WETLANDS, Vol. 18, No. 4, December 1998, pp. 513–529

OPPORTUNITIES FOR ECOLOGICAL IMPROVEMENT ALONG THE LOWER COLORADO RIVER AND DELTA

Mark K. Briggs and Steve Cornelius
Sonoran Institute
7650 E. Broadway Blvd., Suite 203
Tucson, Arizona, USA 85710

Abstract: The lower Colorado River mainstem and delta have been severely damaged by a variety of human-related activities, including river impoundment, agriculture, water diversions, introduction of exotic plants and fishes, and ground-water pumping. In some areas, the native wetland habitat that formerly dominated this region has disappeared completely. Nevertheless, there are areas where significant wetland habitat persists as a result of incidental circumstances or purposeful restoration actions. These areas provide important conservation and restoration opportunities. In this investigation, nine restoration efforts along the lower Colorado River from Parker Dam to the delta region were evaluated to learn how lessons from these experiences can benefit future ecological restoration efforts. In addition, we assessed the general ecological condition of this reach to identify critical native wetland plant communities and recommend strategies for protecting these areas in the future. It is apparent that wetland ecosystems in both the delta and the mainstem would benefit if effluent waters were allocated to support wetlands rather than allocated to evaporative basins. Other important strategies for improving the ecological condition of the river should include altering reservoir releases, improving the effectiveness of revegetation efforts, and developing bi-national, collaborative approaches involving local communities and landowners to identify and carry out projects that benefit both them and the ecological condition of the river.

Key Words: river impoundment, restoration, lower Colorado River, water use, reservoir water releases

INTRODUCTION

The goal of this investigation was to identify opportunities and strategies for improving the ecological condition of the lower Colorado River. This investigation focused on the lower portion of the river, which includes the mainstem from Parker Dam to the delta, as well as the delta itself. This effort has three principal objectives. First, the effectiveness of past riparian restoration efforts along the lower Colorado River (from Parker Dam to the river delta) were evaluated so that lessons gained from these experiences can be applied to future ecological restoration activities. Second, the ecological condition of this reach of the lower Colorado River was assessed, with particular focus on identifying areas that contain significant native wetland habitat or show promise for future restoration activities. Third, courses of action were recommended for enhancing damaged areas and maintaining areas of natural significance.

CHANGES ALONG THE LOWER COLORADO RIVER

The Colorado River watershed is a vast system. From its headwaters in the Rocky Mountains to the Sea of Cortez, the river travels over 2,250 km and drains an area of 632,000 square km, which includes 5,180 square km of northern México. Even within the narrow focus of this investigation—Parker Dam to the Sea of Cortez—there are wide variations in land-use patterns and physical and biological conditions (Figure 1). The current hydrologic, physical, and biological characteristics of this reach and the changes that have taken place in these parameters since the construction of Hoover Dam are fairly well documented (Ohmart et al. 1977, Glenn et al. 1992, Abarca et al. 1993, Glenn et al. 1996) and are reviewed only briefly here.

Historic accounts seem to indicate that the lower Colorado River's riparian ecosystems changed little from the time of early Spanish exploration in the 17th century to the 1930s when construction of Hoover Dam was completed (Ohmart et al. 1977). The completion of Hoover Dam in 1935 sparked a wave of major construction and agricultural projects along the river that have significantly affected the river's ecological condition. Today, as the Colorado River flows from Hoover Dam to the delta, it passes through 28 dams, irrigates over 1 million hectares of agricultural land, and serves or supplements water supplies for

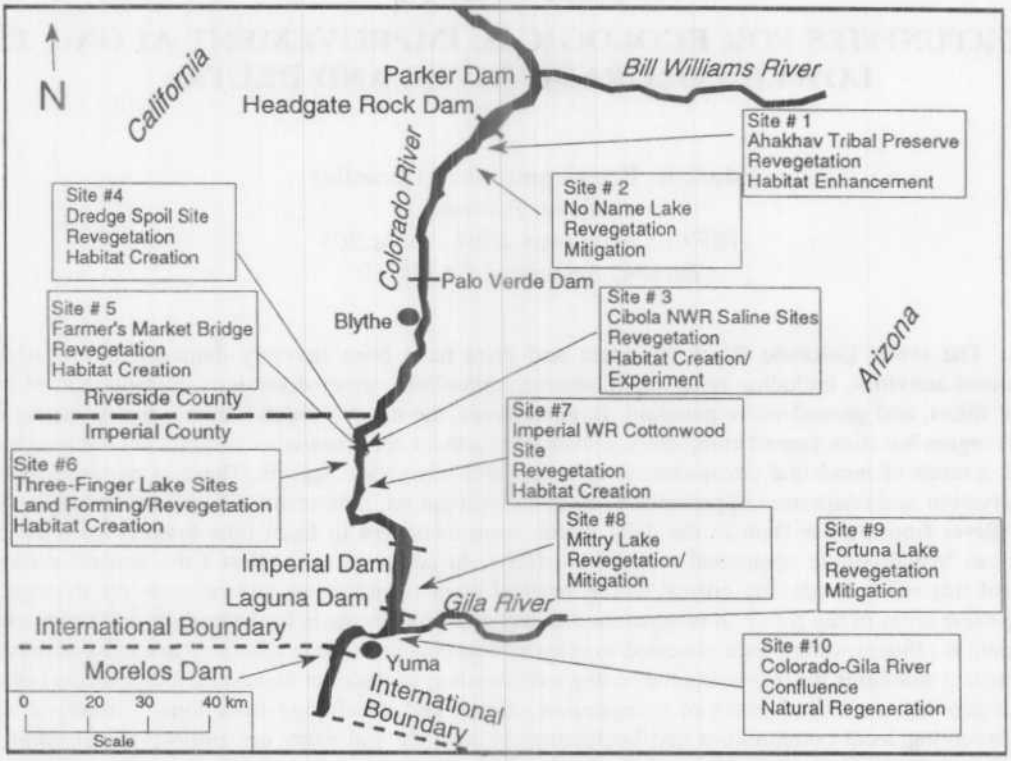

Figure 1. Idealized map of Colorado River mainstem from Parker Dam to the international boundary. Sites included in this investigation are labeled and their approximate location is indicated.

over 20 million people in the U.S. and México (Colorado River Basin Salinity Control Forum 1990).

The Mainstem

The combined environmental impacts of river impoundment, river diversions, ground-water pumping, spread of non-native species, agricultural activities, and other human activities has had a devastating effect on the river's ecology. In particular, the buffering of annual overflows and altering of natural channel dynamics by river impoundment has compromised habitat for native fishes and limited the creation of sandbars and channel islands, which are critical features for the propagation of many native riparian plants (Ohmart et al. 1977)

The completion of Hoover Dam, and then Glen Canyon Dam in 1963, has significantly affected streamflow. Prior to the dams, the Colorado River was a warm, muddy flow with tremendous seasonal fluctuation. After dam construction, the river became a much clearer flow of cold water that fluctuated relatively little. Such hydrologic changes have adversely effected the river's native population of warm-water fish, such as the razorback sucker (*Xyrauchen texanus* Abbott), bluehead sucker (*Catostomus discobolus* Cope), flannelmouth (*Catostomus latipinnis* Baird and Girard), Colorado squawfish (*Ptychocheilus lucius* Girard), humpback chub (*Gila cypha* Miller), and bonytail chub (*Gila elegans* Baird and Girard), while benefiting such non-native fish as the rainbow trout (*Salmo gairdneri* Richardson) and the largemouth bass (*Micropterus salmoides* Lacépède), which are better adapted to the river's artificially created clear, cold waters (Minckley 1991). With the exception of the bluehead sucker and speckled dace (*Rhinichthys osculus* Girard), all of the river's native fish are either endangered or under consideration for federal listing.

The distribution and extent of native riparian forests, such as the cottonwood/willow (*Populus fremontii* Wats./*Salix gooddingii* Ball (S. Nigra Marsh var. vallicola Dudley)) forests, and wetland ecosystems, such as the cattail/rush (*Typha* spp./*Juncus* spp.) marshlands, have changed significantly along parts of the lower Colorado River system. Ohmart et al. (1977) observed, for example, that cottonwood communities along the mainstem have decreased from over 2,000 hectares in the 1600s to less than 200 hectares. Saltcedar (*Tamarix ramosissima* Ledeb.), which was introduced to the western U.S. during the mid-1800s as a soil stabilizer and ornamental plant, now forms homogeneous stands along significant reaches of the lower Colorado River (Ohmart et al. 1977).

