Historical Perspective of Surface Water and Groundwater Resources in the Chihuahuan Desert Network, National Park Service

EDWARDS AQUIFER RESEARCH & DATA CENTER

TEXAS STATE

Stephen D. Porter, Rene A. Barker, Raymond M. Slade, Jr. and Glenn Longley

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Cover photo: Rio Grande Wild & Scenic River segment (Rio Grande upstream from Boquillas, Mexico)

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In cooperation with National Park Service, Chihuahuan Desert Network
Cooperative Agreement H1200050003
Hildy Reiser, PhD; Inventory & Monitoring Network Coordinator

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Table of Contents

List of Figures

List of Tables

List of Appendices

Introduction

The Chihuahuan Desert Inventory and Monitoring Network (CHDN) is one of 32 networks in the National Park Service (NPS) charged with developing long-term natural resource monitoring plans for their park units. The CHDN consists of seven national parks, monuments, recreation areas, and historic sites in New Mexico and Texas (Fig. 1). The CHDN has identified seven protocols that will be used to guide long-term monitoring of 25 vital signs (Reiser et al. 2006; 2008). These 25 vital signs represent a comprehensive monitoring program for the CHDN park units.

As part of a cooperative agreement between the CHDN and the Edwards Aquifer Research and Data Center (H1200050003), Texas State University (EARDC), surface and ground-water data were retrieved from government data bases and published literature, compiled into relational data bases, and analyzed relative to the condition of the water resource and potential changes in water quality and (or) quantity over time. Sufficient data were available to address surface-water quantity, surface-water quality, and macroinvertebrate communities in certain aquatic systems, whereas analyses of ground-water resources were limited to water quantity issues. Long-term surface-water records were limited to sites upstream and along the Rio Grande Wild and Scenic River segment; however, limited water-quality and macroinvertebrate results were available for streams in most of the parks. This report, the first of two reports scheduled in the cooperative agreement, provides results from trend analyses of available data that address four of CHDN's vital signs: surface-water quantity/hydrology, surface-water quality, invertebrates in aquatic systems, and ground-water quantity/hydrology.

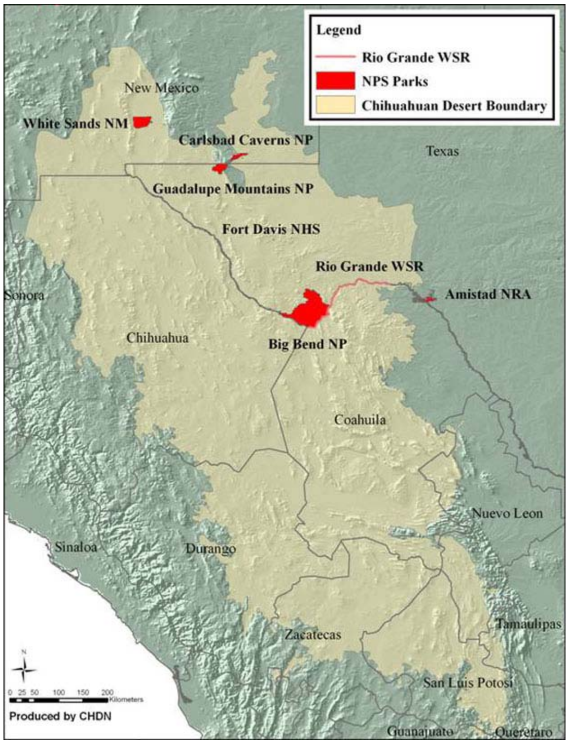


Figure 1. Location of Chihuahuan Desert, the Rio Grande Wild and Scenic River (WSR), and other National Park Service parks within the Chihuahuan Desert Network (CHDN).

Purpose and Scope

The purpose of this report is to improve understanding of surface and ground-water hydrology, water-quality conditions and trends, and the condition of macroinvertebrate communities in major water resources of the CHDN park units. The surface-water quantity section of the report provides a summary of long-term trends of streamflow at six gaging stations in the Rio Grande and Rio Conchos, comparisons of discharge percentiles at the gaging stations, and analyses of gains and losses of streamflow between river reaches. The surface-water quality section of the report provides a summary of conditions and seasonal and (or) annual trends for water temperature, pH, dissolved oxygen, specific conductance, fecal-indicator bacteria, selected major ions, nutrients, metals, and macroinvertebrate communities. The groundwater quantity section of the report provides tables of water well and groundwater-level information for each CHDN park (except the Rio Grande Wild and Scenic River, where no data were available). With the exception of 10 years of data from WHSA's groundwater-monitoring network and BIBE's results from relatively recent (2004 – 2008) water-level monitoring, no systematically collected water-level data are available for wells within CHDN jurisdiction. Hydrographs of long-term water-level data are provided from the closest State- or USGS-operated (privately owned) observation wells that appear to track the effects of recharge to and discharge from the aquifers considered most relevant to the groundwater resources and future water supplies at each CHDN park. Assuming data were sufficient, attempts were made for each park to identify and explain the most important relations among annual precipitation, likely recharge, nearby pumping, and observed water-level trends.

Acknowledgments

We thank Dr. Hildy Reiser (CHDN Inventory & Monitoring Network Coordinator), who has never hesitated to devote the time to communicate important issues involving project planning, structure, and execution. Hildy's efforts to arrange housing and coordinate schedules for our March 31—April 7, 2008 reconnaissance through CHDN are especially appreciated. We are greatly indebted to CHDN personnel took the time and made the considerable effort to educate us regarding various aspects of their respective parks, duties, and concerns during our CHDN reconnaissance. These personnel include Greg Garetz, Matt Oliveres, and Kate Johnson (AMIS); Jeffery Bennett and Betty Alex (BIBE); Paul Burger and Joe Davis (CAVE); John Heiner, Miguel Estrada, and Mark Meacham (FODA); Fred Armstrong and Gorden Bell (GUMO); and David Bustos (WHSA).

Following our return from the parks, NPS employees such as Larry Martin of the NPS Fort Collins, CO office have gone to significant lengths to search for and submit invaluable supplemental information and records—much of it unpublished and otherwise unobtainable. Other CHDN employees, such as Paul Burger and Joe Davis at CAVE, Val Call at GUMO, and David Bustos at WHSA, made similar efforts to follow-up and provide much of the springflow, well-construction, and groundwater-level data presented herein. We particularly appreciate and acknowledge the time provided by Jeffrey Bennett (BIBE) in his presentation of hydrogeologic and water quality issues along the Rio Grande and Wild and Scenic River and his review of our draft manuscript that significantly improved the quality of this publication. Barbara Porter provided assistance with formatting contents, figures, and tables in this report.

Summary

Surface Water Quantity

- Streamflow in the Rio Grande study area is controlled by three major impoundments, Elephant Butte Reservoir in central New Mexico, La Boquilla Reservoir on the Rio Conchos in Mexico, and Amistad International Reservoir near Del Rio, Texas. Since the construction of Elephant Butte Reservoir (1915) and La Boquilla Reservoir (1916), annual mean flow in the Rio Grande has decreased and peak flows have been attenuated, resulting in channel narrowing, changes in width-to-depth ratios, and decreases in sediment transport, as well as changes in the abundance and composition of floodplain vegetation, for example, increases in the abundance of invasive plants (e.g. tamarisk).

- Analyses of streamflow trends at selected USGS/IBWC gaging stations in the Rio Grande indicate decreases in annual mean discharge between 1900 and the regional drought period of the 1950s, followed by increases in annual mean discharge through the 1980s associated with increases in precipitation during the period. Annual mean discharge at the gaging stations has decreased since the early 1990s despite relative increases in precipitation.

- Analysis of continuous streamflow records over a common period of record (1961 - 2007) indicates that about 80 percent of flow in the Rio Grande immediately downstream from the Rio Conchos confluence originates in the Rio Conchos basin. During low-flow conditions, the Rio Conchos provides nearly all of the flow in the Rio Grande downstream from its confluence.

- Analyses of changes in flow conditions between Rio Grande gaging stations and from gain-loss studies in the Wild and Scenic River segment of the Rio Grande were used to provide estimates of ground-water discharges from springs into the Rio Grande. Large gains of discharge in the Rio Grande (100 - 400 ft^3/s) found along the lower Wild and Scenic River segment, from Heath Canyon (near La Linda, Mexico) to Langtry, Texas, are presumed to have originated from the Edwards-Trinity (Plateau) aquifer.

Surface Water Quality

- Relatively little change was observed for water temperature, dissolved oxygen (DO) concentrations, and pH values in the Rio Grande over the past 30 - 35 years. Median water temperature was higher at sites proximate to hot-spring discharges than at other Rio Grande locations. Dissolved oxygen concentrations declined in the Rio Grande downstream from the Amistad International Reservoir dam until the early 2000s. Since that time, dissolved oxygen concentrations have returned to levels typically observed at other Rio Grande sites. NPS personnel at Big Bend National Park report very low DO concentrations associated with early-season flood pulses that have resulted in fish kills in the Rio Grande near Rio Grande Village (Jeffrey Bennett, BIBE, written communication). No water-quality data were found for this location in the Texas Commission on Environmental Quality (TCEQ) data base.

- Median values for fecal-indicator bacteria (fecal coliform and *Escherichia coli*) were similar among sites, correlated positively with streamflow, and significantly higher during the summer recreational season. The percentage of Rio Grande samples exceeding USEPA criteria for contact recreation decreased from about 20 percent at Santa Elena Canyon to about 10 percent at Foster Ranch. Over 40 percent of samples collected from the Rio Grande below Rio Conchos exceeded USEPA criteria. Fecal coliform values have been increasing in the Rio Grande at Santa Elena since the early 1990s, consistent with trends at upstream sites near Presidio, Texas. No trends for fecal coliform values were detected at Rio Grande sites downstream from La Linda, Mexico. Although *E. coli* samples have been collected only since 2001, values appear to be increasing at sites in the Wild and Scenic River segment.

- Median concentrations of chloride, sulfate, and total dissolved solids, as well as specific conductance values, were relatively high in the Rio Grande at sites near Presidio, Texas and decreased with distance down river. Chloride concentrations exceeded the USEPA chronic aquatic-life criterion in 43 to 77 percent of Rio Grande samples collected at sites near Presido, 41 percent of samples from the Rio Grande at Santa Elena, 20 percent of samples from the Rio Grande near La Linda, and about 8 percent of samples from the Rio Grande at Foster. No exceedances were found in any samples collected from the Rio Grande below Amistad Reservoir. Chloride concentrations and specific conductance values in the Rio Grande have increased since the early 1970s; however, values at sites below Santa Elena appear to have decreased since the mid 1990s.

- Nutrient and biological (phytoplankton chlorophyll *a*) indicators of eutrophication generally were highest at the Rio Grande sites near Presidio, decreasing with distance downstream. Median nitrate concentrations increased significantly in the Rio Grande downstream from the Rio Conchos confluence, and median concentrations remained about the same at sites downstream to the Rio Grande at the Foster Ranch station. Nitrate concentrations in the Rio Grande have been decreasing at most sites since the late 1980s. Median concentrations of dissolved orthophosphate were highest in the Rio Grande at Santa Elena. Orthophosphate concentrations in the Rio Grande generally have been increasing since the mid 1980s. Median chlorophyll *a* values were representative of mesotrophic conditions at most sites (oligotrophic below Amistad International Reservoir). About 17 percent of samples from the Rio Grande at Santa Elena exceeded 30 µg/L, a common criterion for eutrophic conditions. Maximum chlorophyll *a* values observed at Rio Grande sites upstream from Foster Ranch varied from 125 to 366 µg/L. Dense growths of filamentous algae (*Cladophora glomerata*) were observed at several Rio Grande sites during a field visit in early April 2008.

- Despite historic mining activities in the region, notably mercury mining in the Terlingua mining district, concentrations of metals in water and sediment samples generally were low at all sites, consistent with natural background levels. Metals appear to be accumulating in the bottom sediments of Amistad Reservoir. Concentrations of arsenic, chromium, and nickel in upper layers of sediment cores (more recent years) exceeded biological threshold effect levels. Several recent studies have reported bioaccumulation of mercury in fish tissue samples collected from sites near the mining district as well as in Amistad Reservoir.

- The quality of surface waters in other CHDN parks ranges from hypersaline conditions that are unfavorable for most freshwater aquatic life (White Sands National Monument) to high-quality, near-pristine waters in Guadalupe Mountains National Park and, presumably, Rattlesnake Springs in Carlsbad Caverns National Park. Limited data available for Limpia Creek, located at the northern boundary of the Fort Davis National Historic Site, indicated relatively good water quality; however, low streamflow conditions, presently (2008) and particularly during the late 1880s, have limited the value of this resource.

Macroinvertebrate Communities

- Although macroinvertebrate data have been collected at various Rio Grande sites since the late 1970s, differences in study design and location, antecedent hydrologic conditions, sample-collection methods, and, particularly, levels of taxonomic resolution (e.g. order/family compared with genus/species) confound analyses of stream condition, much less changes over time. Because some of the available data sets provided only rapid-bioassessment metric values, more complex data sets (e.g. with taxa names and counts) were reduced to a set of two common metrics, taxa richness (number of all taxa in a sample) and E+T richness (number of mayfly+caddisfly taxa in a sample)—an estimate of the number of pollution-sensitive taxa. Taxa and E+T richness generally increase with improvements in water-quality and (or) habitat conditions.

- Median taxa richness (about 10) and E+T richness (5 or less) were lowest at Rio Grande sites above Rio Conchos, at Santa Elena Canyon, and near La Linda, Mexico, indicating degraded ecological conditions. Median taxa richness (20 - 40) and E+T richness (7 - 10) at sites downstream from each of the impaired sites were considerably higher. Results from a recent (1999) study indicated that, while overall taxa richness increased from 42 to 58 in the Wild and Scenic River segment between the Santa Elena Canyon and LaLinda sites, E+T richness decreased from 9 to 5 in the same river segment. Increases in taxa richness with downstream distance in the Wild and Scenic River segment primarily are associated with increases in the number of tolerant taxa rather than improvements in water quality.

- Benthic Macroinvertebrate Rapid Bioassessment Index of Biotic Integrity (BRBIBI) scores for Rio Grande sites in the study area were in the “intermediate” aquatic-life use category. The TCEQ designated aquatic-life use for Rio Grande segments 2306 and 2307 is “high;” therefore, macroinvertebrate IBI scores are indicating that the designated use is not being met.

- Based on similarities in taxa richness, E+T richness, and the distribution of species between macroinvertebrate data reported from the late 1970s and late 1990s, there is no compelling evidence to suggest that the condition of macroinvertebrate communities in the Rio Grande has changed appreciably.

- Macroinvertebrate communities in smaller streams within the CHDN network were variable and somewhat a function of the relative permanency of stream flow. For example, taxa richness in intermittent streams within Big Bend National Park generally was low, despite reasonably good water quality at times the streams were flowing. Water-quality conditions limited macroinvertebrate richness to 7 salt-tolerant taxa in the Lost River (WHSA). By contrast, taxa richness in the McKittrick Creek system (GUMO) varied from 35 to 82, whereas E+T richness ranged from 10 to 18, reflecting greater streamflow permanency in addition to outstanding water quality and habitat conditions.

Groundwater Quantity

- To satisfy potable water needs, every CHDN park is dependent on groundwater that discharges from springs, is pumped from local aquifers, or both.

- The availability of groundwater is continually adjusting to the effects of weather, well withdrawals (pumping), and land use.

- Understanding the nature and effects of weather, pumping, and land use is important toward maintaining viable sources of potable groundwater; monitoring groundwater quantity is vital toward tracking the availability and sustaining the future of groundwater supplies.

- Groundwater recharge to CHDN parks is restricted by the limited and sporadic nature of precipitation and the relatively heavy toll of evapotranspiration; consequently, water-supply wells are vulnerable to seasonal water-level drawdown, if not long-term decline.

- For this reason, the systematic observation of groundwater levels is essential toward evaluating long-term trends in area aquifers, as well as providing a means of effectively managing specific aspects of any park’s dependency on water.

- With the exceptions of recently-activated observation wells in BIBE and a network of eight groundwater-monitoring wells in WHSA, no CHDN park is currently collecting groundwater-quantity data on a systematic basis.

- Outside the BIBE and WHSA exceptions, no water-level record from any CHDN park is sufficiently lengthy to support the construction of hydrographs with which to track and evaluate long-term groundwater-quantity trends.

- Hydrographs are provided herein of water levels available from State- or USGS-operated observation wells that track the effects of recharge to and discharge from aquifers considered most relevant to the groundwater resource and future water supply at each CHDN park.

- The water levels in most long-term observation wells tapping aquifers underlying CHDN parks appear to respond relatively quickly to both precipitation on nearby recharge areas and to variations in pumping stress.

- The water levels in most nearby observation wells appear particularly vulnerable to the effects of drought—most notably those of decreasing recharge and increasing withdrawals of groundwater for irrigation.

- Except for GUMO, with its dependency on the Capitan Reef and Associated Limestones aquifer and this park's potential interest in the status of adjacent Bone Spring-Victorio Peak and Salt Bolson and Delaware Mountain Group aquifers, none of the CHDN parks appear affected by long-term water-level declines of immediate consequence.

- Because of anticipated increases in groundwater withdrawals from the Edwards-Trinity aquifer in Terrell County (and, potentially, in adjacent counties), discharge from this aquifer to springs and seeps that sustain streamflow in lower reaches of the Rio Grande should be monitored to ensure that such development does not significantly impact the region's surface-water resources.

- Despite a hydrograph record of less than 15 months, the Panther Junction observation well in Big Bend reflects a decline since May 2007 of 26 feet.

- Although the cause of the sharply downward groundwater trend in BIBE's Panther Junction well is not understood, this installation's record is too short to support any declaration of concern at this juncture, particularly because this declining tendency appears to have abated since November 2007.

- Despite the fact that observations wells near BIBE, CAVE, FODA, and GUMO tap different aquifers at distant locations, their individual water-level trends appear to track the effects of similar hydrogeologic controls. AMIS and WHSA, on the other hand, exhibit the effects of comparatively unique hydrogeologic settings:

  + Since the early 1970s, the groundwater-level variations near AMIS have been distinctly buffered by water levels in Lake Amistad;

  + The shallow groundwater regime at WHSA is perched above and hydraulically isolated from the regional, basin-fill aquifer of the larger Tularosa basin by an areally extensive remnant of an ancient (Pleistocene) lake bed.

Environmental Setting

Amistad National Recreational Area (AMIS)

Amistad National Recreational Area was created in June 1968 in association with the impoundment of the Rio Grande near Del Rio, Texas. Amistad International Reservoir, a physical ramification of diplomacy between the United States and Mexico, occupies 57,300 acres of the United States-Mexico borderland, and receives drainage from over 123,000 square miles in the Rio Grande, Rio Conchos, Pecos, and Devil's River basins. The reservoir's initial filling was completed in November 1969. Reservoir stages range from a conservation pool of 1,117 feet above mean sea level (amsl) to a maximum flood-control stage of 1,144 feet amsl. These levels relate to 3,500,000 acre-feet of storage to more than 5,600,00 acre-feet of storage, respectively. The lowest-recorded stage of 1058.38 feet occurred on August 5, 1998.

Reservoir stage rises and falls in accordance with the net effect of upstream inflows, evapotranspiration losses, and downstream water uses. Upstream inflows include discharge from the Rio Grande, as well as discharges from numerous subsurface springs. Because the Rio Grande often is dry downstream from El Paso, most inflow to Amistad International Reservoir results from rainfall in adjacent parts of Texas and, in particular, the Rio Conchos basin in Mexico. The large surface area of Amistad Reservoir makes it especially vulnerable to high rates of evaporation, which (according to Dr. John Borrelli of Texas Tech University) is estimated to average nearly 80 inches per year. This translates to a storage loss of more than 400 million gallons per day (mgd). The quantity and quality of inflow to and outflow from Amistad Reservoir are discussed as part of the overall Rio Grande section of this report. Although the inclusion of limnological results from Amistad Reservoir was beyond the scope of this report, recent publications describing and modeling limnological processes in Amistad International Reservoir include those by Groeger et al. (2008; submitted) and Fang et al. (2007).

Amistad Reservoir's vast, low-lying shoreline has become a habitat for invasive plants, including the water-loving *Tamarix* sp. (salt cedar), an exotic plant introduced originally into the U.S. for erosion control. Salt cedar's very high rate of transpiration can release as much as 200 million gallons of water daily to the atmosphere. In addition to a combined evaporation and transpiration toll of perhaps 600 mgd, average (1968-2007) releases of 1,415 mgd (2,190 cubic feet per second (ft^3/s)) of water are required to satisfy downstream surface-water rights.

Drought is a normal component of the arid and semiarid country that comprises most of the Río Grande watershed. The ever-growing human demand on surface and ground water, coupled with the encroachment of exotic, water-thirsty plants, has resulted in a steadily diminishing water supply. The diminishing Río Grande discharge is of increasing concern to the agricultural industry and downstream municipalities.

Big Bend National Park (BIBE)

Big Bend National Park comprises more than 1,250 square miles in the Big Bend region of the Rio Grande, along nearly 110 miles of the Texas—Chihuahua/Coahuila border in Brewster County, Texas. The Rio Grande marks the park's southern boundary, where the river cuts through the region's deepest gorges, mapped as the Santa Elena, Mariscal, and Boquillas canyons. Most of BIBE is composed of arid, relatively low-lying alluvial plains that represent some of the best examples of the Chihuahuan Desert in North America. In contrast, the Chisos Mountains, which comprise the southernmost mountain range in the continental United States, completely enclose central parts of the park where they rise over 7,800 feet above mean sea level (amsl). Annual precipitation in the park ranges from as little as five inches in the lowermost desert to greater than 20 inches in the mountains. Major surface-water resources in or near the park include the Rio Grande and intermittent, tributary streams such as Terlingua, Tornillo, and Alamito Creeks.

Given the expansive and exposed nature of Big Bend's geologic landscape, it is no surprise that the NPS considers BIBE to be "one of the outstanding geological laboratories and classrooms of the world." The park is a geologist's paradise at any scale due to the lack of vegetal cover and strata that are readily accessible and rarely obstructed by the weather or human influences. Although perhaps not so obvious to the casual observer, today's landscape results from an extremely complex geologic history.

Rio Grande Wild & Scenic River (RIGR)

A 196-mile section of the Rio Grande, from Mariscal Canyon (near the southern tip of Big Bend National Park) to the Terrell-Val Verde county line (approximately 20 miles upstream from Langtry, Texas), was designated by Congress as a Wild and Scenic River in 1978. U.S. rivers with this designation are to be preserved in their free-flowing condition, and their associated ecosystems are to be actively protected in their natural state. The designation for the Rio Grande came in recognition of the ecological importance of the riparian and canyon habitats within the free-flowing section of the Rio Grande that borders Big Bend National Park. Downstream from the eastern boundary of Big Bend National Park, the Rio Grande enters a system of desert canyons 83 miles long. Numerous springs and seeps along the Wild & Scenic River section contribute substantial discharges of ground water to the river, increasing the quantity of water transported by the river and improving water quality. The Wild & Scenic River section is managed by BIBE personnel.

Scenic and environmental values along the Wild & Scenic River section have become threatened as a result of water-quality contamination and other human activities. Streamflow in the RIGR section has been controlled by two major impoundments (Elephant Butte and La Boquilla reservoirs) since the early part of the 20th century, resulting in decreased annual mean flows, attenuation of peak flows, decreases in sediment transport, and changes in the composition and abundance of riparian vegetation. Invasive plants, such as river cane and tamarisk, have replaced native populations of cottonwood and willow trees, thereby diminishing the flow of natural springs and changing the composition and ecological value of riparian habitats.

Carlsbad Caverns National Park (CAVE)

Located in southeastern New Mexico near the northern limits of the Chihuahuan Desert, Carlsbad Cavern National Park was established in 1930 to preserve Carlsbad Cavern and more than 85 other caves within the predominantly limestone strata of the ancient Permian Reef

Complex. The U.S. Congress in 1978 designated seventy percent of the park's 46,766 acres as a National Wilderness Area. Despite the Cavern's unlimited appeal to naturalists, scientists, and tourists from all over the world, its major shortcoming has always been the lack of a dependable water source.

Rattlesnake Springs, roughly six miles to the southwest, is a detached 79-acre parcel acquired by the NPS in 1934 for the main purpose of providing a supply of potable water to the main cavern area. Although Rattlesnake Springs was not incorporated into the park system until 1963, the NPS oversaw its maintenance and use between the time of its acquisition and eventual adoption into the park network.

The spring initially satisfied the needs of prehistoric inhabitants and supported the subsistence of several Indian tribes, soldier units, travelers, and early settlers in the area. One of the settlers, Henry Harrison, homesteaded the site during the 1880s and developed the spring to irrigate his fields and orchard. Following its acquisition by the NPS, the area was further developed by the U.S. Civilian Conservation Corps during 1938 to 1942. Rattlesnake Springs was also used by the U.S. military for training exercises during World War II. During more recent times, the NPS has further developed the spring area.

Fort Davis National Historic Site (FODA)

This National Historic Site is located on the northern edge of Fort Davis, Texas in Jeff Davis County. Authorized by Congress in 1961, FODA was established as part of the National Park system on July 4, 1963. The 460-acre site, near U.S. Highway 290 on the north and U.S. 90 on the south, now offers more than twenty of the original stone and adobe structures that are restored as much as practical to their appearance in 1880.

FODA is situated in the high-desert, Trans-Pecos region of Texas. The Trans-Pecos encompasses 50,000 square miles of the nearly 250,000-square mile Chihuahuan Desert situated across the southwestern and north-central regions of the United States and Mexico, respectively. The topography of the nearby Davis Mountains is some of the most rugged in Texas. Within Jeff Davis County, elevations range from 3,871 to 8,382 feet amsl. Mount Livermore (8,382 feet amsl), 15 miles north of FODA, is the second highest peak in Texas. The climate of Jeff Davis County ranges from cool-temperate-humid at elevations above 4,000 ft to arid-subtropical at lower elevations (Bomar 1995). Temperatures exceed 90 ºF only 10 percent of the time at elevations greater than 6,800 ft amsl.

On average, Jeff Davis County receives about 20 in of precipitation annually, most of which falls between the months of June and October (Larkin and Bomar 1983). Rainfall during the spring and summer is dominated by widely scattered thunderstorm activity. Due to the convective nature of thunderstorms and the effect of mountainous terrain on the orographic uplift of cloud masses, the amount of spring and summer precipitation increases with elevation. The influence of orographic lifting on rainfall is reflected by the fact that the area of greatest precipitation is centered over the Davis Mountains, immediately north of FODA.

Guadalupe Mountains National Park (GUMO)

The Guadalupe Mountains National Park, straddles the border between Hudspeth and Culberson counties of Texas and abuts the southern boundary of New Mexico. Established as a National Park in 1972, GUMO encompasses an area of 76,293 acres that includes the four highest peaks in Texas. The Guadalupe Mountain Range slopes upward from low-lying alluvial plains on the south, east, and west at elevations of less than 2,000 feet amsl to Guadalupe Peak at 8,751 feet amsl near the center of the park. GUMO contains some of the better preserved and exposed remnants of the carbonate-rock Capitan Reef, one of the most prominent examples of ancient barrier reefs in the world. Major surface-water resources in the park include the McKittrick Creek system and numerous springs including Choza, Frijole, Guadalupe, Manzanita, Smith, and Upper Pine Springs. The quality of these water resources is excellent, and the remote location of the park provides an important baseline reference for measuring long-term changes in water quality and ecological condition. McKittrick and Choza Creeks recently (2007) were designated as “ecologically unique river and stream segments” by the Texas State Legislature.

White Sands National Monument (WHSA)

The White Sands National Monument was established on January, 18, 1933 to preserve a major portion of the world's largest gypsum dune field, along with several unique plant and animal species that have adapted to the park’s harsh environment. The dune field is situated over nearly 300 square miles of the Tularosa Basin, a downfaulted graben, near the northern margins of the Chihuahuan Desert. The dunes, comprised of nearly 97 percent gypsum, are forever shifting and advancing through various processes of growing, cresting, and slumping. The dunes, which began to form more than 10,000 years ago, owe their continued existence to the closed, internally draining nature of Lake Lucero.

The Lake Lucero playa is literally a natural evaporation pan characterized by torrid temperatures, low humidity, and high winds. According to Bill Conrod, a Natural Resource Specialist at WHSA during 1996-2005, the effective evapotranspiration rate approaches 80 inches per year due to the hot, dry, and windy environment. What little groundwater and surface water there is results from a mean annual precipitation rate of less than 10 in/yr, as computed for nearby Alamogordo, New Mexico.

Water from precipitation in the nearby mountains dissolves the mineral gypsum from the rocks that form the walls of the Tularosa Basin. Surface water and groundwater transport the resulting calcium and sulfate ions downslope, toward the depressed basin. The concentration of dissolved solids increases between the mountain front and basin floor. Due to high-salt content, most groundwater in the basin ranges from brackish to brine, making it unsuitable for drinking.

Calcium and sulfate dissolved from higher-elevation strata are re-concentrated near Lake Lucero, the lowest part of the basin, through the interaction of groundwater and surface water. As moisture evaporates from this shallow-water flatland (playa), large gypsum-rich crystals of selenite remain. These crystals are broken down and redistributed by the hot, dry winds into an assorted configuration of dome, traverse, barchan, and parabolic “sand” dunes.

Surface Water Dynamics in the Rio Grande

The CHDN has identified seven protocols that will be used to guide long-term monitoring of 25 ***vital signs*** that represent a comprehensive monitoring program for ecosystems in the network park units (Reiser et al. 2006; 2008). One of those protocols, surface water dynamics (trends and/or changes of surface water flow characteristics) in the Rio Grande, is discussed in this section.

Introduction and Discussion of Existing Streamflow Data

Six long-term streamflow gaging stations exist on the Rio Grande and Rio Conchos within the study area near Big Bend National Park (BIBE) and the Rio Grande Wild and Scenic River segment (RIGR). The locations and period of record for these stations (Table 1) provide a thorough database for analyzing the historic and current flow conditions in the Rio Grande flowing through the study area. Locations of the gaging stations are shown in Figure 2**.** The International Boundary and Water Commission (IBWC) (http://www.ibwc.state.gov) installed, operates, and presents the discharge data on their homepage at:

http://www.ibwc.state.gov/Water_Data/rio_grande_WF.html#Stream

Historic daily-mean data and 15-minute near real-time data are available from the IBWC water data page, as well as annual data reports presenting, along with streamflow discharge data, all water-resource related data collected during that year:

http://www.ibwc.state.gov/Water_Data/water_bulletins.html

The IBWC reports can be downloaded in PDF format, containing collated stream-gaging records as well as records for (1) waters in reservoir storage, (2) rainfall and evaporation, (3) amounts of irrigated acreage, and (4) water-quality data. The annual bulletins are entitled "Flow of the Rio Grande and Tributaries and Related Data" and are available from 1931 through 2003 (as of June 2008). Streamflow data are aggregated and published as daily-mean discharge data, and are aggregated from 15-minute data values collected at the gaging stations. Also available in the bulletins are annual instantaneous peak-discharge data for each of the stations.

The stations in the study area were installed and activated at various dates—all six stations are currently (2008) active. The period of record for each station is listed in Table 1. Five of the gaging stations are on the Rio Grande and the other station is near the mouth of the Rio Conchos—a major tributary to the Rio Grande. A description of the location and other relevant characteristics for each station are presented in Appendix A1 – A3.

Table 1. Period of record and mean streamflow discharges for gaging stations in the Rio Grande.

		Mean discharge in cubic feet per second		
Streamflow-gaging station number and name (downstream order)	Period of record	Entire period	Prior to regulation	After regulation
08371500 Rio Grande above Rio Conchos	Jan 23, 1900 to Dec 31, 2007	287	790 [1]	204 [2]
08373000 Rio Conchos near Presidio, Texas and Ojinaga, Chihuahua	Apr 1, 1954 to Dec 31, 2007	837		837
08374200 Rio Grande below Rio Conchos	May 1, 1900 to Mar 31, 1914 Jan 1, 1931 to Dec 31, 2007	1370	2550 [1]	1160 [2]
08375000 Rio Grande at Johnson Ranch	Apr 1, 1936 to Nov 30, 2007	1210		1210
08377200 Rio Grande at Foster Ranch	Sep 1, 1961 to Dec 31, 2007	1440		1440
08450900 Rio Grande below Amistad Reservoir	Sep 1, 1954 to Nov 30, 2007	2280	2570 [3]	2180 [4]

[1] Prior to Jan 1, 1915; [2] Beginning Jan 1, 1915; [3] Prior to June 1, 1968; [4] Beginning June 1, 1968

Note: Elephant Butte Reservoir, upstream from the first station above, began filling in 1915 and Amistad Reservoir, upstream from the last station began filling on June 1, 1968

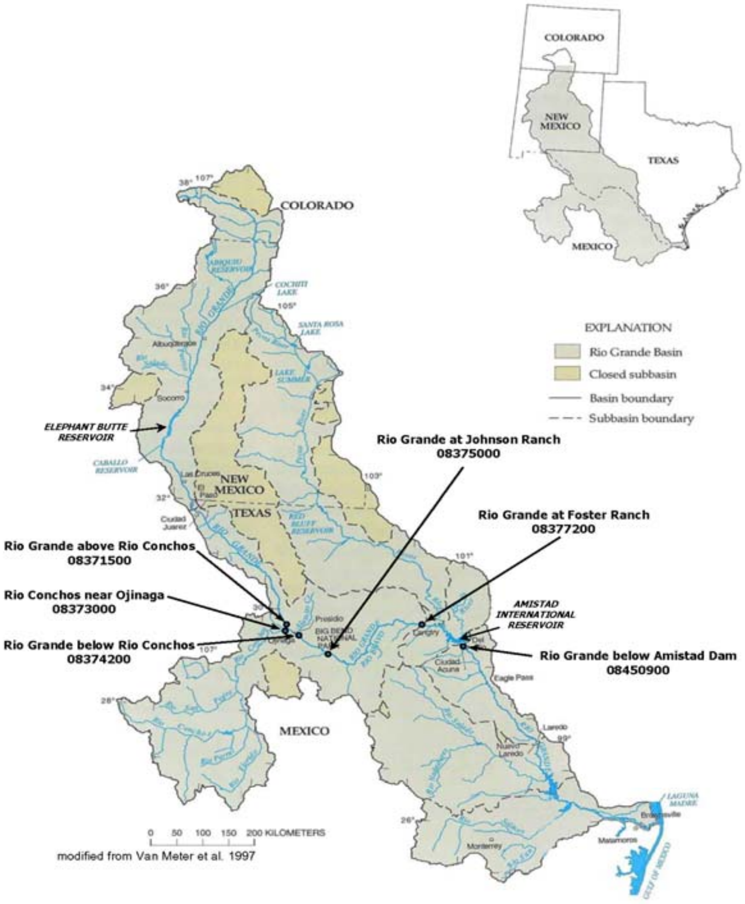
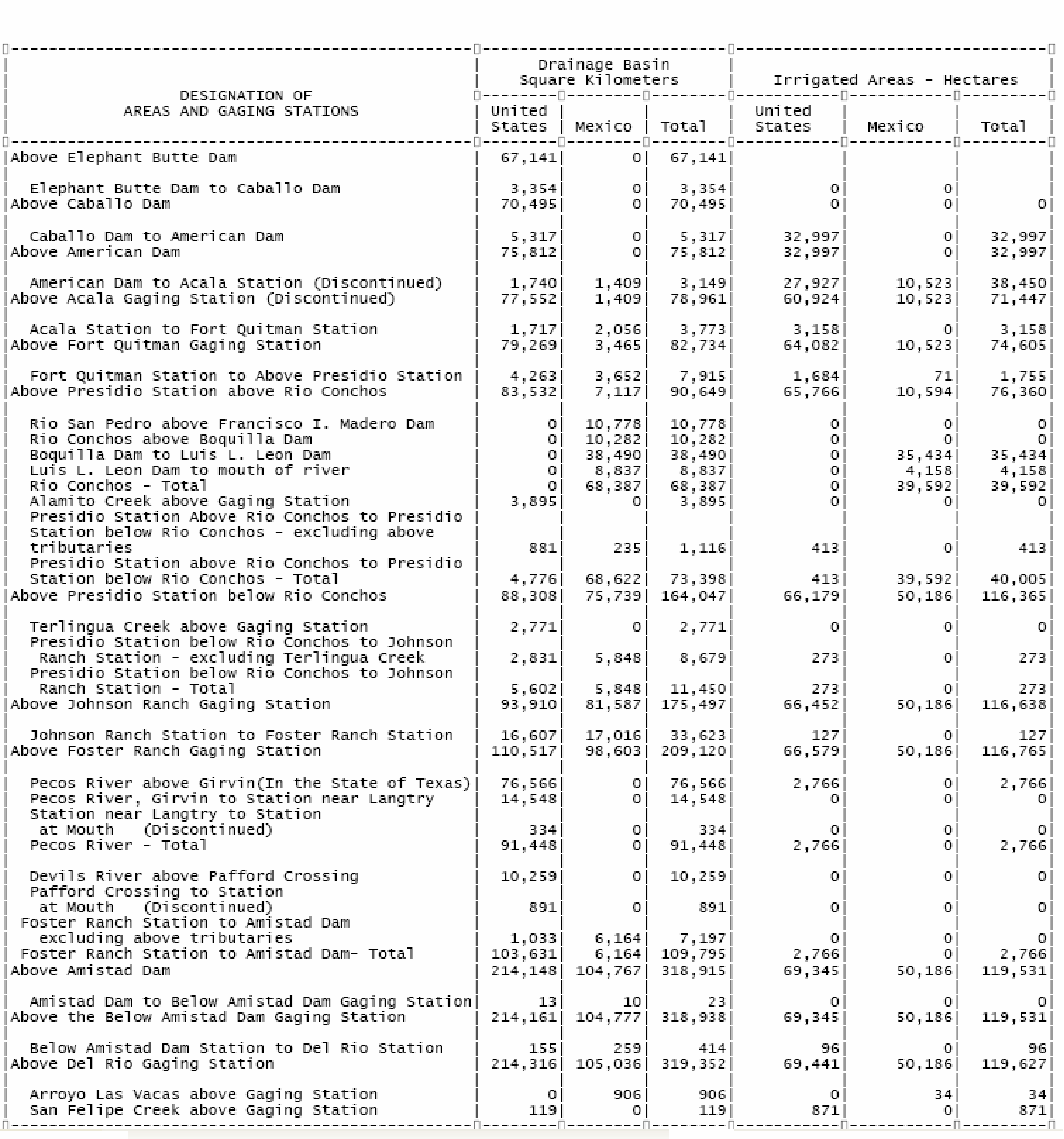


Figure 2. Rio Grande basin and locations of IBWC surface-water gages in study area.

Table 2. Drainage areas and irrigated acres along the Rio Grande and tributaries.
(Note: Drainage area units in square kilometers—to convert to square miles multiply by 0.386; Irrigated area in hectares—to convert to square miles multiply by 0.00386.)



DESIGNATION OF AREAS AND GAGING STATIONS	Drainage Basin Square Kilometers			Irrigated Areas - Hectares		
	United States	Mexico	Total	United States	Mexico	Total
Above Elephant Butte Dam	67,141	0	67,141			
Elephant Butte Dam to Caballo Dam	3,354	0	3,354	0	0	
Above Caballo Dam	70,495	0	70,495	0	0	0
Caballo Dam to American Dam	5,317	0	5,317	32,997	0	32,997
Above American Dam	75,812	0	75,812	32,997	0	32,997
American Dam to Acala Station (Discontinued)	1,740	1,409	3,149	27,927	10,523	38,450
Above Acala Gaging Station (Discontinued)	77,552	1,409	78,961	60,924	10,523	71,447
Acala Station to Fort Quitman Station	1,717	2,056	3,773	3,158	0	3,158
Above Fort Quitman Gaging Station	79,269	3,465	82,734	64,082	10,523	74,605
Fort Quitman Station to Above Presidio Station	4,263	3,652	7,915	1,684	71	1,755
Above Presidio Station above Rio Conchos	83,532	7,117	90,649	65,766	10,594	76,360
Rio San Pedro above Francisco I. Madero Dam	0	10,778	10,778	0	0	0
Rio Conchos above Boquilla Dam	0	10,282	10,282	0	0	0
Boquilla Dam to Luis L. Leon Dam	0	38,490	38,490	0	35,434	35,434
Luis L. Leon Dam to mouth of river	0	8,837	8,837	0	4,158	4,158
Rio Conchos - Total	0	68,387	68,387	0	39,592	39,592
Alamito Creek above Gaging Station	3,895	0	3,895	0	0	0
Presidio Station Above Rio Conchos to Presidio Station below Rio Conchos - excluding above tributaries	881	235	1,116	413	0	413
Presidio Station above Rio Conchos to Presidio Station below Rio Conchos - Total	4,776	68,622	73,398	413	39,592	40,005
Above Presidio Station below Rio Conchos	88,308	75,739	164,047	66,179	50,186	116,365
Terlingua Creek above Gaging Station	2,771	0	2,771	0	0	0
Presidio Station below Rio Conchos to Johnson Ranch Station - excluding Terlingua Creek	2,831	5,848	8,679	273	0	273
Presidio Station below Rio Conchos to Johnson Ranch Station - Total	5,602	5,848	11,450	273	0	273
Above Johnson Ranch Gaging Station	93,910	81,587	175,497	66,452	50,186	116,638
Johnson Ranch Station to Foster Ranch Station	16,607	17,016	33,623	127	0	127
Above Foster Ranch Gaging Station	110,517	98,603	209,120	66,579	50,186	116,765
Pecos River above Girvin(In the State of Texas)	76,566	0	76,566	2,766	0	2,766
Pecos River, Girvin to Station near Langtry	14,548	0	14,548	0	0	0
Station near Langtry to Station at Mouth (Discontinued)	334	0	334	0	0	0
Pecos River - Total	91,448	0	91,448	2,766	0	2,766
Devils River above Pafford Crossing	10,259	0	10,259	0	0	0
Pafford Crossing to Station at Mouth (Discontinued)	891	0	891	0	0	0
Foster Ranch Station to Amistad Dam excluding above tributaries	1,033	6,164	7,197	0	0	0
Foster Ranch Station to Amistad Dam- Total	103,631	6,164	109,795	2,766	0	2,766
Above Amistad Dam	214,148	104,767	318,915	69,345	50,186	119,531
Amistad Dam to Below Amistad Dam Gaging Station	13	10	23	0	0	0
Above the Below Amistad Dam Gaging Station	214,161	104,777	318,938	69,345	50,186	119,531
Below Amistad Dam Station to Del Rio Station	155	259	414	96	0	96
Above Del Rio Gaging Station	214,316	105,036	319,352	69,441	50,186	119,627
Arroyo Las Vacas above Gaging Station	0	906	906	0	34	34
San Felipe Creek above Gaging Station	119	0	119	871	0	871

Drainage Characteristics

The Rio Grande drains one of the largest basins in the United States, originating in southern Colorado and flowing through much of New Mexico before entering Texas near El Paso. Table 2 shows drainage areas for stations and reservoirs on the Rio Grande. As shown in Figure 2**,** a major reservoir (Elephant Butte) impounds the Rio Grande in New Mexico, about 100 miles northwest of El Paso, Texas. Elephant Butte reservoir began filling in 1915. The reservoir controls the flow for subsequent, downstream sites in the study area. The drainage area of the Rio Grande basin above Elephant Butte Reservoir (Table 2) is 67,141 km^2 (25,923 square miles), thus the reservoir captures runoff from a substantial area. The maximum capacity of Elephant Butte Reservoir is about 2,377,000 acre feet, with a normal capacity of about 2,110,000 acre feet. Because of the large storage capacity of the reservoir, much of the normal and flood flow in the Rio Grande is attenuated by Elephant Butte Reservoir.

Large amounts of water diversion and extraction for agricultural and domestic uses in New Mexico and the urban areas of El Paso, Texas and Ciudad Juarez, Mexico have significantly reduced streamflow in the “forgotten reach” of the Rio Grande, from Fort Quitman downstream to Presido, Texas (U.S. Army Corps of Engineers 2008; Wong et al. 2007). By the time the Rio Grande leaves El Paso, so much water has been diverted that the river channel between El Paso and Presidio often is dry (NPS 2006). Nearly 75,000 hectares of agricultural lands upstream from the Fort Quitman gaging station are irrigated from Rio Grande diversions or extraction of groundwater resources along the river (Table 2). As a result of reduced streamflow in the forgotten reach (in addition to attenuated peak flows during the past 90 years), extensive growths of invasive plant species (e.g. *Tamarisk* or “salt cedar”) have choked about 150 miles of the river corridor downstream from El Paso/Ciudad Juarez, constituting the most extensive infestation of this species in the world (Wong et al. 2007). Salt cedar is known to consume large quantities of water that remains in the alluvial channel. During low-flow seasons, and particularly during extended periods of drought, the Rio Grande downstream from Presido is functionally disconnected from its original sources of water (from snow melt in the southern Rocky Mountains and irrigation-return flows), and the quantity and quality of water in the Rio Grande is derived from precipitation and water use practices in the Rio Conchos basin in the State of Chihuahua, Mexico. The Rio Conchos enters the Rio Grande near the towns of Presidio, Texas and Ojinaga, Mexico (Fig. 2).

The Rio Conchos typically supplies the largest percentage of Rio Grande flows allocated by Mexico in accordance with the 1944 Treaty between the U.S. and Mexico. The total annual flow of the Rio Conchos averaged 737,000 acre-feet through the 1980s, more than five times the flow of the Rio Grande measured upstream from the Rio Conchos confluence (Blackstun et al. 1998). The Rio Conchos drains 68,387 km^2 of largely montane and semi-arid land; however, a considerable amount (39,592 hectares) of agricultural land is irrigated in the basin (Table 2). Three water-storage reservoirs (La Boquilla, La Colina, and Luis L. Leon) control flow in the Rio Conchos, approximately 405, 393, and 183 river kilometers upstream, respectively, from the Rio Grande confluence (Appendix A1). The oldest reservoir (La Boquilla) began filling in 1916, one year following the completion of Elephant Butte Reservoir. Another reservoir, Francisco I. Madero, is located on the Rio San Pedro, a tributary to the Rio Conchos.

The final major reservoir in the study area (Amistad International Reservoir; Fig. 2) is located about 110 miles east of Big Bend National Park. The reservoir began filling on June 1, 1968. This reservoir is upstream from only one of the six gaging stations in the study (08450900 Rio Grande below Amistad Reservoir), thus it controls discharge for that station only. Amistad International Reservoir impounds a very large volume of water—about 5,659,000 acre feet of maximum storage and 3,505,000 acre feet of normal storage—controlling runoff from a total drainage area of about 318,915 km^2 (123,133 square miles)(Table 2). Flow conditions in the Rio Grande are influenced by irrigation practices in the basin. Over 119,000 hectares are irrigated from the Rio Grande upstream from Amistad International Reservoir, about 58 percent within the U.S. boundary and 42 percent in Mexico (Table 2)

Flow Characteristics and Assessment

Table 1 presents the mean discharge for each of the 6 stations in the study area, including the mean discharge for the entire period of record, as well as for the periods of record prior to and after regulation by the two reservoirs discussed above. Mean discharges were substantially larger prior to regulation than after regulation. The period of record is limited (15 years) for the first and third stations in Table 1 prior to regulation, thus changes in discharge between natural and regulated conditions could be biased by unusual flow conditions during the short 15-year antecedent period. Flow at the first and third stations was substantially reduced as a result of regulation by Elephant Butte Reservoir. For the “Rio Grande above Rio Conchos” site (Fig. 2), the mean flow was 790 ft^3/s prior to regulation, but only 204 ft^3/s after regulation (Table 1). For the “Rio Grande below Conchos” site, mean flow was 2,550 ft^3/s before regulation and 1,160 ft^3/s after regulation.

The impoundment of the Rio Grande by Elephant Butte Reservoir has substantially reduced the amount of stream flow that is released downstream from the reservoir. The absence of flood peak discharges below Elephant Butte since 1915 has contributed to extensive growths of vegetation (e.g. salt cedar, etc.) along the Rio Grande floodplain in the study area. Historically, the floodplain was maintained by periodic, scouring flood discharges that have not occurred since the Elephant Butte impoundment was completed. These relatively dramatic changes in riverine floodplain conditions during the past 90-100 years obviously have had some effect on aquatic and riparian systems; however, no published water-quality or aquatic-life data exists prior to the 1960s-70s.

Mean Discharge Assessment

Discharge comparisons among stations can only be meaningfully made based on a common period of record; therefore, mean discharges for the longest common period of record (1961-2007) were computed and recorded in Table 3. As the table shows, the mean flow for the Rio Conchos (828 ft^3/s) represents about 80% of the flow for the Rio Grande below Rio Conchos (1,030 ft^3/s). Therefore, about 20 percent of the flow observed at the Rio Grande below Rio Conchos originates from the (upstream) Rio Grande, whereas about 80 percent originates from the Rio Conchos.

Table 3 also can be used to estimate increases in mean discharge between downstream Rio Grande stations, representing inflows to the Rio Grande from tributary streams or ground-water discharge into the Rio Grande between stations. For example, the increase in mean discharge in the Rio Grande from the Johnson Ranch to the Foster Ranch station is 350 ft^3/s (1,440 ft^3/s minus 1,090 ft^3/s). The mean flow increase was relatively small (60 ft^3/s) from the Rio Grande below Rio Conchos to the Rio Grande at Johnson Ranch station. There are no major tributaries to the Rio Grande between the Johnson and Foster Ranch stations. Thus, the small discharge gain likely is attributable to ground-water discharges along this portion of the river (refer to Fig. 3), and (or) the potential gaging error for these data.

Table 3. Mean streamflow discharges for longest common period of record among gaging stations in the Rio Grande study area.

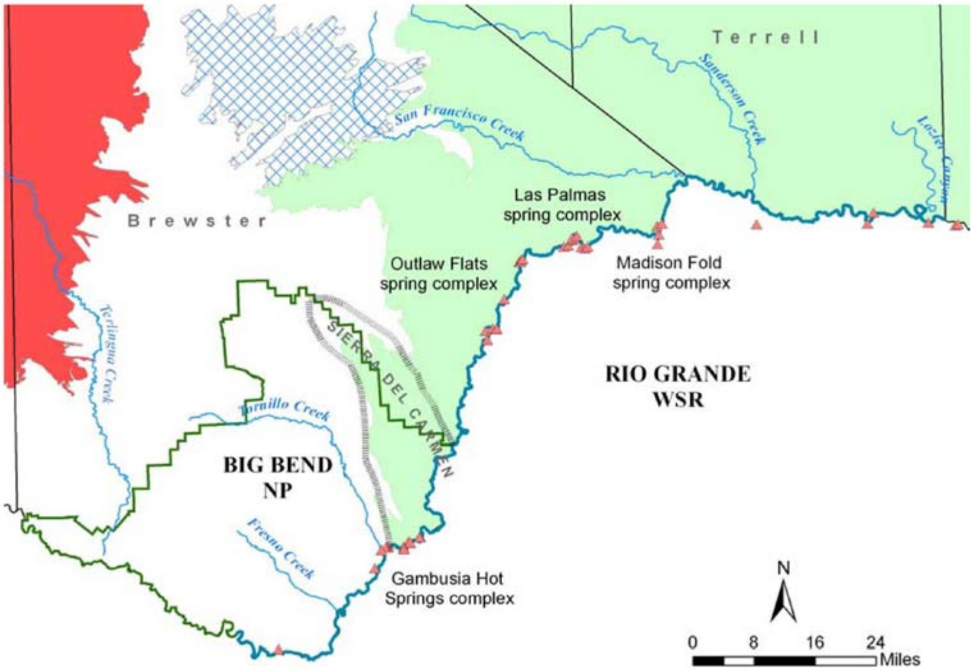
The longest common period of record is Sep 1, 1961 to Dec 31, 2007

Streamflow-gaging station number and name (downstream order)	Contributing drainage area square miles)	Mean discharge in cubic feet per second		
		Entire period	Prior to regulation	After regulation
08371500 Rio Grande above Rio Conchos	35,000	168		
08373000 Rio Conchos near Presidio, Texas and Ojinaga, Chihuahua	26,200	828		
08374200 Rio Grande below Rio Conchos	63,400	1,030		
08375000 Rio Grande at Johnson Ranch	67,800	1,090		
08377200 Rio Grande at Foster Ranch	80,700	1,440		
08450900 Rio Grande below Amistad Reservoir	123,000	2,190	2,300 [1]	2,180 [2]

[1] Prior to June 1, 1968

[2] Beginning June 1, 1968

Note: Amistad Reservoir upstream from the last station began filling on June 1, 1968



(Map from William E. Wellman, Superintendent Big Bend National Park, Written Commun., April 18, 2008)

Figure 3. Locations of springs that discharge into the Rio Grande from carbonate rocks within or adjacent to Big Bend National Park (NP) and Rio Grande Wild and Scenic River (WSR).

Flow Condition Assessment

Comparisons of discharge for various flow conditions in the Rio Conchos and the Rio Grande stations immediately upstream and downstream from the Rio Conchos confluence were calculated and presented in Table 4. Table 5 provides the same comparisons among three Rio Grande stations: below Rio Conchos, Johnson Ranch, and Foster Ranch. These tables present flow percentiles—discharge values associated with the percentage exceedance of the daily mean discharge value. For example, 1,861 ft^3/s is the daily-mean discharge that is exceeded only 1 percent of the time in the Rio Grande above Rio Conchos based on the period of record (Table 4).

Rio Grande flow values for high percentiles of exceedance can be used for among-site comparisons during low-flow conditions. For example, a discharge exceeded 80% of the time also represents the same discharge for which the flow is lower only 20% of the time. During low-flow conditions, the discharge for the Rio Grande above the Rio Conchos is only 0.7 ft^3/s, whereas the Rio Conchos discharge is 90.0 ft^3/s during the same low-flow condition. Comparisons over various levels of low-flow conditions indicate that almost all of the flow in the Rio Grande originates from the Rio Conchos in this segment of the river. This characteristic is probably associated with flow regulation from Elephant Butte Reservoir, considerable urban and agricultural water use from El Paso to the Rio Conchos confluence, and the relatively large contributing drainage area within the Rio Conchos basin (Table 2).

Analysis of Flow from Intervening Areas between Rio Grande Stations

Inflow from ungaged, intervening drainage areas between the Rio Conchos station and those on the Rio Grande immediately upstream and downstream from the Rio Conchos can be estimated with data contained in Table 4. For example, the sum of the drainage areas for the Rio Conchos basin and the Rio Grande above Rio Conchos is 61,400 square miles. However, the drainage area for the station on the Rio Grande downstream from the Rio Conchos is 63,400 square miles. The difference (2,000 square miles) represents the intervening drainage area between these stations, which could contribute runoff from overland flow and small tributaries between the stations and (or) ground-water discharges from the intervening drainage area.

A water budget analysis was used to document discharge from this area. For example, for the 99th percentile flow condition, 26.9 ft^3/s represents the flow in the Rio Grande below the Rio Conchos confluence and 13.1 ft^3/s represents the sum of the discharges for the Rio Conchos and the Rio Grande upstream from the Rio Conchos confluence (Table 4). The difference between these flow values (13.8 ft^3/s) represents the discharge from the intervening 2,000 square miles between the stations. Large flow from such a small area is deemed substantial, possibly representing ground-water discharges (e.g. spring flow) and (or) possible point-source discharges within the intervening drainage area. Flow data for the 100th percentile (minimum flow), indicates that 5.3 ft^3/s is gaged at the downstream station even though the flow at the upper two stations is zero. Therefore, it is likely that 5.3 ft^3/s represents the minimum spring-flow or point source discharge from the intervening area. Water budget analysis for the higher flow conditions indicates that the sum of the gaged flow for the upper two stations slightly exceeds that for the lower station. Those differences could represent discharge lost in the reach (withdrawals, channel loss, ground-water recharge, etc.) or, more likely, gaging error associated with the data.

Table 4. Discharge percentiles for the Rio Conchos and the Rio Grande above and below the Rio Conchos, September 1961 - December 2007.

Note: All discharges in units of cubic feet per second
September 1961 through December 2007 represents the longest common period for all discharge stations

	Station 1 **Rio Grande above Rio Conchos**	Station 2 **Rio Conchos**	Station 3 **Rio Grande below Rio Conchos**	**Intervening drainage area between stations**		
	Discharge	Discharge	Discharge			
Percent by which associated discharge is exceeded	High value 4661 Low value 0 Mean 168	High value 52612 Low value 0 Mean 828	High value 53318 Low value 0 Mean 1029	Sum of discharge for the first 2 stations for selected percentile	Discharge for station 3 minus discharge in previous column [1]	Percent by which discharge for station 3 exceeds total discharge at other 2 stations [2]
0.01	4661	52612	53318	57273	-3955	-7%
1	1861	7239	8933	9099	-166	-2%
2	1310	5245	6109	6555	-446	-7%
3	919	3990	4873	4909	-36	-1%
4	731	3330	3990	4061	-71	-2%
5	643	2881	3561	3524	37	1%
10	367	1769	2150	2136	14	1%
20	240	1020	1278	1261	17	1%
25	201	794	999	996	4	0%
30	163	643	791	806	-15	-2%
40	105	477	614	582	33	6%
50	60.7	388	491	449	42	9%
60	30.4	285	395	315	80	25%
70	12.4	188	293	200	93	47%
75	5.6	134	252	139	113	81%
80	0.7	90.0	212	90.7	121	134%
90	0.0	43.4	124	43.4	80	185%
95	0.0	25.8	79.8	25.8	54	210%
96	0.0	20.8	69.6	20.8	49	234%
97	0.0	16.2	54.4	16.2	38	235%
98	0.0	14.1	42.4	14.1	28	200%
99	0.0	13.1	26.9	13.1	14	106%
100	0.0	0.0	5.3	0.0	5	--

Note: The Rio Conchos is a tributary to the Rio Grande between the two Rio Grande stations shown above.

[1] Represents the discharge by which the flow at station 3 exceeds the discharge for the other 2 stations. Negative values represent discharges for which the station 3 discharge is less than the total discharge for the other stations.

The contributing drainage areas for the above stations are as follows:

Station name	Drainage area (square miles)
Rio Grande above Rio Conchos	35,000
Rio Conchos	26,400
Sum for 2 above stations	61,400
Rio Grande below Rio Conchos	63,400

[2] The drainage area for the third station exceeds that for the first 2 stations by 2,000 square miles, which represents 3 percent of the area for the first 2 stations. Therefore, if the runoff per square mile were uniform for all stations, the station 3 discharges would be expected to exceed the discharges for the other stations by about 3 percent.

Table 5. Discharge percentiles for the Rio Grande gaging stations below the Rio Conchos, at Johnson Ranch, and at Foster Ranch, September 1961 - December 2007.

Note: All discharges in units of cubic feet per second

September 1961 through December 2007 represents the longest common period for all discharge stations

Percent by which associated discharge is exceeded	Station 3 **Rio Grande below Rio Conchos**		Intervening area between gaging staton 3 and 4 [1]		Station 4 **Rio Grande at Johnson Ranch**		Intervening area between gaging staton 4 and 5 [3]		Station 5 **Rio Grande at Foster Ranch**	
		Discharge	Discharge increase in cubic feet per second	in percent [2]		Discharge	Discharge increase in cubic feet per second	in percent [4]		Discharge
	High	53318			High	65324			High	81566
	Low	0			Low	2.82			Low	93.9
	Mean	1029			Mean	1092			Mean	1436
0.01		53318	12005	23%		65324	16243	25%		81566
1		8933	1059	12%		9993	812	8%		10805
2		6109	424	7%		6532	1062	16%		7594
3		4873	318	7%		5191	1024	20%		6215
4		3990	318	8%		4308	918	21%		5226
5		3561	147	4%		3708	777	21%		4484
10		2150	219	10%		2369	470	20%		2839
20		1278	71	6%		1349	360	27%		1709
25		999	81	8%		1080	371	34%		1451
30		791	53	7%		844	374	44%		1218
40		614	28	5%		643	321	50%		964
50		491	25	5%		516	290	56%		805
60		395	21	5%		417	272	65%		689
70		293	19	6%		312	267	85%		579
75		252	9	4%		261	265	102%		526
80		212	7	3%		219	256	117%		475
90		124	-7	-5%		117	243	208%		360
95		79.8	-12.0	-15%		67.8	239	352%		306
96		69.6	-13.8	-20%		55.8	236	423%		292
97		54.4	-8.1	-15%		46.3	230	496%		276
98		42.4	-6.4	-15%		36.0	216	601%		252
99		26.9	-2.9	-11%		24.0	199	829%		223
100		5.3	-2.5	-47%		2.8	91	3225%		94

Note: Station numbers 3-5 near the top of the table represent the downstream order of the stations. Station 3 in this table (Rio Grande below Rio Conchos) corresponds to station 3 in the previous table. Negative values for discharge increases indicate discharge losses rather than gains between the stations.

[1] The drainage areas for stations 3 and 4 are 63,400 and 67,800 square miles respectively, thus the drainage area for the intervening area between the stations is 4,400 square miles which represents 7 percent of the drainage area for station 3.

[2] If the runoff per square mile is uniform for both stations, the increase in discharge between the stations would be expected to be about 7 percent.

[3] The drainage areas for stations 4 and 5 are 67,800 and 80,700 square miles respectively, thus the drainage area for the intervening area between the stations is 12,900 square miles which represents 19 percent of the drainage area for station 4.

[4] If the runoff per square mile is uniform for both stations, the increase in discharge between the stations would be expected to be about 19 percent.

Ungaged flow from the intervening basin(s) between the Rio Grande below Rio Conchos (station 3) and the Rio Grande at Johnson Ranch (station 4), as well as flow between the Johnson Ranch and Foster Ranch (station 5) stations on the Rio Grande, also were estimated from data presented in Table 5. The minimum flow (100th percentile) is 5.3 ft^3/s for station 3 and 2.8 ft^3/s for station 4. The difference between those two flow values (2.5 ft^3/s) represents a loss of flow in the Rio Grande between stations 3 and 4 during low-flow conditions. Losses occur for flow percentiles greater than or equal to the 90th percentile, whereas flow gains occur for all percentiles less than the 90th percentile (Table 5). Flow losses possibly represent water withdrawals, groundwater recharge, or combinations of both processes. Flow gains probably represent a combination of tributary inflows and (or) ground-water discharge into the Rio Grande.

Minimum flow (100th percentile) in the Rio Grande at Johnson Ranch (station 4) is 2.8 ft^3/s, whereas minimum flow for the Rio Grande at Foster Ranch (station 5) is 94 ft^3/s (Table 5). The difference between these flow values (91 ft^3/s) represents a substantial gain in the flow of the Rio Grande between these stations. The intervening drainage area between these stations is 12,900 square miles (Table 5), an increase of only 19 percent of the total drainage area recorded for the Johnson Ranch station. This large gain mostly is attributable to ground-water discharge via spring flows along the Wild and Scenic River segment (refer to Fig. 3). For flow conditions between the 98th and 50th percentiles, gains in Rio Grande flow are between 200 and 300 ft^3/s, which is a remarkably limited range of discharge values—suggesting a relatively constant source of discharge such as springs. Several reports (e.g. Barker and Ardis 1996; Mace et al. 2001) conclude this discharge represents flow from the Edwards aquifer which outcrops proximate to the Rio Grande and whose updip and downdip outcrop boundaries are between those two stations.

Streamflow Gain and Loss Studies on the Rio Grande

The analysis of gains and losses of stream flow in the Rio Grande presented above represents the reaches and intervening drainage areas between stations. However, streamflow gain-loss studies generally indicate gains or losses of streamflow between discharge measuring sites. Such studies have been conducted on many stream reaches in Texas, including those of the Rio Grande (Texas Board of Water Engineers (TBWE) 1960; U.S. Geological Survey (USGS) 1972; Slade et al. 2002; http://pubs.usgs.gov/of/2002/ofr02-068/). During low, steady flow conditions, discharge measurements were made at many stream sites and tributaries along selected reaches. The gain or loss in flow between the measuring sites was calculated and documented. A gain in discharge from an upstream to downstream reach indicates discharge from the aquifer adjacent to the sub-reach between the measuring sites, whereas a loss in discharge indicates recharge to the aquifer. Additional explanation and qualifications for gain-loss studies can be found in Slade et al. (2002).

A summary for all known streamflow gain-loss studies conducted in the main channel of the Rio Grande is presented in Table 6—similar studies also have been conducted in many tributaries and canals associated with the Rio Grande (Slade et al. 2002). For example, the first study (Table 6; Comal to Indio Ranch) was conducted in the vicinity of Eagle Pass, Texas, the reach extending 16 miles upstream and 18 miles downstream from Eagle Pass. All but one of the studies listed in Table 6 were conducted in reaches downstream from Amistad Reservoir (near Del Rio, Texas). The last study listed in Table 6 (Lajitas to Del Rio) provides gain-loss data from Lajitas, Texas (near the western boundary of Big Bend National Park) downstream to Langtry, Texas, near the Rio Grande at Foster Ranch gaging station (Table 7), more or less equivalent with the Rio Grande Wild and Scenic River segment (figs. 1 and 3).

Table 6. Characteristics of streamflow gain-loss studies on the Rio Grande in Texas.

[ft^3/s, cubic feet per second; ft^3/s-mi, cubic feet per second per mile; USGS, U.S. Geological Survey; --, not applicable; TBWE, Texas Board of Water Engineers]

Study no.	Rio Grande Reach identification	Date of study	Reach length (river miles)	Total sites	Sites on main channel	Major aquifer outcrop(s intersected by reach	Total gain or loss (-)in reach (ft^3/s)	Gain or loss per mile of reach (ft^3/s-mi)	Reference
1	Comal to Indio Ranch	1/13-3/18 1928	34	3	3	--	90.0	2.647	TBWE (1960)
2	Del Rio to Eagle Pass	2/9-3/3 1926	64	10	4	Edwards-Trinity (Plateau)	116.0	1.813	TBWE (1960)
3	Eagle Pass to Indio Ranch	1/12-4/12 1928	18	2	2	--	55.0	3.056	TBWE (1960)
4	Eagle Pass to Indio Ranch	2/2-3/14 1928	18	3	3	--	55.0	3.056	TBWE (1960)
5	Eagle Pass to Laredo	2/22-4/12 1928	128	6	6	--	-10.0	-0.078	TBWE (1960)
6	Eagle Pass to Laredo	2/22-4/22 1928	128	2	2	--	-25.0	-0.195	TBWE (1960)
7	Eagle Pass to Laredo	4/3-22 1928	128	6	6	--	-75.0	-0.586	TBWE (1960)
8	Eagle Pass to San Ygnacio	2/12-22 1926	168	22	17	Carrizo-Wilcox	-336.0	-2.006	TBWE (1960)
9	Elephant Butte - Mesilla Valley Unit, East Canal near Anthony	4/21 1971	2.5	4	3	Hueco-Mesilla Bolson	-3.1	-1.235	USGS (1972)
10	Elephant Butte - