating in UGC from 1995 to 2002, were analysed. Catch per unit effort (CPUE) was used as a measure of the average daily density of adult shrimp. Two groups of CPUE and postlarvae abundance were found, with significant differences between them. The highest population density was observed in the years when the river flow was greater than 80 m^3s^{-1}. The lowest density was found for periods when the river flow was lower than 80 m^3s^{-1}. We conclude that the response of the shrimp population is non-linear and that postlarvae abundance and commercial fleet CPUE increased during the years in which freshwater discharge was highest, possibly because the habitat volume increased, consequently resulting in increased food availability for the shrimp.

RESUMEN

A partir del año de 1935, las descargas de agua dulce del Río Colorado al Golfo de California han disminuido drásticamente, afectando el ciclo biológico de especies endémicas y otras en peligro de extinción. En este estudio, se determinó una relación entre la descarga de agua dulce del Río Colorado, la abundancia de postlarva de camarón azul *Litopenaeus stylirostris* (Stimpson, 1874) y la densidad de adultos de camarón en el Alto Golfo de California (AGC). Se utilizó información del

[3]) Fax: +52.6222212238; e-mail: aaragon04@cibnor.mx

Crustaceana 82 (5): 615-625
Also available online: www.brill.nl/cr
DOI:10.1163/156854009X404789

flujo del Río Colorado de 1904 a 2002, de postlarva de camarón azul de 1993-1997 y los registros de captura diaria de las pangas de la flota comercial que operó en el AGC de 1995 a 2002. Como medida de densidad promedio diario de los adultos se utilizó la captura por unidad de esfuerzo (CPUE). Se encontraron dos grupos de abundancia de postlarva y CPUE, con diferencias significativas entre ellos. El valor superior se presenta en los años cuando el flujo del río fue mayor que 80 m^3s^{-1}. El grupo del valor inferior se presentó cuando el flujo del río estaba a menos de 80 m^3s^{-1}. Se concluyó que la respuesta de la población de camarón no es lineal y que la abundancia de postlarva y la CPUE de la flota comercial aumentaron en años cuando la descarga de agua dulce era mayor, posiblemente porque se expandió el volumen del hábitat y con esto hubo una mayor disponibilidad de alimento.

INTRODUCTION

The largest river to cross a desert in the Western Hemisphere, the Colorado River, has been severely altered by 70 years of intensive water use for agricultural, industrial, and urban needs in Mexico and the United States (fig. 1). As a consequence, vast riparian areas of wetlands and coastal ecosystems have been degraded, and the terminal area of the river, in Mexico, now comprises only 10% of its original area (Mexicano-Vargas, 2004). In the Upper Gulf of California, widely known as one of the richest subtropical interior seas in the world (Álvarez-Borrego, 2001), the populations of fish, invertebrates, and marine mammals have been negatively affected, and ecological processes in the coastal marine area have changed substantially (Álvarez-Borrego, 2001).

The collective value of these terrestrial, riparian, intertidal, and coastal habitats has been acknowledged in many ways. For example, in 1993 the Mexican government began to protect these habitats by establishing 934 700 hectares as a reserve called the Biosphere Reserve of the Upper Gulf of California and Delta of the Colorado River, RBAGCDRC (Diario Oficial, 1993).

This project represents an opportunity for the restoration of the delta, since with relatively modest freshwater flows that are adequately managed, a considerable ecological recovery is possible (Mexicano-Vargas, 2004). Although important information has been generated on the ecological processes of the delta and the Upper Gulf, the responses of species to changes in the water flow of the Colorado River have not been documented. The population of shrimp that inhabits the Upper Gulf of California represents one life form that has experienced the most significant changes due to alterations in the freshwater flow in this marine system (Aragón-Noriega & Calderón-Aguilera, 2000; Galindo-Bect, 2003).