Lower Colorado River water is projected to become progressively more saline due to a variety of human-related activities. The U.S. Environmental Protection Agency (EPA) estimated that increased salinity concentrations in the river have been principally caused by out-of-basin exports, irrigation, and reservoir evaporation-accounting for three percent, 37 percent, and 12 percent, respectively, of the increased salinity concentrations that occurred between 1944 and 1988 (Colorado River Basin Salinity Control Forum 1990).

The Delta

Prior to the construction of Glenn Canyon and Hoover Dams, Colorado River water continually reached the delta and the Sea of Cortez, providing nutrients and estuarine habitat for a plethora of marine life. During this time, the silt and water that the river brought to the delta were critical in sustaining dense wetland plant communities that are estimated to have contained 200 to 400 different species (Ezcurra et al. 1988 cited in Glenn et al. 1996). The area occupied by the delta prior to dam construction is estimated at over 780,000 ha and included two below- sea-level depressions, the Salton Sea and the Laguna Salada (Sykes 1937). Tidal marsh and brackish and riparian ecosystems supported jaguar, beaver, and thousands of migratory and resident waterfowl. In addition, the delta was the place of settlement for the Cocopah—speakers of a Yuman family language who occupied parts of the lower Colorado River and delta for over 2,000 years (Alvarez de Williams 1978). At their height during the early 1600s, the population of the Cocopah communities in the delta probably exceeded 6,000 people, who supported themselves by fishing, hunting, and gathering in the lush delta environment. As a result of the ecological decline of the delta and outside population pressures, the population of the Cocopah in México has declined dramatically and was estimated in 1980 at 571 (Alvarez de Williams 1978).

Today, over 1 million ha of land in and surrounding the delta has been converted to farmland. As a result of river impoundment and water diversions, river water rarely flows all the way to the Sea of Cortez, altering the natural salinity balance and decreasing the flow of nutrients that supports upper Sea of Cortez fisheries (Glenn et al. 1996). In addition, reduced silt loads due to river impoundment have actually sparked a period of erosion in the delta, rather than accretion (Thompson 1968). Therefore, the size of the delta will probably decrease over time.

The 1944 Mexican Water Treaty allocates roughly 1,850 km^3 of the lower Colorado River's base flow to México per year, but provides a *pro rata* reduction in times of shortages (Pontius 1997). However, even during times of sufficient flow, much of this water is diverted to the Canal Central for agricultural irrigation in the Mexicali and San Luis districts of México (Glenn et al. 1996). As a result, mainstem water reaches delta wetlands only during times of high flow.

The combination of river impoundment and diversions has had a devastating effect on delta wetlands. In areas formerly dominated by cattails and riparian forests of cottonwoods or willows, a significant amount of the delta region south of the farmland now consists of dry sand, mud, and salt flats dominated by saltcedar, arrowweed (*Pluchea sericea* (Nutt.) Coville), and iodine-bush (*Allenrolfea occidentalis* (Wats.) Kuntze). Freshwater and brackish habitat still remain, but these areas are confined for the most part to agricultural wastewater discharge points, artesian springs, and areas influenced by tidal fluctuations.

Despite the tremendous ecological changes that have occurred in the Colorado River delta, it is important to emphasize that the delta still contains significant wetland and riparian plant communities. Particularly during the last decade, the amount of Colorado River, as well as agricultural return flows, that has reached the delta seems to have increased (probably due in part to the filling of Lake Powell), helping to maintain several key intertidal, brackish wetlands and riparian forests south of the agricultural fields (Glenn et al. 1992, Payne et al. 1992).

The principal wetlands in the delta are (1) the Río Hardy wetlands, which are supported by the Río Hardy River and high flow events in the Colorado River; (2) the Ciénega de Santa Clara, sustained by agricultural runoff emanating from the Wellton-Mohawk canal and the Riito drain; and (3) the El Doctor wetlands, which are supported by artesian springs (Glenn et al. 1996) [Figure 2]. In addition, riparian forests dominated by cottonwood/Goodding willow/saltcedar have established in several locations along the main channel of the Colorado River just north of the areas influenced by tidal fluctuations of the Sea of Cortez.

These wetland and riparian ecosystems are critical to a variety of wildlife. The Ciénega de Santa Clara, for example, provides habitat for the endangered desert pupfish (*Cyprinodon macularis* Baird and Girard) and the Yuma clapper rail (*Ralus longirostris yumanensis* Vieillot) (Abarca et al. 1993). The delta's ecological decline also appears to be intricately related to the decline of two other endangered species: the totoaba fish (*Cynoscion macdonaldi* Gilbert), which was once common throughout much of the delta (Cisneros-Mata et al. 1995); and the vaquita porpoise (*Phoceona sinus* Norris and McFarland), a small harbor porpoise that is heavily dependent on the delta's protected waters and nutrient supply (Moralis and Abril 1994, Turk-Boyer pers. comm.).

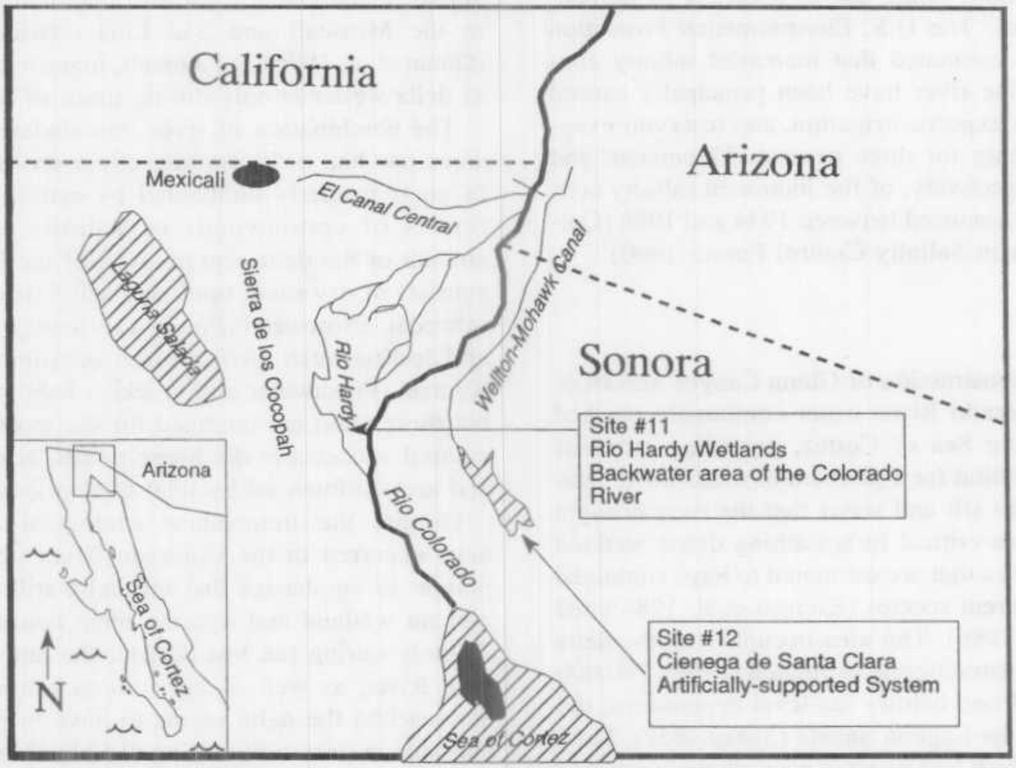

Figure 2. Idealized map of the Colorado River delta and location of sites considered in this investigation.

METHODS

Background information was collected describing the current ecological condition of the lower Colorado River, the degree to which that condition has changed, and some of the principal reasons behind the ecological changes that have occurred. Maps and aerial photographs were collected, and past studies dealing with the river's ecological condition were reviewed. Ecologists, hydrologists, natural resource managers, restoration ecologists, and others with lower Colorado River experience were interviewed to better understand the challenges that will have to be overcome before significant progress can be made in improving the river's ecological condition.

Sites were selected in consultation with local experts with regard to their natural significance or the information they may convey to future restoration efforts. Sites were then visited and field work conducted with personnel who have either studied the area or were involved in the restoration effort.

For each site visited, the following information was gathered:

(1) general background information, including site location, the size of the restoration project, date of project implementation and completion, and project objective;

(2) general ecological condition, including the current composition and structure of the site's plant community, obvious signs of disease or perturbation (e.g., mistletoe (*Phoradendron* spp.) infestation, significant population of non-native species, leaves showing symptoms of high salt concentrations), significant changes in ecological condition (e.g., dramatic changes in depth to saturated soils or streamflow characteristics), signs of soil salinity problems, and obvious signs of erosion;

(3) restoration strategies employed (where appropriate), including information describing the restoration methods, how the strategies were developed, post-project maintenance and monitoring, and evaluation of the effort (how effective the restoration effort was in achieving project objectives), and a general description of the present condition of the site; and

(4) lessons learned, describing how the experiences gained from this review can be used to improve the effectiveness of future restoration and conservation efforts along the lower Colorado River.

