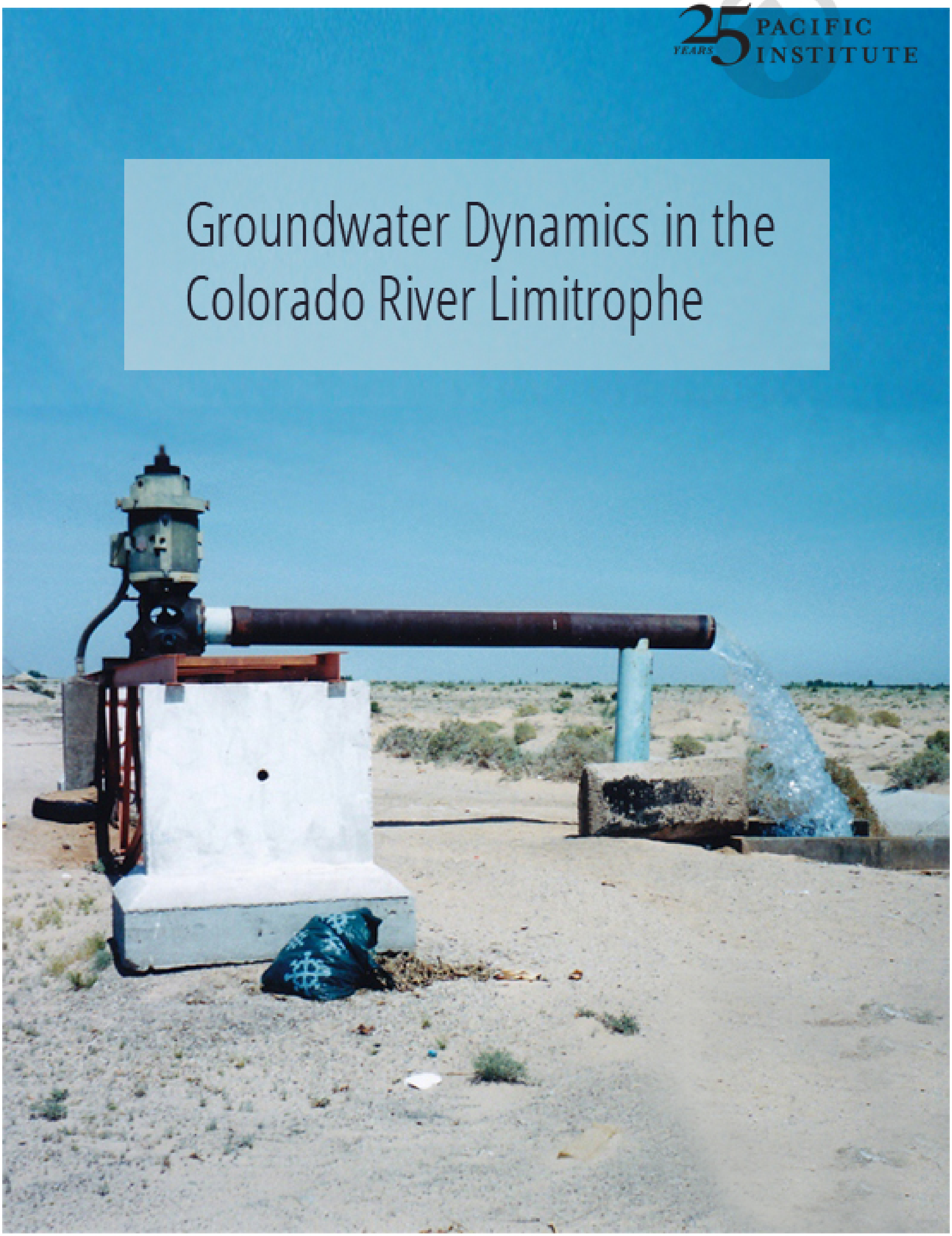
Groundwater Dynamics in the Colorado River Limitrophe



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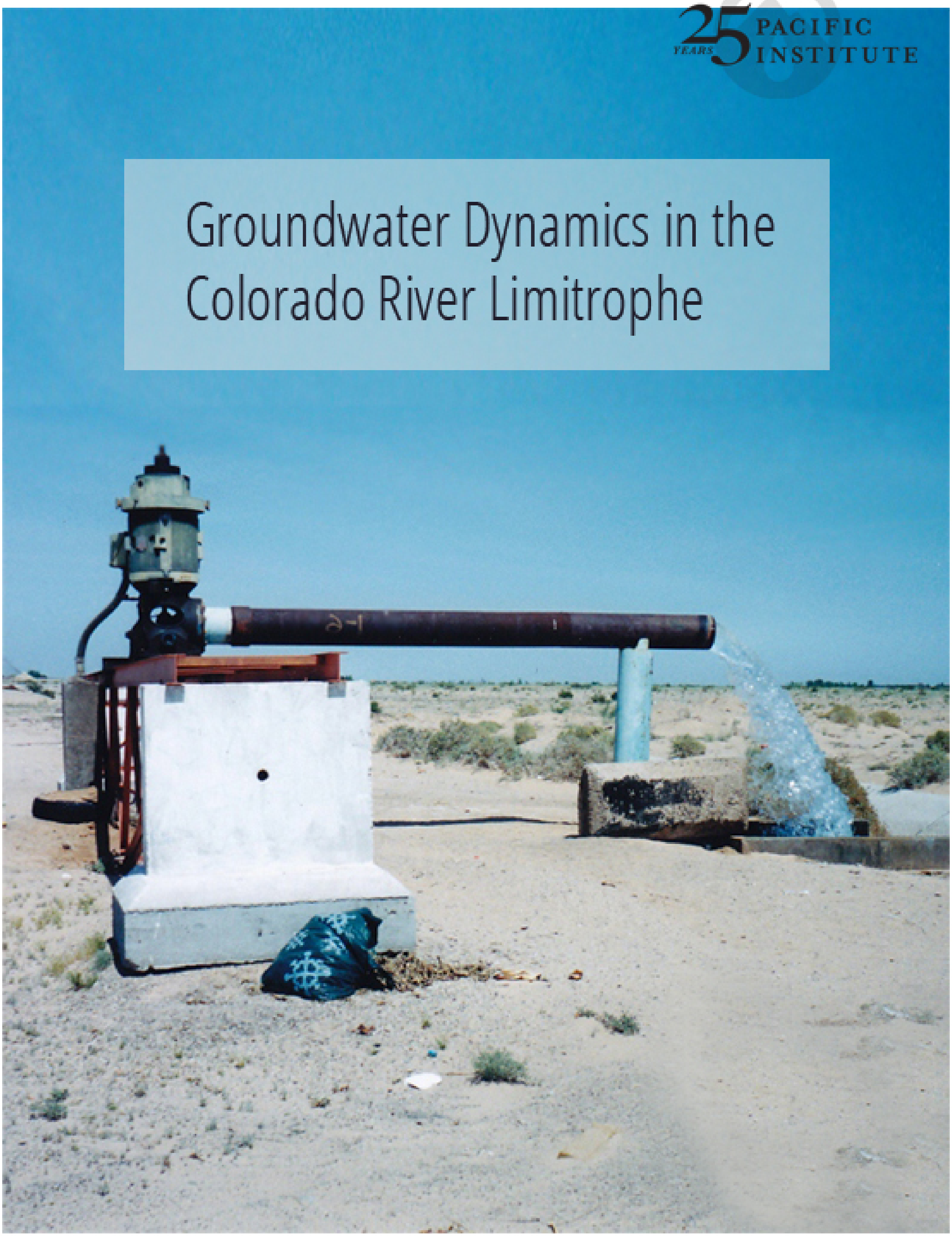

Groundwater Dynamics in the Colorado River Limitrophe

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Cover Photo by Michael Cohen, May 2001, showing a groundwater pump in Mesa Arenosa, Mexico.

About the Author

Michael Cohen is a senior research associate at the Pacific Institute and is based in Boulder, Colorado. He is the lead author of several Institute reports and the co-author of several journal articles on water and the environment in the border region.

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Executive Summary

The sediments of the Colorado River delta cover some two million square miles in the border region near Yuma, Arizona and Mexicali, Baja California (see Figure 1). Over the past century, most of this land has been converted to irrigated agriculture. The Colorado River itself, diverted and channelized and intensively managed, only rarely has enough water to flow even 20 miles past Morelos Dam, the last dam on the river, near the California/Arizona/Baja California border. The river's limitrophe reach – the roughly 22.5 mile stretch from Andrade to San Luis that separates Baja California from Arizona (see Figure 2) – is generally considered the uppermost extent of the remnant Colorado River delta, with some of the most extensive stands of native cottonwoods and willows left on the lower Colorado River and one of the few areas where the river still occasionally has enough water to exceed its banks and reach its floodplain. Because of this, there has been intense restoration interest in the limitrophe reach for more than a decade. In recent years, however, concern has grown that deteriorating groundwater conditions in the lower portion of the limitrophe will limit the success of restoration efforts.

The purpose of this study is to (1) provide a clear description of, and an explanation for, the changing groundwater conditions in and adjacent to the Colorado River's limitrophe reach, and (2) to determine, to the extent feasible, the impact of groundwater pumping on these overdraft conditions. The key question underlying this study asks how changing groundwater conditions in the limitrophe could affect the sustainability of planned habitat restoration projects. The recent decline in groundwater elevation in this final quarter of the limitrophe potentially jeopardizes these restoration efforts and prompted this investigation.

The limitrophe lies in one of the hottest and driest regions in North America. Aside from less than three inches of annual rainfall, the only surface water entering the study area comes from releases from Morelos Dam and several small wasteways that discharge water from the Yuma area irrigation system. Large levees on both sides of the river prevent any surface runoff from reaching the river and constrain the river's movements. Below the surface, groundwater flows to the west into the upper portion of the limitrophe, fed by the heavily irrigated fields in the Yuma area. Limited amounts of groundwater also enter the limitrophe as sub-surface flow beneath Morelos Dam and from leakage from Mexico's Canal Reforma, immediately to the west of the limitrophe. These sources create a relatively high water table in the upper limitrophe, sufficient to sustain perennial flows in the river channel, at least in the upper portions of the limitrophe reach.

Downstream, however, the water table declines, such that the channel of the Colorado River remains dry most of the time. Two factors appear responsible for the decline in groundwater elevations over the past decade, particularly in the final quarter of the limitrophe. The dramatic decline in surface flows below Morelos Dam since 2005 has markedly diminished groundwater recharge and elevation below Gadsden. Also contributing to this decline, and likely related to the decline in surface flows arriving at Morelos Dam, has been the increased pumping within the five-mile exclusionary zone along the Arizona-Sonora border. The magnitude of surface flows appears to be the main factor, affecting groundwater conditions in the limitrophe directly via percolation, and indirectly by prompting increased pumping – especially by Mexico – in the five-mile exclusionary zone along the Arizona-Sonora border, when annual flows arriving at Morelos Dam drop below 1.5 million acre-feet.

This study describes and assesses groundwater conditions in the limitrophe reach of the Colorado River using available data – no new measurements were made for this report. Sources include several state and federal agencies, reporting data from existing streamgages and monitoring and extraction wells. The accuracy of this reported data varies, from very high for the monitoring wells, to within 10 percent for some of the gages, to very low for the calculated streamflow below Morelos Dam and through the limitrophe. Since 2005, the last gage on the Colorado River, at the downstream end of the limitrophe, has been temporary, installed and monitored only when streamflow is expected. Existing information on groundwater movement toward the study area is more than 40 years old, from a time when conditions in the area were very different. Nonetheless, existing information permits general observations about current trends, and enables us to infer groundwater movement in broad terms.

Groundwater conditions in the study area and surrounding regions have been very dynamic for the full 57 years of observation well records. The elevation of the water table often fluctuates on a monthly basis, though the long-term trend in the study area, especially toward the downstream end, has been downward. At the downstream end, the water table fell 30.9 feet from September 1983 to October 2009. Recent groundwater conditions in the area bear little resemblance to pre-development conditions, when the Colorado River recharged the aquifer and water table elevations declined away from the river. Now, the river either gains water from the underlying aquifer, or is wholly disconnected from it.

Groundwater conditions in the study area have deteriorated over the past 57 years, with these impacts becoming increasingly pronounced in the southernmost quarter of the study area. Although monitoring well records are sporadic during some key periods (such as the early 1990s), several general trends are apparent. The water table across the study area reached its maximum elevation at four distinct times: January 1955, January 1958, September 1983, and January 1998, with a lower peak in December 1980. Over the past decade, the water table near Morelos Dam has been about

two feet lower than average elevations in the 1960s and 1970s. Closer to the downstream end of the limitrophe, water table elevations dropped about 27 feet from their elevation in 1960 to their lowest recorded elevation, in October 2009. In addition to this pronounced decline in water table elevation at the downstream end of the study area, such elevations have been much more variable than those closer to Morelos Dam. Downstream water table elevations have fallen and risen and fallen again by more than ten feet within a matter of a couple of months on a few occasions, indicating porous soils and a rapid response to external factors.

Several factors help explain these dynamic groundwater conditions. The variability can be described as a function of the difference between inflows and outflows. Sources of inflow to the aquifer include both recharge from surface waters percolating through the soil and subsurface water movement. In the case of the study area, the intensive irrigation of some 74,000 acres in Yuma County that at least partly drain toward the study area, periodic recharge through the Colorado River channel and floodplain, seepage from irrigation canals, rare instances of significant precipitation, and the movement of subsurface water from the Yuma area toward the river channel all contribute to groundwater recharge in the limitrophe reach. Some recharge may also occur due to seepage from the Canal Reforma, immediately to the west of the study area, affecting the limitrophe directly below Morelos Dam.

Outflows include groundwater pumping, extraction by plant roots, movement of groundwater out of the study area, and discharge to the surface, as springs and seeps. In the Yuma area, irrigators use groundwater pumps and ditch drains to keep the water table below the root zone, to enable better irrigation management and to avoid burning plant roots with salty groundwater. In some areas of Yuma County, groundwater is pumped for irrigation and, from deeper wells, for municipal use. In Mexico, irrigators pump groundwater to supplement surface water, and for domestic use. Within five miles of the Arizona-Sonora border, both nations operate extensive wellfields, in recent years extracting more than 200,000 acre-feet of groundwater per year, combined. Riparian and upland plants also draw from the underlying aquifer, directly affecting conditions in the study area. Pumping operations to the west and southeast of the limitrophe pull groundwater out of the study area, depressing groundwater elevations. Where the water table intersects the land surface, as occurs in the upper portion of the limitrophe reach, discharge from the alluvium generates base flows in the river channel.

Two related water budgets were developed to track the various factors described above. These budgets account for inflows and outflows to the groundwater and surface water systems, for the years 1990-2010. Disaggregating the linked but in some ways distinct surface and groundwater systems in the study area allows for closer examination of the individual terms involved. The time period was selected to

Table ES-1. Study Area Surface Flow Water Budget (KAF)

Inflows	Years	Source	Mean	Wet	Normal
Flows Below Morelos	1990-2010	calculated	370	930	24
Baseflows		*guess*	2	2	2
11 mile WW	1990-2010	gage	4	5	4
Precipitation	1990-2010	gage	1.5	2.0	1.2
21 mile WW	1990-2010	gage	1.3	1.2	1.4
SIB diversion channel	2004-2010	gage	0.4	0.1	0.5
Total	(rounded)		380	940	33
Outflows	**Years**	**Source**	**Mean**	**Wet**	**Normal**
Evap from open water/marsh		estimated	2.4	2.5	2.4
Infiltration		*guess*	*15*	*19*	*11*
Q at SIB	1990-2010	gage	370	960	15
Total	(rounded)		**390**	**980**	**29**
Residual			(10)	(40)	4

avoid the distorting impacts of the very high Colorado River flows of the mid-1980s, when millions of acre-feet flowed through the limitrophe. Tables ES 1 and 2 show the budgets for surface and groundwater in the study area, respectively, list flows (in thousands of acre-feet) as a mean value, and further break these down into “wet” and “normal” years, based on whether more or less than 1.5 million acre-feet flowed to Morelos Dam.[1] The two tables list the source for the different values.

In Table ES-2 on the next page, several items are simply guesses, given the lack of data. Groundwater movement as an inflow comes from a 40-year-old study and is likely obsolete, since it precedes the operation of the wellfields in the five-mile zone buffering the Arizona-Sonora border; the large volumes extracted by the U.S. and Mexican wells in this zone presumably have changed the direction of some groundwater movement, especially near the border. Groundwater movement as an outflow reflects the fact that, in the limitrophe below Gadsden, the water table has no connection to the surface channel and groundwater presumably flows through that area undiminished. However, in the upper three-quarters of the limitrophe there is some connection between the water table and the surface (including riparian vegetation that draws from this water table), so it is likely that this outflow is depleted, both by baseflows and by evapotranspiration. The change in storage estimated in Table ES-2 complements the groundwater movement volume.

Groundwater extraction in the five-mile buffer zone along the Arizona-Sonora border increased markedly over the past 35 years. Average U.S. annual extraction within the buffer zone in the years 1996-2002 was less than 10 percent of its average annual pumping in 2007-09; non-federal pumping within the U.S. side of the exclusionary zone increased by about 35 percent between these two periods. Mexico

[1] “Wet” years are 1993, 1995, 1997-2001, 2010; “normal” years are 1990-92, 1994, 1996, 2002-09.

Table ES-2. Study Area Groundwater Budget (KAF)					
Inflows	**Years**	**Source**	**Mean**	**Wet**	**Normal**
Subflow below dam		*guess*	*1*	*1*	*1*
Infiltration		*guess*	*15*	*19*	*11*
Seepage thru Canal Reforma		*Conagua* 2004	*10*	*12*	*18*
recharge from US irrigation within levees		calculated	*3*	*3*	*3*
recharge from Mexican irrigation within levees		calculated	*8*	*8*	*8*
GW movement	1973	Olmsted	*33*	*33*	*33*
Total			*70*	*75*	*64*
Outflows	**Years**	**Source**	**Mean**	**Wet**	**Normal**
Evap & ET	1997-2007	LCRAS	*21*	*20*	*22*
Mexico pumping within levees		calculated	*26*	*26*	*26*
US pumping within levees		calculated	*10*	*10*	*10*
Change in storage	1990-2010	estimated	*(2.8)*	*6.1*	*(8.0)*
GW movement		guess	*33*	*33*	*33*
Total			*88*	*96*	*84*
Residual			*(18)*	*(20)*	*(19)*

approached its 160,000 acre-foot annual limit in 2007 and again in 2009. The average for the years 1975-2000 was 89,000 acre-feet, increasing to 170,000 acre-feet for the years 2001-2009. For the years 2005-2009, annual reported pumping by both countries was almost 200,000 acre-feet, more than double the rate for the first 25 years of record.

Groundwater conditions and dynamics in the limitrophe reach have changed fundamentally in the past 70 years. The Colorado River used to be a net source of recharge to the local aquifer in the limitrophe. The river was closely connected to the aquifer; depth to groundwater increased with distance from the river. The river's snowmelt-driven flooding inundated the surrounding land, further recharging the aquifer and contributing baseflows during low flow periods. The diversion of essentially the entire flow of the river upstream of the study area, combined with the loss of sediments behind upstream dams and subsequent incision of the river channel below Morelos Dam, means that the river is now a drain in the upper portion of the limitrophe and is completely disconnected from the aquifer in the last quarter of the limitrophe. In the form of irrigation, the river still 'floods' adjacent lands, recharging the aquifer. In the upper portion of the limitrophe, recharge from this irrigation is sufficient to maintain elevated groundwater levels and connectivity with the river. But extensive pumping along the land boundary east of the downstream end of the limitrophe and west of the river has drawn the water table down in the last quarter of the limitrophe, rendering the Colorado River ephemeral for some 40 miles below Gadsden.

These various trends highlight the dramatic differences in surface and groundwater conditions along the roughly 22.5-mile length of the channel through the study area. The upper quarter or third of the Colorado River below Morelos Dam appears to be wet perennially, sustained by seepage and periodic releases from the dam and from the 11-mile wasteway, and, notably, by baseflows generated by a relatively high water table. In this uppermost section, the water table has been fairly stable for more than fifty years, with a few peaks caused by the notable Colorado River floods of the mid-1980s and the late 1990s. The middle portion of the study area, reaching downstream to about the Gadsden bend area, appears to have periodic or intermittent flows and a slightly lower, though still relatively stable water table. Although the surface water loses its connection with the aquifer in this portion, the water table still remains within reach of the roots of established native riparian vegetation. In the last stretch of the study area, below Gadsden, even this root-zone connectivity is lost, as the water table elevation drops precipitously. This last stretch of the study area experiences dramatic fluctuations in the aquifer, in response to increasingly infrequent surface water pulses. As reported by the last gage on the river, the channel in the last stretch of the study area has been dry for more than 90 percent of days since 2005. In Hunter's Hole, just south of Gadsden, anecdotal reports suggest that supplemental irrigation has maintained riparian vegetation, even in locations where the water table has fallen below the reach of cottonwood and willow roots, but the sparse vegetation in other areas below Gadsden indicate that the water table no longer supports riparian vegetation that depends on an accessible water table.

Two related factors explain the recent dramatic decline in the elevation of the water table below the last quarter of the study area: the significant reduction in surface water flows and an increase in the volume of water pumped by Mexico and by the United States in the five-mile zone buffering the border along the Arizona-Sonora border. This volume increased from a 1975-2000 average of about 90,000 acre-feet per year to a 2005-2009 average of almost 200,000 acre-feet per year.

This study indicates that, even after the exceptionally dry period of 2005-2009, when surface flows failed to reach the gage at the downstream end of the limitrophe on 90 percent of days, more than a third of the channel through the limitrophe still exhibited connectivity with the water table, and roughly two-thirds of the limitrophe still had a water table that remained within the reach of the roots of cottonwoods and willows. The plunging water table at the downstream end of the limitrophe suggests that the final five miles of the river within the limitrophe may not respond to efforts to restore riparian habitat, at least not without a long-term commitment to supplemental irrigation, but areas upstream appear well-insulated from the recent drawdown.

Recent trends, such as rapid population growth along the border, increased pumping in the five-mile exclusion zone, and the general lack of significant releases from Morelos Dam, suggest that the sharp drawdown in the water table seen below Gadsden is likely to continue in coming years. However, recharge from periodic, rain-driven releases from Morelos Dam and continuing recharge from groundwater flowing to the upper portions of the study area from irrigated lands in the Yuma Valley, appear to provide baseflows in the uppermost stretch of the channel and a relatively high water table through much of the study area. Given the hydrologic stresses imposed from 2005-2009, this is encouraging news. This study represents the most comprehensive evaluation to date of groundwater conditions and dynamics in the limitrophe reach below Morelos Dam. This study clearly indicates that revegetation and restoration projects in the upper two-thirds of the study area should enjoy long-term success and are worth pursuing.

Recommendations

Site-specific investigations would benefit from additional research (described below). Yet even without this new research, this study clearly indicates that revegetation and restoration projects in the upper two-thirds of the study area should enjoy long-term success and are worth pursuing.

The International Boundary and Water Commission (IBWC) has tentatively planned to conduct a new limitrophe channel survey in the near future, the first since 1999. A new survey would greatly improve understanding of recent channel dynamics, including sediment transport, and would provide a foundation for future restoration efforts. This survey should be conducted as quickly as possible, and should be coordinated with a new survey of vegetation in the limitrophe.

To provide a measurement of actual flows through the uppermost extent of the Colorado River delta, rather than calculating flows based on upstream gage records, the IBWC should install a new streamgage immediately downstream of Morelos Dam.

Additional observation wells or piezometers, especially on the U.S. side of the river, would greatly improve understanding of actual conditions relevant to restoration efforts. Currently, such information must be interpolated from monitoring well data that is intended to meet a very different need. Additional GIS analysis, plotting depths to groundwater for other dates of interest and highlighting differences between these dates, would also be illuminating.

The relationship between the calculated flows below Morelos Dam, recorded flows at the last gage on the river, and water table elevations in the limitrophe warrants further study. Such a study would be critical toward determining surface water requirements for limitrophe reach restoration efforts. The preliminary assessment described in this study suggests that, under current conditions, calculated flows below Morelos Dam in excess of 900 cubic feet per second may flow unbroken through the limitrophe, with about one day's travel time, though at other times, flows below Morelos in excess of 1000 cfs generated no reported flow at the end of the study area. This may simply reflect differences in channel conditions, or errors in the reported and calculated data.

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Abbreviations, Definitions, and Conversions

Abbreviations

AF	acre-feet
AMSL	above mean sea level
ADWR	Arizona Department of Water Resources
AZMET	Arizona Meteorological Network
BLM	Bureau of Land Management
cfs	cubic feet per second
CILA	*la Comisión Internacional de Límites y Aguas*
Conagua	*la Comisión Nacional del Agua* (formerly known as CNA), Mexico's National Water Commission
ET	evapotranspiration
ha	hectare
IBWC	International Boundary and Water Commission
km	kilometer
km^3	cubic kilometer
LCRAS	Reclamation's Lower Colorado River Accounting System
MAF	million acre-feet
MCM	million cubic meters
MGD	million gallons per day
MODE	Main Outlet Drain Extension
NIB	Northerly International Boundary, referring herein to the point where the Colorado River crosses the boundary
PNN	*Pronatura Noroeste*
PRPU	Protective and Regulatory Pumping Unit
Q	discharge (flow, generally expressed here in terms of cfs, AF/day, or AF/year)
Reclamation	Bureau of Reclamation
SIB	Southerly International Boundary, referring herein to the point where the Colorado River crosses the boundary
UABC	*Universidad Autónomo de Baja California*
USGS	United States Geological Survey
YCWUA	Yuma County Water Users Association

Definitions

channel invert	a point feature showing the elevation of the deepest portion of the channel
Colorado River Delta	the full geologic extent of the delta, encompassing ~2 million sq. miles.
limitrophe[1]	the reach of the Colorado River running from the NIB to the SIB
remnant delta	the area between the levees downstream of Morelos Dam, plus the Rio Hardy and El Indio wetlands and the Cienega de Santa Clara
study area	the ~16,000 acres of land between the levees, from Morelos Dam to the SIB
thalweg	the deepest portion of the stream; a linear feature running the length of the channel

Conversions

Length

1 foot	30.48 cm
1 foot	0.3048 m
1 mile	1.609 km

Area

1 acre	4047 m^2
1 acre	0.4047 ha
1 square mile	640 acres
1 square mile	259.0 ha
1 square mile	2.590 km^2

Volume

1 gallon	3.785 liters
1 acre-foot	435,600 ft^3
1 acre-foot	325,851 gallons
1 acre-foot	1233 m^3
1 MAF	1,233 x 10^6 m^3
1 MAF	1,233 MCM
1 MAF	1.233 km^3
1 km^3	1,000 MCM

Discharge

1 cms	35.3 cfs
1 cfs	0.0283 cms
1 cfs	1.98 acre-feet/day
1 cfs	2,447 cubic meters/day
1 cfs	724 AF/year

[1] The Oxford Dictionary defines *limitrophe* as "Situated on the frontier; bordering on, adjacent to (another country). A border land."

Chapter I - Introduction

The geologic extent of the Colorado River delta encompasses some two million square miles, including the lower Coachella Valley, the Imperial and the Mexicali valleys, and extending east past Yuma and south to the Gulf of California (Figure 1) (Sykes 1937). Aldo Leopold visited the delta in the 1920s and later wrote about its tremendous vitality, a mix of land and water exuding abundance and languor (Leopold 1949). The subsequent construction of more than twenty major dams on the Colorado River and its tributaries, the imposition of a tight set of institutional controls dictating operation of these structures, and the conversion of most of the delta's area to irrigated agriculture combined to dramatically reduce the delta's vitality and resilience. What is now often referred to as the delta is a disconnected set of drainage-fed wetlands and a narrow riparian corridor and intermittent river downstream of Morelos Dam that combined comprise less than 10 percent of the delta's geologic extent (Zamora-Arroyo et al. 2005). After more than twenty years of research and calls for rehabilitation of some portion of the delta, and twelve years after the adoption of a binational agreement to cooperate on delta restoration, several active habitat restoration efforts are underway, on both sides of the international boundary. After years of binational negotiations involving water agencies, state representatives, and environmental organizations from both countries, on November 20, 2012, the IBWC adopted Minute 319.[2] This new agreement includes a provision dedicating approximately 158,000 AF of water to portions of the riparian corridor.

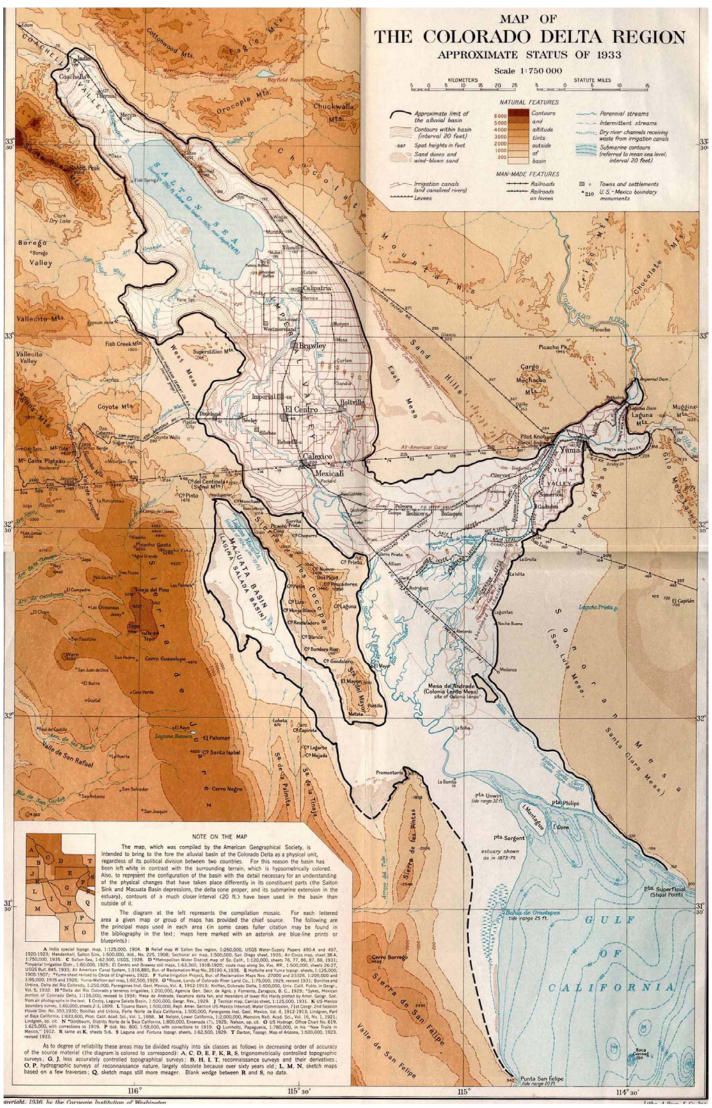

Figure 1. The Colorado River Delta. Source: Sykes (1937).

Diminished flows to the riparian corridor in the past decade threaten these achievements. These diminished flows highlight the need for better understanding of current and historic conditions so that appropriate actions can be taken to protect recent habitat restoration efforts and to ensure that such efforts will be successful over the long term.

The Colorado River's limitrophe reach, the only stretch of the river that divides Mexico from the United States, runs roughly 22.5 miles[3] from the Northerly International Boundary (NIB) near Andrade, California and Algodones, Baja California to the Southerly International Boundary (SIB) near San Luis, Arizona and San Luís Río Colorado, Sonora, as shown in Figure 2. Roughly one mile downstream from the NIB stands Morelos Dam, the last dam on the Colorado River. In most years, Morelos Dam diverts almost the entire remaining flow of the river into Mexico's Canal Reforma, for agricultural and municipal use (Dickinson et al. 2006).

However, infrequent rainstorms over lands irrigated with Colorado River water can prompt irrigators to cancel water orders or otherwise increase Colorado River flows beyond Mexico's immediate diversion needs, generating large though generally brief flows below the dam (Dickinson et al. 2006). These flows, along with large releases from upstream dams in the late 1990s, promoted the recruitment of some of the largest and densest stands of native riparian habitat found anywhere on the lower Colorado River (Zamora-Arroyo et al. 2005). Once established, this riparian vegetation relies on groundwater within range of its roots (Nagler et al. 2008).

The elevation of the water table is a key determinant of the potential success of riparian vegetation – a driving question behind this study. As described in the following, the loss of connectivity with the water table will stress and kill riparian vegetation. Determining where this loss of connectivity occurs, and the factors causing this decline in the water table, are the subjects of this study.

In recent years, particularly in the period 2005-2009, the maximum elevation of this groundwater (known as the water table elevation) has fallen, dramatically in some

[2] IBWC Minute 319 is posted on the IBWC website, at http://www.ibwc.gov/Files/Minutes/Minute_319.pdf

[3] Conventionally, the limitrophe reach is described as running 24 river miles from the NIB to the SIB (see IBWC website homepage at http://www.ibwc.state.gov/), but the actual length of the river in 2006 between these points was approximately 22.5 miles.

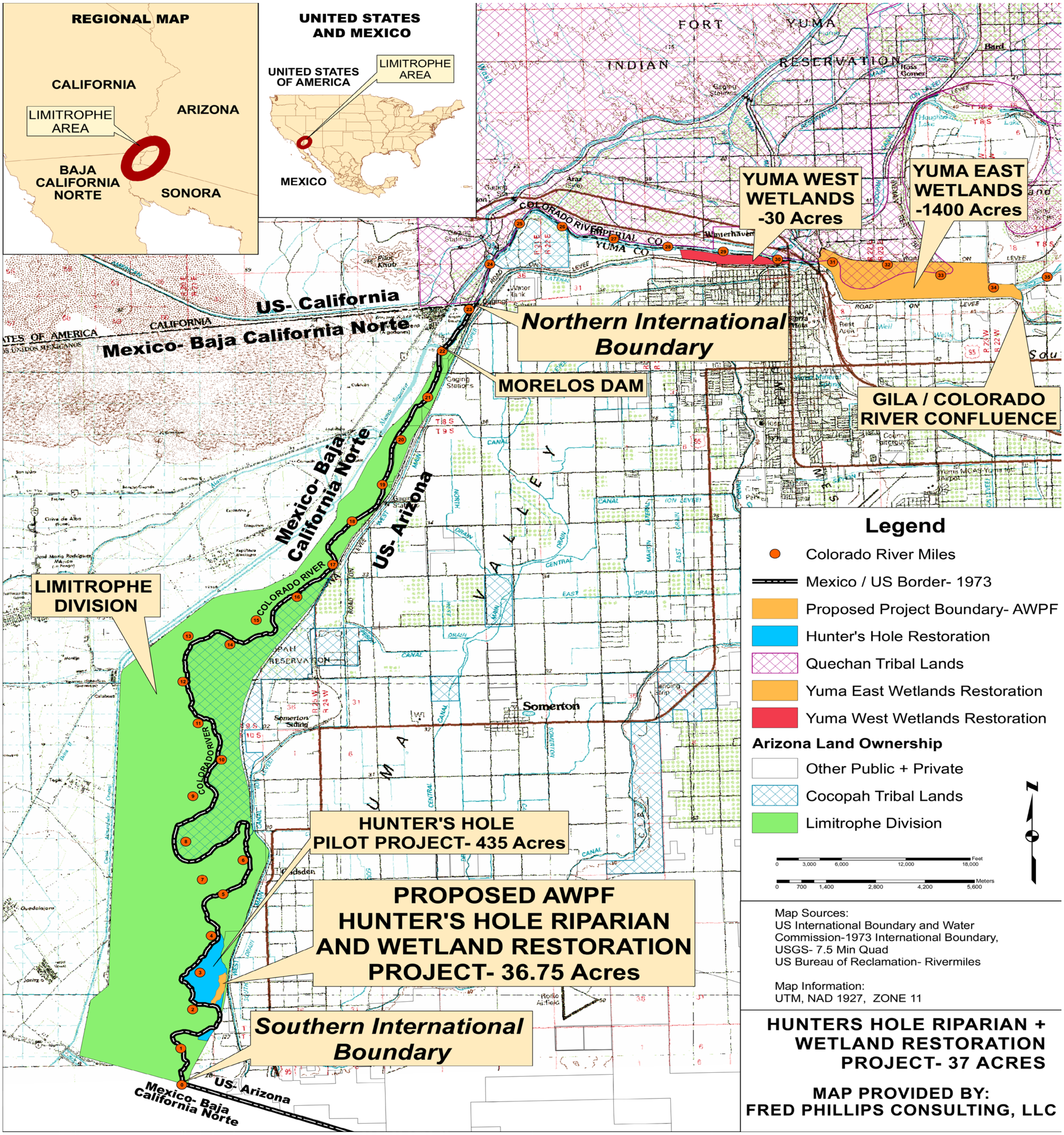

Figure 2. The Limitrophe Region.
Map courtesy of Fred Phillips Consulting, LLC. See www.fredphillipsconsulting.com.

locations, threatening the survival of the existing riparian vegetation below Morelos Dam and the success of existing and planned habitat restoration efforts in the limitrophe. Figure 3, prepared by the U.S. Bureau of Reclamation, shows the change in water table elevations between December 2004 and December 2009. Note that the water table elevation dropped less than five feet north of Gadsden, Arizona in that period, but south of Gadsden water levels show a marked decline, falling more than twenty feet near the SIB. Several areas downstream of Gadsden, on both the U.S. and Mexico sides of the border, are either undergoing habitat restoration or have been identified as potential

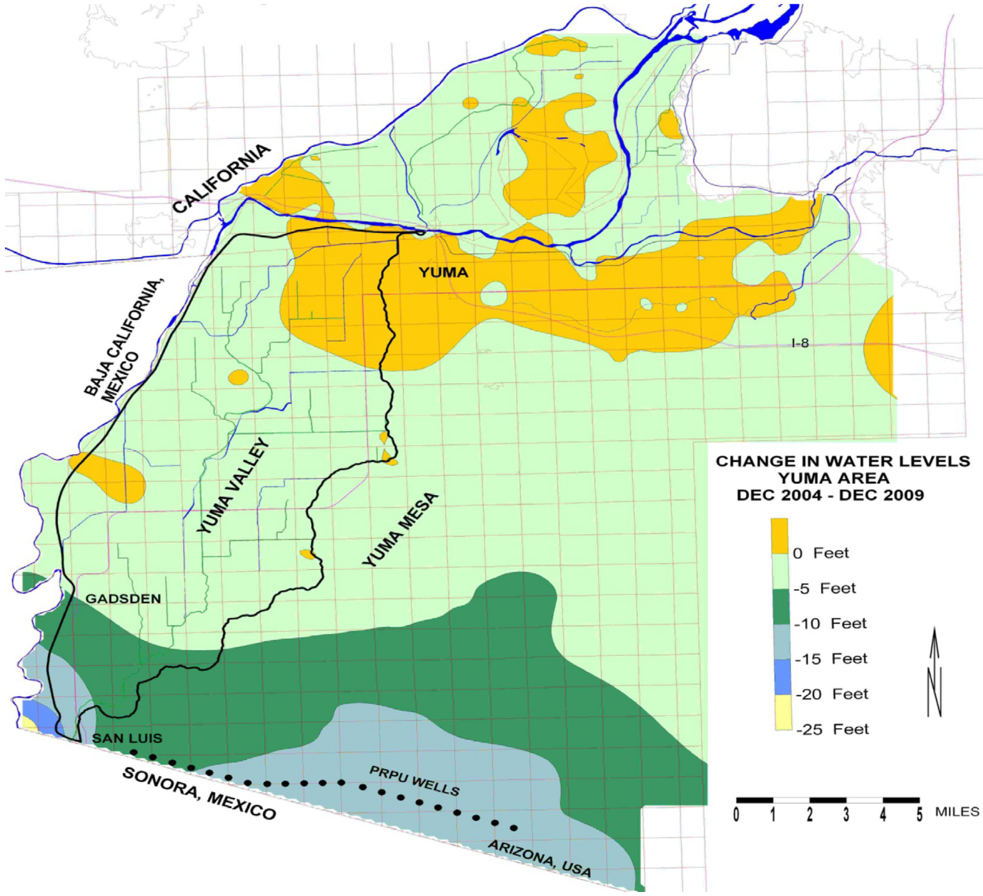

Figure 3. Change in Water Levels, December 2004 - December 2009.
Source: Reclamation.

habitat restoration sites. The recent decline in groundwater elevation in this final quarter of the limitrophe potentially jeopardizes these habitat restoration efforts and prompted the current study.

