AN ABSTRACT OF THE DISSERTATION OF

Jose Francisco Zamora-Arroyo for the degree of Doctor of Philosophy in Geography presented on October 7, 2002. Title: Impacts of Instream Flows on the Colorado River Delta, Mexico: Spatial Vegetation Change Analysis and Opportunities for Restoration.

Abstract approved: Redacted for Privacy

James R. Pease

Until the 1930s, flows of the Colorado River maintained approximately 781,060 hectares of wetlands in its delta. These wetlands provided important feeding and nesting grounds for resident and migratory birds as well as spawning and protection habitat for many fish and other invertebrate species. However, the Delta's wetlands started to disappear as water was used for agricultural and urban uses in the United States and Mexico. The 1944 United States-Mexico water treaty, which allocates 1.8 million m^3/year to Mexico, did not define a minimum flow to maintain the Delta's ecosystems. The resulting degraded Delta lead to the perception in the 1980s that the Delta was a dead ecosystem.

This study investigates whether this "dead Delta" perception is valid. Its central hypothesis is that regenerated vegetation in riparian and flood plain zones is associated with surplus river flows during the 1990s. A vegetation analysis, using satellite imagery and field methods, shows that native trees have regenerated during the last 20 years, and now account for 23% of vegetation in a 100 km, non-perennial, stretch of river below the United States-Mexico border. A spatial trend analysis using multi-temporal data on percent vegetation cover indicates that there are 6,320 hectares that show a significant increasing trend (p-value<0.05) in vegetation cover, with the Delta's riparian zone having at least 18% of its area showing this trend.

The study estimates that a once in four years February to April flow of 300 million m^3 (at 80-120 m^3/s) is sufficient to germinate and establish new cohorts of native trees, and highlights the need for smaller but more periodic flows in order to maintain wetland areas. It is concluded that there is clear evidence of the resilience of the Delta's ecosystems and that the "dead Delta" perception is no longer valid. There exist critical habitat in the Delta that needs to be protected, while there also exist short and long term opportunities to ecologically enhance and expand current habitat. Hydrological and ecological studies are needed to estimate specific water requirements for these areas in order to efficiently target them for immediate and long term conservation actions.

Impacts of Instream Flows on the Colorado River Delta, Mexico: Spatial Vegetation Change Analysis and Opportunities for Restoration

by

Jose Francisco Zamora-Arroyo

A DISSERTATION

Submitted to

Oregon State University

In partial fulfillment of
the requirements for the
degree of

Doctor in Philosophy

Presented October 7, 2002
Commencement June 2003

Doctor in Philosophy dissertation of Jose Francisco Zamora-Arroyo presented on October 7, 2002.

APPROVED:

Redacted for Privacy

Major Professor, Representing Geography

Redacted for Privacy

Chair of Department of Geosciences

Redacted for Privacy

Dean of Graduate School

I understand that my dissertation will become part of the permanent collection of Oregon State University libraries. My signature below authorizes releases of my dissertation to any reader upon request

Redacted for Privacy

Jose Francisco Zamora-Arroyo, Author

ACKNOWLEDGEMENTS

I wish to thank all the people who supported in one way or another my doctoral studies. In particular, I acknowledge my major professor, Dr. James Pease, for his support, encouragement, and friendship throughout my doctoral studies. I have also benefited substantially from the support and experience of my minor professors Dr. Dawn Wright and Dr. Richard Johnston, who were instrumental in integrating GIS and resource economics into my studies. I am grateful to the rest of my professors at the Department of Geosciences, especially to Dr. Charles Rosenfeld, Dr. Jon Kimerling, and Dr. Gordon Matzke for their valuable support and understanding during difficult times. I am also grateful to all my friends with whom I shared wonderful times in Corvallis, especially to Rubén Cruz, Armando Equihua, Gabino García, Héctor Álvarez, Jaime Dávila and their families. I acknowledge the support of CONACYT, which provided me with a scholarship for my doctoral studies.

The research work presented here has been accomplished with the assistance of several people. In particular, I wish to thank Dr. Carlos Valdés, who brought me to the delta of the Colorado River and whose enthusiasm for the area inspired me to initiate and complete this work. I wish to acknowledge Dr. Edward Glenn for his support in the design and implementation of this work. Yamilett Carrillo, Elena Chavarria, Osvel Hinojosa, and Mark Briggs were instrumental in helping me to better understand wildlife and social issues in the delta. I also wish to acknowledge the contribution of Pamela Nagler in developing part of the remote sensing analysis. The assistance of Jaqueline García, Hugo Rodriguez, and Manuel Munoz in fieldwork is greatly appreciated. I also thank all the staff of the CECARENA (ITESM Guaymas), especially Carlos Padilla, María López, and Francisco Muñoz for their help in data integration.

This research was supported in part by North America Wetlands Conservation Council (Grant Agreements 14-48-98210-97-G027 and 14-48-98210-98-G011).

CONTRIBUTION OF AUTHORS

In Chapter 2, Dr. Pamela Nagler contributed equally to the work on conceptualization and analysis of vegetation using remote sensing techniques, and is acknowledged as a co-author. Other authors contributed to the design or implementation of field work associated with the different components of the work: Mark Briggs (vegetation analysis and tree census), Dean Radtke and Dr. Jaqueline Garcia, (ground water monitoring), Hugo Rodriguez (vegetation transects), Dr. Carlos Valdés (vegetation analysis and GIS), Dr. Alfredo Huete (remote sensing techniques), and Dr. Edward Glenn (vegetation analysis). My primary contributions were in the development of the original research idea and in the design and implementation of all field work and percent vegetation cover analysis. I developed all vegetation cover maps for each year using the Thematic Mapper imagery and co-led the work on water monitoring, using 12 well points in the field. Chapter 2 was written initially by me, Ed Glenn and P. Nagler, with Ed Glenn leading the preparation of the final published version by adding comments from us. I revised this version and I am responsible for all additional information incorporated into this dissertation.

In Chapter 3, I developed the original research idea, identified methods for implementation of the analysis, and wrote the chapter. I implemented the spatial trend analysis, and with the support from Osvel Hinojosa, designed and implemented the statistical analysis on the effects of stream flows. Osvel Hinojosa also contributed to the writing of this chapter in the section on effects of stream flows and discussion.

In Chapter 4, Dr. E. Glenn, Dr. P. Nagler, Dr. M Briggs, Dr. William Shaw and Dr. Karl Flessa contributed to identifying sources of information and helped me to integrate it in a coherent manner. The published version of the work presented in this chapter was initially drafted by Dr. Glen with important input from me. However, the version presented in this dissertation was re-written by myself, based on the published article, but with significant additional information. Chapter 5 was entirely written by myself.

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Continued)

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF TABLES

DEDICATION

To

Rocío and Gabriela

I could not have done it without your love, support, and understanding.

All my love to you.

To

My Parents

For their love and sacrifices in providing me a quality education and a sound foundation.

To

My sisters and brothers

For all the wonderful moments we shared together, memories of which helped me to complete this endeavor.

To

James Pease

IMPACTS OF INSTREAM FLOWS ON THE COLORADO RIVER DELTA, MEXICO: SPATIAL VEGETATION CHANGE ANALYSIS AND OPPORTUNITIES FOR RESTORATION.

CHAPTER 1: INTRODUCTION

Historically, approximately 13-15 million acre-feet of water captured in the Colorado River basin yearly fed and sustained approximately 781,060 hectares of wetlands in its delta (Pitt et al, 2000) before reaching the Gulf of California. These wetlands provided an important feeding and nesting grounds for resident and migratory birds as well as spawning and protection habitat for many fish and other invertebrate species (Glenn et al., 1996), many of which were of commercial importance. The human communities in the Delta and in the upper Gulf of California benefited from the river water that used to freely flow to the Gulf, and that contributed to make the Gulf of California one of the richest interior seas in the world. However, with more than ten major dams along the 1,400 mile course through 7 states in the U.S. and two in Mexico (see Fig 1.1), the Colorado River is today one of the most regulated rivers in North America, providing water to irrigate 3.7 million acres of farmland in the southwestern United States and in Mexico as well as providing water for nearly 30 million people (Pitt et al, 2000).

Regulation of the river flow began in 1930 with the construction and filling of Hoover Dam in Nevada. Thus, Hoover Dam marks the beginning of extensive periods during which almost no water reached the natural areas in the Delta. These periods continued until Glen Canyon Dam was built and filled in 1981 (see Fig 1.2). Construction of reservoirs along the Colorado River has created a total water storage capacity of about 60 million acre-feet, which represents four times the river average annual flow (Pontius, 1997, cited in Pitt, 2000. p820). This storage capacity promoted the development of extensive agricultural valleys and urban centers in the U.S. and in Mexico, and as water demand began to increase, Mexico and the United States reached an agreement over the allocation of Colorado River water through the 1944 Treaty on the Utilization of Waters of the Colorado River and Tijuana Rivers and of the Rio Grande (Feb, 3, 1944, U.S.-Mexico, 59 Stat 1219; cited in Pitt et al, 2000. p.827).

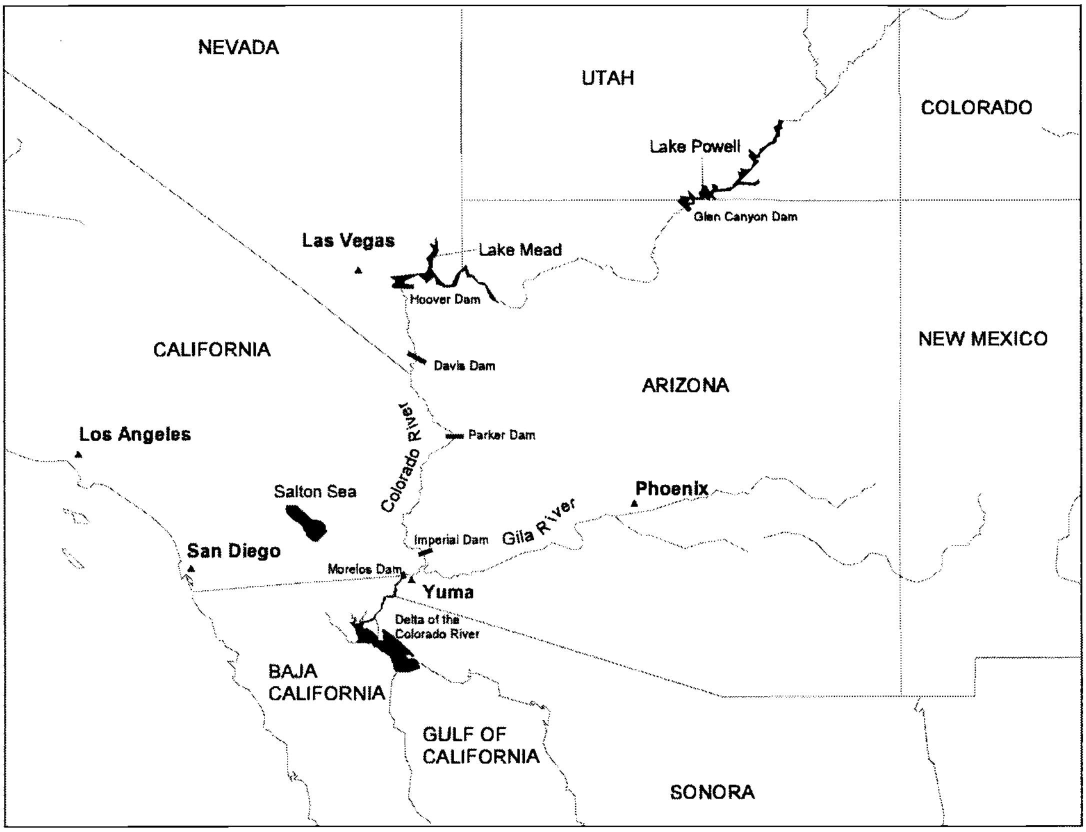

Fig 1.1. Map of the Colorado River showing major dams and the study area in its Delta.

The treaty allocated 1.5 million acre-feet (1,851 million m^3) of water every year from the Colorado River to Mexico. Prior to the treaty, Colorado River water had been allocated in the U.S. through the 1922 water compact to basin states, with 7.5

million acre-feet to the upper basin states and 7.5 million acre-feet to the lower basin states. Total water apportionment to Mexico and United States added up to 16.5 million, which was the estimated annual average water flow during years prior to 1944. However, it turned out that annual flows after 1944 were reduced due to a decline in precipitation (figure 1.2), and currently are estimated to be approximately 13.5 to 15 million acre-feet (Tarboton, 1995, cited in Pitt et al., 2000). Therefore, water apportionment from the Colorado River exceeds annual water catchments in the basin by approximately 1.5 to 3.0 million of acre-feet. This, however, had not been a problem until recently as some of the upper and lower basin states in the United States had not used all of their water allocation, resulting in surplus water which was mainly used by the state of California. It was not until 2000 when states began to claim their full allocation, creating an enormous pressure on California to force it to reduce water consumption from its current 5.2 million acre-feet to its allocation of 4.4 million acre-feet.

Mexico's 1.5 million acre-feet water allocation has always been met by the United States. And, in years with excess flows, Mexico has received an additional 200,000 acre-feet as provided by the treaty. Mexico receives about 90% of its water allocation at Morelos Dam on the Northerly International Border (NIB) and 10% at the Southerly International Border (SIB). Water is diverted at NIB through the Central Canal to supply water for agriculture in the Mexicali Valley and urban uses in Mexicali and Tijuana, whereas at the SIB water is diverted for irrigation of the San Luis agricultural valley.

Currently, the Colorado River Dam system is operated to keep the large reservoirs full, to accommodate electric power generation, recreation, and storage for downstream water uses in the United States and Mexico. However, during the last twenty years, the river flows have been characterized by pulse flows associated with excess runoff in the watershed, resulting in large volumes of so-called "waste spills" being released to the Colorado River Delta and Upper Gulf of California. For example, from 1983 to 1987, a total of 43 million acre-feet reached the Delta, with an annual average of 8.7 million acre-feet, and a maximum peak of 12.6 million acre-feet (15,548 million of cubic meters) in 1984 (see fig. 1.3).

Excess or surplus flows are, however, at risk due to the approval of the Interim Surplus Criteria (ISC) by the U.S. Secretary of the Interior in January 2001. The ISC allows California to exceed their water apportionment during a 15 year period, with the objective of providing the state time to implement conservation measures to reduce its current annual consumption of 5.2 million acre-feet to its 4.4 million acre-feet apportionment. And although the treaty provides Mexico 200,000 acre-feet per year when water is available "....in excess of the amount necessary to supply uses in the United States" (article 10(b), cited in Clark et al., 2001), when an ISC surplus year is declared, the ISC does not provide Mexico any surplus deliveries. Therefore, the Delta's wetlands that appear to have been revitalized by excess flows during the 1980s and 1990s are at risk as the possibility of excess flows reaching the Delta during the next 15 years is significantly reduced.

RESEARCH PROBLEM

From 1960 to 1980, during the filling of major dams in the Colorado River system, very little freshwater reached the Delta (Pitt et al, 2000), and by the end of the 1970s, the historical wetlands of the Delta were reduced to a dry ecosystem, creating a perception of a "dead delta" (Fradkin, 1981). In years with no excess flows, the only water flowing from the United States into Mexico is the 1.5 million acre-feet allowed by the 1944 treaty between Mexico and United States, all of which is used for agricultural and urban uses. Therefore, during years of no excess flows, the only water reaching portions of the Delta on a regular basis is brackish drainage water used for agricultural irrigation purposes in the Mexicali and San Luis valleys, which flow to the Colorado and Hardy Rivers. In addition, the

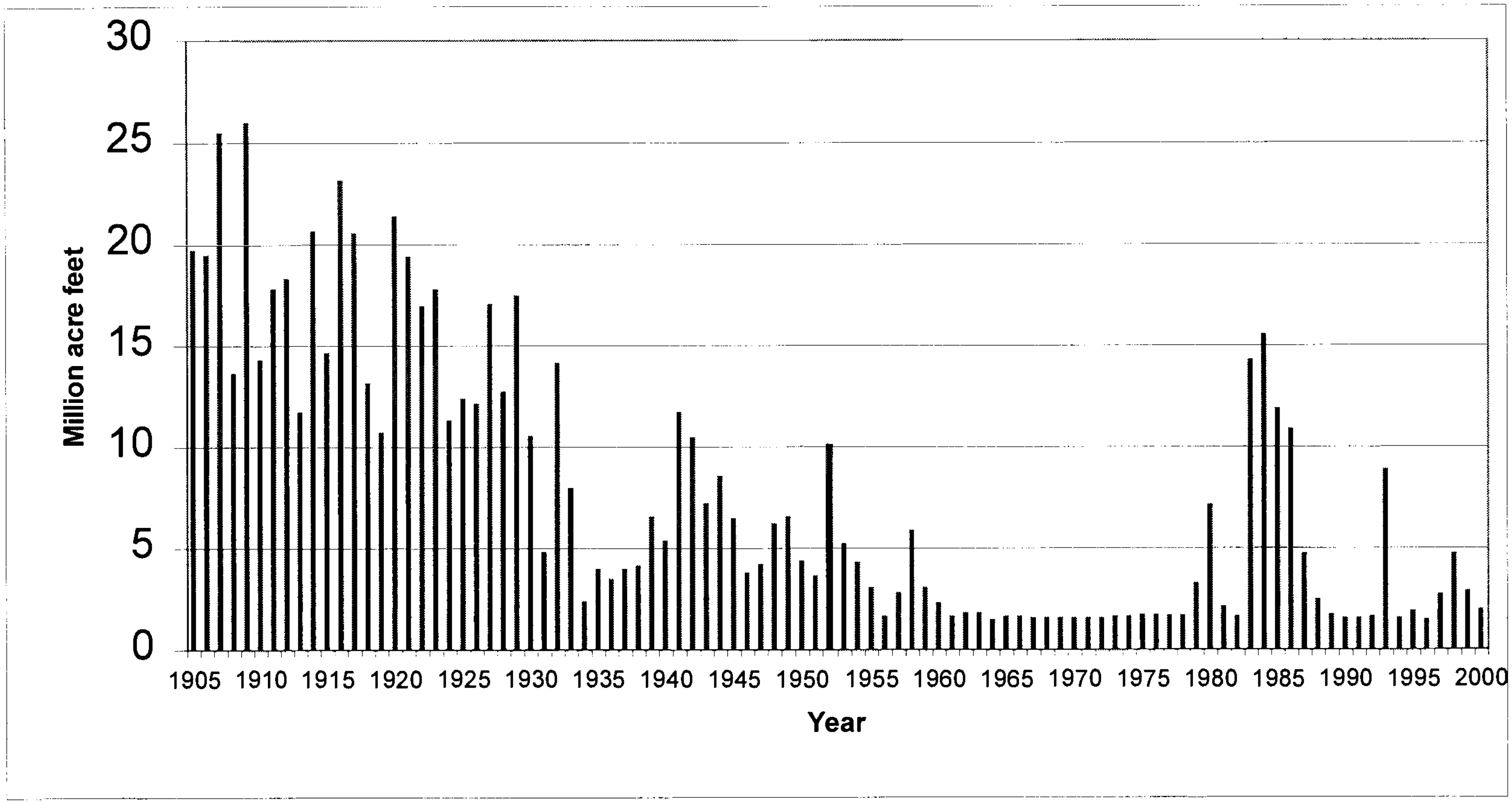

Fig 1.2. Historical flows of the Colorado River below all major dams and diversions (Northern International Boundary), 1905-2000. Data courtesy of Southern Nevada Water Authority, 2001 from flow data obtained from Rod Carson USBR.

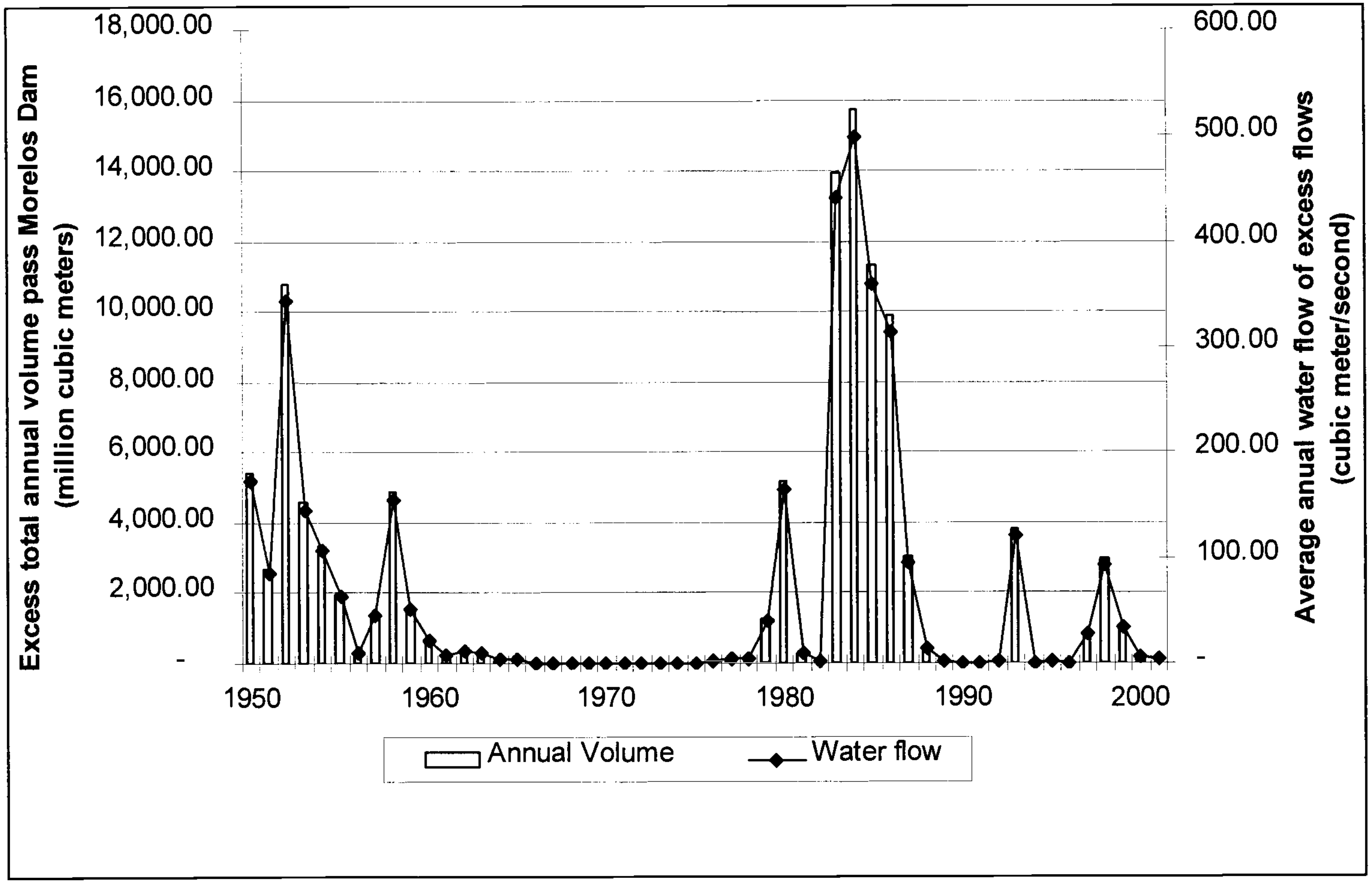

Fig 1.3. Historical Colorado River annual water volumes and water flow rates pass Morelos dam into the river system, 1950-2001. Data from the International Boundary and Water Commission, Mexican section.

Cienega de Santa Clara receives agricultural drainage water from the Wellton Mohawk irrigation district in Arizona through the Main Outlet Drain Extension (MODE).

In spite of these prior dry periods, revitalized vegetation areas in riparian and flood plain zones have been associated with these excess flows during the 1980s and 1990s. These excess flows are the result of natural runoff that exceeded consumption and storage capacity in the U.S. and Mexico, and thereby released to the Delta. This has changed the "dead Delta" perception to one that recognizes that the Delta has some revitalized wetlands with high conservation potential (Glenn et al, 1996; Valdes-Casillas et al., 1998; Pitt et all, 2000). Approximately 60,000 ha (Valdés-Casillas et al, 1998) of revitalized wetlands currently provide critical habitat for many species of resident and migratory birds and for many fish species of commercial value, and still support the remaining human communities living along the river and in the upper Gulf.

During the last five years, ecological, political and social patterns in the Delta have begun to be systematically quantified (e.g. Glenn et al, 2001; Valdés-Casillas et al., 1998; Pitt et al, 2000; and Zamora-Arroyo et al, 2001). Results from these investigations have highlighted the importance of maintaining the wetland areas that have been re-established through excess flows as well as those wetlands being maintained by other water sources, such as from agricultural return water.

This highlights the need to better understand the capacity of the Delta ecosystem to resist disturbance (its resilience), which is considered in general to be a key element in the conservation of biodiversity (Folke et al., 1996). The resilience of the Delta could be associated with natural stream flow variability, which plays a major role in organizing riparian wetlands (Richter and Richter, 2000). Variability of the instream flow patterns reaching the Colorado River Delta in the last 20 years has been characterized by human-induced flows that resemble natural pulse-floods (Cohen et al., 2001). Not surprisingly, during the same period, some areas in the Delta appear to have been through a revegetation process (Glenn

Valdés-Casillas et al., 1998, Zamora-Arroyo et al., 2001), which is an indication of the resilience of its wetlands, an ecosystem that was once considered dead (Fradkin, 1981).

It is also recognized that natural perturbations also influence the resilience of an ecosystem (Costanza and Folke, 1996). It was a natural event, El Niño storms and associated excess water flows in the basin, which triggered a natural ecological restoration process in the Delta, resulting in the revegetation of the riparian wetland areas (Valdes-Casillas et al., 1998; Zamora-Arroyo, et al., 2001). However, we recognize that an ecosystem might have a threshold point at which the system may not be capable of recovery to maintain its ecological functionality. Crossing this threshold, in the case of the Colorado River Delta, would affect not only native wildlife, endangered and threatened species, and the estuarine area in the Upper Gulf of California, but would represent in itself a disturbance to regional and global ecological patterns, as these wetlands are keystone areas in the migratory route of water and land birds (Mellink et al., 1997; Hinojosa-Huerta et al., 2001) and provide a critical interface between freshwater wetlands and the Gulf of California (Glenn et al., 1996).

To maintain the resilience of the Delta's wetlands would require that water from the United States and Mexico be specifically dedicated to sustain the Delta's ecosystems. Therefore, among the most critical questions in managing the Delta ecosystems at a binational level are: first, whether revitalized wetland habitats and their distribution are in fact the result of excess flows during the 1980s and 1990s, and second and the most critical one, how much water is required to support ecological functions of these wetland areas? This second question not only has to do with the amount of water, but also with the quality and timing of these flows and with setting priorities for the Delta ecosystems where environmental benefits for wildlife and wetland dependent human uses could be maximized.

Insights to answering these questions would have important policy and practical implications for two major reasons. First, any proposal for modification of the 1944 Treaty to allocate water or to allow transfer of water for environmental purposes in the Delta will have to be based on sound scientific information. Amendments to the treaty have been agreed upon between Mexico and the U.S., such as the case of salinity issues that were addressed by Minute 242. According to Clark et. al. (2001), a "similar mechanism is available to transfer water to the Delta if the Nations agree." Secondly, in order to maximize wetland restoration benefits from available water from any given source, it is important to determine where current and future available water should be directed. A series of related questions are: what percentage of the total Delta area should be restored or ecologically enhanced? Which areas would have a higher priority based on past trends and current ecological value? And, which wetlands depend on excess flows and which depend on other sources, such as agricultural return water?

The general objective of this dissertation is to provide information that can be used to determine the magnitude, duration, and frequency of flows and where these flows should be directed to restore and maintain the ecological functions of Delta's wetlands. This research contributes to answering the questions outlined above through the testing of the hypotheses presented in the next sections. This research was part of a bi-national and multidisciplinary research effort initiated in 1997 to systematically study the Colorado River Delta region. Prior to this effort, research interest in the Delta was minimal for many years, but has increased recently as scientists, environmental organizations, and natural resource managers have become aware that the "dead delta" perception is no longer accurate.

OBJECTIVES

This research was designed to analyze the effects that instream flows during the latest flood periods (1990s) had on the vegetation patterns of the Colorado River Delta, and to evaluate the resulting restoration and conservation potential for wetland habitats. This analysis becomes an important component of the questions presented above since the allocation of water to the Delta depends in part on the determination that excess flows have had and will actually cause a positive effect on these wetlands. To accomplish this, three specific objectives were defined corresponding to the three papers presented herein:

1. Determine the vegetation cover extent and composition in the Colorado River Delta in the 1990s (Chapter 2).
2. Determine the spatial changes in vegetation in the decade of the 1990s and estimate their association with water flow variables (Chapter 3).
3. Identify restoration opportunities as well as future research and management needs to maintain and expand critical wetland habitat in the Delta. (Chapter 4).

CONCEPTUAL FRAMEWORK

The study focuses on the Delta of the Colorado River, which historically, encompassed several million hectares of land near or below sea level in the United States and Mexico, including two evaporation basins, the Salton Depression (now the Salton Sea) and the Laguna Salada (Sykes, 1937). Aldo Leopold, describing a camping trip he made with his brother in the 1920's, called the Delta the last great blank spot on the map of North America (Leopold, 1949). Much of the historic Delta has been converted to irrigated agriculture or towns and cities. In Mexico, however, there currently remain approximately 170,000 ha of natural area, containing the 60,000 hectares of re-vitalized riparian and brackish wetlands and intertidal habitats (Glenn et al., 1996).

For purposes of this research, the Colorado River Delta is defined by these 170,000 hectares of natural vegetated areas within the floodplain, encompassing approximately 100 river miles in the Mexico portion of the Colorado River, from Morelos Dam at the Mexico-USA border to Montague Island at the river mouth in the Gulf of California (see figure 1.1). Much of this land, and a large portion of the adjoining marine zone, is now protected in the Biosphere Reserve of the Gulf of California and Delta of the Colorado River (Morelos-Abril, 1994).

One critical factor in the maintenance of the ecological function of the Delta's habitat is the presence of vegetation and open water areas, which provide critical habitat for many wildlife species in the Delta. Therefore, to make estimates about the magnitude, duration, and frequency of flows needed to maintain the wetlands' ecological functions, it is necessary to have a better understanding of the vegetation trends in the Delta and their response to instream flows. With this information environmental benefits for wildlife and wetland-dependent human uses can be maximized with the limited water resources available. Therefore, this study focuses on analyzing relationships of vegetation and water flows by investigating two hypotheses:

Hypothesis 1. Ho: there is not a significant spatial trend in increasing percent vegetation cover in the Colorado River Delta during the 1990s.

Hypothesis 2. Ho: the positive change in percent vegetation cover in the Delta during the 1990s is not associated with stream flows of the Colorado River during the same period.

To test the first hypothesis, it was first required to determine the vegetation extent and composition in the Colorado River Delta in the 1990s (chapter 2). This was done using remote sensing techniques by determining a correlation equation between Normalized Difference Vegetation Index (NDVI) and percent vegetation cover. Once a percent vegetation cover map was developed for each of the six years for which information was available (1992, 1994, 1996-1999), the next step called for determining spatial change of vegetation through time and exploring their association with water flow variables (chapter 3). Spatial change analysis was performed using a multiple-year technique, the Mann-Kendall test, following the procedure presented by Gilbert (1987, cited in Schlagel and Newton, 1996). Analysis of the associations of vegetation cover with water flows was investigated for each wetland zone by fitting three different multiple linear regression models to explore the effect that instream flows had on the average percent vegetation cover, total ha of vegetation cover >70%, and total ha of open water. Because limiting data, hypothesis two is not formally tested, but results are used to define more specific hypotheses for future testing. The information resulting from the testing of hypothesis one and the exploration of hypothesis two (objectives 1 and 2) was integrated with other ecological, socioeconomic, and hydrological information to identify and evaluate conservation opportunities in the Colorado River Delta (chapter 4). The relationships among the findings from the analysis of chapters 2, 3 and 4 are then summarized in the concluding chapter (Chapter 5).

This study is presented as three separate articles ("manuscripts"), and each article represents a chapter of this dissertation. As mentioned earlier, the study is part of a bi-national, multidisciplinary and multi-institutional research effort, which is the reason that there are co-authors in each chapter (see contribution of authors section).