SITE DESCRIPTIONS

In total, 12 sites were evaluated as part of this investigation. Of these, nine are restoration efforts that were completed along the river's mainstem, and all but one of these (Three Finger Lake, project #6) used revegetation as the principal strategy. The restoration efforts ranged significantly in size and scope. Some encompassed less than a hectare and involved fewer than a hundred plantings; others encompassed a much larger area and involved thousands of plantings. Three areas of natural significance were also included in this effort. These areas were identified by citizens, scientists, and natural resource practitioners as areas that contain significant amounts of native riparian or wetland plant communities that are not the result of restoration efforts (Valdés, Barrera, and Swett pers. comm.). Of the three sites, one is along the mainstem of the river and the other two are located in the delta. A fourth significant natural area—the El Doctor wetlands of the delta—is only mentioned briefly in the discussion. Sites are labeled numerically from upstream (just south of Parker Dam) to downstream.

Site #1—'Ahakhav Tribal Preserve

Location and Size. This 61-ha revegetation site lies within the 405 ha 'Ahakhav Tribal Preserve, which is managed by the Colorado River Indian Tribes (CRIT) and lies approximately 3 km downstream of Headgate Dam.

Objective. To enhance habitat for wildlife and fish, as well as to provide environmental education, outdoor recreation, and cultural opportunities for tribal and community members.

Completion Date. Planting for this part of the 'Ahakhav Tribal Preserve began in 1996 and will be completed during 1998. Additional riparian restoration activities (mostly revegetation efforts) are planned for the immediate future.

Pre-Project Site Conditions. Pre-project vegetation consisted primarily of saltcedar, arrowweed, honey mesquite (*Prosopis glandulosa* Torrey) and screwbean mesquite (*Prosopis pubescens* Bentham). Soils are mostly sandy.

Project Strategy. Prior to project implementation, site characteristics were evaluated with regard to soil salinity, soil texture, and depth to saturated soils. Undesirable plants were removed with a bulldozer. Over 10,000 screwbean mesquite, honey mesquite, cottonwood, and Goodding willow seedlings were planted on over 40 ha of land. The site evaluation allowed revegetation practitioners to develop a detailed map of site conditions, allowing them to place plant materials in areas characterized by tolerable soil salinity and water availability conditions. Mesquites were planted in areas characterized by relatively high soil salinity (electroconductivity levels in excess of 2 dS m^{-1}). Mesquite were placed in the ground as seedlings (as opposed to cuttings or poles). Cottonwood and willow poles were started in a nursery and planted in areas characterized by low soil salinity. Once in the ground, all plants were irrigated with a drip irrigation system. Plants will be irrigated until roots are considered to have reached saturated soils.

Results. Ninety percent of all plants have survived to date. A significant portion of these have grown to a height of almost 5 m. According to project managers, the high survival rates of planted vegetation demonstrate the importance of mapping site characteristics, particularly soil salinity and water availability characteristics. In addition, taking advantage of low-lying topographical features where water availability is high (e.g., secondary channels) was also considered critical to the survival of obligate riparian species such as cottonwoods and willows (Shaffer pers. comm.).

Site #2—No Name Lake

Location and Size. The 17 ha site is about one river km downstream from Angnes Wilson Bridge and lies adjacent to farmland managed by the Colorado River Indian Reservation.

Objective. To re-establish native riparian plants in an area where the river's riparian habitat has been compromised by agricultural activities and the construction of Parker Dam.

Completion Date. 1987.

Pre-Project Site Conditions. Pre-project, on-site vegetation consisted predominately of arrowweed, with some saltcedar, screwbean mesquite, and willow. The water-table depth was estimated to vary from 4 m on the upstream end of the site to about 1.5 m on the downstream end (Pinkney 1992).

Project Strategy. The site was cleared and root-ripped in April 1987. On-site, desirable vegetation was not disturbed. A 38-cm-diameter auger was used to disrupt the soil down to the saturated zone. Five days prior to planting, salts were leached from soils by flood irrigating. Approximately 1,380 cottonwoods, 370 willows, 3,560 honey mesquites, 45 palo verdes (*Cercidium microphyllum* (Torr.) Rose & I.M. Johnston), 80 California fan palms (*Washingtonia filifera* (L. Linden) H. Wendl), and 100 quailbrush (*Atriplex lentiformis* (Torr.) S. Watson) were planted. Trees and shrubs were in cardboard tubes 10 cm in diameter and 40 cm long. Nitrogen fertilizer was applied using a liquid injector system. Undesirable vegetation was controlled by applying "Arsenal," and a systemic insecticide "Orthene" was applied to control physllids. All plants were irrigated with a drip system (45.5 l each day for the first 30 days; reduced to 3 days a week through September 1987) (Pinkney 1992). Cottonwoods and willows were also planted in an erosional depression located immediately adjacent to the agricultural fields. The depression is roughly 1.5 ha in area and lies approximately two meters below the elevation of surrounding lands.

Results. As of 1990, approximately 53 percent of the total numbers of individuals originally planted had survived (Pinkney 1992). Of this amount, more than 90 percent were honey mesquite and palo verde. The only other plant species with more than 50 percent survival was quailbrush. All of these plants occur outside the erosional depression. Of all the cottonwoods and willows that were planted, only those planted in the erosional depression survived, where water availability was much greater due to periodic irrigation runoff from an adjacent agricultural field. Cottonwood and willow in this depression are over 18 m high and appear healthy. As long as the adjacent field is irrigated, this area will have sufficient moisture to support the existing cottonwood and willow. As of 1997, honey mesquite, palo verde, and quailbrush have established in scattered locations throughout the south end of the site.

Site #3—Cibola National Wildlife Refuge Saline Site

Location and Size. The Cibola National Wildlife Refuge is located in La Paz County, Arizona, due west of Cibola, Arizona. The Cibola NWR is located approximately at River Mile 99 on the lower Colorado River in La Paz County, Arizona. The revegetation site is located in the northeast corner of the refuge and consists of eight 6 m × 9 m plots.

Objective. To better understand the feasibility of establishing native plants in highly saline soils.

Completion Date. September 1986.

Pre-Project Site Conditions. The site was essentially devoid of woody riparian plants at the time of planting. Soils were classified as dense clays, and depth to saturated soils was estimated at 1.5 m. Soil salinity ranged from 6,000 ppm to 60,000 ppm (Pinkney 1992).

Project Strategy. Prior to seeding, all plots were flood irrigated to leach excess salts from the soil profile. The plots were seeded and raked in September 1986. Four of the eight plots were seeded with quailbrush, while the remaining four plots were seeded with equal amounts of screwbean mesquite, honey mesquite, and palo verde. Two of the quailbrush plots and two of the mesquite and palo verde plots were fertilized. The plots were flood irrigated three times in 1986 with 2 to 5 cm of water and once in 1987 with 10 to 15 cm of water (Pinkney 1992).

Results. Germination rates for all plants was initially high. In 1988, quailbrush seedlings were well-established (more than 1,000 seedlings germinated), and approximately 1,900 screwbean mesquite, 600 honey mesquite, and 25 palo verde seedlings had also established. However, mortality was high in the following years. All palo verde subsequently died as well as many of the mesquite seedlings. Rabbit damage also occurred and seemed to affect the survival and growth of honey mesquite more than screwbean (Pinkney 1992). Only three to ten mesquite seedlings were found in 1997 in each of the four plots and all were protected with chicken wire baskets. Experiences here demonstrated that although it is difficult, it is nevertheless possible to revegetate in areas characterized by high soil salinity by using appropriate plant materials and innovative irrigation and planting strategies (Swett pers. comm.).

Site #4—Cibola National Wildlife Refuge Dredge Spoil Site

Location and Size. This site covers 28 ha and is located about 8 km east of Palo Verde, California. It is divided by a levee that parallels the Colorado River. Revegetation work began on the East Dredge Spoil area in 1977 and on the West Dredge Spoil area in 1978.

Objective. To better understand the feasibility of using revegetation to improve the condition of ecologically-damaged reaches of the Colorado River. This was the Bureau of Reclamation's first revegetation experiment.

Completion Date. 1978.