This report describes recent and historic groundwater conditions in the limitrophe reach of the Colorado River and evaluates the various factors that influence these conditions. The remainder of this chapter describes the purpose of this study and provides background on the physical environment and infrastructure that shape and affect the limitrophe. Chapter II describes the methods used in this study, including data sources and problems with some of the data. Chapter III describes historic and recent groundwater conditions in the limitrophe. Chapter IV offers a general water budget for the reach and evaluates factors affecting groundwater recharge and extraction rates and their impacts on the water table. Chapter V summarizes surface flows through the reach and their impacts on groundwater conditions. Chapter VI offers conclusions and recommendations.

Purpose of Study

The purpose of this study is to provide a clear description of and an explanation for the changing groundwater conditions in and adjacent to the limitrophe reach of the Colorado River and to determine, to the extent feasible, the impact of groundwater pumping on these overdraft conditions.

Background

Researchers have studied the remnant Colorado River delta for more than twenty years, calling attention to the delta's degradation and uncertain future while highlighting the existence of extensive brackish wetlands and some of the largest remaining stands of native cottonwood-willow forests along the lower Colorado River (cf. Ezcurra et al. 1988, Glenn et al. 1992, Glenn et al. 1996, Cohen et al. 2001, Zamora-Arroyo et al. 2001, Nagler et al. 2008). These studies challenge the widespread belief that the Colorado River delta has been irreversibly degraded (cf. Fradkin 1981). More recently, several reports and studies have identified the restoration potential of portions of the remnant delta (cf. Briggs and Cornelius 1998, Pitt et al. 2000, Zamora-Arroyo et al. 2005, Medellín et al. 2007). This research and advocacy encouraged the adoption of three agreements between Mexico and the United States to cooperate on the protection of delta habitats,[4] and on-going negotiations

[4] Minute 306, "Conceptual framework for U.S. - Mexico studies for future recommendations concerning the riparian and estuarine

regarding delivery of dedicated instream flows below Morelos Dam.

Several habitat restoration projects have been planned or are already underway in the remnant delta, including wetland restoration efforts in the Rio Hardy system, along the Colorado River mainstem roughly thirty miles downstream of the SIB, and within the limitrophe itself. Habitat restoration projects within the study area include proposals to restore Hunter's Hole, on-going native plant restoration projects on Cocopah tribal lands downstream of Morelos Dam, and proposed projects in Colonia Miguel Aleman, on the right bank of the river across from Hunter's Hole. Hunter's Hole, a roughly 110 acre vegetated former backwater two miles north of the SIB and 2½ miles south of Gadsden, receives surface water from several sources, including the 21-mile wasteway, a siphon from the Bypass Extension canal, and at least one groundwater well. Yet, as described in the following, the water table in the immediate area fell more than ten feet from 2004 to 2009, signaling that existing vegetation and future habitat restoration efforts could be at risk.

Several studies have investigated groundwater conditions in the Yuma area, to the immediate east of the study area, including Olmsted et al. (1973); Harshbarger (1977); Hill (1993);[5] Reclamation's draft "Particle Tracking Study" (undated); and Dickinson et al. (2006). USGS has published studies describing the "accounting surface" for the lower Colorado River that includes general information on groundwater elevations and sources in the Yuma area (Owen-Joyce et al. 1996, Wiele et al. 2009). However, none of these studies focused on groundwater conditions specifically in the limitrophe reach itself, and all predate the recent decline in water table elevations in the limitrophe. Pronatura Noroeste and the Instituto de Ingeniería at the Universidad Autónomo de Baja California recently completed initial studies of the alluvial aquifer within the limitrophe that have yielded important information on current trends within the riparian corridor itself (Ramírez Hernández et al. 2010, 2011).

Physical Environment

The limitrophe lies in the Colorado desert, also known as the lower Colorado River valley division of the Sonoran desert, one of the hottest and driest regions in North America. For the period of record (1987-2010) at the Yuma Valley weather station,[6] mean annual precipitation was only 2.6 inches, with a maximum of 5.90 inches in 2010 and a minimum of 0.04 inch in 2002. Annual maximum temperatures in the region exceed 105° F more than sixty days per year, while minimum temperatures average about 45° F. The average annual reference evapotranspiration rate (ETo) at the Yuma Valley station for the period of record was 85.8 inches, almost seven feet/year greater than the precipitation rate. Local precipitation rarely generates measurable run-off in the limitrophe reach directly, though it may prompt local irrigators to cancel water orders. If insufficient storage exists in the Colorado River system to capture these cancelled water orders, they continue to flow to Mexico. If Mexico does not divert these flows in excess of the delivery schedule into its own delivery system, local precipitation events can indirectly generate flows through Morelos Dam and into the limitrophe.

The limitrophe lies within a low elevation, generally flat basin consisting of local sediments and deltaic soils deposited by the Colorado River. Yuma mesa, to the east, is a former river terrace, rising 50-80 feet above the Yuma Valley (Dickinson et al. 2006). The Colorado River delta, including the limitrophe reach, fills the upper extent of the Salton Trough, a geologic extension of the Upper Gulf of California. The area is seismically active, with several faults trending northwest through the Yuma Valley and limitrophe reach (Dickinson et al. 2006).

The limitrophe contains alluvial soils with moderate to rapid permeability. The U.S. Department of Agriculture Soil Survey of the region (Barmore 1980) notes that limitrophe soils include well-drained sandy soils, sandy loams, and silt loams, characterized by very slow surface run-off due to "somewhat excessively drained soils," with permeability rates of 6.0 to 20.0 inches per hour.

The Colorado River itself starts high in the Rocky Mountains in Colorado, some 1300 miles upstream of the limitrophe reach. The computed average annual "natural flow"[7] of the Colorado River at Lees Ferry[8] for the period 1906-2008 is slightly greater than 15 million acre-feet. The computed average annual natural Colorado River flow at Imperial Dam

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ecology of the limitrophe section of the Colorado River and its associated delta," signed December 12, 2000; Minute 316, "Utilization of the Wellton-Mohawk bypass drain and necessary infrastructure in the United States for the conveyance of water by Mexico and non-governmental organizations of both countries to the Santa Clara wetland during the Yuma desalting plant pilot run," signed April 16, 2010; and Minute 317, "Conceptual framework for U.S.-Mexico discussions on Colorado River cooperative actions," signed June 17, 2010. Minutes available at http://www.ibwc.state.gov/Treaties_Minutes/Minutes.html.

[5] The Yuma area groundwater model developed by the Arizona Department of Water Resources in the early 1990s (described in Hill 1993 and Hill 1996) used hydrologic conditions from the mid-to-late 1980s, after the 1983 250-300 year flood event (Holburt 1984) on the lower Colorado River that inundated much of the delta region and markedly increased the water table elevation in the area. Additionally, the Arizona groundwater model assumed constant head conditions along the southerly international boundary dividing Arizona from Sonora. These two model parameters do not reflect current conditions.

[6] The Yuma Valley weather station (http://ag.arizona.edu/azmet/02.htm) is at the University of Arizona Yuma Agricultural Center Valley Station, 6425 W. 8th Street, Yuma (32° 42' 45" N 114° 42' 18" W).

[7] "Natural flow" refers to the river's flow absent losses due to upstream diversions and reservoir evaporation; actual recorded flows are significantly lower. U.S. Bureau of Reclamation natural flow calculations are available at http://www.usbr.gov/lc/region/g4000/NaturalFlow/index.html.

[8] Lees Ferry lies just above the boundary between the upper and lower Colorado River basins and is the traditional measuring point for Colorado River discharge. Lees Ferry lies 667 miles upstream of Morelos Dam.

– the last point for which such computations are made, 27 miles upstream of Morelos Dam – for this period is 16.3 million acre-feet, reflecting net gains from tributaries below Lees Ferry. The Gila River discharges into the Colorado River mainstem 15 miles downstream of Imperial Dam, but natural flows for the Gila River have not been calculated. Chapter V discusses limitrophe surface hydrology in detail.

As described in Chapter V, the Colorado River usually disappears before it reaches the SIB. In fact, no discharge was recorded for all of 2006, 2007, and 2009 at the SIB. On June 28, 2007, a satellite image shows water in the Colorado River channel running continuously from Morelos Dam to a point roughly eight miles upstream of the SIB. On August 31, 2003, the river terminated roughly 2.3 miles upstream of the SIB. Even during dry years, some water appears in the channel just below the SIB, fed by discharge from Mexico's KM27 wasteway. Aside from this brief occurrence of standing water, during typical conditions, the channel of the Colorado River is dry starting from near Gadsden for some 25 miles downstream, where subsurface agricultural drainage intersects the channel to generate base flow. As described in the following, a relatively high water table generates base flows in the upper portion of the limitrophe, but the falling water table to the south creates a losing reach[9] for the river that extends well into Mexico.

The construction of dams, front works and levees along the river's mainstem and tributaries and strict reservoir operating criteria have almost completely eliminated the lower Colorado River's periodic overbank flooding upstream of Morelos Dam. Such overbank flooding promoted recruitment of native riparian vegetation and linked the river to its floodplain, washing nutrients into the river and leaching salts from the land. Flooding also recharged the alluvial aquifer. River regulation and extensive physical infrastructure have largely eliminated these functions. Intensive, year-round irrigation has replaced this recharge function in some areas, including on lands adjacent to the limitrophe, though such irrigation tends to degrade water quality by introducing greater concentrations of salts, nutrients, pesticides, and other contaminants. In some areas near Yuma, years of intensive irrigation raised the level of the underlying aquifer to nuisance levels. The federal government has been pumping deep wells to control groundwater in the Yuma Valley for more than 50 years.[10] These high groundwater levels drive subsurface flows typically to the west, under the river channel, and to the south, toward large-scale pumping operations in the U.S. Protective and Regulatory Pumping Unit and Mexico's Mesa Arenosa wellfield (Freethey and Anderson 1986, Reclamation undated). See Chapter III in particular, and the rest of this study generally, for extended discussion of groundwater conditions in the limitrophe region.

Sediment

Sediment transport is an important function performed by rivers. The Colorado River historically carried a very heavy sediment load, carving the Grand, Glen, and many other canyons and creating a massive delta at the head of the Gulf of California that in places is more than a mile deep. The old adage about the river was that it was "too thick to drink, too thin to plow." The construction of multiple dams across the Colorado River has compromised this function, to the extent that the former heavy sediment loads carried by the river – indeed, the source of the Colorado's name – have now been captured by upstream dams and the river is largely clear and hungry, carrying much less sediment than its discharge would suggest. The All-American Canal desilting works further deplete the river's sediment load – only about a quarter of the volume delivered to Mexico at the NIB actually flows past Laguna Dam; the rest passes through the desilting works, or is return flows from fields downstream of Imperial Dam. Median suspended sediment concentrations for the river during the period from November 1982 through September 2008 were only 38.5 mg/L. As shown in Figure 4, during the 250-333 year Colorado River flood event in the mid-1980s, these concentrations increased by more than an order of magnitude. Sediment concentrations increased by more than two orders of magnitude during the Gila River floods in 1993, affecting channel alignment and morphology.

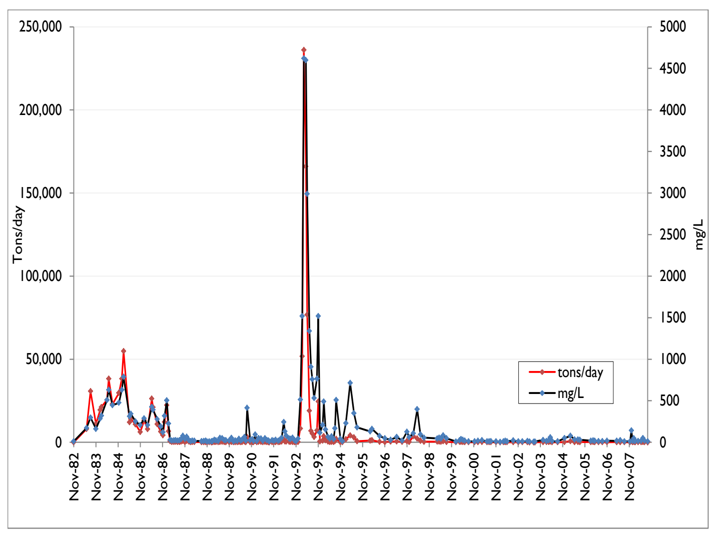

Figure 4. Colorado River Suspended Sediment Concentrations at NIB, November 1982-Sept. 2008.
Source: USGS.

Reclamation's "Colorado River Front Work and Levee System" webpage[11] gives the following description of dredging operations below Morelos Dam:

[9] For general information about gaining and losing stream reaches, see "Using Temperature to Study Stream-Ground Water Exchanges," USGS Fact Sheet 2004-3010 at http://pubs.usgs.gov/fs/2004/3010/.

[10] The Bureau of Reclamation currently holds a permit (No.30-001, Arizona Department of Water Resources, *Permit to Transport Groundwater Withdrawn from the Yuma Groundwater Basin*) for the transportation of up to 25,000 acre-feet per year of Yuma Basin groundwater.

[11] Last visited December 19, 2012.

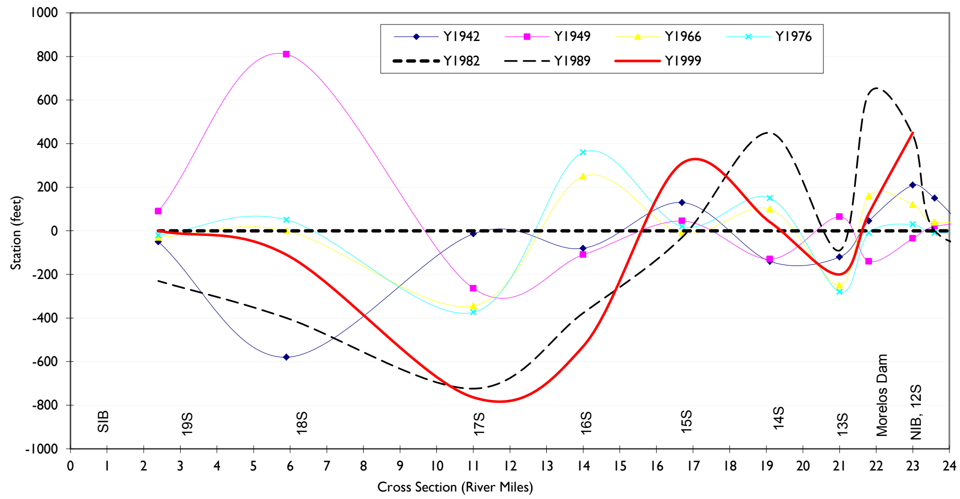

Figure 5. Lateral Channel Migration Referenced to 1982 Alignment.
Adapted from Natural Channel Design 2006.

The Colorado River at and downstream of Morelos Dam forms the boundary between the United States and Mexico. Proceeding downstream for a distance of 20 miles, the left (east) bank of the river is in the United States and the right (west) bank is in Mexico. The river has levees on both sides of the river; the levee on the Mexican side is about 4 feet higher than the levee on the United States side.

The conditions between Morelos Dam to the Southerly International Boundary were not typical of ordinary river conditions, in that no degradation existed downstream of the dam. In fact, the gated portion of the structure did not always form the water surface control that would normally be the case. A downstream plug of sediment introduced in the channel below Morelos sometimes controlled the water surface elevation through the gated structure.

This sediment plug was unintentionally created by the operation of a Mexican dredge in the settlement basin at the head of the Alamo Canal [Canal Reforma], and the method of disposal of sediment employed by Mexico at Morelos Dam. The Alamo Canal desilting basin is an over-width and over-depth section of the canal that runs generally parallel to the river. For several years following the completion of Morelos Dam, sediment was pumped out of the desilting basin onto the ground between the basin and the river [see Figure 10]. Over a period of years, the disposal area was built up by the deposition of dredge spoil until the sediment could not be pumped any higher.

The sediment was then pumped into the river and along the bank between the Mexican levee and the river. On occasion, the sediment deposit has deflected the current of the river against the bank in the United States side of the river, causing erosion. When this occurred, Mexico deposited some of the sediment spoil on the United States side to repair the erosion and return the river to the center of the channel. This type of operation has kept the river away from the United States levee, but has built up the bed of the river with a sediment plug consisting of several million cubic yards of material.

The remainder of the river channel from Morelos Dam to the Southerly International Boundary has historically been choked by sediment carried downstream from the sediment plug. Also, because Mexico customarily diverts most of its Colorado River water supply into the Alamo Canal above Morelos Dam, the flow below Morelos Dam is generally minimal, and the channel is overgrown with vegetation, seriously reducing the channel's flood-carrying capacity. Work has been conducted in the Limitrophe Division periodically to address this situation.

Channel Morphology

The Colorado River meanders between levees below Morelos Dam. The current channel alignment bears little resemblance to the 1973 location used to determine the official Mexico-U.S. boundary,[12] prompting discussions to realign the channel and improve its carrying capacity.[13] Figure 5 adapted from Natural Channel Design (2006), shows lateral channel movement relative to the 1982 alignment. Changing channel morphology affects the establishment of riparian vegetation and the distance their roots must extend to connect to the water table. The river's dynamism and changes caused by flood events since the early 1980s (Tiegs and Pohl 2005) challenge efforts to correlate depths to groundwater reported at observation wells located along the edges of the study area, with depths to groundwater within the river's riparian corridor itself.

A report conducted as part of IBWC's river rectification efforts (TetraTech 2004) provides data from a 1999 survey of thalweg[14] elevations and notes that channel elevations

[12] For a historic image showing the former channel alignment overlain with a more recent (undated) channel alignment, see http://www.ibwc.state.gov/Files/ColoradoRNIB_SIB_.pdf.
[13] See IBWC's *Lower Colorado River Boundary and Capacity Preservation Project*, posted at http://www.ibwc.state.gov/EMD/lcrbcppposit2.pdf
[14] The thalweg is a linear feature denoting the deepest portion of a river channel.

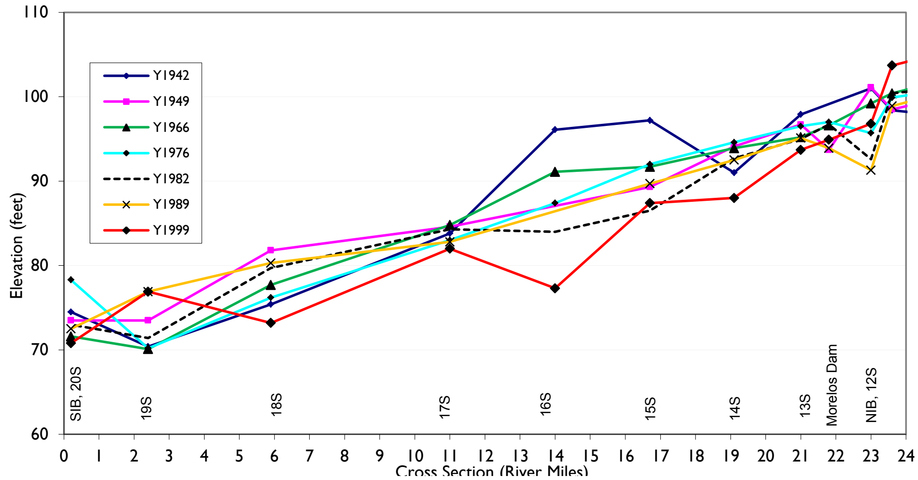

Figure 6. Changes in Thalweg Elevation, 1942-1999.
Adapted from Natural Channel Design 2006.

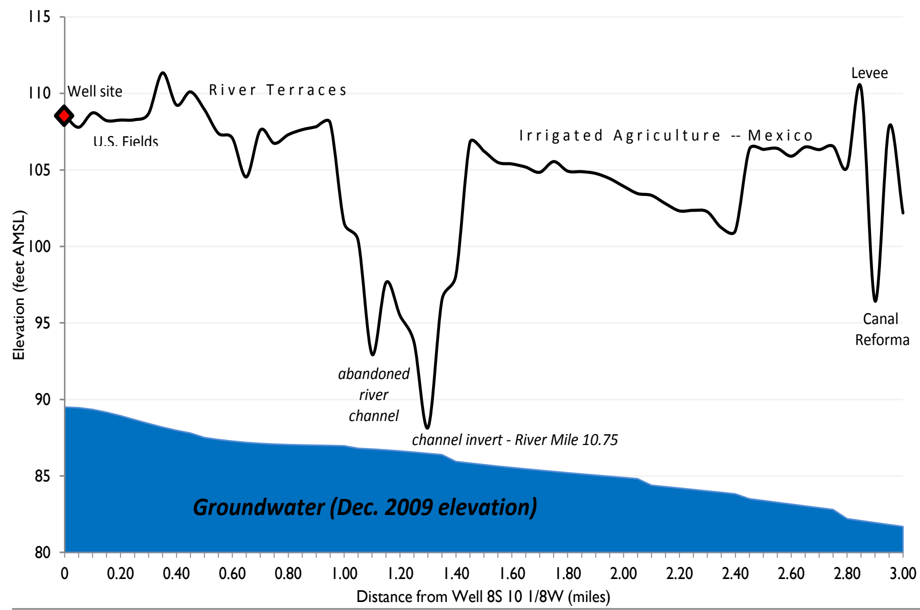

Figure 7. Surface Elevation Profile at River Mile 10.75.
Source: USGS.[15]

have increased near the SIB, reflecting aggradation due to low flows and insufficient energy to move sediments downstream. These dynamic conditions complicate efforts to assess long-term trends in depths to groundwater within the riparian corridor itself. Figure 6 on the next page, adapted from Natural Channel Design (2006), plots thalweg elevations from channel surveys performed over more than fifty years. Unfortunately, the most recent channel survey was made in 1999. Note the channel erosion between the 1989 and 1999 surveys, perhaps as a result of the 1993 or 1998 high flow events.

On the following page, Figure 7 shows the elevation profile of a three-mile transect running west southwest (consistent with the reported direction of groundwater flow in the region (Dickinson et al. 2006)), perpendicular to the river at river mile 10.75, originating at Reclamation monitoring well 8S 10 1/8W.[16] The figure displays the difference between the elevation of the monitoring well and the channel, demonstrating that reported depths to groundwater at the well site are not a reasonable substitute for depths to groundwater for vegetation along the river channel. The figure also shows the interpolated surface elevation of the water table in December 2009, one of the lowest elevations on record. As described in the following section on Vegetation, the depth to groundwater for vegetation along the river channel and the abandoned river channel in this area approaches the limits of native riparian vegetation.

Note that the ground surface elevation of the monitoring well is similar to that of the higher terraces on the river's

[15] From transect heading 240° from well 8S-10 1/8W. Data from the USGS "Imperial County, California, and Yuma County, Arizona, along the Mexico Border, 2007, 1/9-Arc Second National Elevation Dataset."

[16] Monitoring well 8S 10 1/8W is located at 32° 36' 40.30", 114° 47' 20.89".

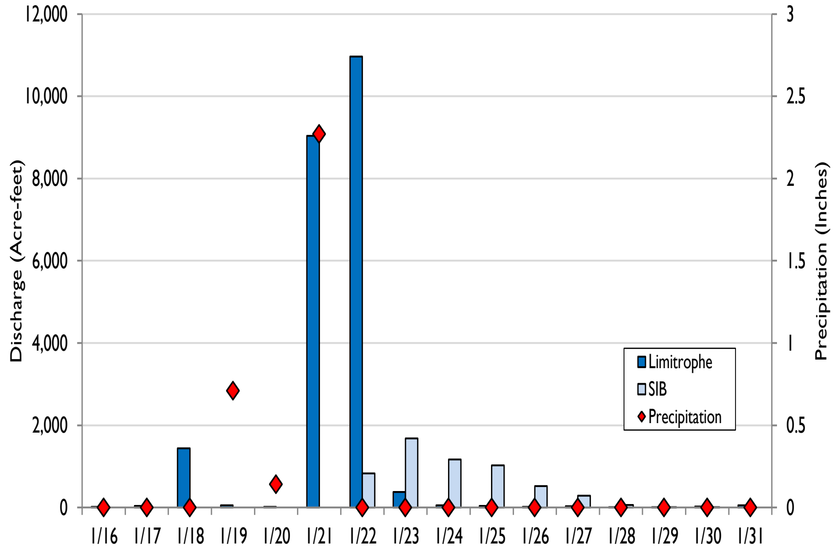

Figure 8. Precipitation and Flow in the Limitrophe, January, 2010.
Sources: IBWC, AZMET.

left bank, but roughly 20 feet higher than the channel invert[17] and roughly 15 feet higher than that of the abandoned river channel. Therefore, reported depth to groundwater at the monitoring well should not be used as a surrogate for depth to groundwater within the riparian corridor itself, since the ground surface for the vegetation in this instance could be 15-20 feet lower than the location of the well. That is, the water table could support riparian vegetation in this area even if reported depths to groundwater at the monitoring well were 20-25 feet.

As discussed in detail in Chapter V, since 2005 the last gage on the Colorado River, at the SIB, has reported no measurable flow at all for more than 90 percent of days. On those infrequent occasions when measurable flow has been recorded at the SIB, there appears to be a one-to-two day travel time between the time water flows past Morelos Dam and when it reaches the SIB. For example, in the seven-day period starting April 4, 2010 (the date of the Easter earthquake that destroyed and damaged some of the water delivery infrastructure in the Mexicali Valley), more than 14,600 acre-feet flowed through the limitrophe, with a maximum daily discharge of more than 2,100 cubic feet per second (cfs). The best fit to recorded flows at the SIB is with a two-day lag, when roughly 62 percent of calculated flows in the limitrophe arrived at the SIB ($r^2 = 0.81$).

In another example, almost 40 percent of total precipitation in 2010 fell on January 21st; a total of 3.12 inches fell in the three days ending January 21st. No flow was recorded at the SIB on the 21st, but 833 AF passed the SIB on the 22nd, and twice that volume passed the SIB the following day. However, reported flow at the SIB does not represent hydrologic conditions in the limitrophe as a whole. Although no gages exist to measure flow between Morelos Dam and the SIB, my calculations indicate that, from January 21st through January 22nd, almost 20,000 acre-feet flowed below Morelos Dam into the upper reaches of the limitrophe. Figure 8 depicts the influence of the mid-January storm event on flows through the limitrophe. The figure also highlights both the lag between releases from Morelos Dam and flows at the SIB, some 21 miles downstream, and the loss of some 16,000 acre-feet to the channel between the dam and SIB over the last half of January, 2010.

Vegetation

In the remnant Colorado River delta, saltcedar (*Tamarix ramosissima*), native to central Eurasia, has largely displaced native riparian species such as cottonwood (*Populus fremontii*) and Goodding willow (*Salix gooddingii*), except in the northern half of the limitrophe. In a June 2002 survey of the limitrophe, cottonwoods and willows covered 205 acres, while shrubs and forbs, such as saltcedar (*Tamarix ramosissima*) and arrowweed (*Pluchea sericea*) covered 2645 acres (Nagler et al. 2008). Cottonwoods and willows comprised 18 percent of the riparian vegetation in the northern half of the limitrophe, replaced by saltcedar (predominantly) and forbs downstream. The transition from woodland species in the upper portion of the limitrophe to the shrub species of the lower limitrophe reduces canopy height and structural heterogeneity, decreasing the diversity and vertical extent of habitat in the riparian corridor (Lite and Stromberg 2005).

Established riparian vegetation typically draws from the alluvial aquifer, affecting groundwater conditions (Nagler et al. 2008). Snyder and Williams (2000) found that willows relied exclusively on groundwater, while cottonwoods adjacent to ephemeral streams relied on water in unsaturated upper

[17] The channel invert is a point feature showing the elevation of the deepest portion of the channel.

soil layers for up to a third of their water use. Previous studies have investigated optimal and threshold depths to groundwater for cottonwoods, willows, and saltcedar (Mahoney and Rood 1998, Shafroth et al. 2000, Stromberg 2001, Amlin and Rood 2002, Lite and Stromberg 2005, Scott et al. 2008). Researchers note that such depths are site-specific, as various factors, notably soil type, climate, water quality, and factors such as grazing and fire, can affect these values.

At the San Pedro River in southern Arizona, cottonwoods and willows dominated saltcedar where the water table was less than 8.5 feet below the surface and the river ran more than 76 percent of the time (Lite and Stromberg 2005). Willows were less tolerant of greater depths to groundwater and to fluctuations in groundwater elevation than were cottonwoods. Saltcedar exhibited the greatest tolerance of low and fluctuating water tables and infrequent surface flows (Lite and Stromberg 2005). Other studies have found low abundance of cottonwoods and willows where depths to groundwater exceeded 11.5 feet, and no survivorship when depth to groundwater exceeded 16.7 feet (Lite and Stromberg 2005). Saltcedar, on the other hand, tolerates depths to groundwater of twenty feet or more (Nagler et al. 2005). Shafroth et al. (2000) note that fluctuating water tables can stress cottonwoods and willows; a deeper, more stable water table can support greater numbers of these trees than a more shallow, but highly variable water table. Amlin and Rood (2002) found that a gradual decline in the water table, of 1-2 cm per day, promoted root growth, though more rapid declines reduced survival. In a study in western Montana, Harner and Stanford (2003) found that cottonwoods grew more rapidly in river reaches where the water table generated baseflows than in losing reaches, where the river stage was above the water table.

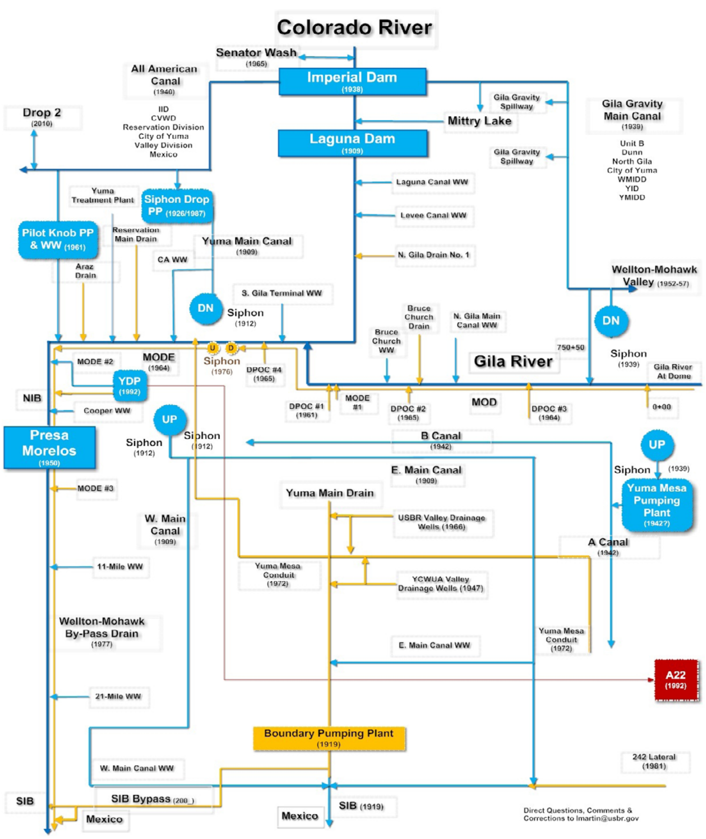

Figure 9. Yuma Area Infrastructure.
Source: Reclamation.

In addition, threshold depths to groundwater vary over cottonwood and willow life cycles. Mahoney and Rood (1998) found that:

> Cottonwood roots grow about 0.5 to 1 cm per day or 60 to 100 cm in the first year....A capillary fringe exists above the water table and is often 30 to 40 cm in elevation, but can range from about 5 to 130 cm depending on substrate texture. The combination of root growth and capillary fringe define the successful recruitment band, which is usually from about 0.6 to 2 m in elevation above the [water table].... The rate of stream stage decline is also critical for seedling survival and should not exceed 2.5 cm per day.

Water quality also affects plant vigor and resilience: saltcedar tolerates greater salinity than cottonwoods and willows (Glenn et al. 1998).

Aggravating the stresses caused by low and fluctuating water tables, Nagler et al. (2005) note that cottonwoods and willows in the limitrophe suffered from 20 percent annual attrition rates, largely from fire. These high attrition rates, combined with less favorable groundwater conditions below Gadsden, help explain the very low numbers of cottonwoods and willows in the lower half of the limitrophe.

Built Environment

The built environment, in contrast to the natural environment, refers to human-made structures and infrastructure. The Colorado River can now only be understood in the context of this built environment, which constrains the river's natural flows and meanders and has completely altered the groundwater system in the region, from one recharged by periodic flooding of the river to one recharged by intensive irrigation and managed by an extensive network of drainage wells. Figure 9 is a schematic prepared by Reclamation, showing surface water delivery infrastructure (in blue) and drainage infrastructure (in gold) for the Yuma area, from Imperial Dam to SIB. The following sections describe infrastructure within the study area itself.

Morelos Dam (Figure 10), the last major structure on the Colorado River, lies 1.1 miles downstream of the NIB and marks the upstream boundary of the remnant delta. The dam, a reinforced concrete structure spanning 1,400 feet, contains 20 radial gates across the Colorado River. Morelos Dam, completed in 1950, has no storage capacity. It typically diverts almost the entire remaining surface flow of the Colorado River into Mexico's Canal Reforma via an intake structure with 12 radial gates, with a design capacity of 8,000 cfs. The dam's structure and underlying steel sheet piling extend approximately 22 feet below the channel surface,

Figure 10. Morelos Dam and the Upper Limitrophe.
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at least partially obstructing Colorado River subflow from passing below the dam into the reach downstream. Total volumes and rates of such subflow are not known. Mexico operates Morelos Dam, under IBWC supervision.[18]

In Figure 10 on the following page, the U.S. side of the border, including part of the Main Outlet Drain Extension (MODE) Bypass Extension, appears on the left side of the image; Mexico's Canal Reforma appears in the upper right of the image. A large mound of dredge spoils appears between Canal Reforma and the river's narrow riparian corridor.

Figure 11. Unsanctioned Diversion from Limitrophe Reach.
Photograph by author, 2001.

