

# ENVIRONMENTAL ASSESSMENT

## Colorado River Floods, Droughts, and Shrimp Fishing in the Upper Gulf of California, Mexico

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**ABSTRACT** / Accurate procedures that measure hydrologic variability would have great value for evaluating ecosystem impacts of upstream water use in the Colorado River Basin. Many local extractive income-based stakeholders rely directly or indirectly on ecosystem health and are adversely affected when the river does not flow. This study focuses on the impact of little or no Colorado River flow on the Mexican shrimp industry. Although there have been complaints that U.S. diversions of Colorado River flow have greatly impaired the shrimp fishery, this research demonstrates that freshwater rarely reaches the Gulf even

during times of flooding, and that other factors such as overfishing may influence the instability of shrimp populations. Advanced very-high-resolution radiometer (AVHRR) satellite imagery was used to assess water volumes diverted away from the channel of the Colorado River and ultimately the Gulf of California during flooding periods. Analysis of data demonstrated that little freshwater actually reaches the Gulf even during floods because of its diversion into a large dry lake bed basin known as Laguna Salada. Fuller use of the Colorado River throughout its entire course to the sea is possible and could benefit a large cohort of users without catastrophic habitat destruction in delta ecosystems. Reconstruction of a natural earthen berm, as proposed by Ducks Unlimited, would maximize the use of floodwaters for ecosystem benefits. These findings have profound implications for local economic activities dependent on hydrologic resources in the Colorado River Delta and Upper Gulf.

Water management is one of the most controversial of issues facing policymakers in arid regions (Getches 1993). Accurate information on ecosystem impacts resulting from diversion of the Colorado River is essential for making informed decisions on use of the resource by stakeholders in the area (Pontius 1997). Previous research examined regulatory aspects and endangered species (J. All unpublished) as well as the biophysical parameters in the Colorado River Delta (All and Yool 2004). The current research examined the quantity and impact of U.S.-released floodwaters on the Upper Gulf- and Delta-based economic systems, primarily fisheries, that depend on ecosystem health. These impacts also are felt indirectly by farmers, subsistence extractors, and ecotourism operators.

Local residents have long been vulnerable to disruptions in the Gulf ecosystem, which occur during both flood and drought (McGuire and Greenberg

1993). Mexican shrimp fishermen have asserted that U.S. diversions of Colorado River water have depleted the Upper Gulf of its vitality, compromising the shrimp fishery (Bagwell 1998; Tobin 2001), whereas many local fishermen and researchers have asserted that freshwater floods enhance shrimp fisheries (Galindo-Bect and others 2000; Postel and others 1998). There is general scientific support for this belief (i.e., that salinity gradients are crucial for habitat determination), and juvenile protection from predators in estuarine systems is well documented (Jassby and others 1995). However, the results described in this report show that even during flood events, since 1983, little Colorado River water actually reaches the Gulf, but instead flows into a closed evaporative basin below sea level known as Laguna Salada. Shrimp populations in the Gulf also are influenced by annual catch rates related to the size of the fishing fleet (McGuire and Valdez-Gardea 1997). Because there is limited effective domestic or international regulation of shrimp harvest in the region, it is argued that relative shrimp abundance is related inversely to the size of the fishing fleet (Vasquez-Leon and McGuire 1993).

Wildlife inhabiting the Gulf is not the only group adversely impacted by the lack of Colorado River flows. As Laguna Salada increases in area during flood flows,

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Delta habitat also is correspondingly deprived of hydrologic resources. Laguna Salada acts as a freshwater sink, depleting the wildlife and endangered species habitat in the Rio Hardy wetlands. As wetland habitat is impaired because of Laguna Salada diversion, stress on certain endangered species such as the Yuma Clapper Rail (*Rallus longirostris yumanensis*) increases tremendously (Glenn and others 1996; Zengel and others 1995).

Laguna Salada was once a valuable fishery known as Lake Maquata (Orcutt 1891). However, years of "drought" after completion of the Hoover and Glen Canyon dams destroyed the Laguna Salada ecosystem completely as all water was impounded to fill the reservoirs. The brief resurgence of life in Laguna Salada following the 1983 El Nino flood (after the reservoirs were filled) was quelled quickly as the water evaporated (Jimenez and others 1984).

To determine freshwater impacts on the Gulf, it is important to assess the amount of water entering the Gulf during flood periods. Satellite imagery is an accurate and cost-effective tool for assessing the ecologic impact of floods in the region (All and Yool 2004; Glenn and others 1996). The actual amount of flow needed to restore a small area of endangered species habitat such as for the Colorado Delta Clam (*Mulinia coloradoensis*) at the mouth of the Colorado River is estimated to be very large (Flessa and others 2001). Restoration of the shrimp habitat would require a vastly larger volume of freshwater, and this is not likely to be released with the current pressures upon Southwestern water supplies.

## Background and Historical Perspective for the Region

The Colorado River Delta once was supplied by thousands of miles of watershed. Billions of cubic meters of water flowed annually from the interior of the Rocky Mountains to the Pacific Ocean. Since visits by Leopold (1949) and Sykes (1937), Delta ecosystem conditions have declined rapidly as upstream water from the Colorado River has been diverted for agricultural and urban users. Before the completion of Hoover Dam in 1935, the Delta received 16 to 18 billion cubic meters of water per year (Stockton and Jacoby 1976). Major impoundments caused first by Hoover Dam and then by Glen Canyon Dam desiccated the Delta. Except for a few limited occasions, no water flowed beyond Morelos Dam at the border in Mexico from 1958 until 1983 as the reservoirs filled, and all downstream riparian areas disappeared (Pitt and others 2000).