Pre-Project Site Conditions. Russian thistle dominated the site prior to project initiation. Soil survey data indicated that soils on the east side of the site are primarily sands with a thin clay layer situated 1 m to 1.5 m below the surface. In contrast, soils on the west side of the site are primarily loam but were covered by 0.5 m to 3 m of dredge spoil material. Depth to the saturated zone of the soil profile varied from 3 m to 4.5 m (Anderson and Ohmart 1982).

Project Strategy. In total, approximately 2,000 cottonwood, willow, honey mesquite, and blue palo verde trees (*Cercidium floridum* Benth.) and shrubs were planted as .5 m tall rooted cuttings. A variety of planting techniques were used. Approximately 125 trees of all species were planted in 20-cm-diameter holes augered to a depth of 1.5 m. Numerous trees were also planted in holes 30 cm in diameter and 3 m deep, as well as holes 5 cm in diameter and 3 m deep. A drip irrigation system was installed that delivered water at a rate of 15 l per hour to each planted tree or shrub. Each tree was watered with 121 l per day for at least 150 days.

Results. Dredge Spoil plantings were counted in June 1990. At that time, an additional 150 cottonwoods had established naturally. Natural recruitment of honey mesquite and palo verde was also occurring (Pinkney 1992). Willow numbers continued to decrease since the first inventory was completed. In 1997, there appears to be significant differences in survival rates and overall plant health between plantings on the west side of the levee and those on the east side, with establishment rates and plant vigor on the west side of the levee (adjacent to the agricultural fields) appearing much greater.

Site #5—Farmer's Bridge

Location and Size. This project consists of two sites located roughly 200 m from the Colorado River along a levee that runs parallel to the river due west of Cibola, Arizona. The levee can be accessed via Farmer's Bridge road. The southern site is roughly 0.4 ha and the northern site is roughly 0.8 ha.

Objective. To re-establish native riparian trees in an area that has experienced significant ecological decline.

Completion Date. 1986.

Pre-Project Site Conditions. Both sites were void of woody plants prior to project initiation. Soils were generally sandy, and depth to saturated soils was estimated to vary between 3 m to 6 m [beneath the surface of the soil] (Swett pers. comm.).

Project Strategy. A total of 65 willow, cottonwood, and screwbean mesquite were planted at the two locations. Poles and seedlings were used in the revegetation effort. Plantings were irrigated with a drip system for the first two summers.

Results. Survival of planted species was greater in the north site than in the south site, possibly due to greater water availability. Twenty trees survive on the southern site. Of these, only one willow and six cottonwoods were found and all show obvious signs of water stress (stunted growth, canopy die-back, thick and yellow leaves). In comparison, mesquite appeared much healthier, averaging roughly 5 m in height with spreading, relatively full canopies. According to the project manager, the use of plant materials that are adapted to current hydrologic conditions (specifically considering depth to saturated soils) is key to success (Swett pers. comm.).

Site #6—Three-Finger Lake

Location and Size. The 50-ha site is located in the Cibola National Wildlife Refuge on the western side of the river due north of Paymaster Landing.

Objective. To restore Three-Finger Lake to its pre-1970 condition.

Completion Date. To be completed during 1998.

Pre-Project Site Conditions. Depending on Colorado River flow, the size of Three-Finger Lake historically ranged from 8 to 60 ha. In 1970, channelization and realignment of the Cibola Division of the river was completed, diverting waters away from Three-Finger Lake and the old river channel. Saltcedar invaded as the lake dried and wildfires eliminated most of the native vegetation. Today, the site is dominated by a dense monotypic stand of saltcedar.

Project Strategy. Beginning in 1994, approximately 50 ha of the lake site was dredged to an elevation of 65 m. In addition, one fish pond was created for rearing native fish. Native riparian vegetation will be planted around the dredged areas.

Results. The project is scheduled to be completed during 1998.

Site #7—Imperial Refuge Cottonwood and Willow Revegetation Site

Location and Size. This 15-ha site lies within the Imperial National Wildlife Refuge, which is located near Martinez Lake, Arizona.

Objective. To re-establish Fremont cottonwood and Goodding willow in an area heavily modified by agriculture pressures and overrun by saltcedar.

Completion Date. 1995 (although other revegetation efforts are planned for the future).

Pre-Project Site Conditions. Wheat and rye were once cultivated on this site. Since abandoned, the fields were overrun by saltcedar, arrowweed, and other undesirable species.

Project Strategy. Over 600 cottonwood and willow trees were planted in January of 1995. Prior to planting, exotic plants (mainly saltcedar) were cleared from the site with a bulldozer. Soil salinity investigations were performed to guide the development of the planting design and two piezometers were installed to monitor water-table fluctuations. Cleared areas were then disked and leveled, and the site was flood-irrigated just before the onset of revegetation to leach excess salts from the soil profile. An auger was used to drill to saturated soils, which at the time of planting varied between 1 to 2.5 m below the soil surface. Holes were spaced 6 m apart. Poles collected from the Imperial Wildlife Refuge's nursery were stripped of leaves and branches and placed in the ground. The average length of the poles used in the revegetation effort was 4 m, and the average diameter at breast height (dbh) was 3.0 cm. Following planting, the site was flooded monthly, and plants received two liquid fertilizer applications during the growing season. In 1996 and 1997, the frequency with which the planted area was flood irrigated was increased to bi-monthly.

Results. All of the cottonwoods that were planted have survived to date. However, by 1997, about 90% of the willows had died. The high mortality rate is believed to be due to localized soil salinity problems. As revegetating with native riparian plants often requires significant irrigation inputs (particularly during the first three summers), having control of the land and the water rights that go with the land is critical to success (Hill pers. comm.).

Site #8—Mittry Lake

Location and Size. The 23-ha Mittry Lake revegetation site is located on the Arizona side of the Colorado River roughly 24 km north of Yuma. The Mittry Lake Wildlife area borders the revegetation site to the west and the Gila Gravity Main Canal is immediately to the east.

Objective. To enhance habitat for wildlife.

Completion Date. April 1986.

Pre-Project Conditions. Vegetation found on-site prior to project initiation consisted mainly of sparse desertscrub on high elevated areas and mixed riparian vegetation along several of the washes on the site's southern end. Soil types were found to be highly variable, ranging from large rocks to silts and clays. Water-table depths were estimated at 2 to 4 m beneath soil surface (Pinkney 1992).

Project Strategy. Six revegetation zones were established on the lake site between March and April 1986. Each of the zones was fenced, and tree planting holes were augered to saturated soil (2 to 4 m deep) using an 38-cm-diameter auger. Holes for shrubs were augered 2 m deep using a 19-cm auger. Planting began in March 1986 and was completed in April 1986. All trees and wolfberry shrubs (*Lycium* spp.) were grown in 4 l cans; quailbrush plants were grown in small biodegradable containers. All trees and shrubs were irrigated using a drip system, and wire baskets were used to protect plants from wildlife damage. Irrigation rates varied, but all plants received water each day for the first 30 days, at a rate of 68 l per day for trees and 11 l per day for shrubs (Pinkney 1992).

Results. At the end of the 1988 growing season, only a few cottonwoods were taller than 4 m. Of the vegetation planted, willows appeared to have the slowest growth rates, possibly due to water stress and damage from deer browsing. Estimates of water-table depths in 1988 indicated that depths were much greater than the 2 to 4 m initially estimated. The largest of the planted trees were those taking advantage of water leaking from a canal just uphill from the revegetation site. Even though wire baskets were used, rabbits and deer still managed to damage significant numbers of planted vegetation. After the third growing season, honey mesquites not significantly damaged by rabbits were roughly 3 m tall. By 1988, some honey mesquites were larger than the planted cottonwoods. Most screwbean mesquites also grew well and were about 1.5 m tall after two years of growth. Palo verde growth rates were generally slower than those of mesquite. Quailbrush grew rapidly and, by the third growing season, some were over one meter tall and producing seed. However, rabbit damage to the lower branches outside of the protective baskets was common. Wolfberry appeared to be stressed during the early portion of the first growing season but seemed to grow better during the fall months. In heavy textured saline soils, *Lycium torreyi* Gray (L. Torreyi var. filiforme Jones) appeared to be more vigorous than *Lycium andersonii* Gray (Pinkney 1992).

Site #9—Fortuna Fish Pond

Location and Size. This 3.2-ha revegetation site surrounds the Fortuna Fish Pond and is located about 16 km east of Yuma, Arizona at the confluence of the Gila River and Fortuna Wash.

Objective. To mitigate for impacts from the construction of the Yuma desalinization plant.

Completion Date. Spring of 1985.