Multiple gages record Colorado River flows and volumes of water discharged to the river at various locations in the study area. The IBWC reports the volume of water diverted at Morelos Dam into Mexico's Canal Reforma, surface discharge measured by gages on the mainstem of the Colorado River at the NIB and at the SIB, as well as at the Cooper Wasteway above Morelos Dam, and at three wasteways below the dam: Wellton-Mohawk MODE #3, 11 Mile, and 21 Mile.[19] Near the 21-mile Wasteway, a siphon periodically diverts small volumes of water from the brackish MODE Bypass Extension into Hunter's Hole. On an emergency basis, Wellton-Mohawk drainage can be discharged to the river immediately below the dam, via the MODE #3 wasteway. The 11-mile wasteway discharges water from the Yuma Project, Valley Division's West Main Canal into the river 3.2 miles downstream of Morelos Dam. The 21-mile wasteway also discharges water from the Yuma Project, Valley Division's West Main Canal, into Hunter's Hole, 17.4 miles downstream of Morelos Dam and 2.2 miles upstream of the SIB. Combined, these three wasteways contributed an annual average of 6,287 AF and median annual discharge of 4,436 AF to the limitrophe below Morelos Dam during the period 1990-2008. These volumes constitute 1.5 percent of annual average flow at the SIB, but 11 percent of median annual flow at the SIB. In Mexico, the KM27 and the KM38 wasteways discharge into the Colorado River downstream of the SIB.

The levees bounding the limitrophe reach effectively prevent any other surface run-off from entering the limitrophe. There are no legally sanctioned diversions in the limitrophe reach below Morelos Dam, though the author has observed

[18] International Boundary and Water Commission, www.ibwc.state.gov/Water_Data/Colorado/Index.html.

[19] These and other IBWC data are available at www.ibwc.state.gov/Water_Data/histflo2.htm..

Figure 12. Mexican Well 737, near Colonia Reforma.
Photograph by the author.

temporary operations extracting water from the river in the upper third of the limitrophe, on the river's right bank (Figure 11). Volumes of water so diverted have not been ascertained.

At least ten wells pump groundwater from within 0.5 mile of the levee on the U.S. side of the limitrophe, while records from Mexico's *Comisíon Nacional del Agua* (*Conagua*) indicate that 42 wells are located between the levees, on the Mexican side of the river.[20] In recent years, Reclamation has estimated annual pumping from the U.S. wells supplying water for irrigation of lands within the levees at 6.0 AF/acre, yielding a total of about 10,000 AF of such groundwater extraction annually, though these are simply estimates based on acreage, rather than measured volumes. Roughly half of the total U.S. irrigated acreage, and presumably a similar percentage of total groundwater extraction, lies in the study area south of Gadsden. Total annual volumes reportedly extracted by the Mexican wells within the levees averaged about 13,000 AF in the mid-1990s, but assuming that 7,500 acres of such land receives the state average of 3.5 AF/acre (Medellín et al 2007) suggests that total groundwater extraction on the Mexican side of the limitrophe is closer to 26,000 AF. Total annual water use (including surface water) in the Mexican portion of the limitrophe reportedly averages 30,000 acre-feet annually (Hinojosa-Huerta 2007). Figure 12 shows Mexican Well 737, near Colonia Reforma. Estimates of total annual groundwater extraction in the Mexicali Valley, to the west and southwest of the limitrophe, and in the Mesa Arenosa, to the southeast of the limitrophe, run from 550,000 acre-feet during high-flow years[21] to more than 730,000 acre-feet during normal-flow years, when the diminished availability of surface water leads irrigators to extract more groundwater (Cohen and Henges-Jeck 2001).

The city of San Luis Río Colorado, just southeast of the southern end of the limitrophe, is the largest municipal groundwater extractor affecting the limitrophe. In 2005, the city delivered more than 24,400 acre-feet, primarily (89 percent) for residential use. Some of this water comes from Mexico's Mesa Arenosa wellfield, though much is extracted from wells within city limits. Much of Mexico's infrastructure reportedly suffers from high (>30 percent) conveyance losses, suggesting that total groundwater extraction by the city may have exceeded 35,000 acre-feet in 2005.

Monitoring Wells

Since 1954, the U.S. Section of the IBWC has monitored a series of 40 wells, running roughly parallel to the Colorado River from Laguna Dam to the SIB. Over time, many of these wells have been replaced and in some instances have been moved as much as 0.5 mile, though the IBWC designation for the well has not changed. In 1986, Reclamation installed a series of shallow observation wells along the MODE and the bypass extension that runs along the eastern edge of the limitrophe. Since 2002, Reclamation has recorded groundwater elevations at these wells on a roughly monthly basis (with some significant gaps). Prior to 2002, there are extensive gaps in the record. Many of these monitoring wells have been replaced over time (J. Nickell, pers. comm.,

[20] See following section on "Data Sources and Limitations" for a discussion of the uncertainty regarding locations of some of the Mexican wells..

[21] I define high-flow years as those in which total annual flow at the NIB exceeds 1,500,000 acre-feet (see Cohen and Henges-Jeck 2001).

April 2010). The Arizona Department of Water Resources maintains an inventory of extractive and monitoring wells in the region,[22] though these records are not complete. The U.S. Geological Survey (USGS) also maintains extensive records of groundwater elevations in the U.S., including four active groundwater observation wells in Yuma County. However, much of the extensive USGS database for the region includes wells with only one data point. *Conagua* maintains an inventory of federal and private wells throughout its Irrigation District 014, encompassing both the Mexicali and San Luís valleys. *Conagua* compiles information on both groundwater extraction by well and annual measurements of static groundwater levels, obtained after a 72-hour shut-off of all federal wells.

Land Use

The lands surrounding the limitrophe are largely in irrigated agriculture, on both sides of the border. Table 1 shows land use classifications and approximate areal extents within the levees, from Morelos Dam to the SIB.

Table 1. Land Uses Below Morelos Dam, between the Levees, June 2002.

	Acres
Agriculture	10,100
Mexico	*8,400*
U.S.	*1,700*
Riparian vegetation	2,850
Shrubs	*2,650*
Native trees	*200*
Bare soil	2,500
Marsh	370
Other (roads, etc)	250
Open water	30
Dead trees	30
TOTAL (rounded)	**16,100**

Sources: Nagler et al. 2008, Hinojosa-Huerta et al. 2007, Natural Channel Design 2006, GIS measurement of U.S. agricultural acreage.

According to Reclamation's Lower Colorado River Accounting System (LCRAS) (2008), major crops planted on U.S. lands near the limitrophe include cotton, cruciferous vegetables, Sudan grass hay, small grains, lettuce, and melons. A large amount of alfalfa is also planted on West Cocopah lands, but LCRAS does not report whether these are on parcels within the levees. In Mexico, lands within the levees are often planted in onions and wheat, though actual acreages were not obtained.

Population

Table 2 shows populations of communities close to the limitrophe. Note the significant growth rates of the U.S. communities nearest the limitrophe. San Luis, San Luis Río Colorado, and Somerton all rely on groundwater, affecting groundwater dynamics in the limitrophe reach. There are also several small villages to the west of the river within the levees, though total populations of these communities is less than 1000 individuals. Growth in San Luis Río Colorado has been at four percent annually (Medellín et al. 2007), while the U.S. City of San Luis, immediately adjacent to the SIB, has grown at a rate of about five percent annually. The City of Somerton, several miles east of Gadsden, has grown even more rapidly, though its total population is still less than a tenth that of San Luis Río Colorado.

Table 2. Populations of Communities In and Near the Limitrophe.

	1990	2000	2010	Growth
San Luis Río Colorado	110,530	145,006	178,380	61%
City of Yuma	54,923	77,515	93,064	69%
City of San Luis	4,212	15,322	25,505	170%
City of Somerton	5,282	7,266	14,287	506%
Gadsden	?	953	678	--

Sources: U.S. Census, INEGI[23]

[22] See https://gisweb.azwater.gov/waterresourcedata/GWSI.aspx.

[23] *Instituto Nacional de Estadística y Geografía*.

Chapter II - Methods

This study describes and assesses recent groundwater conditions in the limitrophe reach of the Colorado River using available and calculated surface flow and groundwater extraction and evapotranspiration data. No new measurements were made for this study. This chapter describes the study area boundaries, sources and limitations of the data, and the methods used to determine depths to groundwater at various locations within the limitrophe.

Study Area Boundaries

This study investigates groundwater conditions in the limitrophe reach of the Colorado River from Morelos Dam to the SIB, comprising some 21.4 river miles[24] and roughly 16 linear miles. Levees constrain this reach of the river; the distance between the levees increases from about 0.5 mile at Morelos Dam to some 2.8 miles apart near the SIB. The limitrophe reach of the river technically extends an additional 1.1 miles farther upstream, running from the NIB to the SIB. In this report, the "study area" refers specifically to the portion of the limitrophe between the levees, from Morelos Dam to the SIB (see Figure 2). "Delta" refers to the full, geologic extent of the Colorado River delta, shown in Figure 1. The river's "remnant delta" refers to the area between the levees downstream of Morelos Dam, plus the Rio Hardy and El Indio wetlands and the Cienega de Santa Clara (Zamora-Arroyo et al. 2005).

Colorado River basin hydrology directly impacts surface and groundwater conditions in the study area. Groundwater in the study area tends to flow to the west, from the Yuma Mesa and Yuma Valley under the river channel and toward the many groundwater pumps on Mexico's side of the river (Dickinson et al. 2006). Groundwater also flows south toward the Arizona/Sonora boundary, to the U.S. Minute 242 wellfield and Mexico's Mesa Arenosa wellfield. Irrigation and groundwater extraction practices in both countries directly affect these groundwater conditions. Additionally, the extent of vegetation in the study area itself drives losses to evapotranspiration (ET), from water drawn predominantly from the underlying aquifer.

Data Sources and Limitations

Data for this study came from several sources, including the U.S. Bureau of Reclamation (Reclamation); the U.S. section of the International Boundary and Water Commission (IBWC); the U.S. Geological Survey (USGS); the Arizona Department of Water Resources (ADWR); la *Comisión Nacional del Agua* (*Conagua*); and individual cities and irrigation districts within the U.S. and Mexico. Since 2007, *Pronatura Noroeste* (PNN) has collaborated with the *Instituto de Ingeniería* at the *Universidad Autónomo de Baja Califórnia* (UABC), surveying a groundwater-monitoring network along the Mexican side of the limitrophe, near the river channel itself. Please refer to "data sources" in the References section for a complete listing. Mexico and the United States both monitor groundwater conditions near the limitrophe, through independent monitoring and/or groundwater pumping wells (see Chapter I).

Mexico typically measures "static" groundwater conditions in Irrigation District 014 by requiring that all federal groundwater pumps cease operation for a period of 72 hours, known as the "September shut-off" (the actual date varies year-to-year), allowing the water table to equilibrate and measuring depth to groundwater at each of the wells. In the U.S., separate monitoring wells measure dynamic conditions and so are affected by variable pumping rates by groundwater wells in the area.

Surface Water

The IBWC reports surface discharge data for several points in the limitrophe reach, including the NIB, the SIB, four wasteways and a diversion channel on the river's left bank, and diversions at Morelos Dam.[25] IBWC generously provided unpublished data through December 2010 to supplement the information posted online. These data are posted as average daily discharge (in cubic meters per second) and have been converted to acre-feet[26] and aggregated as monthly and annual totals. Frequently, reported Colorado River discharge at the SIB (IBWC gage 09-5222.00) is used as a proxy for flows to the remnant Colorado River delta (cf. Pataki et al. 2005, Medellín et al. 2007, Nagler et al. 2008). However, the SIB data incompletely reflect flows through the limitrophe itself. As discussed in Chapter V, water may flow downstream of Morelos Dam, supplemented by wasteway discharges, for some portion of the reach before being absorbed by the channel or consumed by evapotranspiration but not be recorded at the SIB. That is, the upper portion of the limitrophe may enjoy instream flows even when the channel at the SIB is dry.

To supplement the incomplete hydrologic information the SIB gage data represent, I calculated flows in the limitrophe reach as the sum[27] of reported:

[24] Downstream of Morelos Dam, the river largely escapes the channelization and rectification projects that have fixed it in the landscape upstream. Although IBWC proposed a rectification and channelization project in 2003 for the limitrophe, and *Conagua* dredged a pilot channel downstream of SIB, in the limitrophe the river currently meanders between the levees. This meandering and dynamism means that all river mile designations in this report (and elsewhere) are approximate. River mile designations in this report are based on November 2006 conditions.

[25] Data are posted at http://www.ibwc.state.gov/Water_Data/histflo2.htm.

[26] An acre-foot is the conventional unit of measurement for water in the U.S. portion of the Colorado River basin.

[27] Note that this calculation does not include reported discharge from the 21-Mile Wasteway, because the volumes of these releases typically are insufficient to generate a connection to the mainstem; I assume that flows from the 21-Mile Wasteway are consumed by emergent vegetation

Colorado River discharge at the NIB (IBWC gage 09-5220.00)

Cooper Wasteway discharge (09-5318.50)

Wellton-Mohawk MODE Outlet #3 discharge (09-5319.00)

11 Mile Wasteway discharge (09-5325.00)

minus reported diversions at

Morelos Dam (09-5220.30 "Intake Canal at Morelos Diversion Structure")

Note that these calculated flows in the limitrophe reach average less than three percent of gaged flow at the NIB and at the Morelos Dam Intake Canal. This relatively small value falls well within the error rating of these gaged flows, so confidence in the accuracy of the calculated flow in the limitrophe reach is very low. Unfortunately, in the absence of an actual gage immediately below the dam, the confidence in the accuracy of this fundamental factor in determining groundwater recharge rates in the study area is also very low.

Calculated daily flows immediately below Morelos Dam (= NIB + Cooper WW – Intake Canal) include some negative values, indicating an error in reported values for one of the gaging stations, or may be attributable to the slight difference in the timing of measurements between flows at the NIB and diversions at the dam, 1.1 miles downstream. For the period 1980-2010, roughly five percent of daily calculated values immediately below the dam were negative, though 30 percent of such values were negative in 2009 and in 2010. Negative values typically were less than 10 acre-feet, though the largest negative value in the period 1980-2010 was -591 acre-feet. I adjusted all such negative values to zero, but did not correct for any likely but unknown errors that exaggerated calculated flows immediately below Morelos Dam.[28]

This study distinguishes surface water and groundwater, though the two are closely connected in the upper two-thirds of the limitrophe reach. Portions of the Colorado River flow below the channel surface, re-emerging as the water table intersects the land surface. No information could be obtained on the volume of water that flows beneath Morelos Dam as subflow. Much of the water table measured by monitoring wells and piezometers is subsurface drainage from fields in the Yuma area irrigated with Colorado River water; some of this subsurface drainage flows toward the river channel in the limitrophe reach, as discussed in Chapter V.

Groundwater

Reclamation's monitoring well data provide the majority of information on water table elevations and depths to groundwater for the study, supplemented by additional data from the UABC/PNN piezometers in Mexico and limited annual data on static water elevations from *Conagua*. The Reclamation database includes information on well location, field and well-top elevation, tape read, depth to groundwater, and calculated elevation of the water table, as well as remarks (such as well relocations). The piezometer data include well location and depth to groundwater, but not absolute water table elevations. The *Conagua* databases include information on well locations, volumes extracted by month, and annual static water table elevations.

Depth to groundwater is a key factor affecting species composition in the limitrophe reach. Depth to groundwater is also an important criterion for determining the suitability of certain areas for native vegetation restoration efforts. However, depth to groundwater is a relative measure, dependent on both ground surface and water table elevations. Depth to groundwater measurements at Reclamation's monitoring wells, which are typically located along the Bypass Extension canal and are often fifteen feet or more above the elevation of the riparian corridor, must be adjusted to reflect depths to groundwater in the riparian corridor.

A GIS analysis, using information from the USGS 2007 National Elevation Dataset,[29] interpolated the reported December 2009 elevation of the water table from Reclamation monitoring wells and December 2009 piezometer data from UABC/PNN to generate depths to groundwater for the riparian corridor itself.[30] The GIS analysis sampled elevation data every 0.05 mile along a three-mile transect originating at each well and extending west-southwest, consistent with published reports of the direction of groundwater flow, to generate land surface profiles. Interpretation of satellite images then determined the point(s) representing the

and infiltrate into the local aquifer, where they are extracted by local riparian vegetation.

[28] Unlike the IBWC, CILA reports daily values for flows below Morelos Dam, calculated as NIB + Cooper wasteway – diversions at Morelos Dam, in m^3/sec (cms) (data courtesy of O. Hinojosa-Huerta). However, while CILA adjusts all such calculated negative values to zero, it also rounds calculated values of less than 3.4 acre-feet/day to zero. Minimum daily diversions at Morelos Dam are some three orders of magnitude greater than this threshold value, which is well within the reported gaging error at the intake canal. Morelos Dam's gates are not completely watertight; unquantified volumes of Colorado River water do leak through the dam's water control structures, and an additional unmeasured volume of water may seep beneath the dam itself. To approximate these unmeasured volumes, this study only adjusts calculated negative values for flows below Morelos Dam to zero, but does not round small positive values down to zero.

[29] Data from the USGS "Imperial County, California, and Yuma County, Arizona, along the Mexico Border, 2007, 1/9-Arc Second National Elevation Dataset."

[30] Elevation for each well assigned from NED data via Point Intersect function. Groundwater Table elevation for each well calculated by subtracting the Distance to Groundwater Table from Well Elevation. Interpolated an elevation layer of the groundwater table using Inverse Distance Weighted (IDW). The final Depth to Groundwater was calculated by subtracting the groundwater table elevation layer from the NED elevation layer.

elevation of the riparian corridor and associated depth to groundwater for this point. These interpretations offer a more nuanced understanding of depths to groundwater at potential habitat restoration sites in the limitrophe reach than do the raw data from the monitoring wells themselves, but these adjusted data are simply approximations of depths to groundwater at these sites. Due to study limitations, the GIS analysis only plots well data for December 2009, the final month used to develop Figure 3.

Vegetation

Based on previous studies, this study assumes that depths to groundwater of less than 8.5 feet were optimal for cottonwoods and willows in the limitrophe's riparian corridor, with stress presumably occurring at depths greater than 10 feet and mortality when depths exceed 16 feet (Lite and Stromberg 2005). These depths were calculated using the elevation data noted above, for areas identified as part of the riparian corridor, rather than at the sites of the monitoring wells.

Published evapotranspiration (ET) rates for limitrophe vegetation vary dramatically. Nagler et al. (2009) calculated saltcedar ET at 3.7 feet per year at the Cibola National Wildlife Refuge, on the lower Colorado River. Calculated ET rates for cottonwoods are almost indistinguishable at 3.9 feet per year (Nagler et al. 2007), though others (Schaeffer et al. 2000) reported cottonwood ET rates to be half those of saltcedar ET rates. Leenhouts et al. (2006) report cottonwood water use at perennial reaches in the San Pedro River basin – a cooler site than the study area – at about 3.2 feet per year, and about half that rate at intermittent reaches. Dickinson et al. (2006) list crop coefficients and average annual ET rates for several vegetation classes found in the limitrophe, including high-density saltcedar (5.2 feet) and cottonwood (5.1 feet). LCRAS annual reports include detailed tables listing monthly and annual ET rates for various crop and riparian vegetation groups. These values vary annually based on reported AZMET temperature and precipitation, but generally are consistent with Dickinson et al. (2006).

This study compares LCRAS-reported riparian evapotranspiration (for the U.S. side of the limitrophe, for "West Cocopah" and for "State of Arizona-Limitrophe Section") with calculated evapotranspiration from limitrophe vegetation as the product of published ET rates for cottonwood (3.9 feet per year) and saltcedar (3.7 feet per year) (Nagler et al. 2009) and vegetation extents (Natural Channel Design 2006, Reclamation 2007, BLM 2008, Nagler et al. 2008). These values are lower than those reported by Dickinson et al. (2006) and so may underestimate total ET. Nagler et al. (2008) is the only vegetation survey (for the year 2002) that includes estimated vegetation extents within the Mexican portion of the limitrophe; the other surveys (for the years 1986, 1997, 2004, and 2005) only include vegetation acreages for the U.S. portion of the limitrophe, limiting the ability to identify trends for the limitrophe as a whole.

Data Limitations and Error

The reliability and accuracy of the data used in this study vary.[31] Surface flow data for the study area come from daily discharge records reported by the Colorado River at the SIB gage (IBWC gage 09-5222.00)[32] and from calculated flows below Morelos Dam. Both sources are problematic. Because of problems with vandalism and theft, since 2005 the SIB gage has been installed only when IBWC staff believe there will be flows to measure.

This process of installation and removal likely affects calibration and data accuracy (see Appendix B). This also means that the Colorado River gage at the NIB (IBWC gage 09-5220.00) is the last permanent gage on the river. As noted previously, calculated flow immediately below Morelos Dam was negative in roughly five percent of the days in the period 1980-2010.

Groundwater Data Errors

Groundwater data throughout the region include many gaps, sometimes lasting many years. *Conagua* reports static groundwater conditions, measured on an annual basis after all wells have ceased operations for 72 hours, while U.S. observation wells report dynamic groundwater levels, often on a monthly basis. Groundwater pumping data for wells near the limitrophe are especially problematic: much of it is self-reported and likely undercounts the amount of water pumped (Reclamation 1996). Volumes extracted by electric wells are often difficult to track, relying on "pumping factors" or other constants that may not reflect variable operating conditions. For some diesel pumps near the SIB, Reclamation simply estimates volumes based on acreage. This uncertainty stems at least partly from a rule proposed by Reclamation that water extracted from all areas of Yuma Valley south of the NIB is Arizona groundwater and therefore is not subject to Colorado River accounting requirements.[33]

[31] See Gleick (1993) on the inaccuracies and unreliability of measured and derived data.

[32] Gage 09-5222.00 ("Colorado River at SIB") is operated and monitored by staff from the U.S. Section of the IBWC. Officially, per a document posted on the IBWC website at www.ibwc.gov/crp/documents/IBWCgages.xls, the gage operates at a location on the right bank of the river (in Mexico) about 305 meters upstream from the Southerly International Boundary, 3.2 kilometers west of San Luis, Arizona, at 32°29'39"N, 114°48'49"W, north of the highway bridge. However, according to local IBWC staff and confirmed by direct observation (O. Hinojosa-Huerta, pers. comm. 2011), the gage pad actually lies south of the highway bridge, at 32°29'28.92"N, 114°48'47.40"W.

[33] According to staff at Reclamation's Yuma Area Office, "The administrative rule regarding non-contract use of Colorado River water, which includes the accounting surface methodology, is not yet approved. If and when the rule goes into effect, the groundwater in essentially all of Yuma Valley south of the NIB will be considered Arizona groundwater and not Colorado River water. The water table elevation with respect to an accounting surface will have nothing to do with this determination.

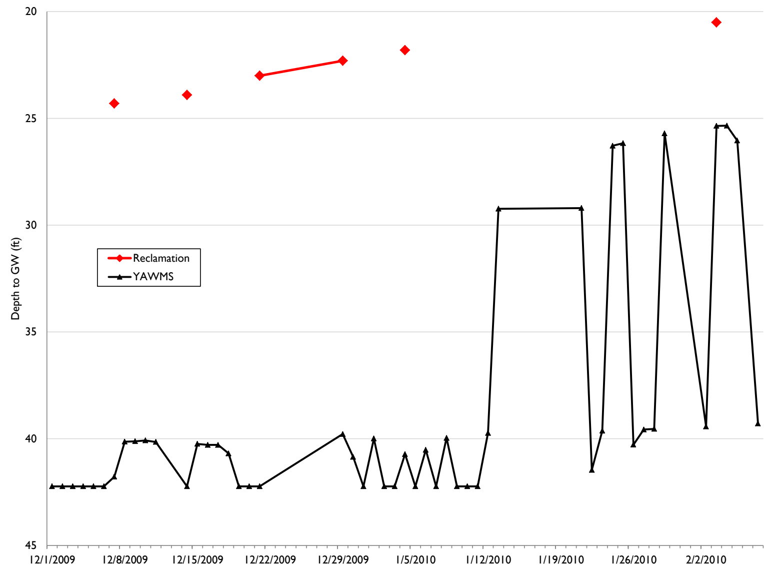

Figure 13. Official Reclamation versus YAWMS Online Reported Depth to Groundwater for Well "13 3/4S-10 3/4W," near Hunter's Hole, December 1, 2009 – Feb. 7, 2010.

Through calendar year 2003, Reclamation's annual Decree Accounting Reports[34] list monthly groundwater extraction volumes for wells on the Cocopah Reservation, north of Gadsden. However, information on volumes "pumped from wells, West Cocopah" is not included in Reclamation's Decree Accounting Reports after 2003. These Cocopah wells presumably affect water table elevations in the area, as would be reflected by monitoring wells such as 8S-10 1/8W. Unfortunately, these monitoring wells report no observations from February 1990 until July 1997, and no observations from April 1998 until July 2003, precluding comparison of pumping rates from the West Cocopah wells and the water table elevation at the nearby monitoring well. In the 1970s, reported pumping from all Cocopah wells was less than 50 acre-feet annually. This incompatibility of data sets hinders efforts to assess the impacts of localized groundwater extraction on local groundwater conditions.

Data for an irrigation well known as "(C-11-25) 3DAC" approximately 1.0 mile northeast of the SIB[35] demonstrate the limitations and uncertainty surrounding reported extractions for pumps in the study area. In 2004, a diesel pump was installed near the former electric pump. Through 2003, Reclamation calculated groundwater extraction for this well from monthly power records and power-discharge measurements. For the diesel well, Reclamation estimated annual use by assuming a flat rate of 6.0 or 6.25 acre-feet of applied water per acre, over 300 acres of land. According to Reclamation's annual accounting reports, water extraction increased from a calculated 323 acre-feet in 2003 (by the electric pump) to a calculated 1875 acre-feet in 2004 (by the diesel pump). For the period 1998-2003, the pump's calculated extraction averaged 328 AF/y. Interestingly, for the period 1991-1997, the pump's calculated use averaged 1865 AF/y, similar to the estimated post-2003 use (the pump is not listed in the 1989 or 1990 accounting reports). This study uses Reclamation's reported volumes of groundwater extraction, even though they are estimates rather than measured volumes.

Some posted information on groundwater conditions has been misleading. The "Yuma Area Water Management System" (YAWMS) previously provided updates of real-time monitoring of 97 groundwater pumping wells and 57 observation wells near the limitrophe.[36] Figure 13 shows depth to groundwater for Well 13 3/4S-10 3/4W, an observation well near the upper end of Hunter's Hole, as reported by YAWMS and also as provided by Reclamation staff. The YAWMS site provided data on a nearly daily basis for this well; the Reclamation data are less frequent, roughly on a weekly basis from December through the first week of January, 2010. Note that the official Reclamation data for the site runs about fifteen feet higher than the YAWMS data, *for the same location*. The YAWMS data also showed fluctuations of fourteen feet, on a daily basis in some instances. The YAWMS website[37] itself cautions:

Though the rule is not yet approved, I believe that water accounting in Yuma Valley is being performed as if the relevant provisions of the rule were in place."

[34] *Compilation of Records in Accordance with Article V of the Decree of the Supreme Court of the United States in Arizona vs. California dated March 9, 1964 (Decree Accounting Reports)*, available at http://www.usbr.gov/lc/region/g4000/wtracct.html.

[35] This well, listed as "Hughes, Earl" in Reclamation's annual Decree accounting reports (available at http://www.usbr.gov/lc/region/g4000/wtracct.html) for the years 1991-2001 and "Earl Hughs" [*sic?*] for the years 2002-2009, is described (2002) as being located at 32°29'55.8"N 114°48'25.6"W.

[36] Prior to March, 2011, this information was posted at http://www.usbr.gov/lc/yuma/programs/YAWMS/index.html.

[37] Visited December 19, 2012.

> 13 3/4S-10 3/4W is one of many "observation" wells operated by the Bureau of Reclamation in the Colorado River Valley. The purpose of these wells is to monitor groundwater levels. **We are experiencing technical difficulties with some of our instrumentation which is giving incomplete or inaccurate readings. During this time, we will no longer display any readings on this web site. We apologize for this inconvenience as we actively work to resolve these issues.** *[emphasis in original]*

Reclamation staff further noted "Any data on the website is preliminary and isn't suited for use in analyses" (J. Scott pers. comm. 2010). YAWMS data only appears in Figure 13; it is not used elsewhere in this report.

These discrepancies highlight the broader challenge posed by data inconsistencies and data gaps. Several wells in the region have data reported by the Arizona Department of Water Resources, USGS, and the Bureau of Reclamation, often at different frequencies and occasionally with different observations for the same well on the same day. Some of the monitoring wells report no readings for as much as 7.5 years; other wells were damaged, destroyed, or relocated, creating data gaps. Other challenges include obvious data transcription errors, such as exist within a *Conagua* database listing coordinates for wells within Mexico's Irrigation District 014 (encompassing the Mexicali and San Luís valleys). These coordinates place eight of the wells (of 815 total wells listed) east of the Colorado River in Arizona, one in Mississippi, and one in the Atlantic Ocean near Bermuda. While these errors are obvious, less clear is the accuracy of the reported depths to groundwater and pumping volumes in some of the datasets.[38]

Streamgage Errors

As shown in the following, the volume and duration of Colorado River flows below Morelos Dam greatly affect groundwater conditions in the limitrophe. Stream gages provide discharge data, though these data contain some degree of error, as described in the following. Three key challenges related to streamgage data emerged in this study: 1) calculated flows below Morelos Dam typically are three orders of magnitude lower than reported flows at NIB, well within reported gage error, diminishing confidence in their accuracy; 2) the absence of a streamflow gage between NIB and SIB challenges efforts to determine actual flows downstream of the dam and the volume of water absorbed by the channel; and 3) discharge reported by the gage at SIB appears to underreport flows.

Figure 14 on the next page displays calculated daily discharge (in cubic feet per second (cfs)) below Morelos Dam[39] for the four years in which no flow was recorded at SIB. Note that in the year 1996, maximum calculated flow below Morelos Dam was less than 20 cfs. In 2005, due to security concerns, IBWC began to install the SIB gage only when it anticipated flows at the site, so in the years 2006, 2007, and 2009, the gage may not have been in place to record the much larger discharge seen in those years. Note that the y-axis is shortened, to display the daily variability in calculated discharge below the dam, truncating the much higher discharge seen in recent years. These peak discharge values are labeled on the graph. Note that 2006 experienced two events in which daily discharge below the dam exceeded 500 cfs, and 2009 saw two peak flows in excess of 1000 cfs below the dam, but no flow was recorded at SIB. Calculated records of discharge below Morelos Dam from December 12-25, 2009 indicate that 7,240 acre-feet flowed in the Colorado River over the course of those 14 days, yet no flow was recorded at the SIB. This suggests that the gage was not in place to record these high flow events.

An interesting comparison can be made between calculated discharge in the four years shown in Figure 14 and in the years 1990 and 1991. These two years had similar peak daily discharges – of 1347 and 1096 cfs – but in the 1990s those peak discharges were followed, with a one-to-two day lag, by (much smaller) flows recorded at the SIB. Although this study did not conduct a rigorous analysis of the relationship between calculated flows below Morelos Dam and reported flows at SIB, a cursory appraisal suggests that the SIB gage data likely under-report actual SIB discharge in the years in which the gage has been a temporary feature, perhaps as a result of a failure to install the gage in every instance in which flows do occur at SIB. This likely under-reporting represents a critical data error, causing calculations of flows absorbed by the channel and lost to evapotranspiration between Morelos Dam and SIB to be larger than they are in reality.

Further complicating the challenge of potential under-reporting at SIB is the inaccuracy of the gages themselves. Table 3 shows the limitations associated with streamflow data for this reach of the river.

Table 3. Accuracy of Select Streamflow Gaging Station Records.

Station Name	Gage	Error
NIB	09522000	~10%
Intake at Morelos Dam	09522030	~15% - ~10%
SIB	09522200	>15%

Source: Hill (1993).

[38] Reclamation notes, "While some data deficiencies do exist, they are well recognized by Reclamation and Reclamation works hard to assure and check the quality of its data and make corrections and improve its methods where needed."

[39] Discharge below Morelos Dam calculated as flows at NIB + Cooper WW + MODE #3 WW +11 Mile WW, minus diversions at Morelos Dam.

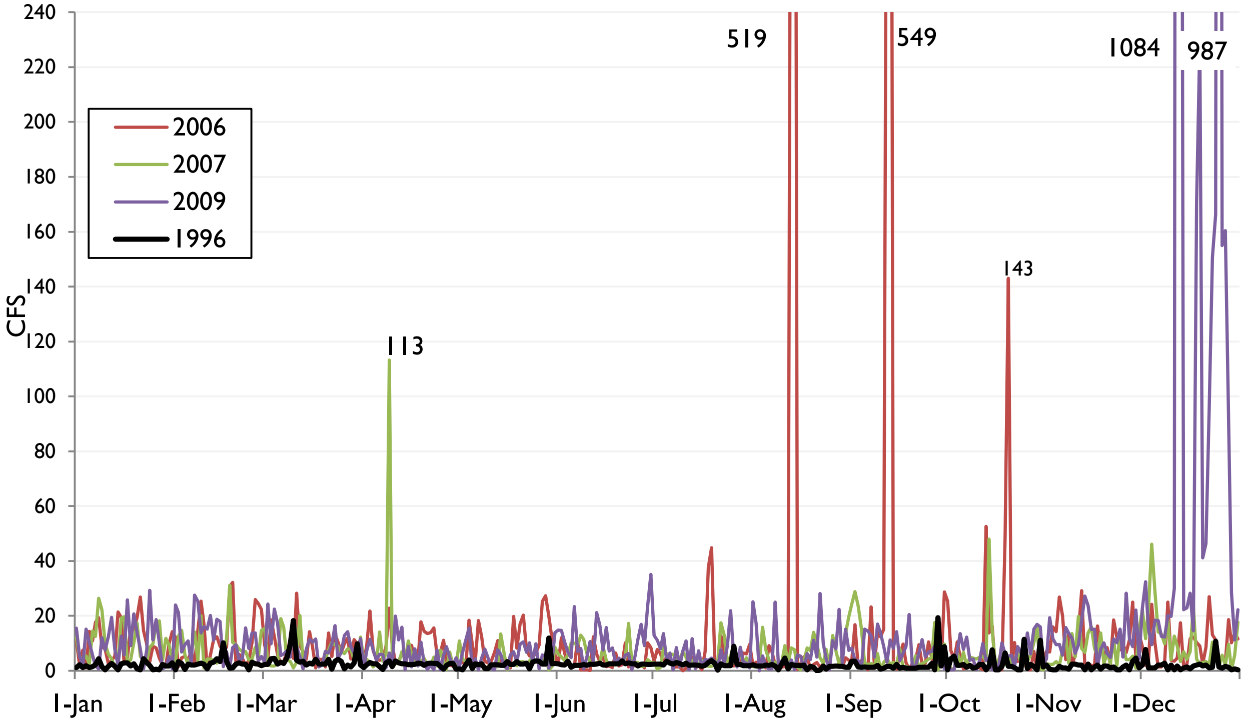

Figure 14. Mean Daily Discharge (cfs) below Morelos Dam in Years with No Reported Discharge at SIB.
Source: IBWC.

Note that the errors listed in Table 3 propagate through subsequent calculations. In particular, calculated flows below Morelos Dam are distorted by the reported error at both the NIB gage and at the Intake at Morelos Dam, as well as by unreported errors from the much smaller flows from the wasteways. The total error in the calculated flow below Morelos Dam, at the upper extent of the limitrophe, can be expressed by the equation[40]:

$$S_x = \sqrt{(S_{NIB}{}^2 + S_{Cooper}{}^2 + S_{Intake}{}^2 + S_{11\text{-mile}}{}^2)}$$

Where S_x = the uncertainty (error) in the calculated flow below Morelos Dam and S_{NIB} = the reported error at the given streamgage. Assuming an error of ten percent for the two wasteways yields a total error for the calculated flow below Morelos Dam of almost 23 percent. From this same equation, the calculated losses below Morelos Dam (eg; flow below Morelos Dam minus reported flow at the SIB) would have an error of at least 27 percent.

Typically, studies use regression analyses to help determine the relationship between the dependent variable – the elevation of the water table at a particular location – and one or more independent variables, such as monthly or annual pumping rates, instream flows, or losses to the channel below Morelos Dam. Some of the data, notably reported water table elevations at the Reclamation monitoring wells, enjoys a high degree of accuracy (W. Greer, pers. comm. 2010). As noted above, data for other key variables, such as pumping rates and daily streamflow volumes, suffer from higher error. Standard regression models assume that the independent variables are without error. The complex regression models (cf. Fuller 1987) needed to account for streamflow gage and groundwater extraction measurement errors are well beyond the scope of this study, so only very limited regression analysis was performed to determine the correlations between the variables discussed in this study.

[40] Source: "Error Analysis," at http://science.widener.edu/svb/stats/error.html.

Chapter III - Groundwater Conditions

Groundwater conditions in the study area and surrounding regions have been very dynamic, over both the long-term record and in recent years. The elevation of the water table fluctuates on a monthly basis, though the long-term trend in the study area, especially toward the SIB, has been downward. Both sides of the border experience large-scale groundwater extraction, both for irrigation and, especially in the Yuma area, for irrigation drainage. Groundwater conditions in the area bear little resemblance to pre-development conditions, when the Colorado River was the predominant source of recharge and water table elevations declined away from the river. Now, the river either gains water from the underlying aquifer, or is wholly disconnected from it. Although Colorado River water still recharges the aquifer beneath the river's floodplain, that water is now conveyed via canals delivering water diverted from the river many miles upstream. This chapter describes historic and recent groundwater conditions in the study area.

Mexico and the United States both monitor groundwater conditions near the limitrophe, through independent monitoring and/or groundwater pumping wells (see Chapter I). Mexico typically measures "static" groundwater conditions in the Mexicali and San Luís valleys (known collectively as Irrigation District 014) by requiring that all federal groundwater pumps cease operation for a period of 72 hours, known as the "September shut-off" (the actual date varies year-to-year), allowing the water table to equilibrate, and measuring depth to groundwater at each of the wells. In the U.S., separate monitoring wells measure dynamic conditions, and so are affected by variable pumping rates by groundwater wells in the area. Since 2007, *Pronatura Noroeste* has collaborated with the *Instituto de Ingeniería*, at the *Universidad Autónomo de Baja Califórnia*, surveying a groundwater-monitoring network along the Mexican side of the limitrophe, near the river channel itself. These three data sources provide the basis for the following overview of recent groundwater conditions in the study area.

Historic Groundwater Conditions

As shown in Figure 15, groundwater conditions in the study area were very different 70 years ago, shortly after the construction of Hoover Dam but prior to the construction of Imperial and Morelos dams. Yuma's population in 1940 was 5,325. However, the Yuma County Water Users Association, irrigating some 45,000 acres of farmland in the Colorado River floodplain east of the study area, formed back in 1903,

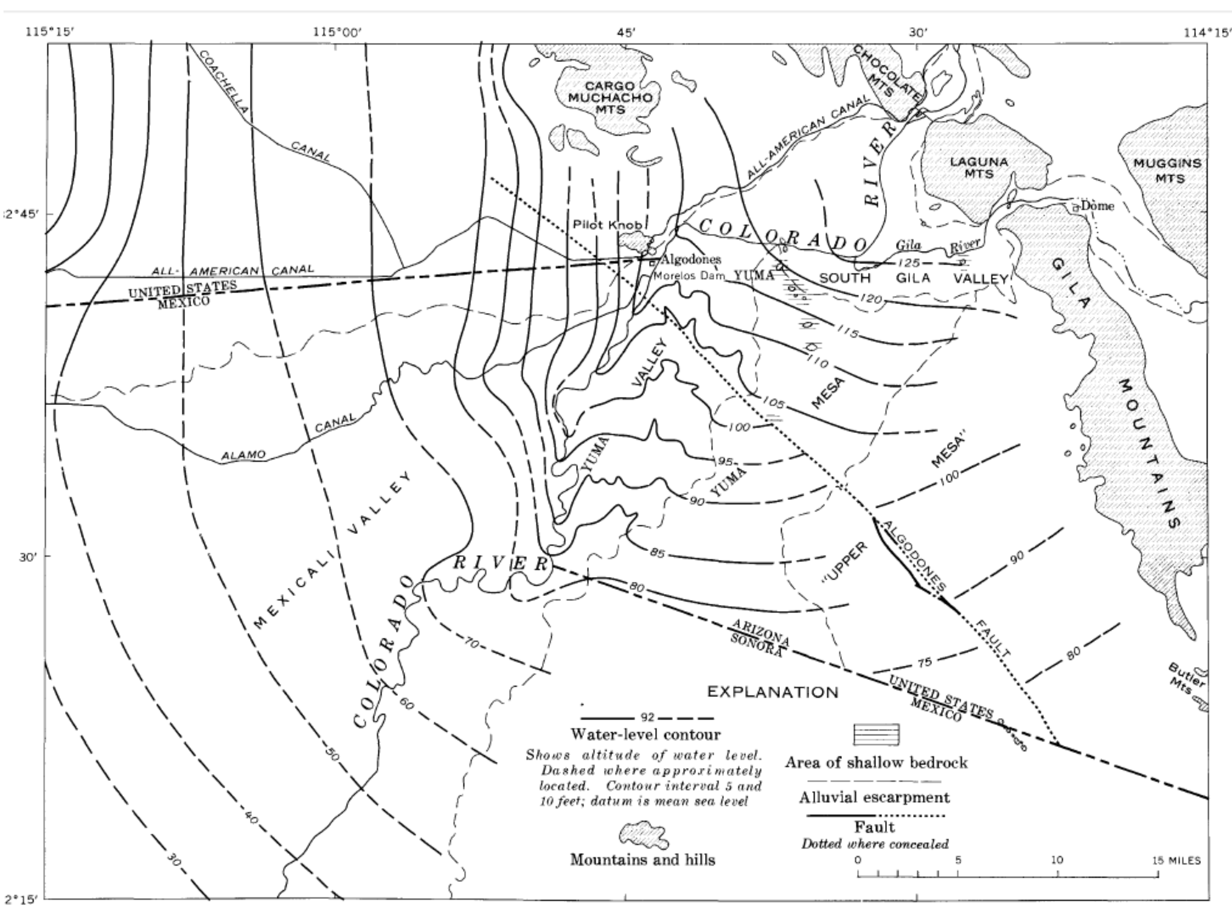

Figure 15. Average Water Level Contours, 1939. Source: Olmsted 1973, Figure 28, p. H86.

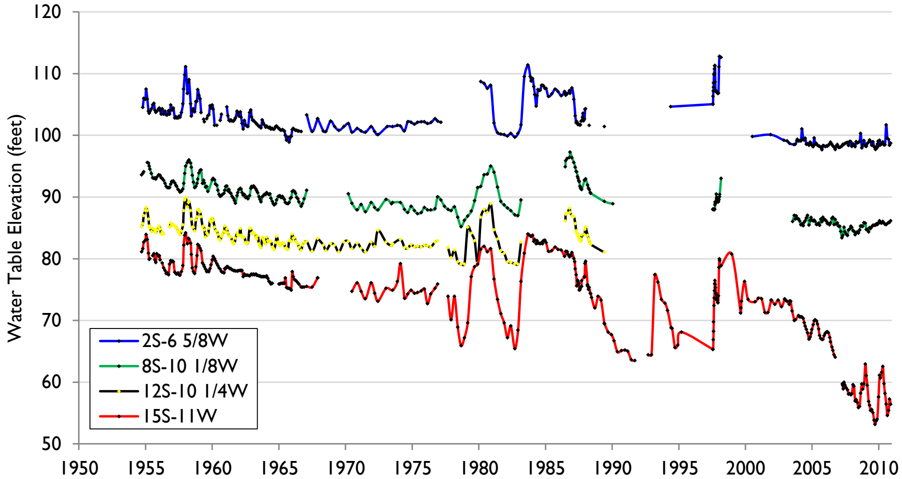

Figure 16. Historic Water Table Elevations, 1954-2010.
Source: Reclamation. Well 12S-10 1/4W was destroyed in 1990.

so land in the area has been intensively irrigated for more than a century.

In 1939, the Colorado River was a net source of recharge to the local aquifers, shown by the higher contours along the river. Note that the elevation of the water table at the SIB in 1939 was roughly 84 feet, about 40 feet higher than current elevations. In 1939, the water table elevation was more than 110 feet near the top of the limitrophe, about ten feet higher than the current elevation.

Figure 16 shows reported water table elevations at four monitoring wells with initial observations on September 16, 1954. Note that long-term records for these wells are problematic, given changes in location and well replacements over the course of this fifty-seven year record.[41] Well 2S-6 5/8W lies near the levee, approximately 0.4 mile south of Morelos Dam and roughly 7.0 miles northeast of well 8S-10 1/8W. Well 12S-10 1/4W, destroyed by high Colorado River flows in June 1983, was located just west of Gadsden.

[41] Well 2S-6 5/8W (also known as IBWC-28 until July 7, 2003, when this designation transferred to well 2 1/2S-6 7/8W) provides a good example of some of these data challenges. In January, 1965, a new well with the same name began operation several feet south of the original well. In February, 1974, notes and locations indicate that the original well again became operational. This well apparently was destroyed in June 1977, and a new well began operation in the same location in March 1980. On July 7, 1986, another new well with the same name (and also designated BD-32) began operation approximately 250 feet due south of the original well. Seven readings in 1987 and 1988 note that the well was dry at 21.0 feet or greater. Another well was installed in July, 2000, after more than two years without any readings, roughly 68 feet northwest of the previous well. Prior to this July relocation, reported depth to groundwater between the old and replacement wells varied by only 0.1 foot, consistent with general trends in depth to groundwater. However, between the March 1998 reading and the July 2000 reading at the replacement well, depth to groundwater fell by 12.8 feet at the site. Well 3 1/8S-7 1/8W, approximately 1.6 miles southwest of well 2S-6 5/8W, does offer records in this period, with reported depth to groundwater falling 2.2 feet from September 1999 to September 2000, but no records for well 3 1/8S-7 1/8W exist for four years prior to the 1999 datum, so it is unclear if the much greater decline in the water table at well 2S-6 5/8W reflected actual conditions or other factors.

Well 15S-11W lies about 1.2 miles northeast of the SIB and roughly 0.6 mile south of the downstream end of Hunter's Hole. Note that for the years 1960-1977, water table elevations at the three upstream wells were essentially in dynamic equilibrium, roughly 15-20 feet below the well surface. Interestingly, the water table elevation below well 15S-11W fell by ten feet during this period.

Well 15S-11W has recorded much greater variability in water table elevations than have the upstream wells. This downstream well has also seen the greatest decline in groundwater elevations over the period of record, of 30.9 feet, from September 1983 to October 2009. Records for the two upstream monitoring wells are incomplete for the period 2000-2010, but generally, groundwater elevations at these two sites are 11-19 percent lower than they were from 1960-1977.

Recent Groundwater Conditions

Dickinson et al. (2006) write that groundwater dynamics in the Yuma area have experienced major changes since the construction of upstream dams. The most dramatic of these changes is that the Colorado River now acts a sink for the nearby aquifer, rather than as a source of recharge. As a result of irrigation, groundwater levels are much higher in the Yuma area than they were historically, especially beneath Yuma Mesa. Dickinson et al. (2006) estimated that the groundwater mound beneath the mesa contains 600,000 to 800,000 acre-feet, pushing subsurface water radially outward.

As shown in Figure 3, "Change in Water Levels Yuma Area Dec. 2004 – Dec. 2009," there was a slight general decline in groundwater elevations in the upper three-quarters of the limitrophe, but a marked, accelerating decline in groundwater elevations from Gadsden south to the SIB. Reclamation staff noted that data from one well near the SIB, known as "16S-11 1/2W," reflect the most significant decline (J. Nickell, pers.

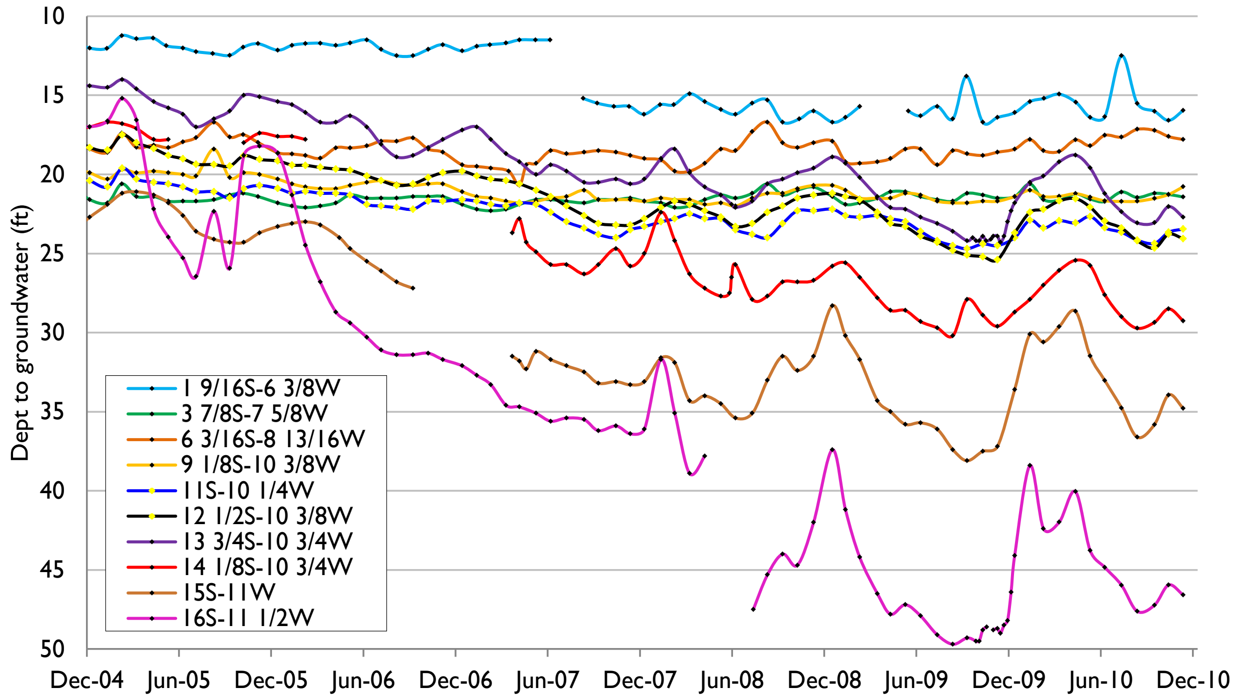

Figure 17. Depth to Groundwater at U.S. Monitoring Wells along the Limitrophe, December 2004 – December 2010.
Source: Reclamation.

comm. 2010). However, other monitoring wells upstream of the SIB also reflect this general trend. Note that the apparent cone of depression in Figure 3 at the SIB is geographically distinct from the general decline in groundwater elevations recorded at the Minute 242 wellfield, along the Arizona/Sonora border east of San Luís Río Colorado, though recent increases in groundwater extraction at the wellfield likely contributed to the declines in both areas (see Chapter IV for a general discussion of groundwater extraction). Figure 17 shows this underlying data as depth to groundwater at select monitoring wells along the eastern edge of the limitrophe.

Figure 17's legend lists the monitoring wells in order from north to south. The first well listed lies just east of Morelos Dam and approximately 0.2 mile east of the river channel. The first five monitoring wells listed lie north of Gadsden, roughly two to three miles apart. The last five wells listed lie south of Gadsden (*see Figure 25 for locations of monitoring wells*). Note that the three southernmost wells show significantly greater variability and overall decline in depth to groundwater than do the other seven wells. At well 16S-11 1/2W, closest to the SIB, depth to groundwater increased by almost 34 feet from March 2005 to December 2009. At well 14 1/8S-10 3/4W, near the Hunter's Hole restoration site, depth to groundwater increased 12.8 feet during that time. In that same period, depth to groundwater at well 3 7/8S-7 5/8W, 2.5 miles downstream from Morelos Dam, increased by less than one foot. Note that the graph shows depth to groundwater; these are relative values, rather than absolute groundwater elevations. These reported depths do not reflect the depth to groundwater within the riparian corridor.

In Figure 17, note the data gap in June, 2008 for well 16S-11 1/2W and the ten-foot decline in reported depth to groundwater from May to August 2008. Records indicate that this well was replaced during that time, and that the surface elevation of the new well site was 8.4 feet higher than at the old location. Looking at the actual elevation of the underlying water table, rather than the reported depth to groundwater, shows that the water table only fell 1.2 feet from May to August 2008, rather than the 9.7 feet indicated by the depth to groundwater records, highlighting the problems associated with relying on reported depths to groundwater and the need to carefully assess the data. On the following page, Figure 18 shows reported water table elevations, rather than depths to groundwater, for the same wells over the same period as Figure 17. A comparison of the two reveals much lower variability and lower declines in water table elevations than is implied by the raw depth to groundwater data. Note that water table elevations were largely stable for the northernmost four wells. Because of differences in absolute water table elevations, the vertical axis in Figure 18 spans 70 feet, while the vertical axis in Figure 17 only spans 40 feet, so Figure 18 on the next page appears to compress the water table decline and variability depicted in Figure 17.

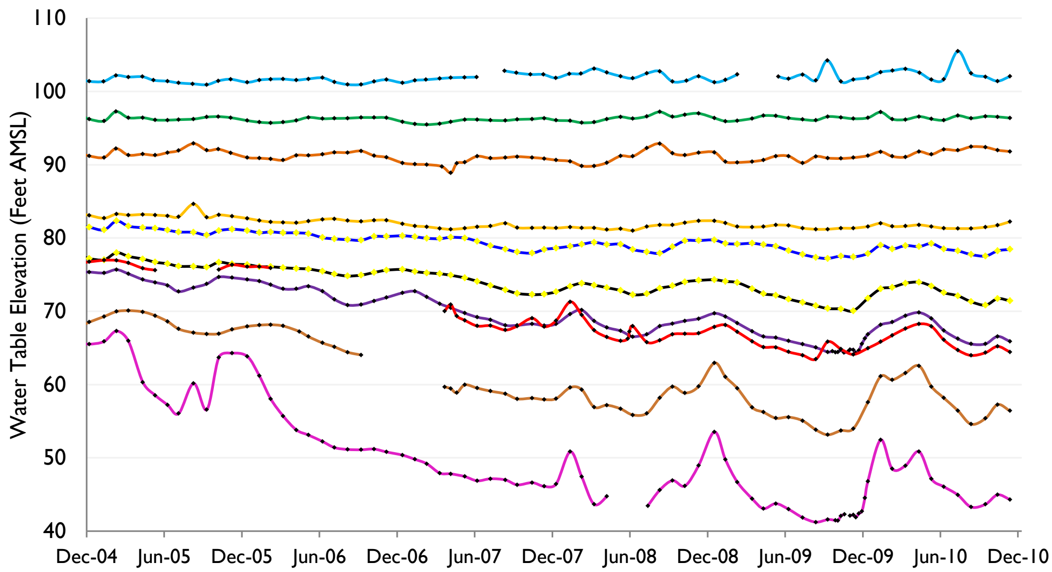

Figure 18. Water Table Elevations at U.S. Monitoring Wells along the Limitrophe, December 2004 – December 2010. Source: Reclamation. Legend in Figure 17.

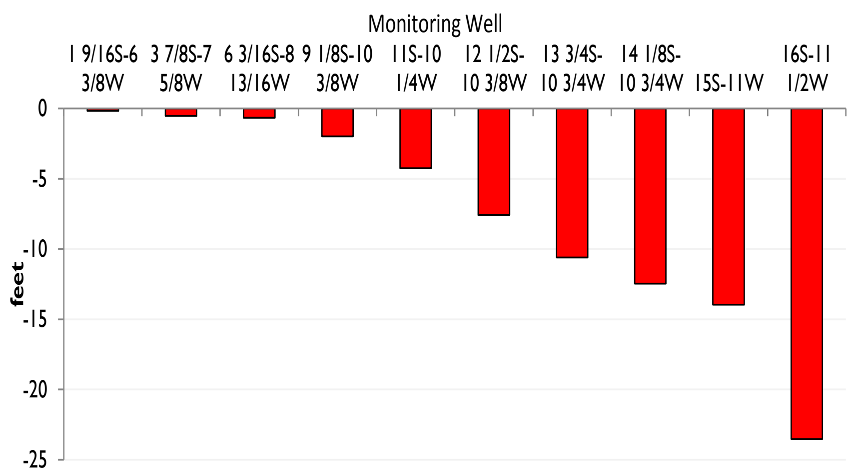

Figure 19. Change in Water Table Elevation, December 2004 – December 2009. Source: Reclamation.

Figure 19 shows the change in water table elevations at the ten wells displayed in figures 17 and 18, between December 2004 and December 2009 (consistent with the time period shown in Figure 3). Note the increasing rate of decline in water table elevations moving from Morelos Dam to the SIB (from left to right in the figure).

Figures 17-19 display information over time for static well locations. Figure 20 displays spatial differences in water elevation at a specific point in time. Figure 20 shows the elevations and approximate river mile locations of Reclamation's monitoring wells,[42] together with riparian corridor elevations and interpolated elevations of the water table below these riparian corridor locations in December 2009. Because these are interpolated data and not empirical measurements, they should be interpreted to reflect general trends in water table elevations, rather than precise values. For the sake of comparison, channel invert elevations, from 1976 and 1999 surveys, are also depicted. Note that this figure combines data from four different times: the 1976 and 1999 channel surveys, land surface elevations from 2007, and water table data from 2009. Note also that the water table is above the 1999 channel invert until about river mile 8 and rises again near river mile 5, near Gadsden, indicating that the river is a gaining reach up to that point. This is consistent with observations of water in the channel, though the actual elevation difference may not be accurate given likely changes to channel elevations since 1999.

Figure 21, from Mexico's *Conagua*, shows depths to the water table on the Mexican side of the limitrophe, in meters, from 2006 data. Note that *Conagua*'s reported groundwater depth of roughly 39 feet near the SIB in 2006 is more than 7 feet lower than lowest elevation reported in 2006 by the

[42] Note that the monitoring wells run roughly along the eastern levee at regular intervals, while the river meanders; river mile designations for the monitoring wells are based on the closest river location.

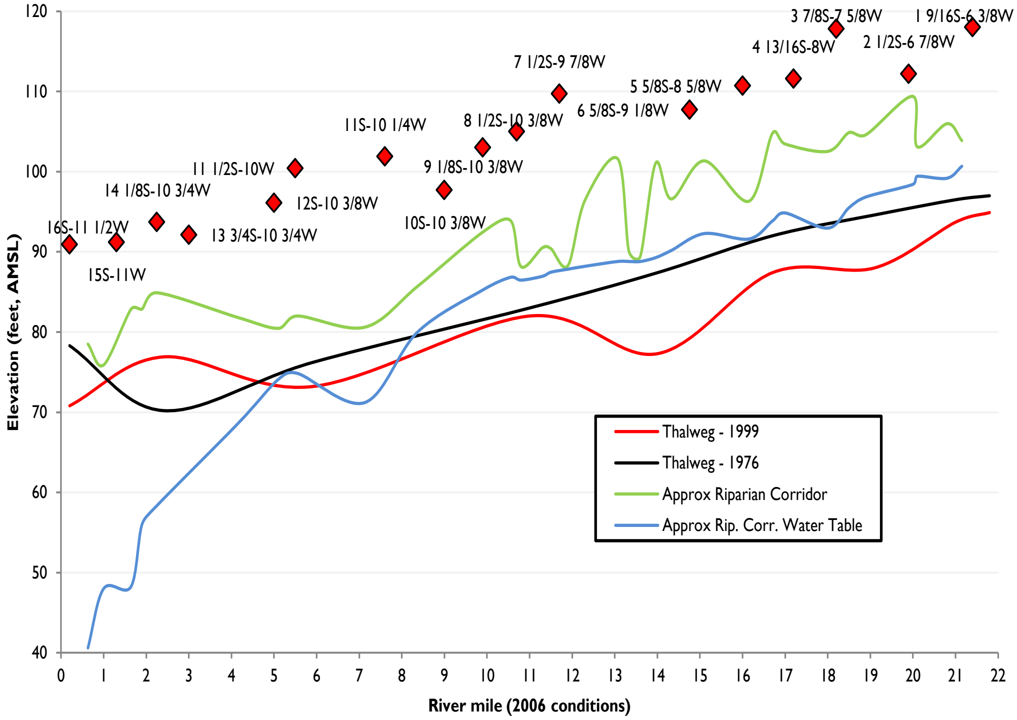

Figure 20. Profile of Riparian Corridor and December 2009 Water Table Elevations.

monitoring well 16S-11 1/2W, the closest well in the U.S. to the SIB, though this may simply reflect differences in well elevations rather than differences in water table elevations.

Figure 22 also shows groundwater elevation contours and the presumed direction of groundwater flow, based on data from 15 piezometers in December, 2007, near Colonia Miguel Aleman. Note that the *Conagua* data reflects static groundwater elevations while the piezometer data in Figure 22 reflect dynamic groundwater conditions. Median depth to groundwater recorded by these piezometers is 25.2 feet. While there is extensive information on locations and capacities of the 41 wells on the Mexican side of the limitrophe within the levees (and in Mexico's District 014 more generally), there is limited data on trends in groundwater elevations, especially near the limitrophe.

Figure 23 on the next page shows depth to groundwater at four locations west of the limitrophe, in Mexico. Well #311 is just south of the SIB streamflow gage, and includes annual 'static' groundwater elevations for most years from 1980-2000. The other three wells are located several miles upstream, and only include data for the years 2000-2004. Note the absence of any consistent trend in depth to groundwater for these three wells, with the middle well trending in the opposite direction of the other two at each annual observation. However, the 2000-2004 trend, for each of the wells, is an overall general decline in groundwater elevation of about ten feet.

Figure 24 compares depth to groundwater at U.S. monitoring wells and Mexican piezometers at roughly equivalent distances from Morelos Dam and from the river channel itself, for the period January 2008 (April 2008 for the piezometer data) through March 2010. Locations of these sites are shown on Figure 25, on the following page. For the sake of comparison, paired sites are color-matched, with U.S. monitoring wells shown with dashed lines. With the exception of well 12 1/2S, all of the wells show a distinct rise in groundwater elevation in the first half of January 2009. Note that, with the possible exception of well 14 1/8S, the U.S. monitoring wells do not show the September 26, 2009 rise in groundwater elevations reflected by the piezometer data. The September rise likely reflects *Conagua*'s "September shutoff" of all groundwater pumps and the subsequent

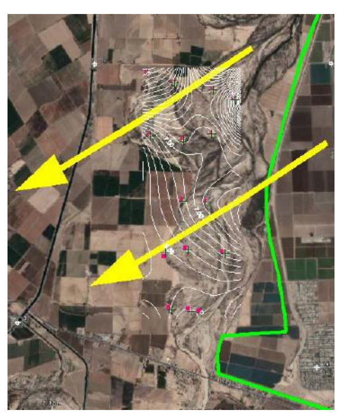

Figure 22. Groundwater Movement, Mexico.
Source: Hinojosa-Huerta et al. 2007.

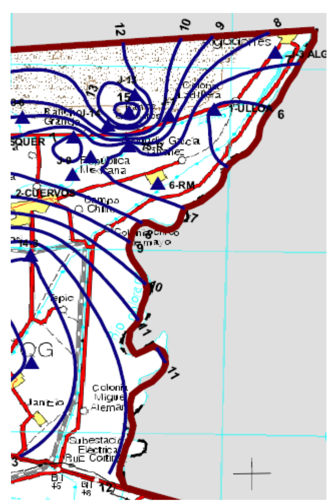

Figure 21. Depth to Groundwater, Mexico, 2006.
Source: *Conagua*.

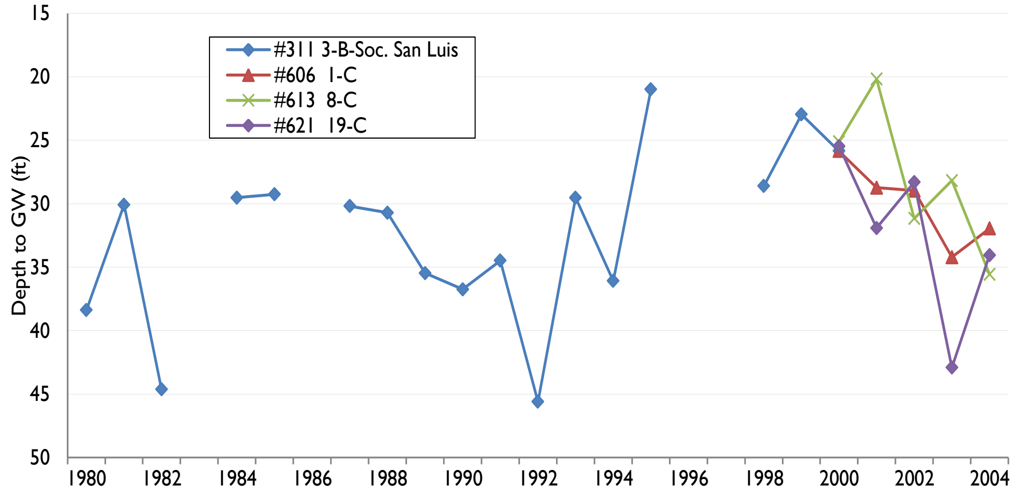

Figure 23. Depth to Groundwater 1980-2004, west of river channel.
Source: Conagua.

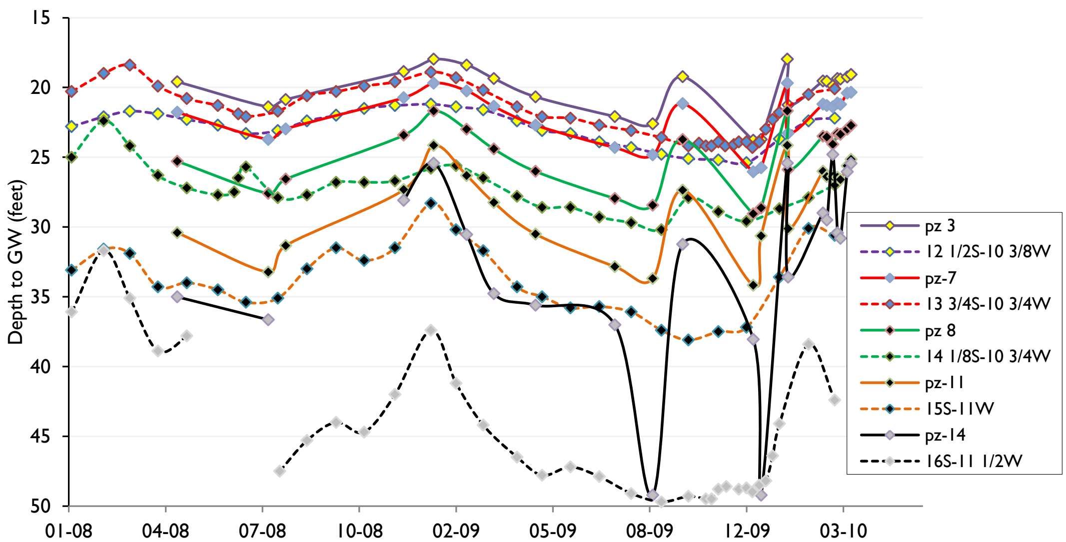

Figure 24. Depth to Groundwater at Paired Monitoring Wells on Opposite Sides of River Channel, 2009-2010.
Sources: Reclamation, Hinojosa-Huerta.

recovery of groundwater elevations, though this effect apparently is localized to the west of the river channel. The causes of the anomalous declines in groundwater elevations at piezometer 14 in August 2009 and in January 2010 are not known. A simple correlation between average monthly depths to groundwater at piezometer number 3 and monthly depths to groundwater at monitoring well 12 1/2S-10 3/8W shows agreement of slightly less than 70 percent.

On the following page, Figure 25 shows the locations of the Reclamation monitoring wells and the piezometers (designated "PZ1," etcetera, or simply numbered). The image shows the difference in elevation between the December 2009 water table and the land surface over the limitrophe reach as a whole. Figure 25 interpolates the elevation of the water table based on reported water elevations in December 2009, using 2007 digital elevation data. The color shading reflects increasing depths to groundwater from north to south along the limitrophe. The mound of dredge spoils[43] is evident immediately to the south of Morelos Dam (at the top of the first image), between the river channel and the Canal Reforma. Note that the river channel lies below the interpolated water table surface for roughly two-thirds of the reach below the dam, indicating that this is a

[43] See discussion of dredge spoil mound on p. 6.

gaining reach, consistent with observed surface flow. Below Hunter's Hole (near well 13 3/4S-10 3/4W), the water table clearly falls far below the surface.

Groundwater conditions in the study area have deteriorated over the past 57 years, with these impacts becoming increasingly pronounced in the southernmost quarter of the study area. Although monitoring well records are sporadic during some key periods (such as the early 1990s), several general trends are apparent. The water table across the study area reached its maximum elevation at four distinct times: January 1955, January 1958, September 1983, and January 1998, with a lower peak in December 1980. Over the past decade, the water table near Morelos Dam has been about two feet lower than average elevations in the 1960s and 1970s. Closer to SIB, water table elevations dropped about 27 feet from their elevation in 1960 to their lowest recorded elevation, in October 2009. In addition to this pronounced decline in water table elevation near SIB, such elevations have been much more variable than those closer to Morelos Dam. Beneath the well closest to SIB, water table elevations have fallen and risen and fallen again by more than ten feet within a matter of a couple of months on a few occasions, indicating porous soils and a rapid response to external factors.

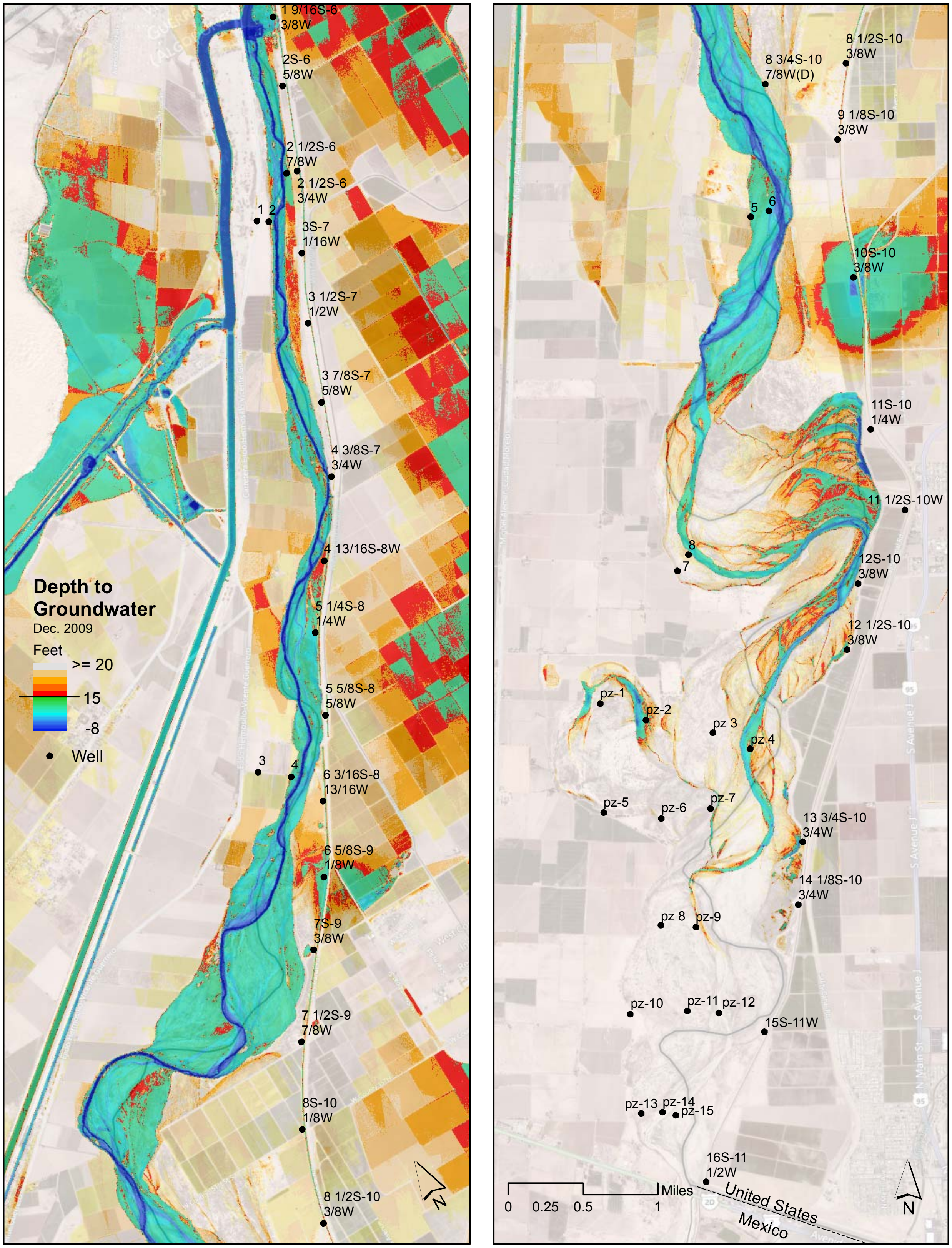

Figure 25. Depth to Groundwater in the Limitrophe Reach, December 2009.
Sources: Reclamation, Hinojosa-Huerta, USGS.[44]

[44] Underlying data from the USGS "Imperial County, California, and Yuma County, Arizona, along the Mexico Border, 2007, 1/9-Arc Second National Elevation Dataset."