Galindo-Bect et al. (2000) concluded that the relationship between freshwater discharge from the Colorado River and shrimp catch was linear. However, Aragón-Noriega & García-Juárez (2002) suggested that the abundance of shrimp postlarvae may decrease dramatically after freshwater discharge falls below a certain threshold. Gracia (1989) found a bell-shaped distribution for the abundance of

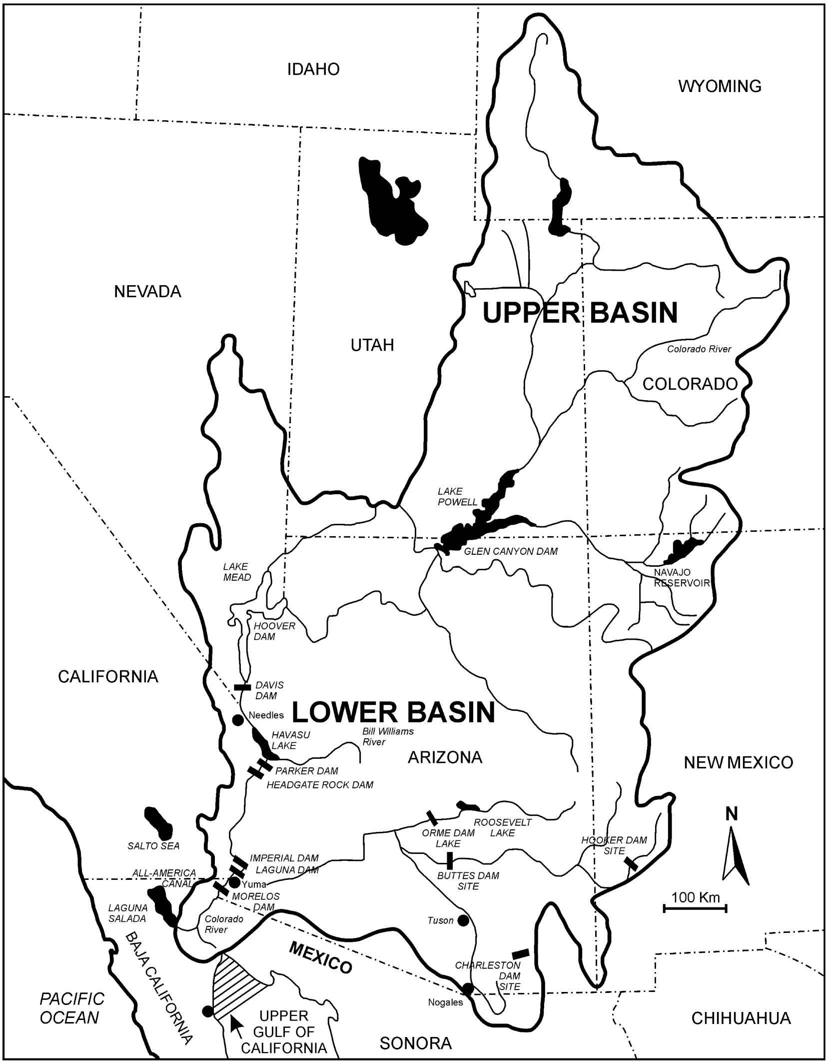

Fig. 1. Colorado River basin, showing the dams.

the shrimp, *Litopenaeus setiferus* (Linnaeus, 1767) in Campeche Sound, coinciding with the Palizada River flows, and concluded that an excess of river discharge into the estuarine environment causes a decrease in the population. This was also hypothesized by Penn & Caputi (1986), but they maintained that the decrease in abundance occurred due to freshwater discharge resulting from disastrous events (cyclones). Both studies support the hypothesis that there is a threshold of optimum environmental conditions for freshwater discharge into the ocean, that is necessary for a population to respond favourably. Once this threshold is exceeded, the population response is negative.

To appropriately document the response of the population of shrimp that live in the Upper Gulf of California to fluctuations in Colorado River freshwater discharge, it is necessary to consider that shrimp catch is unloaded at three main ports: San Felipe (Baja California), and Santa Clara and Puerto Peñasco (Sonora). Due to the area of influence of the Colorado River, only the catches at Santa Clara were used (Aragón-Noriega, 2000).

The objective of this work was to describe the effects of freshwater discharge into the Colorado River delta on the resident population of shrimp, thus broadening the series of data presented by Aragón-Noriega & García-Juárez (2002). We also aimed to further elaborate the initial observations by Galindo-Bect et al. (2000), who published data on a shrimp population inhabiting an area outside the influence of the Colorado River.

MATERIAL AND METHODS

Shrimp postlarvae, almost exclusively *Litopenaeus stylirostris* (Stimpson, 1874) are included in a database generated from 1993 to 1997 through the collective efforts of various researchers; this dataset is used to describe the ecological trends in shrimp populations. The present study utilizes these data to illustrate the effects of Colorado River discharges on the population of shrimp during the postlarval stage. Postlarvae collection was conducted in the channels of Santa Clara (Sonora) and San Felipe (Baja California).

