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Case studies from the Colorado River Delta:
Wetland changes, challenges, and restoration potential

Introduction

The Colorado River stretches approximately 1,400 miles from its headwaters in the Rocky Mountains to its terminus in Mexico at the Gulf of California. This river, much dammed and diverted in the 20th century, delivers water to over 40 million people and irrigates over 5.5 million acres of arable land.[1] As a fixture of American West iconography and the hydrologic lifeline to seven states in the US and two in Mexico, the Colorado River has been the focus of intense academic investigation; by 2020, over 5,500 scientific publications list "Colorado River" as a keyword.[2] Despite the proliferation of research, a critical area of study remained overlooked until the last decade. The Delta, or the sprawling region of wetlands that exists at the mouth of the river in Mexico (Figure 1), once comprised the largest desert estuary in the world.[3] Though the region has been recognized by UNESCO as a Biosphere Nature Reserve,[4] and designated a Ramsar Wetland of International Importance,[5] only 500 studies highlight "Colorado River Delta" as a keyword, or less than 10% of those dedicated to the river as a whole. Of those 500 studies, more than half were published after 2010.[6]

The dearth of information regarding the Colorado River Delta (CRD) is unfortunate given what is well-established about the outsized ecological importance of wetland habitats.[7,8] The Ramsar Convention defines wetlands as "areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water."[9] Collectively, these habitats provide an enormous suite of ecosystem services, some of which are typical of natural environments – biodiversity support, biogeochemical carbon and nitrogen regulation, air and water filtration, and food and fiber provisioning – and some of which are unique, such as aquifer recharge, floor water storage, terrestrial protection from tidal catastrophe, and recreational, economic, and cultural significance.[7] Furthermore, wetlands are home to plant, animal, and soil taxa that have unique features or adaptations to exist in aquatic, saline, or ever-changing environments. Cattail and willow, for example, have developed aerenchyma, or spongy tissue that enable them to pump atmospheric oxygen to their roots so they may survive in anoxic conditions.[10] Histosols, one of the 12 major soil orders, are also common to wetlands, as they form from the underwater decomposition of organic matter. These soils make up less than 2% of the earth's unglaciated surface, but are estimated to store up to 462 Pg of carbon.[11] These and other unique elements are each present in the CRD.

For thousands of years the Colorado River rambled unhindered into the ocean at the Gulf of California, where the surrounding riparian, estuarine, and marsh habitats were well connected and ever shifting depending on river flows, sediment loads, and seasonal, annual, and climatic variations.[12] When conservationist Aldo Leopold explored the region in 1922, he described an environment with "a river [that] was everywhere and nowhere;" "a milk and honey wilderness;" "a hundred green lagoons;" and a "verdant wall of mesquite and willow."[13] Prior to largescale human intervention, the estuary received over 14 million acre-feet (MAF) of water per year and sprawled across several million acres of land.[12] The 1944 treaty that allocated water to the US and Mexico for agricultural and municipal use did not account for the needs of the CRD. Today, the region receives less than 1% of the historic water volume (Figure 2).[14] What used to be a vast desert oasis has been largely reduced to salt and mud flats, with less than 5% of the original wetland acreage remaining.[14] Except under rare flooding or intentional upstream water release events, the river has dried approximately 100 miles north of the ocean since the 1960s. The surviving wetlands are now unconnected, fixed in place by management structures, and recharged primarily through agricultural runoff, wastewater returns, and subsurface seepage.[15]

There are unsurprisingly a broad range of environmental consequences for the CRD due to the upstream damming, channelization, and over-allocation of river flows. Many of these issues plague the river ecology as a whole: invasive species,[16] decreased or altered sediment loads,[14,17] overdraft of surrounding groundwater basins,[18,19] and the suite of threats linked to climate change including rising temperatures and increased incidence of natural disasters.[20,21] There are also challenges unique to CRD wetlands, primarily related to the lack of freshwater inflow: an increase in wetland salinity,[22] rising contaminant concentrations from wastewater and agricultural discharge,[23] and the complicated system of binational agreements required to secure water and funding for ecological restoration.[15] These and other challenges cast doubt on CRD survival, especially against a backdrop of projected increases in agricultural production, population growth, and climate change.

Despite the scale and complexity of the challenges facing the CRD, the region remains an important provider of ecosystem services and is critical for the numerous species that rely on it. As an important stopover for birds migrating along the Pacific Flyway, over 350 species have been documented in this region, including endangered and protected birds such as the Southwestern willow flycatcher and the endemic Yuma clapper rail.[24] The wetlands also serve as a species incubator for the Gulf of California, home to the following aquatic species of concern: the largest remaining population of desert pupfish, the virtually extinct totoaba, the Colorado delta clam, and the vaquita porpoise, or the world's smallest marine mammal.[25] Though the estuary was once written off as a "dead ecosystem,"[26] revived scientific, political, and nonprofit interest in the region has demonstrated that the CRD is indeed alive, of international importance, and may be conserved with careful and collaborative efforts. To illustrate changes, challenges, and restoration potential, two CRD wetlands have been selected as case studies for this review: the limitrophe and the Cienga de Santa Clara. While these regions are by no means the only important CRD habitats, they dominate the scientific literature due to their size, the associated restoration efforts, and their potential for survival into the future.

The Limitrophe

The limitrophe (Figure 1A), or what was once the 22.5 mile stretch of the Colorado River on the border between the US and Mexico, has remained a dry riverbed since the 1960s along with the rest of the southernmost 100 miles of the river.[15] Its location directly beneath Morelos Dam (where Mexico receives and distributes much of its 1.5 MAF per year allotment), however, makes it one of the few remaining regions that occasionally receives enough flow to exceed its banks and reach its floodplain.[19] This is primarily the result of El Nino-cycle flooding events following the 1981 filling of Lake Powell, subsurface seepage from upstream reservoirs, and a high groundwater table due to the contribution of agricultural runoff. Though this water is a mere fraction of what the limitrophe historically received, it is enough to support the largest remnant stand of native cottonwoods and willows.[19] As such, this region has become the focus of intensive binational restoration efforts, carried out primarily through environmental flows, nonnative vegetation removal, and the seeding and replanting of native species.[27]

Environmental flows, defined as managed releases from water control structures designed to support ecosystem functioning, were first introduced to the Colorado River in 2014 following Minute 319.[27] This minute, or addition to the 1944 US-Mexico water treaty, allocated 105,000 acre-feet to flow to the CRD with the following stated objectives: to 1. inundate the floodplain and stimulate recruitment of native cottonwood and willow; 2. fortify existing vegetation; and 3. increase riparian bird diversity and abundance.[28,29] Though this one time "pulse flow" was not of great enough magnitude to restore fluvial processes of erosion, sediment deposition, and vegetation scour, researchers found that it was successful at reducing soil salinity, increasing groundwater table elevation, and moistening the soil surface.[27] Schlatter et al. (2017) observed these benefits to be insubstantial to achieve Minute 319 goals alone. In a study designed to monitor the impact of the 2014 pulse flow (T1), these researchers found that cottonwood and willow density increased only slightly compared to the uninundated control (C), but increased further in plots which were also cleared of nonnatives (T2), or cleared and seeded with cottonwood and willow (T3) (Figure 3). This measured increase in overall vegetation corroborates NDVI (normalized difference vegetation index) observations, which showed a 17% increase in 'greening' following the pulse flow.[30] Unfortunately, this greening was as likely to be from the successful achievement of Minute 319 goals 1 and 2, as the germination and growth of additional stands of nonnative tamarisk. Schlatter et al. (2017) observed that in all treatments, nonnative tamarisk responded more vigorously to the pulse flow than the target species (Figure 3), though researches do not believe this to have negatively impacted the cottonwood and willow. They conclude that pulse flows are an effective method at achieving the stated goals, if combined with active management in the form of pre- and post-flow nonnative removal and native seeding.

To date, over 1000 acres of limitrophe wetlands have been conserved, with the aid of the 2014 pulse flow, and through the efforts of Raise the River.[31] This unique project, a partnership between six US and Mexican NGOs, has raised and provided the resources required to actively manage habitat according to researcher recommendations. This active management has played a large role in achieving goal 3 as well. Following the pulse flow, researchers observed a small overall increase in bird abundance and diversity.[32] This effect was greatest in the actively managed restoration sites of the limitrophe, with abundance increasing from 281 birds per transect to 1,100 birds per transect, and the diversity index increasing by 41%. This is no doubt due to the increased vegetation observed following the pulse flow, as well as the more than 200,000 native trees that Raise the River has successfully introduced to the region.