REFERENCES

Clark Jo., Clinton Michael, Cunningham Paul, Getches David, Lopez Gamez Jose, Hathaway Melissa, Martinez Morales Octavio, Palafox Jaime, and Valdés-Casillas Carlos. 2001. Opciones inmediatas para incrementar el flujo de agua al Delta del Rio Colorado en Mexico. Reporte presentado a la fundacion The David and Lucile Packard Foundation. Mayo del 2001. 41pp.

Cohen M. J., Henges-Jeck, C. and Castillo-Moreno, G. 2001. A preliminary water balance for the Colorado River delta, 1992-1998. Journal of Arid Environments. 49. pp.35-48.

Costanza Robert and Carl Folke. (1996). The structure and function of ecological systems in relation to property-rights regimes. In Hanna Susan; Carl Folke; and Karl-Göran (Eds). Rights to nature: Ecological, economic, cultural, and political principles of institutions for the environment. Island press.

Folke Carl; C. S. Holling & Charles Perrings. (1996). Biological diversity, ecosystems, and the human scale. Ecological Applications, 6: 1018-1024.

Fradkin, P., (1981). A river no more, the Colorado River and the West. Alfred A. Knopf, New York.

Glenn, E. P., Zamora-Arroyo, F., Nagler, P. L., Briggs, M., Shaw, W., and Flessa, K. (2001). Ecology and conservation biology of the Colorado River Delta, Mexico. Journal of Arid Environments. 49: 5-15.

Glenn, E., R. C. Lee, R. Felger and S. Zengel (1996), Effects of water management on the wetlands of the Colorado River Delta, Mexico. Conservation Biology 10, 1175-1186.

Hinojosa-Huerta, Osvel., DeStefano, S., and Shaw, W., Distribution and abundance of the Yuma clapper rail (Rallus longirostris yumanensis) in the Colorado River Delta. (2001). Journal of Arid Environments. 49: 171-182.

Leopold, A., (1949). The green lagoons. Pages 150-158 in A. Leopold, editor. A Sand County Almanac. Oxford University Press, New York.

Mellink, E., Palacios, E. and Gonzalez, S. (1997). Non-breading water birds of the delta of the Rio Colorado, Mexico. Journal of Field Ornithology. 68: 113-123.

Morales-Abril, G., (1994). Reserva de la Biosfera Alto Golfo de California y Delta del Rio Colorado. Ecologica, 3: 26-27.

Pitt, J., (2001). Can we restore the Colorado River delta? Journal of Arid Environments, 49: 211-220.

Pitt, J., Luecke, D., Cohen, M., Glenn, E. and Valdes-Casillas, C., (2000). Two nations, one river: managing ecosystem conservation in the Colorado River delta. Natural Resources Journal, 40: 819-864.

Richter D. Brian & Holy E. Richter. (2000). Prescribing flood regimes to sustain riparian ecosystems along meandering rivers. Conservation Biology, 14: 1467-1478.

Schlagel D. Joel & Carlton M. Newton. (1996). A GIS-based statistical method to analyze spatial change. Photogrametric Engineering & Remote Sesing. 62: 839-844.

Southern Nevada Water Authority. 2001. Colorado River Mexican Delta Tour information package.

Sykes, G., (1937). The Colorado Delta. Carnegie Institution, Washington, D.C., 193 pp.

Valdés-Casillas Carlos, O. Hinojosa-Huerta, M. Muñoz-Viveros, F. Zamora-Arroyo, Y. Carrillo-Guerrero, S. Delgado-Garcia, M. Lopez-Camacho, E. Glenn, J. Garcia, J. Riley, D. Baumgartner, M. Briggs, C. Lee, E. Chavarria-Correa, C. Congdon, and D. Luecke. 1998. Information Database and Local Outreach Program for the Restoration of the Hardy River Wetlands, Lower Colorado River Delta, Baja California and Sonora, Mexico, North American Wetland Conservation Council, Arlington, Virginia USA. 103 pp.

Zamora-Arroyo, F., Nagler, P., Briggs, M., Radtke, D., Rodriquez, H., Garcia, J., Valdés, C., Huete, A. and Glenn, E., (2001). Regeneration of native trees in response to flood releases from the United States into the delta of the Colorado River, Mexico. Journal of Arid Environments, 49: 49-64.

CHAPTER 2

REGENERATION OF NATIVE TREES IN RESPONSE TO FLOOD RELEASES FROM THE UNITED STATES INTO THE DELTA OF THE COLORADO RIVER, MEXICO

Francisco Zamora-Arroyo, Pamela Nagler, and Edward Glenn

An earlier version of this chapter was published as:
Francisco Zamora-Arroyo, Pamela Nagler, Mark Briggs,
Dean Radtke, Hugo Rodriquez, Jaqueline García,
Carlos Valdés, Alfredo Huete and Edward Glenn
Published in the Journal of Arid Environments,
Vol. 49 No. 1. September 2001. pp. 49-64

ABSTRACT

Over the past 20 years, discharges of excess flood waters from the United States to the delta of the Colorado River in Mexico has regenerated native trees, that now account for 23% of the vegetation in a 100 km riparian area below Morelos Dam at the United States - Mexico border. The discharges were associated with the filling of Lake Powell in 1981, the last large reservoir to be constructed on the river, and with El Niño Southern Oscillation (ENSO) cycles that bring surplus winter and spring precipitation to the watershed. The discharges below Morelos Dam produced over-bank floods that germinated new cohorts of *Populus fremontii* and *Salix gooddingii* trees. These trees, when matured, form gallery forest in riparian wetlands in the Delta, which become critical habitat for many wildlife species, especially neotropical birds. Relatively little flood water from the United States is required to support a pulse flood regime that can result in regrowth of native wetland vegetation in the Delta, adding a vertical vegetation complexity as these gallery forests combine with other vegetated and open water areas.

Based on analysis of past flows and existing tree populations, a February to April flow of 300 million cubic meters at 80-120 m^3 sec^{-1} is sufficient to germinate and establish new cohorts of native trees. There was a positive correlation between frequency of Colorado River flows, measured at the Southern International Boundary, and total vegetation cover over the years 1992-1999, showing that more frequent flows would further increase vegetation cover. The results support the importance of pulse floods in restoring riparian vegetation in arid-zone rivers.

INTRODUCTION

Most of the world's large rivers have been harnessed for human use; dams, water diversions, and flow regulation to control flooding have disrupted the natural ecosystems of their riparian corridors (Dynesius and Nilsson, 1994; Nilsson et al., 1997). In the southwestern United States, because of flow regulations, riparian zones have been damaged by loss of the natural pulse-flood regime that formerly washed excess salts from riverbanks and germinated native trees (Briggs, 1996; Busch and Smith, 1995; Poff et al, 1997; Stromberg, 1998a). On the lower Colorado River, the largest and most altered river in the southwestern United States and northern Mexico, an exotic, salt tolerant shrub, *Tamarix ramosissima* (salt cedar), in association with native halophytes, has almost completely replaced the mesophytic native forest that historically dominated the riparian corridor from Grand Canyon to the delta on the Gulf of California (Ohmart et al, 1988; Busch and Smith, 1995). Loss of *Populus fremontii* (Fremont's cottonwood) and *Salix gooddingii* (Goodding's willow) trees and associated epiphytes and understory plants, has lead to a collapse of supporting habitat for numerous species of plants, birds, mammals and reptiles, so that today 45 species in the lower Colorado River ecoregion are listed as sensitive, threatened or endangered (United States Bureau of Reclamation, 1996).

Deterioration of native habitat on regulated rivers can be progressive and irreversible (Nilsson et al., 1997). It is not known whether restoring elements of a natural flow regime would, by itself, permit native species to repopulate Southwestern riparian zones (Briggs, 1996) or whether expensive reseeding efforts would be needed. This study documents the effects of pulse floods on vegetation in the delta region of the Colorado River, below the last diversion of water at Morelos Dam in Mexico. These discharges began after the last large reservoir on the river, Lake Powell behind Glen Canyon Dam, was filled in 1981 (Glenn et al., 1996, 1999). During years of high snow pack and rainfall, excess waters were allowed to flow across the border to Mexico.

The entire discharge of the Colorado River is considered to be over-apportioned for human use with no water specifically allocated for ecosystem maintenance (Morrison et al., 1996). However, the flows of arid-zone rivers are inherently variable. The river's dams are operated to keep the large reservoirs full for electric power generation, recreation, and storage for downstream water use. Hence, when there is excess runoff in the watershed, large volumes of so-called "waste spills" are released to the Colorado River Delta and upper Gulf of California. Since 1981, the major releases have been associated with the El Niño Southern Oscillation (ENSO) cycles in 1983, 1993 and 1997, which brought above-normal winter or spring precipitation into the reservoir system (Glantz et al., 1996; Li and Kafatos, 2000) (Figure 2.1).

This study analyzed the effects of river discharges on abundance of vegetation from 1992 to 1999 and characterized the species composition of existing vegetation using remote sensing and a variety of field methods. The study found that pulse floods have reestablished cohorts of native riparian wetland trees in a 100 km stretch of the riparian zone of the Delta, and that the extent of vegetation cover in this stretch is responsive to flood flows.

MATERIALS AND METHODS

Study Area and Flow Data

The general study area is the zone of natural (non-agricultural) vegetation in the riparian corridor from Morelos Dam to the mouth of the Colorado River in the Gulf of California (Figure 2.2). The main vegetation types and hydrological features of this zone have been described and entered into a Geographic Information System (GIS) database (Valdés-Casillas et al., 1998). The riparian corridor is confined within 6 m tall, earthen levees that keep flood waters out of adjacent agricultural fields. The corridor is less than 2 km wide in the northern stretch as it passes through the agricultural district, then widens to 30 km in the southern stretch as it approaches the Gulf. The river in the Delta is composed of a series of braided channels interspersed with straight sections, which have been dug to facilitate water movement. The primary interest of this study is the 100 km (13,708 ha) stretch of river from Morelos Dam to the junction with the Hardy River. This section, which corresponds to the Morelos, San Luis, and Carranza zones as described in Chapter 3 (see figure 3.1), contains a mixture of exotic non-wetland species, native wetland trees, and shrub vegetation. Below the juncture, saline agricultural drain water enters the river and apparently makes water too saline to support native trees.

We used a combination of low-level aerial surveys, ground transects, and monitoring wells to document the vegetation types and hydrology of this river stretch (sampling locations are in Figure 2.2). The striped area below the native tree zone in figure 2.2 is a mixture of habitat types, including fresh water and intertidal marshes, mud and salt flats, and vast thickets of *Tamarix ramosissima*. Triangles denote sites where ground transects were established to quantify vegetation; place names are the settlements (access points) nearest each transect. Closed circles denote sites where well points were established to monitor the depth and salinity of the water table under the riverbed. Numbered line segments show where strings of digital images were acquired during a low-level fight over the Delta in May, 1999.

This analysis complements that by Valdés-Casillas et al. (1998) by calculating percent vegetation cover and correlating it with past flow events, using satellite images of the Delta and flow data provided by the International Boundary and Water Commission, U.S. Dept. of State, El Paso, Texas, USA. Flows measured at the Southerly International Boundary, 35 km below the last diversion point for water, were assumed to flow to the sea with a residence time in the Delta of 3-5 days (Al Goeff, IBWC, private communication).

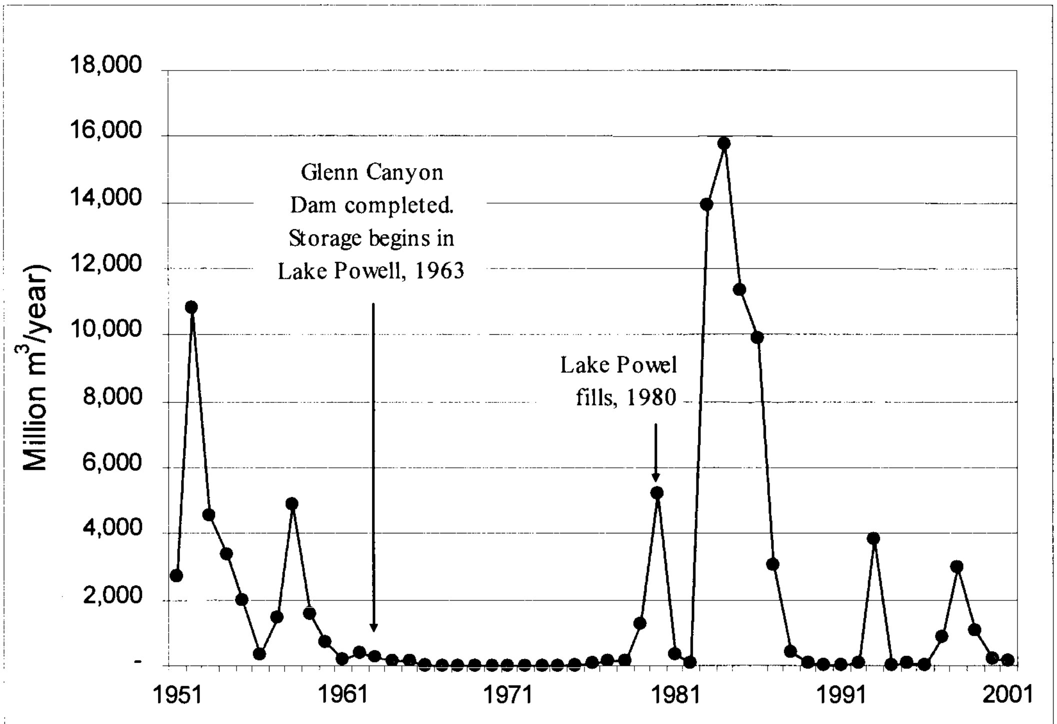

Figure 2.1. Annual water releases passing Morelos dam through the riparian corridor and delta to the Gulf of California, 1951-2001. Source: International Boundary and Water Commission, Mexican section.

Aerial Surveys

A medium-altitude (1,000 m) aerial survey on February 27, 1997, documented by oblique videography, provided a way to gain an overview of geomorphology and vegetation of the riparian ecosystem and to observe patterns of

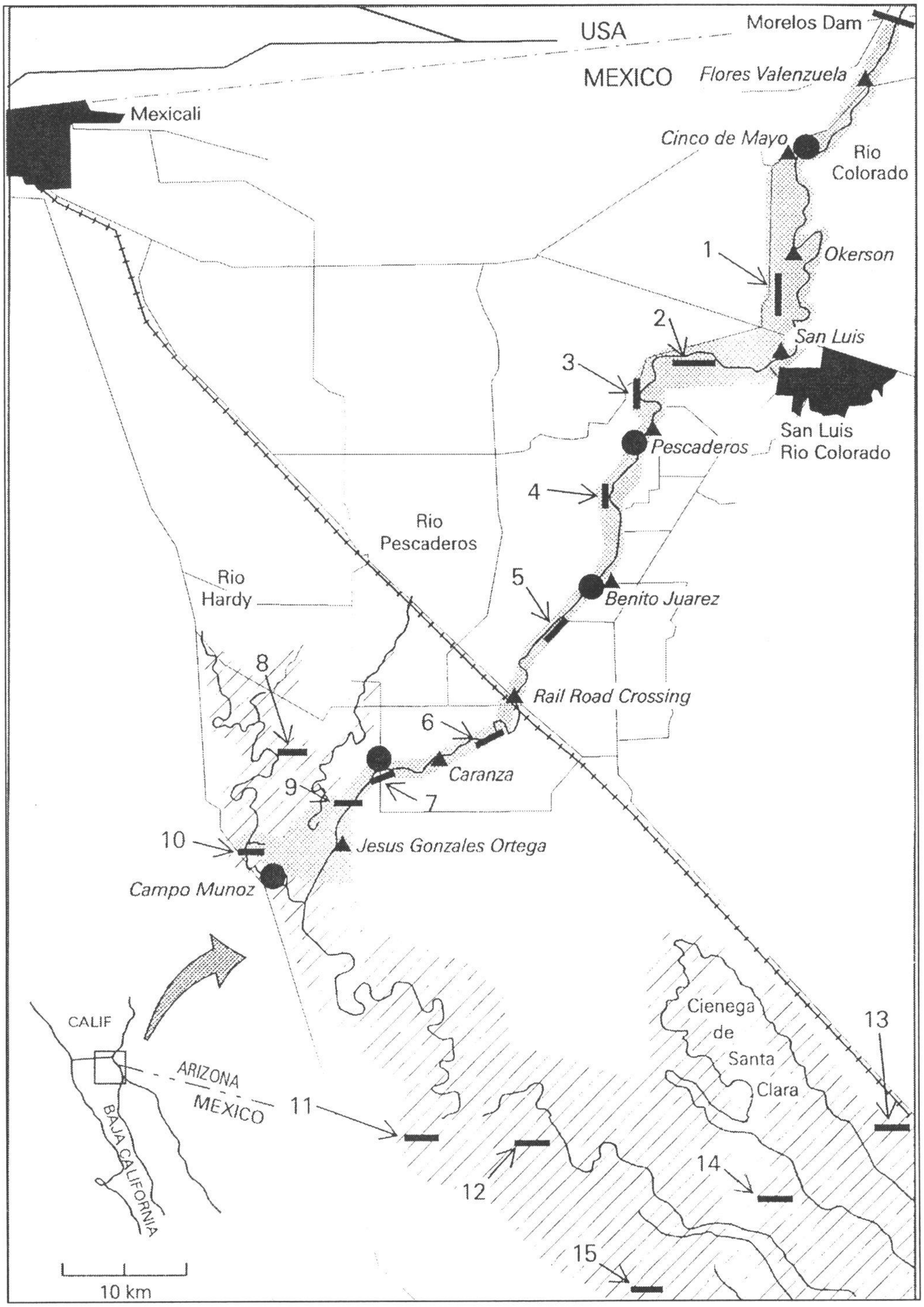

Figure 2.2. Location of study sites in the Colorado River Delta, Mexico. The gray area is the stretch of riparian corridor between the levees which supports native trees, the main focus of this study.

water distribution during a release event of known magnitude. This was followed by a low-level (150 m) aerial photographic survey on May 24, 1999, following three years of water releases, using a multiband (red, blue and NIR) digital camera (DyCam) (Nagler et al., 2001).

Sixty three DyCam images taken within the native tree zone were used to determine the percent of bare soil, trees, shrubs and groundcovers in the present study. Each image covered approximately 67 x 100 m of ground area. Each photograph was imported into a computer viewing program and overlain with a thin-lined, 100-point grid. Land cover class was visually scored at each intersection to determine percent cover of each class. Results were then ground-truthed at nine locations (Nagler et al., 2001). Native trees greater than 6 m height could be distinguished from other vegetation based on the length of shadows they cast in the photos. Shrubs (mainly *T. ramosissima*) were defined as plants that had definite size and shape but were less than 6 m based on shadow length. Groundcovers were green areas on photographs in which individual plants could not be distinguished. Bare soil and water were identified by color (soils were light-colored whereas water appeared nearly black in multi-band images).

Normalized Difference Vegetation Index (NDVI) was used to measure vegetation and map percent vegetation cover, using both aerial photography and satellite images. Among the different types of vegetation indices, the NDVI was selected because of its capacity to reduce many forms of multiplicative noise, such as atmospheric attenuation, illumination differences, and certain topographic variations (Alfredo Huete, personal communication, July 2000). The NDVI is able to reduce this noise by using a rationing concept of the near infrared and red bands. For the 63 DyCam images and an additional twenty one aerial images (a total of 84) , NDVI values were calculated for each image using the ratio of Red and IR bands (Nagler et al., 2001) (Figure 2.2), which resulted in a high coefficient of determination ($r^2 = 0.83$) between percent vegetation cover and reflectance-based

NDVI values calculated for the aerial photographs. A linear regression relationship was then determined by Nagler et al. (2001) to predict percent vegetation cover from NDVI calculated from aerial images. This relationship was used to calibrate satellite images of the Delta to determine percent vegetation cover over past years.

Satellite Imagery

We acquired six Thematic Mapper 5 (TM) satellite images showing summer vegetation patterns before- and after surplus water release events from 1992-1999. Images for Path 38, Row 38 were selected for cloudless days in May, 1992; July, 1994; June, 1996; July, 1997; June, 1998; and May, 1999. An additional satellite image was obtained for February 23, 1997, to delineate areas inundated by flood flows during a winter release event. The February, 1997 and May, 1999 satellite images were taken within three weeks of aerial surveys over the Delta. Images were preprocessed and georectified by EarthSat, Inc., Rockville, MD USA. Digital numbers were converted to exoatmospheric reflectance values (0-1) using archived radiance data for each scene and sun angle functions calculated from solar azimuth and angle based on date, time of day, latitude and longitude, using ENVI software (Christopher Jengo, EarthSat, Inc., private communication). The scenes were masked to include only the area of interest depicted in Figure 2.2, and NDVI values were calculated using ERDAS software.

We used reflectance-based, NDVI values to estimate percent cover on six TM images covering the period 1992-1999. The relationship to calculate percent vegetation cover using NDVI calculated was determined by Nagler et al. (2001).

This relationship is:

$$\text{Percent vegetation cover} = 180\ \text{NDVI} + 7.95\ (r^2 = 0.837).$$

The use of this equation is supported by a near 1:1 correspondence between NDVI values calculated for water, soil and vegetation from a May 1999 satellite image of the Delta and from DyCam images obtained by a low-level over flight the same month (Nagler et al., 2001). NDVI values for different land cover classes were nearly identical over the different TM images (coefficient of variation < 10%) from 1992 to 1999. Figure 2.3 shows these values, where Max and Min refer to the maximum and minimum NDVI values on each image; Mean refers to the mean

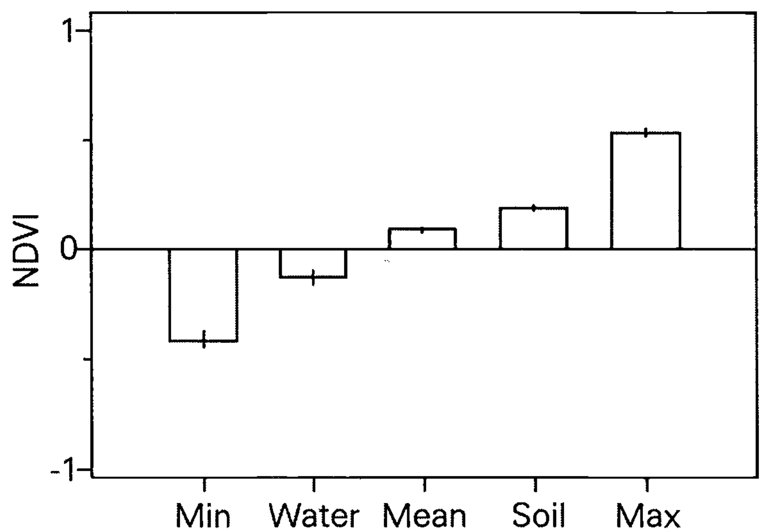

Figure 2.3. Means and standard deviations (error bars) of NDVI values for similar landscape features on 1992-1999 TM images of the Delta

NDVI values of all pixels on each image; and water and soil refer to NDVI values for 5 randomly-selected water and soil areas on each image. Differences among years for soil, water and mean NDVI values were not significant at $P<0.05$ (Max and Min values could not be compared among years as there was only one value available per image).

A change analyses of vegetation density as affected by flood flows into the delta was performed using summer percent vegetation cover calculated from satellite imagery. We restricted the analysis to the 100 km stretch of river containing native trees, from Morelos Dam to the junction with Rio Hardy. The relationship between percent vegetation cover and flood flows was estimated using simple regression analysis for the riparian area along this stretch of the river from Morelos dam.

Ground Transects

In July and August, 1999, we established nine ground transects to document floodplain geomorphology, soil salinity, depth and salinity of groundwater and distribution of plant species by percent cover and plant density. Sampling methods were adapted from those used elsewhere on the Colorado River by others (Busch and Smith, 1995; Ohmart et al., 1988). Transect locations were randomly selected before visiting the river to ensure that they were placed without bias towards particular vegetation conditions. From a randomly selected beginning point located within 5 km of Morelos dam, lines were marked on a topographic map of the river at 10 km intervals and ending near the junction of the Hardy River and Colorado River. The nearest vehicular access point to the line on either river bank was then taken as the starting point for establishing a field transect for each line marked on the map. In some cases the predetermined spot on the map could be accessed in the field, by driving along the levee banks and using GPS, whereas other transects were established as far as 1 km from the predetermined spot due to lack of access to the river.

The anchor point for each transect was established by walking from the vehicular access point to the river channel, then pacing a random distance (0-300 paces by random number selection) upstream or downstream, determined by coin toss. A baseline was then established, running perpendicular to the river from the anchor point to the levee, road, or agricultural field at the back of the floodplain. A stratified sampling method for surveying vegetation was used (Cook and Bonham, 1977) in which each transect was divided into different strata based on plant species composition and elevation with respect to the river channel. This method allowed us to sample as intensively within the native tree stands as within the much more common *T. ramosissima* areas.

We recognized a low-zone stratum, consisting of a beach sloping to a narrow, low terrace, at sites where the river had not incised; this stratum was characterized by stands of the emergent species, *Phragmites australis*, nearest the water with narrow strands of native trees and other vegetation behind. Behind the low-zone was a mid-zone stratum, constituting the major terrace of the flood plain at all sites; this stratum was generally dominated by salt tolerant shrubs (*T. ramosissima* and *P. sericea*) but in some cases native trees were also present as isolated specimens scattered over the terrace. Finally, we recognized a back-zone stratum, where flood water had washed seeds against the containing levees to produce a narrow strand of native trees along the inside bank of the levee. Not all transects had all three strata present. The length of each transect and of each stratum was measured by tape, or by GPS for long transects, GPS. Each transect was surveyed by theodolite to determine elevation of each zone relative to the bottom of the channel (river flow was minimal during surveys).

In each stratum, up to 5 plots, 2 m x 30 m, were established at random intervals along the transect baseline. The 30 m lengths of plots ran upstream or downstream, determined by coin toss, parallel to the river. Canopy cover (percentage of the transect occupied by each plant type) was recorded by height class for each perennial species along the 30 m length of plot nearest the river using the line-intercept method, and plant density was determined by counting individual plants within each plot (Curtis and Cottam, 1962). Height classes were: 0-2.0 m (understory); 2.1-6.0 m (midstory); and >6.0 m (overstory). Since annual plants were scarcely present, the percent of bare soil along the transect was estimated by summing the percent cover of individual species and subtracting from 100. When a stratum was longer than 100 m, plots were located in the 100 m of the zone nearest the river. When strata were too short to support 5 non-overlapping plots, fewer were established with a minimum of two, one upstream and one downstream in very narrow zones. One transect (Pescaderos) consisted of a nearly impenetrable monoculture of *T. ramosissima*; cover and density were estimated along the baseline at this site without establishing side plots. In total, 52 plots in 14 strata were completed. To estimate the percentage cover of species over the entire study area, means and variances of plant composition in each stratum were weighted according to their length compared to the total length of all strata using methods in Cook and Bonham (1977).

Tree Census Data

P. fremontii and *S. gooddingii* trees were not numerous enough in the transect plots to gain an accurate estimate of their distribution by species, size and age class. We did more intensive sampling near 3 transects (2, 6 and 9) that contained well-developed stands of trees. We selected a starting point along the baseline within a stratum containing trees, then determined the species composition, height, and trunk diameter just above the basal swelling of the first 50 trees (> 4 m height) encountered upstream and downstream of the starting point, by selecting the nearest tree to the one just measured as the next one to sample. Tree height was estimated by a triangulation method in which a 2 m measuring stick was held near the tree and visually projected up the length of the tree by an observer standing several tree lengths distant. We estimated age of trees from their trunk diameters by taking core samples from a subsample of trees to correlate number of annual rings with length of core (x 2 to project to trunk diameter assuming cores represent radii of trees), using methods in Stromberg (1998a). However, we found it easier to count rings without sanding cores first. These trees have diffuse pores, making rings difficult to distinguish, so ages are only approximations. At total of 264 trees were measured (50 trees were not available at some sites).

Comparison of Native Tree Cover on United States and Mexico River Stretches

The United States Bureau of Reclamation (BOR) maps vegetation by aerial photography using a semi-quantitative classification system based on vertical structure complexity and percent of native trees (Ohmart et al., 1988; M. Balough, BOR, Boulder, Nevada, unpublished information sheets accompanying 1997 aerial survey data). We used the same general system to classify the 63 aerial images taken along the native tree zone in the Delta. BOR classifies riparian vegetation in 1 ha mapping units using a two-tier system. First the mapping unit is classified by dominant plant type. In general the dominant plant type must constitute > 50% of plant cover, but BOR counts a plot that has >10% *P. fremontii* + *S. gooddingii* as cottonwood-willow habitat because even a few trees are considered to improve habitat value over shrub monocultures. Each mapping unit is then classified into one of six vertical structure classes based on the percent cover by overstory, midstory and understory plants. For example, a plot with 35-80% cover of native trees over 5 m height is considered cottonwood-willow, open gallery forest habitat, while a plot with >80% trees is classified as closed gallery forest.

We classified each aerial image (0.67 ha) having >10% of the vegetation in the tree category as native tree habitat, then used the percentage of groundcover, shrub and trees in each image as rough equivalents of the three height classes of the Bureau of Reclamation to classify those images into gallery forest or shrub vertical structure types. Our height classes are not exactly the same as theirs, however. They consider understory plants as everything < 1m height, but we used 2 m as the cutoff because juvenile plants of all major species were within this range. We used 6 m rather than 5 m as the minimum height for overstory plants, because this cutoff separated mature native trees from *T. ramosissima* and other shrubs. Hence, we tend to underestimate overstory, native tree density compared to BOR methods.

Soil Samples and Groundwater Monitoring

Three soil samples from the top 20 cm of soil profile in each transect (n = 42) were analyzed for percentage of soil texture classes and electrical conductivity (EC) of a 1:1 extract by Laboratory Consultants, Inc., Tempe, Arizona. Soil texture class was determined by the proportion of sand, silt and clay in each sample. Well points (5 cm diameter steel tubes with a perforated sand point at the tip) were installed into the water table at or near 4 of the transects (2-3 per transect spaced ca. 100 m apart perpendicular to the river, 10 total, plus 2 additional points at Campo Munoz, in the tidally influenced portion of river) to monitor ground water. Water depth was determined after pumping 3 or more volumes of water from the casing with a hand pump then allowing the well to recharge; a sample was measured for electrical conductivity (EC) by the U.S. Geological Survey lab, Tucson, Arizona. Well points were sampled in November, 1999 and January and February, 2000.

RESULTS

Transect Results

A summary of soil, groundwater and vegetation conditions in each stratum of each transect is in Figure 2.4. This figure shows the location of the vegetation transects along the river (y-axis) and length of each transect (x-axis) are shown schematically in the upper left hand graph. Some transects were divided into separate zones, results of which are shown separately in the pictographs that follow. The locator graph also shows whether transects were on the east or west side of the river channel. Symbols for individual plant types are shown in the upper right hand box using common names. In the graphs showing results for each zone, the height of the plant symbols indicates plant height (y-axis), while the width of the plant stand indicates % cover. Over each set of plant symbols, % cover (numerator) and density in plants per ha (denominator) is given. Near the name of each transect, the % covered by bare soil is given. The x-axis also indicates the length of the zone in meters, and under the x-axis, the soil type and mean and standard error of soil EC in 1:1 extracts is given. In those transect with well points, the mean and standard error of EC readings in the water table is given under the x-axis near the origin (over wave symbol). Note that well points indicated as in the Carranza transect were actually several kilometers distant (Figure 2.2).

The predominant soil type over all transects was sandy loam. Electric Conductivity (EC) of most soil samples was low (mean = 0.65 dS m^{-1}). From November, 1999 to February, 2000 groundwater was shallow (1-2 m) at all stations, but a decreasing salinity gradient was apparent from south to north within the native tree zone, with groundwater EC's ranging from 1.4 to 4.4 dS m^{-1} (salinity of 840 to 2640 parts per million (ppm)) for well points within the native tree zone. The well points placed below the junction with the Hardy River at the

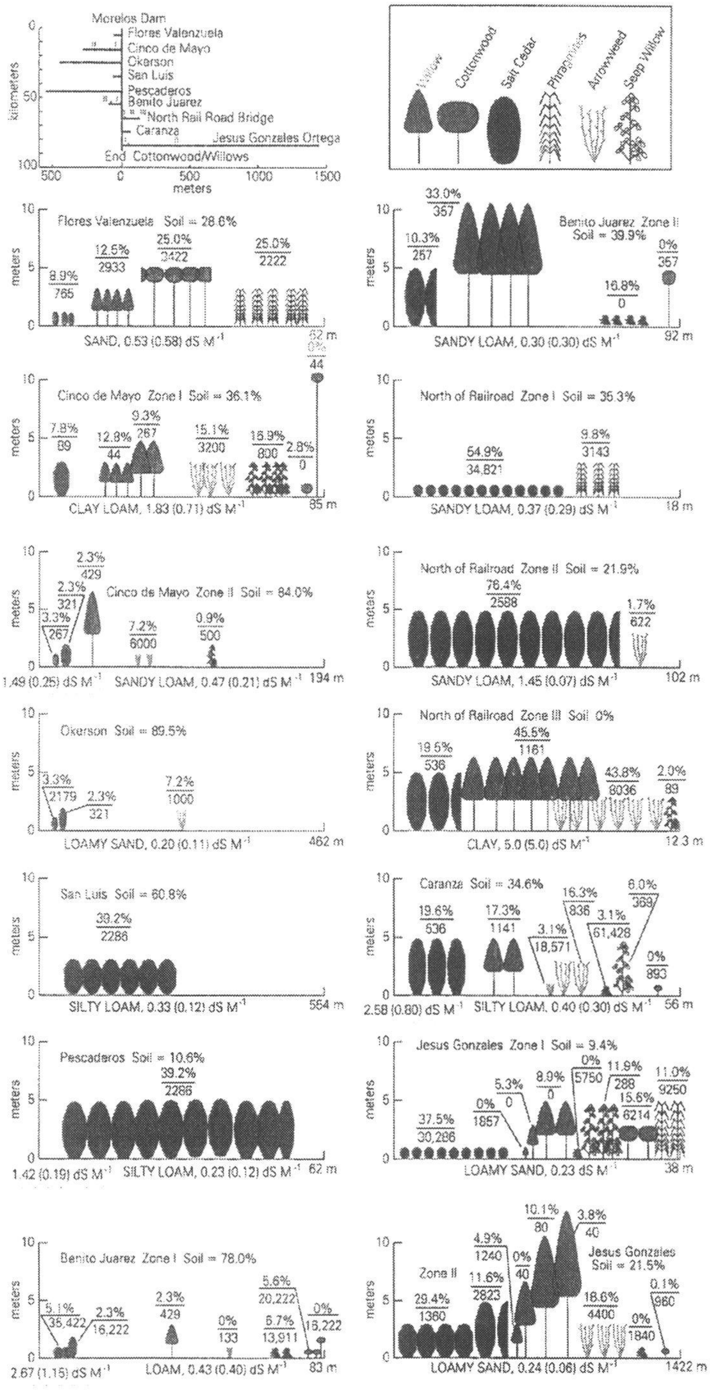

Figure 2.4. Vegetation distribution along 9 transects in the Colorado River delta, Mexico.

Campo Munoz had water of 9.7 dS m^{-1} (5,820 ppm). Groundwater in general was saltier (higher EC) than river water (1.2 dS m^{-1} or 720 ppm), presumably due to evaporation, the influence of saline subsurface drainage from adjacent agricultural fields, and to the flushing of salts from the soil surface to the groundwater by flood waters.

Six plant species were commonly encountered in study plots (Figure 2.4): *T. ramosissima*, a mid-story species (up to 6 m height); *Pluchea sericea* (arrowweed), a salt-tolerant shrub; *Baccharis salicifolia* (seepwillow), a mesophytic shrub; *S. gooddingii* and *P. fremontii* trees, that were present in all size classes but were the only species above 6 m height; and the emergent, aquatic grass, *Phragmites australis* (common reed), found along the water line on three transects where the channel had not entrenched. *Prosopis pubescens* (screwbean mesquite tree) was locally abundant in some parts of the floodplain but was not encountered in the transects. Felger et al. (1998) provide a complete flora of the Delta.

Transects varied in length, from 62 m near Morelos Dam (km 0) to 1,465 m at the southernmost transect, Luis Gonzales (km 95), due to widening of the flood plain as it approached the intertidal zone (Figure 2.4). The first transect, Flores Valenzuela (km 5) was dominated by 3-5 m tall *P. fremontii* and *S. gooddingii* trees (32.5% cover) and bare soil (28.6% cover). A fringe of *P. australis* (25% cover) grew along the active river channel, which was not incised in this reach. The Cinco de Mayo transect (km 15) was wider and had a more varied flora than Flores Valenzuela. In its low zone, it was dominated by bare soil (36.1% cover) and a mix of small *S. gooddingii* trees, and *B. salicifolia*, *P. sericea* and *T. ramosissima* shrubs. The high terrace (Zone II) of the Cinco de Mayo transect was mainly bare soil (84%) with a few tall (to 7 m) *S. goodingii* trees and small shrubs. The next 5 sites, extending south to the railroad bridge (km 75), were dominated by bare soil and *T. ramosissima*, although strands of native trees were found in the back zone growing along the levees at the Benito Juarez and North-of- Railroad transects.

The river channel was incised along this reach and a low zone was absent. The last transect, Jesus Gonzales, was in the wide part of the flood plain, where the river had split into several meandering channels with a well developed low zone. This part of the flood plain supported large numbers of willows, up to 12 m in height, although *T. ramosissima* was the dominant plant.

Plant density data (Figure 2.4) showed that juveniles and seedlings of all species were scattered throughout the transects. Although *T. ramosissima* and *P. sericea* abundant in isolated patches at several transects. *B. salicifolia* seedlings were a main part of the understory at some transects.

Distribution of Trees by Size and Age Class

Detailed tree census data at three transects showed that *S. gooddingii* (65% of trees censussed) was more abundant than *P. fremontii* (35%) in the floodplain (Fig. 2.5 a and b). Annual tree rings were counted in a sub-sample of tree cores to determine age vs. basal diameter (fig 2.5 c, where circles = willow and closed squares = cottonwood). A single regression line passing through the origin was fit to the data to estimate age of trees based on basal diameter. The trees fell into age classes which appeared to correspond to periods of water release, marked with arrows: 1 is the 1997-1999 releases; 2 is the 1993 release; and 3 is the 1983-1986 release (fig 2.5 d). Based on the correlation between basal diameter and number of annual rings, three age classes of trees were apparent: older trees (up to 12 m) with 12-20 annual rings, probably started during the floods of the early 1980's; younger trees (6-10 m) with 5-7 annual rings, probably started after the 1993 flood; and juvenile trees (4 m or less) with 2-4 rings, probably started after the 1997 flood. The 1993 age class was the most numerous for both *P. fremontii* and *S. gooddingii*, but *P. fremontii* (mean age = 7.3 years) tended to be older than *S. gooddingii* (mean age = 4.7 years). Although mean ages were different, mean heights were similar (8.4 m and 8.1 m, respectively).

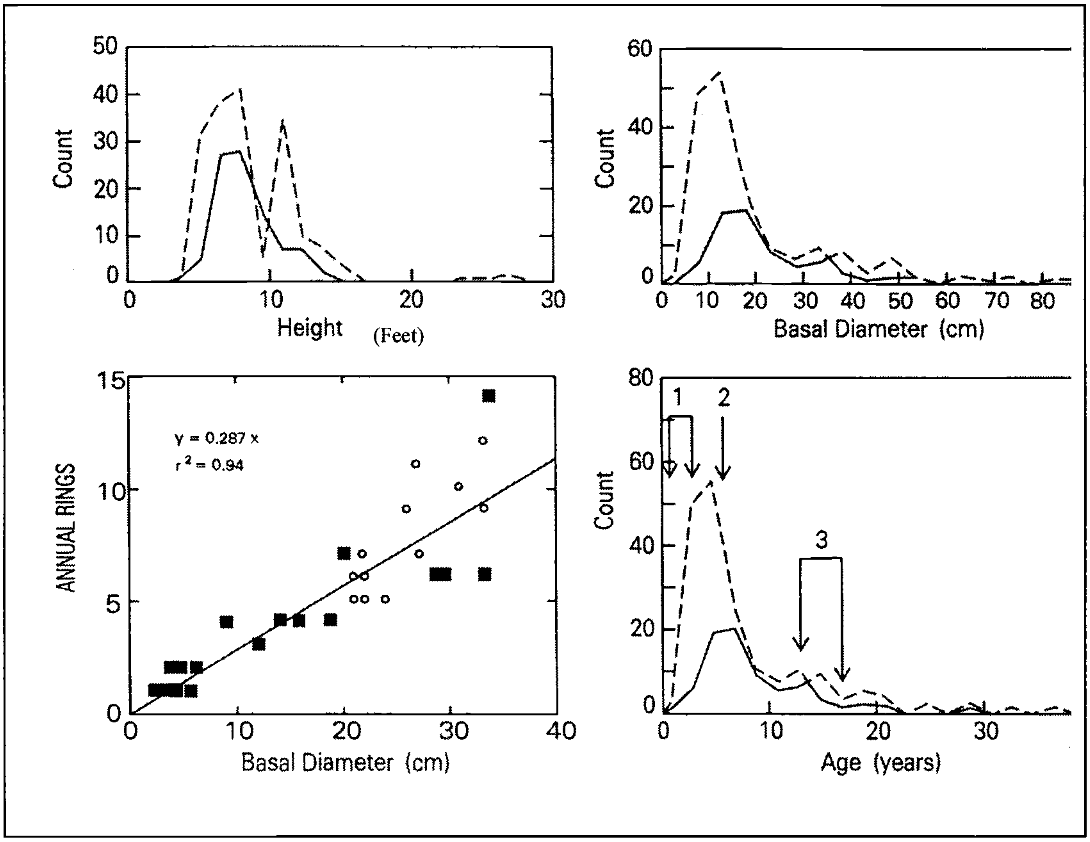

Figure 2.5. Detailed tree census data at three transects surveyed in the Colorado River Delta: a) Height; b) basal diameter for 264 cottonwood (solid line) and willow (dashed line); c) age vs. basal diameter; and d) age vs. count.

Estimates of Plant Distributions Based on Transects and Aerial Surveys

Table 2.1 gives plant distributions computed by weighted average over the transects (part a) and compares estimates of aerial coverage determined by transect and aerial photographic methods (part b). Transect results for each species are divided into understory, midstory and overstory classes based on plant height; these classes correspond approximately to the groundcover, shrub, and tree classes which could be distinguished on the aerial photographs. *T. ramosissima* was by far the most abundant plant in the Delta, accounting for 40% of ground cover, followed by *S. gooddingii* (10.9%) and *P. sericea* (10.3%). Transects and aerial photos gave similar estimates of bare soil (35-37%), midstory shrubs (46-53%) and overstory trees (4.5-7%) but differed in estimates of understory cover, which was higher in aerial photos than in transect results. Thickly-growing plants such as *P. australis* and *P. sericea* often achieved height greater than 2 m and were placed in the midstory class in transects, but individual plants of these species could not be distinguished in aerial photographs so they were classed as understory by the aerial survey method.

Comparison of Native Tree Cover on U.S. and Mexico Portions of the River

We compared the number of hectares of native tree habitat in the Delta with estimates for the regulated portion of the river (above Morelos Dam) made by Bureau of Reclamation (BOR). The results (Table 2.2) show that the Delta supports 2.5 times as much native tree habitat as the stretch from Davis Dam, below Grand Canyon, to Morelos Dam (6 times more per unit area). Approximately 1,800 ha of gallery forest has regenerated in the Delta, compared to only a single stand of 98 ha on the regulated stretch, and this patch actually is in the Delta of the Bill Williams River, a tributary of the Colorado River (Ohmart et al., 1988).

Timing and Flow Rates of Water Releases to the Delta

We examined flows to the Delta over the period 1992 to 1999 to correlate flows with vegetation data. Water releases during major releases varied in volume from less than 100 $m^3 sec^{-1}$ to over 1,000 $m^3 sec^{-1}$ (Figure 2.6). We conducted an

Table 2.1. a) Distribution of species (% ground cover) among understory (< 2 m), midstory (2.1- 6 m) and overstory (> 6 m) height classes for plants in the Colorado River delta. b) Comparison between detection methods.

a) Species	Understory	Midstory	Overstory	Total
T. ramosissima	1.6 (0.2)	38.5 (2.9)	0.0	40.1 (2.2)
P. sericea	1.0 (0.2)	9.3 (2.8)	0.0	10.3 (2.1)
S. gooddingii	0.0	3.9 (0.7)	7.0 (1.3)	10.9 (1.4)
P. fremontii	0.3 (0.1)	0.2 (0.1)	0.1 (0.1)	0.6 (0.1)
B. salicifolia	1.4 (0.4)	0.5 (0.2)	0.0	1.9 (0.4)
P. australis	0.0	0.7 (0.2)	0.0	0.7 (0.2)
b) Comparison of Methods:				
	Understory	**Midstory**	**Overstory**	**Bare Soil or Water**
Transects	4.3 (0.5)	53.1 (3.1)	7.1 (1.0)	35.5 (1.5)
Aerial Survey	12.9 (1.8)	45.6 (2.9)	4.5 (0.6)	37.0 (2.4)

Note: Values are means and standard errors. Data for individual species are from nine transects along the river. The percentage of plants in each height class was compared for the transect method and by interpretation of 63 aerial photos; individual species could not be distinguished in the aerial photographic method.

over flight in February, 1997, when releases were 80-100 $m^3 sec^{-1}$ according to IBWC data, to document the extent of flooding from a low-volume release. We observed extensive over-bank flooding of the river within the levee system, and water was exiting the Delta into the Gulf of California via the river channel and sheet flooding of the lower Delta floodplain. Furthermore, water was flowing into

Laguna Salada, a below-sea-level depression west of the Delta. Mexico Highway 2 that runs from Mexicali to San Felipe, which crosses the southern part of the Delta, was flooded and impassible. Progressively larger volumes of water released during 1997-1999, flooded greater areas of floodplain within the levees and in Laguna Salada, but did not flood agricultural or urban areas. Discharges occurred mainly in winter and spring (February to April), with one fall release (September to December, 1998) and almost no releases in summer.

Correlation between Vegetation Cover and Flow Releases, 1992-1999

In this study percent vegetation cover includes several classes, including open water areas, bare soil areas, and several classes representing different percentages of vegetated cover (see fig 2.6). Percent vegetation cover, as estimated by NDVI values on satellite images of the Delta for different years, showed an apparent positive response to flood flows (Figure 2.6). We quantified the relationship by calculating percent vegetation cover in the first 100 km of river below Morelos Dam for years before and after each flow event in the 1990's. We found a positive relationship between percent vegetation and the total of the three previous years' volume (calculated from flow rates over time) ($r = 0.80$-0.82). However, the strongest correlation was simply with the number of previous years of flow irrespective of volume ($r = 0.97$). Thus, the lowest cover (ca. 50%) was present in 1992 and 1996, years which were preceded by three or more years without river discharge (see figure 2.1). Vegetation cover was ca. 53% in 1994 and 1997, following or during a wet year (1993 and 1997). These values were similar even though the 1993 discharge peaked at >500 m3/sec compared to <100 m3/sec in 1997. Then, vegetation cover increased progressively after 1997 as discharges continued in 1998 and 1999, reaching 62% after three years of discharge.

Table 2.2. Comparison of area of native tree habitat (> 10% *P. fremontii* and *S. gooddingii*) and shrub habitat (*T. ramosissima* + *P. sericea*) on the regulated stretch of the lower Colorado River in the United States, from Davis Dam to the Northerly International Boundary, and on the unregulated stretch in Mexico, from the Northerly International Boundary to the junction with Rio Hardy.

Habitat Type	**U.S. Stretch**		**Mexico Stretch**	
P. fremontii + S. gooddingii greater than 10%	%	Hectares	%	Hectares
Open Gallery Forest	0.0	0.0	12.7	1,818
Closed Gallery Forest	.03	98	0.0	0.0
Shrub Dominated	4.3	1,460	14.3	2,045
Total	4.6	1,558	27.0	3,863
P. fremontii + S. gooddingii less than 10%				
T. ramosissima/ P. sericea	54.1	18,453	73.0	10,453
T. ramosissima/ Prosopis	31.7	10,829	0	0
Other	9.6	3,273	0	0
Totals	100	34,096	100	14,316

Gallery forest has > 80% (closed gallery) or > 35% (open gallery) overstory trees. The "other" category for the U.S. stretch includes emergent marsh and Atriplex (saltbush) habitat not encountered in the river stretch surveyed in the delta.

DISCUSSION

As is the case along many western rivers, the stretch of the Colorado River between Morelos Dam and the Hardy River is dominated by the exotic shrub, *T. ramosissima*. Although often considered an undesirable species, *T. ramosissima* can fulfill valuable ecological functions in riparian ecosystems (Stromberg, 1998b).

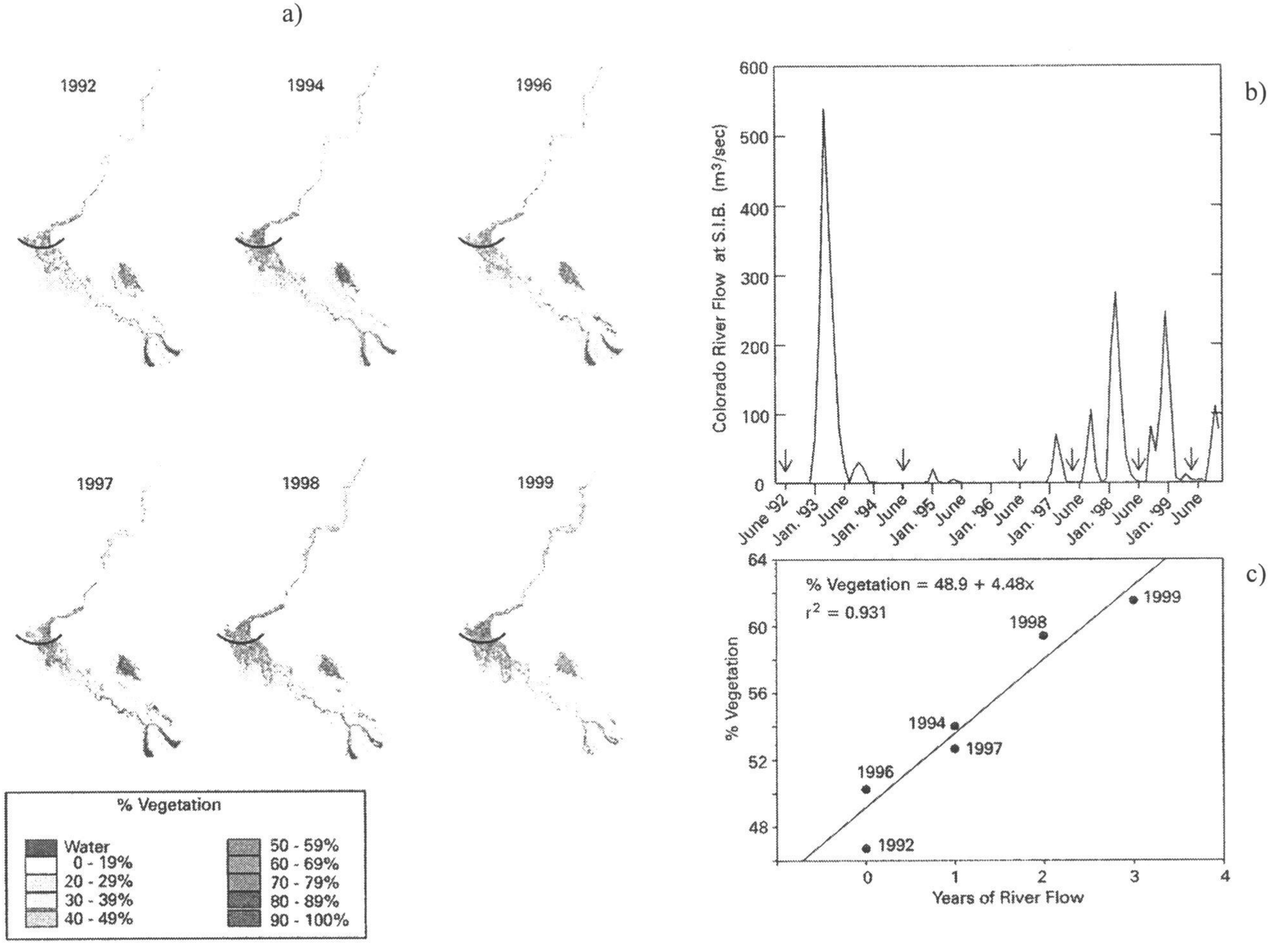

Figure 2.6. Relationship between % vegetation cover and flood events in the Colorado River Delta, Mexico. TM images (A) showing summer vegetation before and after major flood events (B)(arrows show dates of TM images) were classified using NDVI to show % vegetation cover in the native tree zone (the riparian zone north of the dark line across each image). (C) is the regression of % vegetation on the number of prior years of water discharge.

This study shows that with the resumption of pulse floods following the filling of Lake Powell, native riparian wetland trees have also reestablished along this river stretch. The tree cohorts appear to be related to the 1981-1986, 1993, and 1997-1999 releases of water from the United States to the floodplain below Morelos Dam. These releases were related to strong El Niño Southern Oscilation cycles and are expected to continue into the future, whenever precipitation in the watershed exceeds storage capacity in the reservoir system (J. Harkens, River Operations Manager, BOR, Boulder City, Nevada, private communication). Native trees, including many over 6 m height, now account for 20% of the species composition in this river stretch, whereas they remain rare on the U.S. stretch of river above Morelos Dam. Native trees are less salt-tolerant than *T. ramosissima* (Glenn et al., 1998). The results support the pulse-flood hypotheses for the establishment of native trees, which states that occasional over-bank flooding is necessary to wash salts from the banks to allow mesophytic species to germinate (Briggs, 1996; Poff et al, 1997; Busch and Smith, 1995). Otherwise, backside areas become too saline for all but the most salt-tolerant plant species. Floods also serve to deposit bare mineral soil needed for germination of native trees and they moisten the soil at the appropriate time, when seeds are viable. Thus, the winter and spring timing of releases to the Delta were fortuitous.

On the United States stretch of river, by contrast, over-bank flooding is now rare (Ohmart et al., 1988). The carrying capacity of the river channel is large, as most of the diversions take place near the Northerly International Boundary (NIB) (see fig 2.2). Furthermore, the floodplain has been channeled to prevent flooding of private property in many locations. Therefore, excess releases that reach the Delta remain channelized until below Morelos Dam, and do not germinate extensive new cohorts of native trees on the United States stretch of river.

Deliberate floods have been tested as management tools in the Grand Canyon (Collier et al., 1996) and Rio Grande (Molls et al., 1998), but up to now the ecological effects of waste spills into the Delta have not been recognized. Recently, we observed that native trees have also regenerated on the Gila River (southernmost tributary of the Colorado River), apparently as a result of flood releases from Painted Rock Dam following 1993 and 1997 ENSO events (P. Nagler, unpublished results of an aerial survey of the Colorado River and tributaries, April, 2000). The Delta floods appear also to stimulate the shrimp catch in the upper Gulf of California (Galindo-Bect et al., 2000). Large, periodic disturbances such as these releases need to be included in ecosystem management plans (Dale et al., 1998).

CONCLUSIONS

The February-April, 1997, release of 300 million m^3 at 80-120 m^3 sec^{-1} was sufficient to bring the river out of its channel on the Mexican side to inundate most of the floodplain, and water exited to the Gulf of California and Laguna Salada. We conclude that this flow rate and volume is sufficient to inundate at least the northern portion of the floodplain (the cottonwood-willow zone) sufficient to allow the establishment of new stands of native trees. The 1993 release was a single event of approximately 3 months duration in winter and spring, yet it produced the largest cohort of native trees, so we conclude that a 3 month spring release is sufficient to germinate tree seedlings. The 1993 cohort of trees was still abundant in 1999 despite lack of flows from 1994 to 1997, showing that trees can survive at least 4 years between floods. In years without floods, native trees can exist on alluvial water tables (Seaforth et al., 2000; Springer et al., 1999). Depth to groundwater is no greater than 1-2 meters along this stretch of riparian corridor, even in years without surface flow (Mexico National Water Commission, Mexicali, Mexico, unpublished groundwater maps, 1995-1998). Nevertheless, the increase in total vegetation cover in response to multiple years of flooding shows that surface flows also play a role in controlling vegetation cover. Their role in recharging the groundwater or moderating its salinity is unknown. A hydrological model of the Delta floodplain is needed to better understand these relationships.

Gallery forests of the native trees *S. gooddingii* and *P. fremontii* in the Delta can be considered as indicators of wetland regeneration and healthy riparian habitat. This gallery forest provides vertical vegetation complexity that favors the presence of wildlife, particularly birds as they found suitable habitat for nesting, rest and/or feed. However, the future of the regenerated Delta ecosystem is in doubt. In Mexico, plans are underway to further channelize the river to remove obstructions to future releases (Valdés-Casillas et al., 1998) and thus prevent flooding of agricultural and urban areas. In the United States, the criteria for declaring surplus flows have been revised to attempt to retain more of the flood water for human use in the U.S. Nevertheless, results show that the Delta of an arid river can retain natural ecosystem functions that have disappeared from upstream, regulated stretches, and that water availability may actually increase after the dam systems fill. Hence, delta regions of arid rivers should be targets for conservation actions to maintain riparian biodiversity.

REFERENCES

Briggs, M. (1996), Riparian Recovery in Arid Lands, Strategies and References, University of Arizona Press, Tucson.

Busch, D. and S. Smith (1995), Mechanisms associated with decline of woody species in riparian ecosystems of the southwestern US. *Ecological Monographs* **65**: 347-370.

Collier, M., R. Webb and E. Andrews (1996), Experimental flooding in Grand Canyon. *Scientific American* **276**: 82-89.

Cook, C. and C. Bonham, (1977), Techniques for Vegetation Measurements and Analysis for a Pre-And Post-Mining Inventory. Colorado State University Range Science Department Science Series No. 28, 99 pp.

Curtis, J. and G. Cottam, (1962), Plant Ecology Workbook, Burgess Publ. Co., Minneapolis, Minnesota.

Dale, V., A. Lugo, J. MacMahon and S. Pickett (1998), Ecosystem management in the context of large, infrequent disturbances. *Ecosystems* **1**:546-557.

Dynesius, M. and C. Nilsson (1994), Fragmentation and flow regulation of river systems in the northern 3rd of the world. *Science* **266**: 753-762.

Felger, R., B. Broyles, M. Wilson and G. Nabhan (1997), The binational Sonoran Desert biosphere network and its plant life (With plant checklist and index). *Journal of the Southwest* **39**: 411-566.

Galindo-Bect, R., E. Glenn, H. Page et al. (2000), Penaeid shrimp landings in the upper Gulf of California in relation to Colorado River freshwater discharge. *Fishery Bulletin* **98**: 222-225.

Glantz, M. (1996), Currents of change: El Nino's Impact on Climate and Society, Cambridge University Press, England (1996).

Glenn, E., J. Garcia, R. Tanner, C. Congdon and D. Luecke, (1999), Status of wetlands supported by agricultural drainage water in the Colorado River delta, Mexico *HortScience* **34**: 39-45.

Glenn, E., R. Tanner, S. Mendez, T. Kehret, D. Moore, J. Garcia and C. Valdés (1998), Growth rates, salt tolerance and water use characteristics of native and invasive riparian plants from the delta of the Colorado River, Mexico. *Journal of Arid Environments* **40**: 281-294.

Glenn, E., R. C. Lee, R. Felger and S. Zengel (1996), Effects of water management on the wetlands of the Colorado River Delta, Mexico. *Conservation Biology* **10**: 1175-1186.

Li, Z. and M. Kafatos (2000), Interannual variability of vegetation in the United States and its relation to El Nino/Southern Oscillation. *Remote Sensing of Environment* **71**: 239-247.

Molls, M., C. Crawford, L. Ellis, H. Valett and C. Dahm (1998), Managed flooding for riparian ecosystem restoration - Managed flooding reorganizes riparian forest ecosystems along the middle Rio Grande in New Mexico. *Bioscience* **48**: 749-756.

Morrison, J., S. Postel and P. Gleick (1996), The Sustainable Use of Water in the Lower Colorado River Basin, Pacific Institute, Oakland, California USA (1996).

Nagler, P., H. Rodriguez, E. Glenn and A. Huete. (2001). Assessment of spectral vegetation indices for riparian ecosystems in the Colorado River Delta. *Journal of Arid Environments*. **49**: 91-110.

Nagler, P., K. Gillon, J. Pitt, W. Snape and E. Glenn (2000), Application of the endangered species act across international borders: the case of the Colorado River delta, Mexico. *Environmental Science and Policy* **3**: 11-15.

Nilsson, C., R. Jansson and U. Zinko (1997), Long-term responses of river-margin vegetation to water-level regulation. *Science* **276**: 798-800.

Ohmart, R., B. Anderson and W. Hunter (1988), Ecology of the Lower Colorado River from Davis Dam to the Mexico-United States Boundary: A Community Profile. National Technical Information Service, Alexandria, Virginia USA.

Poff, N., J. Allan, M. Bain, J. Karr, K. Prestegaard, B. Richter, R. Sparks and J. Stromberg (1997), The natural flow regime. *Bioscience* **47**: 769-784.

Stromberg J. (1998a), Dynamics of Fremont cottonwood (Populus fremontii) and saltcedar (Tamarix chinensis) populations along the San Pedro River, Arizona. *Journal of Arid Environments* **40**: 133-155.

Stromberg, J. (1998b), Functional equivalency of saltcedar (*Tamarix chinensis*) and Fremont cottonwood (*Populus fremontii*) along a free-flowing river. *Wetlands* **18**: 675-686.

Seaforth P, J. Stromberg and D. Patten (2000), Woody riparian vegetation response to different alluvial water table regimes. *Western North American Naturalist* **60**: 66-76.

Springer, A., J. Wright, P. Seaforth, J. Stromberg and D. Patten (1999), Coupling groundwater and riparian vegetation models to assess effects of reservoir releases. *Water Resources Research* **35**: 3621-3630.

U.S. Bureau of Reclamation (1996), Description and Assessment of Operations, Maintenance, and Sensitive Species of the Lower Colorado River. U.S. Bureau of Reclamation, Boulder City, Nevada.

Valdés-Casillas Carlos, O. Hinojosa-Huerta, M. Muñoz-Viveros, F. Zamora-Arroyo, Y. Carrillo-Guerrero, S. Delgado-Garcia, M. Lopez-Camacho, E. Glenn, J. Garcia, J. Riley, D. Baumgartner, M. Briggs, C. Lee, E. Chavarria-Correa, C. Congdon, and D. Luecke. (1998). Information Database and Local Outreach Program for the Restoration of the Hardy River Wetlands, Lower Colorado River Delta, Baja California and Sonora, Mexico, North American Wetland Conservation Council, Arlington, Virginia USA. 103 pp.

CHAPTER 3

VEGETATION TRENDS AND THEIR RELATIONSHIP WITH INSTREAM FLOWS IN THE COLORADO RIVER DELTA, MEXICO

Francisco Zamora-Arroyo and Osvel Hinojosa-Huerta

ABSTRACT

A trend analysis is performed to multi-temporal data (1992, 1994, 1996-1999) on percent vegetation cover to statically determine what areas have actually experienced an upward change in vegetation cover in the Colorado River Delta. This is the first attempt in the literature to analyze the null hypothesis of a no change in vegetation cover trend in the Colorado River Delta. The analysis considers natural vegetated areas within the floodplain in the Mexico portion of the Delta, from Morelos Dam at the Mexico-USA border to Montague Island at the river mouth in the Gulf of California. The study area comprises approximately 100 river miles and covers a total area of 169,000 ha. Eight zones were defined based on percent vegetation cover and their water sources, and are used to summarize trend analysis results. The results indicates that there are 6,320 ha that show a significant increasing trend in percent vegetation cover ($p<0.05$), whereas only 4,695 ha show a significant ($p<0.05$) downward trend. The three zones with riparian wetland vegetation have between 18% and 46% of their area showing an upward trend in percent vegetation cover. This is clear evidence that there has been a regeneration of riparian vegetation in the Delta during the 1990s.

A statistical analysis was also performed to explore the relationship of percent vegetation cover and water flows and to develop specific hypothesis for future testing. Fifteen variables characterizing instream flows in the 1990s were defined and three different multiple regression analysis models were run to explore the effect that instream flows had on three dependent variables: a) the average percent vegetation cover, b) total ha of vegetation cover >70%, and c) total ha of open water. The variables that had the most significant relationship with areas of vegetation cover >70% are the 4 years average of river flows at SIB ($\underline{p} < 0.02$), 1 month and 3 months average of flows through the SIB, and number of days with average flow $>2m^3/s$ at the SIB. This supports the hypothesis of a large flow every four years needed to flood banks and help establish vegetation and smaller but

periodic or continuous flows greater than 2 m^3/s to maintain it. However, a more complete set of data is required to test this hypothesis. The information presented here, combined with other already available information, should be valuable for the identification of restoration opportunities under different water flow scenarios.

INTRODUCTION

Understanding the capacity of an ecosystem to resist disturbance (its resilience) is considered to be a key element in the conservation of biodiversity (Folke et al., 1996). The resilience of an arid river system, such as the U.S.-Mexico Lower Colorado Basin, could be associated with natural stream flow variability, which plays a major role in organizing riparian wetlands (Richter and Richter, 2000). Variability of the instream flow patterns reaching the Colorado River Delta in the last 20 years has been characterized by human-induced flows that resemble natural pulse-floods (Cohen et al., 2001). Not surprisingly, during the same period, some areas in the Delta appear to have been through a revegetation process (Glenn et al. 1996, Valdes-Casillas et al., 1998, Zamora-Arroyo et al., 2001), which is an indication of the resilience of its wetlands, an ecosystem that was once considered dead (Fradkin, 1981).

Natural perturbations also influence the resilience of an ecosystem (Costanza and Folke, 1996). It was a natural event, El Niño storms and associated excess water flows in the basin that triggered a natural ecological restoration process in the Delta (Valdés-Casillas et al., 1998; Zamora-Arroyo, et al., 2001). However, we recognize that an ecosystem might have a threshold point in which the system may not be capable of recovery to maintain its ecological functionality. Crossing this threshold, in the case of the Colorado River Delta, would impact not only native wildlife, endangered and threatened species, and the estuarine area in the Upper Gulf of California, but it would represent in itself a disturbance to regional and global ecological patterns, as these wetlands are keystone areas in the migratory route of water and land birds (Mellink et al., 1997; Hinojosa-Huerta et al., 2001) and provide a critical interface between freshwater wetlands and the Gulf of California (Glenn et al., 1996).

Therefore, the critical question in managing the Delta ecosystems at a binational level is: how much water is required to support ecological processes at current wetland areas? This question needs to be addressed not only in terms of what the ecosystem needs to protect or maintain current revitalized wetlands areas, but also in terms of water requirements to induce revitalization on additional areas. Hence, the question of water needs not only has to do with the amount of water, but also with the timing and quality of these flows and with setting priorities for the Delta ecosystems where environmental benefits for wildlife and wetland dependent human uses could be maximized. In other words, what is ultimately needed is to determine the ecological demand for water for the conservation and restoration of critical wetlands in the Delta.

The general objective of this work is to provide key information that can be used to determine the magnitude, duration, and frequency of flows needed to restore and maintain the ecological functions of Delta wetlands. This information is developed by performing a trend analysis using multi-temporal data (1992-1999) on percent vegetation cover data to statically determine what areas have actually experienced an upward change in vegetation cover. This is the first attempt in the literature to analyze the null hypothesis of "no vegetation cover trend" in the Colorado River Delta. This study also explores the relationship of percent vegetation cover with variables characterizing instream flows in the 1990s. Based on this analysis, a specific hypothesis for future testing is identified regarding such trends and their relationship with instream flows. The results from this study are used in the next chapter to help in the identification of those areas which could be targeted for restoration.

MATERIALS AND METHODS

Study Area

The analysis considers natural vegetated areas within the floodplain in the Mexico portion of the Colorado River Delta, from Morelos Dam at the Mexico-USA border to Montague Island at the river mouth in the Gulf of California (Fig 3.1). The study area comprises approximately 100 river miles and covers a total area of 169,000 ha. A characteristic feature of the area is its two earthen levees running south from the international border to the Hardy River (West levee) and to the northern portion of the Cienega (East levee). The northern narrow half of the study area includes non-agricultural zones in the floodplain defined by these levees, whereas the wider southern half includes areas within the levees and beyond the levees where there is a strong influence from agricultural drainage, as well as the intertidal zone and the Cienega de Santa Clara. This study area has been expanded from that in Chapter 2 in order to include other important habitat types in addition to the riparian corridor.

Habitat zones and percent vegetation cover analysis

The study area was divided into "habitat zones" based mainly on their vegetation composition and water availability and sources, which are the major factors in the creation of distinct habitat types in the Delta. In some cases, however, a non-ecological criterion was also used to facilitate their management in the future. Limits of each zone were manually digitized using the 1998 Thematic Mapper (TM) image, results from field work, and the 1998 percent vegetation cover map as reference. Field work included a reconnaissance boat trip along the river from the railroad crossing (see fig 2.2 in Chapter 2) for about 35 km

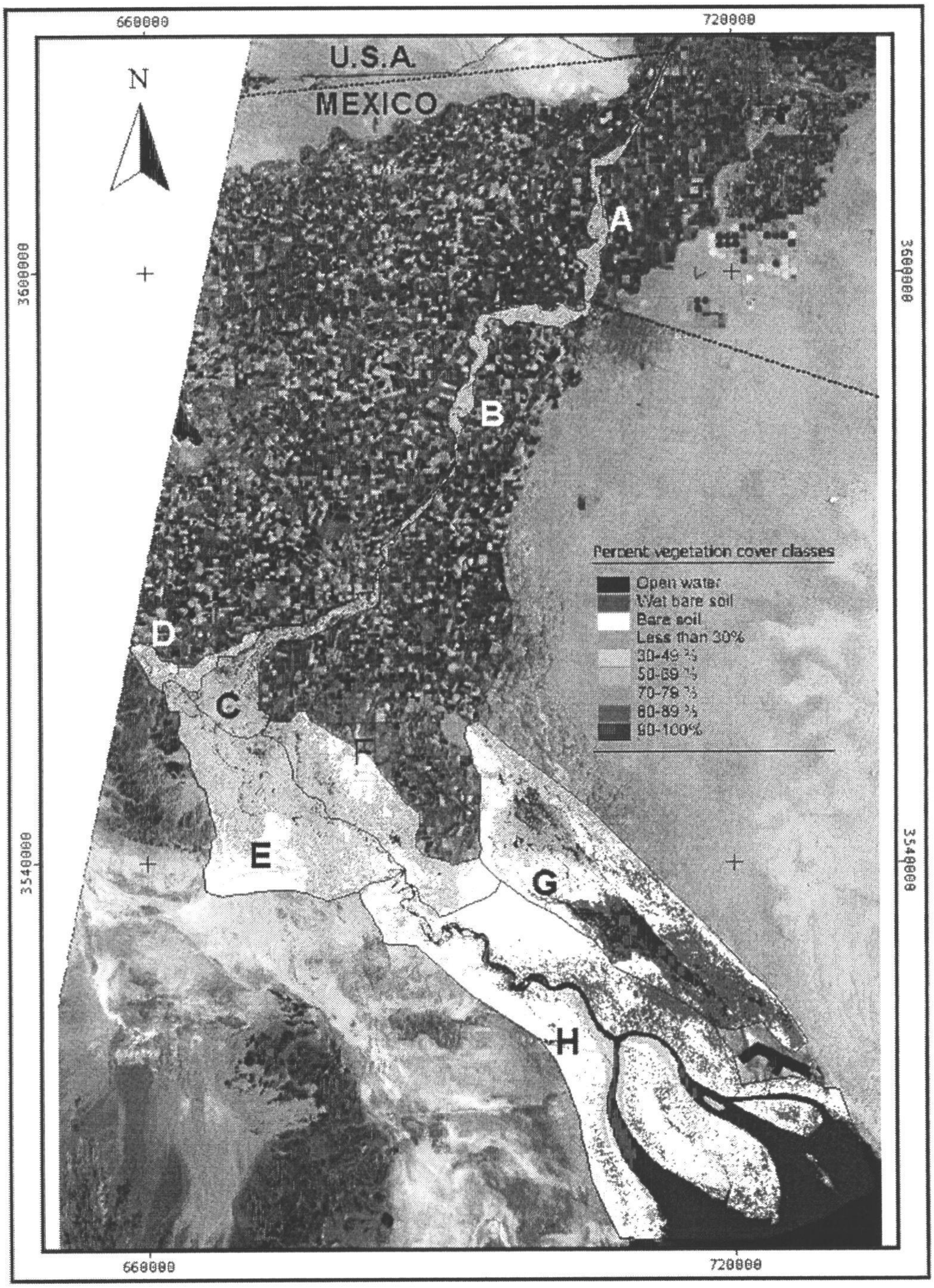

Figure 3.1. Study area and habitat zones in the Colorado River Delta, Mexico. Eight ecozones are defined: A) Morelos; B) San Luis; C) Carranza; D) Mayor-Hardy; E) Hardy-Colorado; F) Dren-Ayala; G) Cienega de Santa Clara; and H) Intertidal. The background image is a percent vegetation cover map for 1998 over a 1998 Thematic Mapper image.

downstream and close to the point where no more native riparian trees are found. Patterns in vegetation cover and composition were determined by Zamora-Arroyo et al (2001) using remote sensing and extensive fieldwork throughout the region from 1997-1999 and at different times of the year to capture seasonal variation. Complete results of percent vegetation cover are presented here and summarized by each habitat zone.

Habitat zones, as defined in this dissertation, could comprise both wetland and non-wetland ecosystems (bare soil and upland vegetation). Therefore, to facilitate the use of these zones for wildlife management purposes and to highlight their association with flood flows, we defined the wetland habitat within each habitat zone. This was accomplished by defining wetland habitat as those areas having a percent vegetation cover greater than 70% or any open water area in the 1998 percent vegetation cover map. Since the percent vegetation cover analysis could not distinguish specific plant species, the results of vegetation analysis by Zamora-Arroyo et al (2001) were used to distinguish wetland habitat dominated by native riparian vegetation and those dominated by non-native vegetation, such as salt cedar (*Tamarix ramosissima*). Particularly useful was the field work that allowed us to verify that, in the riparian corridor (Morelos, San Luis and Carranza), using areas with vegetation cover greater than 70% was a good approximation of wetland habitat and that this is likely to underestimate in most cases the actual wetland habitat in the corridor. The habitat zones described here were used to summarize statistical results from the trend analysis on percent vegetation cover as well as the water flow analysis.

Vegetation trend analysis

A spatial trend analysis was performed on percent vegetation cover of the study area. Vegetation cover maps were calculated by Zamora-Arroyo et al. (2001)

by applying the equation developed by Nagler et al. (2001) to each image. The Mann-Kendall test was then used to perform the spatial trend analysis on percent vegetation cover maps for six years of data (1992, 1994, 1996-1999). We followed the procedure presented by Gilbert (1987, cited in Schlagel and Newton, 1996) to implement he Mann-Kendall test on a pixel basis using ERDAS software. First we calculated the difference between percent coverage values among all possible pairs of years, resulting in two images per each difference. One resulting image contains pixels with a value of +1 if the difference between two years of percent vegetation cover data is positive and 0 in all other cases. The second image contains pixels with a value of –1 if the difference is negative, leaving zeros in all other cases. A similar procedure was applied to all fifteen combinations (subtracting the earlier period from the most recent one), and resulting in 30 new images (15 with only +1 and the other 15 with only –1 values). Finally, a new coverage containing the Mann-Kendall test was created by adding these two separate images, one with the sum of all positive value images (15 total) and one with all negative values images (15 total).

All satellite images were geographically registered by Eosath Corporation based on the 1997 image, using the same map projection and map origin. This minimized the possibility of having areas (pixels) in one image not representing exactly the same area in the other images. Furthermore, since the change analysis was performed on percent vegetation cover classes, the Mann-Kendall trend statistic provides an additional way to account for misregistration as it requires consistent changes in percent vegetation cover in order to indicate a significant trend (Schlagel and Newton, 1996). Because the test required all pixels to have a value for every year of data, it was necessary to eliminate a portion of Morelos and Mayor-Hardy zones from the analysis as the extent of the original satellite images did not allow for calculation of a percent vegetation cover value for these portions.

Effects of instream flows

For each of the wetland zones, we fitted three different multiple linear regression models (Ramsey & Schaffer 1996) to explore the effect that instream flows had on the average percent vegetation cover, total ha of vegetation cover >70%, and total ha of open water (see table 3.1 for model variables). We investigated the relationships of the estimates of vegetation cover from the remote sensing data of each satellite image with Colorado River flows measured at the Southern International Boundary (SIB), which are directed to the floodplain, and with water flows through the Main Outlet Drain Extension (MODE) canal, which are directed to the Cienega de Santa Clara. Data from both flow measurement stations were obtained from the International Boundary and Water Commission (IBWC) Web Page (IBWC 2000).

We created 15 hydrologic variables for each year based on the average daily flow measured at the SIB and MODE canal and on different time periods of average flows prior to the date of each image to be evaluated (Table 3.1). We tested for pairwise correlation of explanatory variables in order to select model variables. If two variables were correlated >0.85, we excluded the variable that had less value for management purposes. We conducted a forward stepwise selection of variables for each model ($p<0.25$) and ran the models including only variables with $p<0.05$.

We focused the interpretation of results on the hydrological variables associated with an increment of average percent vegetation cover, total ha of vegetation cover >70%, and total ha of open water. For each of the models and wetland zones, we tested for autocorrelation of response variables (Sall & Lehman 1996). We also used the Durbin-Watson test to evaluate serial correlation in the models (Pindyck & Rubinfeld 1991). We used JMP IN 3.2.6 (SAS Institute) to perform the statistical analyses.

Table 3.1. Hydrologic variables evaluated as potential explanatory variables to be associated with percent vegetation cover, hectares of vegetation cover >70%, and hectares of open water at each of the wetland zones in the Colorado River Delta.

Variable	Description
Daily flow SIB	Daily average flow (m^3/s) through the SIB at the date of the image
1 month ave. SIB	Average flow (m^3/s) through the SIB considering 1 month prior to the date of the image
3 months ave. SIB	Average flow (m^3/s) through the SIB considering 3 months prior to the date of the image
6 months ave. SIB	Average flow (m^3/s) through the SIB considering 6 months prior to the date of the image
1 year ave. SIB	Average flow (m^3/s) through the SIB considering 1 year prior to the date of the image
2 year ave. SIB	Average flow (m^3/s) through the SIB considering 2 years prior to the date of the image
3 year ave. SIB	Average flow (m^3/s) through the SIB considering 3 years prior to the date of the image
4 year ave. SIB	Average flow (m^3/s) through the SIB considering 4 years prior to the date of the image
Daily flow MODE	Daily average flow (m^3/s) through the MODE at the date of the image
1 month ave. MODE	Average flow (m^3/s) through the MODE considering 1 month prior to the date of the image
3 months ave. MODE	Average flow (m^3/s) through the MODE considering 3 months prior to the date of the image
6 months ave. MODE	Average flow (m^3/s) through the MODE considering 6 months prior to the date of the image
1 year ave. MODE	Average flow (m^3/s) through the MODE considering 1 year prior to the date of the image
No. of days with flows SIB	Number of days with average flow >2 (m^3/s) through the SIB considering 1 year prior to the date of the image
No. of days with flows MODE	Number of days with average flow >2 (m^3/s) through the MODE considering 1 year prior to the date of the image

MODE (Main Outlet Drain Extension) delivers water to the Cienega the Santa Clara.
SIB (Southerly International Boundary).

RESULTS

Percent Vegetation Cover Analysis

Table 3.2 shows the results of the percent vegetation cover analysis summarized by the entire study area (169,000 hectares, see figure 3.1) and for each year a satellite image was available (1992, 1994, 1996-1999). In general, the results show an increment in areas with more vegetation after a year with flows. This pattern is visually apparent in the percent vegetation cover maps between 1992 and 1994 (Fig 3.2) after a year of significant flood (4,135 million m^3) as was 1993 (table 3.3). It is important to notice that previous to 1993, there were four years of very small flows averaging only 16.5 million m^3 per year. The number of hectares of percent vegetation cover classes shows a significant increase from 1992 to 1994, indicating a rapid response from one year to another. This pattern is even more significant when looking at habitat zones in the riparian corridor, in which percent vegetation classes > than 70% more than double from 1992 to 1994 (see fig 3.2 and tables in Appendix 1). After the flood event of 1993, which ended in October, there was again a dry period of three years (averaging 28.5 million m^3 per year), which caused a decline in vegetation cover by 1996 compared with 1994 (see table 3.2 and fig 3.2 and 3.3).

The next flood event was in 1997 with an average flow rate of 41 m^3/s, and followed by more periodic flows later that year and following years (1998 and 1999). Vegetation responded once again after this flood event as indicated by the increasing number of hectares in vegetation cover classes greater than 70% (see table 3.2 and figure 3.4). Although vegetation started to recover with the 1993 flows, it was not until 1997 when this regeneration clearly developed and continues on an increasing rate through 1999 (see table 3.2 and figure 3.4).

The impact of flood events on open water areas are not clear from the results shown in table 3.2 because the large percentage of open water areas that exist are in the intertidal zone tends to minimize the overall impact in the Delta. However, when looking at specific zones, one could find that there was a significant increase in the amount of open water areas during flood years in Morelos, San Luis, and Carranza zones (see appendix I). The impact of flood on open water areas in other zones, such as Hardy-Colorado and Mayor-Hardy, is unclear as these zones receive a continuous flow of water from agricultural drainage in the Mexicali valley. However, satellite images show large inundated areas in the Hardy-Colorado zone during flood years, which are clearly larger than during non-flood years.

Table 3.2. Results of percent vegetation cover analysis in the Colorado River Delta.

Class	**1992**	**1994**	**1996**	**1997**	**1998**	**1999**
Open water	26,190	25,153	28,336	28,880	24,742	17,972
Wet bare soil	18,309	7,719	12,179	19,220	19,677	13,417
Bare Soil	73,285	79,022	77,302	72,953	71,531	81,566
Vegetation						
Less than 30%	23,740	22,925	21,519	17,761	15,779	16,643
30-49%	15,868	17,293	17,025	13,899	16,698	17,358
50-69%	8,605	9,711	7,691	7,563	11,779	13,588
70-79%	2,268	3,551	2,988	3,638	5,218	5,050
80-89%	659	1,359	1,056	2,098	2,250	2,034
90-100%	326	2,520	715	1,910	1,575	1,110
Total hectares	**169,250**	**169,251**	**168,809**	**167,921**	**169,250**	**168,737**
% Veg total	10%	13%	11%	11%	14%	14%
% Open water	15%	15%	17%	17%	15%	11%
% OW & WBS	26%	19%	24%	29%	26%	19%
% Bare soil	43%	47%	46%	43%	42%	48%

OW: Open water; WBS: Wet bare soil. Note: Total hectares are not the same for all years because satellite images for 1996, 1997, and 1999 do not cover the entire study area.

Table 3.3. Flooding events in the Colorado River delta from 1979-2000.

Flooding event	Average flow (m^3/s)	Duration (months)	Total flow Million m^3
May 1979 – January 1981	114.34	21	6,342
January 1983 - February 1988	334.58	61	54,575
January 1993 - October 1993	155.76	10	4,074
January 24,1997 – April 9,1997	40.97	3	315
August 1997 - October 1997	55.91	3	439
January 1998 – May 1998	131.62	5	1,689
September 1998 - January 1999	120.08	5	1,592
September 1999 - December 1999	63.72	4	671

Colorado River flows measured at the Southern International Boundary from the International Boundaries and Water Commission (2000).

Habitat Zones and Wetland Habitat

Eight wetlands zones were defined within the riparian zone from Morelos Dam to the Intertidal zone at the river mouth (see Fig. 3.1). Three of these zones, Morelos, San Luis, and Carranza, form what is known as the riparian corridor. The main water source for these zones is the river flow that crosses Morelos dam and some additional water from untreated sewage from the city of San Luis Rio Colorado and sporadic spills from irrigation canals at KM 27. The southern limit of Carranza corresponds to the point where cottonwoods (*Populus fremontii*) and willows (*Salix gooddingii*) start to disappear; although more recently we have seen these species south of this limit and they also have been reported by aerial surveys (Ed Glenn, personal communication).

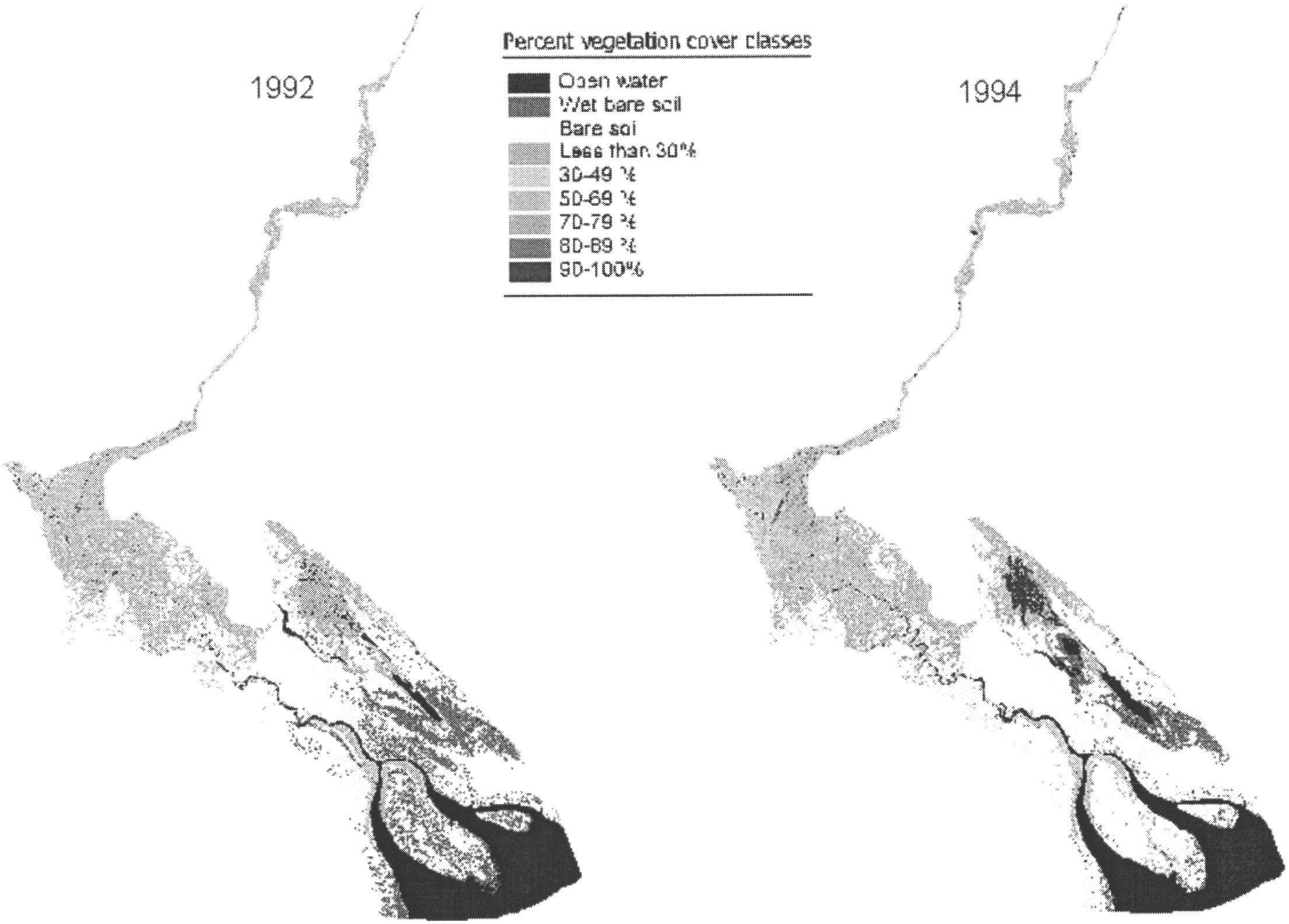

Fig 3.2. Percent vegetation cover maps for 1992 and 1994

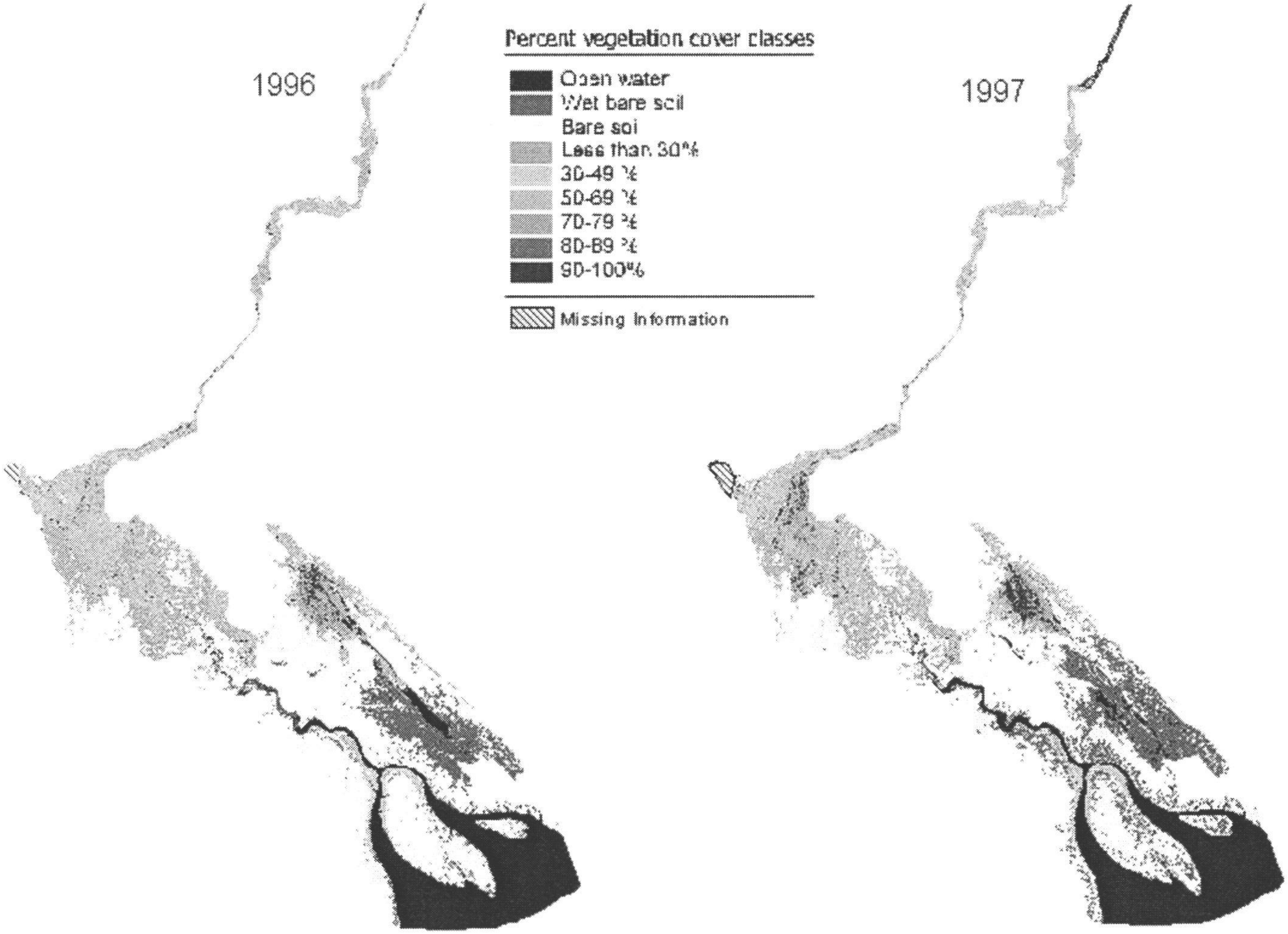

Fig 3.3. Percent vegetation cover maps for 1996 and 1997

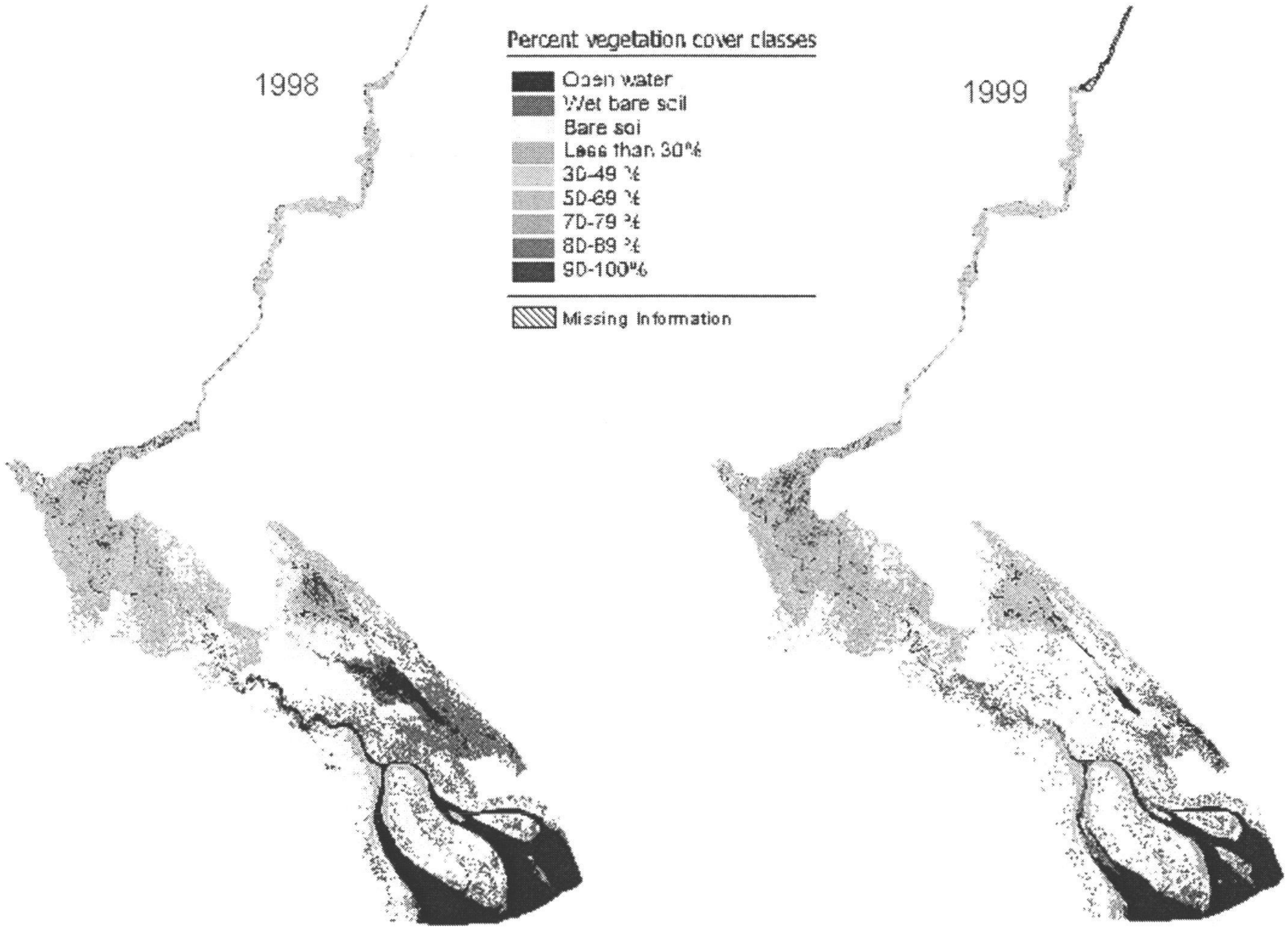

Fig 3.4. Percent vegetation cover maps for 1998 and 1999.

The Mayor-Hardy, Dren-Ayala, and Cienega zones depend almost entirely on agricultural drainage water. And it is clear from the vegetation analysis (see appendix 1) that these zones have more open water areas in years with no excess flows than zones in the riparian corridor, which only have significant large open water areas during years of excess flows. The Hardy-Colorado receives agricultural drainage water as well as Colorado River water, resulting in significant open water areas even during years of no excess flows.

In 1998, the riparian corridor had a total of 4,068 hectares of wetland habitat, from which Carranza has the largest wetland habitat (3,382 ha) representing 49% of its area, whereas San Luis and Morelos have 424 ha and 262 ha of wetland habitat, representing 10.4% and 9.6% of their respective total area (table 3.4). South of the riparian corridor, is the Hardy-Colorado zone with approximately 1,745 ha of wetland habitat, consisting of almost a monoculture of salt cedar, with some cattail and open water areas. Mayor-Hardy is the zone with the least wetland habitat, 108 ha, found mainly along the river channel. Although the Dren-Ayala zone is also fed by agricultural drain water as in Mayor-Hardy, its 968 ha of wetland habitat are found along the banks of the drain (an old river channel) as well as in inundated areas at the end of drain. Wetland habitat in the Cienega is dominated by patches of cattails (2,771 ha) and by open water (3,708) areas, whereas wetland habitat in the Intertidal zone is dominated by open water and mudflats (30,535 ha) and by vegetated areas of salt grass (*distiglis palmeri*) along the edge of Montague and Pelican islands.

Vegetation trend analysis

Figure 3.5 shows the trend analysis of percent vegetation cover for 1992 to 1999 (using six years of data) for the study area. Significant upward trends ($p<0.05$) add up to 6,320 ha or 3.7% of the total study area (black areas in figure

3.5). On the other hand, 4,695 ha (2.7% of total study area, see table 3.5) had a significant downward trend ($P<0.05$). When considering significance values between 0.1 and 0.05 (see fourth column in table 3.5), the analysis also indicates that there are an additional 8,937 ha showing a significant upward trend (gray areas in figure 3.5), most of which are in the Intertidal zone (2,837 ha) and in the Hardy-Colorado zone (2,252 ha). Similarly, there are an additional 7,134 ha showing a downward trend, mostly in the Cienega and Intertidal zones.

Table 3.4. Habitat zones in the Colorado River Delta and number of hectares of wetland habitat in 1998.

Habitat Zone	Total Area (Ha.)	Wetland habitat in 1998. (ha)	% of wetland habitat from total area
Morelos	2,714	262	9.6%
San Luis	4,071	424	10.4%
Mayor-Hardy	2,555	108	4.2%
Carranza	6,923	3,382	48.8%
Hardy-Colorado	23,889	1,745	7.3%
Dren-Ayala	14,417	968	6.7%
Cienega	35,788	6,479	18.1%
Intertidal	78,897	32,570	40.0%
Total Study Area	**169,254**	**45,938**	**27.1%**

Change patterns are more evident when looking at specific habitat zones. For example, a large percentage of the total area of riparian zones had an upward trend in percent vegetation cover (fig 3.6, table 3.5). This is particularly important since these are the areas where gallery forests of cottonwood and willow are found, and are the areas of the Delta more impacted by excess flows. The Hardy-Colorado zone had 2,121 ha (8.9% of its area) showing an upward trend. On the other hand, the Mayor-Hardy, Cienega, and Intertidal zones show very low hectares of significant upward trend, which only account for 3-5% of their total area. This was as expected as these zones mostly depend on a continuous flow of agricultural drainage water instead of instream flows of the Colorado River. However, the Dren-Ayala zone, which depends mainly on agricultural water, had 945 ha showing significant upward trend.

Table 3.5. Trend analysis results by habitat zones according to trend patterns and two significance levels:

a) Upward trend

Zone	Area (Ha.)	Upward trend P<0.05 (ha)	Upward trend 0.1>P>0.05 (ha)	Total ha and % of upward trend
Morelos*	2,201	413 (18%)	311	724 (32%)
San Luis	4,071	1,198 (19%)	683	1,881 (46%)
Mayor-Hardy*	1,701	53 (3%)	71	124 (7%)
Carranza	6,923	738 (10%)	975	1,713 (25%)
Hardy-Colorado	23,889	2,121 (9%)	2,252	4,374 (18%)
Dren-Ayala	14,417	945 (6%)	1,090	2,035 (14%)
Cienega	35,788	444 (1%)	717	1,161 (3%)
Intertidal	78,897	406 (0.5%)	2,837	3,243 (4%)
Study Area	**167,887**	6,320 (4%)	**8,937**	**15,258 (9%)**

b) Downward trend

Zone	Area (Ha.)	Downward trend P<0.05 (ha)	Downward trend 0.1>p>0.05 (ha)	Total ha and % of downward trend.
Morelos*	2,201	49 (2%)	76	125 (5%)
San Luis	4,071	32 (0.1%)	53	85 (2%)
Mayor-Hardy*	1,701	102 (6%)	151	253 (14%)
Carranza	6,923	87 (1%)	103	191 (3%)
Hardy-Colorado	23,889	689 (2%)	1,026	1,714 (7%)
Dren-Ayala	14,417	1,017 (7%)	916	1,993 (13%)
Cienega	35,788	1,256 (3%)	2,029	3,285 (9%)
Intertidal	78,897	1,462 (1%)	2,779	4,240 (5%)
Study Area	**167,887**	4,695 (2.7%)	**7,134**	**11,829 (7%)**

* Satellite images did not cover portions of these zones and have been eliminated; therefore the total area is not equal to that in table 3.4.

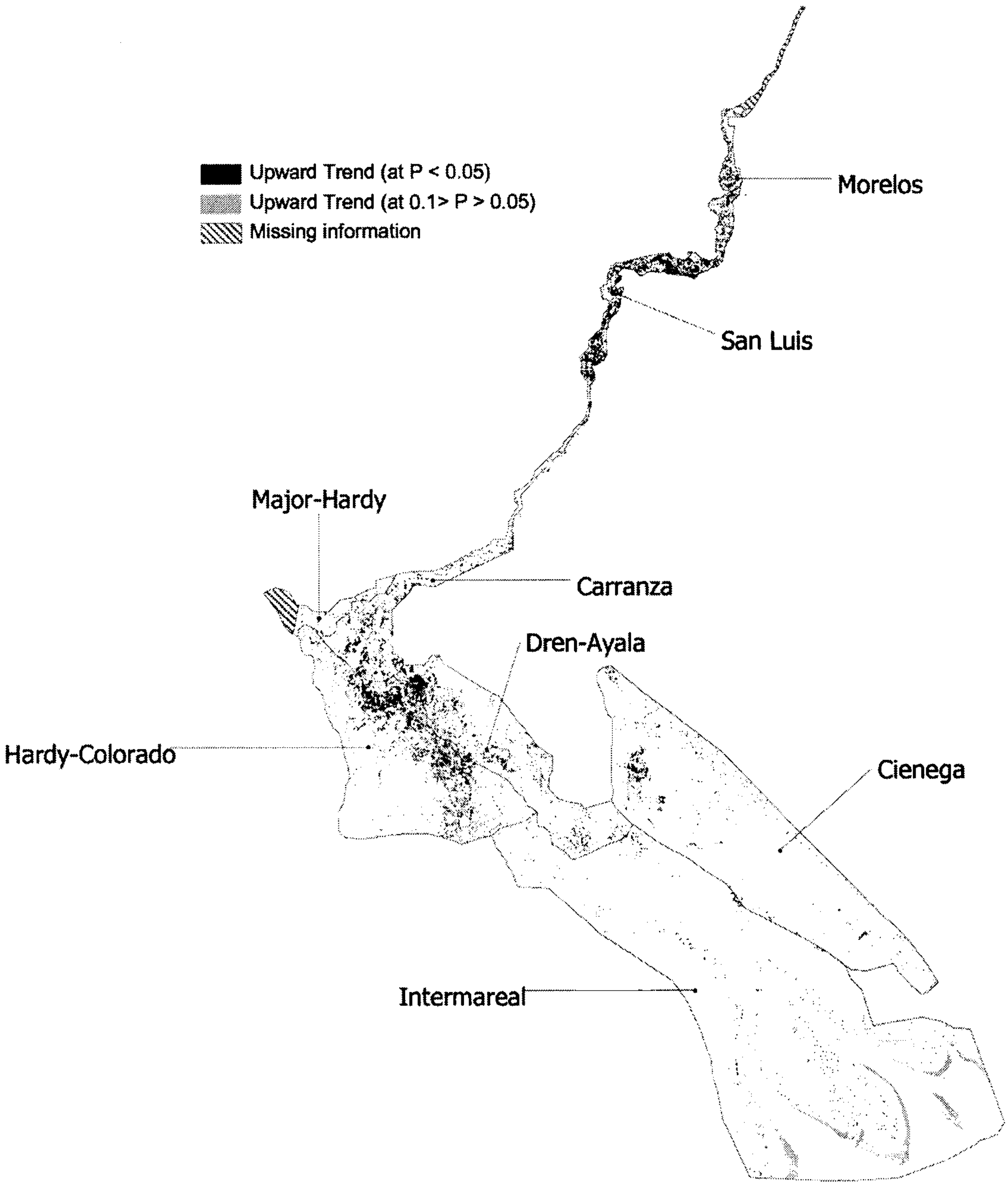

Figure 3.5. Results of the trend analysis of percent vegetation cover for 1992 to 1999. (downward trend not shown to maintain clarity)

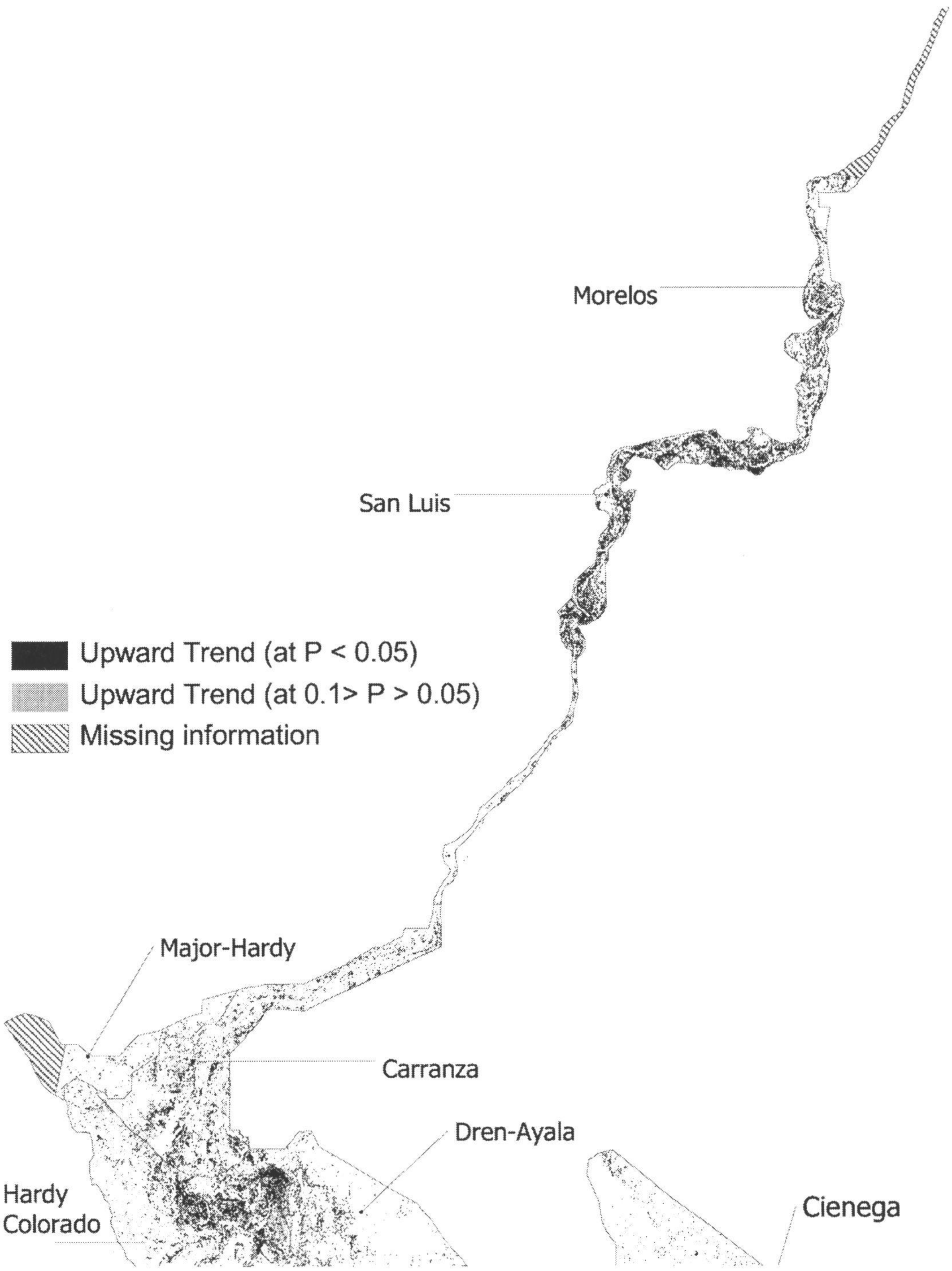

Figure 3.6. Zoom in to trend analysis results for wetland zones in the riparian area.

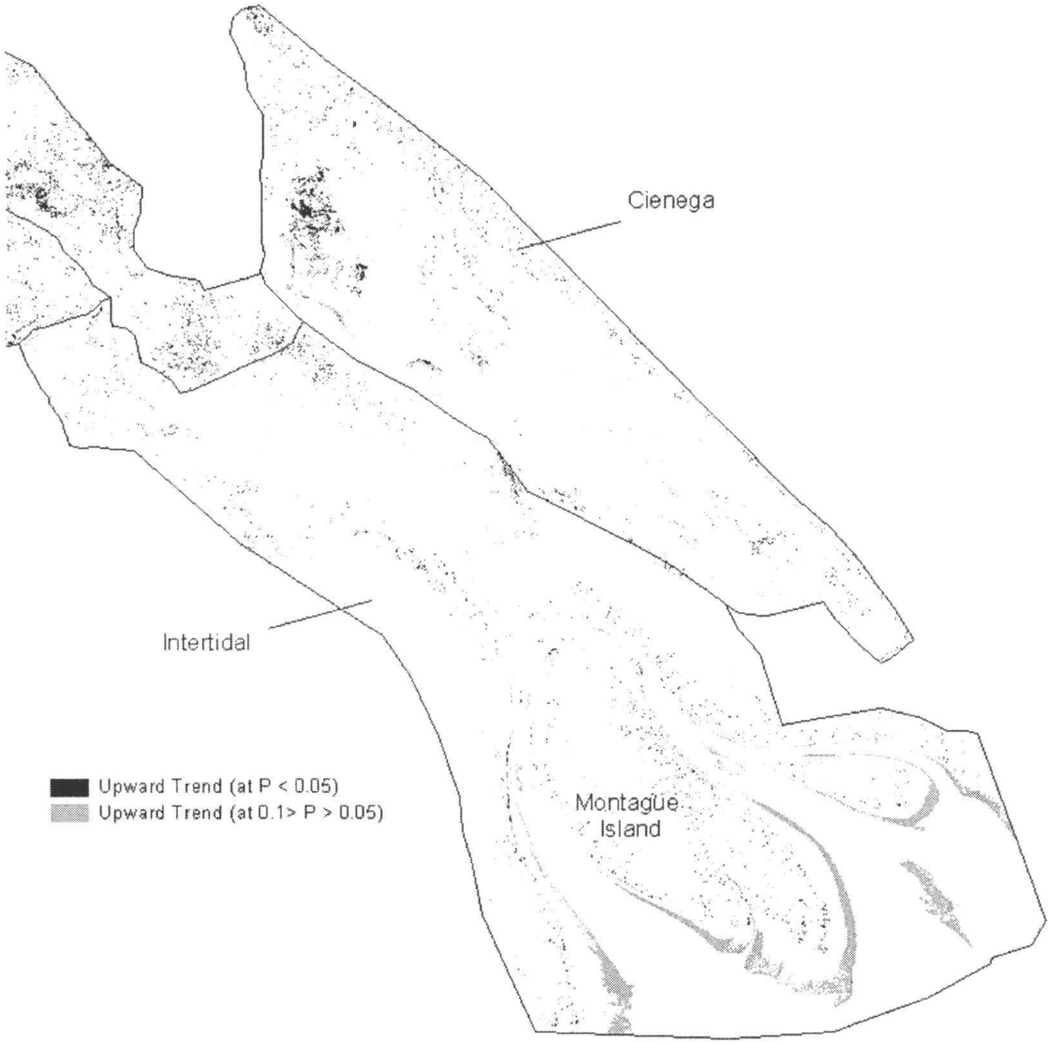

Fig 3.7. Zoom in to trend analysis results in the Cienega and Intertidal wetland zones.

In the Cienega and Intertidal zones, trend patterns are not necessarily associated with vegetation, except in the well known vegetated areas of the Cienega. Based on field observations, it was found that some areas in the Cienega showing an upward trend do not correspond to vegetated areas, which is an indication that the upward trend could be associated with changes from bare soil to wet soil or to vegetation cover classes with less than 45% vegetation cover (see fig 3.7). The intertidal zone also shows areas with upward trend, mainly along the coastline of Montague and Pelicano Islands, and corresponding to an increase in vegetation cover of salt grass (*distiglis palmeri*).

The upward trend coverage was overlaid with a coverage of areas with more than 70% of vegetation cover in 1999. This resulted in 1,752 ha showing both characteristics, a percent vegetation cover greater than 70% and an upward trend at $p<0.05$ (black areas in figure 3.8). Areas meeting this criterion are found mostly in the Carranza zone of the riparian corridor characterized by backwater lagoons adjacent to open gallery forest of native riparian trees and in the Hardy-Colorado zone where a transition begins into more monoculture of salt cedar, but with still some native vegetation and cattail marshes. Therefore, these areas could be seen as areas where conservation or restoration sites could be targeted as they have benefited from available water and have revitalized during the 1990s.

Effects of instream flows

Percent Vegetation cover

For the zones located inside the floodplain, the main variable explaining increments in percent vegetation cover was number of days with average flow $>2m^3/s$ at the SIB (adjusted $r^2 > 0.90$, $p < 0.01$), except for San Luis, in which the monthly average flow at the SIB explained 76 % of the variation ($p = 0.014$). For Mayor-Hardy and Ciénega de Santa Clara, flows through the SIB were significant, but the flows through the MODE were also important in explaining the average percent vegetation cover. Table 3.6 shows the models relating increase percent vegetation cover with hydrological variables.

Vegetation Cover >70%

More variables were included in the models to explain the total hectares of vegetation cover >70% than in the average percentage vegetation cover and open water areas. For the zones of the riparian corridor, a significant variable was the 4 years average of flows through the SIB ($p < 0.02$), except for San Luis, in which most of the variation was associated with the monthly average of flows through the SIB (Table 3.6). Other variables associated with an increase in vegetation cover >70% at zones inside the floodplain were 1 month and 3 months average of flows through the SIB, and number of days with average flow $>2m^3/s$ at the SIB. Increments in vegetation cover >70% at Mayor-Hardy and Ciénega de Santa Clara were associated with flows through the SIB (1 month and 3 months average flow) and through the MODE (6 months average and daily flow) (Table 3.7).

Open Water

The variation in total ha of open water was associated only with flows through the SIB at all the zones (Table 3.8). For the riparian corridor, the period of time of average flows associated with an increment on ha of open water increased moving downstream, with average daily flow significant at Morelos ($p = 0.0014$), 3 months average flow significant at San Luis ($p = 0.0125$), and 6 months average flow significant at Carranza ($p = 0.0124$). Increase in ha of open water was associated with number of days with average flow $>2m^3/s$ through the SIB at Hardy-Colorado ($p = 0.082$) and with 3 months average flow through the SIB at the Ciénega ($p = 0.014$). No variables were significant at explaining variations at Mayor-Hardy and Ayala Drain.

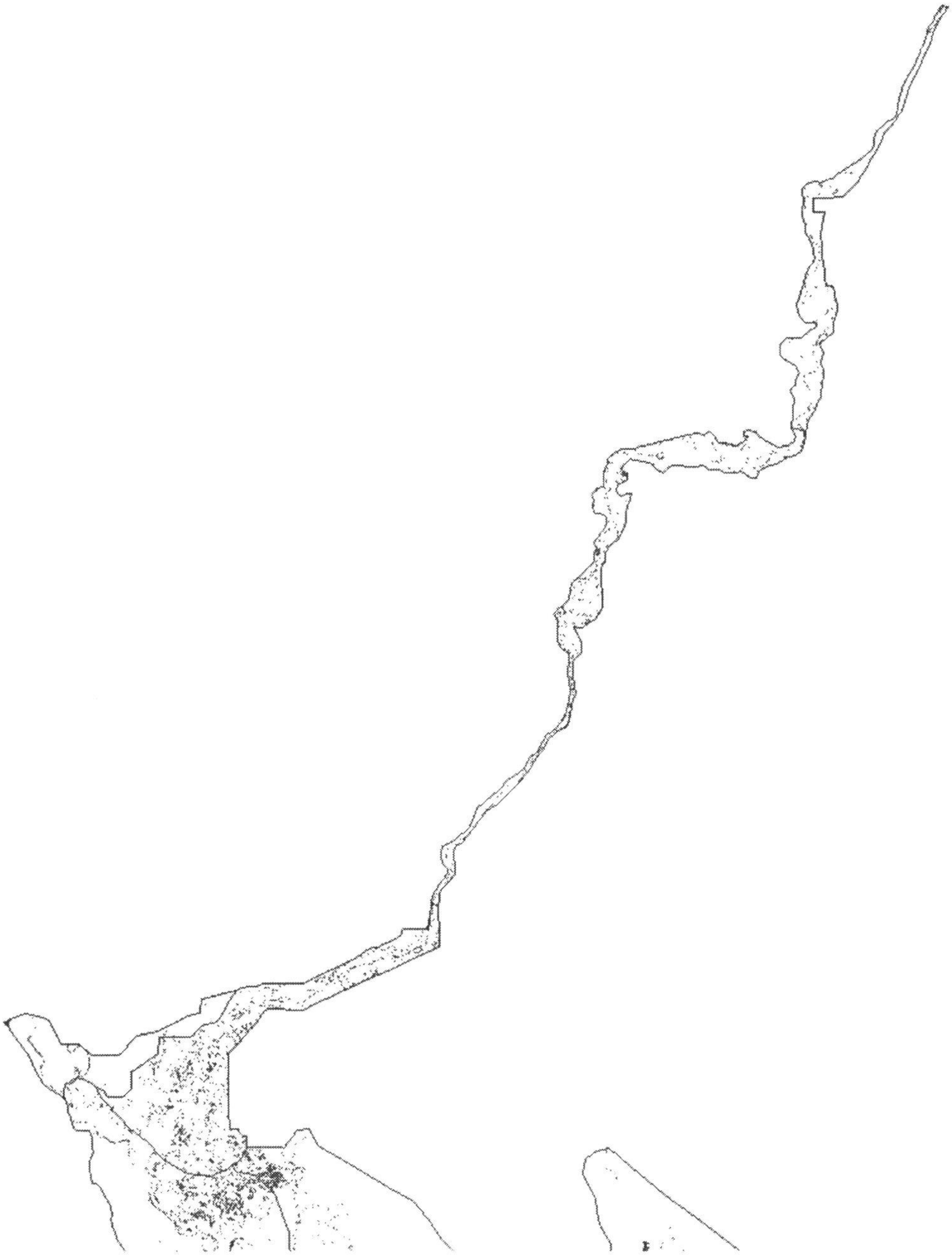

Fig 3.8. Areas showing a percent vegetation cover greater than 70% in 1999 and an upward trend (P<0.05).

Table 3.6. Variables associated with an increase in the average percent vegetation cover for each of the habitat zones of the Colorado River Delta.

Zone (model r^2)	Variables	Estimate (SE)		t-Stat	p-Value
Morelos (0.99)	no. of days with flows SIB	0.0348	(0.0031)	10.96	0.0082
	6 months average SIB	0.0469	(0.0098)	4.78	0.0410
	6 months average MODE	6.1975	(0.6267)	9.89	0.0101
San Luis (0.76)	1 month average SIB	1.4004	(0.3386)	4.14	0.0144
Carranza (0.91)	no. of days with flows SIB	0.0472	(0.0065)	7.21	0.0020
Hardy-Colorado (0.98)	no. of days with flows SIB	0.0409	(0.0025)	16.03	<0.0001
Mayor-Hardy (0.97)	3 months average SIB	0.0553	(0.0092)	5.96	0.0270
	6 months average MODE	2.2497	(0.2688)	8.37	0.0140
Ayala Drain (0.95)	no. of days with flows SIB	0.1980	(0.0020)	9.87	0.0006
Ciénega (0.99)	6 months average MODE	1.3298	(0.9610)	13.83	0.0052
Intertidal (0.91)	1 year average MODE	0.3814	(0.1096)	3.48	0.0401

DISCUSSION

Extensive field observations indicated that the percent vegetation cover maps calculated from satellite images provide an important spatial-temporal tool to measure the impact of instream flows in the Colorado River Delta. By applying this tool, one can quantify the amount of vegetation cover in each habitat zone of the Delta for past and present years. However, it is important to notice that in order to develop an appropriate habitat interpretation of the results, field work is required to identify distributions and structure of vegetation, particularly in the riparian zone.

Table 3.7. Variables associated with an increase in hectares in areas of vegetation cover >70% for each of the habitat zones of the Colorado River Delta.

Zone (model r^2)	Variables	Estimate	(SE)	t-Stat	p-Value
Morelos (0.99)	3 months average SIB	6.5706	(0.1656)	39.67	0.0160
	4 year average SIB	3.1096	(0.0894)	34.77	0.0183
San Luis (0.76)	1 month average SIB	24.8072	(5.9030)	4.20	0.0137
Carranza (0.99)	no. of days with flows at SIB	3.1939	(0.4893)	6.53	0.0227
	4 year average SIB	34.5765	(4.5775)	7.55	0.0171
Hardy-Colorado (0.98)	1 month average SIB	136.6422	(13.8733)	9.85	0.0102
	3 months average SIB	991.5176	(155.268)	6.39	0.0237
Mayor-Hardy (0.99)	3 months average SIB	1.3588	(0.0443)	30.66	0.0011
	6 months average MODE	38.6943	(1.4594)	26.51	0.0014
Ayala Drain (0.92)	no. of days with flows at SIB	2.3559	(0.2936)	8.02	0.0013
Cienega (0.99)	daily flow MODE	393.9964	(11.6762)	33.74	0.0189
	1 month average SIB	3097.9607	(31.5679)	98.14	0.0065
	6 months average MODE	1310.0237	(16.0622)	81.56	0.0078
Intertidal (0.85)	6 months average SIB	30.8755	(10.4253)	2.96	0.0595

Table 3.8. Variables associated with an increase of total ha of open water for each of the habitat zones of the Colorado River Delta.

Zone (model r^2)	Variables	Estimate (SE)		t-Stat	p-Value
Morelos (0.92)	daily flow SIB	0.8267	(0.1045)	7.91	0.0014
San Luis (0.99)	3 months average SIB	0.0215	(0.0024)	8.84	0.0125
	1 year average SIB	0.0195	(0.0012)	15.41	0.0042
	4 years average SIB	0.0105	(0.0014)	7.49	0.0173
Carranza (0.77)	6 months average SIB	0.0085	(0.0019)	4.32	0.0124
Hardy-Colorado (0.81)	no. of days with flows at SIB	0.0017	(0.0003)	4.87	0.0082
Ciénega (0.99)	3 months average SIB	0.1900	(0.0041)	45.62	0.0140

Although detailed observation of percent vegetation cover maps provide in themselves a graphic point of comparison of changes in vegetation throughout a period of years, management decisions call for more robust way to assess this change as well as the variables to which this change is associated. The multitemporal and spatial trend analysis used here provides a statistical way to measure trends in percent vegetation cover and helps to filter out those non-systematic or random variables that might be present year to year. Because the analysis is performed on a pixel by pixel basis, a significant trend would be determined only when there is consistent change throughout the years, thus reducing the impact of lack of independence of percent vegetation cover from one year to another (Schlagel and Newton, 1996). Although the lack of independence might reduce the statistical validity of the significance levels, our field observations in the Delta show that this trend analysis technique is still useful to pinpoint areas of significant change. A further spatial-temporal analysis of the Mann-Kendall test is required to increase the confidence of estimates of percent vegetation cover trends to water flows.

Several authors have indicated that during the 1990s wetland areas have actually regenerated (Glenn 1996; Briggs and Cornelius, 1998; Valdes-Casillas, 1998). Although these observations documented these changes in the field, they lacked multiple year systematic monitoring and therefore did not provide the statistical information to test the hypothesis of spatial change. The multiple-year analysis on percent vegetation cover by Zamora-Arroyo et al (2001) allowed us to perform the trend analysis presented here and to statistically determine whether there has been a change in percent vegetation cover during the 1990s. Results indicated that some areas of the Colorado River Delta show a significant upward trend in percent vegetation cover between 1992 and 1999; this clearly supports the observational and anecdotal data. It is important to notice that in spite of the small sample size (only 6 years), by capturing dry years (1992 and 1996) and wet years (1994, 1997-1999), significant trends were detected.

The relationship of vegetation cover with the number of days that presented a significant instream flow supports the suggestion by Glenn et al, (2001) that a modest annual flow should be allocated for the conservation of the riparian areas of the Colorado River in Mexico. Our results also show that pulse floods every 4 years would allow the regeneration of denser riparian patches. These relationships were particularly significant in areas that have been found to support the most important stands of native riparian trees in the Lower Colorado Basin, such as the Morelos and Carranza zones (Zamora-Arroyo et al. 2001), which are critical habitat for endangered or sensitive species, such as Willow Flycatchers (*Empidonax traillii*), Yellow-billed Cuckoos (*Geococcyx americanus*), and Bell's Vireos (*Vireo bellii*; Garcia-Hernandez et al. 2001, Hinojosa-Huerta et al. in review).

At San Luis, vegetation cover does not seem to be strongly related with hydrological variables, as this area receives other water sources not accounted for in the model, mainly sewage discharge from the city of San Luis Rio Colorado, Sonora, and spillways from the irrigation system of the Mexicali Valley. These variables were not included in the model, as time series of data are not collected for these water sources. The Mayor-Hardy, Ayala Drain, and Ciénega zones also receive other water sources, mostly agricultural drainage discharge form the Mexicali Valley, although the Ciénega's main source is the MODE canal. These sources are most stable than instream flows, thus vegetation cover and open water areas in these zones show less variation through the years and less relationship with river flows. Flows through the MODE canal, which depends on agricultural activity and irrigation patterns in the Wellton-Mohawk region, explained variations in vegetation in some of the wetland zones in the western Colorado Delta. This seems to be an imprecision of the analysis since MODE water does not reach other zones than the Cienega. An explanation for this result is that water reaching other habitat zones follow the same characteristics as MODE water as they also received agricultural drainage water, although in this case from the Mexicali Valley.

Nevertheless, instream flows have critical impacts on habitat features in these western Delta zones, for promoting the establishment of patches of >70% vegetation in the marshes and the maintenance of open water areas. These habitat features are critical habitat for endangered species as the Yuma Clapper Rail (Hinojosa-Huerta 2000) and for wintering and migratory waterbirds for which the Delta is a critical site (Mellink et al. 1997). The patterns of vegetation and open water dynamics in the Colorado floodplain are clearly related to instream flows. Further research, however, should focus in understanding the effect of the instream flows on plant community dynamics, on the ecological relationship of plants with wildlife, and on the ecology of the estuarine/intertidal area.

There exist several limitations of the statistical analysis, and therefore results should be carefully interpreted. Unfortunately, at the time of this analysis it was not possible to acquire neither satellite images for the 1980's nor more frequent images for 1990s, which would have increased sample size and increased the statistical significance of trend analysis as well as of the multiple regression analysis of instream flows and percent vegetation cover. This precluded us from quantifying the amount of vegetation cover after the flood event of 1983-1988, with the largest flood event since the filling of major dam. Similarly, because of the lack of a more complete data set, this study did not test the relationship between water flow variables and vegetation cover. However, the analysis allowed the identification of a specific hypothesis that could be properly tested with additional data. This information, along the possibility of having experimental floods and a hydrological characterization of the Delta, will allow to complement and test the spatial trend and regression model presented here, as well as to incorporate a spatial component to better estimate the response of vegetation cover to instream flows. This will allow the development of confidence estimates of restoration scenarios under different instream flows, critical information for decision-making.

CONCLUSIONS

The present study demonstrated that there has been a change in percent vegetation cover in the Colorado River Delta, particularly in the riparian zones area and the confluence of the Hardy and Colorado Rivers. It also presents information suggesting the hypothesis that these vegetation changes are the results of instream flows that have reached the different habitat zones in the Delta during the 1990s. In particular, we conclude that the following hypothesis should be tested: large flows every four years are needed to flood banks and help establish vegetation and smaller but periodic or continuous flows (daily and monthly averages) greater than

2 m^3/s are also needed to maintain current and newly established vegetation in the riparian corridor. Proper testing of this hypothesis requires the determination of vegetation cover in the riparian corridor at least during each climate season and the incorporation of all water sources reaching the river along the corridor.

The remote sensing and GIS tools used here are useful to continue monitoring the Delta ecosystem and to evaluate the impact of water flows, or lack thereof, on current critical habitat. The capability of these tools to monitor the Delta will be increased as more temporal data (sample size) is available and spatial resolution is increased; their limitations, though, need to be carefully considered for determining vegetation composition. In addition, future research should consider the development of a spatial-temporal statistical model that incorporates vegetation and a more complete set of hydrological variables. This type of model would allow the prediction of vegetation-habitat development in space and time with known confidence, information that will very valuable for decision making.

Considering that bringing back the Colorado River system to its pre-development condition is, in practical terms, impossible and perhaps undesirable considering all the human water dependent uses in the basin, the information provided here should be useful to identify those areas where conservation and/or restoration efforts should be concentrated. Particularly important are areas within the riparian corridor and the Hardy Colorado zones. The great resilience of the Delta has allowed its habitat to rapidly and positively respond to recent instream flows, providing us with an indication of minimum water requirements, quantity and timing, to sustain these improved habitats. Local and state water users in US and Mexico, and government agencies and non-governmental organizations in both countries are now responsible for identifying and implementing actions to maintain and expand these revitalized critical Delta habitats through ensuring that Delta's water requirements are fully identified and met.

REFERENCES

Briggs Mark and Steve Cornelius. (1998). Opportunities for ecological improvement along the lower Colorado River and Delta. *Wetlands*. **18**: 513-529.

Cohen M. J., Henges-Jeck, C. and Castillo-Moreno, G. (2001). A preliminary water balance for the Colorado River delta, 1992-1998. *Journal of Arid Environments*. **49**: 35-48.

Costanza Robert and Carl Folke. (1996). The structure and function of ecological systems in relation to property-rights regimes. In Hanna Susan; Carl Folke; and Karl-Göran (Eds). Rights to nature: Ecological, economic, cultural, and political principles of institutions for the environment. Island Press.

Folke Carl; C. S. Holling & Charles Perrings. (1996). Biological diversity, ecosystems, and the human scale. *Ecological Applications*, **6**: 1018-1024.

Fradkin, P., (1981). A river no more, the Colorado River and the West. Alfred A. Knopf, New York.

García-Hernández, J., Hinojosa-Huerta, O., Gerhart, V., Carrillo-Guerrero, Y., and E.P. Glenn. (2001). Willow flycatcher (Empidonax traillii) surveys in the Colorado River delta wetlands: implications for management. *Journal of Arid Environments*. **49**: 161-169.

Glenn, E. P., Zamora-Arroyo, F., Nagler, P. L., Briggs, M., Shaw, W., and Flessa, K. (2001). Ecology and conservation biology of the Colorado River Delta, Mexico. *Journal of Arid Environments*. **49**: 5-15.

Glenn Edward, Christopher Lee, Richard Felger, and Scott Zengel. (1996). Effects of water management on the wetlands of the Colorado River Delta, Mexico. *Conservation Biology*, **10**: 1175-1186

Hinojosa-Huerta, O. (2000). Distribution, abundance, and habitat use of the Yuma Clapper Rail (*Rallus longirostris yumanensis*) in the Colorado River delta, Mexico. M.S. Thesis, School of Renewable Natural Resources, University of Arizona, Tucson, AZ.

Hinojosa-Huerta, Osvel., DeStefano, S., and Shaw, W. (2001). Distribution and abundance of the Yuma clapper rail (*Rallus longirostris yumanensis*) in the Colorado River Delta. *Journal of Arid Environments*. **49**: 171-182.

Hinojosa-Huerta, O., J. García-Hernández, and Y. Carrillo-Guerrero. In review. Hovering from the Colorado delta to the Gran Desierto: the birds of the Alto Golfo. Dry Borders II.

IBWC. (2000). Internet Home Page http:/www.ibwc.state.gov. Revised on 04/18/2000.

Mellink, E., Palacios, E. and Gonzalez, S. (1997). Non-breading water birds of the delta of the Rio Colorado, Mexico. *Journal of Field Ornithology*. **68**: 113-123.

Nagler, P., H. Rodriguez, E. Glenn and A. Huete. (2001). Assessment of spectral vegetation indices for riparian ecosystems in the Colorado River Delta. *Journal of Arid Environments*, **49**: 91-110.

Pindyck, R.S. & D.L. Rubinfeld. (1991). Econometric models and economic forecast. Third edition, McGraw-Hill International, Singapore.

Richter D. Brian & Holy E. Richter. (2000). Prescribing flood regimes to sustain riparian ecosystems along meandering rivers. *Conservation Biology*, **14**: 1467-1478.

Ramsey, F.L. & D.W. Schafer. (1996). The statistical sleuth. Duxbury Press, Belmont, CA.

Sall, J. & A. Lehman. (1996). JMP start statistics. Duxbury Press, Belmont, CA.

Schlagel D. Joel & Carlton M. Newton. (1996). A GIS-based statistical method to analyze spatial change. *Photogrametric Engineering & Remote Sensing*,. **62**: 839-844.

Valdes-Casillas Carlos, O. Hinojosa-Huerta, M. Muñoz-Viveros, F. Zamora-Arroyo, Y. Carrillo-Guerrero, S. Delgado-Garcia, M. Lopez-Camacho, E. Glenn, J. Garcia, J. Riley, D. Baumgartner, M. Briggs, C. Lee, E. Chavarria-Correa, C. Congdon, and D. Luecke. (1998). Information Database and Local Outreach Program for the Restoration of the Hardy River Wetlands, Lower Colorado River Delta, Baja California and Sonora, Mexico, North American Wetland Conservation Council, Arlington, Virginia USA. 103 pp.

Zamora-Arroyo Francisco, Pamela Nagler, Mark Briggs, Dean Radtke, Hugo Rodríguez, Jacqueline Garcia, Carlos Valdes, Alfredo Huete, and Edward Glenn. (2001). Regeneration of Native Trees in Response to Flood Releases from the United States into the Delta of the Colorado River, Mexico. *Journal of Arid Environments*, **49**: 49-64.

CHAPTER 4

CONSERVATION BIOLOGY OF THE COLORADO RIVER DELTA, MEXICO: RESTORATION OPPORTUNITIES AND RESEARCH PRIORITIES.

Francisco Zamora-Arroyo, Edward P. Glenn, Mark Briggs

An earlier version of this article is published as:
Glenn, E. P., Zamora-Arroyo, F., Nagler, P. L., Briggs, M., Shaw, W., and Flessa, K.
Journal of Arid Environments.
Vol. 49. No.1, September 2001. pp.5-15.

ABSTRACT

The Colorado River Delta in Mexico has been partially regenerated following 20 years of periodic excess water flows from the United States. Lake Powell, the last major impoundment built on the river, filled in 1981. Since then, flood flows in the main channel of the river have occurred in El Nino cycles, and have regenerated native trees and other vegetation in the riparian corridor. The riparian vegetation provides a migration route for endangered southwestern willow flycatchers (*Empidonax traillii*) moving from Mexico to the United States for summer nesting. Agricultural drain water from the Wellton-Mohawk Irrigation District conveyed to the Delta since 1977 has created Cienega de Santa Clara, a 4,200 ha *Typha domengensis* marsh containing the largest remaining population of the endangered Yuma clapper rail (*Rallus longirostris yumanensis*), as well as numerous species of migratory and resident waterfowl.

Wildlife populations in the marine part of the delta continue to be severely affected by the lack of river flow. Currently, there are 170,000 ha of natural area in the lower Delta in Mexico, containing riparian, wetland and intertidal habitats. Much of this land, as well as the adjacent marine zone, is protected in the Biosphere Reserve of the Upper Gulf of California and Colorado River Delta. However, the riparian corridor, which contains critical patches of native gallery forest, is not protected. Opportunities to protect and ecologically enhance this corridor exits, but require the collaboration of natural resource managers, scientists, and non-governmental environmental groups in Mexico and the United States. Additional research is also required to identify those special areas in the delta that need to be protected or restored and to identify how much water is required to accomplish this. Among the research priorities is the need to develop a suitability analysis for the riparian corridor to identify the areas of native forest that will be better to protect and restore under current vegetation patterns and future hydrological scenarios.

INTRODUCTION

Riparian corridors are critical habitat for desert flora and fauna, providing oases of species diversity and high productivity in otherwise dry environments (Poff et al., 1997). They are also critical routes for migratory birds passing through desert regions on their way to nesting or wintering grounds. The lower Colorado River from the Grand Canyon to the Gulf of California provides the greatest extent of riparian and wetland habitat in the Sonoran Desert (Ohmart et al., 1988; Glenn et al., 1996). Over the past 100 years, diversion of water for human use, alteration of the natural flow regime, and invasion of exotic plants and animals has negatively impacted the lower Colorado River ecoregion, such that 45 species on the United States stretch of river are now listed as endangered, threatened or sensitive (Ohmart et al., 1988; U.S. Bureau of Reclamation, 1996). This paper discusses the terminus of the river, the Delta of the Colorado River in Mexico. The Delta has had resurgence in wetland vegetation since the filling of the U.S. dam system on the river in 1981 (Glenn et al., 1996). This paper is part of a special issue of the *Journal of Arid Environments* devoted to recent scientific and policy studies of the Delta, setting the stage for the articles that follow in this special issue.

Historically, the Colorado River Delta encompassed several million ha of land near or below sea level in the United States and Mexico, including two evaporation basins, the Salton Depression (now the Salton Sea) and the Laguna Salada (Sykes, 1937). Much of the historic Delta has been converted to irrigated agriculture or urban uses in towns and cities. In Mexico, however, there remain approximately 170,000 ha of natural area, containing riparian, brackish wetlands and intertidal habitats, running from the Northerly International Boundary (NIB) with the United States to the mouth of the Colorado River in the northern Gulf of California (Glenn et al., 1996). Much of this land, and a large portion of the adjoining marine zone, are now protected in the Biosphere Reserve of the Gulf of

California and Delta of the Colorado River (Morelos-Abril, 1994). The main objective of this paper is to describe these habitats in terms of vegetation and wildlife values, review the ecological and conservation issues which will determine their future, and outline research needs. In addition, we look at the current opportunities for restoration in the riparian corridor and identify specific research needs to advance in the conservation and restoration of this important habitat in the delta.

Although not treated here, other natural areas within the historic Delta region are also key components in the lower Colorado River ecoregion. The Salton Sea is now the object of a major restoration effort, scientific studies to understand its ecological characteristics have been initiated but not yet published (Cohn, 2000). The deteriorated ecological status of the lower Colorado River from Davis Dam to Morelos Dam in the United States was documented by Ohmart et al. (1988) and in subsequent studies by others (Busch and Smith, 1995; Stromberg, 2001).

The lower delta of Colorado River has never been thoroughly studied. D.T. MacDougal of the New York Botanical Garden briefly described the vegetation of the area on several short excursions from Yuma to the Gulf of California or the Salton Sea from 1904-1907 (MacDougal, 1905, 1907). Aldo Leopold, describing a camping trip he made with his brother in the 1920's, called the Delta the last great blank spot on the map of North America (Leopold, 1949). Both MacDougal and Leopold portrayed the Delta as a vast gallery forest of cottonwood (*Populus fremontii*) and willow (*Salix gooddingii*) in the north, interspersed with wetlands containing cattail (*Typha domengensis*) and common reed (*Phragmites australis*) in low areas and mesquite forest (*Prosopis glandulosa* and *P. pubescens*) on higher terraces. Large expanses of salt tolerant vegetation such as salt bush (*Atriplex spp.*), salt grass (*Distichlis spicata*) and arrowed (*Pluchea sericea*) were found throughout the Delta, as the Colorado River carries salts leached from upstream soils. The endemic salt grass, *D. palmeri*, dominated the estuarine zone. Beaver, leopards, and deer were still found in the Delta when Leopold visited.

In 1937 Godfrey Sykes published *The Colorado Delta*, a record of his personal explorations of the Delta by small boat over a period of years. He predicted that the vast, lush Delta viewed by early visitors would be drastically altered by Hoover Dam, started in 1932. True enough, from 1935 to 1960 the amount of water reaching the natural habitats of the Delta in Mexico was reduced by 50-75%, and between 1963 and 1981, almost no water flowed to the Delta and the Gulf of California. This was the result of Lake Mead, behind Hoover Dam, being filled from 1935-1957, and Lake Powell, behind Glen Canyon Dam, was filling from 1964-1981 (Glenn et al., 1996). Excess water in the watershed was simply captured behind the dams rather than transmitted to the Delta and the Gulf of California. Much of the Delta was developed for agriculture, and the perception arose that what was left was a dead ecosystem (e.g., Fradkin, 1981).

Research interest in the Delta was minimal for many years, but has increased recently as scientists, environmental organizations, and natural resource managers have become aware that the "dead delta" perception is no longer accurate, and that the remaining Delta ecosystems have rich conservation potential (Glenn et al., 1996; Pitt, 2001; Pitt et al., 2000; Varady et al., 2001; Zamora-Arroyo and Hinojosa chapter 3). From 1955 to 1989, Science Citation Index lists only 5 publications on the Colorado River Delta; from 1990-1997 there were 10, and from 1998-2001 there were 23. The 14 papers in the present collection add to our knowledge of the delta's water budget (Cohen et al., 2001) and water quality (Garcia-Hernandez, King et al., 2001), species diversity (Garcia-Hernandez, Hinojosa-Huerta et al., 2001; Hinojosa-Huerta et al., 2001), vegetation dynamics as affected by flows from the United States (Zamora-Arroyo et al., 2001) and connections between floods and the ecology of the marine zone (Rodriquez et al., 2001). They discuss possible mechanisms for managing a binational resource like the Delta, where the critical habitats are in one country (Mexico) but a key sustaining resource, water, flows from another country (the United States)(Pitt 2001 and Varady et al., 2001).

ECOZONES IN THE COLORADO RIVER DELTA

Using the habitat zones defined by Zamora-Arroyo and Hinojosa (chapter 3), we divided the natural areas of the Delta into 4 terrestrial ecozones plus the marine zone (Figure 4.1, Table 4.1). Zones in figure 4.1 are overlaid on a June, 1998 Thematic Mapper image of delta. The area inside the zones was classified using the Normalized Difference Vegetation Index (NDVI) to calculated the percentage of vegetation cover in each zone over the years 1992-1999 to show water, soil and vegetation cover as indicated in the Legend (see Nagler et al. 2001; Zamora-Arroyo et al., 2001, and Valdes-Casillas et al., 1998, for methods and details of vegetation surveys). Areas outside the zones are displayed in false color using the IR band (red = vegetation). The marine zone begins at the bottom of the figure.

The vegetation composition of the Delta is not complex. The present vegetation communities, though much reduced in area compared to their historic proportions, are basically similar to those observed by MacDougal, with the remarkable exception of salt cedar (*Tamarix ramosissima*). This salt-tolerant shrub or small tree, an exotic from Eurasia not yet introduced to the Delta at the turn of the 20th century, now dominates the riparian corridor except in the most saline locations (the intertidal zone) and in emergent wetlands. This dominance is due to the lack of water and resulting increased soil salinity in former wetland areas.

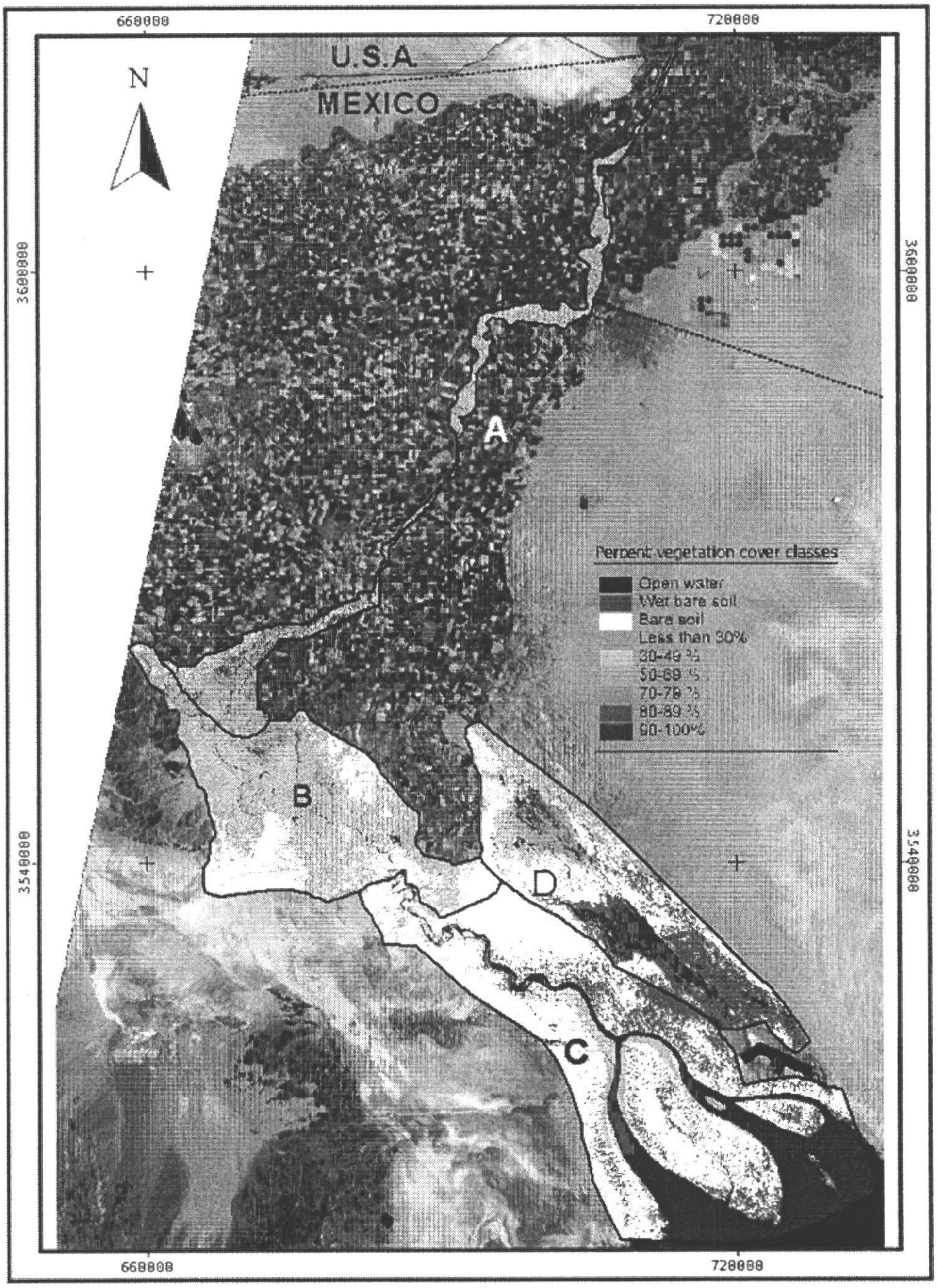

Figure 4.1. Terrestrial ecozones of the lower Delta of the Colorado River in Mexico: A) Salt Cedar/Willow/Cottonwood Zone; B) Salt Cedar Zone; C) Salt Grass and Marine; D) Cattail Zone.

Salt Cedar/Willow/Cottonwood Zone

The first ecozone, which we designated the Salt Cedar/Willow/Cottonwood Zone, is a narrow stretch of habitat between earthen levees, that runs for 100 km (14,000 ha), from Morelos Dam (last diversion point for water on the river) to the junction of the Colorado River with the Hardy River. This river stretch is not perennial, but flows when surplus water is released from the United States. Since the filling of Lake Powell, water has flowed down this stretch to the sea in 10 of 20 years, representing about 20% of the total river flow (Zamora-Arroyo et al., 2001).

This stretch is approximately 45% vegetated, with the remainder consisting of unvegetated sand bars in the river channels and bare earth between plants on the terraces. The vegetation is dominated by *T. ramosissima*, as elsewhere on the river, but cohorts of native trees were established following river flows associated with El Nino/La Nina events in 1983-1988, 1993 and 1997-1999. In 1999, *P. fremontii* and *S. gooddingii* trees, sometimes growing in gallery forests, composed 23% of the vegetation along this stretch (Nagler et al., 2001; Zamora-Arroyo et al., 2001). The other common plant in this zone is the salt-tolerant, native shrub, *P. sericea* which often grows in dense stands that exclude other species (Zamora-Arroyo et al., 2001).

The return of native trees to this stretch illustrates the importance of pulse floods in restoring the ecological character of western United States rivers (Stromberg, 2001). Ecophysiological studies show that native trees tend to be superior to *T. ramosissima* in tolerance to flooding (Vandersandae et al., 2001), siltation (Levine and Stromberg, 2001) and in nutrient recovery (Marler et al., 2001), but are inferior in salt tolerance (Glenn et al., 1998; Vandersandae et al., 2001). Occasional overbank floods on this river stretch have washed salts from the banks and scoured out *T. ramosissima*, allowing the reestablishment of native trees. This stretch, and *T. ramosissima*-dominated habitat to the south, is apparently used as a summer migration route for the endangered southwestern willow flycatcher (*Empidonax traillii*) and perhaps other neotropical migratory songbirds (Garcia-Hernandez et al., 2001). The Salt Cedar/Willow/Cottonwood Zone in the Delta contains the greatest amount of native tree habitat remaining on the lower Colorado River (Zamora-Arroyo et al., 2001).

Table 4.1. Area and vegetation cover of the major ecozones of the Colorado River Delta.

Ecozone	Total (ha)	Vegetated (%)	Vegetated (ha)
Salt Cedar/Willow/Cottonwood	13,711	45.1	6,814
Salt Cedar	40,861	23.1	9,439
Salt Grass	78,897	1.6	1,291
Cattail	35,788	11.5	4,115
Total	169,257	13.0	21,659

Note: Percentage vegetation was calculated using NDVI values correlated with scenes of known vegetation cover for a ground-truthed, 1997 image (Nagler et al.2001, Zamora-Arroyo et al., 2001). Marine zone not included.

Salt Cedar Zone

Below the junction of the Colorado and Hardy Rivers, the river is perennial. It carries saline agricultural return flows from the Mexicali Valley, and is tidally influenced; hence the water and banksides are saline (Glenn et al., 1996; Valdes-Casillas et al., 1998). The river spreads out in this zone and is divided into numerous, braided channels. We designated this middle portion of the Delta the

Salt Cedar Zone, because much of the area between channels is a vast monoculture of *T. ramosissima* thickets. Most of the water entering this section (in absence of flood discharges from the United States) is agricultural return flows from the Mexicali and San Luis Irrigation Districts. They enter in the Rio Hardy and from smaller drains discharging into the western portion of this stretch. Overall, this zone is only 23% vegetated, with the vegetation concentrated near the river channels. In addition to *T. ramosissima*, the emergent plants, *P. australis* and *T. domengensis,* grow along the river and canal banks and in wetland areas created by the discharge of agricultural drains onto the mud flats. There are very few native trees and less *P. sericea* than in the first zone, due to high salinity in the soil and alluvial aquifer (Zamora-Arroyo et al., 2001). Sediments and biota from the Salt Cedar Zone have higher levels of selenium in sediments and biota than other zones (Garcia-Hernandez, King et al., 2001), perhaps due to the predominance of agricultural drainage in its water budget. In general, wildlife use has not been adequately studied, but some endangered Yuma Clapper Rails (*Rallus longirostris yumanensis*) are found in El Indio and other drain-fed wetlands in this zone (Hiñojosa-Huerta et al., 2001).

Salt Grass Zone

We divided the final, intertidal portion of the river into two zones. We designated the west bank of the river as the Salt Grass Zone, since *D. palmeri* is the dominant plant on the Baja and Sonoran banks of the river as it approaches the sea and on Montague Island at the mouth of the river. Overall, this zone is only 1.6% vegetated, as the very high tidal amplitude scours the banks of the river and deposits mud over the tide flats. However, the Salt Grass Zone is an important nesting and feeding area for shorebirds (Mellink et al., 1996, 1997).

Cattail Zone

The east bank of the intertidal portion of river was designed the Cattail Zone because it contains Cienega de Santa Clara, the largest *Typha* marsh in the Sonoran Desert (Glenn et al., 1992; Zengel et al., 1995). It is maintained by discharge of agricultural waste water from Arizona's Welton-Mohawk Irrigation District via the Main Outlet Drain Extension (M.O.D.E.) canal (85% of inflow) and local agricultural drain water (15%) via the Riito canal (Zengel et al., 1995). In addition to *T. domengensis*, it contains 7 other common, emergent marsh species (Zengel et al., 1995). This unique, 4,200 ha wetland supports more than 6,000 Yuma Clapper Rails, by far the largest remaining population of this species (Hinojosa-Huerta et al., 2001). It also supports the endangered Desert Pupfish (*Cyprinodon macularius*)(Zengel and Glenn, 1996), as well as thousands of migratory and resident waterfowl (Mellink et al., 1996, 1997). It is an important feeding station along the Pacific Flyway. Cienega de Santa Clara appears to be the largest remaining cattail marsh on the lower Colorado River.

East of Cienega de Santa Clara along the escarpment that separates the Delta from the Gran Desierto, a string of small pozos (springs) bring fresh water onto the salt and mud flats of the eastern intertidal zone (Glenn et al., 1996). These *Typha*-dominated, pocket wetlands may be part of a long migration route for birds such as the willow flycatcher which travel along the Sonoran coastline to reach the lower Colorado River from wintering areas in southern Mexico and Central America (Garcia-Hernandez, Hinojosa-Huerta et al., 2001). Below the Cienega de Santa Clara, discharge from the marsh system mixes with seawater in an evaporation basin that is only occasionally flushed by high tides. This is important habitat for thousands of shorebirds (Mellink et al., 1996, 1997).

The marine zone

The near-cessation of freshwater flow at the river's mouth has had several direct and indirect consequences for the marine portion of the Delta. The most obvious result of the decline in freshwater influx has been an increase in the salinity of the water in the estuary and upper Gulf. Early observations (Townsend, 1901) and measurements during controlled releases (Lavín and Sánchez, 1999) indicate that salinities in the 32 to 35 parts per thousand (ppt) range were quite common. This is in sharp contrast to measurements made since the construction of upstream water diversions. Now, salinities are typically in the 35-45 ppt range (Alvarez Borrego et al., 1975; Flessa, personal observations). This increase in salinity was most likely the cause of the decline in the population of the bivalve mollusk *Mulinia coloradoensis,* once the most common species of mollusk in the intertidal zone of the Delta (Rodriguez et al., 2001).

The marine part of the Delta is also habitat to two endangered species: the Totoaba (*Totoaba macdonaldi*) a sciaenid fish, and the Vaquita (*Phocoena sinus*), the Gulf of California harbor porpoise. The Totoaba's decline is usually attributed to over fishing, bycatch in shrimp nets, and poaching. In addition, increased salinity in the river's estuary may have degraded the fish's spawning and nursery grounds (Cisneros Mata, et al., 1995). The principal source of mortality of the Vaquita seems to be its capture in fishing nets (Hohn, et al., 1996; D'Agrosa et al., 2000), but the role of increased salinity in its key habitat is unknown.

The increase in the salinity of the water in the river's estuary profoundly changed the circulation in the upper Gulf of California (Lavín and Sánchez, 1999; Lavín, et al., 1998; Carbajal et al., 1997). When the less dense river water entered the estuary, it tended to flow into the Gulf at the surface, inducing a landward bottom flow of more saline, and thus denser, marine water. Such circulation is typical of so-called well-mixed estuaries. Carbajal et al. (1997) estimate that the zone of freshwater mixing extended as far as 60 km from the river's mouth. Their estimate is substantiated by measurements made during controlled releases (Lavín and Sánchez, 1999) and by isotopic studies of Delta shells (Rodriguez et al., 2001).

Since the diversion of much of the river's fresh water, the estuarine circulation is now driven by the evaporation of Gulf water in the river's mouth. High evaporation rates generate dense, saline water that sinks and flows along the bottom of the upper Gulf, while relatively less dense Gulf water flows toward the estuary near the surface. Today's circulation is typical of so-called negative or inverse estuaries (Lavín et al., 1998).

Upstream dams and diversion projects have also trapped and diverted much of the Colorado's sediment load. The river once delivered approximately 160 million metric tons of sediment to the delta every year (van Andel, 1964). Today, that sediment load is almost zero and waves and the strong tidal currents are removing the previously deposited fine-grained sediments (Carriquiry and Sánchez, 1999). This sediment reworking is responsible for the high turbidity of the upper Gulf's waters. Before the dams, turbidity must have been even higher, but no observations were made.

Waves and tidal currents are capable of removing mud and silt, but coarse-grained material such as shells are concentrated in beach deposits known as cheniers (Augustinus, 1989). The shell-rich cheniers line the Baja California side of the delta for a distance of more than 40 km (Kowalewski and Flessa, 1995). The currently active cheniers are though to have begun forming after the completion of Hoover Dam and the resulting reduced sediment load due to the trapping of river sediment in Lake Mead (Thompson, 1968). The cheniers migrate to the west during storms and extreme high tides, marking the retreat of the sediment-starved delta.

The river not only delivered freshwater and sediment to the marine part of the Delta, it also delivered nutrients. Kowalewski et al. (2000) estimate that population densities of bivalve mollusks ranged from 25 to 50 specimens per square meter before the dams. In contrast, surveys of current densities show only densities from 2 to 17 specimens per square meter - a reduction of as much as 94% from pre-dam values. Other marine organisms probably had higher densities as well, as did the waterfowl that fed on them. Kowalewski et al. (2000) attribute the decline in population densities to the lack of river-born nutrients. Indeed, Galindo-Bect et al.'s (2000) observation that the size of shrimp catches in the upper Gulf is positively correlated with the previous year's controlled influx of river water indicates that the river once played a major role in supplying nutrients to the marine life of the Delta.

Unlike the riparian corridor of the Colorado, the marine portion of the Delta has shown little signs of recovery as a result of the delivery of excess flow. It is not yet known what flows might be needed to restore part of the Delta's marine life.

RIVER MANAGEMENT IN MEXICO

The waters of the Colorado River are governed by the "Law of the River." As described by Glennon and Culp, the Law of the River consists of "an array of statutes, court decisions and decrees, contracts, interstate compacts, administrative laws, and international treaties" Part of this law is the U.S. and Mexico Water Treaty signed in 1944, which provides Mexico with a minimum of 1.5 million of acre feet (maf) per year, and up to 1.7 maf in surplus years (see Glennon and Culp for a detailed explanation of the Law of the River).

This water is received by Mexico at Morelos Dam in Mexico, where it is diverted into the irrigation system through the Central Feeder Canal or kept in the mainstream of the river. Morelos Dam is only a diversion dam, and therefore has no storage capacity; that is, the storage capacity for river water reaching Morelos dam is only associated with the capacity of the irrigation system (canals) itself. When this capacity is reached during excess flows, water needs to be left flow through Morelos dam into the mainstream of the river and eventually reach the Gulf of California. It is in fact this excess water that has been associated to the regeneration of native trees in wetlands in the riparian corridor (Zamora et al, 2001, Zamora and Hinojosa, chapter 3).

The National Water Commission (CNA) in Mexico is responsible of operating the agricultural irrigation system and controlling excess flows to protect productive zones in the Mexicali and San Luis valleys from flooding. Since the starting of the irrigation district 14 in 1970, CNA started to build canals and drains to distribute and collect water throughout the irrigation district. The nominal river flow capacity at the NIB in the early 1970s was approximately 4,500 m^3/s. With the construction of the Barrote and Southern Feeder canals along portions of the river, this capacity was reduced to 1,200 m^3/s. However, this much flow was never observed as by the end of 1970s almost no water reached the delta, causing sediments to build up in portions of the river, reducing its flow capacity even more to 300 m^3/s. At the site know as Carranza road crossing, sediment build up caused that river bed to be 9.5 m higher than normal. By 1981, CNA had to implement measures to increase the river flow capacity to 800 m^3/s. This, however, was not enough to accommodate the pick of 1,050 m^3/s reached during the 1983-87 flow events, and for which CNA had to implement urgent protective measures to prevent erosion of the flood control levees. During the 1993 flood, with a maximum of approximately 700 m^3/s, an estimated 12 million m^3 of sediment built up in the Mexican side of the Colorado River, impacting mainly the zone below Carranza crossing, where river bed became 2.5 m. above pre-flooded conditions, reducing flow capacity to 100 m^3/s in some portions of the river (Jose Trejo, CNA, personal communication, 2002).

In order to maintain an adequate capacity to accommodate future river flows, in 1996 CNA began to implement the Pilot Channel project in response to the expectation of receiving 700 m^3/s river flows from U.S. by 1997. This program was designed to remove river sediments and straighten portions of the river to maintain a total river flow capacity of approximately 600 m^3/s and thus provide for protection of agricultural productive zones and human communities. The Pilot Channel starts just south of the town of San Luis Rio Colorado and runs about 61 kilometers downstream (Figure 4.2). The 600 m^3/s flow capacity of the pilot channel is obtained by the 300 m^3/s from the straightening and sediment removal of the river channel, plus another 300 m^3/s created by clearing out 100 meters (from the center of the main channel) of vegetation on each bank of the river. The vegetation clearing allows river flows to remove sediments along the river banks during flooding and thus accommodate up to another 300 m^3/s. According to CNA, vegetation is cleared out along the banks of the river because otherwise vegetation makes the river banks more stable, preventing erosion of banks and allowing water to overbank the channel and potentially damage the protection levees.

To eliminate over bank flooding represents a major threat to native vegetation since it is this over bank flooding that has caused the revegetation by native species by allowing the germination of native vegetation, mainly cotton woods and willows. For example, by early 1998 we observed many seedlings of cotton woods and willows within these 200 meters stretch along the river banks in the Salt Cedar/Willow/Cottonwood Zone. These seedlings established after 1997 overbank flooding events (Zamora-Arroyo et al, 2001). However, field observations in 1998 and 1999 confirmed us that seedlings and older trees were cleared out as part of the CNA´s river management operations to maintain the pilot channel functional. As we discuss below, one opportunity to maintain and restore native vegetation in the riparian corridor consists of finding ways to maintain the pilot channel functional whereas minimizing the clearing of vegetation along the banks.

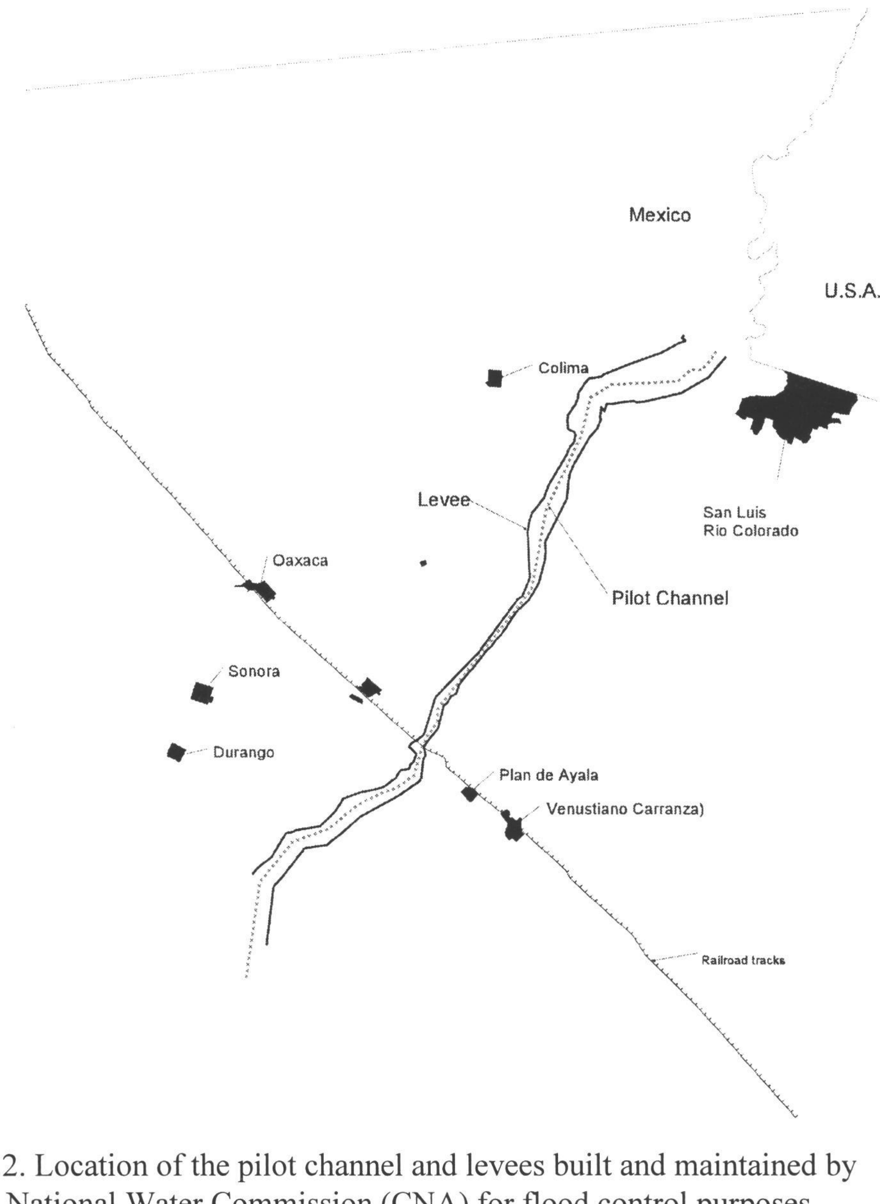

Figure 4.2. Location of the pilot channel and levees built and maintained by Mexican National Water Commission (CNA) for flood control purposes.

RESTORATION OPPORTUNITIES AND RESEARCH PRIORITIES

Conservation of the natural and critical habitat in the Delta of the Colorado River will require the implementation of ecological restoration actions. As pointed out by MacMahon and Holl (2001), restoration should not be seen as an alternative for preservation. This highlights the importance of protecting current natural habitat in the Delta that has regenerated in the last two decades as well as to restore new areas. Defining these terms shall help to clarify the differences. According to Bradshow (1997; in MacMahon and Holl, 2001), restoration refers to "bringing an ecological system back to its original or former state" To be more specific, restoration should consider the ecological functions as well as physical, chemical and biological characteristics of the original state (National Research Council, 1992; in Landers, 1997). On the other hand, "when a system is providing adequate biological integrity, the goal of a management action is to maintain this ecological function" (Landers, 1997).

Based on the definition of restoration, one could argue that the ideal management goal for the Delta might be to restore the entire Delta to its original or pre-development conditions. However, this is practically impossible due to the extend of human and natural alterations of the river. Nevertheless, we argue that the distinction between maintaining and restoring habitat might be useful in practice in the Delta. That is, there currently exist certain habitats in the Delta that are providing critical ecological functions. Although it can be argue that these functions are not entirely the same as in their original state, these areas clearly provide important ecological functions as they support several species of birds, vegetation, fish and other wildlife that the rest of the Delta. This is the case for example of the Cienega de Santa Clara, el Doctor Wetlands, and some dense patches of native riparian forest in the riparian corridor. These should be maintained through implementation of protective measures. Protective measures are urgent as some of these critical habitats are being threatened by river management operations in both sides of the border. On the other hand, restoration measures are needed to ecologically enhance current habitat as well as to create new habitat, and thereby provide for enhancement of ecological functions and wildlife value of special areas in the Delta. New habitat could be created to expand current critical habitat or in completely new areas.

Protective measures and restoration opportunities in the Delta have been explored in more detail during the last decade. The Cienega de Santa Clara and the Rio Hardy Wetlands were among the first sites identified as requiring protective measures and having feasible restoration opportunities as they received brackish agricultural water (Glenn, 1996; Payne et al, 1992; Briggs and Cornelius, 1998). By the end of 1998, advances in the inventory of the Delta hydrological and ecological characteristic allowed for the identification of additional protection needs and restoration opportunities. Sites like Campo Mosqueda, Cucapa El Mayor and Cucapa Complex in the Hardy River were selected based on their habitat value, the urgency to protect and restore them, and the willingness of local people to undertake actions to protect them (Valdes-Casillas et al., 1998). Similarly, the Salt Cedar/Willow/Cottonwood Zone defined above has been identified as having patches of critical habitat that need protection and need to be enhanced though restoration actions (Valdes-Casillas et al, 1998; Zamora-Arroyo et al, 2001; Zamora-Arroyo and Hinojosa, chapter 3).

Restoration opportunities in the riparian corridor

As pointed out by Soulé and Orians (2001), there is an increasing need “for scholars to educate decision makers about the merits of making scientifically informed conservation and natural resource decisions and also about the costs of failing to do so" In the case of the Delta, as is the case in other coastal areas in Mexico, scientists from biological and social disciplines have increased their communication with decision makers, particularly municipal and state authorities. Our experience working with the Baja California Regional Office of the National Water Commission (CNA) indicates that working closely with decision makers can be done and is very valuable. In fact, a major opportunity to protect and restore habitat en the Delta's riparian corridor originates from the close collaboration of academic and non-governmental organizations with CNA.

As mentioned before, CNA has the responsibility of protecting productive areas and human communities from flooding. The implementation of the Flood Control Program by CNA has resulted in the clearing of native riparian vegetation within 200 m. of the center of the main river channel. To find ways to prevent this clearing from happening, a joint effort by several institutions and CNA is preparing to initiate an assessment of ecological restoration opportunities within CNA's flood control program. We argue that current habitat areas in the riparian corridor should be targeted for protective and restoration actions and that these actions can be accommodated into this program. The results of the percent vegetation cover and trend analysis (Zamora-Arroyo et al., 2001; Zamora-Arroyo and Hinojosa, chapter 3) show that vegetation in the Salt Cedar/Willow/Cottonwood Zone has positively responded to instream flows. Furthermore, within these areas, priority sites for protective and restoration measures are those in 1999 had a vegetation cover greater than 70% (Figure 4.3). One way to accomplish this is by analyzing where old river channels have been block by the original construction or maintenance of pilot channel, and by re-open them with the necessary precautions to allow for water to wet or inundate vegetated areas. This can be developed implementing a suitability analysis to outline those areas of native habitat that will be better to protect and restore over the long term. This analysis should consider not only current vegetation patterns, but also other variables such as surface and groundwater water availability, dispersal patterns of native vegetation over non-vegetated land, and CNA river operation actions, among other.

Research priorities

Despite the increase knowledge and understanding of ecological characteristics of the Delta habitats, it is important to recognize the urgent need to increase interaction of disciplines across scale of time and space in order to develop an integrated approach to protect and restore the Delta. Several research questions will benefit from this cross discipline interactions. For example, a fundamental question refers to the estuarine and marine interactions and the importance of freshwater input from the Colorado River. Also important is to advance in the understanding of interactions between river flows, vegetation, and habitat values at different spatial and temporal scales. This of course is linked to the resilience of the Delta habitats and to the need to better understand what factors are affecting this resilience and what could be the threshold values in which this resilience might be at risk.

There are additional research needs in the Delta that need to be completed before a comprehensive conservation and restoration plan can be prepared and implemented. Some of these have been identified by Soulé and Orians (2001) in the field of conservation biology in general, some of which are relevant to the Delta. For example, further investigation should be directed to define the size and site of wildlife corridors. Also relevant to the Delta is the need to look at lag and cumulative effects. Lag effects of instream flows on vegetation recruitment and establishment of native vegetation versus the invasion of exotic plant species are not well understood. The impact that cumulative effects, such as reduced river flows altogether with vegetation clearing and other anthropogenic alterations, on the potential loss of habitat needs to be address if successful restoration projects are sought to be implemented. The role of ecological restoration in the Delta, particularly in large scale projects, deserves increasing attention as we learn from some small-scale restoration projects already being implemented along the Hardy River. For example, a 10 ha restoration site is being developed in the Hardy River, in which about 700 mesquites have been planted, and will be followed by the planting of some cottonwoods and willows along a 100 meters stretch of a agricultural drainage canal. Of course, continuous and long term monitoring and evaluation of these restoration sites and in general of the ecological health of the Delta and naturally regenerated habitats will be essential to support sound decision making. Specifically, the use of remote sensing tools has been promising (Zamora-Arroyo, 2001), but additional research, particularly referent to spatial and time resolutions, are needed to validate these tools.

Recognizing the need to look identify conservation and restoration opportunities and needs of the Delta from a multidisciplinary perspective, a group of institutions is organizing an expert a workshop in October, 2002 with the general goal of developing information needed to develop a comprehensive restoration plan for the Delta. The workshop seeks to encourage the interaction among experts from different disciplines (ecology, hydrology, oceanography, ichthyology, ornithology, geology, and others) to develop an ecological assessment of specific sites within the Delta, including the restoration and risk potential and their water requirements in terms of quantity, quality and timing. One of the end products resulting from this workshop is the identification of the special interest areas in the Delta that need to be protected and restored. This information shall then provide valuable information to the future development of a comprehensive conservation and restoration plan for the Delta.

DISCUSSION

The most salient feature of the fresh water and brackish flows that sustain the Delta is that they are managed flows. They are either agricultural drain waters from the United States and Mexico, or surplus river flows released from United States dams into the channel of the Colorado River (Cohen et al., 2001). Hence, the health of the delta natural areas is almost entirely dependant on water management decisions made in the United States and Mexico. Yet, these natural areas have no official standing in the water management strategies of either country (Pitt, 2001). Their ecological importance, even their existence, was largely unknown prior to 1992, when the operation of the Yuma Desalting Plant threatened to destroy Cienega de Santa Clara (Glenn et al., 1992). In the United States, maintenance of environmental assets in Mexico is not among the criteria the U.S. Bureau of Reclamation uses in managing river flows. In Mexico, large areas of cottonwoods and willows are routinely cleared from the channels following flood releases, to facilitate the movement of water to the sea.

The increasingly important question of "How much water is needed to restore the delta?" (Pitt, 2001; Zamora-Arroyo and Hinojosa, chapter 3) requires urgent attention as urbanization on both sides of the border is increasing the demands for Colorado River water, which is already considered to be over-apportioned among the seven basin states and Mexico. The answer emerging from preliminary studies is that surprisingly little water might suffice to conserve the existing riparian and wetland ecosystems in the delta. Two findings support this hypothesis: 1) a water balance study suggests that even when there are no flood waters released to the delta, vegetation including native trees and marsh plants are supported by agricultural return flows which recharge the alluvial aquifer and wetlands (Cohen et al., 2001); 2) even modest flood releases are sufficient to induce overbank flooding and to germinate new cohorts of native trees (Zamora-Arroyo et al., 2001). Once established, these phreatophytic species extract water from the aquifer and do not require surface flows.

Zamora et al. (2001), analyzing the vegetation response to past flow events, determined that a once-in-four-years, 3-months spring flow of 3 x 10^8 m^3 at 80-120 m^3 sec^{-1} was sufficient to establish new cohorts of native trees in the Salt Cedar/Willow/Cottonwood Zone. Pitt et al. (2000) recommended that in addition to this pulse flood, a smaller, perrenial flow of 4 x 10^7 m^3 was needed to maintain aquatic habitat for birds, fish and insects using this zone. The total (annualized) water requirement of about 10^8 m^3 yr^{-1} is only 0.5% of the mean annual flow of the Colorado River. Yet, policy makers anticipate substantial difficulty in securing even this small amount of water as an environmental allotment, given human demands on the river (Pitt and Varady et al., 2001). A continuing water source for the Cienega de Santa Clara is also in doubt, as the water entering in the M.O.D.E. canal might be diverted to the Yuma Desalination Plant, and replaced with hypersaline brine (Glenn et al., 1992, 1996; Zengel et al., 1995).

The effect of flood flows on the marine environment and the quantities required to boost productivity are, presently, unknown. Oceanographic studies suggest that the upper Gulf of California is not nutrient limited (Hernandez-Ayon et al., 1993; Santa Maria del Angel et al, 1996), hence river flows are not required to stimulate primary productivity. On the other hand, the work of Kowalewski et al. (2000), Rodriguez et al (2001) and Rodriguez et al. (2001) suggests that the former brackish mollusk beds and the unknown fauna that may have depended on them will not return without substantial annual flows. The shrimp catch in the upper Gulf of California responds positively even to the modest releases which have occurred since Lake Powell filled (Galindo-Bect et al., 2000). Much more study is required on the estuarine and marine ecosystem before water requirements can be estimated. The expert workshop shall provide a more thorough analysis and answers to this question.

CONCLUSIONS

Recent studies have shown that the basis for a resurgence in ecosystem function in the lower Colorado River basin exists due to the reestablishment of riparian and wetland vegetation in the delta. This resurgence depends on continued discharge of flood water and agricultural drainage water from the United States to Mexico. The few faunal studies, mostly of endangered species, show that the habitat revival has had positive effect on wildlife. Yet, there is little information on the most of the populations of fish, reptiles, mammals and birds that use the delta and its marine zone. There have been no studies at all of movement of species between the United States and Mexico, even though a species revival in the Delta could help repopulate upstream habitats. This region still can be described as a scientific "blank spot" on the map of North America, deserving much more study to inform those who make decisions about its future.

REFERENCES

Briggs Mark and Steve Cornelius. (1998). Opportunities for ecological improvement along the lower Colorado River and Delta. *Wetlands*. **18**: 513-529.

Alvarez Borrego, S., Flores Báez, B.P., Galindo Bect, L.A., (1975). Hidrología del Alto Golfo de California II. Condiciones durante invierno, primavera y verano. *Ciencias Marinas* **2**, 21-36.

Augustinus, P.G.E.F., (1989). Cheniers and chenier plains: A general introduction. *Marine Geology* **90:** 219-229.

Busch, D., and Smith, S., (1995). Mechanisms associated with decline of wood species in riparian ecosystems of the southwestern U.S. *Ecological Monographs*, **65:** 347-370.

Carbajal, N., Sousa, A., and Durazo, R., (1997), A numerical model of the ex-ROFI of the Colorado River. *Journal of Marine Systems,* **12:** 17-33.

Carriquiry, J.D. and Sánchez, A., (1999). Sedimentation in the Colorado River delta and Upper Gulf of California after nearly a century of discharge loss. *Marine Geology,* **158:** 125-145.

Cisneros-Mata, M.A., Montemayor-López, G., and Román-Rodríguez, M.J., (1995). Life history and conservation of *Totoaba macdonaldi*. *Conservation Biology,* **9:** 806-814.

Cohn, J., (2000). Saving the Salton Sea - Researchers work to understand its problems and provide possible solutions. *Bioscience*, **50:** 295-301.

Cohen M. J., Henges-Jeck, C. and Castillo-Moreno, G. (2001). A preliminary water balance for the Colorado River delta, 1992-1998. *Journal of Arid Environments*, **49**: 35-48.

D'Agrosa, C., Lennert-Cody, C.E. and Vidal, O., (2000). Vaquita bycatch in Mexico's artisanal gillnet fisheries: Driving a small population to extinction. *Conservation Biology*, **14**: 1110-1119.

Fradkin, P., (1981). A river no more, the Colorado River and the West. Alfred A. Knopf, New York.

Galindo-Bect, M., Glenn, E., Page, H., Fitzsimmons, K., Galindo-Bect, L., Hernandez-Ayon, J., and Petty R., (2000). Penaeid shrimp landings in the upper Gulf of California in relation to Colorado River freshwater discharge. *Fishery Bulletin,* **98**: 222-225.

Garcia-Hernandez, J., Hinojosa-Huerta, O., Gerhart, V., Carrillo-Guerrero, Y. and Glenn, E. P., (2001). Willow flycatcher (*Empidonax traillii*) surveys in the Colorado River delta: implications for management. *Journal of Arid Environments*, **49**: 161-169.

Garcia-Hernandez, J., King, K., Velasco, A., Shumilin, E., Mora, M. and Glenn, E., (2001). Selenium, selected inorganic elements, and organochlorine pesticides in bottom material and biota from the Colorado River delta. *Journal of Arid Environments*, **49**: 65-89.

Glenn, E., R. Felger, Burquez, A., and Turner, D., (1992). Cienega de Santa Clara - endangered wetland in the Colorado River delta, Mexico. *Natural Resources Journal,* **32**: 817-824.

Glenn, E., Lee, C., Felger, R. and Zengel, S., (1996). Effects of water management on the wetlands of the Colorado River delta, Mexico. *Conservation Biology,* **10**: 1175-1186.

Glenn, E., Tanner, R., Mendez, S., Kehret, T., Moore, D., Garcia, J., and Valdes, C., (1998). Growth rates, salt tolerance and water use characteristics of native and invasive riparian plants from the delta of the Colorado River delta, Mexico. *Journal of Arid Environments,* **40**: 281-294.

Hernandez-Ayon, J., Galindo-Bect, M., Flores-Baez, B. and Alvarez-Borrego, S., (1993). Nutrient concentrations are high in the turbid waters of the Colorado River delta. *Estuarine and Coastal Shelf Science,* **37**: 593-602.

Hinojosa-Huerta, O., DeStefano, S., and Shaw, W., (2001). Distribution and abundance of the Yuma clapper rail (*Rallus longirostris yumanensis*) in the Colorado River delta. *Journal of Arid Environments,* **49**: 171-182.

Hohn, A.A., Read, A.J., Fernåndez, S., Vidål, O., and Findley, L.T., (1996). Life history of the vaquita, Phocoena sinus, Phocoenidae, Cetacea). *Journal of Zoology* (London), **239**: 235-251.

Kowalewski, M., and Flessa, K. W., (1995), Comparative taphonomy and faunal composition of shelly cheniers from northeastern Baja California, Mexico. *Ciencias Marinas,* **21**: 155-177.

Kowalewski, M., Serrano, G., Flessa, K., and Goodfriend, G., (2000). Dead delta's former productivity: Two trillion shells at the mouth of the Colorado River. *Geology,* **28**: 1059-1062.

Landers H. Dixon. (1997). Riparian Restoration: current status and the reach to the future. *Restoration Ecology,* **45**: 113-121

Lavín, M.F., Godínez, V.M., and Alvarez, L.G., (1998). Inverse–estuarine features of the upper Gulf of California. *Estuarine, Coastal and Shelf Science,* **47**: 769-795.

Lavín, M.F., and Sánchez, S., (1999), On how the Colorado River affected the hydrography of the upper Gulf of California. *Continental Shelf Research,* **19**: 1545-1560.

Levine, C. and Stromberg, J., (2001). Effects of flooding on native and exotic plant seedlings: implications for restoring southwestern riparian forests by manipulating water and sediment flows. *Journal of Arid Environments,* **49**: 111-131.

Leopold, A., (1949). The green lagoons. Pages 150-158 in A. Leopold, editor. A Sand County Almanac. Oxford University Press, New York.

MacDougal, D., (1905). Botanical explorations in Arizona, Sonora, California and Baja California. *Journal of the New York Botanical Garden,* **6**: 91-102.

MacDougal, D., (1907). The desert basins of the Colorado delta. *Bulletin of the American Geographical Society,* **29**: 705-729.

MacMahon A James and Karen D. Holl. 2001. Ecological Restoration, a key to conservation biology´s future. In Conservation Biology: research priorities for the next decade. Michael E. Soulé and Gordon H. Orians (Eds). Pp.245-269.

Marler, R., Stromberg, J. and Patten, D., (2001). Growth response of Populus fremontii, Salix gooddingii, and Tamarix ramosissima seedlings under different nitrogen and phosphorous concentrations. *Journal of Arid Environments,* **49**: 133-146.

Mellink, E., Palacios, E., and Gonzalez, S. (1996). Notes on nesting birds of the Cienega de Santa Clara saltflat, northwestern Sonora, Mexico. *Western Birds,* **27**: 202-203.

Mellink, E., Palacios, E., and Gonzalez, S., (1997). Non-breeding waterbirds of the delta of the Rio Colorado, Mexico. *Journal of Field Ornithology,* **68**: 113-123.

Morales-Abril, G., (1994). Reserva de la biosfera alto golfo de California y delta del Rio Colorado. *Ecologica,* **3**: 26-27.

Nagler, P., H. Rodriguez, E. Glenn and A. Huete. (2001). Assessment of spectral vegetation indices for riparian ecosystems in the Colorado River Delta. *Journal of Arid Environments,* **49:** 91-110.

Ohmart, R., Anderson, B., and Hunter, W. (1988). Ecology of the Lower Colorado River from Davis Dam to the Mexico-United States boundary: a community profile. National Technical Information Service, Alexandria, Virginia.

Pitt, J., (2001). Can we restore the Colorado River delta? *Journal of Arid Environments,* **49:** 211-220.

Pitt, J., Luecke, D., Cohen, M., Glenn, E. and Valdes-Casillas, C., (2000). Two nations, one river: managing ecosystem conservation in the Colorado River delta. *Natural Resources Journal,* **40**: 819-864.

Poff, N., Allan, J., Bain, M., Karr, J., Prestegaard, K., Richter, B., Sparks, R. and Stromberg, J., (1997). The natural flow regime. *Bioscience,* **47**: 769-784.

Roden, G. I., (1964), Oceanographic aspects of the Gulf of California: in van Andel, T. H. and Shor, G. G., eds., Marine Geology of the Gulf of California: American Association of Petroleum Geologists. Memoir 3, Tulsa, Oklahoma, p. 30-58.

Rodriguez, C.A., Flessa, K.W., and Dettman, D.L., (2001), Effects of upstream diversion of Colorado River water on the estuarine bivalve mollusc Mulinia coloradoensis. *Conservation Biology,* **15**: 249-258.

Rodriguez, C., Flessa, K., Tellez-Duarte, M., Dettman, D., and Avila-Serrano, A., (2001). Macrofaunal and isotopic estimates of the former extent of the Colorado River estuary, upper Gulf of California, Mexico. *Journal of Arid Environments,* **49:** 183-193.

Santamaria del-Angel, E., Millan-Nunez, R., and DelaPena-Nettel, G., (1996). Effects of turbidity on primary productivity at two stations in the area of the Colorado River delta. *Ciencias Marinas,* **22**: 483-493.

Sykes, G., (1937). The Colorado Delta. Carnegie Institution, Washington, D.C., 193 pp.

Thompson, R. W., (1968), Tidal Flat Sedimentation on the Colorado River Delta, Northwestern Gulf of California: Geological Society of America Memoir 107, Boulder, Co. 133 p.

Townsend, C.H., 1901. Dredging and other records of the U.S. Fish Commission Steamer "Albatross" with bibliography relative to the work of the vessel. US Fish Commission Report for 1900, p. 387-562.

U.S. Bureau of Reclamation, (1996). Description and Assessment of Operations, Maintenance, and Sensitive Species of the Lower Colorado River. U.S. Bureau of Reclamation, Boulder City, Nevada.

Valdes-Casillas, C., Hinojosa-Huerta, O., Munoz-Viveros, M., Zamora-Arroyo, F., Carrillo-Guerrero, Y., Delgado-Garcia, C., Lopez-Camacho, M., Glenn, E., Garcia,-Hernandez, J., Riley, J., Baumgartner, D., Briggs, M., and Lee, C., Chavarria-Correa, E., Congdom, C., and Luecke, D., (1998). Information Database and Local Outreach Program for the Restoration of the Rio Hardy Wetlands, Lower Colorado River Delta, Baja California and Sonora, Mexico. North American Wetland Conservation Council, Arlington, Virginia.

Van Andel, T.H., 1964, Recent marine sediments of the Gulf of California: in van Andel, T. H. and Shor, G. G., eds., Marine Geology of the Gulf of California: American Association of Petroleum Geologists. Memoir 3, Tulsa, Oklahoma, p. 216-310.

Vandersandae, M., Glenn, E. and Walworth, J., (2001). Comparative tolerances of five riparian plants from the lower Colorado River to salinity, drought, and inundation. Journal of Arid Environments.

Varady, R., Hankins, K., Kraus, A., Young, E. and Merideth, R., (2001). To the Sea of Cortez: nature, water, culture and livelihood in the lower Colorado River Basin and delta - an overview of issue, policies, and approaches to environmental restoration. *Journal of Arid Environments,* **49:** 195-209.

Zamora-Arroyo, F., Nagler, P., Briggs, M., Radtke, D., Rodriquez, H., Garcia, J., Valdes, C., Huete, A. and Glenn, E., (2001). Regeneration of native trees in response to flood releases from the United States into the delta of the Colorado River, Mexico. *Journal of Arid Environments,* **49:** 49-64.

Zengel, S., and Glenn, E., (1996). Presence of the endangered Desert Pupfish (Cyprinodon Macularius, Cyprinidontidae) in Cienega de Santa Clara, Mexico, following an extensive marsh dry-down. *The Southwestern Naturalist,* **41**: 73-78.

Zengel, S., Mertetsky, V. Glenn, E., Felger, R, and Ortiz, D., (1995). Cienega de Santa Clara, a remnant wetland in the Rio Colorado delta (Mexico): vegetation distribution and the effects of water flow reduction. *Ecological Engineering,* **4**: 19-36.

CHAPTER 5: CONCLUSIONS

The Colorado River is one of the world's most harnessed rivers. Its natural flows and ecology have been disrupted by the construction of dams, water diversions, and flow regulation. One of the most disrupted ecosystems along the Colorado River has been its delta, with about 90% of its original wetlands disappeared (Glenn et al., 1996). This situation has raised many questions among decision makers about the need to restore its Delta as the perception of a dead ecosystem developed during 1980s. The research presented here adds to the increasing knowledge about the Delta ecological significance. Particularly, the results provide significant evidence about the resilience of the Delta habitats and the resulting positive change in vegetation during the 1990s, which supports the rejection of the perception of a dead Delta. This information brings additional elements to clarify the debate of whether water should be dedicated to the Delta to support its ecosystems. It is clear from this research that overbank flooding every few years, with smaller but more continues flows throughout the year do make a difference in the regeneration of vegetated habitat, which now account for 23% of vegetation in a 100 km, non-perennial, stretch of river below Morelos Dam at the United States - Mexico border. The return of native trees, some times as patches of gallery forest, illustrates the importance of pulse floods in restoring the Delta ecosystem.

Several authors have indicated that during the 1990s wetland areas have actually regenerated (Glenn 1996; Briggs and Cornelius, 1998; Valdés-Casillas, 1998). Although these observations documented these changes in the field, they lacked a multiple year systematic monitoring and therefore did not provide statistical information to test the hypothesis of spatial change. The multiple-year analysis on percent vegetation cover by Zamora-Arroyo et al (2001) allowed us to perform the trend analysis presented here and to statistically determine whether there has been a change in percent vegetation cover during the 1990s. Results indicated that some areas of the Colorado River delta show a significant upward trend in percent vegetation cover between 1992 and 1999; this clearly supports the observational and anecdotal data. It is important to notice that in spite the small sample size (only 6 years), by capturing dry years (1992 and 1996) and wet years (1994, 1997-1999), significant trends were detected.

The relationship of vegetation cover with the number of days that presented a significant instream flow supports the suggestion by Glenn et al, (2001) that modest flow should be allocated for the conservation of the riparian areas of the Colorado River in Mexico. Our results also show that pulse floods every 4 years would allow the regeneration of denser riparian patches. These relationships were particularly significant in areas that have been found to support the most important stands of native riparian trees in the Lower Colorado Basin, such as Morelos and Carranza zones (Zamora-Arroyo et al. 2001), which represent critical habitat for endangered or sensitive species, such as the Willow Flycatcher (*Empidonax traillii*), Yellow-billed Cuckoos (*Geococcyx americanus*), and Bell's Vireos (*Vireo bellii*; Garcia-Hernandez et al. 2001, Hinojosa-Huerta et al. in review).

At San Luis, vegetation cover does not seem to be strongly related with hydrological variables, as this area receives other water sources not accounted for in the model, mainly sewage discharge from the city of San Luis Rio Colorado, Sonora, and spillways from the irrigation system of the Mexicali Valley. The Mayor-Hardy, Ayala Drain, and Ciénega zones also receive other water sources, mostly agricultural drainage discharge form the Mexicali Valley, although the Ciénega's main source is the MODE canal. These sources are most stable than instream flows, thus vegetation cover and open water areas in these zones show less variation through the years and less relationship with river flows.

Instream flows have critical impacts on habitat features in these western Delta zones, by promoting the establishment of patches of >70% vegetation in the marshes and the maintenance of open water areas. These habitat features are critical habitat for endangered species as the Yuma Clapper Rail (Hinojosa-Huerta 2000) and for wintering and migratory waterbirds for which the delta is a critical site (Mellink et al. 1997). The patterns of vegetation and open water dynamics in the Colorado floodplain are clearly related to instream flows. Further research, however, should focus in understanding the effect of the instream flows on plant community dynamics, on the ecological relationship of plants with wildlife, and on the ecology of the estuarine and intertidal area.

There exist several limitations of the statistical analysis on spatial change and relationship of vegetation patterns and instream flows. Unfortunately, at the time of this analysis it was not possible to acquire neither satellite images for the 1980´s nor more frequent images for 1990s, which would have increased sample size and increased the statistical significance of trend analysis as well as of the multiple regression analysis of instream flows and percent vegetation cover. This precluded us from quantifying the amount of vegetation cover after the flood event of 1983-1988, the largest flood event since the filling of major dam. Similarly, because of the lack of a more complete data set, this study did not test the relationship between water flow variables and vegetation cover. However, the analysis allowed the identification of a specific hypothesis that could be properly tested with additional data. This information, along the possibility of having experimental floods and a hydrological characterization of the Delta, will allow to complement and test the spatial trend and regression model presented here, as well as to incorporate a spatial component to better estimate the response of vegetation cover to instream flows. This will allow the development of confidence estimates of restoration scenarios under different instream flows, critical information for decision-making.

Although a hydrological model is need to provide better and specific estimates of water requirements in the Delta, I conclude that for the riparian corridor (salt cedar/cottonwood and willow ecozone) a spring flow of 300 million m^3 is sufficient to germinate and establish new cohorts of native trees. In addition, it is necessary to test the hypothesis about the need of smaller but periodic or continuous flows (daily and monthly averages) greater than 2 m^3/s to maintain current and newly established vegetation in the riparian corridor. Proper testing of this hypothesis requires the determination of vegetation cover in the riparian corridor at least during each climate season and the incorporation of all water sources reaching the river along the corridor.

Extensive field observations indicated that the percent vegetation cover maps calculated from satellite images and the trend analysis represent an important spatial-temporal tool to monitor the impact of instream flows in the Colorado River Delta. By applying this tool, one can quantify the amount of vegetation cover in each habitat zone of the Delta for past and present years. However, it is important to notice that in order to develop an appropriate habitat interpretation of the results, field word is required to identify distributions and structure of vegetation, particularly in the riparian zone. Although detailed observation of percent vegetation cover maps provide in themselves a graphic point of comparison of changes in vegetation throughout years, management decisions call for a more robust way to assess this change as well as the variables to which this change is associated. The multi-temporal and spatial trend analysis used here provides a statistical way to measure trends in percent vegetation cover and helps to filter out those non-systematic or random variables that might be present year to year. Because the analysis is performed on a pixel by pixel basis, a significant trend would be determined only when there is consistent change throughout the years, thus reducing the impact of lack of independence of percent vegetation cover from one year to another (Schlagel and Newton, 1996). Although the lack of independence might reduce the statistical validity of the significance levels, our field observations in the Delta show that this trend analysis technique is still useful to pinpoint areas of significant change. A further spatial-temporal analysis of the Mann-Kendall test is required to increase the confidence of estimates of percent vegetation cover trends to water flows.

Approximately 2,000 of ha areas with in the riparian corridor with vegetation coverage greater than 70% and showing a significant positive trend should be target for conservation actions, particularly protective actions that provide for periodic flows to maintain these critical habitats. Other conservation actions involve restoration projects that need to be implemented to enhance the ecological functions of these habitats by expanding current habitats and/or creating corridors to connect these areas. This is particularly viable in the riparian corridor where water can be diverted into open and vegetated areas by opening old river channels. The resulting enhanced vegetation will benefit river management operations by providing protective barriers against erosion of flood control levees during large flood events.

Despite the increase knowledge and understanding of ecological characteristics of the Delta habitats, it is important to recognize the urgent need to increase interaction of disciplines across scale of time and space in order to develop an integrated approach to protect and restore the Delta. Several research questions will benefit from this cross discipline interactions. For example, a fundamental question refers to the estuarine and marine interactions and the importance of freshwater input from the Colorado River. Also important is to advance in the understanding of interactions between river flows, vegetation, and habitat values at different spatial and temporal scales. This of course is link to the resilience of the Delta habitats and to the need to better understand what factors are affecting this resilience and what could be the threshold values in which this resilience might be at risk.

There are additional research priorities in the Delta that need to be completed before a comprehensive conservation and restoration plan can be prepared and implemented. Further investigation should be directed to define the size and site of wildlife corridors. Also relevant to the Delta is the need to look at lag and cumulative effects. Lag effects of instream flows on vegetation recruitment and establishment of native vegetation versus the invasion of exotic plant species are not well understood. The impact that cumulative effects, such as reduced river flows altogether with vegetation clearing and other anthropogenic alterations, on the potential loss of habitat needs to be address if successful restoration projects are sought to be implemented. The role of ecological restoration in the Delta, particularly in large scale projects, deserves increasing attention as we learn from some small-scale restoration projects already being implemented along the Hardy River. One example is a 10 ha restoration site being developed in the Hardy River, in which about 700 mesquites have been planted, and will be followed by some cotton woods and willows along a 100 meters stretch of a agricultural drainage canal. It is expected that the experience from this pilot restoration projects will be soon transfer to the riparian corridor. Of course, continuous and long term monitoring and evaluation of these restoration sites and in general of the ecological health of the Delta and naturally regenerated habitats will be essential to support sound decision making. Specifically, the use of remote sensing tools has been promising, but additional research, particularly referent to spatial and time resolutions, are needed to validate these tools.

Considering that bringing back the Colorado River system to its pre-development condition is practically impossible and perhaps undesirable considering all the human water dependent uses in the basin, the information provided here should be useful to identify those areas where conservation and/or restoration efforts must be concentrated. Particularly important are areas within the riparian corridor and the Hardy Colorado zones. The great resilience of the Delta has allowed its habitat to rapidly and positively response to recent instream flows, providing us with an indication of minimum water requirements, quantity and timing, to sustain these improved habitat. Local and state water users in the US and

Mexico, government agencies and non-governmental organizations in both countries are now responsible for identifying and implementing actions to maintain and, why not, expand these revitalized critical delta habitats through ensuring that Delta's water requirements are fully identified and met.

BIBLIOGRAPHY

Alvarez Borrego, S., Flores Báez, B.P., Galindo Bect, L.A., (1975). Hidrología del Alto Golfo de California II. Condiciones durante invierno, primavera y verano. *Ciencias Marinas* **2**, 21-36.

Augustinus, P.G.E.F., (1989). Cheniers and chenier plains: A general introduction. *Marine Geology* **90:** 219-229.

Briggs, M. (1996), Riparian Recovery in Arid Lands, Strategies and References, University of Arizona Press, Tucson.

Briggs Mark and Steve Cornelius. (1998). Opportunities for ecological improvement along the lower Colorado River and Delta. Wetlands. 18: 513-529.

Busch, D., and Smith, S., (1995). Mechanisms associated with decline of wood species in riparian ecosystems of the southwestern U.S. *Ecological Monographs*, **65:** 347-370.

Carbajal, N., Sousa, A., and Durazo, R., (1997), A numerical model of the ex-ROFI of the Colorado River. Journal of Marine Systems, 12: 17-33.

Carriquiry, J.D. and Sánchez, A., (1999). Sedimentation in the Colorado River delta and Upper Gulf of California after nearly a century of discharge loss. Marine Geology, 158: 125-145.

Cisneros-Mata, M.A., Montemayor-López, G., and Román-Rodríguez, M.J., (1995). Life history and conservation of Totoaba macdonaldi. Conservation Biology, 9: 806-814.

Cohen M. J., Henges-Jeck, C. and Castillo-Moreno, G. (2001). A preliminary water balance for the Colorado River delta, 1992-1998. Journal of Arid Environments. 49. pp.35-48.

Cohn, J., (2000). Saving the Salton Sea - Researchers work to understand its problems and provide possible solutions. Bioscience, 50: 295-301.

Collier, M., R. Webb and E. Andrews (1996), Experimental flooding in Grand Canyon. Scientific American 276: 82-89.

Cook, C. and C. Bonham, (1977), Techniques for Vegetation Measurements and Analysis for a Pre-And Post-Mining Inventory. Colorado State University Range Science Department Science Series No. 28, 99 pp.

Costanza Robert and Carl Folke. (1996). The structure and function of ecological systems in relation to property-rights regimes. In Hanna Susan; Carl Folke; and Karl-Göran (Eds). Rights to nature: Ecological, economic, cultural, and political principles of institutions for the environment. Island press.

Curtis, J. and G. Cottam, (1962), Plant Ecology Workbook, Burgess Publ. Co., Minneapolis, Minnesota.

D'Agrosa, C., Lennert-Cody, C.E. and Vidal, O., (2000). Vaquita bycatch in Mexico's artisanal gillnet fisheries: Driving a small population to extinction. Conservation Biology, 14: 1110-1119.

Dale, V., A. Lugo, J. MacMahon and S. Pickett (1998), Ecosystem management in the context of large, infrequent disturbances. Ecosystems 1:546-557.

Dynesius, M. and C. Nilsson (1994), Fragmentation and flow regulation of river systems in the northern 3rd of the world. Science 266: 753-762.

Felger, R., B. Broyles, M. Wilson and G. Nabhan (1997), The binational Sonoran Desert biosphere network and its plant life (With plant checklist and index). Journal of the Southwest 39: 411-566.

Folke Carl; C. S. Holling & Charles Perrings. (1996). Biological diversity, ecosystems, and the human scale. Ecological Applications, 6: 1018-1024.

Fradkin, P., (1981). A river no more, the Colorado River and the West. Alfred A. Knopf, New York.

Galindo-Bect, M., Glenn, E., Page, H., Fitzsimmons, K., Galindo-Bect, L., Hernandez-Ayon, J., and Petty R., (2000). Penaeid shrimp landings in the upper Gulf of California in relation to Colorado River freshwater discharge. Fishery Bulletin, 98: 222-225.

Garcia-Hernandez, J., Hinojosa-Huerta, O., Gerhart, V., Carrillo-Guerrero, Y. and Glenn, E. P., (2001). Willow flycatcher (Empidonax traillii) surveys in the Colorado River delta: implications for management. Journal of Arid Environments, 49: 161-169.

Garcia-Hernandez, J., King, K., Velasco, A., Shumilin, E., Mora, M. and Glenn, E., (2001). Selenium, selected inorganic elements, and organochlorine pesticides in bottom material and biota from the Colorado River delta. Journal of Arid Environments, 49: 65-89.

Glantz, M. (1996), Currents of change: El Nino's Impact on Climate and Society, Cambridge University Press, England (1996).

Glenn Edward, Christopher Lee, Richard Felger, and Scott Zengel. (1996). Effects of water management on the wetlands of the Colorado River Delta, Mexico. Conservation Biology, 10:1175-1186

Glenn, E., J. Garcia, R. Tanner, C. Congdon and D. Luecke, (1999), Status of wetlands supported by agricultural drainage water in the Colorado River delta, Mexico HortScience 34: 39-45.

Glenn, E., R. Tanner, S. Mendez, T. Kehret, D. Moore, J. Garcia and C. Valdes (1998), Growth rates, salt tolerance and water use characteristics of native and invasive riparian plants from the delta of the Colorado River, Mexico. Journal of Arid Environments 40: 281-294.

Glenn, E., R. Felger, Burquez, A., and Turner, D., (1992). Cienega de Santa Clara - endangered wetland in the Colorado River delta, Mexico. Natural Resources Journal, 32: 817-824.

Hernandez-Ayon, J., Galindo-Bect, M., Flores-Baez, B. and Alvarez-Borrego, S., (1993). Nutrient concentrations are high in the turbid waters of the Colorado River delta. Estuarine and Coastal Shelf Science, 37: 593-602.

Hinojosa-Huerta, O. (2000). Distribution, abundance, and habitat use of the Yuma Clapper Rail (Rallus longirostris yumanensis) in the Colorado River delta, Mexico. M.S. Thesis, School of Renewable Natural Resources, University of Arizona, Tucson, AZ.

Hinojosa-Huerta, O., DeStefano, S., and Shaw, W., (2001). Distribution and abundance of the Yuma clapper rail (Rallus longirostris yumanensis) in the Colorado River delta. Journal of Arid Environments, 49: 171-182.

Hinojosa-Huerta, O., J. García-Hernández, and Y. Carrillo-Guerrero. In review. Hovering from the Colorado delta to the Gran Desierto: the birds of the Alto Golfo. Dry Borders II.

Hohn, A.A., Read, A.J., Fernández, S., Vidál, O., and Findley, L.T., (1996). Life history of the vaquita, Phocoena sinus, Phocoenidae, Cetacea). Journal of Zoology (London), 239: 235-251.

IBWC. (2000). Internet Home Page http:/www.ibwc.state.gov. Revised on 04/18/2000.

Kowalewski, M., and Flessa, K. W., (1995), Comparative taphonomy and faunal composition of shelly cheniers from northeastern Baja California, Mexico. Ciencias Marinas, 21: 155-177.

Kowalewski, M., Serrano, G., Flessa, K., and Goodfriend, G., (2000). Dead delta's former productivity: Two trillion shells at the mouth of the Colorado River. Geology, 28: 1059-1062.

Landers H. Dixon. (1997). Riparian Restoration: current status and the reach to the future. Restoration Ecology, 45: 113-121

Lavín, M.F., and Sánchez, S., (1999), On how the Colorado River affected the hydrography of the upper Gulf of California. Continental Shelf Research, 19: 1545-1560.

Lavín, M.F., Godínez, V.M., and Alvarez, L.G., (1998). Inverse–estuarine features of the upper Gulf of California. Estuarine, Coastal and Shelf Science, 47: 769-795.

Leopold, A., (1949). The green lagoons. Pages 150-158 in A. Leopold, editor. A Sand County Almanac. Oxford University Press, New York.

Levine, C. and Stromberg, J., (2001). Effects of flooding on native and exotic plant seedlings: implications for restoring southwestern riparian forests by manipulating water and sediment flows. Journal of Arid Environments, 49: 111-131.

Li, Z. and M. Kafatos (2000), Interannual variability of vegetation in the United States and its relation to El Nino/Southern Oscillation. Remote Sensing of Environment 71: 239-247.

MacDougal, D., (1905). Botanical explorations in Arizona, Sonora, California and Baja California. Journal of the New York Botanical Garden, 6: 91-102.

MacDougal, D., (1907). The desert basins of the Colorado delta. Bulletin of the American Geographical Society, 29: 705-729.

MacMahon A James and Karen D. Holl. (2001). Ecological Restoration, a key to conservation biology's future. In Conservation Biology: research priorities for the next decade. Michael E. Soulé and Gordon H. Orians (Eds). Pp.245-269.

Marler, R., Stromberg, J. and Patten, D., (2001). Growth response of Populus fremontii, Salix gooddingii, and Tamarix ramosissima seedlings under different nitrogen and phosphorous concentrations. Journal of Arid Environments, 49: 133-146.

Mellink, E., Palacios, E. and Gonzalez, S. (1997). Non-breading water birds of the delta of the Rio Colorado, Mexico. Journal of Field Ornithology. 68: 113-123.

Mellink, E., Palacios, E., and Gonzalez, S. (1996). Notes on nesting birds of the Cienega de Santa Clara saltflat, northwestern Sonora, Mexico. Western Birds, 27: 202-203.

Molls, M., C. Crawford, L. Ellis, H. Valett and C. Dahm (1998), Managed flooding for riparian ecosystem restoration - Managed flooding reorganizes riparian forest ecosystems along the middle Rio Grande in New Mexico. Bioscience 48: 749-756.

Morales-Abril, G., (1994). Reserva de la biosfera alto golfo de California y delta del Rio Colorado. Ecologica, 3: 26-27.

Morrison, J., S. Postel and P. Gleick (1996), The Sustainable Use of Water in the Lower Colorado River Basin, Pacific Institute, Oakland, California USA (1996).

Nagler, P., H. Rodriguez, E. Glenn and A. Huete. (2001). Assessment of spectral vegetation indices for riparian ecosystems in the Colorado River Delta. Journal of Arid Environments, 49: 91-110.

Nagler, P., K. Gillon, J. Pitt, W. Snape and E. Glenn (2000), Application of the endangered species act across international borders: the case of the Colorado River delta, Mexico. Environmental Science and Policy 3:11-15.

Nilsson, C., R. Jansson and U. Zinko (1997), Long-term responses of river-margin vegetation to water-level regulation. Science 276: 798-800.

Ohmart, R., B. Anderson and W. Hunter (1988), Ecology of the Lower Colorado River from Davis Dam to the Mexico-United States Boundary: A Community Profile. National Technical Information Service, Alexandria, Virginia USA.

Pindyck, R.S. & D.L. Rubinfeld. (1991). Econometric models and economic forecast. Third edition, McGraw-Hill International, Singapore.

Pitt, J., (2001). Can we restore the Colorado River delta? Journal of Arid Environments, 49: 211-220.

Pitt, J., Luecke, D., Cohen, M., Glenn, E. and Valdes-Casillas, C., (2000). Two nations, one river: managing ecosystem conservation in the Colorado River delta. Natural Resources Journal, 40: 819-864.

Poff, N., J. Allan, M. Bain, J. Karr, K. Prestegaard, B. Richter, R. Sparks and J. Stromberg (1997), The natural flow regime. Bioscience 47: 769-784.

Ramsey, F.L. & D.W. Schafer. (1996). The statistical sleuth. Duxbury Press, Belmont, CA.

Richter D. Brian & Holy E. Richter. (2000). Prescribing flood regimes to sustain riparian ecosystems along meandering rivers. Conservation Biology, 14: 1467-1478.

Roden, G. I., (1964), Oceanographic aspects of the Gulf of California: in van Andel, T. H. and Shor, G. G., eds., Marine Geology of the Gulf of California: American Association of Petroleum Geologists. Memoir 3, Tulsa, Oklahoma, p. 30-58.

Rodriguez, C., Flessa, K., Tellez-Duarte, M., Dettman, D., and Avila-Serrano, A., (2001). Macrofaunal and isotopic estimates of the former extent of the Colorado River estuary, upper Gulf of California, Mexico. Journal of Arid Environments, 49: 183-193.

Rodriguez, C.A., Flessa, K.W., and Dettman, D.L., (2001), Effects of upstream diversion of Colorado River water on the estuarine bivalve mollusc Mulinia coloradoensis. Conservation Biology, 15: 249-258.

Sall, J. & A. Lehman. (1996). JMP start statistics. Duxbury Press, Belmont, CA.

Santa Maria del-Angel, E., Millan-Nunez, R., and DelaPena-Nettel, G., (1996). Effects of turbidity on primary productivity at two stations in the area of the Colorado River delta. Ciencias Marinas, 22: 483-493.

Schlagel D. Joel & Carlton M. Newton. (1996). A GIS-based statistical method to analyze spatial change. Photogrametric Engineering & Remote Sensing,. 62: 839-844.

Seaforth P, J. Stromberg and D. Patten (2000), Woody riparian vegetation response to different alluvial water table regimes. Western North American Naturalist 60: 66-76.

Springer, A., J. Wright, P. Seaforth, J. Stromberg and D. Patten (1999), Coupling groundwater and riparian vegetation models to assess effects of reservoir releases. Water Resources Research 35: 3621-3630.

Stromberg J. (1998a), Dynamics of Fremont cottonwood (Populus fremontii) and saltcedar (Tamarix chinensis) populations along the San Pedro River, Arizona. Journal of Arid Environments 40: 133-155.

Stromberg, J. (1998b), Functional equivalency of saltcedar (Tamarix chinensis) and Fremont cottonwood (Populus fremontii) along a free-flowing river. Wetlands 18: 675-686.

Sykes, G., (1937). The Colorado Delta. Carnegie Institution, Washington, D.C., 193 pp.

Thompson, R. W., (1968), Tidal Flat Sedimentation on the Colorado River Delta, Northwestern Gulf of California: Geological Society of America Memoir 107, Boulder, Co. 133 p.

Townsend, C.H., (1901). Dredging and other records of the U.S. Fish Commission Steamer "Albatross" with bibliography relative to the work of the vessel. US Fish Commission Report for 1900, p. 387-562.

U.S. Bureau of Reclamation (1996), Description and Assessment of Operations, Maintenance, and Sensitive Species of the Lower Colorado River. U.S. Bureau of Reclamation, Boulder City, Nevada.

Valdes-Casillas Carlos, O. Hinojosa-Huerta, M. Muñoz-Viveros, F. Zamora-Arroyo, Y. Carrillo-Guerrero, S. Delgado-Garcia, M. Lopez-Camacho, E. Glenn, J. Garcia, J. Riley, D. Baumgartner, M. Briggs, C. Lee, E. Chavarria-Correa, C. Congdon, and D. Luecke. (1998). Information Database and Local Outreach Program for the Restoration of the Hardy River Wetlands, Lower Colorado River Delta, Baja California and Sonora, Mexico, North American Wetland Conservation Council, Arlington, Virginia USA. 103 pp.

Van Andel, T.H., (1964), Recent marine sediments of the Gulf of California: in van Andel, T. H. and Shor, G. G., eds., Marine Geology of the Gulf of California: American Association of Petroleum Geologists. Memoir 3, Tulsa, Oklahoma, p. 216-310.

Vandersandae, M., Glenn, E. and Walworth, J., (2001). Comparative tolerances of five riparian plants from the lower Colorado River to salinity, drought, and inundation. Journal of Arid Environments.

Varady, R., Hankins, K., Kraus, A., Young, E. and Merideth, R., (2001). To the Sea of Cortez: nature, water, culture and livlihood in the lower Colorado River Basin and delta - an overview of issue, policies, and approaches to environmental restoration. Journal of Arid Environments, 49: 195-209.

Zamora-Arroyo, F., Nagler, P., Briggs, M., Radtke, D., Rodriquez, H., Garcia, J., Valdes, C., Huete, A. and Glenn, E., (2001). Regeneration of native trees in response to flood releases from the United States into the delta of the Colorado River, Mexico. Journal of Arid Environments, 49: 49-64.

Zengel, S., and Glenn, E., (1996). Presence of the endangered Desert Pupfish (Cyprinodon Macularius, Cyprinidontidae) in Cienega de Santa Clara, Mexico, following an extensive marsh dry-down. The Southwestern Naturalist, 41: 73-78.

Zengel, S., Mertetsky, V. Glenn, E., Felger, R, and Ortiz, D., (1995). Cienega de Santa Clara, a remnant wetland in the Rio Colorado delta (Mexico): vegetation distribution and the effects of water flow reduction. Ecological Engineering, 4: 19-36.

APPENDIX

PERCENT VEGETATION COVER RESULTS BY HABITAT ZONE

Habitat zone: Morelos

Morelos	1992	1994	1996	1997*	1998	1999*
open water	18.19	14.86	10.31	1.74	60.51	43.61
Wet bare soil	3.65	4.87	1.62	0.73	25.09	19.25
bare soil	368.51	220.52	202.73	267.31	130.85	94.30
less than 30%	1437.35	1200.58	1383.34	1233.07	792.91	465.41
30-49%	646.22	808.75	749.62	581.57	1133.08	1099.78
50-69%	190.79	297.77	242.86	117.77	370.14	398.81
70-79%	24.85	86.17	59.53	21.76	99.01	57.34
80-89%	8.28	36.47	27.21	6.57	43.45	15.02
90-100%	16.24	44.09	36.86	7.22	59.04	7.22
Total hectares	2714.08	2714.08	2714.08	2237.74	2714.08	2200.74
% veg total	23.23	30.25	27.88	23.11	35.49	36.88
% open water	0.67	0.54	0.37	0.07	2.22	1.98
% ow & wbs	0.80	0.72	0.43	0.11	3.15	2.85
% bare soil	13.57	8.12	7.46	11.94	4.82	4.28

* Satellite images did not cover portions of the zone, and therefore the sum of all classes is not the same as other years.

Habitat zone: San Luis

San Luis	1992	1994	1996	1997	1998	1999
open water	1.05	20.71	13.07	10.88	96.08	60.75
wet bare soil	1.62	9.09	3.81	4.87	32.16	30.05
bare soil	332.12	197.85	108.75	227.09	176.73	130.28
less than 30%	2428.78	1927.46	1955.65	1529.62	757.82	658.65
30-49%	1009.46	1383.42	1378.63	1538.4	1779.07	1704.26
50-69%	235.14	381.83	423.66	532.59	901.75	1066.89
70-79%	44.83	88.21	110.62	145.39	219.87	263.98
80-89%	13.32	29.24	42.39	51.33	67.82	74.72
90-100%	5.27	33.78	35	31.43	40.28	82.03
Total hectares	4071.59	4071.59	4071.58	4071.60	4071.58	4071.61
% veg total	23.55	29.37	30.74	33.09	39.97	43.32
% open water	0.02	0.50	0.32	0.26	2.35	1.49
% ow & wbs	0.06	0.73	0.41	0.38	3.14	2.23
% bare soils	8.15	4.85	2.67	5.57	4.34	3.19

Habitat zone: Carranza

Carranza	1992	1994	1996	1997	1998	1999
open water	0.16	17.62	14.78	49.46	84.39	55.15
Wet bare soil	0.41	5.44	29.48	32.57	23.47	20.38
bare soil	34.35	43.44	151.15	71.06	96.81	56.93
less than 30%	803.47	294.76	541.85	449.49	212.24	183.24
30-49%	2687.00	1231.37	2231.49	1735.61	823.86	786.25
50-69%	2293.63	2794.38	2676.03	2261.54	2383.46	2155.14
70-79%	719.00	1749.18	944.72	1221.38	1851.52	1913.82
80-89%	261.30	575.72	249.36	645.33	896.07	1082.4
90-100%	123.04	210.45	83.49	455.9	550.53	669.04
Total hectares	6922.36	6922.36	6922.35	6922.34	6922.35	6922.35
% veg total	49.84	60.89	51.70	58.08	64.55	66.86
% open water	0.00	0.25	0.21	0.71	1.21	0.79
% ow & wbs	0.01	0.33	0.63	1.18	1.55	1.09
% bare soils	0.49	0.62	2.18	1.02	1.39	0.82

Habitat zone: Hardy-Colorado

Hardy-Colorado	1992	1994	1996	1997	1998	1999
open water	149.61	216.13	133.29	112.57	264.06	245.86
Wet bare soil	97.95	50.84	89.75	125.81	62.29	103.15
Bare soil	9870.12	6995.33	9287.17	10658.26	7538.89	6856.76
Less than 30%	6925.81	6417.26	6814.77	5384.81	3737.40	3352.39
30-49%	4589.86	6631.45	5581.05	3659.51	6205.91	6067.42
50-69%	1702.71	2906.63	1700.28	2191.36	4598.87	5086.79
70-79%	385.57	570.11	203.71	985.74	1044.14	1532.87
80-89%	116.15	88.45	47.92	488.32	282.74	482.8
90-100%	52.22	13.8	32.07	283.63	155.7	161.95
Total hectares	23890.00	23890.00	23890.01	23890.01	23890.00	23889.99
% veg total	18.14	24.59	18.83	20.98	29.19	32.21
% open water	0.62	0.90	0.55	0.47	1.10	1.02
% ow & wbs	1.03	1.11	0.93	0.99	1.36	1.46
% bare soils	41.31	29.28	38.87	44.61	31.55	28.70

Habitat zone: Mayor-Hardy

Mayor-Hardy	1992	1994	1996*	1997*	1998	1999
open water	64.57	61.32	48.73	30.94	54.42	68.96
wet bare soil	16.48	20.46	7.79	5.84	13.23	27.61
bare soil	390.85	372.25	255.76	402.86	510.9	539.08
less than 30%	995.65	1074.76	891.03	602.20	978.11	1060.96
30-49%	858.46	738.17	672.86	472.24	711.44	614.46
50-69%	202.33	215.24	204.11	166.18	231.81	204.6
70-79%	19.41	38.25	25.91	16.73	35.82	28.83
80-89%	4.54	13.32	4.95	2.92	9.25	7.71
90-100%	1.62	20.14	1.29	1.38	8.92	1.7
Total hectares	2553.91	2553.91	2112.43	1701.29	2553.90	2553.91
% veg total	24.82	25.27	26.04	23.23	24.04	21.82
% open water	2.52	2.40	2.30	1.81	2.13	2.70
% ow & wbs	3.17	3.20	2.67	2.16	2.64	3.78
% bare soils	15.30	14.57	12.10	23.67	20.00	21.10

Satellite images did not cover portions of the zone, and therefore the sum of all classes is not the same as other years.

Habitat zone: Dren-Ayala

Dren-Ayala	1992	1994	1996	1997	1998	1999
open water	11.94	13.15	75.62	49.46	79.11	87.15
wet bare soil	6.74	5.84	20.46	27.21	18.35	68.79
Bare soil	5483.08	4803.23	5233.15	5718.8	5266.29	5430.13
less than 30%	4824.35	4544.05	4883.08	4425.13	3304.72	3376.92
30-49%	2804.13	3076.39	3119.12	2765.79	2907.12	2640.78
50-69%	1001.99	1498.19	912.56	1031.23	1952.81	1797.34
70-79%	222.63	391.34	122.81	252.69	609.34	655.32
80-89%	46.86	68.31	29.07	99.09	182.18	245.54
90-100%	15.80	17.45	22.08	48.57	98.03	115.98
Total hectares	14417.52	14417.95	14417.95	14417.97	14417.95	14417.95
% veg total	18.50	22.05	18.49	18.78	24.52	23.94
% open water	0.08	0.09	0.52	0.34	0.54	0.60
% ow & wbs	0.12	0.13	0.66	0.53	0.67	1.08
% bare soils	38.03	33.31	36.29	39.66	36.52	37.66

Habitat zone: Intertidal

Intertidal	1992	1994	1996	1997	1998	1999
open water	24232.58	22460.01	26343.05	27248.38	20395.43	15642.79
wet bare soil	11741.23	2269.18	5156.08	8362.03	10140.94	9111.82
bare soil	34941.93	31427.90	29846.28	35696.27	39090.74	41936.38
less than 30%	1716.52	2978.52	1930.06	1655.12	2480.53	3892.78
30-49%	1363.76	1824.71	1803.19	1601.67	1646.51	2221.5
50-69%	561.58	717.21	91.05	178.04	377.04	342.2
70-79%	0.08	38.25	0.24	1.46	9.09	1.62
80-89%	0.08	14.94	0.00	0.40	2.76	0
90-100%	0.00	11.12	0.00	0.96	4.86	0
Total hectares	78897.20	78897.20	78897.21	78897.21	78897.20	78897.22
% veg total	1.44	2.10	1.35	1.26	1.611	2.12
% open water	30.71	28.46	33.38	34.53	25.85	19.82
% ow & wbs	45.59	31.34	39.92	45.13	38.70	31.37
% bare soils	49.78	61.57	55.22	50.50	55.56	60.43

Habitat zone: Cienega

Cienega	1992	1994	1996	1997	1998	1999
open water	1712.38	2348.78	1696.79	1376.27	3708.24	1767.86
wet bare soil	6440.81	5353.37	6869.60	10661.18	9361.66	4035.98
Bare soil	17525.59	17806.46	18491.02	15759.75	13972.32	20774.67
less than 30%	4608.21	4487.11	3119.04	2481.99	3515.09	3652.2
30-49%	1909.03	1598.42	1489.42	1543.84	1490.64	2223.29
50-69%	2417.26	899.81	1440.20	1084.19	963.49	2536.25
70-79%	851.15	589.69	1520.12	992.65	1349.30	596.43
80-89%	208.26	532.18	654.75	803.64	765.78	126.3
90-100%	111.6	2168.45	503.34	1080.77	657.75	71.31
Total hectares	35784.29	35784.27	35784.28	35784.28	35784.27	35784.29
% veg total	10.69	13.77	11.48	11.47	11.18	10.01
% open water	4.78	6.56	4.74	3.84	10.36	4.94
% ow & wbs	22.78	21.52	23.93	33.63	36.52	16.21
% bare soils	48.97	49.76	51.67	44.04	39.04	58.05