Pre-Project Site Conditions. Saltcedar, arrowweed, and creosote bush (*Larrea tridentata* (Moc. & Ses.) Cav.) were the dominant woody species found on the site prior to project initiation. Soil surveys indicated generally sandy soils with a 15-cm-thick clay layer found approximately 1.2 m beneath the soil surface on the western portion of the site. Depth to saturated soils was estimated to be less than 3 m. However, soil moisture readings indicated that there was a significant difference in water availability above and below the clay layer (25 percent and 3 percent, respectively) (Pinkney 1992).

Project Strategy. Approximately 300 cottonwood, willow, and mesquite seedlings (grown in 3.8 liter containers) were planted in pre-augered holes around the periphery of Fortuna Pond during the spring of 1985. In November 1986, approximately 100 cottonwood and willow cuttings and poles were also planted. The cuttings were planted in saturated soils around the edge of the pond; no holes were augered for the cuttings. The poles were 2.5 to 3 m long and were planted in 5-cm-diameter holes augered to about one meter deep. Most of the plants were protected initially with 1-m-tall chicken wire baskets. In 1986, 1.5-m-tall welded wire baskets were placed around some plants to protect against beaver damage (Pinkney 1992). Plants were irrigated each day in 1985 from planting to September. Afterwards, irrigation was cut off until May 1986, when the trees began to appear stressed. Daily watering continued to September 1986 at roughly 12 l per day (Swett, pers. comm.).

Results. Two years following the completion of the revegetation work, approximately 30 percent of the trees had died. In 1988, more than 70 percent of the cottonwoods and willows along the edge of the pond were over 3 m tall; some of the trees along the outlet channel and the edge of the pond were 6 m tall or more. By 1997, many of the trees were over 10 m tall and appeared to be growing vigorously.

Site #10—Colorado River-Gila River Confluence

Location and Size. This is a naturally vegetated site at the confluence of the Colorado and Gila Rivers, just downstream from Prison Hill in Yuma, Arizona. The site is situated along 4 km of the West Main Colorado River canal and encompasses over 80 ha.

Ecological Characteristics. Most of the vegetation probably appeared following the high magnitude flows of 1993 and 1994, although large cottonwood trees along the southern portion of the site probably came up following the floods of 1983. Further work is required to develop a detailed description of this site's current ecological characteristics and the degree that is has changed since 1983. Nevertheless, it is apparent that significant natural regeneration took place, and the area is now dominated by an extensive riparian forest that consists of such native species as Fremont cottonwood, Goodding Willow, mesquite, seep willow (*Baccharis glutinosa* Pers.), and cattail.

Conservation Challenges. Taking advantage of such dramatic natural regeneration by allocating waters to maintain wetland plant communities that have developed following large flow events could be an effective conservation approach. Additional areas that contain significant desirable riparian habitat need to be identified for possible protection. Even if such areas cannot be protected, there may be some strategies (e.g., reducing vehicular traffic, altering recreation use, changing livestock management) that could go a long way in increasing the value of habitat to wildlife.

Site #11—Río Hardy Wetlands

Location and Size. The Río Hardy wetlands are in the Colorado River delta on one of the western most branches of the river (Figure 2).

Ecological Characteristics. Flow into the Río Hardy comes principally from agricultural runoff and geothermal wells discharged into the channel (Payne et al. 1992). A third source is backflow from the mainstem of the Colorado River during times of high flow. The Río Hardy wetlands are dominated by halophytic plants such as iodine-bush and quailbrush and less salt-tolerant plants such as arrowweed and desert broom (*Baccharis emoryi* Gray).

Conservation Challenges. The vegetation of this area has changed significantly since the turn of the century. As described by McDougal (1904), this area was once dominated to the north by a riparian forest of cottonwood and willow and to the south by an extensive tidal-influenced plain of saltgrass. In between there were scattered mesquite trees and saltbushes. Today, the riparian forest is no longer present, and the wetland is dominated for the most part by halophytic plants (Glenn et al. 1996). From at least 1977 to 1983, the Río Hardy wetlands were maintained by ponded waters behind a natural dam (Glenn pers. comm.). The destruction of the dam during high flow events of 1983 has caused the wetlands to drain and generally decline (Payne et al. 1992), although large flows during 1992 and 1993 caused the wetland area to increase from a low of 1,175 ha in 1988 to 24,000 ha in 1993 (Glenn et al. 1996).

Site #12—Ciénega de Santa Clara

Location and Size. The Ciénega is located on the eastern side of the delta and covers roughly 20,000 ha, with 4,500 ha thickly vegetated (Figure 3).

Ecological Characteristics. In total, there are 22 wetland plants in and along the periphery of the Ciénega. The main portion of the Ciénega is dominated by *T. domengensis* Pers. and at least eight other hydrophytes (Glenn et al. 1996). It is supported principally by agricultural runoff from the Wellton-Mohawk canal, with lesser inputs from the Riito Drain.

Figure 3. The Ciénega de Santa Clara covers nearly 20,000 ha and provides critical habitat for a variety of wildlife species, including several that are federally endangered.

Conservation Challenges. The principal conservation challenge facing the cienega is the possibility that the Wellton-Mohawk canal will be turned off. The Wellton-Mohawk canal was planned as a temporary answer for agricultural wastewater deposition until the desalinization plant went on line. Although the Santa Clara system is also supported by waters emanating from the Riito Drain, flow in the Wellton-Mohawk canal is much greater and therefore more crucial. If this source of water is indeed eliminated, a significant portion of the Ciénega will be compromised. In addition, the Ciénega faces challenges from the invasion of exotic plants and increasing salinity levels.

DISCUSSION

The ecological condition of the lower Colorado River has deteriorated significantly over the last 65 years. The cottonwood-willow forests that once dominated the mainstem and the delta have been reduced to isolated stands and individual trees. Only remnants currently exist of the once immense delta marshlands, with significant portions being tenuously maintained via a system of agricultural runoff canals. From an ecological standpoint, the loss of these wetland ecosystems is probably one of the major environmental issues facing the U.S.–México border region today.

River impoundment, the diversion of river waters for farms and cities, and agricultural activities are the principal causes for the dramatic decline of the river's ecological condition. The challenges to bringing the river back to an improved level of ecologic health are monumental, requiring comprehensive solutions that address the underlying causes of ecologic decline. Providing water specifically for ecological improvement, altering dam releases to promote natural regeneration, conserving water throughout the river's watershed, and addressing water allocation issues are just some of the regional challenges that will need to be addressed before significant progress can be made in improving the river's overall ecological condition.

Since the lower Colorado River is rapidly approaching the point where every drop of water is specifically allocated, it will be necessary to "find" the water to meet the environmental needs of the basin. Given the current socio-political and economic landscape of the Colorado River, however, it is likely that years of negotiation may be required before some of these long-term strategies can be implemented. In the meantime, it is reasonable to look for less politically charged strategies that can bring immediate, although more local, benefits to the river's ecological condition. Such strategies include improving the effectiveness of restoration efforts, maintaining existing critical natural areas, and purchasing marginal agricultural land to re-establish native wetland ecosystems.

The recommendations or strategies that are presented below run the gamut from policy recommendations (strategies that would require some kind of policy change before they could be implemented) to restoration/protection recommendations (strategies that focus on improving the effectiveness of wetland restoration and protection efforts). As some of restoration and protection recommendations (e.g., improving the effectiveness of riparian revegetation efforts) do not require major changes in the socio-political landscape, they could potentially be implemented on a much shorter time frame than recommendations which are purely policy orientated. However, other restoration and protection recommendations (e.g., augmenting agricultural return flows to the Río Hardy wetlands) would require a change in policy before they could be carried out.

Improve the Effectiveness of Colorado River Restoration Efforts

Evaluating the results of past restoration efforts along the Colorado River provides a wealth of information regarding how to improve the effectiveness of similar efforts. Some of the principal lessons drawn from these past restoration experiences are described below. They are general in nature and focus more on planting strategies that can be applied on a regional basis than site specific planting techniques or issues.

Develop Project Objectives that are Clear and Specific. As almost all components of a restoration project hinge on project objective (the personnel that become involved in the restoration effort, the strategies that are ultimately employed, the time frame for project completion, the project budget), an ill-defined objective can significantly hinder the effectiveness of the restoration effort (Briggs 1996). In addition to benefiting individual projects, clear and concise project objectives would make evaluating results less problematic, which in turn could greatly benefit future restoration efforts.