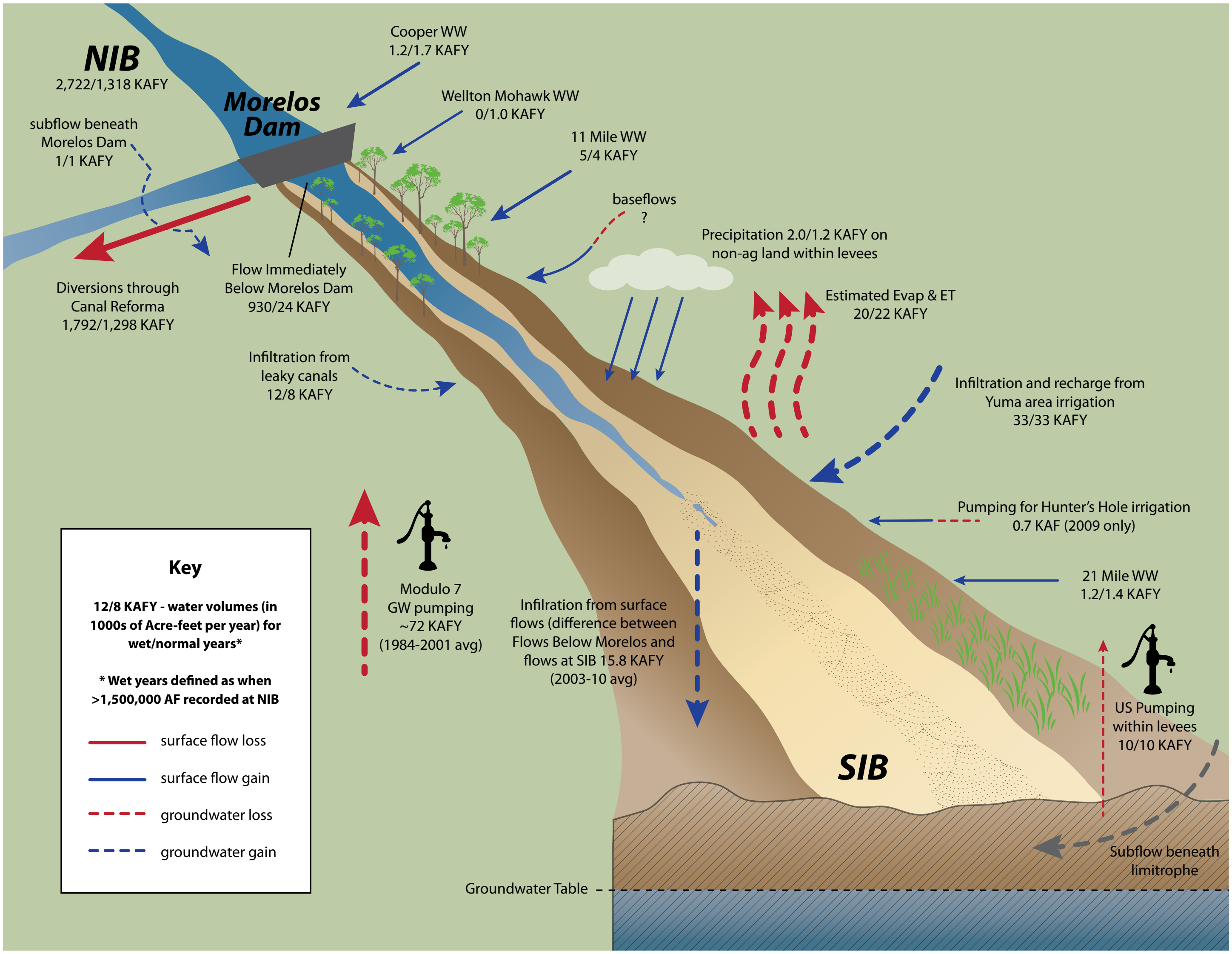

Figure 26. Study Area Inflows and Outflows.

Chapter IV - Groundwater Dynamics

Several factors help explain the variability in groundwater elevations discussed in Chapter III. This variability can be described as a function of the difference between inflows and outflows. Sources of inflow include both recharge from surface waters percolating through the soil and subsurface water movement. In the case of the study area, the intensive irrigation of some 74,000 acres in Yuma County at least partly draining toward the study area,[45] periodic recharge via the Colorado River channel and floodplain, seepage from irrigation canals, rare instances of significant precipitation, and the movement of subsurface water from the Yuma area toward the river channel all contribute toward groundwater recharge in the limitrophe reach. The PNN/UABC study (Ramírez et al. 2011) also suggests some recharge occurs due to seepage from the Canal Reforma, affecting the limitrophe directly below Morelos Dam.

Outflows include groundwater pumping, extraction by plant roots, movement of groundwater out of the study area, and discharge to the surface, as springs and seeps. In the Yuma area, irrigators use groundwater pumps and ditch drains[46] to keep the water table below the root zone, to enable better irrigation management and to avoid burning plant roots with salty groundwater. In some areas of Yuma County, groundwater is pumped for irrigation and, from deeper wells, for municipal use. Within five miles of the Arizona-Sonora border, both nations operate extensive wellfields, in recent years extracting more than 200,000 acre-feet of groundwater per year, combined. Riparian and upland plants also draw from the underlying aquifer, directly affecting conditions in the study area. Pumping operations to the west and southeast of the limitrophe pull groundwater out of the study area, depressing groundwater elevations. Where the water table intersects the land surface, as occurs in the upper portion of the limitrophe reach, discharge from the alluvium generates base flows in the river channel. With the exception of surface water and precipitation (see discussion in Chapter V), each of these factors is discussed in the following.

On the previous page, Figure 26 shows a simplified overview of water movement into and out of the limitrophe reach, as described above. The figure includes reported and estimated volumes for "normal" and "wet" years over the past two decades. "Normal" years are those in which the volume of water passing the NIB was less than 1.50 MAF; wet years saw greater than this amount.

Table 4. Study Area Surface Flow Water Budget

Inflows	Years	Source	Mean	Wet	Normal
Flows Below Morelos	1990-2010	calculated	370	930	24
Baseflows		*guess*	2	2	2
11 mile WW	1990-2010	gage	4	5	4
Precipitation	1990-2010	gage	1.5	2.0	1.2
21 mile WW	1990-2010	gage	1.3	1.2	1.4
SIB diversion channel	2004-2010	gage	0.4	0.1	0.5
Total	(rounded)		380	940	33
Outflows	**Years**	**Source**	**Mean**	**Wet**	**Normal**
Evap from open water/marsh		estimated	2.4	2.5	2.4
Infiltration		*guess*	*15*	*19*	*11*
Q at SIB	1990-2010	gage	370	960	15
Total	(rounded)		**390**	**980**	**29**
Residual			(10)	(40)	4

Chapter III described the variable groundwater conditions in the study area, highlighting the dramatic decline in water table elevations near the SIB over the past 57 years and the more stable elevations evident near Morelos Dam. Two related water budgets were developed to track the various factors affecting groundwater conditions in the study area. These budgets account for inflows and outflows to the groundwater and surface water systems, for the years 1990-2010. Disaggregating the linked but in some ways distinct surface and groundwater systems in the study area allows for closer examination of the individual terms involved. The time period was selected to avoid the distorting impacts of the very high Colorado River flows of the mid-1980s, when millions of acre-feet flowed past the SIB. Tables 4 and 5 show the budgets for surface and groundwater in the study area, respectively, list flows (in thousands of acre-feet) as a mean value, and further break these down into "wet" and "normal" years, based on whether more or less than 1.5 million acre-feet flowed past NIB.[47] The two tables list the source for the values listed: gage data, with the exception of the SIB gage in recent years, generally has a reported error of 15 percent or less. Calculated values have a higher error, reflecting the effects of combining several error terms and the difference in magnitude between the reported flows at the NIB and the Morelos Dam diversion and the calculated flows below the dam. Estimated values are calculations based on survey data with estimated acreage that may not be wholly reliable. "Guesses" are simply educated guesses, essentially placeholders reflecting a lack of information on which to base a reasonable estimate. "Baseflows" could be calculated with a sophisticated model of the limitrophe reach, using current channel geometry and a series of interpolations of water table elevations through the reach, as well as better information on transmissivity of limitrophe soils. In other parts of this report, "Infiltration" is assumed

[45] Total Yuma County crop acreage in 2008, including trees and vines, was 262,605 acres. Most of this acreage drains north, toward the Colorado and Gila rivers, and south, where it is intercepted by surface drains or pumps along the Arizona-Sonora border. Source: Arizona Cooperative Extension.

[46] According to Reclamation, subsurface "tile" drains are not used to any extent in the Yuma area.

[47] "Wet" years are 1993, 1995, 1997-2001, and 2010; "normal" years are 1990-1992, 1994, 1996, and 2002-2009.

to be the difference between total limitrophe inflows and total limitrophe outflows, but that would be circular for this budget. Instead, the normal year value is estimated based on this difference, but the "wet" year value is simply assumed to be a greater value, even though the residual suggests that it, or some other term in outflows, may already be too large.

Table 5. Study Area Groundwater Budget

Inflows	Years	Source	Mean	Wet	Normal
Subflow below dam		*guess*	*1*	*1*	*1*
Infiltration		*guess*	*15*	*19*	*11*
Seepage thru Canal Reforma		*Conagua* 2004	10	12	18
recharge from US irrigation within levees		calculated	3	3	3
recharge from Mexican irrigation within levees		calculated	8	8	8
GW movement	1973	Olmsted	33	33	33
Total			70	75	64
Outflows	**Years**	**Source**	**Mean**	**Wet**	**Normal**
Evap & ET	1997-2007	LCRAS	21	20	22
Mexico pumping within levees		calculated	26	26	26
US pumping within levees		calculated	10	10	10
Change in storage	1990-2010	estimated	*(2.8)*	*6.1*	*(8.0)*
GW movement		guess	*33*	*33*	*33*
Total			88	96	84
Residual			(18)	(20)	(19)

In Table 5, several items are simply guesses, given the lack of data. Groundwater movement as an inflow is a value reported by Olmsted (1973) and is likely dated, since it precedes the operation of the Minute 242 wellfields, which presumably have changed the direction of some groundwater movement, especially near the border. Groundwater movement as an outflow reflects the fact that, in the limitrophe below Gadsden, the water table has no connection to the surface channel and groundwater presumably flows through that area unimpeded. However, in the upper three-quarters of the limitrophe there is some connection between the water table and the surface (including riparian vegetation that draws from this water table), so it is likely that this outflow is depleted, both by baseflows and by evapotranspiration. The change in storage term therefore complements the groundwater movement terms, though it is calculated based on average change in water elevations and Ramírez et al.'s (2011) estimate of the volume of water required to raise water elevations.[48]

[48] According to Ramírez et al. (2011), "Approximately 6.7 MCM are needed to increase the aquifer level 0.5 m" (5,400 AF to raise 1.6 feet).

Recharge

There are two key sources of recharge for the shallow aquifer in the study area: subsurface drainage from irrigated agriculture in portions of Yuma County, and percolation from Colorado River surface flows below Morelos Dam. These are discussed in detail in the remainder of this report. Several minor sources of recharge also contribute to the shallow aquifer: direct precipitation, sub-flow below Morelos Dam, and seepage from the Canal Reforma. The concrete-lined Bypass Extension of the Wellton-Mohawk drainage canal contributes a negligible amount of seepage to the area. A $300 million project to line[49] 23 miles of the All American Canal was completed in 2009, preventing an estimated 67,700 acre-feet from seeping through the canal into the ground. Most of this seepage flowed south into Mexico. Given groundwater gradients in the area, most of this seepage presumably flowed southwest, toward Mesa Andrade and the Mexicali valley, rather than toward the study area.

Sub-flow from the Colorado River upstream of Morelos Dam likely contributes to groundwater in the study area, at an undetermined volume. Recharge from seepage through the unlined Canal Reforma, identified by Ramírez (2011), may contribute an additional 10,000 acre-feet annually.[50] Direct precipitation on the study area contributes about 3,400 acre-feet on an average annual basis, a small fraction of the potential evapotranspiration from the reach. Because of the extensive drainage infrastructure in the Yuma area, even large precipitation events do not directly increase surface or groundwater flow to the study area: runoff from such precipitation is intercepted by surface drains and conveyed to the Colorado River or to the land boundary delivery point. However, large precipitation events have a very significant *indirect* impact on study area recharge, by causing irrigators in the Yuma, Imperial, Coachella, and Mexicali valleys to cancel water orders. Although the new Brock Reservoir[51] adds some limited storage to the Colorado River delivery system, most such canceled water orders flow past Morelos Dam into the study area, causing peak flows and dramatically increasing the volume of water seeping into the channel and backwaters.

[49] Actually, the "lining" project consisted of building a new, parallel canal, rather than lining the existing canal.

[50] This estimate is based on Conagua (2004), reporting 51.1 KAF/year in annual losses from "main infrastructure." I assumed 10 KAF (as an order of magnitude estimate) flows toward the limitrophe and the remainder seeps from portions not adjacent to the limitrophe or otherwise flows toward the west, based on the relative lengths of the main infrastructure:
- Canal Reforma - 17 miles long; capacity 3670 million gallons per day (MGD)
- Canal Revolucion - 2.5 miles long; capacity 870 MGD.
However, 97.2% of the "main infrastructure" reportedly is lined; Conagua did not report what portion of the losses come from the unlined portion.

[51] Formerly known as the Drop 2 reservoir.

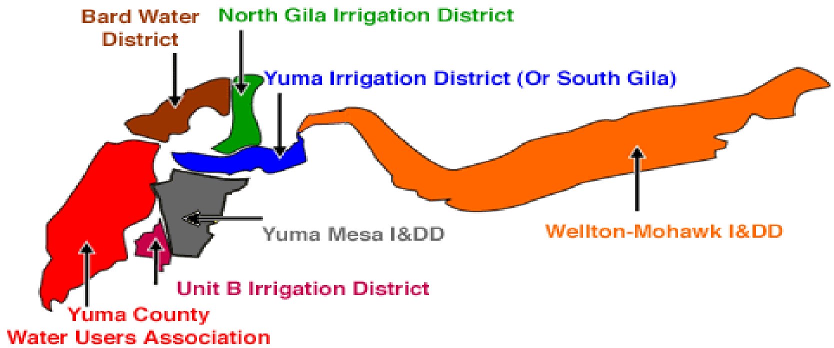

Figure 27. Yuma Area Irrigation Districts.
Source: Yuma Area Ag Council. See http://www.yaac.net/irrigation.html.

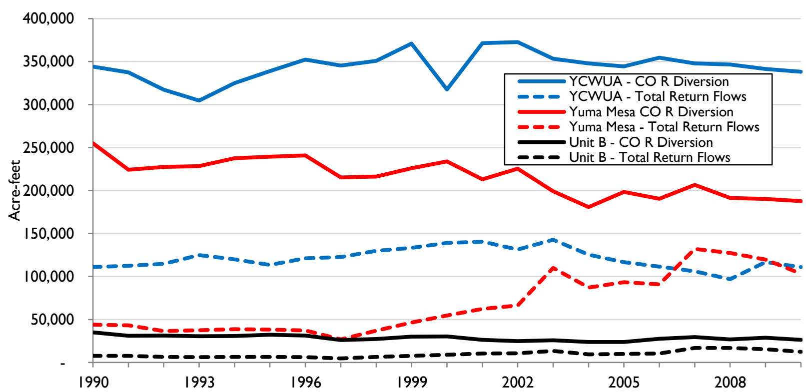

Figure 28. Annual Diversions and Return Flows of Yuma Area Irrigation Districts, 1990-2010. Source: Reclamation annual decree accounting reports.

Prior to the construction of dams and diversions, the Colorado River provided the main source of groundwater recharge in the study area, during both high and low flows. Olmsted et al. (1973) note that in 1925, the river created a distinct groundwater ridge sloping away from the channel. With the construction of dams and diversions, Colorado River flows diminished and sediment loads decreased, causing the river below Laguna Dam to cut some 10-20 feet into its former floodplain. At this lower elevation, the river now drains subsurface water from surrounding lands, a complete reversal from pre-dam conditions (Olmsted at al. 1973).

Irrigated Acreage

Figure 27 shows the irrigation districts in the Yuma area. Of these, the Yuma County Water Users Association (YCWUA) irrigated 53,000 acres, Yuma Mesa irrigated almost 18,000 acres, and Unit B irrigated 2,800 acres in 2008. Return flows from the other districts do not directly affect the study area.[52]

Figure 28 shows annual diversions and return flows for these three irrigation districts. Note that in 2003, Reclamation began to credit individual contractors for "unmeasured return flows."[53] As shown in the graph, this new accounting generated an average of 31,000 AF/year of new return flow credits for Yuma Mesa, and some 38,000 AF/year for the three districts combined. Note also that Yuma Mesa's reported return flows increased by 173 percent from 1990 to 2009, while at the same time total diversions decreased by 25 percent. YCWUA's reported return flows increased by 5 percent while its total reported diversions decreased by 1 percent over this period. Total combined diversions for the three districts decreased by 73,800 AF (12 percent) from 1990-2009, while reported combined returns flows for the three districts increased by 98,300 AF (55 percent). According to the Law of the River (cf. Nathanson 1980), such return flows must be available for delivery to downstream users or to meet Treaty obligations to Mexico; subsurface return flows[54] that enter the limitrophe reach below Morelos Dam are not accounted for and therefore are not reflected in Figure 28.

[52] Infrequently, small volumes of agricultural drainage pumped from beneath Wellton-Mohawk are siphoned from the MODE Bypass Extension into Hunter's Hole.

[53] Prior to 2003, unmeasured return flows were credited to the state as a whole, rather than to individual contractors.

[54] Note that surface return flows, via the various wasteways, are credited as return flows.

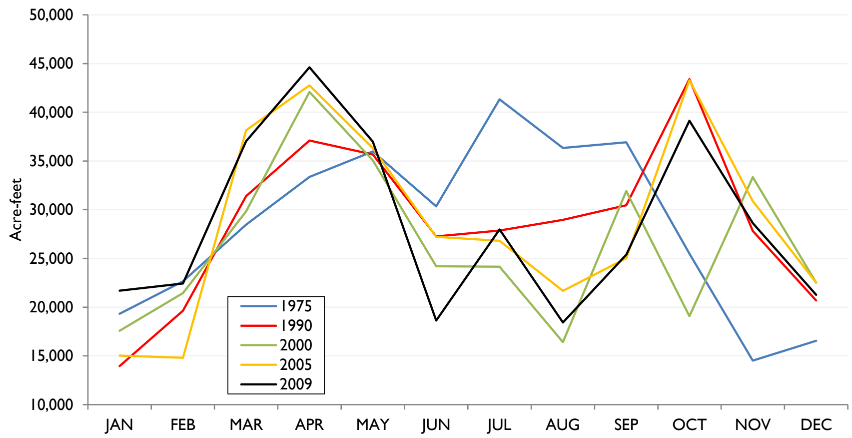

Figure 29. Reported Monthly Diversions, YCWUA. Source: Reclamation annual decree accounting reports.

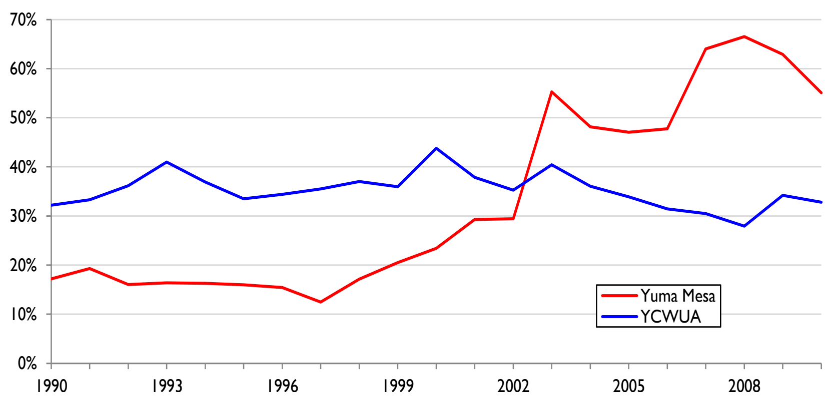

Figure 30. Yuma irrigation districts' total reported return flows as a percentage of total reported diversions, 1990-2010. Source: Reclamation annual decree accounting reports.

Figure 29 plots monthly diversions for the YCWUA (which comprises the Valley Division of the Yuma Reclamation Project) for several years, showing seasonal variability in the application of irrigation water. Note the Spring and October peaks in irrigation in most years, reflecting cropping patterns.

Figure 30 plots return flows as a percentage of diversions for both Yuma Mesa and YCWUA for the years 1990-2009. The dramatic increase in returns for Yuma Mesa reflects increased groundwater pumping in recent years,[55] to reduce groundwater levels in eastern Yuma Valley, but the most significant changes are institutional, such as the post-2002 reporting of unmeasured return flows for individual contractors.[56] Note that the values for Yuma Mesa post-2002 are exceptionally high, approaching two-thirds of the volume of water diverted. Some of this increase may be explained by the increased pumping volumes at the Minute 242 wellfield post-2002. Although Yuma Mesa receives current year return flow credits for this pumping, there is a delay

[55] According to one reviewer, "From the late 1990s through 2008, Yuma Mesa Conduit discharge was underreported – so some of the increase is due to better reporting."

[56] The 2008 Decree report describes the complicated accounting process used to determine Yuma Mesa diversions, returns, and consumptive uses, to check the volume of consumptive use by the Gila Project Mesa Division against its entitlement, as:

This is the summation for the Yuma Mesa Division of the Gila Project, consisting of the North Gila Valley Irrigation and Drainage District, Yuma Irrigation District, and the Yuma Mesa Irrigation and Drainage District:

Item		*[2008] Annual Totals (AF)*
Diversion at Imperial Dam	A/	319,806
Pumped from wells		1,613
Surface returns from South Gila Valley (S. Gila Canal Wasteway)		2,778
Return flow North Gila Valley (6 drains & wasteways)		7,788
Total Yuma Mesa Division Unmeasured Returns		53,909
Return flow Yuma Mesa Outlet Drain	B/	37,935
Return flow protective and regulatory pumping unit	C/	43,319
Estimated unmeasured groundwater return flow	D/	27,274
Return flow share of Gila Main Canal loss	E/	25,834
Subtotal return flow		198,837
Consumptive Use		122,582

(A) Total surface diversion for the North Gila Valley Irrigation and Drainage District, Yuma Irrigation District, and the Yuma Mesa Irrigation and Drainage District.

(B) Estimated at 85 percent of the Yuma Mesa Outlet Drain with balance credited to 'Unit B'.

(C) Estimated at 85 percent of Protective and Regulatory Pumping Unit with balance credited to 'Unit B'.

(D) Estimated at 38 percent of the North Gila Valley Diversion at Imperial Dam plus 14 percent of Yuma Irrigation District diversion at Imperial Dam. (Based on analysis of the USGS Report 83-4220 entitled 'A Method for Estimating Ground-Water Return Flow to the Lower Colorado River in the Yuma Area')

(E) Diversion times mileage weighted share of Gila Main Canal loss, less canal surface evaporation (1,397 af/yr), and phreatophytes (2,154 af/yr).

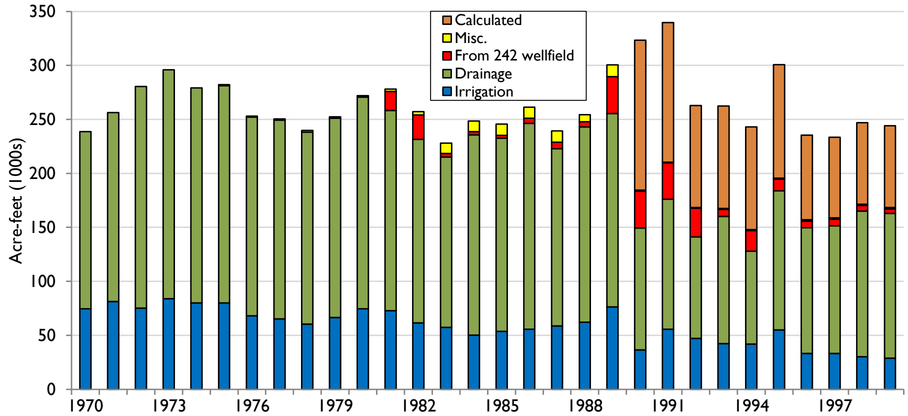

Figure 31. Groundwater Extraction in the Yuma Area,1970-1999.
Source: Dickinson et al. 2006.[57]

in groundwater movement from the mesa to the wellfield.[58] Accounting for these subsurface return flows is much less precise than for surface returns.

Until 2006, the unincorporated township of Gadsden, Arizona, 3 miles north of San Luis and 2.3 miles north of Hunter's Hole, lacked wastewater treatment services; most residents relied on septic systems and leach fields to discharge roughly 50 acre-feet per year to the aquifer. Other cities and towns on the U.S. side of the limitrophe treat wastewater and discharge it into the Yuma Drain for delivery to Mexico at the land boundary near the SIB.

Reclamation's draft particle tracking study (undated), based on ADWR's groundwater model and using the high water table from the late 1980s, calculated that 62,000 acre-feet of groundwater flowed annually from the Yuma area south toward Mexico's Mesa Arenosa wellfield and that an additional 19,000 acre-feet flowed annually to the study area. The particle tracking study also calculated that 23,000 acre-feet flowed annually from or under the Colorado River into the U.S.

Extraction

Reclamation's annual Decree Accounting Reports no longer include information on groundwater extraction for locations near the limitrophe,[59] though the USGS continues to estimate the amount of water extracted in its annual pumper reports. Recent records for groundwater extraction on the Mexican side of the limitrophe could not be obtained. Dickinson et al. (2006) compiled and estimated annual groundwater extraction volumes for the Yuma area, the Mexicali Valley, and for "Sonora Mesa irrigation," for the years 1970-1999. The trends in extraction within the Yuma area are shown in Figure 31. For the period 1970-1998, Dickinson et al. (2006) reported 439,000 acre-feet of annual groundwater extraction by "Government" wells and 152,000 acre-feet of annual groundwater extraction by "Private" wells.

Groundwater extraction for municipal deliveries is a small but growing factor in the area. As shown in Table 2, the populations of the cities of San Luis and San Luis Río Colorado (SLRC, in Figure 32 on the following page) are growing very rapidly. Both of these cities extract groundwater from within the five-mile exclusionary zone, so their pumping volumes are also reported elsewhere. Still, it is important to highlight these volumes, given the rapid growth of these cities. Unlike agriculture in the area, which is subject to pressure from urban areas to relinquish its water, these cities are fixed in the landscape. Both cities draw water from wells located very close to the Colorado River at the SIB, though their wells typically draw from greater than 200 feet. The per capita delivery rate for San Luis is low, at about 120 gallons per capita per day (GPCD), suggesting that future population growth will likely see a nearly linear increase in water deliveries. On the following page, Figure 32 shows total groundwater extraction by the cities in the immediate area, for which data were available.

Extraction and the Water Table

The water table elevation at well 8S-10 1/8W, located about 7.5 miles downstream of Morelos Dam, fell three feet from October 2006 to April 2007, possibly as a result of "West Cocopah Well No. 6," noted as operating in Feb. 2007. This well is noted as being off in October 2009, though the actual date well operation ceased is not noted. Actual volumes of water extracted by the pump are no longer reported.

[57] Dickinson et al. (2006) define the Yuma area to include much of the lands in the U.S. downstream of Laguna Dam that are irrigated with Colorado River water, including the Bard region in southeastern California, the South Gila Valley, Yuma Mesa, and the Yuma Valley.
[58] Reclamation staff noted that, "There is no intent in determining return flows to give credit only to waters returned in the same year they were applied as irrigation. In many cases, travel times from the point of application as irrigation to the point of discharge are tens to hundreds of years or longer."
[59] In 2004, Reclamation's regional director determined that "Well pumping will continue to be accounted for *only* in areas where groundwater is flowing *toward* the reach of the Colorado River that is upstream of the Northerly International Boundary (NIB) with Mexico" (letter dated Nov. 7, 2005 to chairperson of the Cocopah; *emphases in original*).

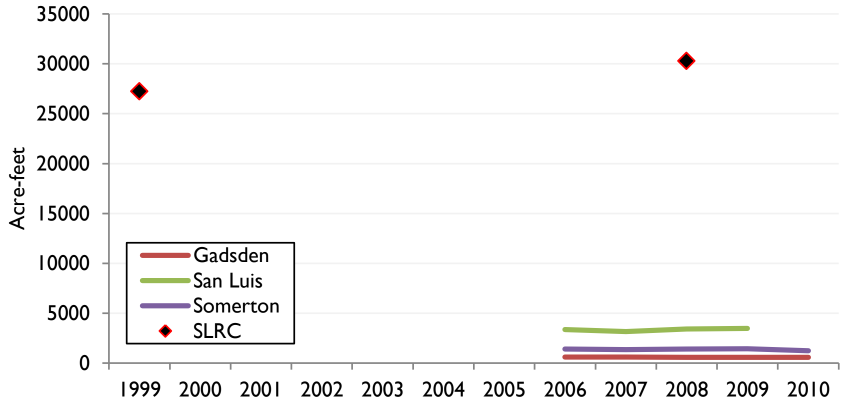

Figure 32. Municipal Groundwater Extraction near the Limitrophe.

Records for 13 3/4S-10 3/4W, located 2.4 miles north of the SIB, at the northern end of Hunter's Hole, show a ten foot decline in water table elevations from December 2002 to December 2009, and roughly a 27-foot drop from August 1999 to October 2009 (though the 1999 records were from a slightly different location). Reclamation records note that a diesel well was "ON" in April 2008, though groundwater surface elevation had already fallen almost seven feet by that time. In June 2008, records note that "Hunter's Hole well" was on, perhaps accounting for the drop of two feet in two months. The three-foot rise from June 2008 to January 2009 is not explained. In October 2009, when the water table elevation was another two feet lower, records indicate "Hunter's Hole well ON, Hunter's Hole siphon OFF." Records for 13 3/4S-10 3/4W indicate that the water table dropped 0.63 feet from September 4 to October 26, 2009. Reportedly, the pump at Hunter's Hole operates at a rate of approximately 4,000 gallons per minute (M. Brabec, pers. comm. 2010), or roughly 20 acre-feet per day. This pump operated 24 hours a day from September 15 through October 25, 2009 (M. Brabec, pers. comm. 2010), extracting approximately 700 acre-feet during this period.

Figure 33 shows the locations of two U.S. monitoring wells – "16S-11 1/2W" and "15S-11W" – and three irrigation wells, including the southernmost Earl Hugh(e)s well, "(C-11-25) 3DAC/ADW-12/AEW-33." The figure shows San Luis, Arizona and roughly the last three miles of the limitrophe reach, centered on the BLM-administered lands between the river and the Bypass Canal. Figure 34 plots reported water table elevations at "16S-11 1/2W" in **green** against reported volumes pumped by the Hughes well in **red**. For the sake of comparison, the graph also plots water table elevations at "15S-11W" in **black** against reported volumes pumped by the proximate Brown well, in **purple**. The values on the secondary y-axis are in reverse order, to facilitate comparison with water table elevations. The sharp decline in Hughes use from 1997 to 1998 does appear to correlate well with a significant increase in groundwater elevations at "16S-11 1/2W," though the similar increase at "15S-11W" does not correlate with use at the nearby Brown well. A linear regression of monthly pumping volumes at the Hughes well against changes in monthly elevation at monitoring well 16S-11 1/2W generates an r^2 value of less than 0.1, though a regression of annual pumping volumes against December elevations at the monitoring well yields an r^2 value of 0.5. However, a similar comparison of annual pumping at the Brown well with reported December elevations at well 15S-11W yields an r^2 value of 0.1. That is, there appears to be very little correlation between local groundwater extraction rates and water table elevations as reported by nearby monitoring wells. For the years after 2002, the well pumping volumes reflected in Figure 34 are based on an assumed flat rate of 6.0 or 6.25 acre-feet per acre.

Figure 35 compares reported pumping volumes with proximate water table elevations, using reported volumes from West Cocopah wells. To facilitate comparison, annual pumping volumes

Figure 33. Locations of Irrigation and Monitoring Wells Near the SIB.

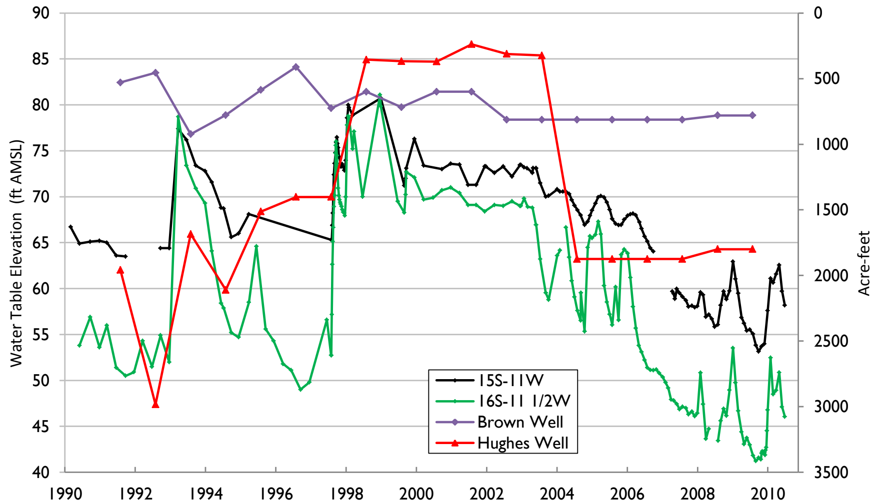

Figure 34. Groundwater Pumping and Water Table Elevations Near the SIB, 1990-2010. Source: Reclamation. Values on secondary y-axis in reverse order.

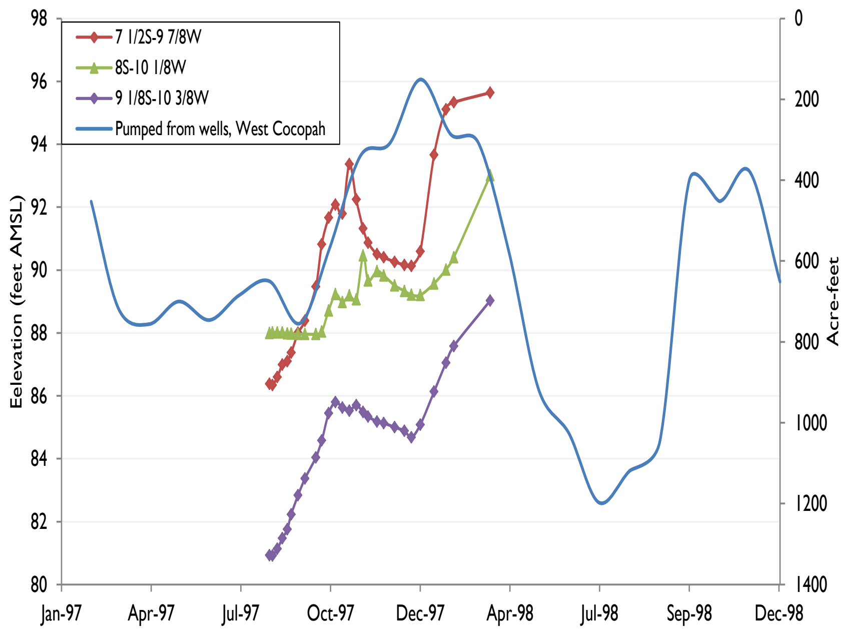

Figure 35. Groundwater Pumping and Water Table Elevations near West Cocopah, 1997-1998. Source: Reclamation. Values on secondary y-axis in reverse order.

are shown in reverse order. Because the nearby monitoring wells have extensive data gaps, the figure only shows reported groundwater extraction and water table elevations for 1997-1998. After 2003, these pumping volumes are not reported. Note that the reported July-September, 1997 water table elevations at well 8S-10 1/8W do not reflect the rising trend evident at the other two wells. From August through October, 1997, the reported water table elevations show an expected correlation with reported pumping volumes, but the post-October decline in the water table, especially at well 7 1/2S-9 7/8W, does not correlate well with the decreasing amount of water pumped by the nearby wells. That is, the water table continues to fall, even though less water was being extracted by the pumps. This suggests that other factors exert greater influence on the water table elevation.

Mexico's *Conagua* reports monthly pumping data for most wells in Irrigation District 014. These data were obtained for the years 1984-2001. Figure 36 shows the locations of the "modulos" within Irrigation District 014, as well as the locations of registered wells. Modulo 7 borders the Colorado River, extending to the west of the limitrophe

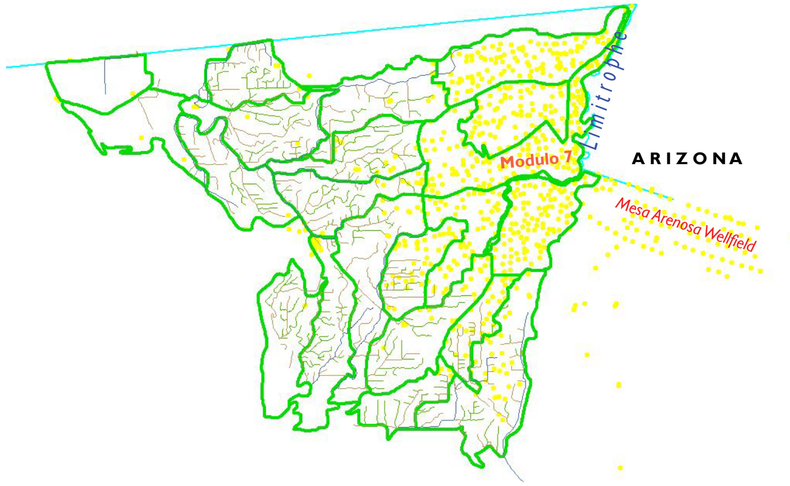

Figure 36. Irrigation District 014, with Modulo Boundaries and Wells.
Source: Hinojosa-Huerta.