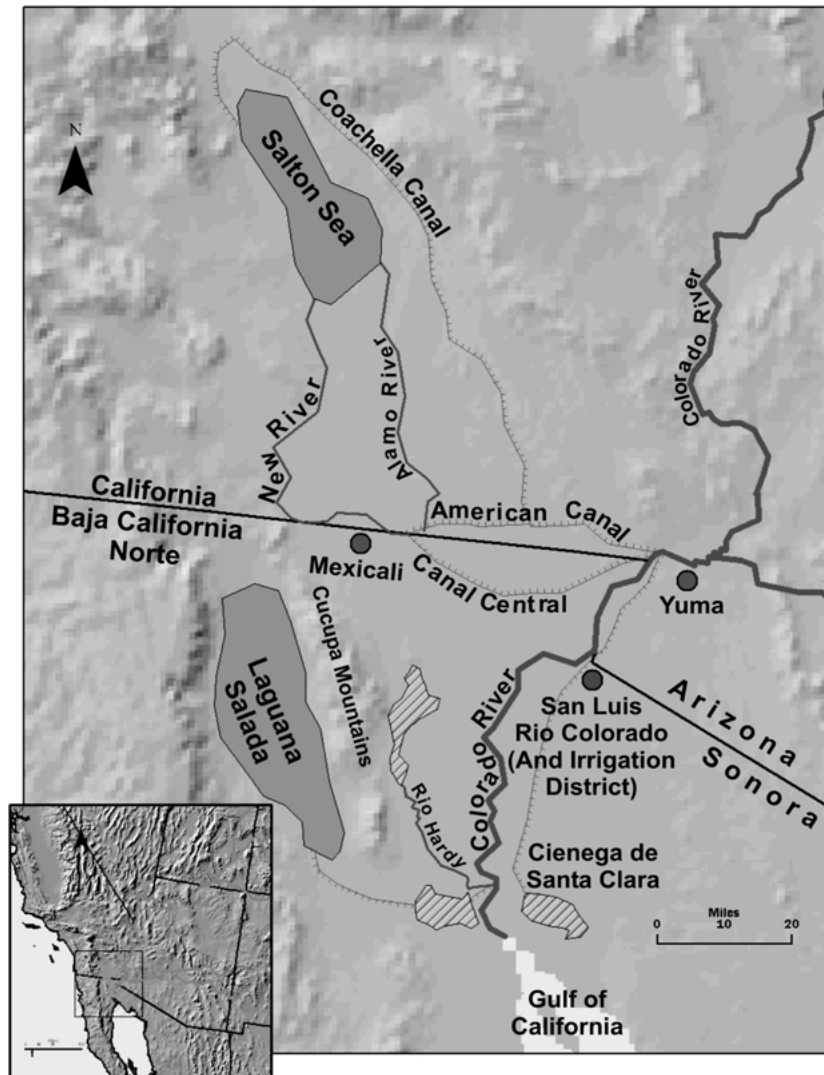
The former Delta currently comprises the Salton Sea and the agricultural areas of the Imperial Valley in the United States as well as the Mexicali Valley and San Luis Rio Colorado Irrigation Districts in Mexico (Briggs and Cornelius 1998; Figure 1). Much of the remnant functioning Delta and Upper Gulf is included within a Mexican Biosphere preserve because of its rare plants, birds, and other wildlife (SEMARNAT 2002; Zengel and others 1995). Hundreds of square miles of barren salt flats are found in the Laguna Salada area and near the Gulf shoreline (Glenn and others 1992). No information on the wildlife habitat in Laguna Salada has been recorded. Only a few hundred square kilometers in the Delta remain as ecologically functioning wetlands: most notably the Cienega de Santa Clara, fed from U.S. agricultural runoff, and the Rio Hardy wetland, which receives water during flood events (Glenn and others 1999; Zengel and others 1995). The Rio Hardy area is the homeland for a group of indigenous people, the Cucapa (Hays 1996).

In 1983, two hydrologic events occurred that created major flooding of the Colorado River. As a result, massive flows returned to the Delta and Gulf, reestablishing riparian vegetation in the Delta area (Holburt 1984). First, Lake Powell finished filling, and as a result, man-made diversion structures could no longer absorb major floods. Second, the largest El Nino event of the century (at that time) caused major rain and snowfall events that led to widespread flooding across the southwestern United States (Piechota and others 1997). Water managers, unprepared for the synergy of these two factors, were forced to allow great amounts of water to be released across the border to protect the dams from destruction (Holburt 1984). Later major El Nino flood events in 1993 and 1997 were better managed thanks to the lessons of the 1983 event, but large amounts of water still crossed the border.

Direct measurements of these flood flow volumes in Mexico do not exist. The United States Geological Survey collects extensive records on Colorado River flow, but these are limited to the territory of the United States, and there are no direct continuous measurements of Colorado River flow in Mexico south of the Southern International Boundary after 1968 (<http://water.usgs.gov/>; Cohen and others 2001). Flow patterns for this report were estimated indirectly using remotely sensed imagery, existing flow records, and field investigation.

In general, Colorado River floods normally occur in early April as snow melts in the Rocky Mountains and tropical storms move into the lower Colorado watershed (Redmond and Koch 1991). Massive flooding can occur when these two events coincide.

## The Colorado River Delta Area



Source: ESRI Data

Prepared by: Debra Kreitzer

**Figure 1.** The Colorado River delta. The Laguna Salada and Salton Sea are both basins below sea level. Delta wetlands are marked by grey hatching. From Environmental Systems Research Institute (ESRI) data.

Non-flood-managed peak flows usually occur in late April or May, after snowmelt but before agricultural diversions and usage during the summer months (Cohen and Henges-Jeck 2001). Numerous studies have demonstrated the relationship of El Niño events to increased precipitation and streamflow in the western United States (Andrade and Sellers 1988; Cayan 1996; Kahya and Dracup 1996; Kiladis and Diaz 1989).

### Economic Interests

People living in the Delta region are mainly fishermen, farmers, and workers employed in service indus-

tries for these professions (McGuire and Greenberg 1993). Most fishing income in the past was derived from the shrimp industry. Fishing is dependent on habitat quality, whereas farming relies strongly on availability of irrigation water. Human vulnerability to fluctuations in ecosystem productivity in these areas is pronounced for the Gulf fisheries (McGuire and Valdez-Gardea 1997). Local resource users are the most familiar with the physical realities of river flow and may be in the best position to note variability. Negative economic repercussions from extreme years, resulting from both floods and drought, are felt most directly by these individuals (Greenberg 1998).

Other activities such as tourism and subsistence extraction (notably among the Cucapa tribe) are similarly dependent on ecosystem health (Nijhuis 2000; Richardson and Carrier 1992). Ecotourism may become a factor in the regional economy, especially with the presence of several endangered bird species. However, for the foreseeable future there is no infrastructure or capital available, and ecotourism will remain a marginal part of the regional economy (Loomis 2001). There also is some subsistence extraction, notably among the Cucapa tribe, but the subsistence industry has very few practitioners and is fading in importance (Nijhuis 2000; Postel and others 1998).