The effectiveness of the restoration effort at the Fortuna Fish Pond (Site #9), for example, was almost impossible to evaluate. The objective of this effort was to mitigate disturbances caused by the construction of the Yuma desalinization plant. Without a detailed analysis of the effects of the construction disturbances, however, there is no way of knowing when restoration efforts have reached the point of ecological compensation. A more acceptable approach would be to describe the objective in terms of the habitat type that needs to be restored (e.g., × hectares of cottonwood/willow habitat for southwestern willow flycatchers (*Empidonax traillii extimus* AOU). Such a well-defined objective will allow restoration managers to describe the restoration endpoint in sufficient detail and in a manner that can be evaluated. For example, the objective of an effort to restore willow flycatcher habitat can be described by plant density, diversity, and vertical complexity if the habitat requirements of the willow flycatcher are well-enough known.

Consider Using Restoration Strategies Other than Revegetation. The Bureau of Reclamation, Bureau of Land Management, Fish and Wildlife Service, and others have used revegetation strategies extensively along the lower Colorado River to re-establish native riparian plants. Despite some notable revegetation successes, it is obvious that the results of these artificial-planting efforts pale in comparison to natural regenerative capabilities. Comparing the natural regeneration that was experienced at the confluence of the Colorado and Gila Rivers following the 1983 and 1993 floods to the results of artificial revegetation efforts underscores the need to create opportunities for more cost-effective approaches. Such comparisons may be unfair, but they nevertheless highlight the need to evaluate the restoration efforts that are being implemented along the lower Colorado River to determine whether the money being spent is having the desired effects.

Revegetation is often limited in its effectiveness because it often does not address the causes of ecological deterioration. Essentially, the goal of revegetation is to replace lost plants. If the underlying causes for the loss are not adequately addressed or are not well understood, it is very likely that human-planted materials will meet the same demise as those that they are trying to replace. Most successful revegetation efforts are implemented in concert with strategies that address the reasons behind the ecological damage that has occurred (Briggs 1996).

The question that needs to be answered is whether the money, time, and energy that is spent on revegetation can be better directed on implementing other types of restoration or conservation efforts? To answer this important question, it is imperative that river managers assess a range of restoration options and attempt to tie strategies to the unique characteristics of specific reaches of the river.

Base Restoration Strategies on a Thorough Evaluation of Site Ecological Conditions. Generally, successful restoration projects are based on a sound understanding of the site's current ecological condition. Depth to saturated soils, soil salinity concentrations, presence of exotic plants, and intensity of use by recreationists and livestock are just some of the factors that need to be evaluated to develop a sound site restoration plan (Briggs 1996). Such information is also critical for developing realistic project objectives. Of these factors, evaluating soil chemistry prior to revegetation has been particularly critical for revegetation efforts along the lower Colorado River (Anderson 1989). The experiences of some riparian revegetation efforts indicate that flood-irrigating prior to planting may help to re-

Figure 4. Eleven-year old-cottonwoods planted at the Farmer's Bridge revegetation site show obvious signs of water stress.

move salts from soils to concentrations acceptable to at least some native riparian plant species. However, the riparian revegetation experiences along the lower Colorado River also indicate the need for further research on salt and water tolerances of non-agricultural plant species.

Use Plant Materials that are Adapted to Current Site Ecological Conditions. Revegetation planners often attempt to re-establish the exact plant community that was present prior to disturbance even though the community may no longer be adapted to the site's current ecological conditions. At the Farmer's Bridge revegetation effort (Site #5), for example, cottonwoods and willows were planted in an attempt to re-establish them in an area where they once dominated. As the depth to saturated soils at this site is significant, all of the cottonwoods and willows that were planted either died or suffer from water stress, while the majority of the mesquite that were planted have survived and appear healthy (Figure 4). In future similar situations, the use of alternative species, such as mesquite, quail bush, or saltbush that may not have been members of the pre-disturbance plant community, yet are native to the region and are better able to survive in the changed hydrologic environment (or more saline conditions), can significantly improve overall revegetation effectiveness.

Take Advantage of Agricultural Return Flows or Runoff. Results experienced at Dredge Spoil Site (Site #4) and No Name Lake (Site #2) demonstrate the validity of planting vegetation in areas that are likely to experience significant agricultural runoff. Both sites receive runoff from adjacent agricultural fields during the hot, dry summer months. This seems to have had a remarkable effect on survival and growth rates of planted trees. At the Dredge Spoil site, for example, the riparian vegetation planted on the levee side immediately adjacent to the agricultural fields appear much healthier and seem to have experienced greater growth rates than those on the opposite side of the levee.

Future revegetation efforts should take advantage of similar opportunities. In addition, it has been noted that establishing native, riparian plants immediately adjacent to farmland can provide useful habitat for a variety of avian species. Although more research is needed, results of some riparian revegetation efforts indicate that establishing riparian habitat for avian insectivores adjacent to agricultural land can provide benefits for farmers as well (Anderson et al. 1984).

Take Advantage of Sites that are Inherently More Mesic. Old river meanders and other low elevation topographic features can be characterized by relatively high water availability. Such areas can offer ideal conditions for the re-establishment of native, obligate riparian plants and should be considered for future revegetation efforts. At the No Name Lake site (site #1), the only obligate riparian trees to establish and grow were those planted in the relatively low elevation of the lake's depression.

Develop Restoration Projects with a Long-term Outlook. All too often, restoration efforts fail simply because there was no technical expertise or funding available following project completion. By its very nature, restoration has a long-term time frame. Success is therefore measured over a protracted time period, requiring an institutional capacity and a political will that must persist well beyond the time the last plant is placed in the ground. At the very least, the design of the restoration effort needs to include funding and personnel for maintaining irrigation systems and fences, controlling exotic plants, replacing lost plant materials, and monitoring results for three years following project completion (monitoring should continue over a longer time frame).

Identify and Protect Existing Wetland Ecosystems

In both the delta and the lower reaches of the Colorado River, there remain significant areas occupied by native, wetland habitat. The cottonwood-willow riparian forest at the confluence of the Gila and Colorado Rivers, the Ciénega de Santa Clara, and the marshlands of the Río Hardy are examples. Whether these areas were created naturally or artificially, with intent or completely by accident, their protection should be a clear short-term priority for lower Colorado River conservation efforts. Additional existing natural areas should be identified and plans to maintain or enhance their ecological condition should be developed.

The Ciénega de Santa Clara. The Ciénega de Santa Clara exemplifies this priority. The Ciénega is maintained for the most part by drainage flow from Arizona's Wellton-Mohawk Canal. Since the canal's completion in 1978, the Ciénega has grown from 200 ha (estimated in 1973) to about 20,000 ha (Glenn et al. 1996). If the Yuma desalinization plant begins operation and the Wellton-Mohawk waters are diverted to irrigation districts in Mexacali, the largest remaining wetland in the region may be significantly compromised (Zengel et al. 1995, Glenn et al. 1996). Conservation efforts need to focus on ways to maintain flow into the Ciénega. If the desalinization plant does go on line, other sources of water need to be found to make up for water lost to plant operations. Such alternative waters could be found by allocating Colorado River water for ecosystem maintenance or diverting agricultural return flows from México southward.

Río Hardy Wetlands. The Río Hardy wetlands have experienced growth and decline over the past 50 years. During the period of 1947 to 1983, the wetlands of the Río Hardy were maintained by water impounded behind a natural bar that existed roughly 35 km from the mouth of the Colorado River (Payne et al. 1992). However, the bar was destroyed by the high flows of 1983, and the resulting drainage reduced the size of the wetlands from 63,000 ha in 1983 to 1,175 ha in 1988. High flows during 1992, however, have increased the wetlands to 24,000 ha, but this increase is likely temporary if some type of impoundment structure is not recreated (Glenn et al. 1996).

Conservation/restoration efforts in the near future should focus on augmenting agricultural return flows to the Río Hardy wetlands and preventing waters from escaping once they reach the wetlands. Ducks Unlimited engineers have recommended repairing the natural dam that was destroyed by the flooding of 1983 (Payne et al. 1992). This strategy would probably reduce drainage from the Río Hardy wetlands and help to restore at least a portion of the former wetland area. Conducting a feasibility study of this and similar strategies to maximize the environmental use of waters entering these wetland areas should be a priority.

The Colorado-Gila River Confluence. The cottonwood-willow riparian forest at the confluence of the Colorado and Gila rivers is a product of natural riparian regeneration following the high flows of 1983 and 1993. The expanse of this area demonstrates the often dramatic resiliency of riparian ecosystems. Such natural regeneration also represents an important restoration/conservation opportunity. As in this case, nature has done the majority of the ecological improvement work. Flooding has re-worked alluvial sediments to create ideal seedbed conditions for riparian plants, and nearby riparian plants have disseminated seed.