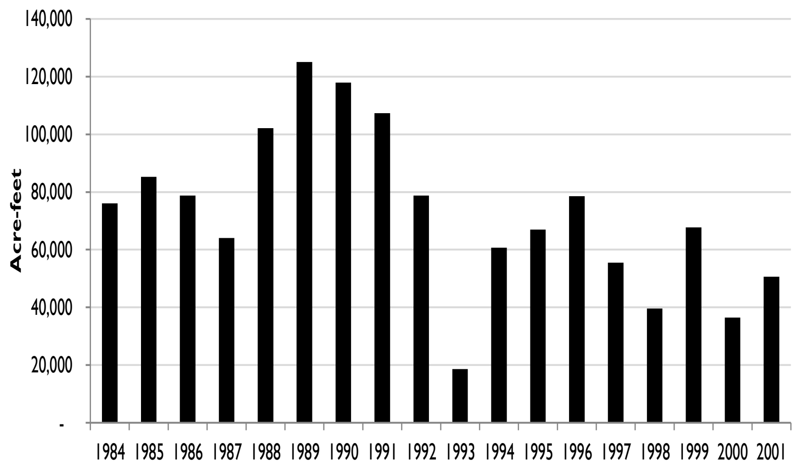

Figure 37. Reported Pumping Volumes in Modulo 7, 1984-2001.
Source: Conagua.

reach; it includes roughly 32,000 acres of irrigated fields. Total reported annual pumping for Modulo 7, for the years 1984-2001, is shown in Figure 37 on the next page. Average annual extraction during these years was 75,600 acre-feet. It is not known why total reported pumping in 1993 was less than half of the next lowest volume; it may be that high Colorado River flows that year reduced the need for groundwater, though similar reductions in pumping were not observed during the high flows of the mid-1980s. The total number of registered wells in Modulo 7 was 113 in 2001, though of these, only 54 reported any pumping that year. Carrillo-Guerrero (2009) reports total groundwater pumping for irrigation in Modulo 7 of at least 40,000 acre-feet in the water year 2007-08, though more specific information could not be obtained.

On the following page, Figure 38 compares monthly pumping volumes in Modulo 7, to the west of the limitrophe, with reported water table elevations at Reclamation's monitoring wells to the immediate east of the limitrophe. To facilitate comparison, pumping volumes are shown in reverse order. Although the aggregated pumping data do not reflect spatial differences in pump locations – differences that affect the timing and magnitude of impacts on the monitoring well data – they do provide a sense of monthly pumping variability and general trends. These trends do not correlate well with fluctuations in the water table: a regression analysis indicates that the magnitude of monthly pumping in Modulo 7 accounts for only 31 percent of the variance in reported water table elevations at well 16S-11 1/2W.

Vegetation

Established riparian vegetation typically draws from the alluvial aquifer, depleting groundwater (Glenn et al. 2008). Data on the volumes of water extracted by vegetation in the study area, and on the total acreage of such vegetation, come from several sources. On the following page, Table 6 shows different estimates of vegetation and land cover in the limitrophe reach, as provided by Natural Channel Design

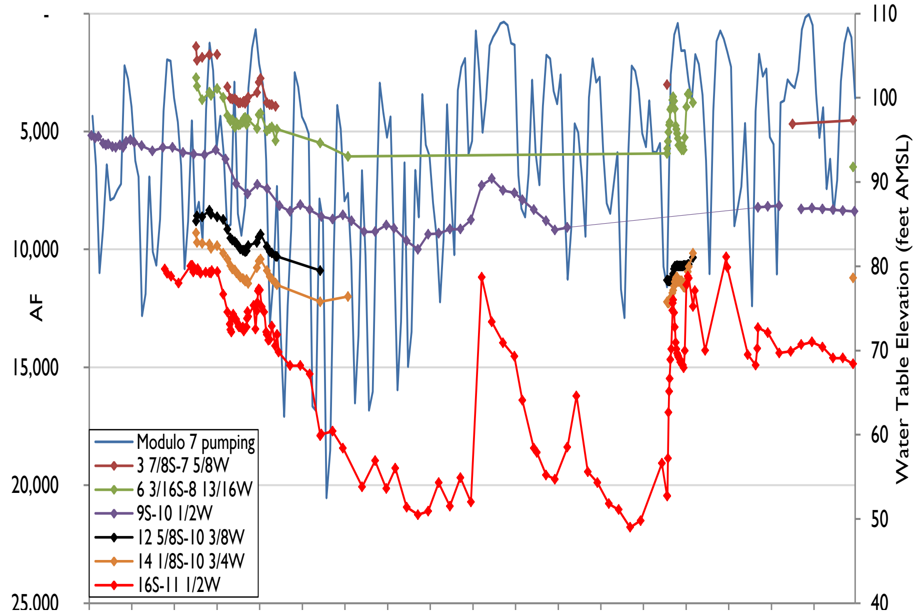

Figure 38. Reported Monthly Pumping Volumes in Modulo 7 and Water Table Elevations, 1984-2001. Values on primary y-axis in reverse order. Sources: Conagua, Reclamation.

Table 6. Vegetation Communities in the Limitrophe Reach.

Community	1986	1997	2002	2004*	2005†
Total Saltcedar	*1,594*	*5,103*	*4,756*	*2,555*	*2,996*
Total Cottonwood/willow	*1,274*	*1,016*	*373*	*265*	*456*
Total Riparian Vegetation	2,868	6,119	5,129	6,974††	3,452
Total Mesquite	0	100	4	62	65
Marsh			29	54	50
Bare Soil			3,576		
Open Water			245	65	
Total Reported Acres	2,868	6,219	8,982	7,155	3,567

Sources: Natural Channel Design (2006), †Reclamation (2007), *BLM (2008), Nagler et al. (2008). ††Per BLM, this is the total acreage of riparian vegetation in the limitrophe, though the survey only reported community acreages for the U.S. portion of the limitrophe.

(2006), BLM (2007), and Nagler (2008). Note that only Nagler et al. (2008) explicitly report specific vegetation acreages for the limitrophe as a whole; the other surveys are limited to the U.S. side of the river. However, the acreages reported by the different studies are very similar for many of these vegetation classes, suggesting either that the surveys were broader than reported, marked changes occurred over time, or that different survey methods generated very different results. Note that our GIS analysis indicates that the total acreage in the study area – from Morelos Dam to the SIB, between the levees – is approximately 16,100 acres, of which some 10,000 acres were in agriculture in 2010, suggesting that the 2002 and 2004 survey data shown in Table 6 may over-estimate the extent of the vegetation communities in the study area, or may count some agricultural land as "bare soil".

Reclamation's LCRAS annual reports provide acreages and ET for land on the U.S. side of the limitrophe, broken down into "West Cocopah" and "State of Arizona-Limitrophe." LCRAS (2005) reported a total of 13.5 acres of cottonwood-willow habitat on West Cocopah lands and zero acres on State of Arizona - Limitrophe lands in 2005, more than an order of magnitude lower than the 2005 Reclamation survey data (2007) shown in Table 6 on the next page. LCRAS reported total saltcedar extent in 2005, including low-density and mixed-community saltcedar, of 1300 acres, less than half that reported by the 2005 Reclamation survey data (2007).

Figure 39 compares total riparian ET for "West Cocopah" and "State of Arizona - Limitrophe" (LCRAS annual) with the calculated ET for saltcedar, cottonwoods, and willows from the vegetation extents listed in Table 6. Presumably, the riparian vegetation draws almost all of this water from the alluvial aquifer. Reported average annual riparian ET for the period 1997-2007, for the U.S. side of the limitrophe only, was 10,600 acre-feet (LCRAS annual); volumes calculated from the survey data shown in Table 6 were not consistent. "State of Arizona – Limitrophe" includes about 1100 acres of land, primarily south of Gadsden, and accounts for roughly 40 percent of reported riparian ET in all years except 1997, when reported ET was less than half that reported for all other years (LCRAS annual).

Falling water tables directly affect vegetative extraction rates. As noted in Chapter I, falling water tables can stress and ultimately kill riparian vegetation. Low water tables likely explain the low abundance of cottonwoods and willows in the lower limitrophe reach, and may explain the observed decline in ET rates at Hunter's Hole from 2004 to 2008.

Minute 242 Wellfields

Minute No. 242, an agreement between the U.S. and Mexican sections of the IBWC dated August 30, 1973, includes the following:

> Pending the conclusion by the Governments of the United States and Mexico of a comprehensive agreement on groundwater in the border areas, each country shall limit pumping of groundwater in its territory within five miles (eight kilometers) of the Arizona-Sonora boundary near San Luis to 160,000 acre-feet (197,358,000 cubic meters) annually.

Operations under the minute began in June, 1974, following enactment of the Colorado River Basin Salinity Control Act. To date, the U.S. has constructed 21 of 35 planned wells within its Protective and Regulatory Pumping Unit (PRPU), also known as the Minute 242 wellfield. The U.S. mixes its PRPU groundwater with drainage water in the East Main Canal Wasteway, as part of the total deliveries to Mexico at the land boundary near San Luis.

Mexico pumps Minute 242 groundwater from its Mesa Arenosa wellfield, to supplement surface water deliveries and to mix with the U.S.'s Colorado River deliveries at the land boundary into the Sanchez Mejorada canal, even though the groundwater quality is lower than that of mainstem deliveries and of groundwater pumped from lands to the west of the limitrophe (Carrillo-Guerrero 2009). Private and municipal entities also operate independent wells within this five mile exclusionary zone, primarily for municipal uses in the cities of San Luis and San Luís Río Colorado. Groundwater extraction by such independent wells is included in the total reported annual pumping data for each country.

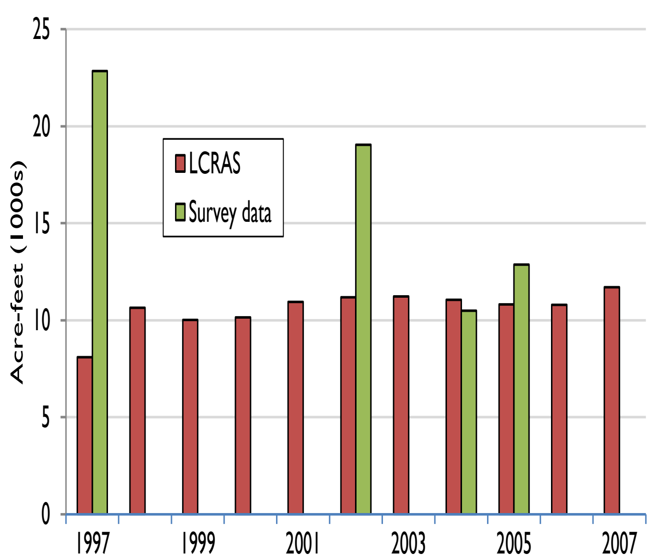

Figure 39. Riparian Vegetation ET in the U.S. Portion of the limitrophe, 1997-2007.

Sources: Natural Channel Design, Reclamation, BLM, Nagler et al. (2008).

Figure 40 on the following page shows total pumping within the exclusionary zone for the years 1975-2010. Mexico's pumping dropped to zero during the years 1998-2000, due to the availability of large volumes of better-quality Colorado River water. Average U.S. annual pumping from its PRPU wellfield in the years 1996-2002 was less than 10 percent of its average annual pumping in 2007-09; non-federal pumping within the U.S. side of the exclusionary zone increased by about 35 percent between these two periods. Note that Mexico approached its 160,000 AF annual limit in 2007 and again in 2009. Figure 40 also displays the increasing trend in total pumping within the five-mile exclusionary zone. Note that the average for the years 1975-2000 was 89,000 acre-feet, increasing to 170,000 acre-feet for the years 2001-2009. For the years 2005-2009, annual reported pumping by both countries was almost 200,000 acre-feet, more than double the rate for the first 25 years of record. Note that total pumping declined by 33 percent from 2009 to 2010, likely as a result of the Easter 2010 earthquake that damaged a large portion of Mexico's irrigation infrastructure, reducing the ability to convey water.

Figure 41 on the next page plots water table elevations at the four southernmost U.S. monitoring wells against the total reported quantity of groundwater pumped within five miles of the border, in Mexico and in the U.S. Note that the volumes of groundwater extraction, on the secondary y-axis, are in reverse order, to facilitate comparisons with water table elevations. Note also that water table elevations are date specific, while pumping volumes are annual; to facilitate comparison with changing groundwater conditions, these annual values have been arbitrarily plotted in late September of each year. Pumping volumes correlate well with changing depth to groundwater at the wells in the southern limitrophe, suggesting that large-scale pumping in the exclusionary zone diverts groundwater that would otherwise flow to the limitrophe. The change in water table elevations from 2004-2009 (see Figure 3) correlates with the recent period of increased pumping, explaining the zone of falling water table elevations around the Minute 242 wellfields east of San Luis. However, as discussed in Chapter V, these water table declines also correlate well with the significant reduction in Colorado River flows through the limitrophe reach, complicating the interpretation of these results. Although this pumping does not directly explain the cone of depression centered at the SIB, it suggests that diverted groundwater flows may exacerbate other factors affecting the lower third of the limitrophe region, as described in Chapter V.

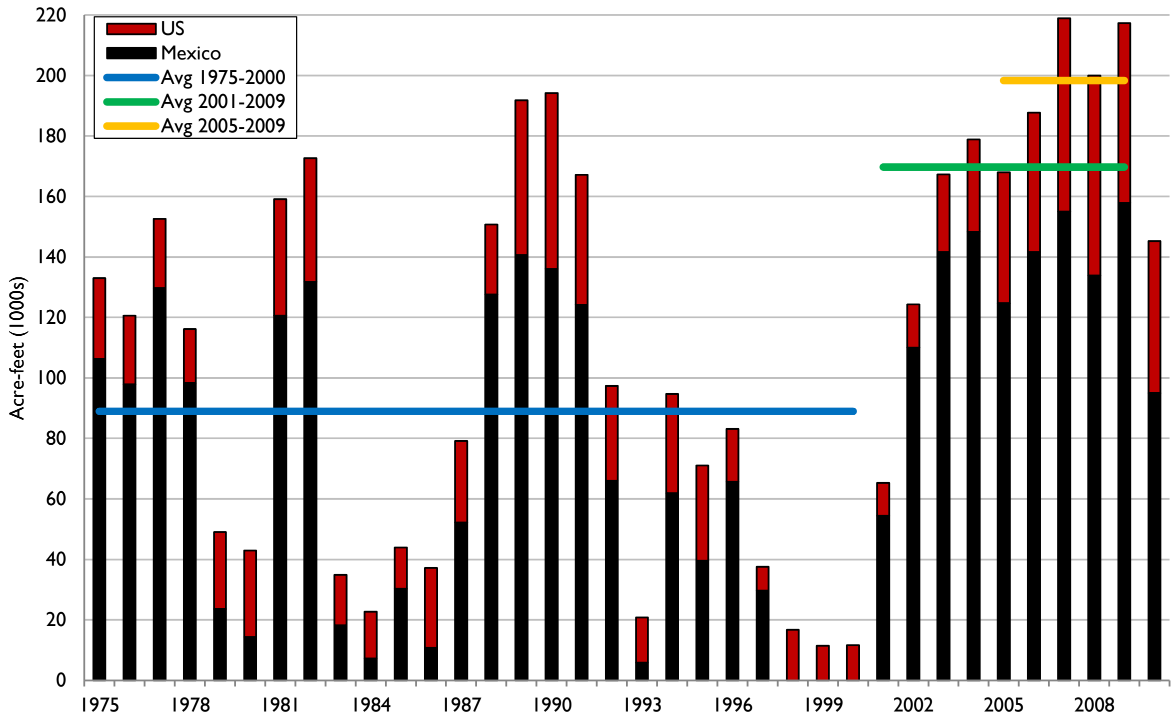

Figure 40. Total Reported Quantity of Groundwater Pumped within Five Miles of the SIB, in Mexico and in the U.S., 1975-2010.
Source: IBWC.

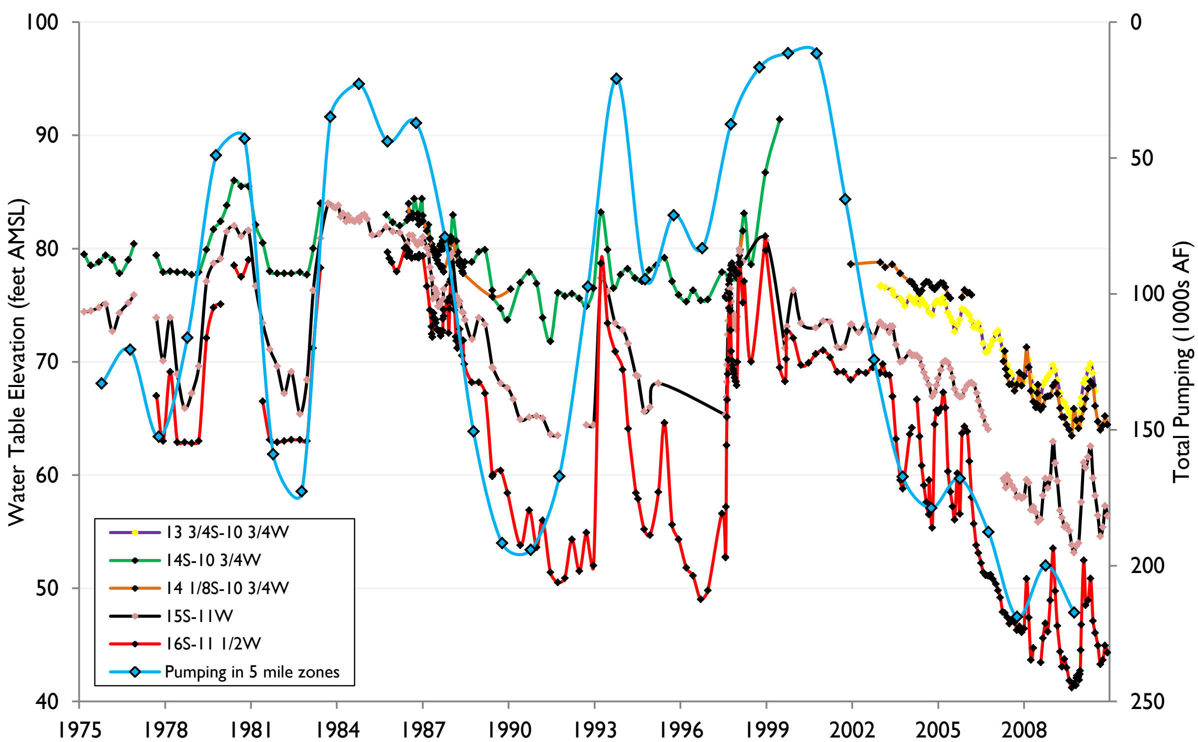

Figure 41. Water Table Elevations and Total pumping in exclusionary zones,1975-2010.
Sources: Reclamation, IBWC. Note that values on second y-axis are in reverse order.

Chapter V - Surface Flows

The Colorado River basin covers some 244,000 square miles, roughly 99 percent in the U.S. and 1 percent in northwest Mexico. A tremendous disparity in the spatial and temporal distribution of water characterizes the Colorado River basin. More than 80 percent of runoff in the basin originates from less than 20 percent of the basin, generally in the Rocky Mountains at elevations greater than 8000 feet (Hoerling et al. 2009). The Colorado is largely snowmelt-driven: some 70 percent of the river's annual pre-impoundment flow occurred from May through July (Harding et al. 1995). Much of the basin, especially the border region, is extremely arid, with less than 3 inches of precipitation per year. The river itself runs more than 1,400 miles from its headwaters to its mouth at the Gulf of California, though in recent years the Colorado River rarely has had enough water to run uninterrupted to the SIB. During those rare instances when water flows past the SIB, the river occasionally runs another 75 miles to its mouth at the Gulf of California.

Since the closing of Glen Canyon Dam in 1963, the measured annual flow of the river at the NIB exceeded 1.6 million acre-feet (MAF) less than a third of the time. Average recorded annual flow at the NIB for the period 1950-2010 was 3.06 MAF while the median for the period was 1.54 MAF, reflecting the higher flows before the closing of Glen Canyon Dam and the high flow period of 1983-1988. At the SIB, roughly 22 miles downstream from the NIB, average recorded annual flow from 2001-2010 was 0.027 MAF; in 2006, 2007, and again in 2009, no measurable discharge was recorded at the SIB.[60]

The Law of the River[61] governs Colorado River allocations, flows, and use, controlling and monitoring the river more tightly perhaps than any other river in the world (Getches 1985). By treaty[62], the U.S. annually delivers a minimum of 1.5 MAF of water to Mexico, within a prescribed salinity range. Of this volume, up to 0.15 MAF may be delivered at the land boundary near San Luis. To date, the U.S. has never failed to deliver at least 1.5 MAF of Colorado River water to Mexico. Within the U.S., the Law of the River generally grants the right to 15 million acre-feet/year of Colorado River water, divided between the upper basin (comprised of the upper division states of Colorado, New Mexico, Utah, and Wyoming) and the lower basin (comprised of the lower division states of Arizona, California, and Nevada).

Ten major dams along the mainstem and more than 80 major diversion points along the river control and divert the Colorado River. The U.S. has sufficient storage capacity to hold four years' flow of the Colorado River. Mexico, however, lacks any Colorado River surface storage capacity, relying instead on groundwater, recharged primarily by Colorado River flood flows and infiltration from irrigation, to supplement surface water deliveries. Farmers throughout the basin divert an estimated 70-80 percent of the river's waters to irrigate some 3,000,000 acres.

As shown in Figure 42, consumptive use[63] of Colorado River water within the U.S. grew steadily from 6.5 MAF in 1950 to a maximum of 12.6 MAF in 2001, but this fell to about 11 MAF per year from 2003-2007, and then rose again to about 12 MAF in 2008. Several factors have contributed to the recent decline, most notably a decline in California's use from a high of more than 5.36 MAF in 2002 to about 4.4 MAF in subsequent years. Other factors include the multi-year drought that curtailed run-of-the-river upper basin diversions, and the recent economic downturn, reducing municipal use, especially in Nevada.

Although records of total Colorado River deliveries to Mexico are readily available, long-term consumptive use records for Mexico are not. In 1995, Mexican irrigators used 1.5 MAF of Colorado River water, roughly equivalent to the total delivery that year. In 1999, they used 1.36 MAF, less than half of that year's delivery. Total municipal use in the Mexican portion of the basin, largely extracted from groundwater, is less than 0.4 MAF annually (Cohen and Henges-Jeck 2001). Since Mexico lacks surface storage capacity for Colorado River water, deliveries that exceed direct irrigation demand and the limited volumes (0.06 MAF per year) used for direct groundwater recharge, flow down the channel toward the Gulf of California, as shown by records from the gaging station at the SIB. Since the closing of Morelos Dam in 1950, the difference in the annual average flows recorded at the NIB and at the SIB averages 1.6 MAF, with a median value of 1.4 MAF. Unfortunately, no gaging station currently operates below SIB, to measure the volume of Colorado River water flowing to the Gulf of California (Cohen et al. 2001). Despite these very low flows and reports from the late 1970s (Fradkin 1981) and from recent years (Waterman 2010) about the dry Colorado River, anecdotal reports indicate that the river does periodically flow unbroken to the gulf (Hinojosa-Huerta, pers. comm., 2010).

The 2011 water year (starting in October 2010) saw unusually heavy snowfall in the northern portion of the Colorado River basin, and higher than average spring and summer precipitation through much of the upper basin. According to Reclamation, the observed 2011 April – July unregulated inflow into Lake Powell was 12.89 MAF or 162 percent of average. Total run-off in the basin in the 2011

[60] See discussion of SIB gage accuracy on pp. 17-18 and in Appendix B.

[61] The "Law of the River" refers to the complex, evolving set of laws, treaties, decrees, regulations, contracts, and other legal decisions determining and guiding the management and allocation of the Colorado River. See D. Getches, 1985, Competing demands for the Colorado River, *University of Colorado Law Review* 56: 413-479, and U.S. Department of the Interior, Bureau of Reclamation, 2010, *Colorado River Documents 2008*, Denver: U.S. Government Printing Office.

[62] *Treaty Respecting Utilization of Waters of the Colorado and Tijuana Rivers and the Rio Grande, United States-Mexico*, 59 Stat. 1219. (1944).

[63] As defined in the Supreme Court's Consolidated Decree of 2006, "consumptive use" means "diversions from the stream less such return flow thereto as is available for consumptive use in the United States or in satisfaction of the Mexican Treaty obligation."

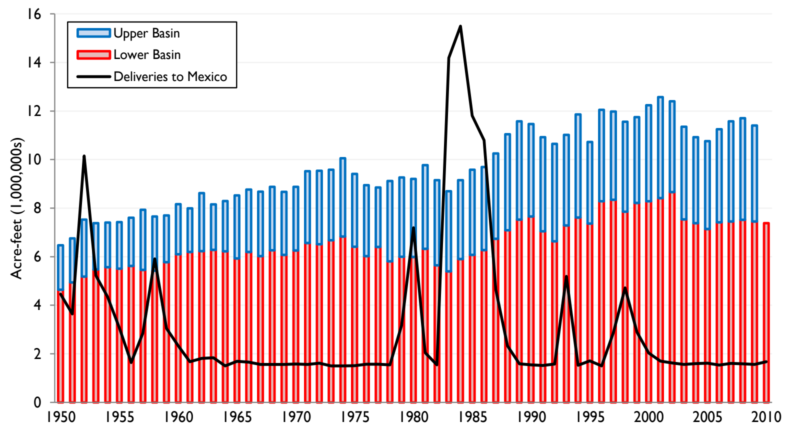

Figure 42. Annual Colorado River Consumptive Use (U.S.) and Deliveries to Mexico, 1950-2010.
Source: Reclamation. (Upper Basin consumptive use provisional 2006 through 2009.)

water year was 139 percent of average, at least temporarily halting the decade-long drought that decreased runoff from 2000 through 2009. In that ten-year period, annual natural flows exceeded the hundred year average only two times. Annual flows from 2000-2009 were about 75 percent of the historic average, yet resulted in no reductions in deliveries to lower basin or Mexican users. Instead of reducing deliveries to users, the shortage was absorbed by the reservoirs, causing total system storage to fall by roughly 23 MAF – about 150 percent of the river's average annual flow.

Thanks to the 2011 water year's very high run-off, the surface elevation of Lake Mead rose to more than 37 feet higher than 2010 elevations. But one wet year does not overcome the Colorado River's long-term supply-demand imbalance. Total demands on the Colorado River now exceed supply: Colorado River users now face a structural deficit. To date, basin water users have overcome this supply imbalance by drawing from storage, but this is not a sustainable approach over the long term. Rapid population growth in the region and the likelihood that climate change will diminish supply[64] will only exacerbate this imbalance in coming years.

Mainstem and wasteways

Figure 43 shows reported monthly Colorado River flow at the NIB and at the SIB from 1950 through 2010. Note that the accuracy of the SIB gage has been characterized as very poor (Hill 1993); since 2005, the gage has been temporary, installed only when IBWC staff anticipate flows. In Figure 43 (next page), note the periodic peak flows in the 1950s, 1980s, 1993, and at the turn of the century. From 1963 through 1980, Reclamation used Colorado River water in excess of that needed for U.S. and treaty deliveries to fill Lake Powell, explaining the absence of peak flows at the NIB and SIB during this extended period. At the scale of this figure, reported monthly SIB flows in the 1960s and 1970s appear similar to reported SIB flows in the 2000s. However, as shown in Table 7, actual reported values between these two periods differed dramatically. In the 1960s, only five percent of the months recorded no flow at all ("Q=0") at the SIB; in the 2000s, fully half of the months showed no flow at the SIB. Note also the significant difference in median flows between the 1960s-70s and the 2000s; such data clearly illustrate the declining trend in flows through the limitrophe. In the 1990s, there were more months with no recorded flow at the SIB than there were in the 2000s, but the large flood in 1993 and the high flows in 1997 and 1998 meant that much more water overall flowed past the SIB in the 1990s. Unfortunately, large data gaps exist in the monitoring well records during the 1990s, precluding any meaningful comparison between the two decades.

Table 7. Monthly SIB Flows, by Decade. Source: IBWC.

Acre-feet	mean	median	max	min	Q=0 (number of months)
1950s	249,629	139,140	1,078,420	1,663	-
1960s	14,833	6,203	237,722	0	6
1970s	17,260	12,041	153,108	0	10
1980s	405,167	209,467	1,738,851	0	24
1990s	61,337	0	1,182,444	0	61
2000s	4,020	6	61,196	0	60

[64] See for example Christensen, N.S., and D.P. Lettenmaier, 2007. A multimodel ensemble approach to assessment of climate change impacts on the hydrology and water resources of the Colorado River Basin, *Hydrology and Earth Systems Sciences* **11**: 1417-1434; Barnett, T.P., and T.W. Pierce, 2009, Sustainable water deliveries from the Colorado River in a changing climate, *Proceedings of the National Academy of Sciences*, www.pnas.org_cgi_doi_10.1073_pnas.0812762106; and Reclamation, 2011, SECURE Water Act Section 9503(c) – Reclamation Climate Change and Water, Report to Congress. Available at http://www.usbr.gov/climate/SECURE/docs/SECUREWaterReport.pdf.

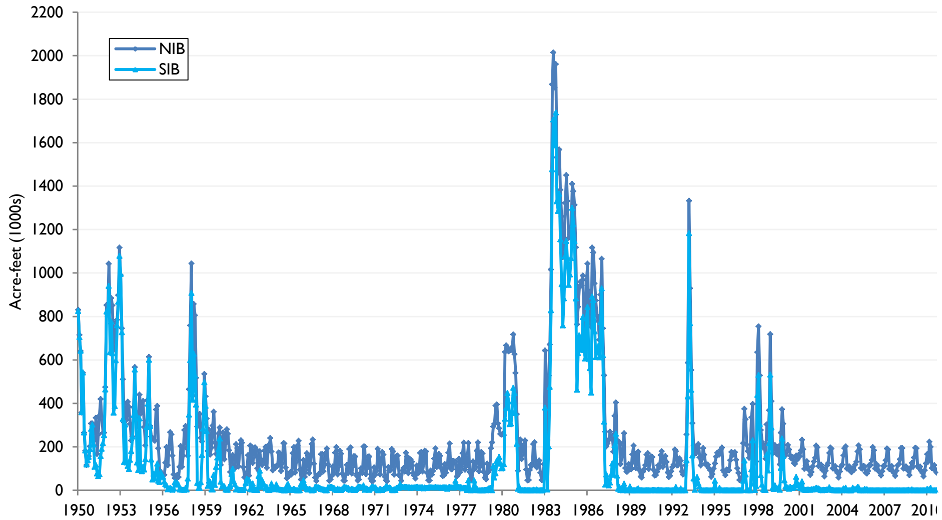

Figure 43. Monthly Colorado River Flow at NIB and at SIB, 1950 - 2010.
Sources: USGS, IBWC.

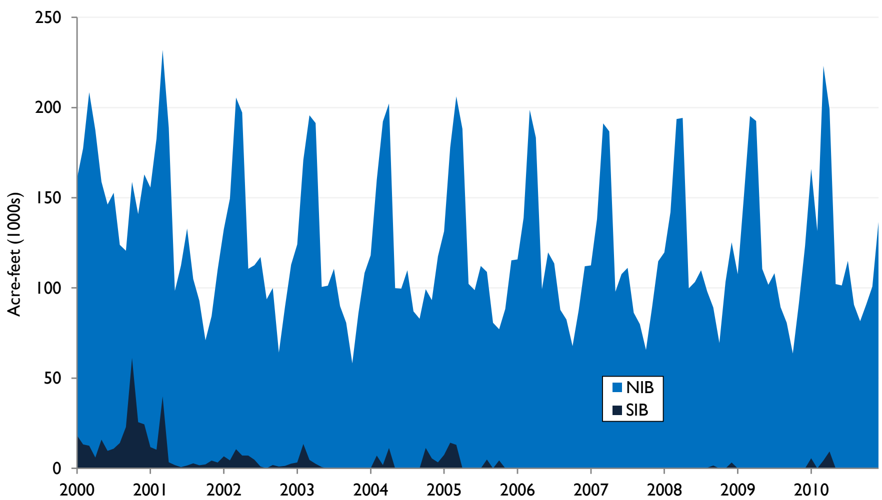

Figure 44. Monthly Colorado River flow at NIB and at SIB, January, 2000 to December, 2010.
Sources: USGS, IBWC.

Figure 44 shows monthly Colorado River limitrophe flows at a finer scale, focusing on the period from January 2000 through December 2010. Note that the vertical scale is roughly a tenth that of Figure 43. Both graphs show the marked seasonal variability in deliveries at the NIB, with deliveries typically peaking in March each year, at a volume more than double that of September-October deliveries. Figure 44 also shows that reported flow at the SIB in the first half of the 2000s was greater than that in the second half. Between November 2005 and December 2009, reported monthly flow at the SIB exceeded 100 acre-feet only four times. From November 2005 through December 2009, a combined total of 5,585 acre-feet reportedly flowed past the SIB.

Reported discharge at the SIB is frequently used as a proxy for flows in the remnant Colorado River delta. Yet water may flow through the upper portions of the limitrophe without reaching the SIB. For example, several years have recorded zero flow at the SIB, but calculated flow below Morelos Dam and reported flows from the 11-mile and 21-mile wasteways have been much greater than zero in those years. Figure 45 on the next page plots calculated flow in the limitrophe reach below Morelos Dam against reported flow at the SIB, for the years 2002-2003. Values for each are plotted as a five-day rolling average, to smooth the sharp variability of some of the daily values. Note that reported flows at the SIB exceeded calculated limitrophe flow at several times during these years, such as during the latter half of May 2002. It is not clear if this lag behind the calculated limitrophe peak flows in mid-April reflects a slow-moving pulse of sub-surface flows or simply reflect errors in reporting. The relationship between discharge rates, soil saturation conditions, and travel time between Morelos Dam and the SIB merit further investigation.

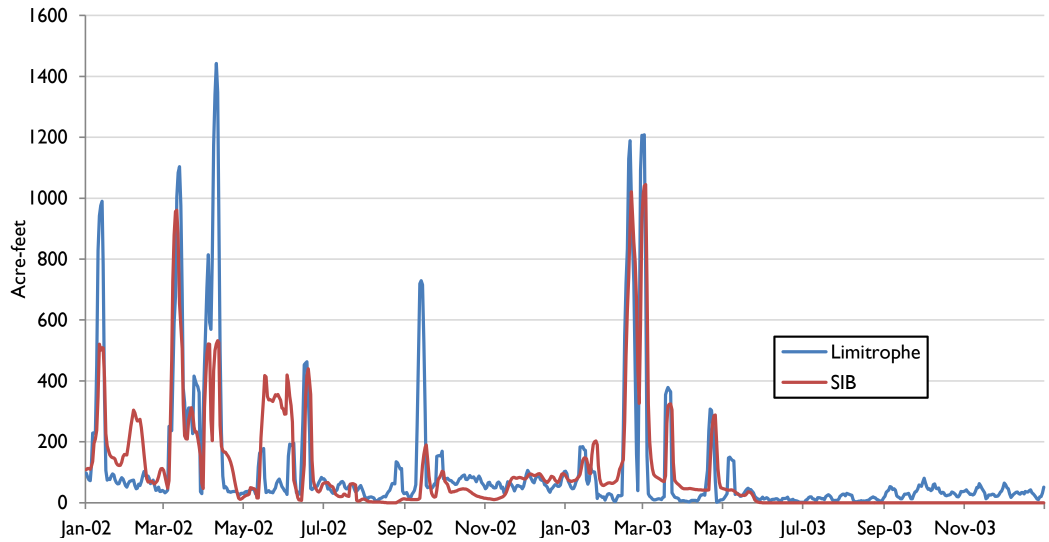

Figure 45. Rolling 5-day Average Calculated Flow Below Morelos Dam and Reported Flow at SIB, 2002-2003.
Source: IBWC.

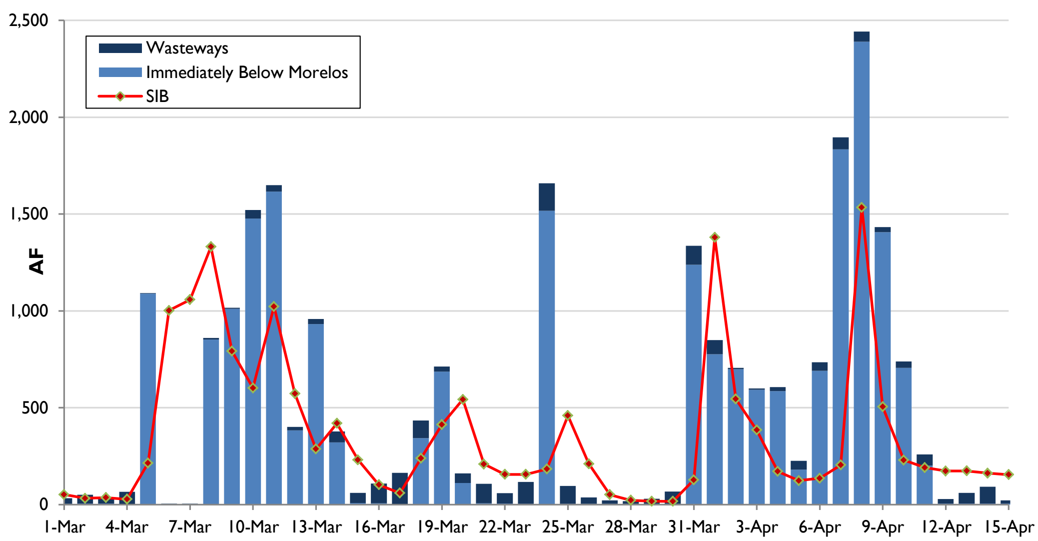

Figure 46. Daily flows below Morelos Dam and at the SIB, March 1-April 15, 2002.
Source: IBWC.