While the effects of active management in the limitrophe offer sparks of hope in an otherwise bleak landscape, there remain challenges which may be difficult to address through conservation alone. As many wetland plants are phreatophytic, their deep roots require constant access to the saturated soil zone above the groundwater table.[33] Increased agricultural production along the Colorado River basin, however, has continued to deplete groundwater resources. Though groundwater dynamics here are complex, with many inflows and outflows (Figure 4), elevation of the groundwater table in the northernmost region of the limitrophe has decreased by an average of 2 ft. since the 1960s; in the southernmost region, it has decreased by an average of 27 ft.[19] By most projections, the demand for groundwater will continue to increase under a warming planet and with increases in population and agricultural production.[18,34] If groundwater resources are not actively regulated to reduce consumption, the survival of limitrophe vegetation, and therefore the bird species that depend on it, is under threat. Largescale shifts in river and groundwater resources are required if conservation efforts are to be meaningful beyond the short-term.

Cienega de Santa Clara

In 1972 Minute 242 was created to address the ongoing problem of increasing salinity in the Colorado River.[28] Though the US had never failed to meet its promised water allocation to Mexico, the water had become salty to the point of poisoning the crops of Mexican farmers. Upstream, American farmers were irrigating their lands and channeling the used water back to the river, despite high salinity levels from contact with soil and fertilizer. Minute 242 guaranteed that Mexico's allotted 1.5 MAF would no longer be of degraded quality, and dedicated funding towards a future desalinization plant now known as the Yuma Desalting Plant (YDP). In 1977, US farmers began to channel their 100,000 acre-feet per year of saline agricultural wastewater towards a barren floodplain in Mexico's Sonoran Desert, as a temporary solution until the completion of YDP.[35] Today, this formerly barren floodplain is now the Cienega de Santa Clara, or the largest wetland in the CRD (Figure 1B). At over 400,000 acres, this wetland supports the largest populations of many of the endangered or protected birds, fish, and mammals in the CRD, and provides habitat to every bird species to have been observed in the region.[36,37] Though the creation of the Cienega de Santa Clara was an unintentional act of upstream water management, it now sits within the UNESCO Biosphere Nature Reserve, and is the target of concerted conservation efforts amidst increasing salinity,[22] contaminant concentrations,[38] and density of invasive species.[16]

Despite the ecological importance of the Cienega de Santa Clara as the largest remaining wetland in the CRD estuary, its survival is under immediate threat. Increased upstream water demand has forced water users to look towards the 100,000 acre-feet per year saline water with renewed interest, especially as desalinization technologies have become more viable through cost and energy efficiencies.[39] Conservationists argue that the Cienega de Santa Clara is too important to cease water delivery, while water users highlight that the diversion was always intended to be temporary. Fortunately for the marsh, Arizona's YDP required so much time and money to build that by the time it opened in 1992 the technology was already obsolete. To date, the plant has operated only 3 times since completion – during trial runs in 1992, 2007, and 2010 – but costs nearly $6 million per year to maintain. During these pauses in water diversion to the Cienega de Santa Clara, and one other 8-month pause due to canal repairs in 1992, scientists were able to observe the impacts of flow-reduction on wetland habitat, and make projections about the fate of the marsh if water delivery should cease.

Following declines in water flow from May 1992 to January 1993, Zengel et al. (1995) observed a 60-70% decline in marsh foliage through aerial documentation.[40] Corresponding measurements of salinity, nitrate concentration, and water depth revealed conditions beyond what most native species can tolerate. This "living laboratory" demonstrated what would later be tested through direct experimentation: flow reduction combined with evapotranspiration produces salinity beyond the survival limits of cattail (Typha domingensis), or the dominant vegetative species in the Cienega de Santa Clara.[22] During this flow reduction researchers also observed a dramatic decline in pupfish density, with not a single pupfish found at multiple sampling locations within three of four sites they had previously been reported.[41] The site where pupfish were found was still flooded even after the 8-month dry down, though researchers hypothesize it would not remain so during more extensive flow reductions. They conclude that the Cienega de Santa Clara could no longer support populations of these endangered fish without continued inflow. Likewise, Zengel et al. (1995) hypothesize that the Cienega de Santa Clara is unlikely to survive YDP operation, and warn against a future where water is reclaimed for human consumption in lieu of marsh delivery.

During the 2010-2011 trial run of YDP, university scientists, governmental agencies, and environmental groups worked together to shift the management of the Cienega de Santa Clara from passive to active.[35] In Minute 316, the US and Mexico agreed to find alternative sources of water for replacement flows and to conduct environmental monitoring.[28] The result was no net difference in water delivery to the Cienega de Santa Clara, and therefore none of the harsh consequences observed in the 1992 flow reduction. Though it is unclear where water for replacement flows could be secured if YDP were to operate in perpetuity, the success of Minute 316 demonstrated the power of collaborative conservation, and laid the framework for these largescale agreements in the future.

Wins for the wetlands

The limitrophe and the Cienega de Santa Clara case studies well encapsulate the many challenges and complexities of environmental management in the CRD. Despite binational and nonprofit conservation efforts, there are many threats to the survival of these wetlands. Collectively, scientific research indicates that more active management in the CRD is likely to have the most positive outcomes for the limitrophe and the Cienega de Santa Clara. This conclusion likely holds for the CRD as a whole, as well as for the many plant and animal species that rely on it. Active management may play a role in short-term CRD conservation, but without serious and long-term commitment from industry and governments, the efforts may be in vain. Collaborative groups may plant and seed native trees, but if groundwater pumping continues at an unsustainable pace, then these trees will not survive. Alternative water sources may be diverted to the Cienega de Santa Clara, but without a long-term, secure water source, the wetlands may always be at risk.

Though research has shed light on a potentially abysmal fate for the Colorado River Delta, that the science is being conducted in this region at all is a hopeful change from ten years ago. This science is just one of many wins for the wetlands, beginning in 1993 with the UNESCO Biosphere Nature Reserve designation, and, most recently, with the addition of Minute 323 in 2017. Seizing on the success of the 2014 pulse flows, Minute 323 has secured 210,000 acre-feet of water to reconnect the Colorado River with the ocean once again.[28] This agreement has also committed $9 million to restoration and $9 million to scientific monitoring and evaluation. While the future success of CRD conservation efforts remains unclear, scientists, governmental agencies, and environmental groups will be there to document it. As Dale Turner of the Nature Conservancy said in 2019: “We will never get an estuary as it was a century ago, not in our lifetimes, but what we can do is recreate a functional habitat that supports populations of the native species that belong there. That’s success to me.”[13]

Figure 1. Map of the Colorado River Delta with locations of case studies: A. The limitrophe and B. The Cienega de Santa Clara

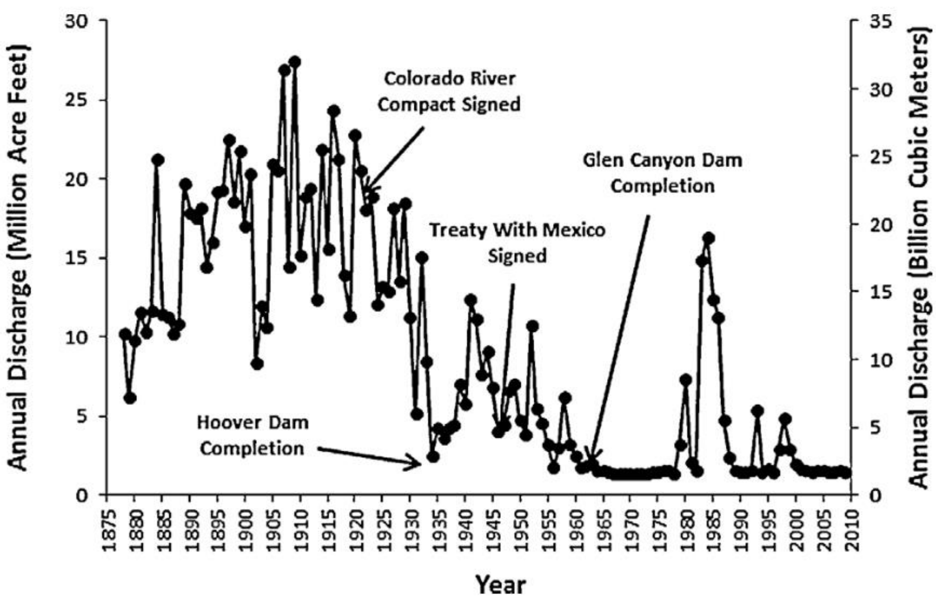

Figure 2. Colorado River flow at the US-Mexico border from 1878 to 2009, with historic events included in timeline. Adapted from Zamora et al. (2013).[14]

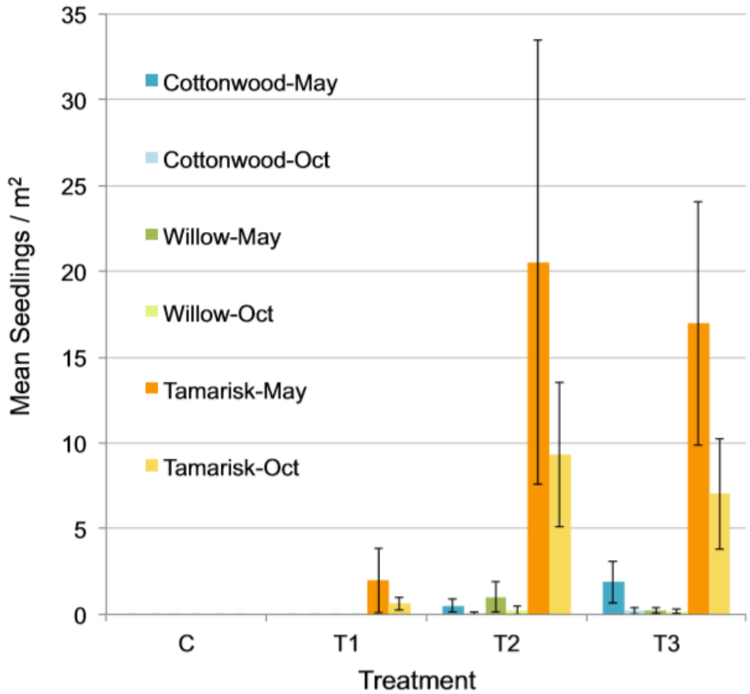

Figure 3. Tamarisk, cottonwood, and willow mean density per m^2 of treatment at two sampling times. Error bars are standard error of the mean. C= control; T1 = inundated; T2 = inundated and cleared; T3 = inundated, cleared, and seeded. Adapted from Schlatter et al. (2017).[27]

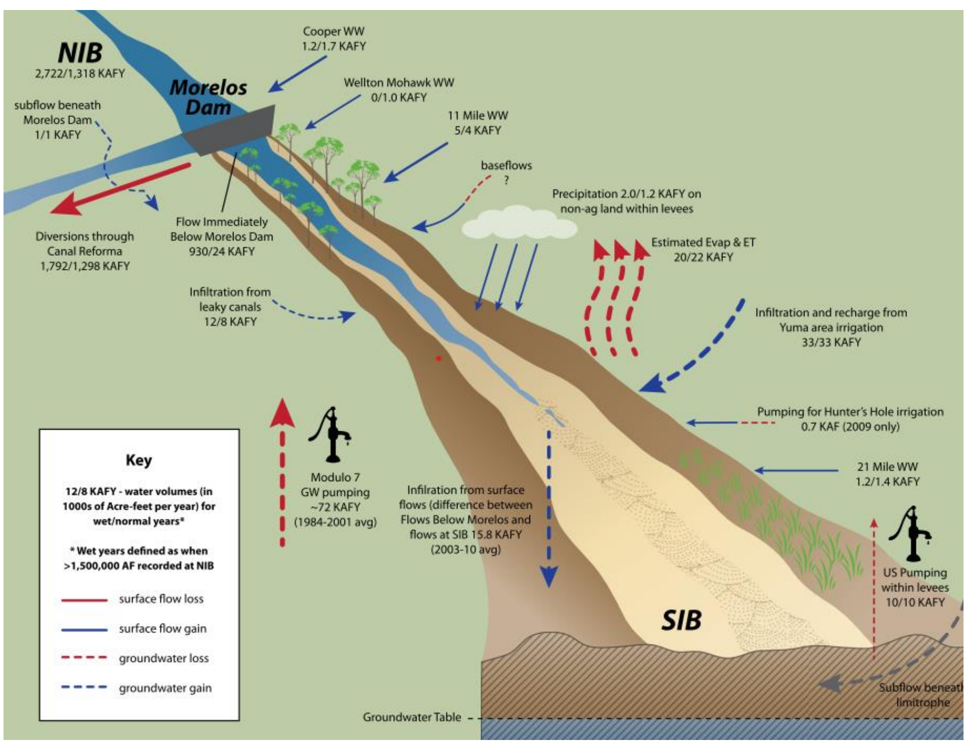

Figure 4. Groundwater inflows and outflows at the uppermost region of the limitrophe beneath Morelos Dam (Adapted from Cohen 2013).[42]

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