For the purpose of determining if the impact of Colorado River freshwater discharges is also reflected in a greater commercial shrimp catch, records on commercial catches in the Gulf of Santa Clara were obtained. Unlike at other localities (e.g., south of Sonora and Sinaloa), in the UGC artisanal fishing is practised in coastal areas. Data were obtained from the fishing offices of the former SEMARNAP (Secretariat of Environment, Natural Resources and Fisheries) and the current SAGARPA (Ministry of Agriculture, Livestock, Rural Development, Fisheries and Food) at each locality. Artisanal fishing is limited by the cost of the distance fishermen have to travel, so it is limited to areas neighbouring the landing port; this type of fishing is conducted in areas less than 20 m deep. The area covered by artisanal fishers lies exclusively within the UGC. Notably, 97% of the catch from artisanal fishing consists of blue shrimp.

Catch data were obtained for 1995 to 2002. For the purpose of obtaining a more accurate measurement of catch per unit of effort (CPUE), access to daily records of plant deliveries was requested from the two oldest cooperatives, which have the largest number of partners in the village of the Gulf of Santa Clara. With this advantage, more reliable data were obtained on CPUE. Although some cooperatives report to the SAGARPA a catch volume that is purportedly obtained only by officially registered pangas, the daily record per panga is the index that determines payments from the cooperatives to each partner.

Data on the Colorado River outflow were obtained from the Bureau of Reclamation in Yuma, Arizona, U.S.A. These data are from 1904 to 2000. Data on freshwater flow from the Morelos Dam from 1995 to 2003 were obtained at the office of the International Boundary and Water Commission (IBWC).

For the comparison of postlarvae abundance (PL) among years, the data were expressed as PLm^{-3}. This measure was obtained by dividing the number of postlarvae caught by the volume of water filtered in each sample. Abundance expressed in PLm^{-3} was standardized to Z values, using the following equation:

$$Z \text{ value} = (X_i - X_p)/S,$$

where X_i is abundance at the i-th trawling, X_p is the average abundance of all the samples, and S is the standard deviation of the samplings (Zar, 1996). Standardized postlarvae relative abundance was compared to the outflow of the river.

Total catch was correlated with river flow within years and then catch was compared to river flow from the previous year. Catch per unit of effort (CPUE) was defined as kg/trip (each trip lasted one day). An average CPUE was calculated for each year of fishing and an ANOVA was applied to determine whether differences existed among years. A Least Squares Difference (LSD) test was applied to determine during which years there was a difference.

A linear equation and a polynomial equation were applied to the data to obtain the best fit. The least sum of squares criterion was used to obtain the appropriate adjustment of the equation.

RESULTS

The analysis of the Colorado River freshwater discharges into the delta of the Upper Gulf of California is made up of two distinct periods. The first occurred before the filling of the Hoover Dam began in 1935, and the second period extended from 1935 to the present (fig. 2). During periods of intense rainfall, mainly during El Niño events and mountain thaws in the United States, flow increased due to the venting of dams built upstream. It was determined that the river water flow exhibited seasonal behaviour for the period 1904-1934, with maximum flow occurring in June. The next greatest discharge months were May and July (fig. 3). Outflow volumes for these months exceeded 1000 m^3s^{-1}. For 1935-1997, it was observed that river flow did not vary significantly during any month of the year and that the average monthly volume did not exceed 200 m^3s^{-1}.