Future priorities should include identifying similar natural areas throughout the basin and developing plans for their protection. As is the issue throughout the lower Colorado River, "finding" the water required to maintain these areas is the key challenge. In addition, other issues, such as vehicular traffic, development pressures, water pollution, etc., may need to be addressed if the Colorado-Gila River riparian ecosystem and other similar areas are to remain viable in the future.

Appropriate Water Resources for Restoration

Restoration cannot happen unless water is allocated specifically for that purpose. However, the 1922 Colorado River Compact does not dedicate waters to maintain healthy wetland/aquatic ecosystems. The same is true for international treaties between the U.S. and México that contain no language on environmental considerations. Yet, it is highly likely that all of the legally allocated water will be for human consumptive uses in the near future by the seven basin states and México. Simply put, water management and planning does not consider aquatic ecosystems. The fact that Colorado River water is almost completely exhausted before it reaches the delta underscores this point. It is therefore critical to change traditional water policies that currently focus solely on human consumptive needs so that they reflect a more sustainable management of the river's waters.

Morrison et al. (1996) pointed out that one of the major obstacles in the way of gaining water allocation for restoration is the lack of scientific information that quantifies the amount of water needed for some degree of wetland restoration. Essentially, restoration allocations will probably not be made until there is a better understanding of the ecological benefits that the water is likely to bring.

Expand Revegetation Efforts in the National Wildlife Refuges

Some of the most extensive (at least in terms of the area covered) riparian revegetation efforts along the lower Colorado River have been experienced in the Imperial and Cibola National Wildlife Refuges. In general, such protected areas offer great potential for revegetation because the land and the water are under the direct control of the managers, and they are better able to manipulate restoration strategies to fit site-specific conditions. At the Imperial Wildlife Reserve, for example, revegetation efforts have established cottonwood, mesquite, willow, and other species on over a hundred hectares. Moreover, the refuge has been able to do this without infringing upon the water rights of others. In addition, there is room to accomplish more, as less than half of Imperial's 27 million cubic meters consumptive use allocation is being used (Ellis pers. comm.). In a sense, riparian revegetation has become a farming operation where cottonwoods and willows are the crop of choice instead of alfalfa (Swett pers. comm.). Yet, increasing funds to support such efforts can create significant riparian habitat in areas where such habitat has just about disappeared.

Develop a Concerted Binational Effort for Restoring the Delta

Since México has legal entitlements to less than 10 percent of the river's annual flow, it is unfair and unrealistic to assume that México should take sole responsibility for restoring the delta. A binational effort that provides the framework for a variety of cooperative cross-border ventures is critical for the future of the delta (Morrison et al. 1996). Given the disproportionate Colorado River allocations between the two countries, water and restoration assistance should be provided to México from the U.S. In addition, it should be noted that U.S. interests will probably benefit from the recreational qualities that a restored delta will bring. Birding, camping, kayaking, and other nonconsumptive uses could expand tremendously in a restored delta region, bringing significant economic benefits to local communities and to tourism interests in both México and the U.S.

Develop and Implement Community-Based Conservation Approaches

Over 20 million people have a direct stake in the current and future use of lower Colorado River water (Morrison et al. 1996). The great majority of these users live far from the river and are interested in it principally as a water source. Through state and federal channels, their voices can be heard regarding a variety of river-related issues (e.g., allocation, water quality, etc.). Riverside communities have an even larger stake in the river's health by virtue of the real and potential economic, social, and environmental values it provides. However, they may not have the appropriate opportunity for input into decisions that affect their lives even more directly than those living afar. Providing a forum that will bring community citizens together to discuss common problems and identify concrete ways they can engage each other and the water and land managers would be mutually beneficial to both the river and the towns and communities. Gatherings of local stakeholders from both sides of the border to discuss the sustainable use of Colorado River water has been initiated and will continue to expand (Nagel, pers. comm.).

A regional economic study by the Sonoran Institute in 1996 identified nature-based tourism as a priority option for building a firmer sustainable business environment and local economic opportunity in the Sonoran Desert borderlands, including the lower Colorado River and delta region (Nimkin 1996). Opportunities of this kind have been developed most extensively in the Reserva de la Biosfera Alto Golfo y Delta del Rio Colorado where Conservation International-Mexico and Secretaria Medio Ambiente Recursos Naturales y Pesca (SEMARNAP) have collaborated in promoting the Ciénega Santa Clara as a destination and carrying out nature guide training for the neighboring Ejido Luis Encinas Johnson. Other opportunities may exist in association with the Imperial, Cibola and Bill Williams National Wildlife Refuges, and the Río Hardy in Baja California.

Create Zones of Protection

Providing increased levels of protection can help to maintain critical wetland areas in the long-term. The Ciénega de Santa Clara is part of the much larger Reserva de la Biosfera Alto Golfo de California y Delta del Río Colorado. This protected area was established by the Mexican Government in 1993 to conserve the ecosystems of the Sonoran Desert, Upper Gulf and the Colorado delta, and to provide and protect fishing and tourism activities. This international reserve is recognized by UNESCO and offers significant protection to core ecosystems. Future Colorado River conservation efforts need to focus on protecting additional native wetland and riparian areas.

Modify Reservoir Operations and Water Use Practices

Altering dam releases to enhance or maintain the Colorado River's wetland habitat needs to be a future priority. The successful completion of the 1996 test flow or "flood" from Glen Canyon Dam to restore river beaches may set the stage for further manipulations of dam releases for environmental purposes. If such artificially-produced floods can remove sand and silt out of reservoir storage to downstream sites, a variety of objectives could be accomplished. Depositional bars can be created to enhance natural propagation of native riparian plant species, and backwater breeding areas for many native fish can also be created immediately downstream of newly-formed depositional bars.

Performing such releases for environmental purposes may be more likely than before, as flood-water management along the lower Colorado River in the last decade is changing because Lake Powell behind Glen Canyon Dam has nearly filled to capacity. This means that flood flows will probably pass through Glen Canyon Dam much more frequently, increasing the amount of water brought into the lower reaches of the river and the delta (Payne et al. 1992, Glenn et al. 1996). If this scenario is accurate, a variety of restoration opportunities that involve innovative manipulations of dam releases to benefit river ecology may exist that were not possible before.

Resolve Other Water-Related Issues

Along the lower Colorado River and in the delta, there seem to be numerous areas that are ecologically damaged due, at least in part, to water-related issues that are not directly associated with reservoir management and water allocation. These "other" water-related issues include addressing ground-water over-pumping, water pollution, and improving water conservation measures (Morrison et al. 1996). In comparison to altering dam releases or allocating water for environmental purposes, tackling some of these issues may be an effective way of realizing short-term ecological improvements. Implementing water conservation measures to reduce ground-water pumping in areas such as Mexicali, Blythe, and Yuma could reduce draw-down of nearby wetlands. In some areas, lining irrigation canals with concrete could significantly reduce water loss, possibly freeing some water for environmental purposes.

Use Wastewater More Effectively

The river has approached the point of full utilization, where essentially every drop of water that passes through is spoken for. Therefore, obtaining significant amounts of water specifically for wetland enhancement will become increasingly difficult. On the other hand, the amount of wastewater (agricultural drainage and municipal effluent) is growing significantly. Although this water has no human use, some is well-suited for maintaining wetland vegetation (Glenn et al. 1997). A significant amount of the brackish wetlands in the delta is almost completely sustained by "unusable" agricultural runoff. A priority of future wetland conservation efforts should be to develop strategies for using wastewater more effectively. Indeed, at a meeting between the heads of water-management agencies of the U.S. and México, scientists, agricultural, municipal, and environmental representatives suggested that the improved management of wastewater could reestablish up to 40,500 ha of wetland habitat in the delta (Glenn et al. 1997).

Although the volume of municipal sewage effluent produced each year is much smaller than that produced from agriculture runoff, it is likely to increase with expanding urbanization. Depending on the quality of the effluent, some may also be suitable for maintaining wetlands. Moreover, certain wetland areas could be developed specifically to help clean municipal wastewater, thus providing the dual benefit of wetland habitat creation and contaminated water filtration. Of course, safeguards would have to be developed so that wetlands do not become inexpensive disposal zones for raw sewage.

