Missing Water

The Uses and Flows of Water in the Colorado River Delta Region

Michael J. Cohen
and
Christine Henges-Jeck

a report of the

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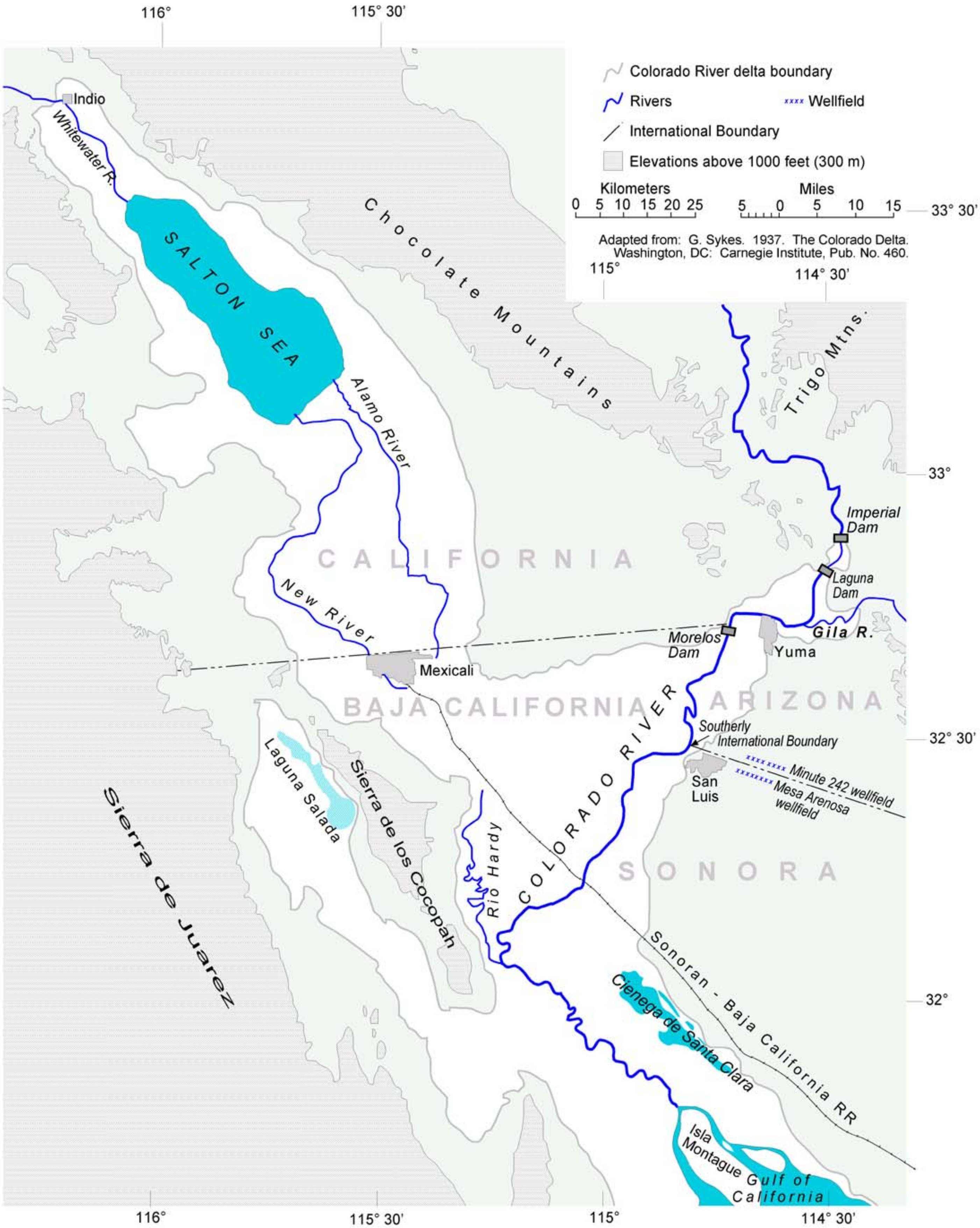


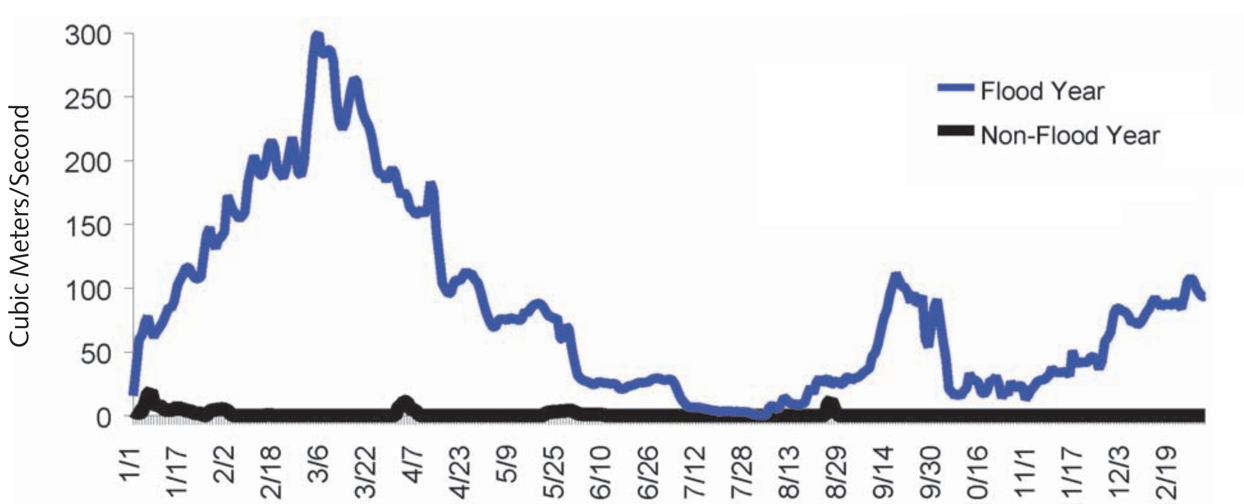
Figure EO-1 The Colorado River Delta Region

Executive Overview

In *A River No More*, Philip Fradkin (1981) writes of a Colorado River that no longer reaches the sea. Thirty miles (48 km) upstream from where the river disappears seasonally, and only 128 miles (206 km) upstream from the river's mouth, more than 6,000,000 acre-feet[1] (7.4 km^3) flow through the river's channel each year. *Missing Water* describes the fate of the millions of acre-feet of water diverted from the Colorado River, and the total inflows to and outflows from the Colorado River delta region more generally.

This study uses the hydrologic boundaries of the delta region described by Sykes (1937), encompassing some 3,325 square miles (8,611 km^2) in the states of Arizona, Baja California, California, and Sonora. For purposes of comparison, the report divides the study area into three sub-regions: Arizona, California, and Mexico, the last encompassing the Baja California and Sonora portions of the delta region.[2] The delta itself is comprised of more than a trillion tons of sediment carved from the river's upstream canyons. The Colorado River carried this sediment downstream, depositing it into the vast trench of the Upper Gulf of California, eventually filling in the uppermost 160 miles (257 km) of this trench – in places, the sediment is more than a mile deep. The delta region extends from near present-day Indio, California, southeast through the Salton Basin to the Gulf of California, with a stem reaching northeast past Yuma, Arizona, and another arm reaching into the Laguna Salada (Figure EO-1).

Although the tremendous fluctuations in the annual and seasonal flow of the Colorado River were largely eliminated by the construction of major dams on the river, flow through the study area still varies markedly from year to year, particularly below Morelos Dam, the last dam on the river. To reflect this variability, the study period is separated into Non-Flood (1991, 1992, 1995, 1996) and Flood (1993, 1997, 1998) years. Figure EO-2 shows average daily recorded flow at the last gauging station on the Colorado River, for Non-Flood and Flood years. Note that recorded daily average flow was at or near zero for most of the Non-Flood years, and also briefly dropped to zero in Flood years.



Source: IBWC (1991-1998).

Figure EO-2 Mean Daily Discharge at the Southerly International Boundary.

1 The conventional measurement of Colorado River water is the acre-foot, the volume of water required to cover an acre of land to a depth of one foot. An acre-foot is 325,851 gallons (1,233.48 m^3), approximately the amount of water two families of four use annually.

2 Data for Mexico's Irrigation District 14 were not available by state, so the Baja California and Sonora portions were combined.

During Non-Flood years, the Colorado River at Imperial Dam contributed 85% of total inflows to the delta region, decreasing to 75% during Flood years. Figure EO-3 displays the sources and average quantities of inflows to the delta region in Flood and Non-Flood years. With the exception of the lower Coachella Valley, the Colorado River was the source of almost all of the groundwater extracted from beneath the study area. In Figure EO-3, the term "Other Groundwater" refers to water pumped from the Minute 242 and Mesa Arenosa wellfields east of the delta region.

In this study, groundwater extraction was counted as an inflow to the region, because such extraction supplemented surface flows. Dependence on groundwater varied throughout the delta region, ranging in Non-Flood years from no reported extraction in California's sub-region Imperial Valley, to about 8% of the surface water diverted in the Arizona sub-region, to roughly 54% of the surface water diverted in the Mexico sub-region. During Flood years, when additional surface supply was available, groundwater extraction remained relatively unchanged in the California and Arizona sub-regions, but dropped to about 28% of the surface water diverted in the Mexico sub-region, reflecting both an actual and a relative decrease in groundwater pumping. It appears that the aquifer in the Mexico sub-region is recharged by periodic flood events on the Colorado River, offsetting reported groundwater overdraft in the sub-region. To a large extent, reliance on groundwater reflected the institutional arrangements on the river that establish priority of use and allocate water among users.[3]

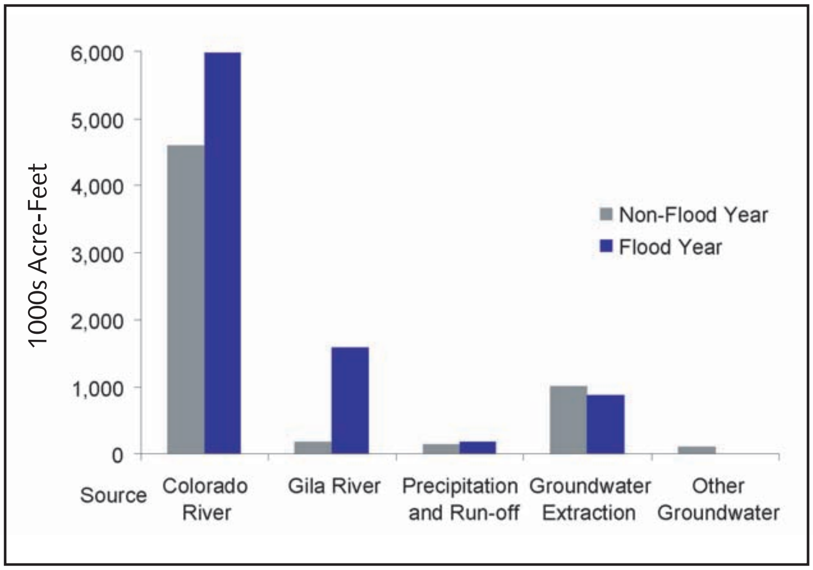


Figure EO-3 Inflows to the Colorado River Delta Region.

Most inflows ultimately exited the delta region to the atmosphere (directly as evaporation or, via crops and other vegetation, as evapotranspiration (ET)), although in Flood years a quarter of the total inflows exited the region as surface water to the Upper Gulf of California. Figure EO-4 displays the volumes of the major forms of outflows from the delta region for Non-Flood and Flood years.

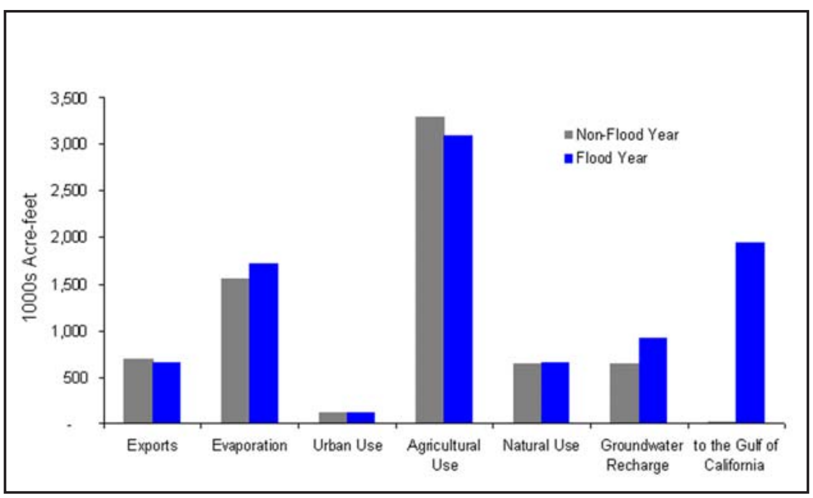


Figure EO-4 Outflows from the Colorado River Delta Region.

This study looked at uses of water in three different sectors – agricultural, urban, and natural – as a means of distinguishing between the different users of water in the delta region. Evaporation was reported separately so as not to distort total estimated use within the agricultural or environmental sectors, where such use would normally be allocated. For example, the largest open-water surface in the area is the Salton Sea, an agricultural sump that provides environmental values; evaporation from the Sea could reasonably be allocated to either sector. Figure EO-5 displays the use of water within the different sectors for Non-Flood and Flood years.

[3] Nothing in this study is meant to interpret the Law of the River or to assess the use of Colorado River water contract holders.

Agriculture was the single largest user of water in the delta region, consuming almost one-half of total inflows during Non-Flood years. The total amount of irrigated land in the delta region, including land supporting more than one crop cycle annually, exceeded 1.2 million acres (486,000 ha); data on actual physical acreage were not available for the Mexico sub-region. Nonetheless, irrigated physical acreage was reasonably assumed to exceed one million acres (400,000 ha) in both Flood and Non-Flood years, more than one-half of the total land area of the delta region, reflecting the availability of predictable supplies of water, the fertility of the soil, and the productive climate. This land supported a large variety of crops. For purposes of comparison, this study selected the three largest crops by acreage for each of the major irrigation districts in the delta region and compared their acreage and water use, as shown in Figure EO-6. The three largest crops by acreage – wheat, alfalfa, and cotton – constituted more than half of the total irrigated acreage in all years, and accounted for more than two-thirds of total crop ET in all years.

Urban water use accounted for about 2% of total regional water consumption. Much of this urban demand was met with groundwater, but total groundwater extraction for urban use was not reported uniformly in the region. Municipal effluent from Yuma and San Luís Río Colorado returned to the Colorado River mainstem; effluent from Mexicali and urban areas in the Imperial Valley flowed to the Salton Sea; while effluent in the lower Coachella Valley was used primarily for groundwater recharge (Figure EO-7).

Water use by natural vegetation, defined by this study as emergent wetland and riparian vegetation (phreatophytes), was about 10% of total inflows during Non-Flood years and 7% during Flood years. Such natural use did not account for use by upland species such as mesquite and ocotillo, which do not draw from surface water. Established riparian vegetation draws from the alluvial aquifer

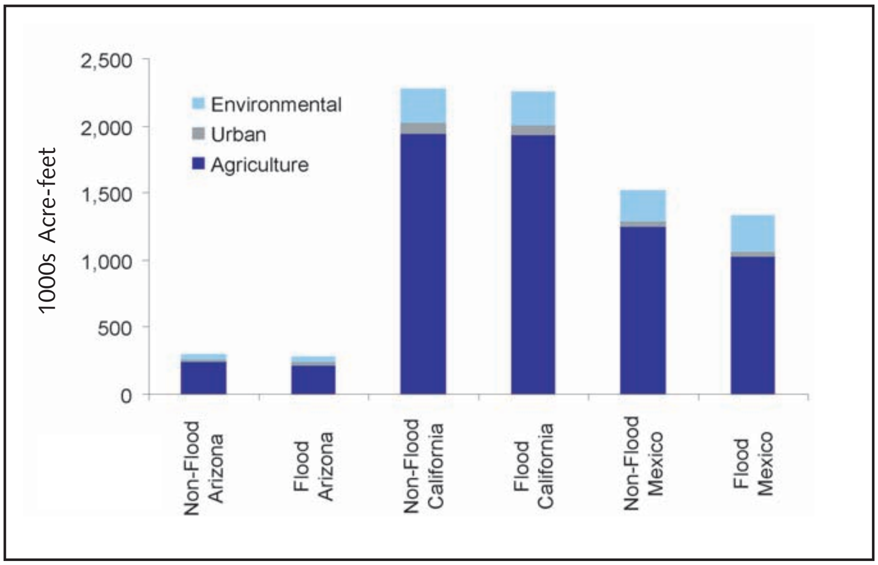


Figure EO-5 Sector Water Use by Sub-Region in the Colorado River Delta Region.

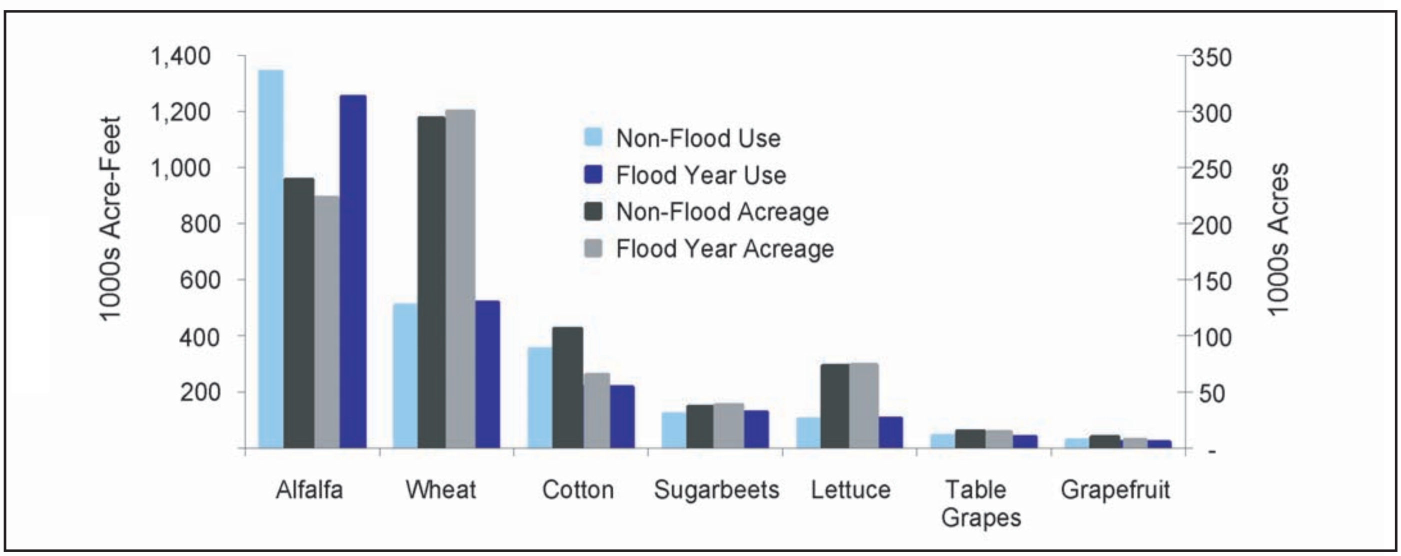


Figure EO-6 Agricultural Water Use and Acreage in the Colorado River Delta Region, by Crop.

rather than from surface water, but reported phreatophyte coverage in the region did not distinguish between emergent wetland species such as cattails and reeds, and riparian species such as saltcedar and willows, so this report aggregates all such use. Along the mainstem, periodic inundation recharges the alluvial aquifer, apparently sustaining established riparian vegetation during periods of low or no flow.

Missing Water describes the inflows and outflows of water to the Colorado River delta region. Most of the inflows included in this study were from measured data, while most of the outflows were calculated. Numerous data limitations affect the accuracy of this report, including missing data and data of unreported origin, data inconsistency, and inaccuracy of the data themselves. Major data gaps include the absence of data on Colorado River flows below the Southerly International Boundary, groundwater recharge rates, and the absence of any published data on flows to the Laguna Salada. Data reporting was inconsistent across sectors; for example, some data were reported by calendar year and others by crop cycle. The magnitude of gauge error for U.S. streamflow gauges ranged from ~10% to >15%. Such data limitations point to the need for additional research.

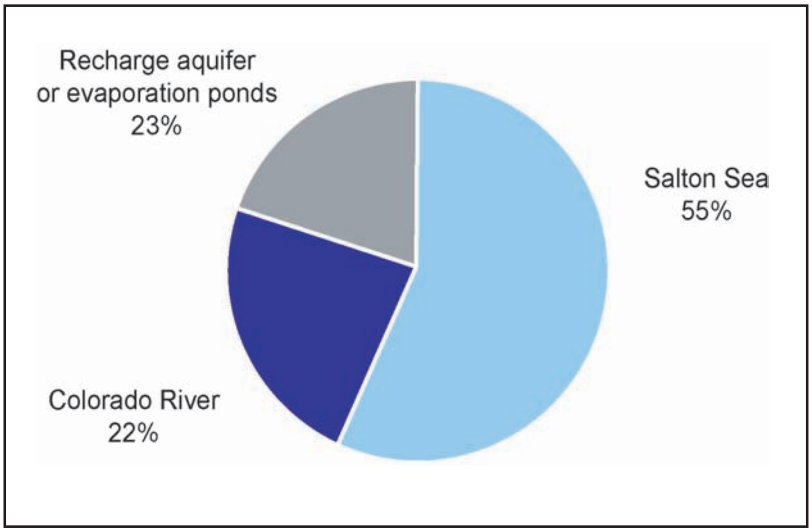


Figure EO-7 Destination of Urban Wastewater Returns.

The former meanders of the Colorado River through its extensive delta have been replaced with a complex, sophisticated infrastructure that delivers river water to, and removes wastewater from, most of the delta region, in a much more predictable and reliable fashion. As Philip Fradkin noted, the Colorado River disappears well before its mouth during most years, often for months at a time. Downstream from the last gauging station on the river, mainstem flows are replaced by untreated municipal effluent, intermittent returns of excess diversions, and agricultural wastewater, rewetting the channel for extended periods. Such returns do reach the sea, though given the extreme tides of the Upper Gulf and the greatly diminished flows of the Colorado River, it may be more apt to say that the sea now reaches the river.

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Chapter One: Introduction

The purpose of this study is to assess and present information in a manner that allows a broad and accurate understanding of the inflows, outflows, and uses of water in the greater Colorado River delta region. The study uses the hydrologic boundaries of the delta described by Sykes (1937). This region encompasses roughly 3,325 square miles (8,611 km^2), extending over parts of Arizona and California in the U.S., and over parts of Baja California and Sonora in Mexico (see Figure EO-1). The Colorado River provides virtually all of the water for agricultural, urban, and natural uses within this broadly-defined delta. To limit confusion with the current, limited extent of the remnant delta, this report uses the general term "Colorado River delta region," or "region," to refer to the full hydrologic extent of the Colorado River's delta.

The Colorado River delta region is the subject of increasing binational attention. Much of this interest focuses on the wetland and riparian areas of the remnant delta, a region of some 230 square miles (60,000 hectares (ha)) along the limitrophe[1] and straddling the Baja California-Sonora border. Yet a limited focus on the remnant delta would be overly restrictive: the uses and flows of water throughout the entire Colorado River border region are of interest, for the area is the locus of water transfers, a quantification agreement, water conservation efforts, a proposed aqueduct and new turnout, channel modification, habitat conservation and restoration plans, and wastewater treatment efforts.

Each of these projects and actions requires an understanding of the uses and flows of water in the particular area under consideration. Absent from these various efforts is a holistic review of the uses and flows of water throughout the region as a whole. This study seeks to fill this gap by providing a robust, binational overview of the water resources of the Colorado River border region.

In order to improve understanding and inform on-going planning and decision-making, the information in this report is organized according to water use, source, political region, and relative quantity of flow. The time period used in this study is 1991 to 1998. Almost half of those years witnessed above-average flows through the system, due to flooding along the Gila River or space-building releases at Hoover Dam triggered by above-average Upper Basin inflows and near-capacity storage. To reflect the variability of discharge through the region, the report separates the study period into Non-Flood and Flood years, with Flood years defined as those in which maximum mean daily discharge at the Southerly International Boundary (SIB) exceeded 2,800 cfs (80 m^3/second) (Zamora-Arroyo et al. 2001).

The study is organized as follows. The remainder of this chapter describes the study area, including an overview of the construction of dams and diversionary infrastructure on the Colorado River. Chapter Two briefly describes the institutional context governing deliveries of water to the delta region. Chapter Three discusses the methods used in the report, the system boundaries, the sources of data, and limitations of these data. Chapter Four describes historical flows through the region, sources and quantities of inflows and outflows, groundwater extraction and infiltration, and the physical infrastructure that conveys water through the delta region. Chapter Five discusses agricultural, urban, and natural uses of water in the delta region. Chapter Six offers several general conclusions and identifies existing data gaps. Appendix A provides a brief overivew of salinity in the delta region, while Appendix B defines the acronyms used in this report.

Description of the Study Area

Alluvial soils define the extent of the Colorado River delta region, though soil types vary from the compacted fine clay soils of the Imperial Valley to the porous sandy soils on the river banks downstream of Morelos Dam. Soil type determines drainage, runoff, water storage capacity, which crops can be grown successfully, and other land uses. Soils in the delta region are generally level to moderately sloping. Drainage characteristics range from excessively drained sands and cobbly sands to somewhat poorly drained silty clays (USDA 1980).

Formation of the Colorado River Delta

Two major factors created the delta of the Colorado River: the tremendous quantities of sediment carried by the

[1] The 23.2 mile (37 km) stretch of the border between Mexico and the United States that is defined by the Colorado River.

river itself, and the dynamic structure of the basin where the river deposited these sediments. Over the course of several million years, the Colorado River transported more than a trillion tons of sediment from the Rocky Mountains downstream to the river's mouth (Sykes 1937). The material scoured from the Grand Canyon, Glen Canyon, and other parts of the basin filled some 160 miles (260 km) of the upper reach of the Gulf of California to a depth of thousands of feet (DOI 1974), effectively filling one canyon with the material removed from others. Prior to the construction of upstream dams (which trap sediment), the Colorado transported from 50 - 500 million tons (45 - 455 million metric tons) of sediment annually (Minckley 1991), depositing 70 to 80 percent of this in its delta (Morrison et al. 1996). Per unit of water, this sediment load is ten times that of the Nile and seventeen times that of the Mississippi River (de Buys 1999).

The Rio Hardy wetlands and the Sierra de los Cocopah range.

Unlike the Nile or the Mississippi, however, both of which empty onto shallow continental shelves along broad seas, the Colorado drains into a narrow submarine trench with an estimated depth of 9,000 feet (2,700 m) (Sykes 1937). This trench lies within a dynamic zone of crustal spreading known as the Gulf of California Rift Zone (Cohen et al. 1999); the trench slowly expanded even as the river deposited sediment into it. The river initially met the Gulf more than 100 miles (160 km) below the Gulf's northernmost extent, gradually filling in the submarine trench to the extent that the river now drains some sixty miles farther south (Sykes 1937). The delta region can be visualized as a giant "T", one arm extending northwest and the other southeast, with a short stem running roughly perpendicular to these, stretching back toward Yuma, Arizona (see Figure EO-1) The tremendous tides of the Gulf, with an amplitude of more than 25 vertical feet (>8 m) at the river's mouth (Lavín et al. 1997), also contributed to the formation of the delta, redistributing sediments throughout the Gulf.

Prior to impoundment, the Colorado frequently shifted course, jumping its banks as sediment filled the channel: undeveloped areas of the delta are replete with oxbows and backwaters, vestiges of former meanders. Periodically, the river flowed northwest, toward present-day Indio (Sykes 1937). Eventually, two natural berms formed, one south-east of present-day Mexicali and the other south of the Sierra de los Cocopah Mountains, dividing the basin into three sub-basins, with the northern basin draining into the present-day Salton Sea, a smaller southwestern sub-basin draining into the ephemeral Laguna Salada, and the remainder draining into the Upper Gulf of California (see Figure 1.1). The division between the Laguna Salada and Gulf drainages is slight; high flows along the mainstem and Rio Hardy will partly drain to the Laguna, and spring tides from the Gulf occasionally crest the berm and drain to the Laguna as well. The maximum elevation of the delta region occurs at the toe of Imperial Dam, with a surface elevation 150 feet (46 m) above mean sea level (msl). The maximum elevation of Indio, California, near the farthest extent of the northwestern arm of the delta region, is 30 feet (9.1 m) msl. The lowest elevation is at the bottom of the Salton Sea, approximately -271 feet (-82.6 m) msl (current surface elevation of the Sea is -227.8 feet (-69.4 m) msl). The lowest elevation of the Laguna Salada basin is -10 feet (-3 m) msl.

The Colorado River watershed as a whole covers some 244,000 square miles (632,000 km^2), 2,000 (3,200 km) of which lie in Mexico (Getches 1985). The Salton Sea and Laguna Salada basins cover an additional 8,360 square miles (21,700 km^2) and approximately 2,100 square miles (5,440 km^2), respectively. The Salton Basin includes part of San Gorgonio Mountain (elevation 11,502 feet (3,506 m)), with estimated mean annual runoff of 20 inches (51 cm), but most of the Salton basin has an estimated mean annual runoff of less than one inch (2.5 cm) (Hely and Peck 1964). Estimated mean annual runoff in the Laguna Salada basin is generally less than 0.5 inches (1.2 cm), while estimated mean annual runoff in the delta region itself is generally less than 0.02 inches (.05 cm) (Hely and Peck 1964).

The Colorado River runs some 1,400 miles (2,250 km) from its headwaters in the Rocky Mountains in Colorado to its mouth at the Gulf of California. The study area includes the final 128 miles (206 km) of the Colorado River, from Imperial Dam to the Gulf. Traveling downstream from Imperial Dam, the river encounters Laguna Dam (6.0 miles (9.7 km)), the mouth of the Gila River (15 miles (24 km)), the Northerly International Boundary (NIB) with Mexico (28.0

miles (45.1 km)), Morelos Dam (29.1 miles (46.8 km)), the Southerly International Boundary (49.2 miles (79.0 km)), the bridge of the Sonora-Baja California Railroad (74.4 miles (119.7 km)), and the mouth of the Rio Hardy (91 miles (146 km)). The Gila River, draining a watershed of some 58,000 square miles (150,000 km^2) in southern Arizona and parts of New Mexico and Sonora, runs 630 miles (1,010 km) to join the Colorado River near Yuma, Arizona. The other perennial streams in the study area are former channels of the Colorado River; they now primarily convey agricultural and municipal wastewater. Of these, the Alamo River, running north about 60 miles (97 km) from the border to drain into the Salton Sea, is the largest in terms of mean annual discharge. The New River runs about 20 miles (32 km) north through the Mexicali Valley and the City of Mexicali to the border, and then another 60 miles (97 km) through the Imperial Valley, and also drains into the Salton Sea. The Rio Hardy conveys agricultural drainage from the lower Mexicali Valley, running about 15 miles (24 km) southeast to drain into the Colorado River near the inter-tidal zone. The Whitewater River, also known as the Whitewater River Stormwater Channel, primarily conveys water from intermittent storm events to the Salton Sea.

Climate

The delta region lies within the Sonoran desert. The region is hot and dry: precipitation averages less than three inches (7.5 cm) annually, while maximum daily temperatures may exceed 100° F (38° Celsius) more than 5 months each year.[2] The climate generates a significant net outflow of water, with pan evaporation rates in the region exceeding nine feet (2.7 m) per year (Owen-Joyce and Raymond 1996). Precipitation tends to fall in two distinct seasons, with winter precipitation generated by moisture from the Pacific Ocean and summer rainfall, often occurring in brief, high-intensity storms, generated by moisture from the Gulf of California (Hely and Peck 1964). Brief storms can produce substantial runoff from surrounding mountains, though most of this runoff tends to be absorbed by the sandy alluvial soils of the basin floor (Olmsted et al. 1973).

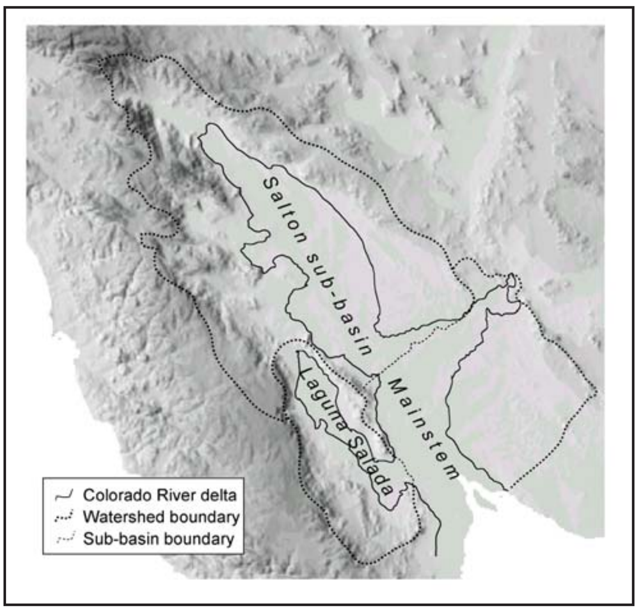

Figure 1.1 Topography of the Colorado River Delta Region.

Source: Topography derived from USGS GTOPO30 data www.edcdaac.usgs.gov/gtopo30gtopo30.html courtesy of Greeninfo Network www.greeninfo.org.

Human History of the Region

Despite the climate, various tribes, including the Desert Cahuilla Indians in the north, the Kamia, the Quechan, and the Cocopah (Cucapá in Mexico), have lived in the region for hundreds, perhaps thousands of years (Kelly 1950). The fertile, alluvial soil and ample sunshine make the area a prime location for agriculture.

As early as 1849, plans were conceived to irrigate the fertile Salton Sink with Colorado River water, but it was another fifty years before development plans were realized (Hundley 1975). In 1901, the California Development Company cut a channel into the banks of the Colorado River just north of the NIB to deliver water through Mexico and into a former channel of the Colorado River, known as the Alamo River. The first water flowed into the Imperial Valley in June of that year, and within eight months 2,000 settlers had dug 400 miles (645 km) of canals and prepared 100,000 acres (40,000 ha) of land for cultivation (Hundley 1975). In 1905, floods along the mainstem broke through a temporary headgate, diverting an increasing proportion of the Colorado River into the irrigation canal, ultimately widening the intake to half a mile (0.8 km) across and diverting the entire river into its former channel (de Buys 1999). For two years, some or all of the Colorado River flowed through the intake,

[2] IID Fact Sheet – Weather Summary (2000).

inundating hundreds of thousands of acres in the Salton basin and creating the Salton Sea[3] (Sykes 1937). The flood flows carved the New River out of the soft delta sediments, destroyed most of Mexicali, and transported an estimated 450 million cubic yards (340 MCM) of sediment into the Salton Sea (de Buys 1999).

Periodic flooding also occurred along the lower Gila River, inundating the town of Yuma, Arizona, and surrounding farmland. Faced with cycles of flooding and drought, the people of the region looked to the federal government for an infrastructure to regulate the flows of the Colorado and Gila rivers, calls that were echoed by southern California interests eager to convey water from the river to their growing cities (Reisner 1993). The federal government authorized the construction of a massive infrastructure to tame the Colorado River and improve the predictability and reliability of deliveries. Laguna Dam, the first major dam on the Colorado River, was completed in 1909 to serve the Gila and Yuma projects.[4] Roosevelt Dam, on the Salt River east of Phoenix, Arizona, was closed in 1911, markedly reducing flooding on the Gila River. The Yuma Siphon, completed in 1912, initially conveyed water from the Yuma Main Canal outlet structure on the California side of Laguna Dam, under the Colorado River into Arizona to serve the Yuma Project. Hoover Dam, 293 river miles (472 km) upstream of Imperial Dam, regulates releases to the Colorado River border region. Imperial Dam, completed in 1938, is a diversion dam at the upstream boundary of the delta region; it diverts water into the All-American Canal (primarily serving California, completed in 1940) and the Gila Gravity Main Canal (serving Arizona, completed in 1939). In 1941, a turnout was completed in the All-American Canal to supply part of the Reservation Division in California, and all of the Valley Division in Arizona, with water diverted at Imperial Dam, effectively bypassing the diversion function of Laguna Dam. The last major structure on the river, Morelos Dam (completed in 1950), diverts water into Mexico's Alamo Canal, initially constructed in 1900 to divert water into the Imperial Valley. The Coachella Canal, diverting water from the All-American Canal to irrigate land in Coachella Valley, was completed in 1948. The Wellton-Mohawk canal, diverting water from the Gila Gravity Main Canal, was completed in 1951. Painted Rock Dam, the last dam on the Gila River before its confluence with the Colorado River, was completed in 1960.

At the beginning of the 20th century, U.S. interests owned or controlled large portions of the delta region in Mexico (Ward 1999). Mexico's Cárdenas administration (1934-1940) expropriated many of these large landholdings, promoting migration to the region and the development of ejidos (communal farms), leading to large-scale clearing and conversion of delta wetlands to agriculture (Ward 1999). These lands, initially irrigated almost exclusively by Colorado River surface water, were organized into Irrigation District 14, administered by Mexico's Comisión Nacional de Agua. Total irrigated acreage peaked at 475,952 acres (192,612 ha) by the end of the 1950s, decreasing thereafter. Large-scale groundwater extraction began in the mid-1950s, partly in response to decreased mainstem flows due to the filling of Glen Canyon reservoir and partly due to increased U.S. consumptive use (Bradley and De Cook 1978).

These dams and canals facilitated the conversion of some 1.2 million acres of land in the border region to irrigated agriculture, generating more than $2 billion in revenue in 1997 for the region as a whole. Agriculture remains the primary economic engine in the border region, though in recent years industrial production, primarily maquiladoras in Mexicali, have become a major source of revenue in the Mexican region of the delta. The entire region has witnessed marked population growth over the past decade, as shown in Table 1.1.

Table 1.1
Population in the Colorado River Delta Region.

	1990	2000
Lower Coachella Valley	84,139	126,177
Imperial Valley	110,749	154,549
Mexicali	601,938	764,902
Yuma Area	78,803	108,055

Sources: Arizona Department of Economic Security; California Department of Finance 2000; CVWD 2000; INEGI.

3 During the course of its meanders through the delta region, the Colorado River periodically drained north into the Salton Basin, forming and stranding previous incarnations of the Salton Sea that were known as Lake Cahuilla.

4 Sykes (1937: 67) reports that the reservoir formed by Laguna Dam "was filled with sediment practically to the lip of the dam within a few weeks after its completion."

Chapter Two: Institutional Context

In the United States, a complex set of treaties, laws, compacts, contracts, court decisions, and regulations, known as the Law of the River, controls the flows and uses of the Colorado River. The Law of the River, to a large extent, determines the quantity and timing of water entering the study area. In Mexico, regulation of Colorado River use is centralized at the federal level, though information on this legal structure is less readily available. This chapter describes, in general terms, the most salient of these U.S. and Mexican institutions.

The flows of the Colorado River below Hoover Dam are controlled and regulated based on flood control requirements, downstream diversion orders, and demands for hydroelectric power (cf. Nathanson 1980). The degree of institutional control over the Colorado River can not be overstated: the 1983 flood has been the only instance since the construction of Hoover Dam in 1935 when discharge from the dam, and along the lower Colorado River, was not completely controlled by the U.S. Bureau of Reclamation (USBR) (Holburt 1984). The concept of a major river whose flow can be turned on and off is difficult to comprehend, but it is the central fact of the lower Colorado River. Except in rare instances of unusually high inflows to Lake Mead and limited storage availability (triggering U.S. Army Corps of Engineers Flood Control Release Guidelines), the flows in the lower Colorado River are released by the USBR. USBR determines release rates based on a complex algorithm to meet the downstream beneficial consumptive use orders for agricultural diversions and urban diversions. This algorithm integrates agricultural diversion orders, required deliveries to Mexico, storage requirements, flood control, and hydroelectric power generation contracts. The determination of releases takes into consideration the priorities of water use as required by applicable federal law (USBR 1996). Instream flows through the study area are almost entirely dependent on releases from upstream dams.

Within the Law of the River are two main elements addressing U.S. obligations to Mexico: the 1944 *Treaty on the Utilization of Waters of the Colorado and Tijuana Rivers and of the Rio Grande* with Mexico[1] and Minute 242 of the International Boundary and Water Commission (IBWC), issued in 1973. The former guarantees delivery of 1,500 KAF (1,850 MCM)/year to Mexico. In the absence of surplus flows, the responsibility for the delivery of these waters is to be shared equally by the upper and lower basins (Hundley 1966; 1975). Article 10(b) of the Treaty allocates an additional 200 KAF (246.7 MCM) to Mexico when the U.S. Section of IBWC determines that there exists a surplus of Colorado River water above the amount needed to supply U.S. uses; such Treaty surpluses were declared 1997-2000.

After a long dispute between Mexico and the U.S. about the quality of water delivered to Mexico which had been degraded by brackish discharge from Arizona's Wellton-Mohawk Irrigation and Drainage District in the early 1960s, the two countries adopted Minute 242 of the IBWC (Fradkin 1981; Wahl 1989). Minute 242 states that 1,360 KAF (1,678 MCM) of annual water deliveries to Mexico at Morelos Dam would have an average salinity no more than 115 ppm (±30 ppm) greater than the salinity of the river at Imperial Dam; the remaining 140 KAF (173 MCM), delivered at the international boundary with Mexico near San Luis, would have "a salinity substantially the same as that of the waters customarily delivered there" (in Hundley 1986:39). Congress then passed the Colorado River Basin Salinity Control Act of 1974, authorizing measures to enable compliance with Minute 242, including the construction of the $250 million Yuma Desalting Plant[2] (Wahl 1989) and the construction of the Main Outlet Drain Extension (MODE) and its bypass extension, discharging agricultural drainage into Mexico's Cienega de Santa Clara (Glenn et al. 1992).

During the study period, sufficient water was available at Lake Mead to meet Treaty obligations to Mexico and to satisfy U.S. diversion orders by contract holders in Arizona and California. In 1996, a limited U.S. surplus was declared to satisfy the diversion orders of users upstream of the study area; no surplus waters were made available that year for Mexico.

In Arizona, the Gila River is fully appropriated by users upstream of the study area and is subject to continuing adjudication (see Thorson 2000), meaning that discharge of the Gila River to the delta region is limited to agricultural drainage and infrequent flood flows. The Yuma County Water Users Association, formed to receive water from the

[1] See Hundley (1966) for a comprehensive history of the 1944 Treaty with Mexico.
[2] The plant was essentially completed in 1992 and is currently maintained at standby status.

federal Yuma Project in 1903, has among the highest priority rights to Colorado River water in Arizona. Such water rights are stated as "the quantity reasonably required for the irrigation" of the Yuma Project lands (50,000 acres (20,000 ha) in the Valley Division and 3,300 acres (1,340 ha) outside of the study area, on Yuma Mesa) (Nathanson 1980). The Gila Project provided for delivery of water to 15,000 acres (6,070 ha) in the North and South Gila Valleys within the study area, and 25,000 acres (10,120 ha) in the Yuma Mesa Unit and 75,000 acres (30,400 ha) in the Wellton-Mohawk division, both of which lie outside of the study area but receive water from the Gila Gravity Main Canal that runs through the study area. Water rights for Gila Project lands are quantified on the basis of capacity of the Gila Gravity Main Canal (Nathanson 1980).

California's 1931 Seven Party Agreement (in Nathanson 1980) codified the priority of rights to Colorado River water established by the precedence of use by the seven entities that had diverted or applied for river water (Gottlieb and FitzSimmons 1991). The Seven Party Agreement established a seven-tier set of rights, in the following order of seniority: (1) the Palo Verde Irrigation District (PVID); (2) the Yuma Project Reservation District (comprised of the Indian and Bard Units); (3) the Imperial Irrigation District (IID), the Coachella Valley Water District (CVWD), and the Palo Verde Mesa of PVID; (4) the Metropolitan Water District of Southern California (MWD) and/or the City of Los Angeles (L.A.); (5) MWD and/or L.A., and the City and County of San Diego; (6) IID, and PVID for use in the "Lower Palo Verde Mesa"; and (7) "all remaining water available for use within California, for agricultural use in the Colorado River Basin in California." The first three sets of priorities provide for a total consumptive use of 3,850 KAF (4,750 MCM) annually. PVID has rights to such waters as may be required for the beneficial use of 104,500 acres (42,300 ha); rights to the remainder of the 3,850 KAF (4,750 MCM) fall to users in the study area, exclusive of such waters as may be necessary for the beneficial use of 16,000 acres (6,480 ha) of Palo Verde Mesa lands.

Table 2.1 displays the consumptive use of the irrigation districts within the study area and other districts receiving water through the study area, as well as deliveries to Mexico, for purposes of comparison with the volumes calculated by this study (shown in Chapter Five). Nothing in this study is meant to interpret the Law of the River or to assess the use of Colorado River water contract holders. It should also be noted that the definitions employed within this report do not adhere strictly to the definitions contained within the Law of the River.

Table 2.1 Mean Annual Consumptive Use and Deliveries to Mexico.

	Non-Flood Year	Flood Year
	1000s Acre-Feet	
Arizona		
Wellton-Mohawk I&D District	270	257
City of Yuma	14	15
N. Gila Valley ID	20	19
Yuma ID	52	49
Yuma Mesa I&D District	194	186
Unit "B" I&D District	25	22
Yuma County Water Users Assoc.	221	208
Cocopah Indian Reservation	5	11
Total Arizona est. unmeasured returns*	177	150
California Sub-Region		
Yuma Project Reservation Div., Indian Unit	42	35
Yuma Project Reservation Div., Bard Unit	52	51
Imperial Irrigation District	2,925	3,011
Coachella Valley Water District	321	331
California Sub-Region Total	**3,341**	**3,429**
Total California est. unmeasured returns*	93	90
Mexico Sub-Region		
Delivery at NIB**	1,493	3,678
Delivery at South Int. Land Boundary	116	118
Total Treaty Delivery	1,580	4,261
Bypass Pursuant to Minute 242	120	88

*USBR estimated unmeasured returns for the state as a whole

**Deliveries to Mexico by location were only reported for the study years 1995-1998; "Total Treaty Delivery" reflects the mean for all study years, so this is not the sum of the above two terms. Source: USBR (1991-98a).

For example, in USBR's annual *Compilation of Records* reports, "consumptive use" is defined as "diversions including underground pumping, less measured return flow and less current estimated unmeasured return flow" to the Colorado River mainstem. To provide a more detailed accounting, this study defines use as diversions less returns within the study area boundaries as a whole, rather than solely to the mainstem. Additionally, "flood years" on the Colorado River may be taken to mean years in which flood control releases were made, as established by Army Corps of Engineers guidelines; during the study period, such releases were made in 1997-1998. This study defines "Flood years" based on discharge at SIB, adding 1993 to the above.

The Mexican Constitution establishes the legal framework for water management in Mexico and reserves to the federal government the rights to national waters, including the Colorado River (Castro 1995). The Constitution also reserves ownership of groundwater to the national government (Cossio Diaz 1995). In practice, Mexico's Comision Nacional de Agua (CNA) determines deliveries of Colorado River water and regulates groundwater extraction within the delta region (Mumme 1996). CNA determined cropping patterns and allocated water accordingly. In recent years, however, efforts have begun to decentralize this authority and provide for greater autonomy at the local level (Clinton et al. 2001).

Chapter Three: Methodology

This study developed a water balance for the Colorado River delta region using available surface flow and groundwater extraction data, calculated volumes of evaporation and evapotranspiration, and estimated outflows based on historical records. This chapter describes the study area boundaries, the rationale for disaggregating the data spatially and temporally, sources and limitations of the data, and the methods used to develop the water balance.

Study Area Boundaries

To avoid confusion with the limited extent of the remnant Colorado River delta, this study uses the term "Colorado River delta region" or "region" to refer to the hydrologic boundaries of the delta of the Colorado River. However, these boundaries are not uniformly distinct due to shifting of Colorado River sediments, mixing with and coverage by local alluvium, and cartographic limitations due to the scale of Sykes' map. Additionally, the boundaries have been modified slightly in some places to reflect the locations of gauging stations or other data considerations. For example, the study uses Milepost 87 as the location at which the Coachella Canal enters the delta region, because of the availability of discharge records for that location, rather than because that is the definitive point at which the canal crosses Sykes' boundary. For each tabulation in the following chapters, the context of the flows or use measured is described.

To provide a basis for comparison and to afford greater clarity, the study area is divided into three sub-regions: Arizona, California, and Mexico (see Figure 3.1). Because Mexico's Irrigation District 14 includes cultivated acreage in both Baja California and Sonora, flow and use data for these states are combined within the Mexico sub-region. Disaggregating the data into these sub-regions arguably creates an arbitrary distinction and enshrines political boundaries at the expense of a holistic approach, yet the sub-regions provide a reasonable, ready means of disaggregating use and also recognize the role of different authorities in managing resources within their borders.

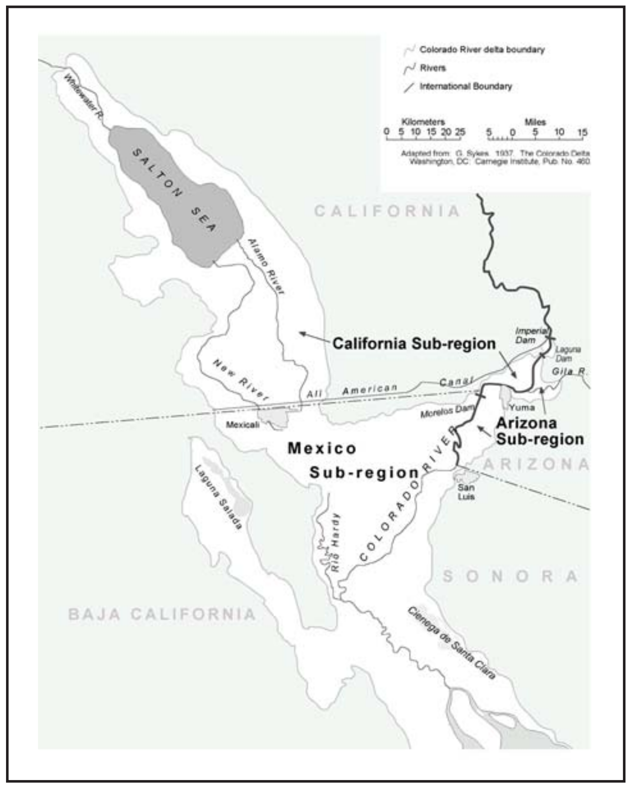

Figure 3.1
The Arizona, California, and Mexico Sub-Regions.

Non-Flood and Flood Years

To reflect the variability of Colorado River flows, the report divides the study period into Non-Flood and Flood years. Non-Flood year data reflect an average of the years 1991, 1992, 1995, and 1996. Flood year data reflect an average of the years 1993, 1997, and 1998. The year 1994 was not included in the study due to concerns that lingering flood damage from the 1993 Gila River flood event would distort cropping patterns and use in the Arizona and Mexico sub-regions. Mean annual discharge at SIB for Non-Flood years was 21.5 KAF (26.6 MCM); for Flood years, mean annual discharge was two orders of magnitude higher: 2,120 KAF (> 2,600 MCM). This distinction between Non-Flood and Flood years highlights the significant difference in discharge between these two categories. Mean discharge for the period as a whole would mask these differences, providing an inaccurate picture of the quantity of water (and related uses) in any given year.

The selection of the study period reflects a desire to maximize the number of data points while minimizing distortions due to changes over time, such as population growth, crop shifting in response to market and other forces, and other factors. Attempts to generalize data over multiple years can be subject to limitations and inaccuracies, particularly distortions due to demographic changes.[1] Despite significant population growth in the delta region, the data reflect very limited changes in urban use (an aggregate of domestic, municipal, and industrial consumptive uses) from 1991 through 1998.

The cause of water losses from canals may be difficult to tally. Courtesy of Jennifer L. Pitt.

Groundwater

The vast majority of the groundwater underlying the delta region originated from the Colorado River. Groundwater, as used in this report, refers only to the method by which the water was captured for use, as distinguished from surface water diverted directly from the mainstem of the Colorado River. Groundwater and surface water are closely linked; rivers and canals, for example, often lose water to seepage during high flows, and gain water from bank storage during low flows (Dunne and Leopold 1978). Yet, to provide a better understanding of the uses of water in the region, this study accounts for groundwater extraction and recharge as separate terms in the water balance, as inflows and outflows, respectively. Groundwater mining (extraction above recharge levels) effectively creates an additional source for consumptive use, one that would be masked if groundwater were not treated as a distinct source. Information on groundwater flows, recharge, and extraction rates vary for different areas of the delta region, and those records that do exist are not consistently reliable. Several on-going studies seek to better assess and improve understanding of the source, extent, quality, and flows of groundwater in the region.

Data Sources and Limitations[2]

No new measurements were made for this report. Rather, the water balance is a compilation of existing records and assessments of these records. Primary data sources for this study include the U.S. Geological Survey (USGS), the U.S. Bureau of Reclamation (USBR), the Mexican and U.S. sections of the International Boundary and Water Commission (IBWC), la Comisión Nacional de Agua (CNA), la Comisión de Servicios de Agua del Estado, la Comisión Estatal de Servicios Públicos de Mexicali, and la Secretaría de Agricultura, Ganadería y Desarollo Rural, and individual cities and irrigation districts within the U.S and Mexico. Please refer to "Data Sources" in the References section for the complete listing.

Numerous data limitations affect the accuracy of this report. Specific problems with data include: missing data and unreported sources; data variability; and inaccuracy of data. For many areas of the delta region, data were not available. Major data gaps in this report include the absence of data on the discharge of the Colorado River below SIB, volume of runoff in the Mexico sub-region, and the quantity of Colorado River water and local run-off flowing to the Laguna Salada. Flow measurements at El Marítimo, the last gauging station on the Colorado River, only exist for the years 1960 - 1968; measurements were influenced by inflows from the Rio Hardy, agricultural returns, and the tides from the Upper Gulf, challenging efforts to correlate estimated flows with subsequent stage records or flows at SIB. Other gaps include incomplete information on phreatophyte type and coverage in the region and extremely limited information on aquifer recharge rates.

Variability of data, definitions, standards, and temporal and spatial boundaries make comparisons difficult. Examples of such variability range from units of measurement to reporting standards. Groundwater reporting was particularly unreliable: much of the data is voluntarily self-reported by well-operators and likely undercounts extraction (USBR 1996). Variability in the time period over which data were collected also clouds comparisons and decreases the reliability of data. For example, CNA reports crop planting patterns and water deliveries by water year, rather than the calendar

[1] From 1990 – 2000, for example, Mexicali's population grew an estimated 21%, the Imperial Valley's by 28%, and the Yuma area's by 27% (Arizona Department of Economic Security 2001; California Department of Finance 2001; and INEGI 2000).

[2] See Gleick (1993) for an appropriate caution on the inaccuracies and unreliability of measured and derived data.

year data used in this study; some of these CNA data are reported seasonally, complicating efforts to convert the data to a calendar year format.

Additionally, reported data, including such presumably reliable data as streamflow gauge records, may not be wholly accurate. Owen-Joyce and Raymond (1996) assess the accuracy of gauging stations recording diversions from and returns to the Colorado River mainstem above NIB; with the exception of the Yuma Main Canal Wasteway station, they report that the U.S. station records used within this report are within 10% of actual discharge, 95% of the time. Table 3.1 displays the reported accuracy of other gauging records. The accuracy of the measured data suggests that the discharges reported in this study are, at best, within 10% of actual conditions. Other data, particularly groundwater data and derived data, are likely less accurate, though sensitivity analyses were not performed as part of this study.

Table 3.1 Accuracy of Select Streamflow Gauging Station Records.

Station Name	Gauge Number	Percent Error
Yuma Main Canal Wasteway*	09525500	>15%
Gila River near Dome	09520500	~10%*; >15% - ~15%†
NIB†	09522000	~10%
Intake at Morelos Dam†	09522030	~15% - ~10%
SIB†	09522200	>15%
Alamo River nr. Niland**	10254730	~15%
New River nr. Westmorland**	10255550	~10%

Sources:
*Owen-Joyce and Raymond (1996)
† Hill (1993)
**USGS

Methods

The study used a mass balance to estimate flows through the region. The mass balance equation (Owen-Joyce and Raymond 1996) can be described as:

$$Q_{ds} = Q_{us} + Q_{rf} + P + T_r - Q_{ex} - E - CU_d - ET - \Delta S_r - \Delta S_a - Q_{sb},$$

where
Q_{ds} = flow at the downstream boundary
Q_{us} = flow at the upstream boundary
Q_{rf} = return flow to the river (from outside the region)
P = precipitation (on open water surfaces)
T_r = tributary inflow (local runoff)
Q_{ex} = exported water
E = evaporation from open water surfaces
CU_d = domestic, municipal, and industrial use
ET = evapotranspiration
ΔS_r = change in reservoir storage (including the Salton Sea)
ΔS_a = change in aquifer storage
Q_{sb} = flow to sub-basin.

Total inflow, for the region as a whole or a particular sub-region, can be described as:

$$IF = Q_{us} + Q_{rf} + P + T_{r.}$$

Total outflow can be described as:

$$OF = Q_{ds} + Q_{ex} + E + CU_d + ET + Q_{sb} + \Delta S_r + \Delta S_a.$$

As defined above, inflows less outflows in any given year should equal zero. If the individual terms do not balance, inflows will not equal outflows, generating a residual, which can be expressed as a percentage of inflows. A lower residual may suggest a relatively higher accuracy of the water balance equation, but it may also reflect the presence of two or more errors that tend to balance.

Records for discharge at the downstream boundary (Q_{ds}) for the Arizona and California sub-regions are fairly complete; no similar records exist for the Mexico sub-region, or for the system as a whole. The last active gauging station on the mainstem of the Colorado River is at SIB, approximately 75 river miles (120 km) above the river's mouth. Discharge at the river's mouth has been estimated in the literature to be equivalent to discharge at SIB (Lavín and Sánchez 1999; Galindo-Bect et al. 2000). Historically, two gauges existed downstream of SIB: El Marítimo and M.C. Rodriguez. El Marítimo, the last gauging station on the Colorado River, was located on the river's right bank, 47.6 miles (76.6 km) below SIB, 18.6 miles (30.0 km) below the railroad bridge, and 2.0 miles (3.2 km) below the confluence of the Colorado River and Rio Hardy (see Figure 4.3). Discharge data at this station are only available from January, 1960 through July, 1968, when it was determined that tidal influences distorted the readings (CILA 1968). Station records subsequent to 1968 are limited to mean daily gage height, which reflects tidal influence as well as mainstem discharge and agricultural drainage. The M.C. Rodriguez gauging station, located on the left bank of the Colorado River about 24.5 miles (39.4 km) downstream from SIB and 4.5 miles (7.2 km) upstream from the railroad bridge, was dismantled August 31, 1983, due to high water and eroding banks. Maximum recorded instantaneous discharge at this station was 31,800 cfs (901 m^3/sec), on August 15, 1983. Records at this station reflected seepage from canals that run adjacent to the river. Figure 3.2 compares annual discharge records from SIB, M.C. Rodriguez, and El Marítimo gauging stations. Note that in 1962-1963, reported discharge at the two downstream stations exceeded that at SIB, possibly reflecting wasteway returns below SIB, or reporting or measurement error.

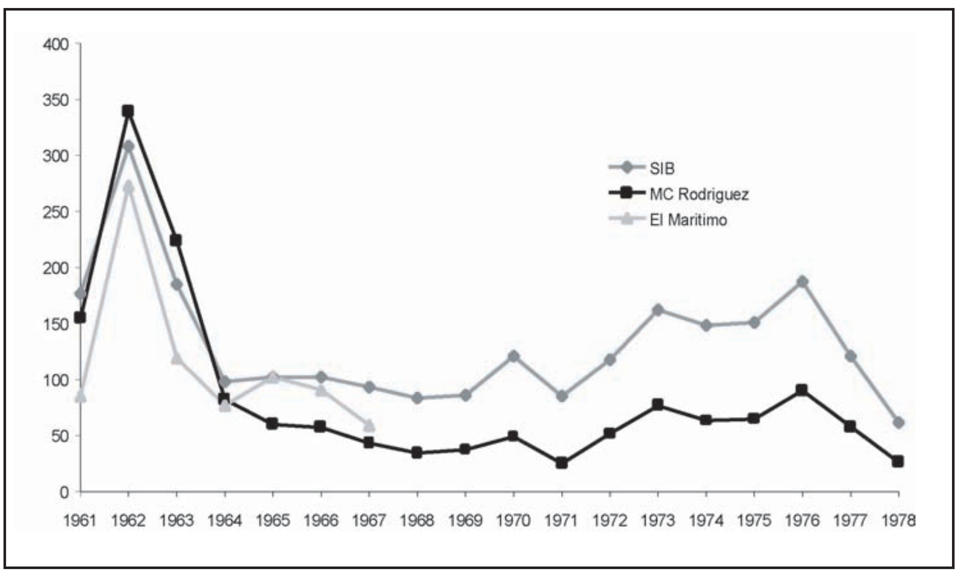

Figure 3.2 Reported Flow Below Morelos Dam, 1961-1982.

To estimate the flow of the Colorado River near the railroad bridge and at its mouth during the study period, linear regressions were run for mean daily discharge records for SIB and M.C. Rodriguez stations, and for SIB and El Marítimo stations, respectively, for the years 1960 and 1964.[3] The results of the best fit for these

Table 3.2 Correlation of Mean Daily Discharge at SIB and Downstream Stations.

		1960		1964	
station	lag	r^2	regression equation	r^2	regression equation
M.C. Rodriguez	1 day	0.967	y = 0.959x + 25.2 cfs (0.71 m^3/sec)	0.873	y = 0.893x - 7.24 cfs (0.21 m^3/sec)
El Marítimo	2 days	0.944	y = 0.834x + 50.0 cfs (1.42 m^3/sec)	0.696	y = 0.694x + 69.9 cfs (1.98 m^3/sec)

3 The year 1960 was presumed to be a Flood year, with maximum mean daily discharge of 6100 cfs (173 m^3/sec) at SIB, while 1964 was presumed to be indicative of a Non-Flood year, with maximum mean daily discharge of 1600 cfs (45.3 m^3/sec) at SIB.

correlations are presented in Table 3.2. In the table, "lag" reflects travel time for water between SIB and the downstream station, as determined by the best fit equation. Note that discharge records were available by day, limiting temporal resolution: actual travel time may have been several hours more or less than this, and would be expected to vary with magnitude of discharge. The correlation coefficients are lower for both stations during presumed Non-Flood years, likely reflecting the increased influence of variable return flows between SIB and the downstream stations.

These correlations were used as a guide to estimate discharge at downstream stations in Non-Flood and Flood years. Several factors, including the construction of levees, altered channel size and shape due to intervening flood events, changing irrigation practices, the variability of discharge to the Laguna Salada, and the questionable accuracy of El Marítimo records themselves, limit the reliability of these correlations for estimating discharge at the mouth of the Colorado River.

Sources of surface water inflow records, including discharge at the upstream boundary (Q_{us}) and return flows (Q_{rf}), varied by sub-region. Inflows to the Arizona sub-region were largely derived from USBR and USGS data. Discharge into the sub-region from the Colorado River, Gila River, All-American Canal, and other irrigation districts[4] was recorded annually (USBR 1991-98a; USBR; USGS). Recorded inflows to the California sub-region via the All-American Canal at Imperial Dam, the Coachella Canal, and the New, Alamo, and Whitewater Rivers were obtained from the USBR, USGS, and IBWC (1991-98). Discharge at Drop 4 of the All-American Canal was derived from IID-reported discharge at Drop 1, 16 miles (26 km) upstream, by assuming a constant outflow rate (3.2 KAF/mile (2.5 MCM/km)) due to seepage, phreatophyte ET, and evaporation based on estimated total outflow in the unlined portion of the canal (Mumme 1996) and reported pan evaporation rates. Records of inflows to the Mexico sub-region at NIB and near SIB were obtained from IBWC (1991-1998).

Precipitation (P) in the Arizona sub-region was calculated from the acreage of open water (Hill 1993) and precipitation records for the Yuma Citrus Station (IBWC 1991-1998). Precipitation on the Salton Sea was from the USBR Salton Sea model (Weghorst, pers. comm.); precipitation on other open water surfaces in the California sub-region was calculated from IID's reported rainfall and acreage of open water (Jensen 1995; Hill 1993). Precipitation for the Mexico sub-region was calculated from precipitation records for the "Delta" and "Riito" stations, as reported by IBWC (1991-1998), and reported extent of open-water surface area (Zamora-Arroyo, pers. comm.), plus an estimate of total open-water surface area in Mexico's Irrigation District 14 (2,200 acres (890 ha)). Records of precipitation and evaporation were incomplete for the "Delta" station for the years 1995 and 1996, so means for the Mexico sub-region did not include these years.

Factors such as soil depth and permeability, vegetative cover, and rainfall intensity and duration affect runoff and tributary inflow (T_r) (Hely and Peck 1964). Hely and Peck (1964) estimated runoff for the lower Colorado River-Salton Sea area by measuring initial soil infiltration and correlating this with soil type to project a runoff curve. This runoff curve was then used to project runoff as a percentage of precipitation, ranging from effectively 0% for sandy alluvial soils, to roughly 8% for less permeable alluvial soils, to more than 20% for foothill/plateau areas with less permeable soils. This study estimates runoff at 8% of precipitation, to account for the lack of rainfall records for the mountain regions balanced against expected infiltration in the permeable alluvial soils between the base of the mountains and the hydrologic systems in this study. More accurate projections of runoff require records of finer temporal resolution than were available for this study, as well as analysis of the permeability of soils underlying ephemeral streams (Hely and Peck 1964). Therefore, the calculations of tributary runoff are offered as a general estimate.

Annual records of "Exports" (Q_{ex}) and "Returns from exports" (Q_r) for the Arizona sub-region were calculated from USBR (1991-1998a) and IBWC (1991-1998).[5] Records of water exported from the Mexico sub-region to Tijuana and Tecate were obtained from CNA.

For the Arizona sub-region, evaporation (E) was calculated from an estimate of open water surface area (1,000 acres (405 ha)) and reported pan evaporation rates (IBWC 1991-1998). Most of the evaporation in the California sub-

[4] Discharge from other irrigation districts included agricultural wastewater from Yuma Mesa, Yuma Auxiliary, and WMIDD.

[5] Water exported from the Arizona sub-region was delivered to: Wellton-Mohawk Irrigation and Drainage District; Marine Air Corps; South Pacific Railroad; Yuma Mesa Irrigation District; half the University of Arizona farms (one of the farms is in Yuma Valley, the other is in Yuma Mesa); Yuma Fruit Growers; Unit B Irrigation District; and the Yuma Proving Ground.

region was from the Salton Sea, according to the USBR Salton Sea model. Evaporation from delivery canals, reservoirs, and drains in the Coachella Valley, Imperial Valley, and Reservation Units was calculated from acreage data (Jensen 1995; CVWD 2000; Hill 1993) and reported pan evaporation rates (IBWC 1991-98). For the Mexico sub-region, evaporation was calculated from total area of open water (Zamora-Arroyo, pers. comm.) and reported pan evaporation rates for the "Delta" station, as reported by the IBWC (1991-1998), using a pan-to-free water surface coefficient of 0.70 (NOAA 1982).

Urban consumptive use in the Arizona sub-region was taken from Lower Colorado River Accounting Report Demonstration of Technology (LCRAS DOT).[6] The city of Yuma disaggregated the water applied to industrial and to municipal use (Baer, pers. comm.). In the California sub-region, urban consumptive use in the Coachella Valley and Reservation Units was reported by the CVWD and USBR's LCRAS DOT reports, respectively, and was calculated for the Imperial Valley, assuming a 60% consumption rate for municipal users and a rate of 15.5% for industrial users (CVWD 2000; USBR 1995-98; USBR). Although the City of San Luís Río Colorado, Sonora, lies outside the study region, its municipal effluent (records from OOMAPAS) discharged to the Colorado River below SIB and was included as a return flow in the Mexico sub-region. Records of consumptive use in Mexicali were from CESPM.

In the Arizona sub-region, evapotranspiration (ET) was from LCRAS DOT reports. The LCRAS DOT reports recorded consumptive use for the agricultural[7] and environmental sectors from 1995 through 1998.[8] ET rates used in the Yuma area for 1995 and 1996 were 10-15 inches (25-38 cm) higher than the averaged ET rates in the 1997 and 1998 reports due to corrections for the disparity in values reported by the CIMIS and AZMET stations (USBR 1995-98). In the absence of more accurate data, the overall ET rates from 1998 (2.05 af/acre (0.62 m) for agricultural use and 4.08 af/acre (1.24 m) for natural use) were applied to crop acreages and natural vegetation in 1995 and 1996 to derive a more accurate estimate of consumption.

ET for the California sub-region was calculated from existing records. Agricultural consumptive use was derived from reported delivery and wastewater discharge records where available (USBR 1991-98b; CVWD 2000). CVWD (2000) provided 1999 agricultural wastewater discharge data, while IID reported 1991-1998 discharge to the Salton Sea (in Tostrud 1997). IID's agricultural wastewater discharge was adjusted for calculated phreatophyte use along drains and the Alamo and New rivers, evaporation, recharge, pre-delivery losses, and urban wastewater discharge.

ET rates for the delta region's major crops were drawn from existing sources (see Table 3.3). Crop ET rates vary according to a number of factors, including temperature, humidity, and wind, making such rates site-specific. As shown in Table 3.3, there is a range of estimates available for determining ET. In an effort to avoid extreme estimates, this study calculated ET by using rates within the range of published estimates. For example, several ET rates (Erie et al. 1982; CDWR 1993; IID; Jensen 1995) existed for cotton, alfalfa, and sugarbeets, so these values were averaged for this study; CDWR (1994) published a range of ET rates, which was used to verify the accuracy of the calculated mean. Only one ET rate was available for wheat and lettuce (Erie et al. 1992; Jensen 1995). ET for grapes was calculated from the high and low ends of the ET ranges reported by CDWR (1993; 1994).

Environmental ET is limited to estimated phreatophyte consumption; it does not include upland vegetation, which draws predominantly from groundwater. While emergent vegetation, such as that occurring in Mittry Lake and the Cienega, draws from surface water (Glenn et al. 1992; 1996), established riparian vegetation draws from the underlying alluvial aquifer (Dawson and Ehleringer 1991; Stromberg 1993), effectively representing a conjunctive use. The extent of phreatophyte coverage was not disaggregated by type (i.e., wetland reeds vs. riparian saltcedar), and in many cases was simply reported as a general use by phreatophytes (cf. Jensen 1995), so this report aggregates emergent wetland and established riparian use. Phreatophytes grew along agricultural delivery canals and drainage ditches throughout the

[6] For the following entities: the City of Yuma; Desert Lawn; Southern Pacific Railroad; Yuma Union High School; USBR Yuma Area Office; the Cocopah R.V. Park; Somerton; Gadsen; San Luis; and Yuma County.

[7] USBR LCRAS DOT records for the following districts were used: Desert Lawn Memorial; Fort Yuma Indian Reservation, Arizona homesteads; Fort Yuma Indian Reservation, Mittry SWA&YPG Arizona; Imperial National Wildlife Refuge; Mittry Lake SWA; North Cocopah; North Gila Valley; Sturges Ranch; State of Arizona; State of Arizona, limitrophe; University of Arizona agricultural station (only half of this number was used because half of the station lay outside the region); West Cocopah; Yuma Irrigation District; Yuma Valley Irrigation District.

[8] Users along the lower Colorado have expressed concern over the report's methodology and potential for errors.

Table 3.3 Mean Annual Evapotranspiration (ET) Rates by Crop for the Colorado River Delta Region (AF/acre).

	Erie et. al 1982	CDWR 1994	CDWR 1993	Jensen 1995	Imperial County undated	**Study ET**
Cotton	3.43	3.2-3.3	3.30	3.10	3.45	**3.32**
Alfalfa	6.19	4.3-6.6	4.3-6	5.48	5.20	**5.62**
Wheat	2.15	n/a	n/a	n/a	n/a	**2.15**
Sugarbeets	n/a	3.80	3.80	2.81	n/a	**3.31**
Grapes	n/a	2.4-3.3	2.4-3	n/a	n/a	**2.85**
Citrus	n/a	2.10	n/a	3.45	n/a	**2.78**
Lettuce	n/a	n/a	n/a	1.41	n/a	**1.41**

region. The acreage and characteristics of vegetation along delivery canals throughout the region and wastewater ditches in the Arizona and Mexico sub-regions were unavailable.[9]

Environmental ET in the Arizona sub-region was reported by the USBR's LCRAS DOT reports (USBR 1995-98). Phreatophyte consumptive use in the California sub-region was drawn from several sources. Drains and rivers (New and Alamo rivers) carrying agricultural drainage from IID and urban wastewater from Mexicali and Imperial Valley cities supported approximately 11,400 acres (4,600 ha) of vegetation (Boyle, in Jensen 1995). The Coachella Valley's phreatophyte ET pre-delivery was negligible, as shown by the CVWD's water delivery efficiency rate of 99% (CVWD 2000). Losses to ET post-delivery in the Coachella Valley were recorded by Bechtel (as reported in Tostrud 1996) and adjusted for groundwater consumption by established riparian vegetation. Tostrud (1996) reported that 30% of delivery losses in the IID were to phreatophyte ET. Estimates of environmental consumption post-delivery by Boyle (in Tostrud 1996) and IID (in MWD 2000) were averaged. The ET of natural vegetation surrounding the Salton Sea was calculated from acreage of specific vegetation types (Salton Sea Database Program 2000) and the ET rates for that vegetation as reported in the USBR's LCRAS DOT reports (USBR 1995-98). Evapotranspiration (ET) rates for phreatophytes in the remnant delta were calculated from reports of vegetation density, extent, and type (Valdés-Casillas et al. 1998; Zamora-Arroyo et al. 2001) and the USBR's LCRAS DOT report's (USBR 1997) 1997 ET coefficients, adjusted to reflect varying pan-evaporation rates. Additional phreatophyte use in the Mexico sub-region was estimated from the extent of unlined canals and drains, proportional to the phreatophyte ET in the Imperial Valley.

Change in reservoir storage (ΔS_r) reflects the change in contents of the Salton Sea, as calculated by a model provided by USBR; the Sea provides the only notable surface storage capacity in the delta region.[10] Change in groundwater storage (ΔS_a) was assumed to be negligible in irrigated areas of the California sub-region due to the extensive use of tile drains in the Imperial and Coachella valleys and sub-surface returns to the mainstem from the Reservation Units. A static groundwater recharge number for the Coachella Valley was calculated from the 1999 groundwater budget in the Coachella Valley Water Management Plan (2000).[11] In the Reservation Units, groundwater recharge was calculated from the difference between groundwater extraction and change in underground storage (USBR 1996).

Groundwater recharge in the Arizona sub-region was estimated as the difference between reported groundwater extraction and reported change in underground storage for the Yuma, South Gila, and North Gila Valleys in 1992 (Non-

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[9] The USBR's LCRAS DOT reports provided the amount of phreatophyte acreage and consumption per user in Arizona; they did not specify whether this water was from the Colorado River, delivery canals, or drainage ditches.

[10] IID maintains >3 KAF (3.7 MCM) of storage in regulatory reservoirs, while CVWD's Lake Cahuilla terminal reservoir has a capacity of some 1.5 KAF (1.8 MCM)

[11] Some of the line items under groundwater recharge were omitted from the calculation because they were counted elsewhere in this study. These line items included: flow to drains; domestic and golf course returns; wastewater percolation; and inflows from outside the study area.

Flood year) and 1993 (Flood year) (USGS 1996). Although change in underground storage was measured by the USBR, under-reporting of extraction volumes (see above) would similarly reduce the estimated inundated recharge.

For the Mexico sub-region, groundwater extraction for agricultural and urban uses was derived from several sources, as discussed in Chapter Four. Estimated groundwater recharge for the Mexico sub-region was drawn from isolated reports and reported conveyance losses by CNA, plus an estimated volume of recharge from the inundated floodplain during Flood years. This Flood year recharge was based on depth to groundwater in 1999-2000 (reported at 3-7 feet (1-2 m) in the Colorado River floodplain between the levees); estimated area within the levees between Morelos Dam and the Rio Hardy, and the water-holding capacity (30%) (Dunne and Leopold 1978) of the reported soil type (predominantly sandy loam) (Zamora-Arroyo et al. 2001). This maximum instantaneous volume does not account for groundwater movement, either to areas outside the levees or returns to the river as floodwaters receded. Additionally, the reported depth to groundwater may represent a rise in groundwater storage due to the 1997-1998 flooding, rather than a static elevation, suggesting that the calculated value should be treated as a minimum.

In Flood years, water from the Colorado River mainstem has discharged into the Laguna Salada basin (Q_{sb}) (Valdes-Casillas et al. 1998; Luecke et al. 1999). A review of Landsat 4 Multispectral Scanner Satellite images (path 39 row 38) revealed standing water in the Laguna Salada in 1993, 1997, and 1998. In November, 1998, one of the authors observed water flowing from the Colorado River mainstem through a canal to the Laguna Salada basin, but discharge was not determined. Discharge to the Laguna Salada was estimated based on anecdotal observations, an unpublished report (Compean-Jiménez et al., no date) that estimated the 1984 extent of the inundated area at 100,000 acres (40,000 ha), with a maximum depth of 13 feet (4 m) and a volume of 590 KAF (730 MCM), and from a GIS-based estimate of the 1997 extent of the Laguna at 23,000 acres (9,300 ha). The diversion to the Laguna Salada lies approximately 10 river miles (16 km) below the former site of El Marítimo, so estimated discharge to the Laguna was subtracted from total discharge reaching the mouth of the river at the Upper Gulf.

The Upper Gulf of California is characterized by extreme tides (amplitude > 25 feet (8 m) (Lavín et al. 1997)) that strongly affect the final 12 miles (19 km) of the river (Luecke et al. 1999) and distorted river stage measurements at El Marítimo, 25 miles (40 km) above the river's mouth (CILA 1960-1968), and reportedly affect areas 10 miles (16 km) further upstream (Payne et al., no date). Occasionally, high tides also flow into the Laguna Salada, further challenging efforts to determine the source of standing water in the region. Due to difficulties encountered in accounting for tidal effects, this study does not include the intertidal zone, defined here as the final 12 miles (19 km) of the river, within the water balance.

Chapter Four: Hydrology

This chapter discusses the hydrology of the Colorado River delta region, including historic and recent mainstem discharge, sources and quantities of inflows and outflows, groundwater extraction and recharge, and the physical infrastructure that conveys water through the region. This chapter describes flows for the region as a whole, and for the three sub-regions within Arizona, California, and Mexico.

Colorado River Flows

Prior to the construction of regulatory structures along its length, the seasonal and annual discharge of the Colorado River varied dramatically, ranging from prolonged droughts to raging floods (O'Connor et al. 1994; Tarboton 1995). The long-term mean annual discharge of the Colorado River near Lee's Ferry, Arizona, 647 miles (1,042 km) upstream of Imperial Dam (the upstream limit of the study area), has been estimated at 13,500 KAF (17,000 MCM) (Meko et al. 1995). Mean annual discharge at Lee's Ferry during the period of record (1906-1998) has been estimated at 15,000 KAF (18,500 MCM). The USBR (Harkins, pers. comm.) estimates that outflows, due to evaporation, phreatophyte use, and other system losses, from Lee's Ferry to the NIB, exceed inflows by roughly 500 KAF (600 MCM) annually, suggesting that these adjusted records are a reasonable proxy for discharge at the upstream system boundary. Before upstream impoundments and diversions dewatered the Gila River, it contributed an additional estimated 1,300 KAF (1,600 MCM)/ year to the discharge of the Colorado River, at their confluence near Yuma (USBR 1952), 14.7 river miles (23.7 km) downstream from Imperial Dam. During the period of record (1951-1999), mean annual recorded discharge of the Gila

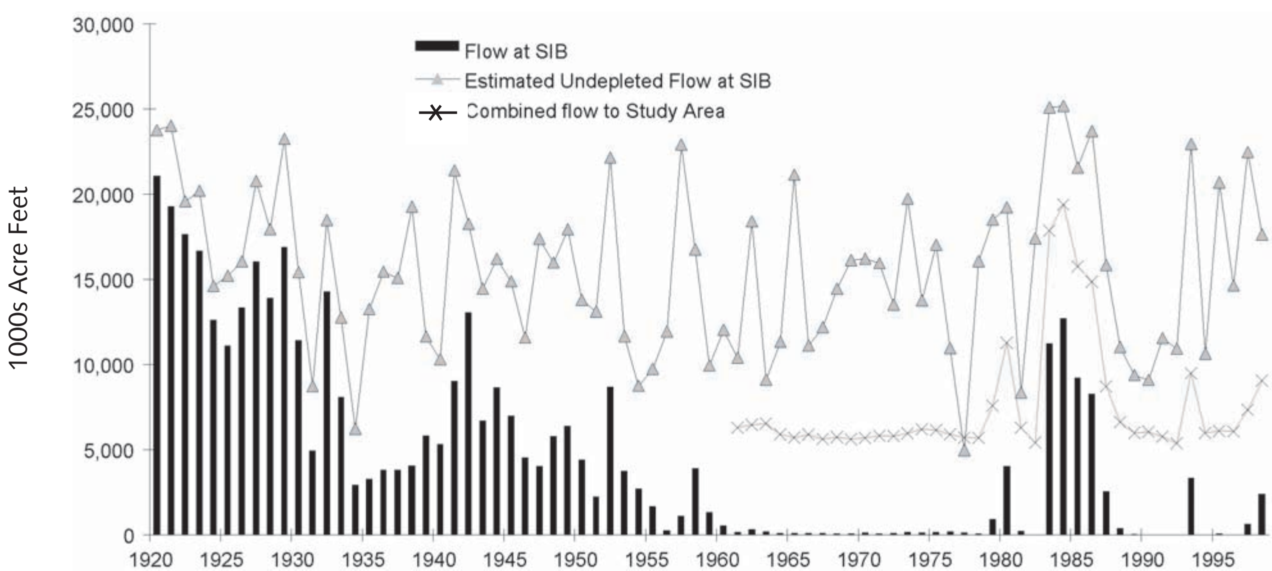
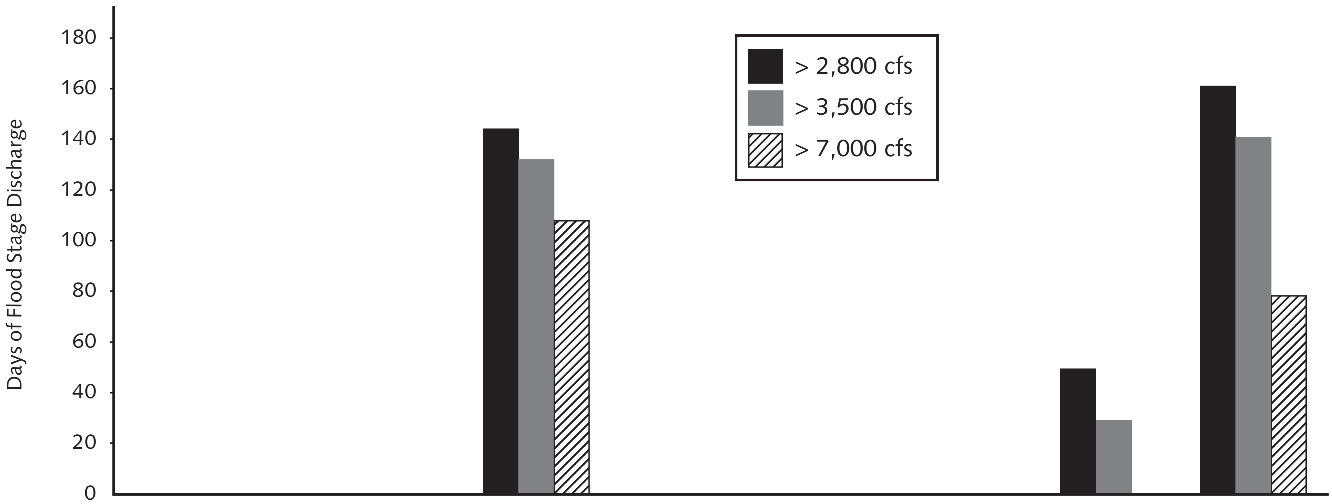


Figure 4.1 Measured and Estimated Undepleted - Unregulated Flow Through the Delta Region, 1920-1998.[1]

[1] Sources: calculated discharge at SIB prior to 1935 from Morrison et al. (1996); measured discharge at SIB 1935-1998 from IBWC; estimated undepleted-unregulated Colorado River discharge at Lee's Ferry and recorded discharge above Imperial Dam from USBR; undepleted-unregulated Gila River discharge based on an annual estimate from USBR (1952); recorded Gila River discharge near Dome, Arizona, from USGS.



	1991	1992	1993	1994	1995	1996	1997	1998
Max. instant. Q	477 (13.5)	1,980 (56)	22,920 (649)	908 (25.7)	2,830 (80)	0	6,600 (187)	10,990 (308)
Max. daily Q	346 (9.8)	1,660 (47)	22,810 (646)	795 (22.5)	2,720 (77)	0	6,140 (174)	10,800 (306)

Figure 4.2 Total days of flood stage discharge at SIB, 1991-1998, with maximum instantaneous and daily discharge (Q) in cfs (m^3/sec) (IBWC 1991-1998).

River near Dome was 230 KAF (280 MCM), while median annual discharge for this period was 6 KAF (7 MCM).[2] The combined discharge of the Colorado and Gila rivers flowed through the Colorado River delta.

Except in years with unusually high run-off, virtually the entire flow of the Colorado is now captured and used before it reaches the river's mouth (Morrison et al. 1996). Figure 4.1 compares discharge at the last gauging station on the Colorado River, at the SIB (49 river miles (79 km) below Imperial Dam), with the estimated combined discharge of the undepleted and unregulated Colorado and Gila rivers, and with the total surface flow entering the study area, defined here as the flow of the Colorado River above Imperial Dam plus the flow of the Gila River near Dome. In 1977, the estimated undepleted and unregulated flow of the Colorado River at Lee's Ferry was 5,000 KAF (6,200 MCM), less than the amount actually delivered to Imperial Dam from storage at Lake Mead.

Flood Flows

As shown in Figure 4.1, the unregulated flows of the Colorado River are extremely variable. For example, mean annual discharge of the Colorado River at SIB during the most recent 30 year period of record (1969-1998) measured 1,900 KAF (2,350 MCM), while median annual discharge was only 150 KAF (190 MCM) ($\sigma = 4{,}400$ MCM). Regulated Colorado River discharge also displayed marked variability during the study period. Almost half of those years witnessed overbank flooding below Morelos Dam, due to space-building releases at Hoover and Painted Rock dams triggered by above-average inflows and near-capacity storage.

To reflect this variability, the report divides the study period into Non-Flood and Flood years, with Flood years defined as those in which maximum mean daily discharge at SIB exceeded 2,800 cfs (80 m^3/second), the minimum estimated threshold for overbank flooding below Morelos Dam (Zamora-Arroyo et al. 2001). Figure 4.2 displays the total number of days, by year, within the study period in which mean daily discharge equaled or exceeded this minimum estimated flood stage, as well as the total number of days in which mean daily discharge exceeded the flood stage

[2] Data calculated from National Water Information System-Automated Data Processing System (NWIS-ADAPS) Report of mean daily discharge for station 09520500 (Gila River near Dome, Arizona). Raw data courtesy of Bill Roberts, USGS.

Table 4.1 Mean Annual Colorado River Discharge Through the Delta Region.[3]

1000s Acre-Feet	Non-Flood Year	Flood Year
Colorado R. above Imperial Dam	**5,643**	**7,044**
Colorado R. below Imperial Dam	**277**	**717**
Gila River near Yuma	181	1,585
Yuma Wasteway	232	204
Pilot Knob Wasteway	507	1,475
Other returns Imperial – Morelos*	172	145
Colorado R. at NIB	**1,455**	**4,139**
Colorado R. below Morelos	**34**	**2,064**
U.S. returns Morelos - SIB	2	4
Colorado R. at SIB	**22**	**2,120**
San Luís R.C. effluent nr KM 27*	8	9
KM 27 wasteway	17	194
KM 38 wasteway	1	10
Colorado R. at M.C. Rodriguez*	**19**	**2,035**
Colector del Sur drain*	9	10
Principal del Sur drain*	25	24
Rio Hardy*	40	48
Colorado R. at El Maritimo*	**16**	**1,770**
Colorado R. at Upper Gulf of California*	**16**	**1,570**

* Derived data; others are streamflow gauge records.

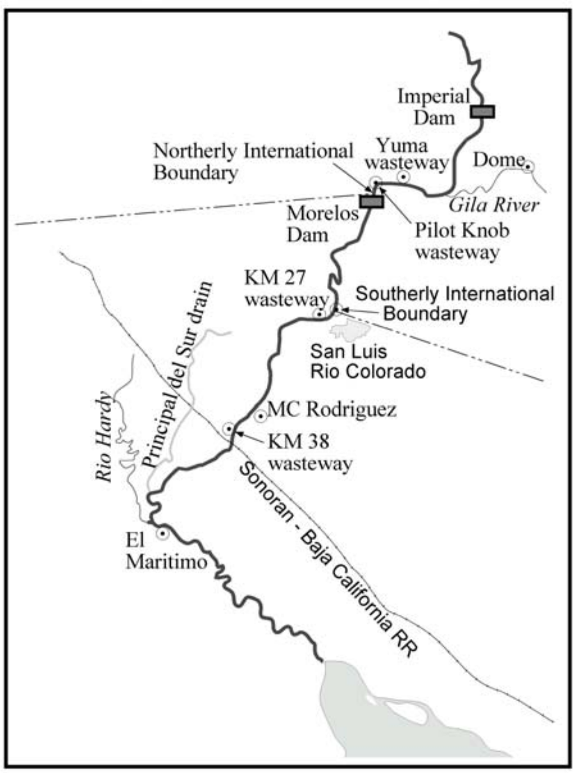


Figure 4.3 Infrastructure in the Colorado River Delta Region.

estimates of 3,500 cfs (100 m^3/sec) and 7,000 cfs (200 m^3/sec) of Luecke et al. (1999). Along the x-axis below each year are the annual maximum instantaneous and mean daily discharge, in cfs and in (m^3/sec). No measurable discharge was recorded in the Colorado River at SIB in 1996.

Mainstem Discharge

Table 4.1 displays mean annual discharge at Colorado River mainstem gauging stations in the study area during Non-Flood and Flood years, and reported and estimated returns to the mainstem along its length. The location of these stations is shown in Figure 4.3. Low-flow years on the Gila River (1991, 1996-1998) do not match the study's Non-Flood years (1991-1992, 1995-1996). Mean annual discharge for low-flow years on the Gila River near Dome, Arizona is 9.1 KAF (11 MCM), only 5% of the volume reported for Non-Flood years. The mean for Flood years reflects the Gila River flood event of 1993, with total recorded discharge of 4,700 KAF (5,800 MCM).

The Yuma Main Canal wasteway discharges to the mainstem on the California side of the river, 6.5 miles (10.5 km) upstream of NIB. The Pilot Knob wasteway is located on the All-American Canal, 20.8 miles (33.5 km) downstream from the intake at Imperial Dam. It discharges to the mainstem about 1 mile (1.6 km) above NIB. In Table 4.1, "Other returns Imperial - Morelos" include records from the Reservation Main Drain No. 4 (immediately upstream from the Yuma Main Canal wasteway), the Yuma Mesa Outlet drain (1.7 miles (2.7 km) below the Yuma wasteway), the Araz Drain (2.5 miles (4.0 km) above NIB) from California's Reservation Division, and the Cooper wasteway (0.5 miles (0.8 km) downstream from NIB and 0.6 miles (1.0 km) above Morelos Dam) discharging regulatory waste water (approx. 1.5 KAF (1.8 MCM)/year) from the Cooper Canal serving the Valley Division of the Yuma Project. USBR's annual (1991-1998a) estimates unmeasured return flow to the Colorado River from the Arizona sub-region at 25.6 KAF (31.6 MCM) in Non-Flood years and 24.9 KAF (30.7 MCM) in Flood years, exclusive of an additional unquantified amount from

[3] Sources: IBWC; USBR; Valdés-Casillas et al. 1998; CILA; OOMAPAS.

During Non-Flood years, an average of 17 KAF of excess diversions returned to the river through the gates of the KM 27 wasteway in Mexico.

the California sub-region. Some of these returns are reflected in "Other returns," while others enter the mainstem below Morelos. Presumably, unmeasured returns from the Mexican side of the limitrophe also contributed to mainstem discharge, though estimates of such returns were not available.

Between Morelos Dam and SIB, the Eleven Mile wasteway (3.2 miles (5.1 km) downstream of Morelos Dam) and the Twenty-one Mile wasteway (17.4 miles (28.0 km) downstream) discharge excess diversions from the Valley Division of the Yuma Project in Arizona into the Colorado River mainstem. On an emergency basis, Wellton-Mohawk drainage water from the Main Outlet Drainage Extension (MODE) has been discharged to a point immediately below Morelos Dam (IBWC 1991-1998). These records are reported in Table 4.1 as "returns Morelos – SIB." Discharge of the Colorado River decreased by a third between Morelos Dam and SIB during Non-Flood years, presumably due to seepage, evapotranspiration, and evaporation. The Soil Conservation Service (USDA 1980) classifies soils on the U.S. side of the limitrophe as a mix of sandy and silty soils with moderate to excessive drainage, suggesting a high seepage potential.[4]

"San Luís R.C. effluent" refers to untreated wastewater discharged by the City of San Luís Río Colorado into the mainstem roughly 2 miles (3 km) downstream from SIB. Some of the water Mexico diverts at Morelos Dam is conveyed via the Central Feeder Canal to a point 3.1 miles (5.0 km) downstream from SIB, where it may be returned to the river via the KM 27 wasteway on the right bank of the river or may be diverted to the Bacanora-Monumentos Canal system via the Sanchez Mejorada siphon, to irrigate fields in the San Luis Valley on the left bank of the river. The KM 38 wasteway, 28.1 miles (45.3 km) downstream from the SIB and 0.8 miles (1.3 km) upstream from the railroad bridge, returns water from the Barrote Canal to the mainstem (IBWC 1991-1998). The combined discharge of the San Luís effluent and the two wasteways exceeded reported mainstem discharge at SIB during Non-Flood years.

Discharge at the M.C. Rodriguez and El Marítimo stations was calculated using the regression analysis described in Chapter Three. This estimated discharge at M.C. Rodriguez was less than reported discharge at SIB, despite inflows from the wasteways and effluent. Such decreases may be due to groundwater recharge and phreatophyte use, or may reflect an error in the regression analysis. The Carranza drain discharges to the mainstem approximately 6 miles (10 km) below the railroad bridge; the Principal del Sur drain discharges approximately another 6 miles farther downstream. The Rio Hardy, carrying agricultural drainage from the Mexicali Valley and an estimated 4.8 KAF (5.9 MCM) of run-off from the adjacent Sierra de los Cocopah range in Non-Flood years and 3.6 KAF (4.4 MCM) in Flood years, discharges to the mainstem approximately 17 miles (27 km) below the railroad bridge and 30 miles (49 km) below SIB.

Sub-Regional Flows

As described previously, the system boundaries for the delta region as a whole were based on Sykes' (1937) research on the hydrologic extent of the Colorado River delta. The three sub-regions are based solely on political boundaries within this hydrologic extent, to better describe flows within the region. Discussion of the water balances for each of these sub-regions follows.

Arizona Sub-Region

Arizona diverts Colorado River water at Imperial Dam for irrigation and urban uses in the Yuma area via the Gila Gravity Main Canal, and through the Yuma Siphon off the All-American Canal. Additional water enters the sub-region

[4] Output from the Arizona Department of Water Resources groundwater model for the Yuma area for the years 1979 (representative of a Flood year) and 1982 (representative of a Non-Flood year) suggest that annual contributions to streamflow below Morelos from the aquifer on the U.S. side (recharged by percolation from intensive irrigation in the area) may be on the order of 20 KAF (24 MCM), though this model has not been ground-truthed (Greer, pers. comm.).

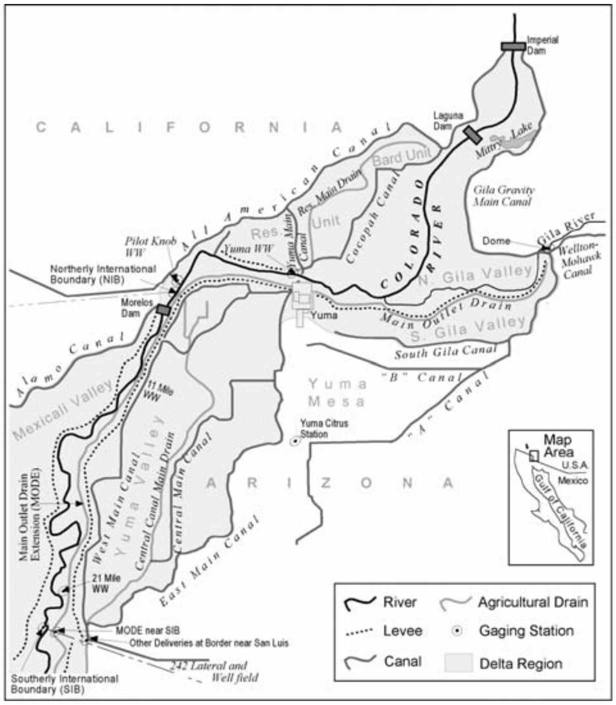


Fig. 4.4 The Arizona Sub-Region and the Mainstem Portion of the California Sub-Region.

Table 4.2 Arizona Sub-Region Water Balance.

	Non-Flood Year	Flood Year
	1000s Acre-Feet	
Inflows		
Gila Gravity Main Canal	781	731
Gila River at Dome	181	1,585
Yuma Siphon	367	373
Returns from exports	172	145
Precipitation and other Local Sources	3.2	3.5
Groundwater extraction	37	40
242 Well Field near San Luis	18	4
Total	**1,559**	**2,882**
Outflows		
Exports	675	622
Evaporation	8.6	8.6
Urban Consumptive Use	22.7	21.9
Agricultural ET	235	211
Phreatophyte ET	39.7	41.7
MODE near SIB	119	88
Other deliveries near SIB	123	116
Returns to the Colorado River	250	1,900
Groundwater Recharge	46	63
Estimated unmeasured returns	26	25
Total	**1,545**	**3,097**
Residual	**14**	**(215)**

Sources: IBWC (1991-98); USBR (1991-98a,b)

through intermittent flows of the Gila River, return flows from irrigation and drainage districts outside the delta region, surface water pumped from the river itself, and groundwater extracted from shallow aquifers within the sub-region. Surface water exits the sub-region through ET, evaporation, recharge, returns to the mainstem, exports to districts outside the region (such as Yuma Mesa and WMIDD), and deliveries to Mexico via the Sanchez Mejorada Canal (at the land boundary near San Luis) and the MODE.

The mean annual inflows and outflows for the Arizona sub-region are presented in Table 4.2; locations of the stations are displayed in Figure 4.4. Open water surface area in the sub-region was estimated at 1,000 acres (400 ha); total precipitation was based on records from Yuma Citrus Station (IBWC 1991-1998). USBR LCRAS DOT reports estimate unmeasured tributary inflow to the Colorado River between Imperial and Morelos Dams at 3 KAF (4 MCM)/year. Groundwater extraction data were self-reported and are potentially incomplete.[5] Inflows reported at "242 Well Field near San Luis" almost immediately exited the sub-region, as "Other deliveries [to Mexico] near SIB." "Returns from exports" refers to inflows of agricultural drainage from irrigation districts that lay outside the delta region but diverted Colorado River water through the sub-region, such as Yuma Mesa and Wellton-Mohawk.

Chapter Five discusses the methods used to estimate the agricultural, urban, and natural consumptive uses listed under "Outflows." "Groundwater infiltration" was calculated from reported extraction and measured change in underground storage (USBR 1996).[6] Based on this measured change, net groundwater extraction in the sub-region was 37 KAF (46 MCM) in 1992 and 40 KAF (50 MCM) in 1993. "Exports" refers to water delivered to Colorado River users in Arizona outside the delta region. "Returns to the Colorado River" aggregates total returns to the mainstem, wasteway returns below Morelos Dam, and Gila River discharge. The residual, expressed as a percentage of inflows, is 0.9% in Non-Flood years, and -7.5% in Flood years. Not included in the above water balance are sub-surface flows from the Arizona sub-region to Mexico.

5 USBR (1996) considers extraction estimates an "absolute minimum," because "there were numerous private wells which pumped in the area from which there were no pumping data available." Groundwater data are from: Yuma Valley; South Gila Valley; and North Gila Valley, for 1992 and 1993 only.

6 Because extraction estimates are presumed to be low (see above), calculated recharge is also expected to be low. Net groundwater extraction, based on measured change in groundwater storage, are probably a more reliable figure.

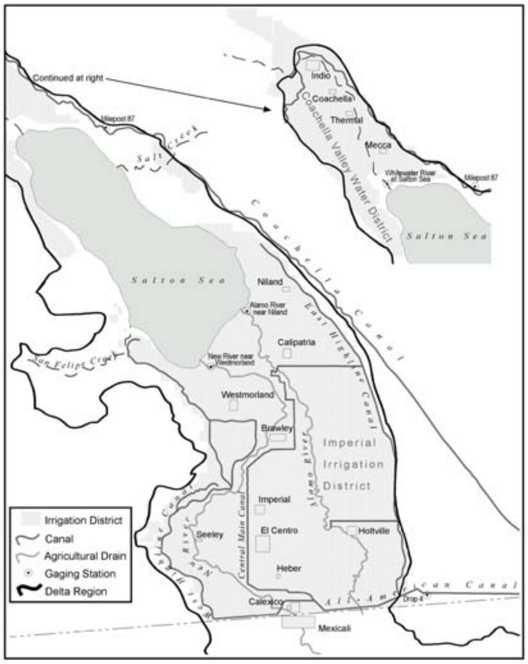


Figure 4.5 The Salton Basin Portion of the California Sub-Region.

California Sub-Region

California diverts Colorado River water at Imperial Dam via the All-American Canal for agricultural and urban uses in and near the Reservation Units and in the Imperial Valley, and, via the Coachella Branch of the Canal, in the Coachella Valley. Additional water enters the sub-region as return flows from Mexico in the New and Alamo rivers, as groundwater extracted in the lower Coachella Valley, as return flows and intermittent storm run-off in the Whitewater River, precipitation on open-water surfaces (predominantly the Salton Sea), and other local run-off. The portion of the California sub-region that does not border the mainstem is largely below sea level, so most of the surface water entering the sub-region as a whole does not return to the mainstem. Surface water exits the sub-region through ET, evaporation, groundwater recharge, and limited returns to the mainstem.

The All-American Canal, a partially-lined gravity-flow canal, runs 82 miles (132 km) from Imperial Dam to the southwest corner of the Imperial Valley. Between the Imperial Dam and Pilot Knob, the Reservation Units divert water from the All-American Canal via the Yuma Main Canal and four smaller canals. After leaving the delta at Pilot Knob, the canal crosses 14 miles (23 km) of sand dunes before reaching Drop One, where the Coachella Canal branches from the All-American Canal to deliver water to the CVWD. For much of its length (see Figure 4.5), the Coachella Canal skirts the border of the delta region. For the purposes of this study, Colorado River water was assumed to re-enter the delta near Milepost 87 of the Coachella Canal as it enters the Coachella Valley (near the northeast end of the Salton Sea). In the Imperial Valley, water re-enters the delta at Drop Four of the All-American Canal, 52 miles (84 km) downstream of Imperial Dam and 16 miles (26 km) downstream of Drop One.

Total reported groundwater recharge for the lower Coachella Valley in 1999 (CVWD 2000) was 186.9 KAF (230.5 MCM), of which 1.4 KAF (1.7 MCM) was from natural recharge, 130.3 KAF (160.7 MCM) from agricultural returns, 24.7 KAF (30.5 MCM) from domestic and golf course returns, 0.9 KAF (1.1 MCM) from wastewater percolation, and 29.6 KAF (36.5 MCM) from sub-surface inflows from outside the study area and other districts receiving water through the study area. IID maintains approximately 1,406 miles (2,263 km) of drainage ditches that collect surface runoff and subsurface drainage from 32,227 miles (51,864 km) of tile drains in the Imperial Valley, limiting the amount of groundwater recharge in the area.[7]

Inflows and outflows for the California sub-region are presented in Table 4.3; locations of the stations in the Salton Basin are displayed in Figure

Table 4.3 California Sub-Region Water Balance.

	Non-Flood Year	Flood Year
	1000s Acre-Feet	
Inflows		
Net All-American Canal	225	195
All-American Canal at Drop 4	2,810	2,880
Coachella Canal at Milepost 87	274	284
Alamo River at the Border	1.5	1.6
New River at the Border	135	175
Whitewater River near Indio	1.7	12
Precipitation and other Local Sources	100	140
Groundwater extraction	194	198
Total	**3,741**	**3,886**
Outflows		
Exports	1	1
Evaporation	1,493	1,443
Urban Consumptive Use	71.1	70.7
Agricultural ET	1,810	1,840
Phreatophyte ET	257	245
Urban Wastewater Recharge/Evaporation	30	30
Groundwater Recharge	100	116
Change in Storage (Salton Sea)	(12)	78
Returns to Colorado River	156	128
Total	**3,906**	**3,952**
Residual	**(165)**	**(66)**

Sources: CVWD 1999; IBWC (1991-98); IID; USBR (1991-98a,b); Weghorst, pers. comm.

7 The volume of the aquifer underlying the Imperial Valley is estimated at 1.1 billion to 3.0 billion acre-feet, of which 20% is estimated to be recoverable (Imperial County General Plan). The quality of this groundwater, with a reported salinity in excess of 2,000 mg/l, makes it unsuitable for agricultural or domestic use.

4.5, while stations near the mainstem are included in Figure 4.4. "Net All-American Canal" reflects water diverted by California users from the All-American Canal between Imperial Dam and where the canal exits the delta region, at Pilot Knob. System outflows between Pilot Knob and Drop 4 of the All-American Canal, and along the length of the Coachella Canal until Milepost 87, occurred outside the region and were not included in this balance.[8] "Coachella Canal at Milepost 87" reflects total reported discharge of the canal at that location, as reported by CVWD. Groundwater extraction was from CVWD and from the Reservation Units.

Under "Outflows," evaporation was predominantly (97%) from the surface of the Salton Sea (mean surface area 240,000 acres (97,000 ha)), with additional sources including canals, drainage ditches, and the Alamo, New, and Whitewater rivers. Chapter Five describes agricultural, urban, and natural uses in detail. "Urban wastewater recharge/evaporation" reflects CVWD's use of recharge ponds for municipal effluent. A small quantity of water was exported from the system to the upper Coachella Valley. "Returns to Colorado River" includes water run through the Pilot Knob and Yuma Main Canal wasteways from the All-American Canal, and return flows from the Reservation Units.[9] "Change in Storage" reflects variation in the size of the Salton Sea; see Table 4.4 for a water balance for the Salton Sea. The residual for the California sub-region water balance, expressed as a percentage of total inflows, is -4.2% in Non-Flood years and -1.7% in Flood years.

Table 4.4 Salton Sea Water Balance

	Non-Flood Year	Flood Year
	1000s Acre-Feet	
Inflows		
Alamo River nr. Niland	598	629
New River nr. Westmorland	436	488
Whitewater River nr. Mecca	54	53
Precipitation	63	90
Other	246	170
Total	**1,397**	**1,430**
Outflows		
Evaporation	1,410	1,352
Change in Contents	**(13)**	**78**

Sources: USGS; Weghorst, pers. comm.

The Salton Sea is the terminal sump for most of the Imperial Valley's agricultural drainage. Figure 4.6 graphically represents inflows and outflows for the Sea. "Other" inflows is a residual term computed as total inflows less precipitation less measured discharge of the three gauged rivers. "Other" includes agricultural drainage, natural tributary inflow from Salt Creek, San Felipe Creek, and other ephemeral desert washes, and groundwater seepage. USBR estimated "Other" at 180 KAF (222 MCM), while Cohen et al. (1999) estimated this category at 174 KAF (215 MCM) for the period 1960-1995. Over this 36-year period, estimated mean annual inflow to the Sea was 1,346 KAF (1,660 MCM).

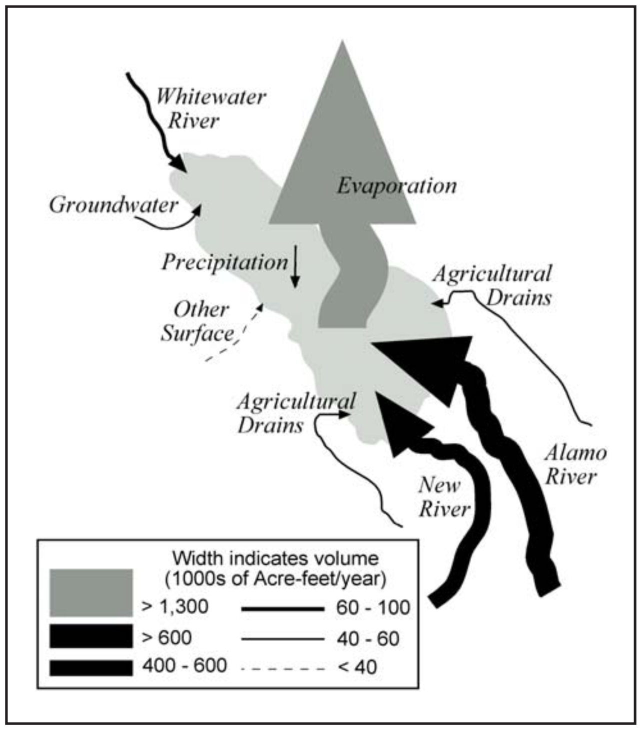


Figure 4.6 Salton Sea Inflows and Outflows
Source: Cohen et al. 1999.

8 Seepage from the Coachella Canal, estimated at 35 KAF (43 MCM)/year, generally flows down-gradient to the Salton Sea. Seepage from the All-American Canal between Pilot Knob and Drop 4 is estimated at 68 - 100 KAF (84 - 123 MCM)/year; much of this flows as groundwater into Mexico, where it is extracted (Hayes 1991).

9 USBR's annual *Compilation of Records* credits the State of California as a whole with roughly 90 KAF/year of unmeasured return flows; an unquantified portion of these unmeasured returns presumably originate in the sub-region, but were estimated for this study.

The discrepancy between these estimates and the computed term included in Table 4.4 may be attributable to gauging station error.[10] The residual, expressed as a percentage of inflows, is 7.7% in Non-Flood years and 9.0% in Flood years.

Morelos Dam, the last dam on the Colorado River. Courtesy of Jennifer L. Pitt.

Mexico Sub-Region

The mainstem of the Colorado River marks the boundary separating the Arizona and California sub-regions, so its flows were not captured within these sub-regions. Similarly, the river does not enter the Mexico sub-region until SIB. Deliveries to Mexico on the mainstem at NIB were largely diverted (>97% in Non-Flood years, 50% in Flood years) at Morelos Dam into the Alamo Canal. Surface water also enters the Mexico sub-region as deliveries at the border near San Luis, as groundwater extracted outside the study area and conveyed to the sub-region from Mexico's San Luis Mesa Arenosa wellfield, and local runoff. In addition to ET and evaporation, surface water exits the system to California via the New and Alamo rivers, as groundwater recharge, and to the Gulf of California through the Colorado River channel and, during flood events, via sheet flooding of the lower delta floodplain (Zamora-Arroyo et al. 2001). Mexico also exports water from the sub-region via the Colorado River-Tijuana Aqueduct to Tecate, Tijuana, and Ensenada.

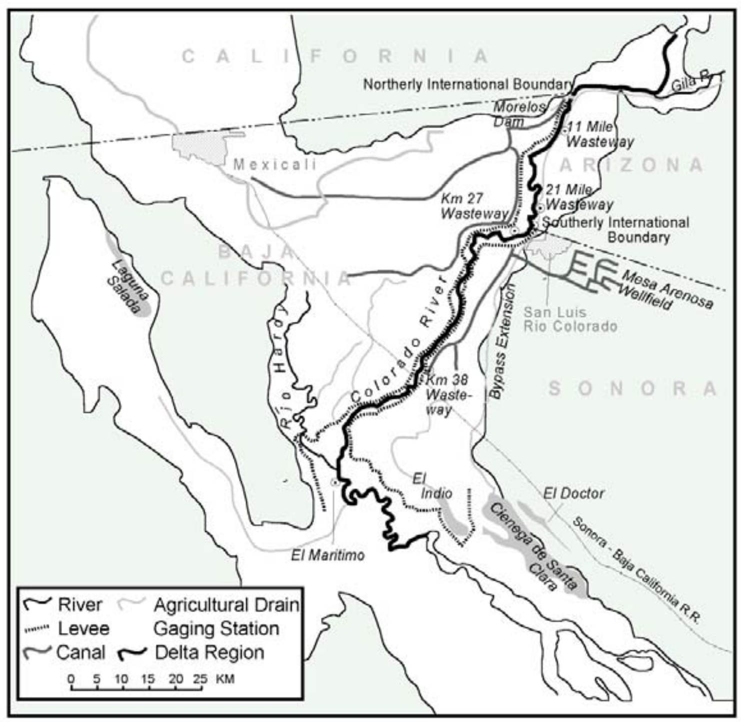


Figure 4.7 The Mexico Sub-Region.

CNA and private well operators delivered Colorado River water to the Mexico sub-region through a complex infrastructure of wells and canals. CNA reports 292 miles (470 km) of main canals in the sub-region, of which 217 miles (350 km) are lined, and 1,490 miles (2,399 km) of secondary canals, of which 1,150 miles (1,850 km) are lined. Trava Manzanilla (1991) reports 658 wells operating in the sub-region (422 government-owned and 236 private), plus an additional 67 federal wells operating in the five-mile (8 km) zone established by Minute 242, east of San Luís Río Colorado. A network of 262 miles (422 km) of principal drains and 771 miles (1,240 km) of secondary drains conveying agricultural wastewater discharged into the New River to the north, and to the Colorado and Rio Hardy to the south. Lands east of the Colorado River, in the San Luis Valley, drained to the Cienega de Santa Clara and El Indio wetlands, via the Riito (mean annual discharge 13 KAF (16 MCM)) and Plan de Ayala (mean annual discharge 15 KAF (18 MCM)) drains, respectively (Valdes-Casillas et al. 1998). Water was exported from the sub-region via the Colorado River-Tijuana Aqueduct, which runs 76.5 miles (122 km) with 3,772 feet (1,150 m) of lift (IBWC 2001). The Main Outlet Drain Bypass Extension (Bypass Extension), diverting brackish (>2,800 mg/l) agricultural

[10] The accuracy of the Alamo River gauge has been reported as "poor," with a margin of error >15% (USGS).

Table 4.5 Reported and Estimated Volumes of Groundwater Extracted in Mexico's Irrigation District 14.

Source	Year	Volume Extracted	Intake at Morelos
CNA	1990	900 KAF (1,100 MCM)	1,399 KAF (1,725 MCM)
Calculated from IBWC	1992	690 KAF (850 MCM)	1,396 KAF (1,722 MCM)
IBWC*	Normal †	650.6 KAF (8,025 MCM)	1,399 KAF (1,725 MCM)
Tostrud draft estimate	No excess	840.5 KAF (1037 MCM)	1,360 KAF (1,680 MCM)
CNA	1999	730 KAF (892 MCM)	1,897 KAF (2,340 MCM)
Calculated from IBWC	1993	807 KAF (995 MCM)	1,978 KAF (2,439 MCM)
IBWC*	High ††	548.5 KAF (677 MCM)	2,345 KAF (2,893 MCM)
Tostrud draft estimate	Excess	592.8 KAF (731 MCM)	~1,700+ KAF (2,097 MCM)

*IBWC data reprinted in Hill (1993). † average of 1978, 1982, and 1989 data.
†† average of 1979-1981, 1983-1988 data.

drainage pumped from Arizona's WMIDD, runs 35 miles (56 km) from near SIB to the Cienega de Santa Clara (Valdés-Casillas et al. 1998). Effluent from Mexicali discharged into the New River, while effluent from San Luís Río Colorado discharged into the Colorado River just downstream of SIB.

Groundwater records for the Mexico sub-region were incomplete and varied by source. Table 4.5 shows reported and estimated groundwater extraction rates for the study period and compares these with reported intake at Morelos Dam (IBWC 1991-1998), an indicator of surface water use. IBWC (1991-1993) reported that 33-34% of the total acreage in the Mexicali Valley was served by groundwater, though this estimate was not reported subsequent to 1993. For this estimate, total groundwater extraction was assumed to be half of the reported intake at Morelos Dam, less reported wasteway returns and reported diversions to recharge areas. The limited CNA groundwater extraction data obtained for this study do not contradict Tostrud's (draft manuscript 2000) intuitive projection that the Mexico sub-region decreases its reliance on groundwater when additional Colorado River surface water is available. In Non-Flood years, CNA discharged 31.6 KAF (39.0 MCM) of Colorado River water diverted at Morelos Dam into groundwater recharge areas, increasing this to 75.4 KAF (93.0 MCM) in Flood years. Discharge from groundwater pumps alongside the major canals decreased from 14.2 KAF (17.5 MCM) in Non-Flood years to 0.4 KAF (0.5 MCM) in Flood years. Additionally, Mexico's extraction of groundwater from its wellfield within the five-mile zone established by Minute 242 declined from 73.9 KAF (91.1 MCM) in Non-Flood years to 11.8 KAF (14.6 MCM) in Flood years, all of which suggests that Mexico's reliance on groundwater decreases when additional surface supplies are available.

Estimates also vary on the volume of groundwater recharge in the Mexico sub-region. CNA reported conveyance losses of 645 KAF (796 MCM) in the sub-region in 1999. Subtracting for evaporation and evapotranspiration by phreatophytes along the canals, this suggests that total seepage from delivery canals may be on the order of 500 KAF (617 MCM)/year. Román (in Waller 1992) estimates recharge of the Mexicali aquifer, from the Colorado River, All-American Canal, Mexican conveyances, and deep percolation from fields, at about 570 KAF (700 MCM)/year. Mumme (1996) reports that as much as 100 KAF (120 MCM)/year of the water pumped in the Mexicali Valley is attributable to seepage from the All-American Canal.

Seepage through the channel of the Colorado River during the study period is not known. Tostrud's draft report (2000) estimates that the Colorado River's high flow period of 1983-1989 (mean annual discharge at SIB of 6,333 KAF (7,812 MCM)) recharged the aquifer by 537 KAF (662 MCM)/year. Hely and Peck (1964) report initial infiltration rates of more than 2 inches (5 cm) in 30 minutes for the sandy soils adjacent to the mainstem, suggesting that Tostrud's recharge estimate is plausible.

Mean annual inflows and outflows for the Mexico sub-region are presented in table 4.6; locations of the stations are displayed in Figure 4.7. "Intake at Morelos" reflects water diverted from the mainstem into the Alamo Canal at Morelos Dam. "Deliveries from San Luis Mesa Arenosa Wellfield" reflect groundwater extracted within the 5 mile (8 km) protective and regulatory pumping boundary (opposite Arizona's Minute 242 wellfield) and discharged into the

Wells in the Delta Region pumped more than 1,000 KAF (1,200 MCM) annually during Non-Flood years.

Table 4.6 Mexico Sub-Region Water Balance

	Non-Flood Year	Flood Year
	1000s Acre-Feet	
Inflows		
Intake at Morelos Dam	1,420	2,075
Colorado River at SIB	22	2,120
MODE near SIB	119	88
Other deliveries near SIB	122	116
Precipitation and other Local Sources	27	25
San Luis Mesa Arenosa wellfield	73	5
Groundwater extraction	770	630
Total	**2,553**	**5,059**
Outflows		
Exports	20	32
Evaporation - mainstem & wetlands	43.6	67.6
Evaporation - Laguna Salada	-	183
Evaporation - agricultural canals & ditches	10.7	11.4
Urban Consumptive Use	32.3	32.7
Agricultural ET	1,250	1,030
Phreatophyte ET	345	370
Flow into the Gulf of California	18	1,950
Alamo River at the Border	1.5	1.6
New River at the Border	135	175
Groundwater recharge	500	750
Total	**2,356**	**4,603**
Residual	**197**	**456**

Sources: IBWC (1991-98); CNA.

Sanchez Mejorada and Revolución canals. Mean area of open water, including the mainstem, wetlands, canals, and drainage ditches, was 2,230 acres (900 ha) in Non-Flood years and, adding the estimated surface area of the Laguna Salada, 23,000 acres (9,300 ha) in Flood years. Sub-surface flows, such as the estimated inflow of 68-100 KAF (84 - 123 MCM)/year of groundwater from All-American Canal seepage (Hayes 1991), are not included. The difference in discharge for the MODE near SIB is a result of the 1993 Gila River flood event, which interrupted discharge from Wellton-Mohawk and decreased total deliveries for that year to 61.5 KAF (75.8 MCM). Precipitation and other sources includes estimated runoff from the Rio Hardy and Laguna Salada watersheds, plus an estimate of annual discharge from the artesian springs at the southeastern edge of the delta region (Glenn et al. 1996).

Chapter Five describes agricultural, urban, and natural consumptive uses in detail. "Evaporation" was disaggregated to reveal the variability introduced by the filling and evaporation of the Laguna Salada, and the increase in Flood years due to inundation of the floodplain. During Non-flood years, the ET for phreatophytes along the mainstem (included within the general phreatophyte ET in Table 4.6) exceeds reported Colorado River water flows below Morelos Dam (see Table 4.1) by a factor of five, indicating that such vegetation draws from the alluvial aquifer rather than from surface water. "Groundwater recharge" reflects recharge through normally dry alluvial soil inundated during flood events, both within the levees and in the Laguna Salada basin. "Flow into the Gulf of California" was calculated from the regression analysis described above and includes an estimate of overland flow during Flood years (Zamora-Arroyo et al. 2001). This volume differs from estimated discharge in the Colorado River channel itself (see Table 4.1), to account for additional sources discharging to the Gulf, such as the Cienega de Santa Clara during Non-Flood years, and to estimate discharge to the Gulf via sheet flow from inundated areas during Flood years.

Colorado River Delta Region

Mean annual inflows and outflows for the Colorado River delta region as a whole are presented in Table 4.7; locations of the stations are displayed in Figure 4.3. Surface water from the Colorado River contributed 85% of the total measured system inflows during Non-Flood years, and 75% during Flood years (with an additional 18% contributed by the Gila River during Flood years). In Non-Flood years, sources other than the Colorado River contributed <2% of the

Table 4.7 Colorado River Delta Region Water Balance.[11]

1000s Acre-Feet	Non-Flood Year	Flood Year
Inflows		
Colorado River below Imperial Dam	280	720
Gila River at Dome	181	1,585
Whitewater River near Indio	1.7	12
Gila Gravity Main at Imperial Dam	781	731
All-American Canal Net Diversion	225	195
Wasteways between Imperial and Morelos	911	1,824
All-American Canal Drop 4	2,810	2,880
Coachella Canal near North Shore	274	284
Return Flows from out of delta exports	172	145
Precipitation and other local sources	130	170
Groundwater extraction	1,001	868
242 Well Field near San Luis	18	4
San Luis Mesa Arenosa wellfield	73	5
Total	**6,858**	**9,423**
Outflows		
Exports	696	655
Evaporation	1,556	1,714
Urban Consumptive Use	126.1	125.3
Agricultural Consumptive ET	3,295	3,081
Phreatophyte ET	641.7	656.7
Urban Wastewater Recharge or Evaporation	30	30
Groundwater Recharge	646	929
Flow into the Gulf of California	18	1950
Change in Storage (Salton Sea)	(12)	78
Total	**6,997**	**9,219**
Residual	**(139)**	**204**

total volume measured in this study.[12]

The residual is -2.0% in Non-Flood years, and 2.2% in Flood years. These aggregated residuals are markedly less than the residuals for the California and Mexico sub-regions, suggesting that the discharge between sub-regions was not fully captured within this analysis. Potential sources of error include the largest identified sources of inflows and outflows. Of the inflows, estimated groundwater extraction and reported Yuma Main Canal wasteway records (included in "Wasteways between Imperial and Morelos") are the most likely sources of error. With the exception of "Exports," all of the identified outflows are calculated terms and potential sources of error. The limited availability of information on groundwater recharge is the most likely source of error, though incomplete records of phreatophyte type and extent may compound this error.

[11] Sources: USBR; USGS; IBWC; Mumme 1996; Tostrud 1997; Glenn et al. 1999; CNA.

[12] This study only included precipitation falling on open-water surfaces. Total precipitation on the delta region as a whole in Non-Flood years was estimated at 500 KAF (620 MCM), and 720 KAF (890 KAF) in flood years, representing 7% of the adjusted total inflow in each instance. At an average of <3 inches (<8 cm)/year, mean annual precipitation is markedly less than potential evapotranspiration (>78 inches (2.0 m) /year) in the region (Owen-Joyce and Raymond 1996).

Chapter Five: Sector Uses

Most of the water that entered the Colorado River delta region was consumed within the region through ET, urban consumption, or evaporation. In this study, "applied water" refers to water delivered for an intended use, such as the quantity of water delivered to a field for irrigation or, at a different scale, the water delivered to an agency for distribution to municipal customers. Applied water less returns to the system (such as surface water run-off and groundwater recharge) equals the consumptive use or "use," of a particular sector. In many instances, return flows for various uses were not reported or measured and, therefore, consumptive use was calculated (these calculations are described in Chapter Three).

Table 5.1 Mean Annual Consumptive Use, by Sector, in the Colorado River Delta Region.[1]

(1000s AF)	Agriculture	Urban	Environmental
Non-Flood	3,300	126	642
Flood	3,080	125	657

This study defines three sectors of consumptive use: agricultural, urban (including domestic, municipal, and industrial), and environmental. Table 5.1 gives mean annual consumptive use, by sector, for the delta region as a whole in Non-Flood and Flood years. Uses within these three sectors are described in the following, and are further broken down by sub-region.

Agriculture

Within the agricultural sector, water was applied for irrigation[2], stock watering, and uses associated with fish farming. Water demands vary by use: for example, applied water demands for crops ranged from 2.0 AF/acre for lettuce to 7.5 AF/acre for alfalfa in the Coachella Valley (CVWD 1999).[3] Water not used was discharged to various waterbodies in the delta region. Agricultural wastewater from the Arizona sub-region returned to the Colorado River mainstem or discharged to Mexico at SIB. In the California sub-region, wastewater from irrigation districts along the river returned to the mainstem, while in the Imperial and Coachella Valleys it discharged to the Salton Sea via extensive sub-surface tile drains that underlay these irrigation districts. In the absence of such drains, such as in Mexico's District 14, infiltration from water applied as irrigation recharged the aquifer.

More than one-half of the delta region's total land area was irrigated. Except for the Mexico sub-region, irrigated acreage varied only slightly between Non-Flood and Flood years. As Table 5.2 illustrates, irrigation districts in the Arizona and California sub-regions cultivated 2.8% more land in Flood years (760,000 acres/308,000 ha) than in Non-Flood years (739,000 acres/299,000 ha). Mexico's District 14 cultivated 7.2 % fewer acres in Flood years than in Non-Flood years despite 65% more Colorado River water crossing the border.

Table 5.2 Cultivated Acreage in the Colorado River Delta Region's Major Irrigation Districts (acres).

Sub-Region	Non-Flood Year	Flood Year
Arizona	115,000	124,000
California	624,000	636,000
Mexico	487,000	452,000
TOTAL	**1,226,000**	**1,212,000**

Sources: CNA; USBR 1991-98b.

Applied Water

Eight major irrigation districts and several smaller agricultural areas in the delta region divert Colorado River water for irrigation. The major irrigation districts' mean

1 Sources: CNA; CVWD 2000; IID 1999; Jensen 1995; USBR 1995-98; Metropolitan Water District 1998; CRWQCB; OOMAPAS; Salton Sea Database Program; Tostrud 1997; USBR 1995-98; Valdés-Castillas et al. 1998; Zamora-Arroyo et al. 2001.

2 Irrigation practices include water applied for: field preparation; leaching salts; fulfilling crop water use requirements (ET); and climate control purposes.

3 Applied water demands also vary between irrigation districts due to differences in soil type, climate, or cultural factors such as plant spacing.

Non-Flood and Flood year water applications to irrigation are displayed in Table 5.3.[4] As shown in Table 5.3, agricultural users in the California sub-region applied to their crops more Colorado River water than the combined total of such users in the Arizona and Mexico sub-regions. Although differences between Non-Flood year and Flood year diversions in the Arizona and California sub-regions were negligible, Mexico's District 14 irrigated fewer acres in Flood years and applied more Colorado River water to offset the groundwater used in Non-Flood years.

Groundwater

With the exception of IID, most agricultural districts in the region supplemented Colorado River surface supplies with groundwater (see Table 5.3). Table 5.4 shows reported groundwater extraction for irrigation districts, in Non-Flood and Flood years, as a percentage of each sub-region's total agricultural water application. Mexico's District 14 extracted more groundwater water, 770 KAF (950 MCM) in Non-Flood years and 630 KAF (780 MCM) in Flood years, than all of the other irrigation districts combined.[5] The largest reported groundwater application to the California sub-region's crops occurred in the Coachella Valley, where groundwater supplied 19%, or approximately 65 KAF (80 MCM), of applied irrigation water (CVWD 2000). IID, the largest user of surface water in the region, did not report applying groundwater for irrigation.

Water Use

Estimating consumptive use of applied agricultural water generally involved subtracting wastewater discharge from recorded deliveries. As shown in Table 5.1, crops used approximately 80% of the total water used in the delta region. Dividing consumptive agricultural use by crop acreage revealed that the California sub-region used the most

Table 5.3 Mean Annual Water Applied for Irrigation in the Colorado River Delta Region's Major Irrigation Districts (1000s AF).

	Colorado River Water		Ground Water		Total	
Diverter:	Non-Flood Year	Flood Year	Non-Flood Year	Flood Year	Non-Flood Year	Flood Year
Arizona						
North Gila Irrigation District	45	43	-	-	45	43
Yuma Irrigation District	55	53	10.8	10.8	65.8	63.8
Yuma Valley Irrigation District	250	242	26.2	29.2	276	271
Other Irrigators	53.6	55.9	-	-	53.6	55.9
Subtotal	404	394	37	40	440	434
California						
Coachella Valley Water District	276	278	64.7	65.1	341	343
Yuma Project, Reservation Division	82	77	21.2	24.5	103	102
Imperial Irrigation District	2,580	2,490	-	-	2,580	2,490
Subtotal	2,938	2,845	85.9	89.6	3,024	2,935
Mexico, District 14	**1,354**	**1,820**	**770**	**630**	**2,124**	**2,450**
TOTAL	**4,696**	**5,059**	**893**	**760**	**5,589**	**5,819**

Sources: CNA; USBR 1996; USBR 1991-98a.

[4] The Yuma Project Reservation Division consists of two irrigation districts: the Bard Unit and the Indian Unit.

[5] Mexico: Groundwater used for irrigation was not separated from the amount used for urban purposes in the literature.

Table 5.4 Agricultural Application of Groundwater in the Colorado River Delta Region (1000s AF)

	Non-Flood Year	% of Total	Flood Year	% of Total
Arizona	37	8.4	40	9.2
California	86	2.8	90	3.1
Mexico, Dist. 14	770	36.3	630	25.7

Sources: CNA; CVWD 2000; IBWC 1991-1998; Tostrud 1997; USBR 1996.

water per acre: in Non-Flood years, this sub-region's agricultural sector used 2.9 AF/acre compared to the Arizona sub-region's consumption of 2.0 AF/acre and the Mexico sub-region's consumption of 2.6 AF/acre. Similarly, in Flood years, the California sub-region's agricultural sector used 2.9 AF/acre and the Arizona and Mexico sub-regions used 1.7 and 2.3 AF/acre, respectively (see Table 5.5).

Note that the ratios of water consumption to irrigated acreages used herein are based on cropped acreage as opposed to physical acreage. While physical acreage refers to the number of acres under cultivation in an irrigation district at any one time, cropped acreage refers to the total acreage of crops grown in an irrigation district annually and includes double-cropping, the practice of growing multiple crops per acre. Irrigation districts in the Arizona and California sub-regions double-cropped from 14% (California sub-region, Non-Flood years) to 45% (Arizona sub-region, Flood years) of their acreage annually. Data on the Mexico sub-region's double-cropping practices were not available. As Table 5.6 demonstrates, mean water use per acre increases significantly when applied to physical acreage.

Crop Mix and Evapotranspiration

Farmers in the delta region can harvest alfalfa more than four times each year. Courtesy of David Hannaway, Forage Information System, Oregon State University.

ET is the largest component of agricultural water use. Because ET rates vary by crop type, the crop mix in each irrigation district directly influenced water use in the sub-regions. Table 5.7 shows the acreage of the region's major crops.[6] By area, wheat and alfalfa were the region's two largest crops in all years followed by cotton in Non-Flood years and lettuce in Flood years. Over the period of the study, approximately 25% of the region's crops consisted of wheat and nearly 20% consisted of alfalfa. The acreage of cotton varied from 9.0% in Non-Flood years to 5.0% in Flood years and lettuce was approximately 6% in all years (USBR 1991-98b; SAGAR).

Table 5.8 shows the mean evapotranspiration of the region's major crops. The California sub-region used more water per acre primarily because the ET rate of alfalfa, the Imperial Valley's largest crop, skewed the average for the sub-region as a whole, masking less water intensive specialty crops, such as table grapes and lettuce, that predominated in the Coachella Valley and the sub-region's other irrigation districts. As the region's most water intensive crop, alfalfa had an estimated ET rate of 5.6 AF/acre (Erie et al. 1982; Jensen 1995). Although it constituted less than 30% of the California sub-region's total agricultural acreage, alfalfa used almost 57% of the water used by this sub-region's agricultural sector. The sub-region's second largest crop, wheat, had an ET rate of 2.15 AF/acre (Erie et al. 1982; Jensen 1995).

The Arizona sub-region's crop mix was weighted toward less water intensive crops, generating a lower overall consumptive use than the California sub-region. As shown in Table 5.7, the Arizona sub-region's largest crop, lettuce, comprised approximately 32% of the sub-region's total acreage. With an ET rate of 1.41 AF/acre, lettuce accounted for 22% (Non-Flood) to 27% (Flood) of the water used by the Arizona sub-region's agricultural sector. Like the California sub-region, the Arizona sub-region's second largest crop by area was wheat.

In the Mexico sub-region, wheat dominated the crop mix. Wheat comprised 41% of the sub-region's acreage in

[6] The delta's major crops are defined as the three largest crops, by acreage, for: CVWD; IID; Reservation Division, Indian and Bard Units; the Arizona sub-region's irrigation districts; and Mexico's District 14.

Table 5.5 Mean Agricultural Water Use in the Colorado River Delta Region.

	Arizona Non-Flood Year	Arizona Flood Year	California Non-Flood Year	California Flood Year	Mexico Non-Flood Year	Mexico Flood Year
Crop Area (1000s acres)	115	124	625	636	486	452
Water Use (1000s AF)	235	211	1,810	1,840	1,250	1,030
Water Use per cropped acre (AF/acre)	**2.0**	**1.7**	**2.9**	**2.9**	**2.6**	**2.3**

Sources: CVWD 2000; SAGAR; Tostrud 1997; USBR 1991-98b; USBR 1995-98.

Table 5.6 Mean Acreage to Consumption Ratios in the Colorado River Delta Region's Major Irrigation Districts.

	Arizona Non-Flood Year	Arizona Flood Year	California Non-Flood Year	California Flood Year	Mexico Non-Flood Year	Mexico Flood Year
Water Used (1000s AF)	235	211	1,810	1,840	1,250	1,030
Physical Acreage (1000s acres)	61.5	61.1	536	535	n/a	n/a
Cropped Acreage (1000s acres)	115	124	625	636	486	452
Physical Acreage: use/acre	3.8	3.5	3.4	3.4	n/a	n/a
Cropped Acreage: use/acre	2.0	1.7	2.9	2.9	2.6	2.3

Sources: CVWD 2000; SAGAR; Tostrud 1997; USBR 1991-98b; USBR 1995-98.

Table 5.7 Mean Annual Acreage of the Colorado River Delta Region's Major Crops (1000s Acres).

	Arizona Non-Flood Year	Arizona Flood Year	California Non-Flood Year	California Flood Year	Mexico Non-Flood Year	Mexico Flood Year	Regional Non-Flood Year	Regional Flood Year
Wheat	23.8	22.1	72.8	81.8	198	197	295	300
Alfalfa	3.1	2.2	184	175	51.9	46.2	239	223
Cotton	7.8	7.6	7.5	6	91.3	51.7	107	65.3
Lettuce	37	40.3	35	32.2	1.1	1.5	73.1	74
Sugarbeets	-	-	36.7	38.4	-	-	36.7	38.4
Grapes	-	-	14.7	13.9	0.1	0.2	14.8	14.1
Grapefruit	0.9	0.5	8.7	6.8	0.1	-	9.7	7.3
TOTAL	**73**	**73**	**359**	**354**	**343**	**297**	**775**	**722**
TOTAL ACREAGE	**115**	**124**	**624**	**636**	**487**	**452**	**1,226**	**1,212**

Sources: SAGAR; USBR 1991-98b.

Non-Flood years and 44% in Flood years, yet it used only 34% of the water used by this sub-region's agricultural sector in Non-Flood years and 41% in Flood years (CNA; SAGAR). The Mexico sub-region's second largest crop, cotton, had a higher ET rate (3.32 AF/acre) and used 24% (Non-Flood) and 17% (Flood) of this region's total agricultural consumptive use (Erie et al. 1982; CDWR 1993; Jensen 1995).

Urban

The urban sector, comprising domestic, municipal, and industrial uses of water, used less water than the region's other sectors (see Table 5.1). Water in this sector is applied to such uses as turf irrigation, domestic uses, manufacturing, and other municipal uses. This study did not include water used by geothermal plants.[7] Urban consumption accounted for approximately 2% of total regional water consumption. Colorado River water was supplemented by higher quality groundwater in many areas, demonstrating higher water quality requirements in this sector than in the other sectors (see Table 5.9).

Applied Water

The three sub-regions fulfilled their urban demand with a combination of Colorado River water and groundwater, although within each sub-region, dependence on groundwater varied markedly. In the Arizona sub-region, the largest application of urban water occurred in the city of Yuma. In Non-Flood and Flood years, Yuma diverted Colorado River water via the All-American Canal and the Yuma Main Canal to meet its annual demand of 27 KAF (33 MCM) (USBR 1991-98a). Several other, smaller entities[8] in the Arizona sub-region diverted approximately 13 KAF (16.0 MCM) annually from an undistinguished combination of groundwater aquifers and the Colorado River (USBR 1991-98a).

The largest urban demand within the California sub-region existed in the Coachella Valley: CVWD delivered 83 KAF (102 MCM) of groundwater annually (CVWD 2000). Urban demand in the Imperial Valley was fulfilled solely with Colorado River water. IID conveyed 2% of its diversion from the Colorado River to the following ten cities for treatment and delivery to domestic, municipal, and industrial customers: Brawley; Calapatria; Calexico; El Centro; Heber; Holtville; Imperial; Niland; Seeley; and Westmorland. In Non-Flood years, these cities delivered 46 KAF (57 MCM) to urban users and in Flood years, they delivered 48 KAF (59 MCM)[9] (USBR 1991-98b). The Indian Units along the lower Colorado in the California sub-region delivered less than 1 KAF annually to the urban sector (USBR 1991-98a; USBR 1991-98b).

Due to water quality considerations, the Mexico sub-region relies upon groundwater, or a mix of groundwater and Colorado River water, for the urban sector. Total groundwater extracted annually for urban use (including that exported via the aqueduct to Tecate, Tijuana, and Ensenada) was reported as 160 KAF (197 MCM) annually (CNA). Some of this water was conveyed to urban users in Mexicali, in addition to being exported out of the region for urban uses in Tecate, Tijuana, and Ensenada. Mexicali's urban users received 63 KAF (78 MCM) of water in Non-Flood years and 67 KAF (83 MCM) in Flood years from a combination of the Colorado River and local groundwater (CESPM). Larger deliveries in Flood years likely reflect population growth in the more recent period encompassed within Flood years.

As shown in Table 5.9, urban water use in the Colorado River delta region was primarily for domestic and municipal purposes, although some industrial use existed, mostly in the Imperial Valley and Mexicali. The Imperial Valley supported a larger industrial base with approximately 36% of its urban deliveries, or roughly 17 KAF (21 MCM), going to industrial users annually (IID 1999). Along the mainstem, industrial use records were only available for Yuma, Arizona, which delivered approximately 20 percent of its urban delivery, or 5.6 KAF (7 MCM), to industrial users annually (Baer, pers. comm.; USBR 1995-98). Industrial users in Mexicali received 21%, or 13 KAF (16 MCM), of Mexicali's urban water

[7] Geothermal plants in the Imperial Valley re-inject extracted groundwater into the aquifer, while those in the Mexicali Valley contain such water in lined evaporation ponds.

[8] These entities include: Desert Lawn; Southern Pacific Railroad; Yuma Union High School; the Yuma Area Office of the USBR; Cocopah RV Park; Somerton; Gadsen; San Luis; and Yuma County (USBR 1991-98a).

[9] Population growth in the Imperial Valley of 28% between 1990 and 2000 (California Department of Finance) accounted for increased demand in later (Flood) years.

Table 5.8 Mean Evapotranspiration of the Colorado River Delta's Major Crops.

1000s AF	Arizona Non-Flood Year	Arizona Flood Year	California Non-Flood Year	California Flood Year	Mexico Non-Flood Year	Mexico Flood Year	Regional Non-Flood Year	Regional Flood Year
Alfalfa	17.2	12.5	1,037	982	292	260	1,346	1,255
Wheat	51.3	47.5	157	176	425	423	633	647
Cotton	25.8	25.1	25	19.9	303	172	354	217
Lettuce	52.2	56.9	49.3	45.4	1.5	2.1	103	104
Sugarbeets	-	-	122	127	-	-	122	127
Table Grapes	-	-	42.9	39.6	0.3	0.7	43.2	40.3
Grapefruit	2.5	1.3	24.2	18.9	0.2	0.1	26.9	20.3
TOTAL MAJ. CROPS	**149**	**143**	**1,457**	**1,409**	**1,022**	**858**	**2,628**	**2,411**
TOTAL WATER USE	**235**	**211**	**1,810**	**1,840**	**1,250**	**1,030**	**3,295**	**3,081**

Sources: CDWR 1993; Erie et al. 1982; Jensen 1995; SAGAR; USBR 1991-98b.

Table 5.9 Mean Annual Urban Water Delivery in the Colorado River Delta Region.

1000s AF	Arizona Non-Flood Year	Arizona Flood Year	California Non-Flood Year	California Flood Year	Mexico Non-Flood Year	Mexico Flood Year	Regional Non-Flood Year	Regional Flood Year
Delivery to Urban	42	40.3	131	131	63.4	67.3	236	238
Source								
Colorado River	42	40.3	47.7	48.5	n/a	n/a	n/a	n/a
Groundwater	n/a	n/a	83	82	n/a	n/a	n/a	n/a
Destination								
Domestic	36.3	35	114	113	50.2	49.7	200	198
Municipal	5.7	5.3	16.8	17.5	13.3	17.6	35.7	40.4

Sources: CVWD 2000; IID 1999; CRWQCB; OOMAPAS; USBR 1991-98a; USBR 1991-98b.

Table 5.10 Mean Annual Urban Water Consumption and Wastewater Discharge.

1000s AF	Arizona Non-Flood Year	Arizona Flood Year	California Non-Flood Year	California Flood Year	Mexico Non-Flood Year	Mexico Flood Year	Regional Non-Flood Year	Regional Flood Year
Water Used	22.7	21.9	71.1	70.7	32.3	32.7	126	125
Domestic	21.8	21	68.4	67.8	30.1	29.8	120	119
Municipal	0.9	0.9	2.8	2.9	2.2	2.9	5.9	6.7
Wastewater Discharged	19.3	18.4	59.6	59.8	31.1	34.6	110	113
To Salton Sea	-	-	29.1	29.1	31.1	34.6	60.2	63.7
To Colorado River	19.3	18.4	0.4	0.4	-	-	19.7	18.9
To recharge/evap.	-	-	30.1	30.3	-	-	30.1	30.3

Sources: CESPM; CRWQCB; CVWD 2000; McNaughton, pers. comm.; Tostrud 1997; USBR 1991-98a; USBR 1991-98b; USBR 1995-98.

supply in Non-Flood years and 26%, or 18 KAF (22 MCM) in Flood years (CESPM).

Urban Use and Wastewater

Domestic users in the urban sector generally use 60% of the water they divert (USBR 1995-98) and industrial users use nearly 16% (USGS). These estimates indicate that over the study period, 110 KAF (136 MCM) of wastewater was discharged in Non-Flood years and 113 KAF (139 MCM) was discharged in Flood years (see Table 5.10.) Approximately 73% of the region's urban wastewater discharged to the Salton Sea or returned to the Colorado River. The remaining 27% of wastewater left the region through evaporation and seepage ponds.

In the Arizona sub-region, the City of Yuma's wastewater was treated and returned to the Colorado River. The destination of the Arizona sub-region's remaining wastewater (< 5.5 KAF) was unavailable. After treatment, all of the Imperial Valley's wastewater and about 10% of the Coachella Valley's wastewater discharged to the Salton Sea through drains and the New and Alamo rivers (CRWQCB). Most of the Coachella Valley's wastewater (90%) left the region via evaporation or infiltration ponds (CRWQCB). The communities adjacent to the Colorado River in the California sub-region treated less than 1 KAF (1.2 MCM) of wastewater annually; the destination of that wastewater was unavailable (USBR 1991-98a).

In the Mexico sub-region, most of Mexicali's wastewater discharged to the Salton Sea via the New River. Approximately 87% of Mexicali's 31 to 35 KAF (38 to 43 MCM) of wastewater was collected for treatment: 90% of the collected wastewater was treated and released into the New River. The remaining 10% of the collected wastewater, and the uncollected wastewater, was discharged, untreated, into canals flowing to the New River (McNaughton, pers. comm.).

Mexico's Mesa Arenosa wellfield pumped 73 KAF annually during Non-Flood years.

The Colorado River sustains a large number of phreatophytes.

Environmental

Estimated environmental ET is limited to phreatophytes. It does not include estimates of ET for upland vegetation, which draws from groundwater, rather than from surface water. Approximately 200,000 acres (81,000 ha) of emergent wetland and riparian vegetation existed in the delta region. Supported primarily by agricultural drainage water, this vegetation grew along the Colorado River mainstem, New and Alamo rivers, irrigation delivery canals and drainage ditches, and areas where agricultural drainage water collected, such as the Cienega de Santa Clara and El Indio wetlands. Springs and shallow aquifers also sustained small pockets of vegetation, such as El Doctor wetlands, in some areas.

Natural Use

The region's natural vegetation used 642 KAF (796 MCM) in Non-Flood years and 657 KAF (810 MCM) in Flood years. Vegetation growing along the Colorado River mainstem used 206 KAF (254 MCM) in Non-Flood years and 238 KAF (294 MCM) in Flood years. Most of the water use by this vegetation (72%, Non-Flood year to 75%, Flood year) occurred in the Mexico sub-region.

Vegetation along the delta region's delivery canals and drainage ditches used over 300 KAF (370 MCM) of water annually.[10] Most of this ET occurred in California's Imperial Valley and Mexico's District 14, where some delivery

[10] This is an estimate because the Arizona sub-region's ET from delivery canals and drainage ditches is not disaggregated from ET along the Colorado.

canals and most drainage ditches were not lined. Although IID routinely removes vegetation from the banks of its delivery canals and drainage ditches (except where vegetation stabilizes these slopes), approximately 160 KAF (197 MCM) annually was used by riparian and wetland vegetation growing along drainage ditches and the New and Alamo Rivers, and, to a lesser extent, unlined delivery canals (Tostrud 1997). In Mexico's District 14, vegetation on the banks of delivery canals and earthen drainage ditches consumed 107 KAF (132 MCM) in Non-Flood years and 100 KAF (123 MCM) in Flood years. Vegetation in the CVWD used little water (approximately 35 KAF/43.1 MCM annually), because most water was delivered through pipes with an efficiency rate of 98.5% and the district's wastewater collection system was similarly enclosed, with few open ditches (CVWD 1999).

Table 5.11 Mean Annual Evapotranspiration by Natural Vegetation.

	Non-Flood Year (1000s AF)	Flood Year
Arizona		
Mittry Lake Wildlife Area	8.6	9.9
Imperial Dam to Morelos Dam	31.1	31.8
Arizona Total Natural ET	**39.7**	**41.7**
California		
Mainstem Riparian Zone	18.3	17.3
Wetland Vegetation in Salton Basin	195	188
Vegetation around the Salton Sea	43.4	39.9
California Total Natural ET	**257**	**245**
Mexico		
Mainstem and Rio Hardy	148	179
Cienega de Santa Clara	54.8	61.4
El Indio	35.6	29.9
Other Wetland Vegetation in the Mexicali Valley	107	100
Mexico Total Natural ET	**345**	**370**
Regional Total ET	**642**	**657**

Sources: USBR 1995-98; Valdes-Casillas et al. 1998; Luecke et al. 1999; Zamora-Arroyo et al. 2001.

Vegetation supported by discharge from drainage canals and rivers in the California and Mexico sub-regions also used significant quantities of water. The vegetation surrounding the Salton Sea used 43 KAF (53 MCM) of water in Non-Flood years and 40 KAF (49 MCM) in Flood years (Salton Sea Database Program). In the Mexico sub-region, the vegetation of the Cienega de Santa Clara and El Indio wetlands used approximately 91 KAF (112 MCM) annually.

Conclusion

Colorado River water flows through most of the delta region, though the river's meanders have been replaced with a complex and sophisticated infrastructure that delivers water to, and carries it away from, more than a million acres of irrigated land. This water is used to produce a variety of forage and truck crops in an extremely hot and arid climate, generating agricultural evapotranspiration in excess of 3,000 KAF (3,700 MCM)/year. Such evapotranspiration represented the single largest consumptive use of water in the delta region in both Non-Flood and Flood years, consuming almost half of total inflows during Non-Flood years. Evapotranspiration from phreatophytes accounted for < 10% of total inflows during Non-Flood years, while evaporation from open-water surfaces accounted for about a quarter of such inflows. Urban consumptive use was negligible (~2%); even with expected population growth in the region, such use will continue to represent a very small percentage of total regional demand (though local impacts, and impacts on water quality, will be more pronounced).

During Non-Flood years, only about 10% of total inflows to the delta region exited the region as surface water, east as exports to Wellton-Mohawk and, in much smaller volumes, west to Tijuana and Tecate. During Non-Flood years, <0.4% of the recorded flow at Imperial Dam, the uppermost limit of the study area, was estimated to reach the mouth of the river. In Flood years, this rose to > 27%. During Non-Flood years, roughly 80% of the total water entering the delta region exited to the atmosphere, ten times the total volume of precipitation that fell on the region as a whole.

The distinction between Non-Flood and Flood years revealed marked differences in discharge within the Mexico sub-region, but showed limited differences in the other sub-regions. In the Mexico sub-region, Flood years witnessed an increase in diversions of surface water, a decrease in groundwater extraction, and an increase in groundwater recharge, both within recharge basins and from the inundated Colorado River floodplain. Such increased recharge helped to reverse the groundwater overdraft during Non-Flood years, though it should be emphasized that this study was limited to surface water flows and did not attempt to account for the full range of groundwater inflows and outflows, such as the sub-surface movement of water between the sub-regions. Floodplain recharge would account for the high level of mainstem phreatophyte ET calculated by this study, which exceeded surface water availability in Non-flood years by a factor of five.

Groundwater extraction in the lower Coachella Valley and in the Mexico sub-region indicated that surface water did not exist in sufficient quantity or quality, or both, to meet local demand. In the Arizona sub-region, groundwater was extracted to lower the elevation of the water table below crops' root zone, and in some instances because access to such water was more convenient than surface water. With the exception of the lower Coachella Valley, data on groundwater extraction were limited and of unknown reliability. Data on groundwater recharge rates were even less available. Such data limitations challenged efforts to develop a rigorous water balance for the Arizona and Mexico sub-regions, and for the delta region as a whole.

As noted in Chapter Three, the accuracy of reported data was generally limited to 90% for the most accurate streamflow gauges. With the exception of some return flow measurements, most of the outflows were calculated by this study. Some computations, such as the volume of local runoff and mainstem water entering the Laguna Salada basin, were speculative and offered only as general estimates.

These general computations, prompted by the absence of data on several important terms for the water balance, warrant further research. Data gaps include:

- Discharge for the Colorado River below SIB, which could be obtained by the re-establishment of the M.C. Rodriguez Station
- Groundwater extraction in the Arizona and Mexico sub-regions
- Groundwater extraction by urban users
- The relationship between the alluvial aquifer and the Colorado River mainstem below Morelos Dam, including time-series data on depth to groundwater
- Verified time-series data on groundwater extraction in the Arizona and Mexico sub-regions
- Actual ET rates by major crops in the delta region
- Estimates of the variation in extent and volume of the Laguna Salada over time, and depth to groundwater in the basin.

Appendix A - Water Quality

Although several contaminants degrade the quality of water in the Colorado River delta, salinity is of the broadest concern. High salinity causes between $500 million and $750 million annually in damages to agricultural, municipal, and industrial users in the lower Colorado River basin of the United States (DOI 1999); figures for Mexico were unavailable. Salt-induced damage includes reduced crop yields, more frequent replacement of municipal plumbing, and shorter life of industrial equipment (Colorado River Basin Salinity Control Forum 1996).

High salinity in the Colorado River delta results from a combination of natural and human processes. Without the interference of human activity, saline springs, erosion of saline geologic formations, and the concentrating effects of evaporation and transpiration would generate a salinity of 334 mg/l at Imperial Dam (Colorado River Basin Salinity Control Forum 1996; DOI 1999). In the past several decades, human activities have exacerbated the Lower Colorado's salinity problem: by 1997, out-of-basin exports, irrigation, construction of reservoirs that encourage evaporation, and municipal and industrial uses increased mean annual salinity to 704 mg/l at Imperial Dam (USBR).

As noted in Chapter Two, elevated salinity in the 1960's prompted the addition of Minute 242 to the 1944 US-Mexico treaty. Minute 242 states that the mean annual salinity of the water delivered to Mexico at the Northerly International Boundary would not exceed 115 mg/l (±30 mg/l) greater than the salinity of the river at Imperial Dam.[1] Title I of the Colorado River Basin Salinity Control Act (P.L. 93-320), passed in 1974, outlined the structural means for implementing Minute 242. Title II of this Act created a water quality control program responsible for implementing specific measures to meet the objectives and standards of the Clean Water Act (DOI 1999). Salinity above Morelos Dam remained within the parameters set by Minute 242 throughout the study period. In Non-Flood years, water at Imperial Dam contained 784 mg/l of TDS and the water above Morelos contained 906 mg/l, a difference of 122 mg/l. In Non-Flood years, the salinity diffential was 122mg/l and in Flood years, it decreased to 47mg/l (USBR; IBWC 1991-98).

Table A.1 Salinity in the Delta Region.

	Total Dissolved Solids	
Sample Point	**Non-Flood Year (mg/l)**	**Flood Year (mg/l)**
Colorado River at Imperial Dam	784	713
Colorado River at NIB	906	760
Other deliveries near SIB	1,274	1,222
MODE	2,838	2,045
New River at Border	2,836	2,583
Salton Sea	42,271	43,304

Despite decreased salinity above Morelos Dam, salt concentrations increased in the mainstem below SIB, the New River, drainage canals, and where agricultural discharge collected (Table A.1). Salinity increased in Non-Flood years, as total discharge decreased. At the border, water in the New River and the MODE had the same salinity, 2,800 mg/l, in Non-Flood years. In Flood years, the New River's salinity dropped to 2,600 mg/l and the MODE's to 2,000 mg/l (IBWC 1991-98 and USBR 2001). Salinity of the mainstem above its confluence with the Rio Hardy ranged from 1,810 mg/l to 560 mg/l during a 1997 flood event (Valdés-Casillas et al. 1998).

Regional salinity was highest in water bodies sustained by agricultural drainage water. The Salton Sea's salinity fluctuated between 42,000 mg/l in Non-Flood years and 43,000 mg/l in Flood years. The Sea is a terminal body of water with a surface elevation of approximately 227 feet below sea level, where evaporation rates exceed 8 feet annually. Water evaporating from the Sea leaves behind salt and other elements. Salinity in the Cienega de Santa Clara was estimated to range between 3,000 and 5,000 mg/l (Valdes-Casillas et al. 1998).

In addition to salinity, increased selenium and other contaminants are of concern in the region. Although small,

[1] Several of the salinity levels in the United States are recorded in ppm but were converted to mg/l in this report. At levels below 7,990, ppm and mg/l are interchangeable units (USGS 1993).

selenium concentrations in the Salton Sea indicate its presence in the region's drainage water conduits such as the New and Alamo Rivers. Other contaminants that degrade the region's water quality include nutrients, pesticide residues, and heavy metals. Analysis of such constituents lies beyond the scope of this report.

Appendix B – Abbreviations and Conversions

Abbreviations

AF	acre-feet
CESPM	Comision Estatal de Servicios Publicos de Mexicali
CILA	Comision Internacional de Limites y Aguas
CNA	Comision Nacional de Agua
CRWQCB	California Regional Water Quality Control Board – Colorado River Region
CVWD	Coachella Valley Water District
DOI	U.S. Department of the Interior
DWR	California Department of Water Resources
EPA	Environmental Protection Agency
FWS	U.S. Fish and Wildlife Service
IBWC	International Boundary and Water Commission
IID	Imperial Irrigation District
KAF	thousand acre-feet
LCRAS DOT	Lower Colorado River Accounting System Demonstration of Technology
MCM	million cubic meters
mg/l	milligrams per liter
NIB	Northerly International Boundary
NOAA	National Oceanic and Atmospheric Administration
OOMAPAS	Organismo Operador Municipal de Agua Potable, Alcantarillado y Saneamiento de San Luís Río Colorado
ppm	parts per million
ppt	parts per thousand
RWQCB	Regional Water Quality Control Board
SAGAR	Secretaría de Agricultura, Ganadería y Desarrollo Rural
SIB	Southerly International Boundary
SWRCB	State Water Resources Control Board
TDS	total dissolved solids
USBR	U.S. Bureau of Reclamation
USGS	U.S. Geological Survey
WMIDD	Wellton Mohawk Irrigation and Drainage District

Conversions

Length

1 foot	0.3048 m
1 mile	1.609 km

Area

1 square foot	0.0929 m^2
1 acre	4046.9 m^2
1 acre	0.40469 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	325,851 gallons
1 acre-foot	1233.48 m^3
1 million acre-feet	1,233 x 10^6 m^3 (MCM)
1 million acre-feet	1.233 km^3

Discharge

1 cfs	0.0283 m^3/sec
1 MAF/year	1,233 MCM/year

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