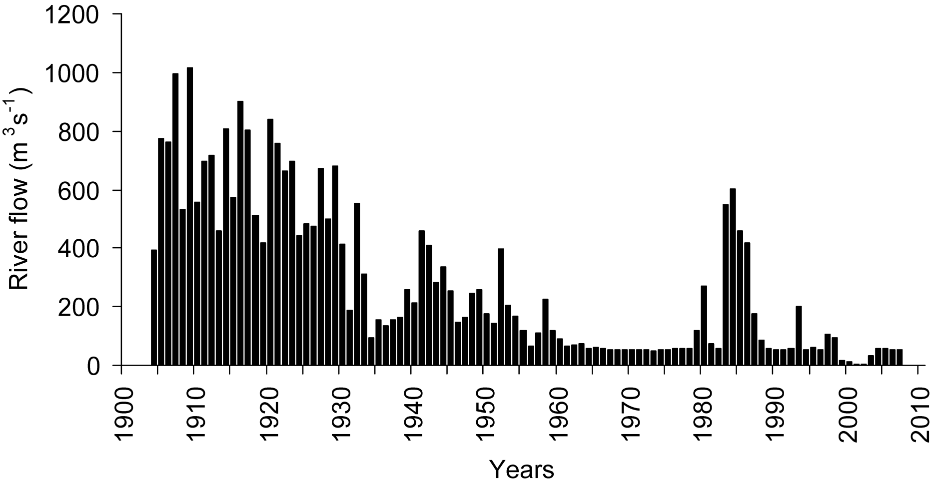

Fig. 2. Annual average Colorado River flow crossing the United States-Mexico border from 1904 to 1998. [Source: Bureau of Reclamation in Yuma, Arizona, United States.]

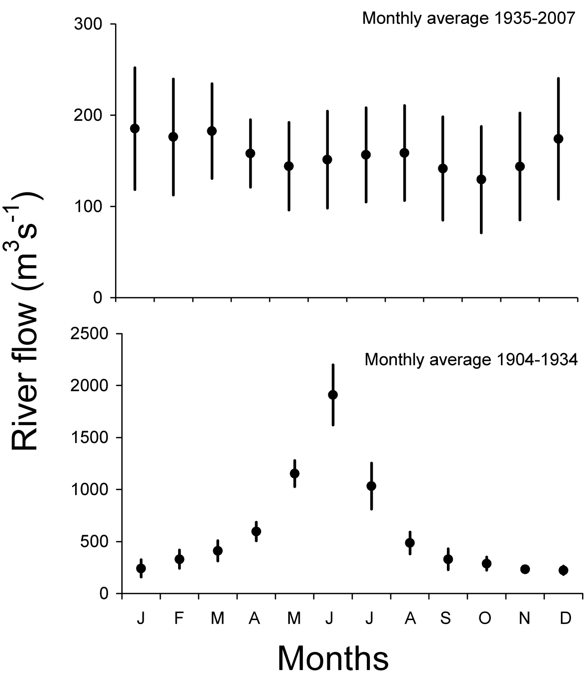

Fig. 3. Monthly average outflow values of the Colorado River for the periods prior to (1904-1934) and after (1935-1997) the construction of the Hoover Dam. The bars represent the standard deviation.

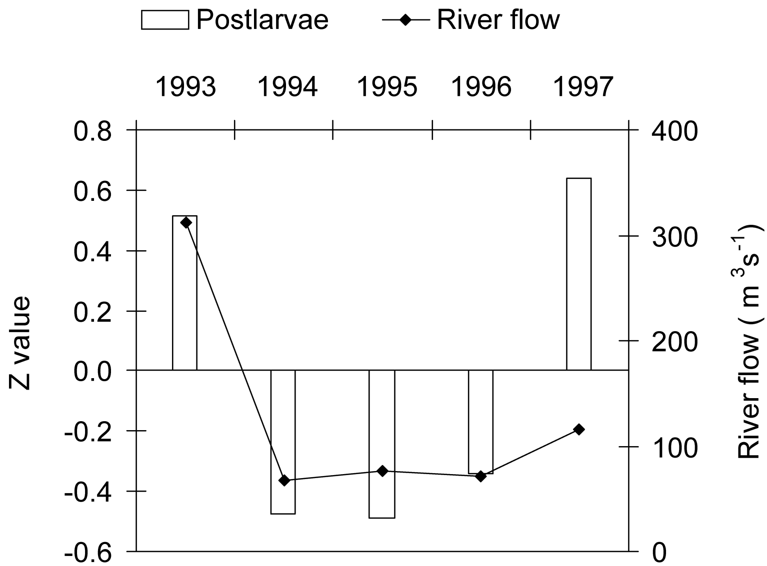

Fig. 4. Variation in standardized relative abundance (Z value) of blue shrimp, *Litopenaeus stylirostris* (Stimpson, 1874) postlarvae during the days of maximum recruitment, and the Colorado River outflow crossing the United States-Mexico border from 1993-1997.

Figure 4 shows that during the years in which the average river outflow exceeded 80 m^3s^{-1}, the Z value of *Litopenaeus stylirostris* postlarvae abundance was positive. However, under 80 m^3s^{-1} of outflow, the abundance was negative. While outflow in 1993 exceeded 300 m^3s^{-1}, the abundance was the same as in 1997 when outflow barely exceeded 80 m^3s^{-1}. We thus observed a non-linear relationship between postlarvae abundance and freshwater discharges from the Colorado River into the delta.

Artisanal fishing in the UGC is conducted yearly from September to December. Shrimp are occasionally unloaded in January but this represents less than 1% of the season's total catch and this catch was therefore excluded from the analysis. The river outflow measurements that were used in this study correspond to the annual average of the monthly mean of water that flows out of the Morelos Dam; this is not necessarily the same amount that arrives at the mouth of the river, entering the marine environment.

Figure 5 shows a direct relationship between the discharge of the river and shrimp catch in the UGC area. When discharges from the river increase, there also is an increase in shrimp catch during the following season, except for 2002, when the catch rate increased but freshwater discharge did not.

The unusual trend in 2002 occurred when the fishing area was restricted to larger boats, and catches in 2002 and 2003 were supplemented with catch from areas that were not affected by Colorado River discharge. There was a relationship between

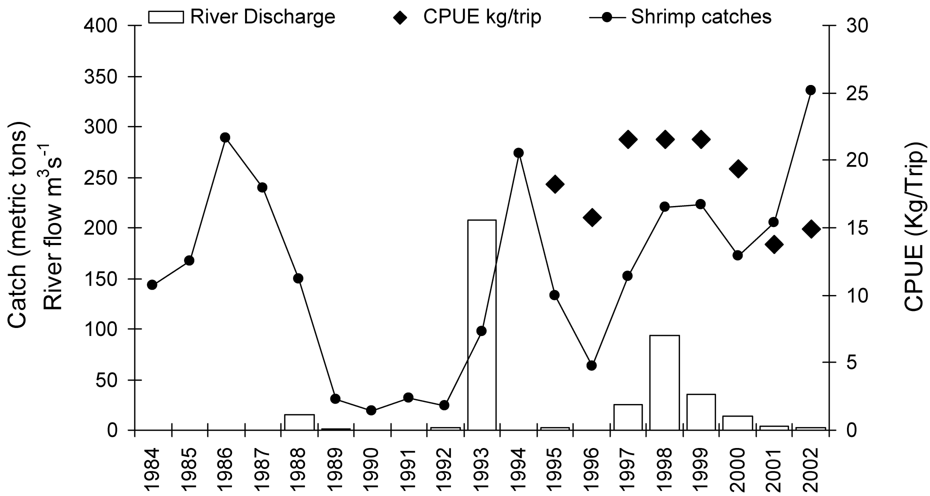

Fig. 5. Values of shrimp, *Litopenaeus stylirostris* (Stimpson, 1874) catch and catch per unit of effort (CPUE) landed by the artisanal fleet in Santa Clara (Sonora), and the Colorado River water flow crossing the Mexico-United States border.

catch in Santa Clara and the river flow each year, except for a one-year gap in the period 1993-2003. It was observed that the coefficient of determination was very low ($r^2 = 0.075$). In the one-year gap (1993-2001 period), the coefficient increased considerably ($r^2 = 0.4457$).

In contrast, CPUE follows the same pattern in relation to river discharge; that is, effort in catch remains proportional to fluctuations in Colorado River discharge. This phenomenon is related to the river flow with a simple linear regression and a polynomial equation (fig. 6). Using both equations, the coefficient of determination was calculated; it was higher for the polynomial equation ($r^2 = 0.793$) than for the linear equation ($r^2 = 0.4686$).

DISCUSSION

Freshwater discharge from the Colorado River most likely has two positive effects on the habitat for postlarvae in the UGC: increased load capacity through the addition of nutrients, and increased habitat area. This may result in postlarvae having more space for population growth and more nutrients available to them. Cisneros-Mata et al. (1995) concluded that this same effect takes place with juveniles of *Totoaba macdonaldi* (Gilbert, 1890) (Pisces, Sciaenidae) that use the UGC as a breeding area.

The relationship between relative abundance and river outflow is non-linear. Although discharge increased two-fold, abundance did not increase proportionally.

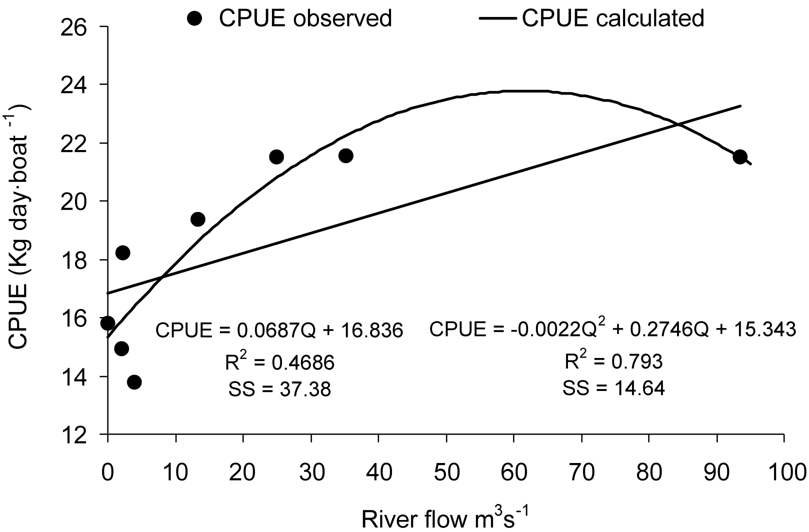

Fig. 6. Relationship between CPUE of *Litopenaeus stylirostris* (Stimpson, 1874) of the artisanal fleet of the Gulf of Santa Clara, and the flow of the Colorado River during the period 1993-2003. CPUE was estimated using linear and polynomial equations. SS indicates the sum of squares in each equation.

The data indicate that a limit of 100 m^3s^{-1} of freshwater flow is necessary to promote shrimp breeding conditions. Although this flow does not travel directly to the sea, it serves as an indicator. After this water level reaches the Morelos Dam, the dam sends water discharge to the sea, thus increasing the area (Mexicano-Vargas, 2004) of habitat available to postlarvae; this also results in more food and shelter being available.

The total catch apparently has a linear relationship with river outflow. However, CPUE does not exhibit this linear relationship. Total catch is affected by variations in effort and it is also possible that an increase in catch is more closely related to an increase in effort than to increased resource abundance.

CPUE may be used as an indicator of abundance (Hilborn & Walters, 1992; Sparre & Venema, 1995). Acknowledging that actual total effort is difficult to quantify due to the high rate of poaching that this type of fishery involves, catch per trip (kg/trip) is accepted as an accurate representation of CPUE. In this work, data were obtained on real trips conducted by pangas in the Gulf of Santa Clara. We found that relative blue shrimp abundance was higher during years in which the river outflow was greater than 100 m^3s^{-1}.

In other places, and for different species of penaeid shrimp, it has been reported that there is an increase in catch when there is an increase in river outflow providing fresh water to fishing and breeding areas (Penn & Caputi, 1986; Del Valle, 1989; Gracia, 1989, 1991). Remarkably, the CPUE obtained in this study for *Litopenaeus* *stylirostris* in the UGC also increased with an increase in Colorado River outflow, but instead of following a linear relationship, the data revealed a threshold in which environmental conditions regulate population abundance; this is in turn regulated by biological conditions.

The results of Gracia (1989) and Penn & Caputi (1986) support the findings of this work in identifying a threshold of optimal environmental conditions related to river discharge. However, one caveat remains: in this work, there are no data on a freshwater discharge so large that a decrease was observed in the blue shrimp population.

It is important to highlight that the fishing area that is influenced by the Colorado River is not entirely within the UGC. In this study, it was necessary to discriminate among the data from different fishing areas, especially for 2002 and 2003. In these years, the buffer zone was closed to boat fishing, and this caused an invasion by small boats into other fishing areas not influenced by the river. Nevertheless, by considering only CPUE in the "traditional" fishing area, it was possible to observe that population abundance does respond to variations in Colorado River freshwater discharge.

Finally, we conclude that the freshwater input from the Colorado River has a positive effect on postlarvae relative abundance, and thus on the commercial shrimp catch in the Upper Gulf of California.

ACKNOWLEDGMENTS

EMPA thanks CONACYT (grant 216235) and IPN-PIFI (grant B071625 and 2008 0462) for scholarship during his graduate studies. EAAN received financial support from CIBNOR contract EP 5.2.

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First received 27 June 2008.
Final version accepted 19 August 2008.