Note that no flow was recorded at the SIB from May 27-December 31, 2003, though calculated daily flow below Morelos Dam averaged 25 acre-feet in that period. Of these calculated flows, 99.3 percent came from the 11-mile and 21-mile wasteways. Aside from limited losses to ET, this flow below Morelos Dam and from the wasteways apparently infiltrated into the channel and recharged the local water table. The total volume of these calculated and reported flows below Morelos Dam from May 27 through December 31, 2003, when no flow was reported at the SIB, was roughly 5,500 acre-feet.

Figure 46 illustrates the relationship between limitrophe flows and flows at the SIB during the period of March 1 through April 15, 2002 depicted in Figure 45. Unlike the rolling five-day averages shown in Figure 45, Figure 46 depicts reported daily flows for the 11-mile and 21-mile wasteways (combined as "wasteways" in the figure) and the calculated daily flows immediately below Morelos Dam. Several errors reveal themselves in this more detailed observation. On March 5, 2002, total calculated flows in the limitrophe[65] were 1,100 acre-feet; total calculated flows from March 5-7 were 11 acre-feet higher. Yet the corresponding values for reported flow at the SIB were 220 acre-feet and 2,300 acre-feet. That is, more than twice as much water reportedly flowed past the SIB as flowed below Morelos Dam during this three-day period. The small flow event of March 17-22, with total calculated limitrophe flows of 1,600 acre-feet,

[65] The total of the calculated volume of flow immediately below Morelos Dam plus the reported total flow of the two wasteways.

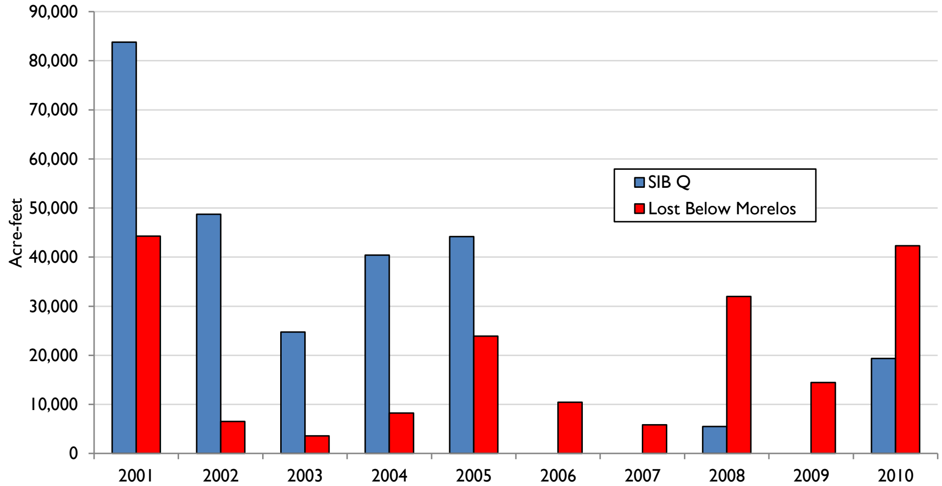

Figure 47. SIB Flow and losses to channel below Morelos Dam, 2001 –2010.
Source: calculated from IBWC data.

apparently prompted about 1,600 acre-feet to flow past the SIB during that period. Yet during the period March 23-28, calculated limitrophe flows of 1,900 acre-feet generated only 1,100 acre-feet at the SIB.

There are several possible explanations for the reported difference in SIB flows following the March 17-22 and March 23-28 limitrophe flows. Although I would expect the latter period to show greater flow at the SIB, since the channel would have already been wet, diminishing infiltration, the high limitrophe flow on March 24 may have increased river stage, possibly filling backwaters or otherwise diverting flow from the mainstem to secondary channels that were not receiving water at lower river stage. Or there may have been errors in the calculated and/or reported flows.

Figure 47 compares reported flow at the SIB with the difference between the calculated flows below Morelos Dam[66] and flow at SIB, for the period January 2001 – December 2010. In the high flow years of 1998-2000, this difference was a negative value – reported flow at the SIB was greater than the calculated flow below Morelos. Several factors could explain this negative value: errors in the data, returns from bank storage, and the period in which data was reported.[67] The simplest explanation for this unexpected negative value is that the recorded values at one or more of the gages were in error. Historically, the SIB gage has had a reported error of greater than 15 percent, significantly greater than the 3.5 percent difference in calculated and recorded flows at the SIB in 1999. However, in 2000, this difference rose to 39 percent, so gage error is likely not the culprit. One possible explanation is that the additional SIB flow came from bank storage. In December 1998, the depth to groundwater at monitoring well 16S-11 1/2W, near the SIB, rose to within 1.4 feet of the surface below the well itself. Extrapolating the elevation of the water table based on the GIS analysis of 2007 land surface conditions and 1999 river channel elevations suggests that the water table may have been ten feet above the bottom of the river channel at the SIB in December 1998, which would explain the high calculated base flows at the time.

In Figure 47, note that the total difference between calculated limitrophe flows and reported flows at the SIB was higher in 2006 (10,500 acre-feet) than in 2003 (3,600 acre-feet), despite the much higher total volume of limitrophe flows in 2003 (28,000 acre-feet) than in 2006 (10,000 acre-feet). This discrepancy illustrates the importance of discharge rates. As shown in Figure 45, most of the total 2003 flows occurred in two large peak flows and two smaller peak flows; the maximum calculated discharge below Morelos Dam was more than 1500 cfs on February 27, 2003, suggesting that larger pulse flows may move too quickly to be absorbed by the channel. Note also that, prior to 2006, the volume of flows "lost" below Morelos was always less than the volume of flows recorded at SIB. In what may be a coincidence, this period coincides with the time when the SIB gage was a permanent fixture; after 2005, IBWC has installed the SIB gage on a temporary basis. The inconsistency of the reported flows at SIB relative to the calculated flows in the limitrophe suggest that the gage may not have been installed at every instance of flow in the channel, resulting in the discrepancy shown in Figure 47.

Appendix B describes a preliminary comparison of daily discharge rates below Morelos Dam and at the SIB. The relationship between discharge and channel infiltration in the limitrophe reach, important for understanding instream flow deliveries and channel surface water - groundwater

[66] See Chapter II for a description of the method used to calculate these flows.

[67] Depending on the magnitude of flows, water released through Morelos Dam may take from several hours to several days to travel downstream to the SIB gage. While high magnitude releases could be recorded the same day downstream, low, steady flows might not reach the SIB gage for two to three days, which could result in flows below Morelos Dam being recorded in a different month or even year than flows recorded at the SIB.

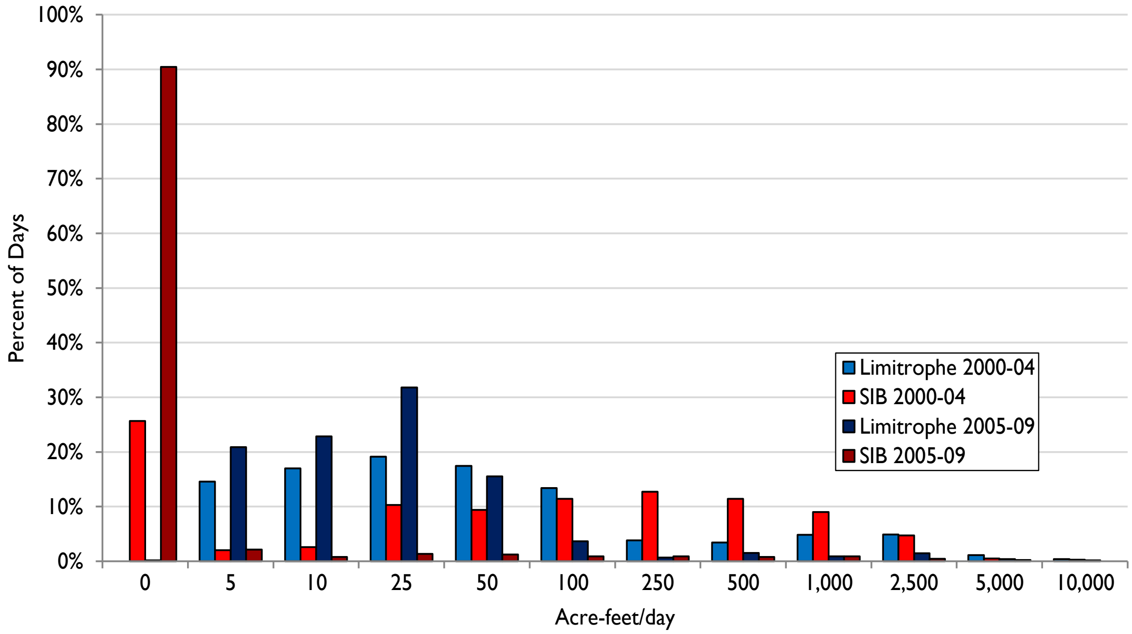

Figure 48. Frequency histogram showing the distribution of daily discharge volumes in the limitrophe and at the SIB.
Source: calculated from IBWC data.

interactions, merits further study. Such an assessment should also include a current channel survey.

Table 8. Summary statistics for Figure 48.

	Limitrophe		SIB	
AF per day	2000-2004	2005-2009	2000-2004	2005-2009
mean	212	72.6	237	27
median	23.8	12.2	50	-
max	9,770	6,060	8,970	4,270
number of days	1,827	1,826	1,827	1,826

Figure 48 shows the frequency, as a percentage of total days, with which a given daily discharge occurred in the years 2000-2004, and in the years 2005-2009. For example, for "5", the bar represents the percentage of the total number of days in which recorded flow was greater than zero but less than five. Note that the limitrophe values are derived data, rather than reported gage data, and further that such values have been adjusted to eliminate negative values, which occur in more than five percent of calculated daily discharge rates below Morelos Dam, as reported diversions at the dam exceeded the combined recorded flows at the NIB and from the Cooper wasteway. Note the significant difference in flows in the earlier versus the later period. For the years 2000-2004, more than 74 percent of days had flows at the SIB. For the years 2005-2009, less than 10 percent of days had any recorded flow at the SIB. This has been a dramatic, recent change. Table 8 shows summary statistics for these values. In Table 8, note that mean and median values for the SIB for the early period are higher than the corresponding values for the limitrophe, reflecting high base flows in the early part of the decade.

Groundwater and Surface flows

The dramatic decline in surface flows at the SIB in the latter half of the last decade has clear implications for groundwater recharge, water table elevations, and the health of the riparian corridor. This section assesses the impacts of declining flows in the lower limitrophe on local groundwater elevations. Figure 49 plots reported water table elevations at monitoring wells in the upper, middle, and lower portions of the limitrophe against monthly surface flow at the SIB, for the period of record. Note that water table elevations at all three wells peaked at the same time, in response to the 1983-1988 floods, though in each case these maximum water table elevations were less than a foot higher than the maximum elevations shown in 1957. Slightly lower water table elevations were also reported at these wells (where data exist) in response to the 1980 and 1998 flood events, even though these events were of much lower magnitude. The marked decrease from the 1950s to the 1960s and 70s in average monthly flow at the SIB likely explains the roughly five-foot decline in water table elevations at well 15S-11W and the slightly smaller declines at the upstream wells, though not the fluctuations in these elevations.

Note that no flow at all was recorded at the SIB from January 2006 through December 2007, and again at any time in 2009, correlating well with the significant decline in groundwater

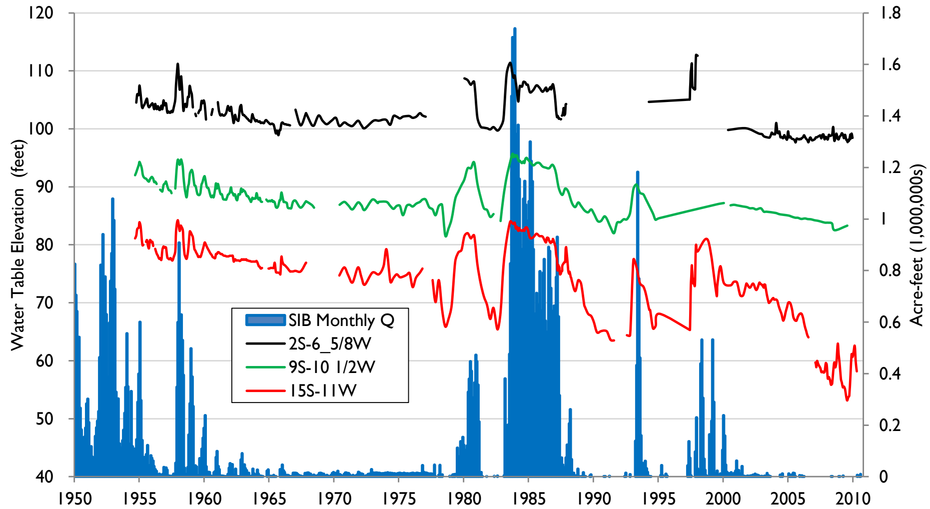

Figure 49. Water table elevations vs. SIB monthly flows, 1950-2010. Sources: Reclamation, IBWC.

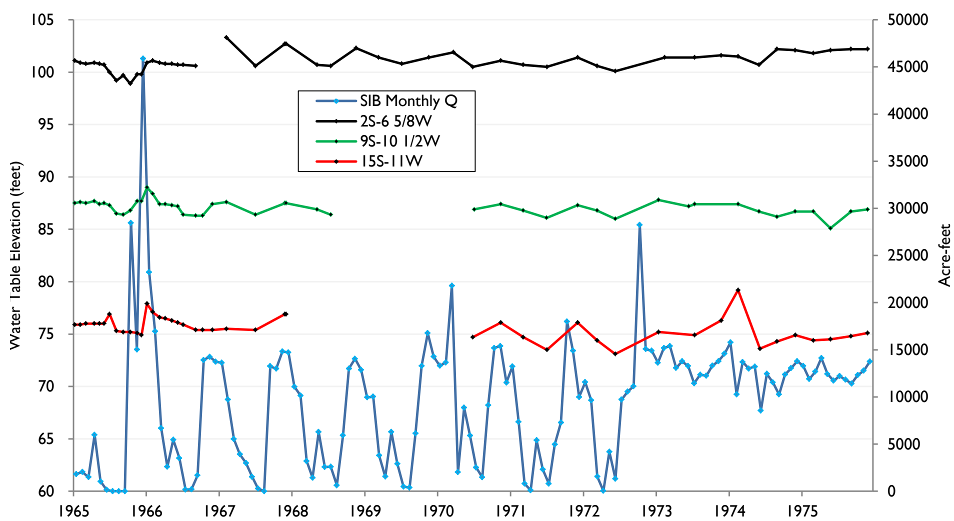

Figure 50. Water Table Elevations vs. SIB Monthly Flows, 1965-1975.
Sources: Reclamation, IBWC.

elevations at well 15S-11W and to a lesser extent with the gradual decline at well 9S-10 1/2W, near Gadsden. The calculated flows immediately below Morelos Dam likely explain the relatively low fluctuations in water table elevations reported by the well near Morelos Dam. Pulse flows in 1993, early and late 1998, and late 1999 correlate well with rising groundwater elevations, as do smaller, brief pulses in October 2000 and March 2001. Zero flow in 2009 clearly contributed to falling groundwater elevations at the SIB and Gadsden wells, but again did not appear to affect the well near Morelos Dam. Small flows in January and March 2010 apparently increased SIB groundwater elevations near the SIB by more than ten feet.

Figure 50 depicts the seasonal variability of Colorado River flows at the SIB, especially from 1965-1972, and the response of the water table to this variability. Note that the water table elevations at the three wells – located near Morelos Dam, roughly in the middle of the limitrophe, and near the SIB, respectively – show much less variability than they do in recent years. The key difference between the period shown in Figure 50 and in recent years is the magnitude of reported flows at the SIB. During the time shown in Figure 50, monthly flows averaged 9,500 acre-feet; from 2006 through 2010, the monthly average was 400 acre-feet. These recent low flows apparently are not sufficient to recharge the aquifer, resulting in the declining water table seen in the lower portion of the limitrophe.

The next three figures explore the relationship between reported flows at the SIB and reported water table elevations adjacent to Hunter's Hole, approximately two

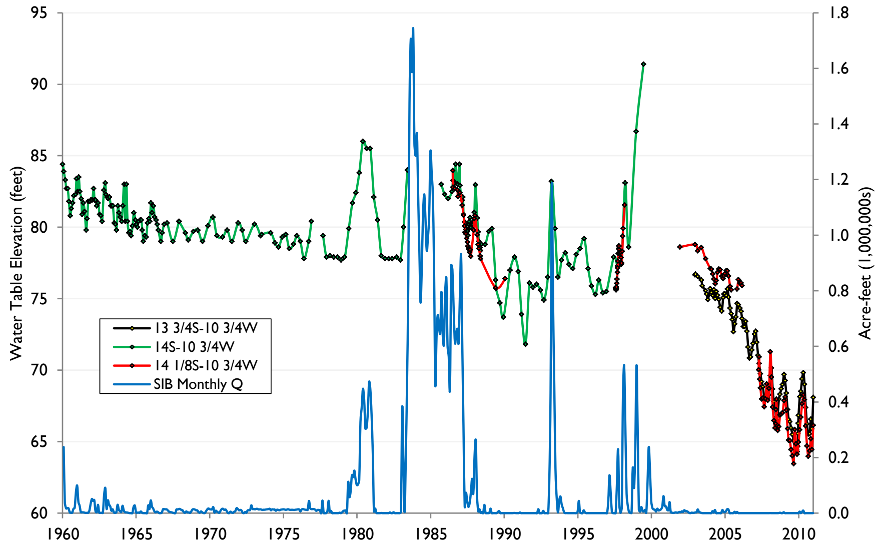

Figure 51. Water Table Elevation near Hunter's Hole and Monthly Flows at SIB, 1960-2010.
Sources: Reclamation, IBWC.

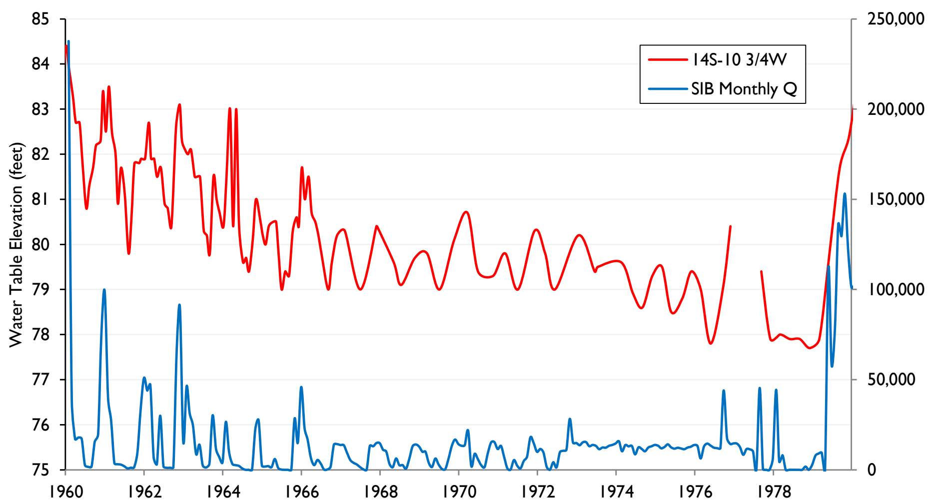

Figure 52. Water Table Elevation near Hunter's Hole and Monthly Flows at SIB, 1960-1979. Sources: Reclamation, IBWC.

miles upstream from the SIB gage. Figure 51 depicts these data from 1960-2010; Figure 52 focuses on the years 1960-1979, a prolonged period with limited high flow events; and Figure 53 reflects data from January 2002 through December 2010. Data limitations hamper this assessment; none of the observation wells was operational through the full period of record, and large gaps appear in the records of each monitoring well. In Figure 51, the water table at well 14S-10 3/4W responds to the 1980 and 1993 floods (the addition of new rip-rap to protect against the 1983 flood destroyed the well), though the reported elevations of December 1998 and June 1999 may reflect transcription errors. Water table elevations at well 14 1/8S-10 3/4W correlate well with those at well 14S-10 3/4W and at well 13 3/4S-10 3/4W. Note the gradual, 6.5 foot decline in water table elevations from January 1960 until March 1979, and the eight-foot rise over the next 15 months, in response to more than 2.68 MAF of reported Colorado River flow at the SIB during those months. By May 1981, the Colorado River no longer reached the SIB; by September, the water table had fallen to its pre-flood elevation.

Figure 52 shows monthly flows at the SIB and reported water table elevations at well 14S-10 3/4W, near the southern end of Hunter's Hole. Note that peak water table elevations declined 4.2 feet from 1960 to 1966, and then entered a period of dynamic equilibrium, with seasonal fluctuations apparently driven by Colorado River flows, for the following seven years. Interestingly, despite a period of relatively high monthly Colorado River flows (monthly average 1973-74: 13,000 acre-feet), the water table declined 2.4 feet from its peak in 1973 to its nadir in February 1976. Interestingly, the monthly volume of Colorado River water lost between Morelos Dam and the SIB during the early 1970s averaged

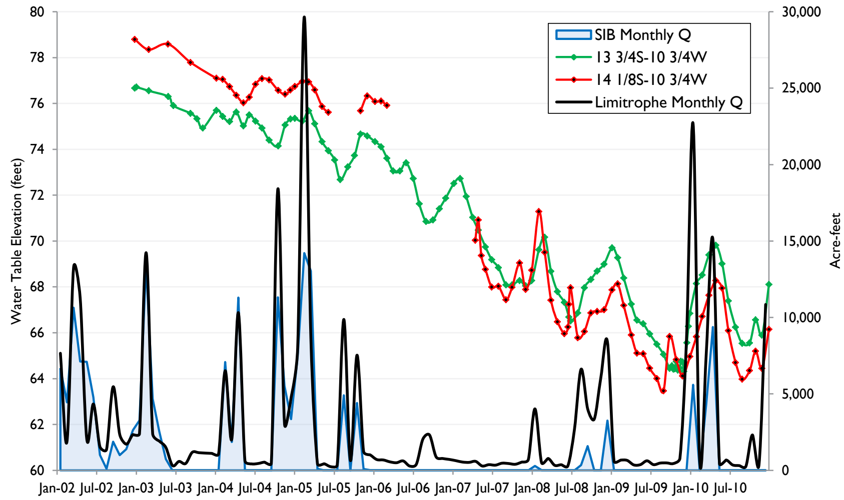

Figure 53. Water Table Elevation near Hunter's Hole and Surface Flows, Jan. 2002-Dec. 2010.
Sources: Reclamation, IBWC.

about 6,600 acre-feet, but this volume rose to 23,000 acre-feet in September 1976, likely explaining the 2.6 foot rise in the water table at that time.

Figure 53 clearly shows the water table's falling elevation in the latter half of the 2000s, dropping 11.3 feet from March 2005 to October 2009 in the context of extended periods of zero flow at the SIB and increased withdrawals from the Minute 242 wellfields. Note that the water table rose almost two feet in the last two weeks of December 2009, despite no reported flow at the SIB, reflecting the 7,600 acre-feet of flows immediately below Morelos Dam[68] and the additional 570 acre-feet of discharge from the 11-mile and 21-mile wasteways from December 11 through December 29, 2009. Records indicate that the Hunter's Hole pump, discharging water into Hunter's Hole restoration sites, was running on December 3 but was turned off December 7 and remained off. The total volume of water extracted by this pump, as a function of rated pump capacity, would have been about 120 acre-feet over this period. The source of the 2.4 foot rise in the water table elevation from September to October 2009, at well 14S-10 3/4S is not known. Note that the water table elevation at well 13 3/4S-10 3/4W rose 5.5 feet from its low on December 7, 2009 to its high on May 4, 2010; during this period, a total of 35,000 acre-feet of Colorado River water were lost between Morelos Dam and the SIB.

Chapter IV compares reported volumes of groundwater extraction and water table elevations. Figure 35, for example, compares reported pumping volumes from West Cocopah and reported water table elevations at nearby wells. Figure 54 on the next page compares these same elevations with calculated daily flows through the limitrophe reach (in lavender), reported flows at the SIB (in blue), and the calculated non-negative difference between these two values (in green), all shown on the secondary y-axis. The area shown in green is simply the non-negative difference between the other two values. Note that this difference in flows has a calculated potential error of greater than 27 percent, and that the reported flows at the SIB have an error of greater than 15 percent. Negative values (that is, days in which reported flows at the SIB exceeded calculated limitrophe flows) are not shown in Figure 54.

On the next page, Figure 55 shows both the calculated positive and negative differences in values between limitrophe and SIB flows. The three monitoring wells have extensive data gaps, with no data reported between January 31, 1990 and July 31, 1997, and again from March 13, 1998 until December 14, 2001. Note that the reported July-September 1997 water table elevations at well 8S-10 1/8W do not reflect the rising trend evident at the other two wells. From August through October 1997, the water table elevations appear to vary in response to reported pumping volumes, but the post-October decline in the water table, especially at well 7 1/2S-9 7/8W, does not reflect the decreasing amount of water pumped by the nearby wells.

The late January 2010 channel loss of about 16,000 acre-feet, shown in Figure 53 as the difference between "Limitrophe Monthly Q" and "SIB Monthly Q," correlates with a rise in the elevation of the water table near the SIB of about 5.7 feet, as shown in Figure 56 on the following page. From December 2009 to May, 2010 the water table near Hunter's Hole rose about 5.5 feet; during this period, a total of 35,000 acre-feet of Colorado

River water were lost between Morelos Dam and the SIB. The loss between Morelos Dam and the SIB of some 5,400 acre-feet as a result of Colorado River releases through the dam in early April raised the water table near the SIB by 2.0 feet from April 2 to May 4, though by June 2 the

[68] This volume includes the very unusual release of 2,000 acre-feet of water from the Wellton-Mohawk MODE #3 Wasteway immediately below Morelos Dam; in most years, total annual discharge from this wasteway is zero.

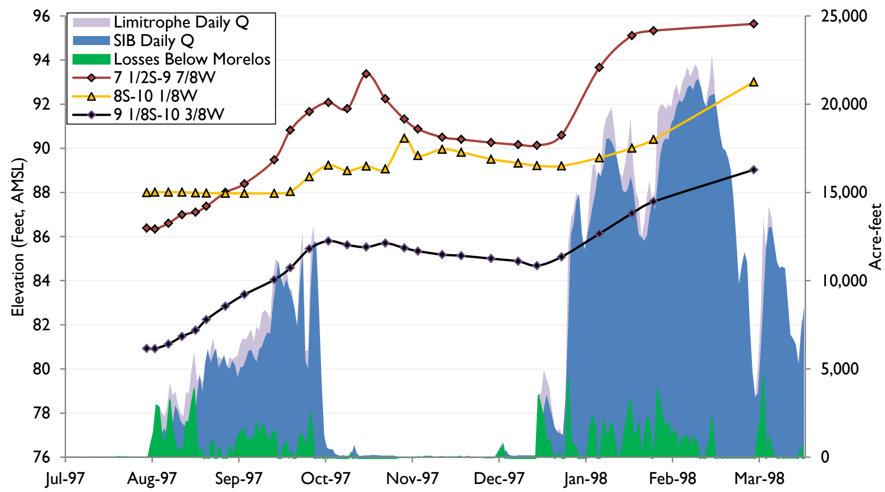

Figure 54. Water Table Elevations near West Cocopah and Colorado River Flows, July, 1997-March, 1998.
Sources: Reclamation, IBWC. Compare with Figure 35.

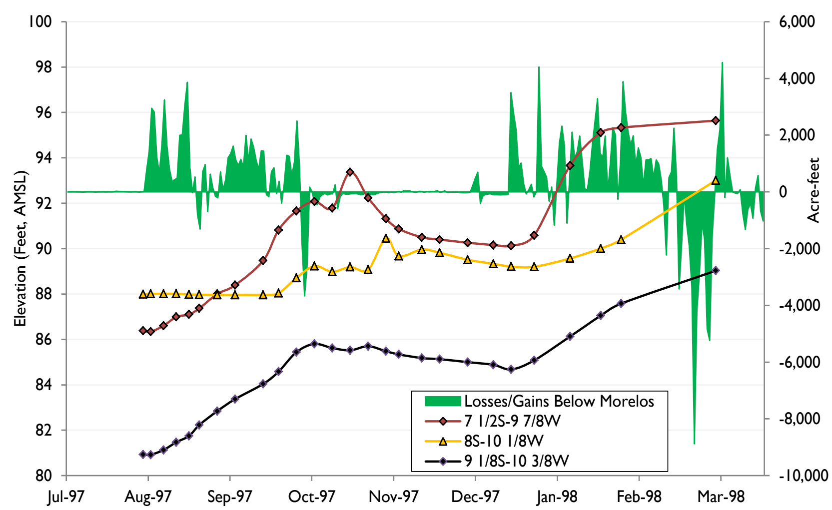

Figure 55. Water Table Elevations near West Cocopah andDifferences between Calculated Colorado River Flows below Morelos Dam and Reported Flows at the SIB, July 1997 – March 1998.
Sources: Reclamation, IBWC.

water table had fallen 3.8 feet and fell another foot by July 1. This suggests that this April release generated a temporary subsurface "wave" that radiated away from the channel, rather than raising the water table more generally. The October and December 2009 limitrophe flows also raised the water table, by almost nine feet near the SIB, and by more than ten feet relative to the June 2009 elevations.

Ramírez et al. (2011) estimate that 5,400 acre-feet are sufficient to raise the elevation of the water table by 1.6 feet. In December 2010, nearly 11,000 acre-feet of flows "lost" between Morelos Dam and SIB (where no flow was recorded[69]) apparently were sufficient to raise the elevation of the water table beneath monitoring well 16S 11 ½ W more than nine feet , a rate roughly triple that estimated by Ramírez et al. (2011). However, as noted previously, it is likely that the SIB gage under-reported flow during December 2010, so channel infiltration was likely less and closer to the rate estimated by Ramírez et al. (2011).

Figure 41 suggests a strong relationship between pumping in the 5 mile exclusionary zone and groundwater elevations in the limitrophe. Yet, as shown in Figure 57, there also appears

[69] Note previous discussion of potential under-reporting by the temporary SIB gage; it is likely that some of these "lost" flows actually did reach the SIB but were not recorded.

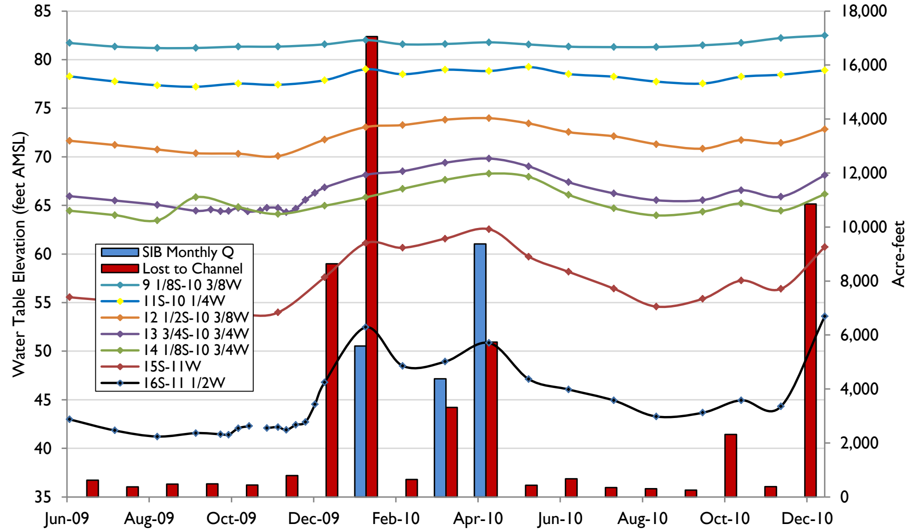

Figure 56. Water Table Elevations and Monthly Limitrophe Flows, June 30, 2009-Dec. 31, 2010.
Sources: Reclamation, IBWC.

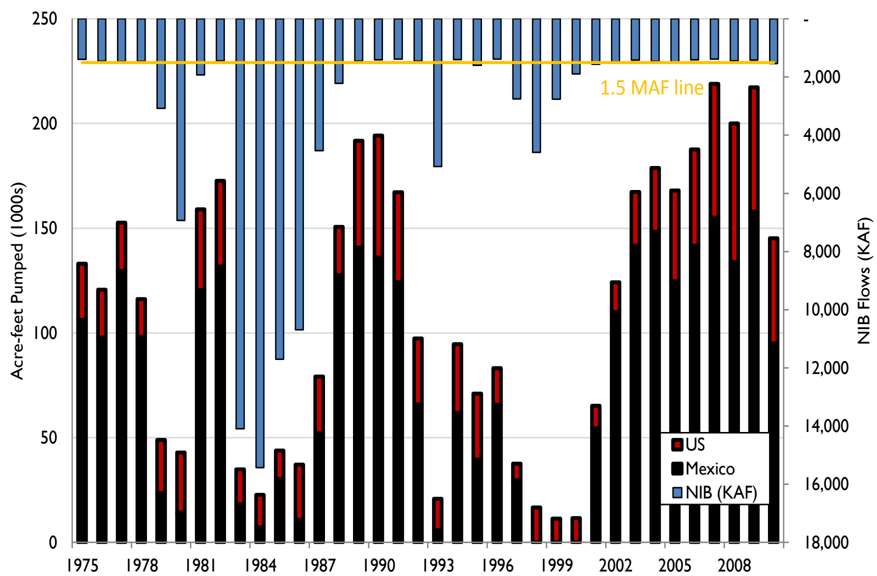

Figure 57. Colorado River Deliveries and Pumping in the Exclusionary Zone, 1975-2010.
Values on secondary y-axis are in reverse order. Sources: IBWC, USGS.

to be a strong correlation between surface water deliveries at the NIB and pumping volumes, as well as surface flows through the limitrophe. Not accounting for the reported ten percent error in the NIB streamflow record and an unknown (but potentially significant) error in reported pumping volumes in the 5 mile exclusionary zones, a regression analysis indicates that the magnitude of flows at the NIB account for almost 59 percent of the variance in annual pumping rates by Mexico, but only 36 percent of the U.S.'s annual pumping rates. That is, the magnitude of surface flows at the NIB appears to be the root cause, affecting groundwater conditions in the limitrophe directly via percolation, and indirectly by prompting increased pumping – especially by Mexico – in the exclusionary zone, especially when flows at the NIB drop below 1.5 MAF, indicated by the horizontal orange line at the top of the graph. The marked decline in Mexico's pumping in 2010 is likely attributable to damage in their water infrastructure and subsequent reduced demand. Note that volumes of Colorado River deliveries at the NIB are in reverse order on the secondary y-axis, to facilitate comparison with pumping volumes (on the primary axis).

Figure 58 summarizes the annual data shown above. Note that Mexican groundwater extraction in the 5-mile exclusionary zone averaged 120,000 acre-feet per year when annual Colorado River flows at the NIB were less than 1.5 MAF, but only 17,000 acre-feet per year when

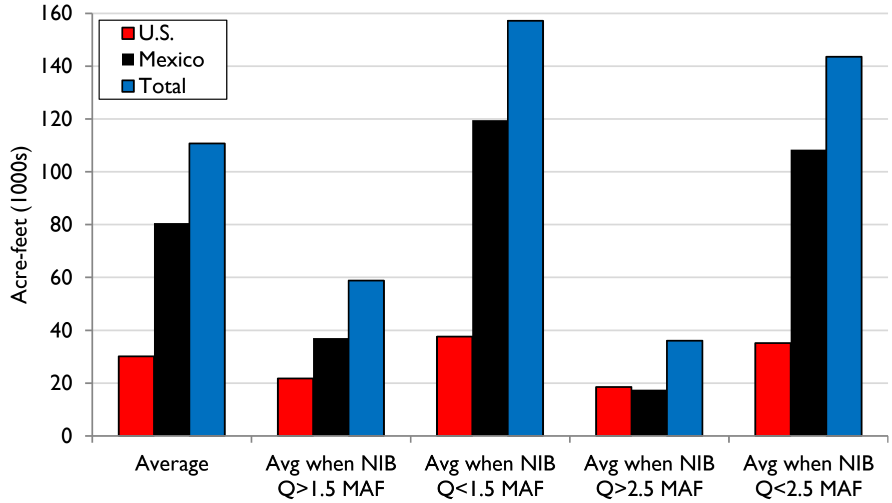

Figure 58. Pumping in the Exclusionary Zone, 1975-2010.

annual Colorado River flows at the NIB were greater than 2.5 MAF. Mexico pumped less water than the U.S. when annual Colorado River flows at the NIB were greater than 2.5 MAF, but on average Mexico pumps 170 percent more water from the exclusionary zone than the U.S.

Carrillo-Guerrero (2009) notes that in 2008, 220 of the 709 registered wells in Mexico's Irrigation District 014 were operated by private concessions that were not connected to surface water infrastructure. Predictably, pumping rates at these private wells showed no correlation with surface water availability: groundwater was their only water source.