There are costs and benefits of any water use. Tourism and commercial fishing, including shrimping and sport fishing, are extrinsic returns from a healthy aquatic ecosystem. This can be contrasted to agricultural and municipal uses of water, which may be viewed as intrinsic costs relative to the health of the ecosystem resulting from depletion of the resource. These are the criteria water managers consider in regulating hydrologic resources, and there are no zero values. The North American Free Trade Agreement (NAFTA) changed regional policies because irrigated agriculture became even more profitable than in the past because of increased demand for vegetable and fruit production (Organization for Economic Cooperation and Development 1997). When high-value crops are easier to sell, more are produced and greater amounts of irrigation water are required. Farms in the Delta have benefited in high-flow years from increased water supplies for irrigation. However, excess floodwater is effectively drained from the Rio Hardy wetlands and impounded in Laguna Salada to prevent farmland inundation. As a result, the ecosystem in the Delta and Gulf suffers from a lack of freshwater (Payne and others 1992).

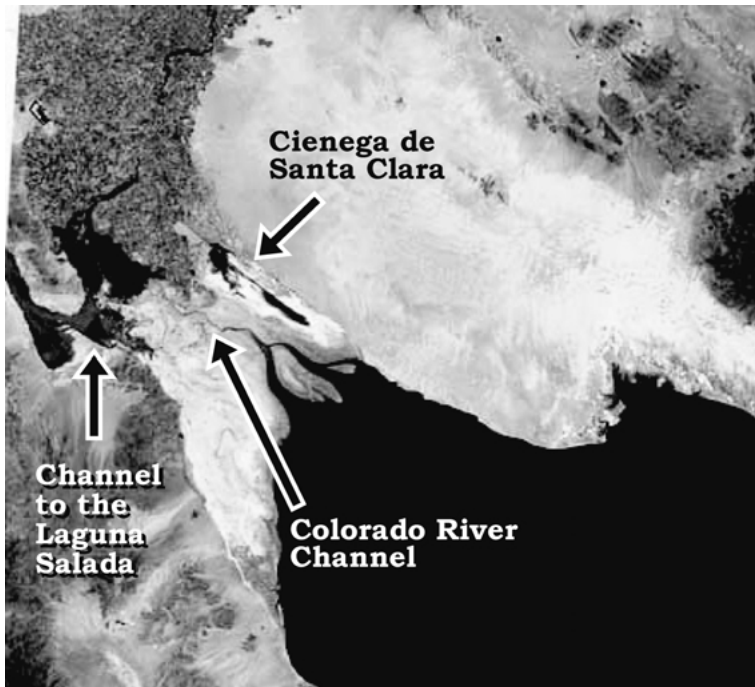
Agricultural irrigation currently dominates the water usage agenda in northern Mexico (Cummings and Nercissiantz 1992; Waller 1994). The Colorado River provides water to 500,000 acres of irrigated farmland in the Mexicali Valley via the Alamo Canal (Furnish and Ladman 1975) and the San Luis Rio Colorado Irrigation District (Holburt 1982). Farmers in the region are well organized politically so that regulatory changes relative to water usage are very difficult. Waller (1994) reported that plans drawn up by the rural Peoples Revolutionary Party to divert water from Mexicali farms for urban use in Baja California were undertaken to support urban growth and draw votes away from the urban political parties in 1990. However, to placate agricultural interests, President Salinas de Gortari had to concede hundreds of millions of pesos to increase

transport efficiency so that no farm fields lost any water. He also turned over control of the irrigation infrastructure to local interests in a significant, long-awaited reform. The interplay of politics thus delivers continued benefits to both the status quo and new users of water.

Farm management and investment decisions do not (and cannot) incorporate planning for floods, so excess water is not used in agriculture. Irrigation and diversion data for Morelos Dam and the San Luis Colorado River (SLRCID) indicate that these areas do not have the ability to exploit the massive excess water supplies of floods (All 1997; Cohen and Henges-Jeck 2001). Rather than allow potential floods to damage valuable farmland, water is drained from the Rio Hardy wetlands through a diversion to Laguna Salada and lost (Figure 2). The image in Figure 2 was taken in 1985 toward the end of the multiyear flood that began in 1983. It can be seen clearly that water is moving to the northwest toward Laguna Salada. Little or no water is in the channel southeast toward the sea. Floodwaters could be allowed to pond in the Rio Hardy marshlands and then flow into the sea to benefit both the Delta and the Gulf (Payne and others 1992) if it were not for farmers' fears of flooding.

The local fishing industry in the Gulf of California was dominated in the past by shrimping. Shrimp fishing is profitable and considered to be essentially immune to overfishing, according to Serge Garcia of the UN Food and Agriculture Organization (McGuire 2004). In 1983, Garcia theorized that because of the major interannual variability in the shrimp harvest and extremely high fecundity, shrimp populations generally are not dependent on fishing pressure, and that not until the fishing pressure reaches a "collapse level of effort" does the population begin to suffer more permanent impairment (Garcia 1983, as cited in McGuire 2004).

In the late 1970s and early 1980s, the shrimp catch collapsed (Delegacion Federal de Pesca 1993). Influenced by the overfishing immunity theory of the Food and Agriculture Organization, local fishermen and other observers concluded that the growing numbers of fishing boats were not responsible for the collapse of the fishery and that, instead, negative ecologic factors played a major role. When the shrimp catch rebounded a few years later after the 1983 El Nino event and subsequent flooding on the Colorado River, it was deduced that the lack of freshwater flows associated with the building of the Glen Canyon Dam had been the ecologic factor responsible for adversely affected shrimp biology and abundance (Bagwell 1998; Pontius 1997). Flooding in the early 1980s also coincided with



**Figure 2.** Landsat MSS satellite image from June 28, 1985. Water is flooding toward Laguna Salada to the northwest. The Colorado River channel in the southeast flowing toward the Gulf of California is nearly empty. The Cienega de Santa Clara is fed by an agricultural drainage canal from the United States. The area in the northwest corner is the San Luis Rio Colorado Irrigation District in Mexico. Source: Arizona Regional Image Archive.

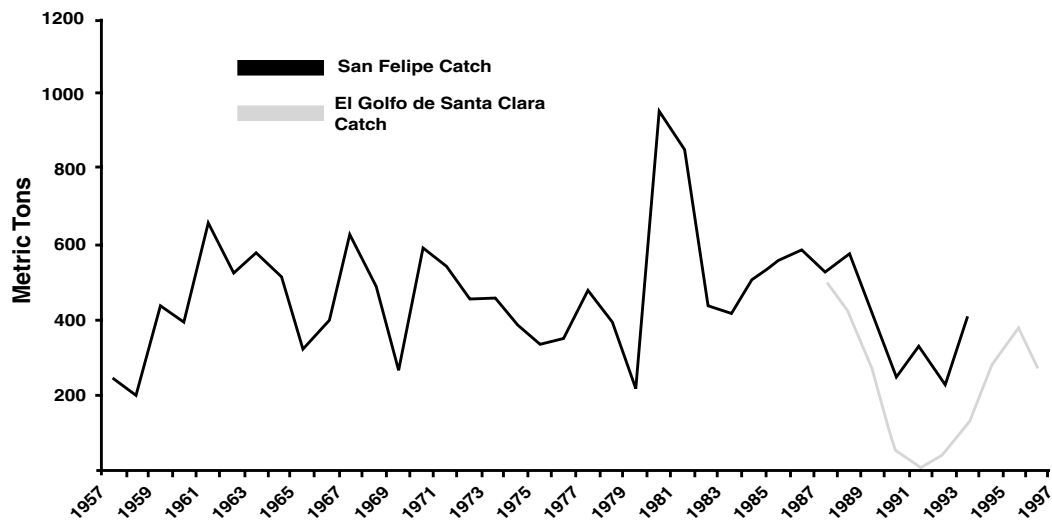


**Figure 3.** Offshore shrimp boats, Guaymas, Mexico, 1953–1990. The numbers dramatically increased in the 1970s. The shrimp populations collapsed, and this was followed by a sharp decline in the number of fishing boats in the 1980s. There was a rebound after the 1983 El Niño. Source: Delegacion Federal de Pasca.

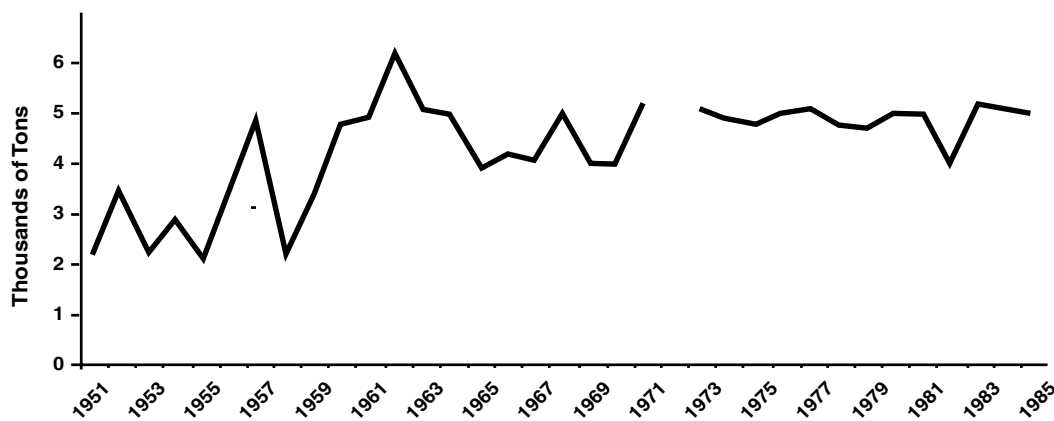
fewer numbers of shrimping boats in the area (Figure 3). The question whether declines in shrimp harvests were caused by overfishing or lack of freshwater flow (or by other unknown factors) is empirical, but both coincided with a drastic reduction in shrimp abundance. A combination of overfishing and impaired habitat is responsible for major shrimp harvest losses. The question becomes which has the greater impact? Despite the overfishing immunity theory, it is more likely that cession in fishing pressure was

responsible for the harvest rebound rather than the change in the ecosystem, which is demonstrated later to be less dynamic than generally assumed.

After the 1983 flood, fishing communities responded to their belief that freshwater enhancement stimulates shrimp populations by increasing investment and fishing effort (Figure 3). These investments are not reduced during average or drought years when no freshwater reaches the Gulf. Investment in boats, specialized gear, and other equipment required for



**Figure 4.** Shrimp harvest from the Upper Gulf of California in metric tons, 1957–1997. These data are from two ports in the Upper Gulf of California: San Felipe and El Golfo de Santa Clara. El Golfo lies within the Biosphere Reserve and had data available only from 1987 to 1997. There was a major decline in shrimp production in 1981 followed by a rebound in 1983. However, the rebound was below catch in previous decades. Source: Delegacion Federal de Pesca.



**Figure 5.** Shrimp catch in the Gulf of California in thousands of tons, 1950–1985. The catch is marked by high interannual variability. For the entire 35-year period, the early 1980s decline and rebound do not appear remarkable. The rebound in catch after the 1983 El Niño returns the catch to the same level as in the previous decade. Source: Magallon 1987.

shrimping is high (McGuire and Valdez-Gardea 1997). Typically, many years of fishing success are required for profit on investment to be achieved. Fishing intensity spirals upward during good years and cannot be retracted easily when fishing is poor.

During the early 1970s, the number of fishing boats increased dramatically until warnings about possible overfishing were offered (Vasquez-Leon and McGuire 1993). Economic hardships during the late 1970s and early 1980s led to a decline in the number of boats, and the reduced fishing intensity may have allowed shrimp populations to recover. Shrimp harvest data from San

Felipe and El Golfo de Santa Clara showed marked increases after El Niño events of the early 1980s (Figure 4) (Delegacion Federal de Pesca 1993; Magallon-Barajas 1987), but in fact the shrimp industry has been marked by great variability throughout its history (Figure 5). Establishing the validity of freshwater flows into the Gulf during floods would clarify whether freshwater enhancement conserves shrimp populations and better inform politics that would seek to divert freshwater for the purpose of enhancing shrimp yields.

Publicized demands for more freshwater stem from a local belief that freshwater inflows from the Colorado

River, such as during ENSO events, are crucial to the health of shrimp, fish populations, and ecosystem productivity (Bagwell 1998; Pontius 1997). Fishermen recall the “golden years” for the local fishery—before Glen Canyon Dam was built, (but also when there was a smaller fleet) and the flood events of 1983 and 1993 (McGuire and Greenberg 1993; McGuire and Valdez-Gardea 1997; Pontius 1998; Vasquez-Leon and McGuire 1993).

The preferred juvenile shrimp habitat in the Gulf is in the shallow estuary of the Colorado River’s mouth (Pico and Mathews 1975). Freshwater inflows lower salinity values in the Colorado River estuary and increase the difference between the most saline water and the least saline water (Lavin and Sanchez 1999). This creates an increased salinity gradient that benefits shrimp as they mature and inhibits predation (Zein-El-din and Renaud 1986). Studies in the San Francisco Bay have shown that salinity is driven primarily by freshwater inflows, with lesser impacts by vertical and lateral mixing and sea level heights (Peterson and others 1995). High dams on rivers have been shown to interfere with the life cycle of shrimp (Holmquist and others 1998).

El Nino events increase the primary productivity of the Gulf (Ruiz and Lyle 1992; Valdez-Holguin and Lara-Lara 1985). These benefits would be expected to reverberate upward through the trophic levels. Another possible beneficial impact of El Nino is increased nutrient loads carried in the silt or dissolved in the water carried by the Colorado River (Rodriguez and others 2001). Diversion structures in the upper Colorado have halted delivery of silt-rich water to the Delta and Gulf (Carriquiry and Sanchez 1999). Several authors have posited that loss of these nutrients has contributed to the decline in Gulf fisheries (cf. Postel and others 1998). Alternatively, it also is possible that losses of silt have been offset by the addition of farm fertilizers and other anthropogenic sources of nutrients in the agricultural wastewater that reaches the Gulf (Pitt and others 2000). Flessa and others (2001) have noted that nutrients supplied by the Colorado River probably sustain mollusks such as clams and other marine organisms in the Gulf. Also, nutrients continue to be received in the Gulf as a result of the tidal action upon the Delta (Lepley and others 1975; Pitt and others 2000; Valdez-Holguin and Lara-Lara 1985). Overall, productivity remains very high for the Gulf, as compared with other regions of the world (Valdez-Holguin and others 1995).

Although it is possible to show rebounds in the shrimp harvest during the 1983 El Nino, changes in the number of fishing boats (Figure 3) present an alternative hypothesis for the sudden drop in populations

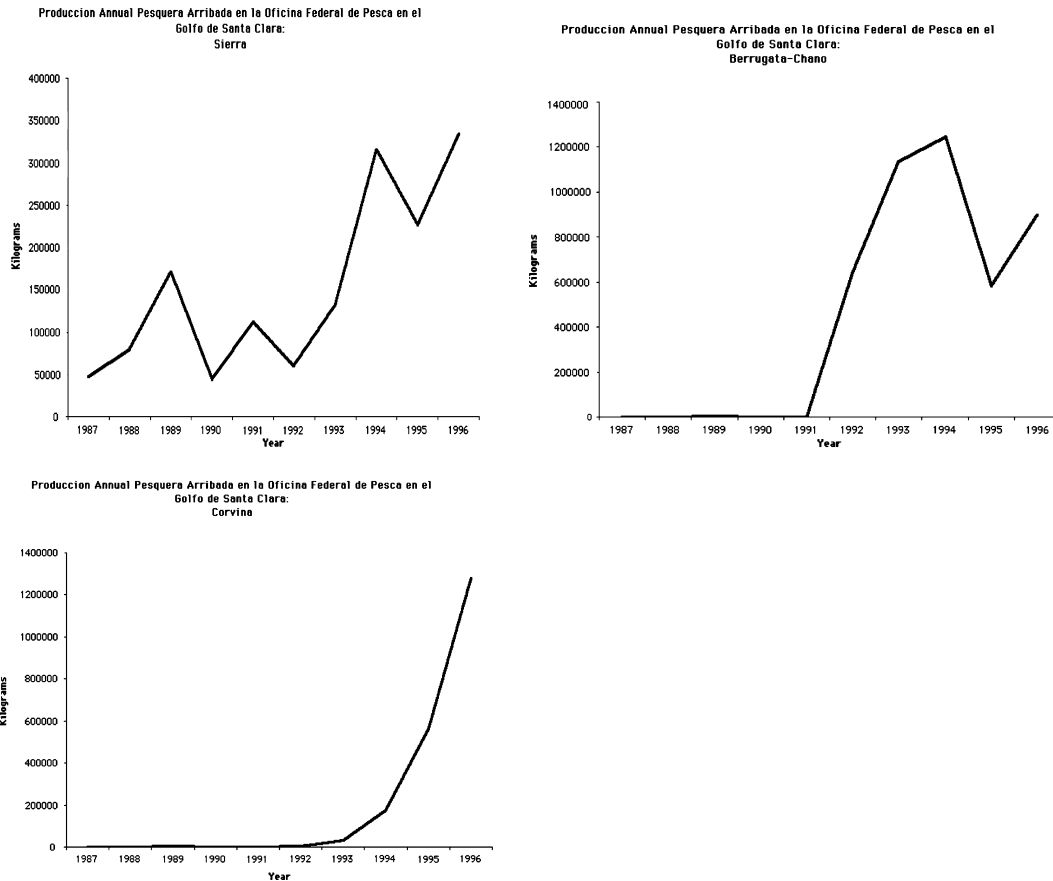
during the mid-1980s. Several years of extremely heavy fishing may have influenced the reductions in the shrimp population. The decrease in shrimp abundance stimulated some of the fishermen to redirect boats to harvest other fish species (Figure 6) or move to other fisheries. Reductions in shrimp fishing pressure may have allowed the shrimp populations to rebound coincidentally with the 1983 flood event.

### Flood Flow Diversions to Laguna Salada

Fundamental to assessment of the impact that El Niño-driven flooding has had on the marine ecosystem is knowledge of how much freshwater actually has entered the Gulf during specified intervals. There is little doubt that some water reached the Gulf during 1983 (Jimenez and others 1984; Valdez-Holguin and Lara-Lara 1985). However, in 1983, an earthen berm located in the river’s channel was washed away (Payne and others 1992). This berm had acted to keep water in the channel, and thus flowing toward the Delta wetlands and the Gulf. After this change in the channel geomorphology, overflows were diverted to Laguna Salada, and in subsequent flood years, satellite images indicate that little water reached the Gulf (Figure 2). Satellite imagery is appropriate for an assessment of freshwater flow into Laguna Salada because it has sufficient temporal frequency and capacity of observation to show floodwater dynamics on a regional scale (Birkett 2000).

South of the Morelos Dam diversion are several paths that Colorado River water can take. The River may continue down its original channel to the Gulf of California. Flows may remain in wetlands such as the Rio Hardy Wetland (Valdes-Casillas and others 1998; Zengel and others 1995). Water also may be diverted into agricultural fields in the San Luis Rio Colorado Irrigation District in Mexico (Fimbres 1983). Finally, it may be directed into Laguna Salada (Figure 1).

Laguna Salada is a closed basin to the west of Mexicali in the state of Baja California Norte, Mexico. It is bordered on the north by the Cerro del Centinela, on the east by the Sierra Cucapa, and on the west by the Sierra de Juarez. It has served as a flood drainage basin for the Colorado River over thousands of years (Jimenez and others 1984). Known as Lake Maquata before the beginning of diversions of the Colorado in the late 1800s, it was an excellent fishery supporting the Cucapa people (Orcutt 1891). Currently, it supports no wildlife because it is dry during many years, and these extinction periods are too frequent for the local aquatic species to survive (Felger 2000). It currently is supplied water during floods along a 10-foot-deep canal completed in 1974 that originates at the



**Figure 6.** Other species of fish harvested near the mouth of the Colorado River from 1987 to 1996. The species data are for sierra, corvina (sea bass), and chano. These species are less profitable than shrimp and did not begin to be harvested until after shrimp population declines and economic crisis within the shrimp industry necessitated such a shift. The dramatic increase in harvest was not sustainable, and variability by 1995 can be seen in the sierra and chano catches. Source: Delegacion Federal de Pesca.

channel of the Colorado River (Jimenez and others 1984). This canal was built to protect Mexican farmland during floods in conjunction with a series of levees that channel water away from former wetlands. According to records at the National Climatic Data Center, there is very little annual precipitation in the area to fill Laguna Salada (<http://lwf.ncdc.noaa.gov/oa/ncdc.html>).

## Data and Methods

Colorado River volume and flow are measured officially for the last time at the United States–Mexico border at the Southern International Border. Large El Nino flood events allowed excess water to cross the Mexican border and flow into the Delta in 1978, 1983–1987, 1993, and 1997–1999. There are four major sinks after the border to which water can flow: the Mexicali Valley via the diversion at Morelos Dam, the SLRCID

Irrigation District, the Laguna Salada, and the Gulf of California. The diversion at Morelos Dam has a maximum capacity of approximately 3,500 cubic feet per second ( $\sim 100 \text{ m}^3/\text{sec}$ ) (All 1997). The volume of water that can be used in SLRCID is limited. Data on water use for both of these areas were gathered and published by the Pacific Institute for Studies in Development, Environment, and Security (Cohen and Henges-Jeck 2001). However, direct measurement data on Laguna Salada are not available in any form. Because the amount of water entering the irrigation districts is essentially fixed by the size of the diversions at Morelos Dam, any water left must flow either to Laguna Salada or the Gulf. Any water impounded by Laguna Salada is not available for ecosystem benefits in the Gulf. Infiltration and evaporation are of limited importance for the flowing water in the channel because it flows in hours rather than days from the border to the Gulf. In the past, water from agricultural runoff has entered



Laguna Salada through drains in Mexico (Jimenez and others 1984). However, recent examination of these drains has showed that they have not been used for many years (All 2001). According to maps, Laguna Salada is a depression similar in overall size to the Salton Sea depression (~1,000 square kilometers). The Salton Sea receives and evaporates approximately 1.6 billion cubic meters per year (Brazil 2001). Inflow essentially equals evaporation because the Salton Sea does not grow in size, and calculations of the International Geosphere–Biosphere Programme indicate that groundwater discharge is very small because of impermeable sediments in the Delta (Muniz-Arriola and others 2002).

There are no direct measurements of water volume for Laguna Salada in part because direct measurement of stream flow volumes is an intensive, expensive process (Bureau of Reclamation 1997; Department of Agriculture 1979). For single measurements, the channel cross section is measured and then a flow meter is used at various heights in the channel to measure velocity such that  $\text{area} \times \text{velocity} = \text{volume per time unit}$ . Channel cross sections are subject to major modification, especially in semiarid environments (Knighton 1998), and therefore must be measured anew every time assessment of the stream flow is desired. For long-term monitoring purposes, a flume is constructed in such a way that the height of the water flowing past a measuring stick equals the volume per time unit. This technique is expensive and requires frequent maintenance. Mexico's data-gathering agencies do not have sufficient resources for such costly activities in remote locations such as Laguna Salada.

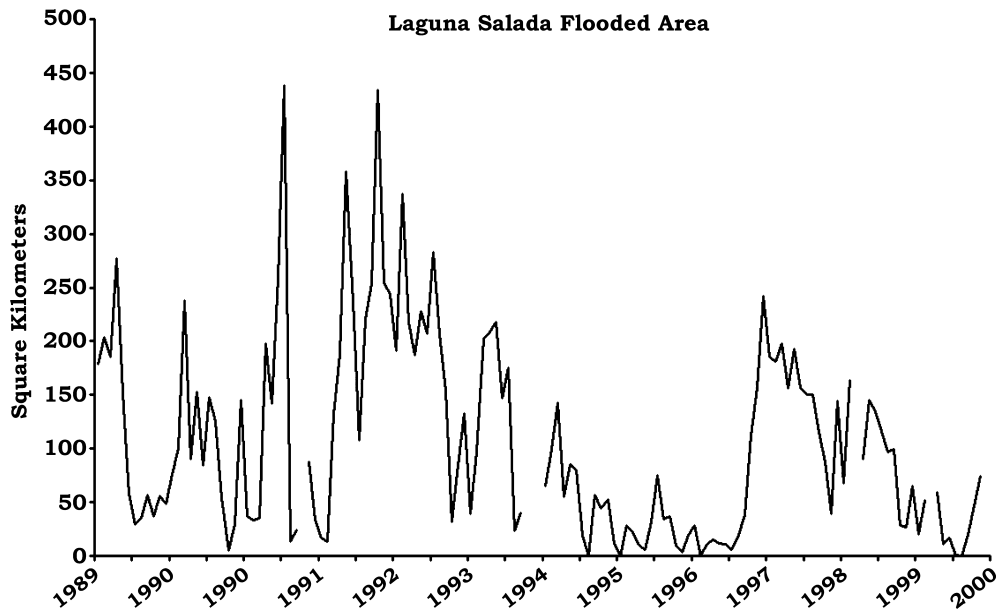
The depth and/or volume of water in areas such as Laguna Salada are not readily measurable using satellite remote sensing data (Lyon and Hutchinson 1995). However, the spatial extent of water can be measured directly, and once this is known, volume may be estimated using a cross section of the lake bed. Satellite data provide archival sources of data for sequential assessment of many biophysical processes. Such data have been used extensively to monitor floods and large lake volumes (Birkett 2000; Sheng and others 2001). Research by Birkett in 2000 at Lake Chad, Africa, provides a good model for the current study. Lake Chad is a semiarid lake subject to semiarid pressures similar to those of Laguna Salada. Using AVHRR and TOPEX/Poseidon satellite data, Birkett was able to track floods and droughts as they altered Lake Chad's boundaries. Application of AVHRR data has been used to determine lake surface areas as well (Harris 1994; Harris and Mason 1989; Prata 1990). Schneider and

others (1985) have used AVHRR to observe lake boundary and vegetative growth qualitatively.

Monitoring of Laguna Salada is similar to flood monitoring, and similar techniques were used. Although the resolution of AVHRR (1.1 km at the nadir) is not appropriate for all uses (Sheng and others 2001), it is excellent for large flood monitoring in flat areas because of its temporal availability, large area coverage, and low cost (Sheng and others 2001). These factors are especially important in developing countries where ground data are limited or unavailable, as in the current study. Flood monitoring has been undertaken successfully with National Oceanic and Atmospheric Administration (NOAA) images for many years (Ali 1989; Rasid and Paramanik 1990; Wiesnet and others 1974) and was facilitated in the current study by a lack of the cloud cover that often accompanies floods. The use of maximum value composite (MVC) data also limits the impact of cloud contamination (Holben 1986). Single-channel identification of water bodies using AVHRR is difficult, and multichannel techniques such as a Normalized Difference Vegetation Index image (NDVI) are necessary (Sheng and others 2001). The NDVI is calculated from the reflected solar radiation in the near-infrared (NIR) and red (RED) wavelength bands via the algorithm:  $\text{NDVI} = (\text{NIR} - \text{RED}) / (\text{NIR} + \text{RED})$  (NOAA 2000).

The current study used NOAA AVHRR data from the U.S. Geological Survey's Earth Resources Observation and Science (EROS) Data Center. These data were processed into a MVC dataset composed of biweekly maximum NDVIs from 1989 to 2000. Use of MVC corrected for potential issues with clouds, smoke, or haze (Holben 1986). Wet soil was not a major issue because of the extremely high temperatures and evaporation rates (Pilon and others 1988). Damp soil does not remain wet for the entire month of a data image. The NDVI data were corrected radiometrically and georegistered by EROS (Eidenshink 1992). The data were analyzed using Earth Resources Data Analysis System (ERDAS) Imagine software. The area of Laguna Salada was identified as a subset for study. To create the subset boundaries, a maximum exterior bounding rectangle for the largest flood extent on record was used as a baseline, and then a sea level elevation boundary was added to the surrounding area to ensure that the entire area, even partially flooded pixels, was examined and classified.

Distinguishing water from land was relatively simple because of the extremely flat nature of the land and the lack of wetland areas that could mask water signals. Metternicht and Zinck (1998) found that reflectance in the near infrared wavelength band was the strongest relationship for evaluating bare soils.



**Figure 7.** Flooded area of Laguna Salada in square kilometers. The number of flooded pixels in Laguna Salada for the given data set are shown. Each pixel is  $1 \text{ km}^2$ . This figure was derived from AVHRR data.

Their study site was a laguna flat of alluvial sediment with slopes of less than 1%, similar to Laguna Salada. Metternicht and Zinck reported that AVHRR channel 2 ( $0.9 \mu\text{m}$ ) was best for distinguishing the water signal from the land signal. At this wavelength, water appears black, whereas vegetation is very bright. Sheng and others (1998) examined various methods for separating land and water during flooding. They found that the difference between channels 1 and 2 and the ratio of channels 1 ( $0.6 \mu\text{m}$ , visible wavelength) and 2 ( $0.9 \mu\text{m}$ , near infrared wavelength) both provided satisfactory results when an adequate threshold was established, such that all pixels above the threshold are land and all below it are water. Prata (1990) also had success with this technique in studying Lake Eyre because the use of both channels corrects for errors derived from shallow sediment-filled water. Travaglia and others (1995, as reported in Birkett 2000) used NDVI to distinguish vegetated bare soil and open water for wetland regions in Africa. As a water-identifying tool, NDVI is not appropriate if floating vegetation is present (Schneider and others 1985), but that was not a problem at Laguna Salada.

Threshold exceedance, often used to determine the occurrence of change in a change-vector analysis, is simpler to use than calculations of complex image noise models (Sohl 1999). Various authors have used a simple intensity threshold technique for distinguishing water and land (Bryant 1999; Harris and Mason 1985), and this technique was used in the current study.

A subset area of Laguna Salada and its basin was cut from available AVHRR data. The land peak digital number (DN) values and the water peak DN values were derived for each date, and median DN values were calculated. The threshold was set between the water and land peaks in a histogram. The midpoint between the two was taken as the upper limit of the threshold for water. No problems occurred in the current study with variable peak widths and multiple spikes because of the basin's very uniform nature and lack of vegetation. Once thresholds were set (and other changes had been discarded through the use of ground data), then the pixels were classed as water or not water. These water pixels then were summed to get a total inundated area, with each pixel having an approximate area of  $1 \text{ km}^2$  (Sheng and others 2001).

## Results and Discussion

Examination of a 1989–2000 time series demonstrated that maximum lake extent generally occurred during the summer (Figure 7). This corresponds with U.S. Geological Survey data on Colorado River flow at the United States–Mexico border. Peak flows lead directly to large spatial extensions of Laguna Salada, but because the inflows never extended lake volume to its maximum sea level boundaries, it is unlikely that excessive amounts of freshwater reached the Gulf.

The spatial extent of Laguna Salada demonstrated marked variability over the study period. The extremely

high variability is somewhat surprising because this is a terminal basin, and thus would be expected to fill gradually and then dry out. The fluctuation is probably attributable to the extremely high evaporation rates that quickly eliminate shallow inflows such that both the flood peaks and small floods do not appear as flooded pixels. The average slope in the basin has been estimated at 35.7 cm per kilometer (All 2001).

The shallow slope of the salt flat dictates that slight changes in volume could lead to dramatic changes in spatial extent. Because MVC data were used and bare soil has a higher DN than water, if the area encompassed by a pixel is flooded for only part of the month, it will appear as bare ground. Thus, the datasets showed the minimum inundated pixels per month. Even with this strong tendency to underestimate flood extent, Laguna Salada maintained an area encompassing 200 to 400 km<sup>2</sup> during and after the wettest flood years. Evaporation at Laguna Salada has not been measured, but has been estimated at 2,420.63 mm per year, representing an average evaporated volume of 13,967.79 m<sup>3</sup> per hectare annually (Jimenez and others 1984). This evaporation rate is similar to measured rates in the region, such as at the Salton Sea and at U.S. weather stations at Yuma and Calexico (Brazil 2001; U.S. Department of Energy 2004; <http://wlf.ncdc.noaa.gov/oa/ncdc.html>).

This amount of evaporation, combined with the large volumes of water present during floods, suggests that nearly all the floodwaters during the study period were diverted from the Delta and Gulf into Laguna Salada. The fact that Laguna Salada had water in it for most of the years in the dataset indicates that more water than previously suspected is entering the Rio Hardy marsh and moving through to Laguna Salada. This water probably is seepage from SLRCID irrigation activities. Whatever the source, the water could be potentially valuable for wildlife habitat if it remained in the Rio Hardy for a time and then moved to the Gulf instead of being lost to Laguna Salada.

In 1992, Ducks Unlimited (DU) and Ducks Unlimited Mexico (DUMAC) proposed rebuilding an earthen dam or berm in the Colorado River channel (Payne and others 1992). This natural berm had been located originally downstream of the Rio Hardy wetland and just upstream from the diversion to Laguna Salada. The naturally created berm was washed away during the catastrophic flooding of the 1983 El Niño. Before its destruction, the berm had impounded water for the Rio Hardy wetlands and allowed them to achieve a much larger size than their current extent (Luecke and others 1999; Postel and others 1998). The removal of this structure not only drained the marsh, but it also

allowed the channel to migrate slightly so that Laguna Salada became the preferred route of water flowing in the channel rather than one toward the sea. Despite farmers' fears, either Laguna Salada or the sea probably will function as an effective drain to protect farmland. Both DU and DUMAC were concerned about the rare and endangered species of birds in the Rio Hardy wetland when they proposed to rebuild the berm because it would have increased the residence time of water in the marsh and should have helped to restore its size toward the pre-1983 boundaries (Payne and others 1992). The berm would have had the additional benefit of directing floodwaters back toward the Gulf of California.

Ducks Unlimited obtained a \$250,000 grant to rebuild the structure, but was denied the permits to build it because the Mexican government felt such construction was not in keeping with the spirit of a biosphere preserve (Streeter 1999). As discussed previously, political pressure from large farmers worried about flood damage to their lands in the SLRCID possibly influenced this decision as well.

Analysis of Laguna Salada data indicates that large influxes of freshwater from the Colorado River rarely reach the Gulf of California. Thus, other factors such as overfishing in the shrimp habitat are responsible for the "boom" and "bust" cycles in the region's fishing industry. A final piece of evidence supporting this possibility is data on the Colorado Delta Clam population. Like shrimp, this species also is dependent on freshwater flows, but the clams are not harvested and thus not affected by fishing pressure. Clam populations plummeted by 94% after the completion of Hoover Dam in the 1930s, and no recovery was recorded during the flood periods (Rodriguez and others 2001).

The more transient responses and fluctuations in shrimp populations may be attributable to human or other pressures, and minute changes in freshwater flow may have less impact than is claimed. The major ecosystem disruption for the Gulf occurred in the 1930s with the completion of Hoover Dam. Another disruption came in the 1960s, during the completion of Glen Canyon Dam. Yet, the transient shrimp population rebound in 1983 is back to 1970s levels after the freshwater flow into the Gulf had virtually ceased (Figure 5). Therefore, shrimp harvest increases during ENSO were attributable to increased fishing pressures (Figure 3) rather than an ecosystem impact. The myth that the harvest would be increased during the El Niño meant more boats plying the waters so that the harvest was increased. More fishermen spent more hours and days on the water because they believed there would be

more shrimp, so they captured more shrimp during these increased efforts.

## Conclusions

This study used satellite imagery to demonstrate that large volumes of freshwater are diverted away from potential enrichment of the wildlife habitat in the Colorado River Delta and the Gulf of California toward a barren salt flat called Laguna Salada. If freshwater had reached the Gulf, it would have benefited shrimp populations. Because the water flows toward Laguna Salada and away from the Gulf, it is not likely responsible for fertilization of the shrimp fisheries in the 1980s and 1990s as has been claimed. Instead, other factors such as changes in the size and structure of the shrimp fishing fleet may have negatively influenced shrimp populations. The populations did not recover until competition among fishermen was reduced. Yet, the increased amounts of water in the Colorado River channel were given the “credit” for increased ecosystem productivity.

Farmers in the region face the consequences of precautionary and emergency releases from upstream dams, primarily to avoid the destruction of diversion structures and to prevent flooding of croplands. The farmers in San Luis would be better served if releases from impoundment structures were timed according to forecasts of El Niño events and prior knowledge of drought conditions. Then the diversion into Laguna Salada would not be necessary. However, the current operation of diversion structures based on the “Law of the River” does not permit this type of flexibility.

The amount of water necessary to restore marine habitat is unknown, but it undoubtedly is large (Flessa and others 2001). The data in this report show that the DU/DUMAC proposal should be reconsidered because of the major impact it would have for Delta and Gulf species. Floodwaters are more beneficial in the Delta and Gulf than those lost in a terminal salt flat. There are several U.S.-listed endangered species that would benefit from a restored Rio Hardy wetland (J. All, unpublished). The DU/DUMAC proposal also would have major benefits for the Gulf if it rechanneled floodwater and farm seepage toward the sea rather than into Laguna Salada. The Delta and Gulf ecosystems would be improved by freshwater flows, and this would benefit the local economy and improve the shrimp habitat as well. In this case, the environment and economics are not necessarily in conflict or competing for the same resources. Instead, by restoring the productivity of the ecosystem in the Gulf, the surplus shrimp (as defined in Garcia 1983)

can be removed while the remainder thrives. Limits on the numbers of boats and catches could help ensure that the fishery remains viable for the upper Gulf. According to a variety of researchers, freshwater flow would have a positive impact for the Delta and the Gulf. Freshwater diverted toward the Gulf would enhance the wildlife habitat. It is obvious that water is too valuable a resource to be lost in this desert landscape.

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