CONCLUSION

Due to a variety of human-related impacts, much of the lower Colorado River native wetland ecosystem is damaged or has disappeared completely. Only remnants remain of the magnificent riparian cottonwood-willow forests that once graced significant reaches of the lower Colorado River. In the delta, the majority of the remaining marshlands are maintained via tenuous associations with agricultural runoff canals. As ecological conditions along the lower Colorado River deteriorated, so too has the well-being of the people and wildlife that depend on the river for their survival. During the height of their dominion, the population of the Cocopah, the original river people, exceeded 6,000. Today, scattered communities consisting of a few hundred individuals remain, located for the most part on the backwaters of the Río Hardy and near San Luis and Somerton, Arizona. Wildlife species such as the totoaba (a fish species cherished by the Cocopa), the vaquita porpoise, desert pupfish, and the Yuma clapper rail, all of which once thrived in the delta's ecosystem, are listed as endangered under the U.S. Endangered Species Act.

From an ecological and conservation perspective, the situation along the lower Colorado River has reached a critical juncture. To make significant progress in repairing the ecological condition of the river, it is imperative to address difficult and politically-charged bi-national policy issues such as ground-water drawdown, water allocation, and dam releases. Some of these strategies may require years of negotiations and planning, however, before they can be implemented. This underscores the need to look for creative solutions that can be carried out more rapidly. Strategies such as using wastewater for environmental purposes, developing plans to protect areas characterized by significant native plant communities (e.g., cottonwood/willow forest at the confluence of the Colorado and Gila Rivers), improving the effectiveness of wetland revegetation techniques, increasing areas protected by state and/or federal agreements, and using community-based conservation approaches would have dramatic, albeit local, effects on enhancing or maintaining the ecological condition of the lower Colorado River.

Of these approaches, immediate attention should be given to using agricultural runoff and municipal effluent for environmental purposes. Currently, much of the wastewater drains north and is squandered in the enclosed Salton Sea basin. Working with the communities that line the Colorado River should be another top priority. Such community-based conservation approaches could have the dual benefit of bringing ecological relief to the river and economic and/or health benefits to riverside residents. As they directly involve riverside peoples, community-based approaches also have long-term staying power—a critical element in the success of any conservation/restoration effort.

ACKNOWLEDGMENTS

This study was supported by grants from the Defenders of Wildlife and the México Affairs Office of the National Park Service. We thank John Fritschie and Craig Miller (Defenders of Wildlife) and Howard O. Ness (US/Mexico Affairs Office, National Park Service) for their assistance. We also express our sincere appreciation to Anita Alvarez de Williams, Gina Walther, and Claudia Schroeder (El Museo de Baja California); Oscar Ramirez and Alberto Tapia (La Universidad de Baja California); and John Swett (Bureau of Reclamation) for providing background information and giving us a river and delta tour that we will not soon forget. In addition, we thank María Elena Barajas and Enrique Flores (Departamento de Ecología, Estado de Sonora); Juan Carlos Barrera and José Campoy (Reserva de la Biósfera Alto Golfo de California y Delta del Río Colorado); Mitch Ellis and Carmen Kennedy (Imperial National Wildlife Refuge); Edward Glenn, Rene Tanner, and William Matter (University of Arizona); Robert D. Ohmart and Duncan Patten (Arizona State University); David Reyna Ortiz (Instituto Nacional de Ecología); Fred Phillips and Terry Shaffer (Colorado River Indian Tribes); Lisa Carder (Sonoran Institute); and Carlos Valdés Casillas (Instituto Tecnológico y de Estudios Superiores de Monterrey) for reviewing, editing, and supporting this effort.

LITERATURE CITED

Abarca, F.J., M.F. Ingraldi, and A. Varela-Romero. 1993. Observations on the desert pupfish (*Cyprinodon macularius*), Yuma clapper rail (*Rallus longirostris yumanensis*) and shorebird communities in the Ciénega de Santa Clara, Sonora, México. Nongame and Endangered Wildlife Program Technical Report. Arizona Game and Fish Department, Phoenix, AZ, USA.

Alvarez de Williams, A. 1978. Southwest Cocopah. p. 99–113. *In* A. Ortiz (ed.) Handbook of North American Indians, vol. 10. Smithsonian Institution, Washington, DC, USA.

Anderson, B.W. 1989. Research as an integral part of revegetation projects. p. 419–423. *In* D.L. Abell (tech. coor.) Proceedings of the California Riparian Systems Conference: Protection, Management, and Restoration for the 1990s. U.S. Department of Agriculture/Forest Service General Technical Report/PSW-110.

Anderson, B.W., R.D. Ohmart, and H.A. Allen, Jr. 1984. Riparian birds in the riparian/agricultural interface. p. 190–195. *In* R.E. Warner and K.M. Hendrix (eds.) California Riparian Systems. University of California Press, Berkeley, CA, USA.

Briggs, M.K. 1996. Riparian Ecosystem Recovery in Arid Lands. University of Arizona Press, Tucson, AZ, USA.

Cisneros-Mata, M., G. Montemayor-Lopez, and M. Roman-Rodrequez. 1995. Life history and conservation of *Totaba macdonaldi*. Conservation Biology 9:806–814.

Colorado River Basin Salinity Control Forum. 1990. Water quality standards for salinity Colorado River system. 106 West 500 South, Suite 101, Bountiful, UT, USA 84010.

Eddleman, W.R. 1989. Biology of the Yuma Clapper Rail in the southwestern U.S. and northwestern México. U.S. Bureau of Reclamation, Yuma Projects Office, Yuma, AZ, USA.

Glenn, E.P., C. Congdon, and J. Garcia. 1997. New value for old water. World and I April 1997:204–211.

Glenn, E.P., C. Lee, R. Felger, and S. Zengel. 1996. Effects of water management on the wetlands of the Colorado River delta, México. Conservation Biology 10:1175–1186.

Glenn, E.P., R.S. Felger, A. Burquez, and D.S. Turner. 1992. Ciénega de Santa Clara: endangered wetland in the Colorado River delta, Sonora, México. Natural Resources Journal 32:817–824.

Hendrickson, D.A. and A. Varela-Romero. 1989. Conservation status of the desert pupfish, *Cyprinodon macularius*, in México and Arizona. Copeia 1989:478–483.

Lee, C.T. 1994. Mapping wetland dynamics in the lower Colorado River delta using archival landsat map satellite imagery. Arizona Remote Sensing Center, Office of Arid Lands Studies, University of Arizona, Tucson, AZ, USA.

McDougal, D.T. 1904. Delta and delta vegetation. Botanical Gazette 38:44–63.

Minckley, W.L. 1991. Native fishes of the Grand Canyon Region: An Obituary? p. 124–177. *In* Colorado River Ecology and Dam Management. National Academy Press, Washington, DC, USA.

Morales-Abril, G. 1994. Reserva de la Biosfera Alto Golfo de California y delta del Río Colorado. Ecologica 3:26–27.

Morrison, J.I., S.L. Postel, and P.H. Gleick. 1996. The sustainable use of water in the lower Colorado River basin. Pacific Institute and Global Water Policy Project, 1204 Preservation Park Way, Oakland, CA, USA.

Nimkin, D. 1996. Sustainable development opportunities in the Arizona-Sonora borderlands. Unpublished report prepared by David Nimkin for the Sonoran Institute, Tucson, Arizona.

Ohmart, D. R., W.O. Deason, and C. Burke. 1977. A riparian case history: the Colorado River. p. 35–47. *In* R.R. Johnson and D.A. Jones (tech. coor.) Preservation and Management of Riparian Habitat: A Symposium. U.S. Department of Agriculture/Forest Service General Technical Report/RM-43.

Payne, J.M., F.A. Reid, and E.C. Gonzalez. 1992. Feasibility study for the possible enhancement of the Colorado River delta wetlands, Baja California Norte, México. Report to Ducks Unlimited, Inc., and Ducks Unlimited of México, Sacramento, CA, USA.

Pinkney, F.C. 1992. Revegetation and enhancement of riparian communities along the lower Colorado River. U.S. Department of the Interior, Bureau of Reclamation, Ecological Resources Branch, Ecological Resources Division, Denver, CO, USA.

Pontius, D. Colorado River Basin study. 1997. Report to the Western Water Policy Review Advisory Commission. National Technical Information Service, Springfield, VA, USA.

Sykes, G. 1937. The Colorado River delta. Carnegie Institution of Washington, DC, USA. Publication no. 460.

Thompson, R.W. 1968. Tidal flat sedimentation on the Colorado River delta, northwestern Gulf of California. Geological Society of America, Boulder, CO, USA. Memoir 107.

Zengel, S.A., V.J. Meretsky, E.P. Glenn, R.S. Felger, and D. Ortiz. 1995. Cienega de Santa Clara, a remnant wetland in the Río Colorado delta (México): vegetation distribution and the effects of water flow reduction. Ecological Engineering 4:19–36.

Manuscript received 12 June 1997; revision received 29 January 1998; accepted 13 April 1998.