Chapter VI – Conclusions and Recommendations

Groundwater conditions and dynamics in the limitrophe reach have changed fundamentally in the past 70 years. As shown in Figure 15 (see pg. 19), the Colorado River used to be a net source of recharge to the local aquifer in the limitrophe. The river was closely connected to the aquifer; depth to groundwater increased with distance from the river. The river's snowmelt-driven flooding inundated the surrounding land, further recharging the aquifer and contributing baseflows during low flow periods. The diversion of essentially the entire flow of the river upstream of the study area, combined with the loss of sediments behind upstream dams and subsequent down-cutting of the river channel below Morelos Dam, means that the river is now a drain in the upper portion of the limitrophe, and is completely disconnected from the aquifer in the last quarter of the limitrophe. In the form of irrigation, the river still 'floods' adjacent lands, recharging the aquifer. In the upper portion of the limitrophe, this irrigation is sufficient to maintain elevated groundwater levels and connectivity with the river. But extensive pumping along the southern land boundary and west of the river has drawn the water table down near the SIB, rendering the Colorado River ephemeral for some 40 miles below Gadsden.

Over the past 70 years, the water table dropped some 40 feet near the SIB, and about 10 feet near Morelos Dam. Yet, as shown in Figure 16, the water table throughout the limitrophe rose to about the same elevation in late 1998 (in response to Colorado River floods that year) as it had been in 1955, when monitoring wells were first installed. In the 57-year period of monitoring well records, the water table near Morelos Dam fell by about five feet and by about eight feet at about the limitrophe's midpoint, but by about 30 feet near the SIB. The water table in the southern portion of the limitrophe has experienced dramatic fluctuations since 1978, rising or falling more than ten feet eight times in that period. From 1955 to 1977, water tables throughout the limitrophe experienced an overall decline of about five feet, though only the last quarter of the study area experienced sharp rises and declines in the water table elevation.

These trends continued in recent years. The water table in the southernmost quarter of the limitrophe experienced an extreme decline – of more than 27 feet near the SIB – from the end of 1998 to October, 2009. Several miles upstream, near Gadsden, where the river bends once again toward the south, the water table fell 8.7 feet over these eleven years. Yet only three miles north of Gadsden, the elevation of the water table in October 2009 was essentially the same as it had been in July 2003.

These various trends highlight the dramatic differences in surface and groundwater conditions along the roughly 22-mile length of the channel through the study area. The upper quarter or third[70] of the Colorado River below Morelos Dam appears to be wet perennially, sustained by seepage and periodic releases from the dam and from the 11-mile wasteway, and, notably, by baseflows generated by a relatively high water table. In this uppermost section, the water table has been fairly stable for more than fifty years, with a few peaks caused by the notable Colorado River floods of the mid-1980s and the late 1990s. The middle portion of the study area, reaching downstream to about the Gadsden bend area, appears to have periodic or intermittent flows and a slightly lower, though still relatively stable water table. Although the surface water loses its connection with the aquifer in this portion, the water table still remains within reach of the roots of established native riparian vegetation. In the last stretch of the study area, below Gadsden, even this root-zone connectivity is lost, as the water table elevation drops precipitously. This last stretch of the study area experiences dramatic fluctuations in the aquifer, in response to increasingly infrequent surface water pulses through the channel. As reported by the SIB gage, the channel in this last stretch of the study area has been dry for more than 90 percent of days since 2005. In Hunter's Hole, just south of Gadsden, anecdotal reports (F. Phillips, pers. comm. 2010) suggest that supplemental irrigation has maintained riparian vegetation, even in locations where the water table has fallen below the reach of cottonwood and willow roots, but the sparse xeric vegetation in other areas below Gadsden indicate that the water table no longer supports riparian vegetation that depends on an accessible water table.

Two related factors explain the recent dramatic decline in the elevation of the water table below the last quarter of the study area: the significant reduction in surface water flows (including zero reported flow at the SIB at any point in 2006, 2007, and 2009 and only 5,500 acre-feet in 2008) and an increase in the volume of water pumped by Mexico and by the United States in the 5-mile zone buffering the border east of the SIB. As shown in Figure 40 (see pg. 33), this volume increased from a 1975-2000 average of about 90,000 acre-feet per year to a 2005-2009 average of almost 200,000 acre-feet per year.

The volume of surface flows appears to be the root cause responsible for groundwater fluctuations in the limitrophe reach, and especially in the area downstream of Gadsden. Surface flows below Morelos Dam directly contribute to groundwater recharge through the channel; unusually high surface flows at the NIB (>1.5 MAF/year) also indirectly increase the elevation of the water table by prompting Mexico to decrease its pumping from the five-mile zone buffering the border east of the SIB, allowing groundwater from the Yuma Mesa and Valley to flow toward the limitrophe reach rather than toward the wellfield. The dramatic and unprecedented decline in surface flows from 2005 through 2009 in particular, and throughout much of the 1990s and

[70] Because of the lack of stream gages between Morelos Dam and the SIB, and the limited availability of aerial photographs of the reach, these characterizations of streamflow are necessarily general.

2000s generally, correlates well with the marked decline in the water table elevation in the last quarter of the limitrophe.

Surface flow through the study area recharges the underlying aquifer, especially in the lower two-thirds of the limitrophe, where the water table falls below the elevation of the channel. The volume of this recharge, estimated as the difference between calculated flows directly below Morelos Dam and reported flows at the SIB, correlates even more strongly with the elevation of the water table than does the total volume of flow reported at the SIB. As shown in Figure 56 (see pg. 41), the high flows in December 2009 – January 2010, and again in December 2010, all raised water table elevations significantly in the last quarter of the limitrophe, but had smaller effects upstream. Several discrete factors drive recharge rates through the study area, including: discharge (large, brief releases of water from Morelos Dam will generate less recharge than would the same volume of water released over a longer period); existing channel conditions (a dry channel will tend to absorb more water than a saturated channel); and channel substrate (sandy soils have higher infiltration rates than do clay soils). These various factors show that analysis of recharge rates requires an appropriate time scale: monthly or annual assessments of releases from Morelos Dam are not appropriate for determining or projecting recharge rates through the study area.

Surface flows and channel recharge are only part of the equation determining groundwater conditions and dynamics in the study area. Two other key factors, as shown in Table 5 (see pg. 20), are groundwater movement and extraction. Limited data on pumping rates and sub-surface agricultural return flows below Morelos Dam hinder efforts to determine relationships between pumping and sub-surface return flows and water table elevations. Existing information on groundwater movement into and through the study area is more than 40 years old, pre-dating the current period of low surface flows and high rates of groundwater water extraction. As shown in Table 5, groundwater movement is (or was) the largest single factor in the groundwater balance, and in normal years was equivalent to the total calculated recharge from all surface water sources. The lack of recent data on this key factor in the water balance was a significant constraint in this assessment. From the relatively stable conditions in the upper limitrophe, we can infer that groundwater – fed by recharge from irrigated agriculture in the northern portion of the Yuma Valley – continues to flow toward the study area. The falling water table in the last quarter of the study area suggests that either groundwater no longer flows toward the west in that area, or that insufficient volumes flow in that direction.

Reported changes in pumping within the five-mile exclusionary zone along the Arizona-Sonora border, including the 90 percent increase in such pumping from 2001 to 2009, is almost certainly responsible for falling water table elevations near the border itself (as shown in Figure 3), and is probably extracting subsurface flows that otherwise would increase water table elevations in the lower limitrophe, especially near the SIB. This pumping, especially in Mexico, shows an inverse correlation with the volume of water delivered at the NIB.[71] Although pumping rates dropped by about a third in 2010, this was likely due to reduced demand associated with damage caused by the April, 2010 earthquake; pumping will likely return to 2009 levels once the infrastructure is repaired. Given the low probability of a recurrence of the high NIB deliveries in the 1980s and late 1990s that also led to decreased pumping, it is likely that the recent and current high pumping rates will continue, depressing groundwater elevations along the border and limiting long-term groundwater recovery in the lower limitrophe, even despite the small pulse flows that reached the SIB in 2010.

Less clear is the impact of pumping within Mexico's Modulo 7, to the immediate west of the Colorado River in the limitrophe reach. If such pumping follows the recent trends in the five-mile zone, then it will pull more subsurface water from the study area, contributing to the falling water table. Monthly post-2001 data from Modulo 7 would improve understanding of the impacts of this factor on the limitrophe itself.

This study indicates that, even after the exceptionally dry period of 2005-2009, when surface flows failed to reach the SIB gage on 90 percent of days, roughly 75 percent of the channel through the study area remained within ten feet of the water table – within the tolerance range of native riparian vegetation. This is very encouraging news, indicating that most of the limitrophe remains suitable for revegetation efforts that will be sustainable over the long term, at least as long as irrigated agriculture in the Yuma Valley remains viable. The plunging water table near the SIB suggests that the final five miles of the river within the study area will not respond to efforts to restore riparian habitat, at least not without a long-term commitment to supplemental irrigation, but areas upstream appear well-insulated from the recent drawdown.

Recent trends, such as rapid population growth along the border, increased pumping in the five-mile exclusion zone, and the general lack of significant releases from Morelos Dam, suggest that the sharp drawdown in the water table seen below Gadsden is likely to continue in coming years. However, recharge from periodic, rain-driven releases from Morelos Dam and continuing recharge from groundwater flowing to the upper portions of the study area from irrigated lands in the Yuma Valley, appear to provide baseflows in the uppermost stretch of the channel and a relatively high water table through much of the study area, as shown in Figure 25 (see pg. 24). Given the hydrologic stresses imposed from 2005-2009, this is encouraging news.

[71] U.S. pumping in the in the five-mile exclusion zone is also a function of Colorado River system storage. When Lake Mead is high, there is a tendency to reduce pumping to save costs; when storage is low, pressure mounts to supplement system supplies.

Recommendations

This study represents the most comprehensive evaluation to date of groundwater conditions and dynamics in the limitrophe reach below Morelos Dam. Further, more site-specific investigations would benefit from further research (described below). Yet even without this new research, this study clearly indicates that revegetation and restoration projects in the upper two-thirds of the study area should enjoy long-term success and are worth pursuing.

IBWC has tentatively planned to conduct a new limitrophe channel survey in the near future, the first since 1999. A new survey would greatly improve understanding of recent channel dynamics, including sediment transport, and would provide a foundation for future restoration efforts. This survey should be conducted as quickly as possible, and should include a detailed description of the existing channel and backwaters.

To provide a measurement of actual flows through the uppermost extent of the Colorado River delta, rather than calculating flows based on upstream gage records, the IBWC should install a new streamgage immediately downstream of Morelos Dam. Such a streamgage would provide critical verification of actual deliveries to the limitrophe reach, as may be required by a new binational agreement.

A key data gap is the actual depth to the water table within the riparian corridor itself. The PNN/UABC piezometers offer information on such depths at several locations, but additional data points, especially on the U.S. side of the river, would greatly improve understanding of actual conditions relevant to restoration efforts. Currently, such information must be interpolated from monitoring well data that is intended to meet a very different need. Additional GIS analysis, plotting depths to groundwater for other dates of interest and highlighting differences between these dates, would also be illuminating.

This study also highlights the need for a new survey of vegetation in the limitrophe. Historic vegetation survey data for the limitrophe vary significantly, even by the same agency. Significant differences also exist in reported ET rates for key vegetation community types in the limitrophe reach. These factors limit understanding of trends in vegetative water use, and groundwater dynamics as a whole. New survey data, along with classification and analyses of existing remote sensing imagery, would enable efforts to correlate vegetative extent with water table elevations. Such information will be critical to developing a robust groundwater model for the region.

The relationship between the calculated flows below Morelos Dam, recorded flows at the SIB, and water table elevations in the limitrophe warrants further study. Such a study will be critical toward determining surface water requirements for limitrophe reach restoration efforts. The preliminary assessment described in this study suggests that, under current conditions, calculated flows below Morelos Dam in excess of 900 cfs may flow unbroken to the SIB, with about one day's travel time, though at other times, flows below Morelos in excess of 1000 cfs generated no reported flow at the SIB. Again, this may simply reflect differences in channel conditions, or errors in the reported and calculated data.

Data Error

Potentially significant data errors cloud much of this analysis. These errors vary in magnitude across different measurements. The reported accuracy of the observation well measurements is within 0.1 percent, providing a clear picture of water table elevations near the wells themselves. Unfortunately, the elevation and even the exact location of the river channel itself is far less accurate: the last channel survey was in 1999, challenging efforts to correlate water table elevations beneath the observation wells with actual depths to groundwater – a key determinant of riparian vegetation success – along the riparian corridor itself. Groundwater extraction rates within the 5-mile exclusion zone presumably are accurate, but no information could be obtained about recent extraction rates immediately to the west of the study area, and reported extraction rates in lands immediately to the east of the study area are simply estimates based on irrigated acreage. There does not appear to be any recent information on groundwater movement into or through the study area; the most recent information (Olmstead 1973) is 40 years old and does not reflect current conditions.

The accuracy of reported streamflow at various points in the study area – the key variable determining groundwater elevations – is very low. Three key challenges related to streamgage data emerged in this study: 1) calculated flows below Morelos Dam typically are three orders of magnitude lower than reported flows at NIB, well within reported gage error, diminishing confidence in the accuracy of these calculated flows; 2) the absence of a streamflow gage between NIB and SIB challenges efforts to determine actual flows downstream of the dam and the volume of water absorbed by the channel; and 3) discharge reported by the gage at SIB appears to under-report flows. The last gage on the Colorado River, at the SIB, is now temporary, placed only when flows are expected. The SIB gage data almost certainly suffers from significant under-reporting; as described in Chapter II and elsewhere, the gage likely was not in place on several occasions when the Colorado River was flowing.

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Appendix A – U.S. Monitoring Wells in the Limitrophe

Yuma Grid	Alternate Name	Range of Readings
1 9/16S-6 3/8W	BD-31	July 1986 – present
2S-6 5/8W	IBWC-28	Sept 1954 – June 1986
2S-6 5/8W	BD-32	July 1986 – present
2 1/2S-6 7/8W	IBWC-28	July 2003 – present
2 1/2S-6 3/4W	BD-33	July 1986 – present
3S-7 1/16W	BD-34	July 1986 – present
3 1/8S-7 1/8W	IBWC-29	Sept 1954 – Oct 2009
3 1/2S-7 1/2W	BD-35	July 1986 – present
3 7/8S-7 5/8W	BD-36	July 1986 – present
4 3/8S-7 3/4W	BD-37	July 1986 – present
4 13/16S-8W	BD-38	July 1986 – present
5 1/4S-8 1/4W	BD-39	July 1986 – present
5 5/8S-8 5/8W	BD-40	July 1986 – present
6S-8 7/8W	IBWC-30	Sept 1954 – Oct 2009
6 3/16S-8 13/16W	BD-41	July 1986 – present
6 5/8S-9 1/8W	BD-42	July 1986 – present
7S-9 3/8W	BD-43	July 1986 – present
7S-9 1/2W	IBWC-31	Sept 1954 – March 2004
7 1/2S-9 7/8W	BD-44	July 1986 – present
8S-10 1/8W	IBWC-32 & BD-45	Sept 1954 – present
8S-10 1/2W	IBWC-33	July 1970 – June 1994
8S-11W	IBWC-33	Sept 1954 – Feb 1967
8 1/2S-10 3/8W	BD-46	July 1986 – present
8 3/4S-10 7/8W(D)	LCRP-9	Oct 2003 – present
9S-10W	IBWC-34	Apr 1955 – March 1991
9S-10 1/2W	IBWC-35	Sept 1954 – Oct 2009
9 1/8S-10 3/8W	BD-47	July 1986 – present
10S-10 1/4W	IBWC-36b	Nov 1956 – Oct 2009
10S-10 3/8W	BD-48	July 1986 – present
10S-11W	IBWC-36	Sept 1954 – Dec 1966
10 1/2S-10 1/4W	BD-49	July 1986 – Dec 2003
11S-10 1/4W	BD-50	July 1986 – present
11 1/2S-10W	BD-51	July 1986 – present
12S-10 1/4W	IBWC-37	Sept 1954 – March 1983
11 1/4S-10W	IBWC-37A	Nov 1984 – Oct 2009
12S-10 1/4W	BD-52 (original)	July 1986 – June 1989
12S-10 3/8W	BD-52 (new)	Dec 2001 – present
12 5/8S-10 3/8W	BD-53 (original)	July 1986 – March 1998
12 1/2S-10 3/8W	IBWC-37B (BD-53-new)	Dec 2002 – present
14S-10 3/4W	IBWC-38 (original)	Sept 1954 – June 1999
13 3/4S-10 3/4W	IBWC-38 (BD-55)	Dec 2002 – present
13 1/8S-10 1/2W	BD-54	July 1986 – June 1989
14 1/8S-10 3/4W	BD-56	July 1986 – present
15S-11W	BWC-39 (BD-57)	Sept 1954 – present
16S-11W	IBWC-40 (original)	Sept 1954 – July 1964
16 1/8S-11 1/8W	IBWC-40 (new)	Jan 1965 – Sept 1974
16S-11 1/2W	IBWC-40 (BD-58)	Sept 1977 – present

Source: J. Nickell, Bureau of Reclamation, pers. comm. April 2010.

Appendix B – Water Balance Consulting's Colorado River Limitrophe Analysis

Water Balance Consulting

MEMO

To: Michael Cohen, Pacific Institute
From: Kevin Wheeler, Water Balance Consulting LLC
Date: 08-Dec-11
Re: Colorado River Limitrophe Analysis

Message

Pacific Institute contracted with Water Balance Consulting LLC to analyze existing data related to the flows in the Colorado River between the Northerly International Boundary (NIB) and Southerly International Boundary (SIB). This memo describes the analysis of these flows and provides suggestions for further study of this region.

This reach, commonly referred as the Limitrophe, is approximately 24 miles long, flows generally north to south and forms a portion of the border between the United States on the east and Mexico on the west. The reach is characterized by a meandering channel bed with extremely irregular geometry and variation in channel sinuosity and slope. The limitrophe is directly below Morelos Dam which is the last control structure on the Colorado River. Waters flowing within the channel are typically irregular and are the result of either:

- Non-Storable Flows (NSF's) that are released from Morelos Dam that occur due to releases from Parker Dam that are in excess of the diversion capacity of both the United States and Mexico.
- Seepage from the Morelos Dam
- Discharges from the MODE#3 outlet (Wellton-Mohawk Drainage Water Discharge to Colorado River)
- Discharges from the Eleven Mile Wasteway
- Discharges from the Twenty-One Mile Wasteway

Flow measurements taken at approximately 7 locations that are relevant to the limitrophe and are published by the International Boundary and Water Commission. These locations are:

- Colorado River at Northerly International Boundary
- Cooper Wasteway (Valley Diversion, Yuma Project)
- Intake Canal at Morelos Diversion Structure
- Wellton-Mohawk Drainage Water Discharged to Colorado River
- Eleven Mile Wasteway (Valley Division, Yuma Project)
- Twenty-One Mile Wasteway (Valley Division, Yuma Project)
- Colorado River at Southerly International Boundary

The primary purpose of was to review the data provided by IBWC and to understand the methods used to determine the flows at the SIB. This consisted of 3 phases including:

1. Conversations with IBWC staff to understand these methods and the unique challenges that exist to develop data at this location.
2. Review of the rating curve and shift methods reported by the IBWC for the SIB
3. Comparative Analysis of the calculated inflows to the Limitrophe to the reported flows at the SIB

<u>Southerly International Boundary Gage Methods</u>

Conversations with IBWC staff focused on the methods used to measure flows at the SIB. It is known that historical flow records were developed in the past with use of a traditional stream gage, however IBWC staff indicated that the SIB Gage is at continuous risk of vandalism, therefore no recording devices are currently left in place. Alternatively IBWC staff performs manual flow and stage measurements if and when flows occur at the SIB gage site. Due to the manual nature of these measurements, it is probable that some quantity of flows is not captured due to the practical aspects of staff scheduling and timing of changes in flows.

<u>Rating Curve Shift Methods</u>

The second part of this analysis focused on understanding the methods used by IBWC to calculate stream gage shifts and the potential impacts on the reported flow measurements at the SIB. A rating table was provided that was labeled as water year 2005 and related gage height to discharge. In addition, a stage computation sheet and hand-drawn diagrams were provided that appears to show linear interpolations of stream gage shifts. The method for determining rating curve shifts was determined by analyzing these plots. It was observed that points were plotted representing known gage heights of the water surface and calculated shifts based on periodic measurements. Specifically the measured flows, observed depth on a staff gage, and the depth of zero flow (value of a staff gage at the sediment bed and water interface) were compared to the values on the 2005 rating table. With this information, shifts at the two end points could be plotted and shifts at intermediate depths could be estimated. Although this method is technically credible, some misplotted values were noted and no rationale for various inflection points could be determined, particularly when extrapolations beyond measured shifts were used. More detailed communication with the IBWC staff that produced these hand-drawn plots would be required to explain these anomalies and would clarify the detailed decisions that were made but not obvious from the plots themselves.

Comparative Analysis of Limitrophe Inflows to SIB Gage

The third part of this analysis consisted of a comparison between the calculated amount of water entering the limitrophe and the amount of water that is reported at the SIB. It is assumed that some amount of loss would occur into the subsurface and this phase attempted to estimate the quantity of these losses.
The basic equation used to determine the amount of water entering the limitrophe included the following:

Colorado River at Northerly International Boundary
\+ Cooper Wasteway (Valley Diversion, Yuma Project)
\- Intake Canal at Morelos Diversion Structure
\+ Wellton-Mohawk Drainage Water Discharged to Colorado River
\+ Eleven Mile Wasteway (Valley Division, Yuma Project)
\+ Twenty-One Mile Wasteway (Valley Division, Yuma Project)

If the calculated flows exiting Morelos Dam (NIB + Cooper – Morelos Diversion) resulted in a negative flow, it was assumed that this contribution to the limitrophe was zero.

The results derived from the above equation were plotted against the flows reported at the SIB gage (Colorado River at Southerly International Boundary). A year-by-year analysis of this comparison provided a visual understanding of the seepage losses in the limitrophe. However it is also noted that the basis on which this comparison is made is potentially flawed due to the indirect nature of the values being compared. For example the equation described above is dominated by the subtraction of two comparatively large numbers (Colorado River at Northerly International Boundary - Intake Canal at Morelos Diversion Structure) therefore small errors in either of these two numbers can results in large uncertainties in the amount of contribution to the limitrophe through Morelos Dam. Since no permanent systematic errors were known to exist with any of the data provided by IBWC, the comparison over the period for which data from all these elements were available (1977-2005) yielded valuable information. Conclusions could be drawn that average daily flows entering the limitrophe of less than 2 cubic meters per second (cms) or approximately 70 cubic feet per second (cfs), rarely resulted in any noticeable flows at the SIB gage.

Numerical methods for determining loss rates were explored. With limited information on the physical properties of the channel, three simplified methods were explored: Constant Gain/Loss, Flow Variable Gain/Loss and Percolation Gain/Loss

The Constant Gain/Loss method uses an empirical relationship to calculate channel loss using a fixed flow rate reduction and a ratio of the flow. A fixed flow rate is subtracted from the routed flow and the remainder is multiplied by a ratio.
Outflow = (Inflow – X)* (1-Y)
X = Fixed Value; Y = Loss Fraction (0 to 1)

The Variable Gain/Loss method is similar to the Constant Gain/Loss Method, but the Loss Fraction is a variable and depends on the average flow rate for a fixed prior period. In addition,

a fixed threshold value can be selected that assumes a zero flow if the inflow is below this value.
Outflow = If (Inflow < X then 0, else Inflow)* (1-Y_z)
X = Fixed Threshold Value; Y_z = Variable Loss Fraction (0 to 1) as a function of z previous days

Percolation Loss/Gain method uses a constant infiltration rate in combination with the inundated area in the reach to compute channel loss. This requires an elevation-discharge function and percolation rate.

The Constant Gain/Loss method was deemed too simplified because it did not account for the large variability of seepage losses due to the effects of antecedent moisture conditions in the limitrophe. The Percolation Loss/Gain method was also infeasible without acquiring additional data on the hydraulics of the channel. The Variable Gain/Loss method was applied through a spreadsheet model and optimization function.

To apply the Variable Gain/Loss method, the calculated inflows to the Limitrophe were compared to a fixed threshold value. If the inflows were below this threshold, the outflow was assumed to be zero. If the inflow were greater than this threshold, the inflows were multiplied by a percentage loss fraction that is selected from a table based on the value of the average flow over a selected period of days. An estimated threshold value of 2 cms was determined through visual inspection of the data and a period of 20 days was selected to represent the maximum period of influence from antecedent conditions. An objective function was constructed that represented the sum of the absolute values of the differences between the reduced calculated inflows and the gaged flows at the SIB. A Generalized Reduced Gradient (GRG) Nonlinear optimization algorithm was used to minimize the result of this objective function by modifying the percent loss values for each flow over the averaging period.

The results are a distribution of flow losses ranging from 70% for 20 day average flow to less than 5% losses for flows greater than 50 cms as shown in Figure 1.

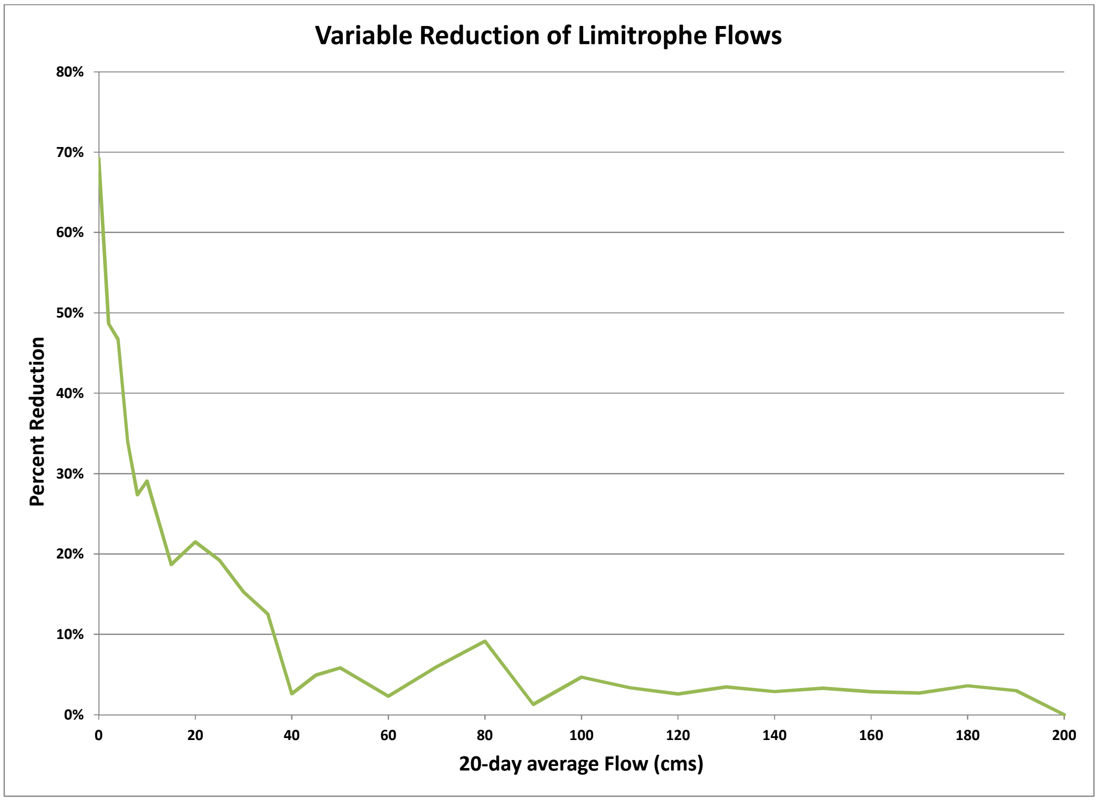

Figure 1. Modeled variable reduction of flows between the Inflows to the limitrophe and the flows reported at the SIB

A lag of 1 day was assumed in the model based on visual observation of peak inflows into the limitrophe and peak flows passing through the SIB. Several more sophisticated lag methods could be applied, but with increased assumption requirements.

Additional Analysis Possibilities

The model descried above applies a simple lag and gain/loss method to the inflows to the limitrophe to calculate an outflow from the limitrophe. Many potential improvements can be made to this analysis including a more thorough understanding of the quality of the input data, modifying the above analysis to reflect any erroneous data reported by IBWC, and applying alternative methods to better estimate the quantity and timing of flows through the limitrophe.

Ungaged Flows through the SIB

The utility of this analysis is limited by the accuracy of the data itself. Through this analysis, it became apparent that various methods for collecting gage data at the SIB have been used throughout the years. Comparing the inflows into the limitrophe to the flows reported at the SIB, it appears as though some flows are not captured at the SIB gage. An example of potentially missed flows is shown in Figure 2. This is expected due to the manual methods used to collect data at the SIB which is necessary according to IBWC. The above analysis can be modified to extract such occurances and to refine the loss estimates.

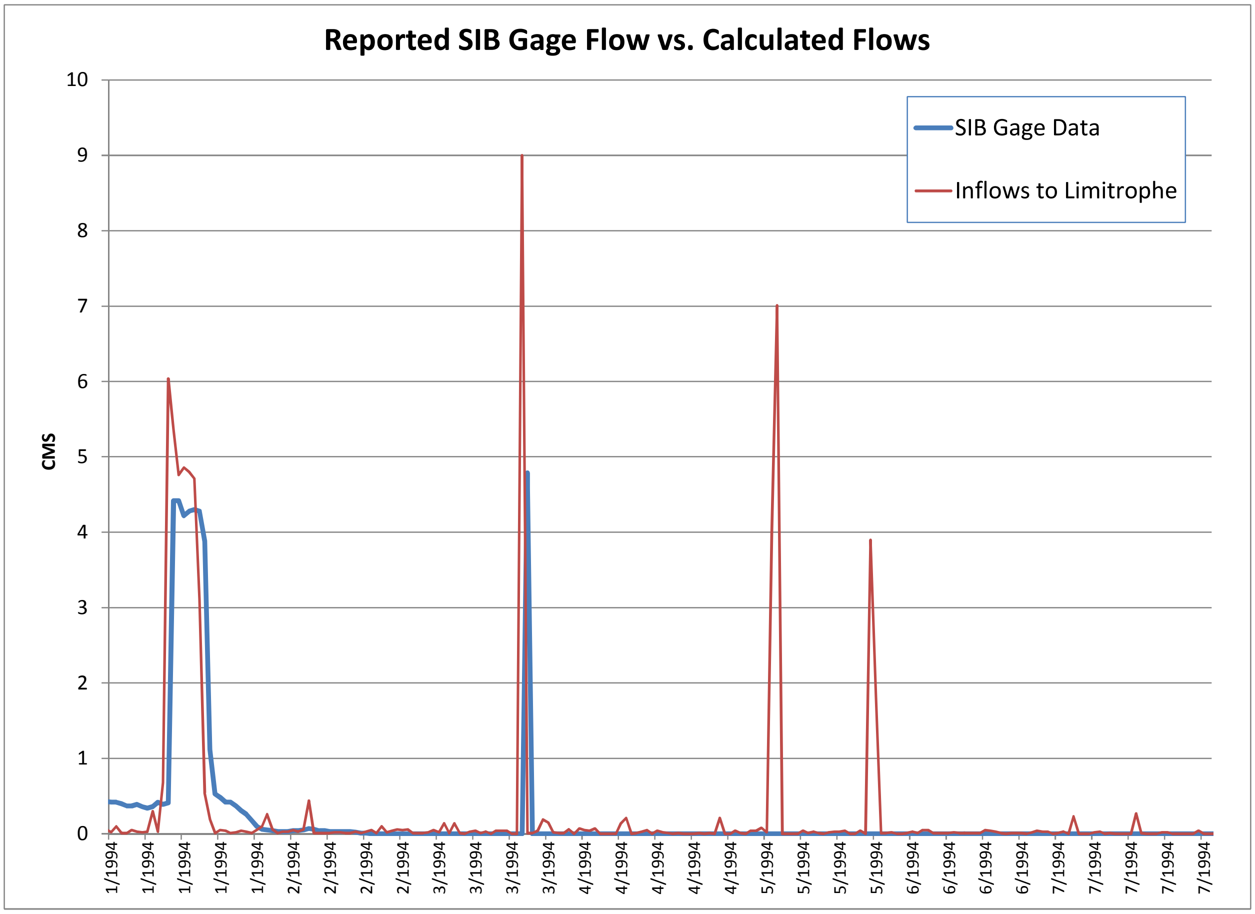

Figure 2. Example of Apparent Inflows into the Limitrophe not captured by the SIB Gage measurement

Additional uncertainly exists in the data used to calculate the inflows into the limitrophe. During the period of record, the methods and equipment that were used to measure flows likely varied and therefore anomolies may exist that affect the results of this analysis. No efforts were made in this study to analyze the quality of the the data for flows entering the limitrophe.

Possible Routing Method Improvements

Improvements to the routing method could be performed with additional information and resources. A list of various routing methods and the information required to apply these methods are provided below:

Lag Routing

- Simple Time

Straddle Stagger Routing

- Lag – Travel Time through Reach
- Duration – Amount of spreading in a flood peak

Muskingum Routing

- Muskingham K = Travel Time
- Muskingham X = Weighting between inflow and outflow influence (attenuation)

Modified Puls Routing (Storage Routing)

- Storage-Discharge Function

Kinematic Wave Routing

- Reach Length
- Slope
- Manning's n
- Channel Geometry

Muskingum-Cunge Routing

- Length
- Slope
- Manning's n
- Channel Geometry

Bank storage

Although modification of loss rates were considered in the analysis described above, there is no consideration for the effects of bank storage allowing flows to occur after flood flows in the channel have subsided. Observations such as Figure 3 in the comparative analysis demonstrate examples when this potentially occurs or other sources or sinks of water may exist.

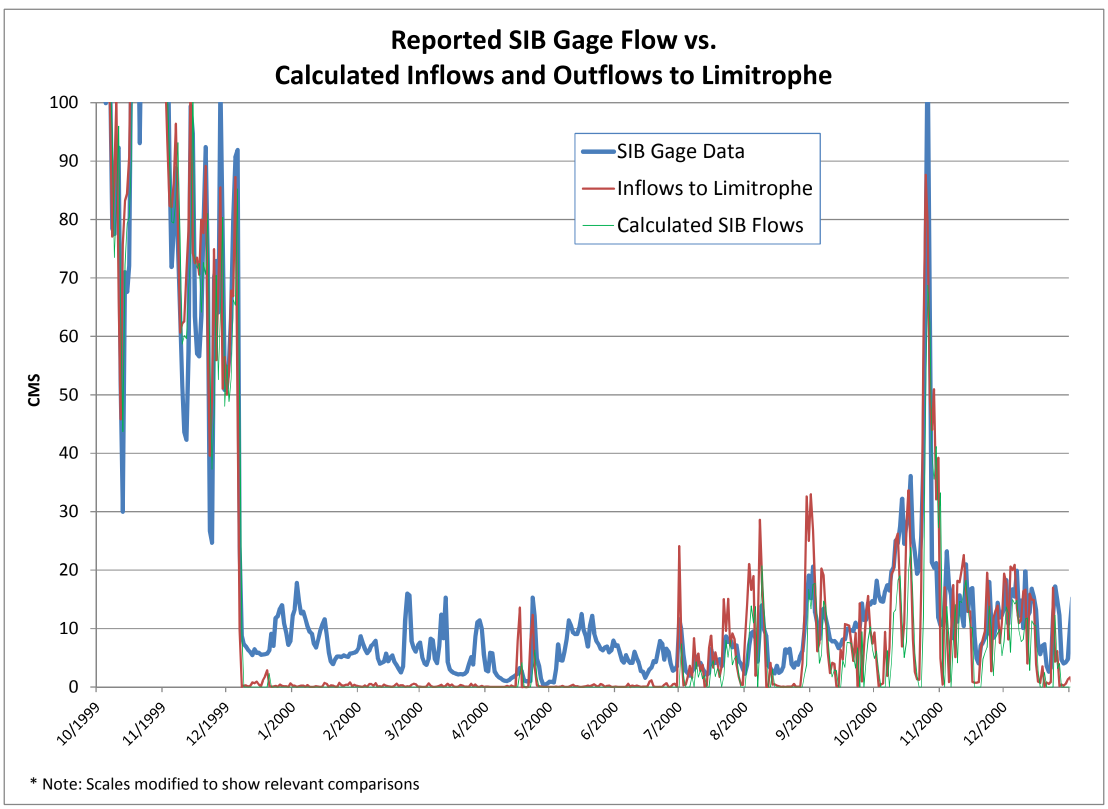

Figure 3. Flows recorded at the SIB and not directly accounted for through known inflows

Conclusion

The analysis presented above attempts to create an understanding of the data published by IBWC that affects flows in the limitrophe region of the Colorado River. The methods for data collection at the SIB are challenging due to the circumstances which precludes a more traditional stream gage equipment to be used. A comparative analysis of the flows entering the limitrophe with the flows reported at the SIB demonstrate the level of similarity between these datasets. Differences between these datasets are potentially the result of physical processes such as seepage losses, attenuation, bank storage, or data issues such as unmeasured or mismeasured flows. Techniques were used to estimate seepage losses and a simplified routing method was applied. Suggestions for further analysis are also presented in this memo.

Included is an appendix of annual plots comparing SIB Gage Data, inflows to the limitrophe and calculated flows at the SIB after accounting for lags and losses as described above.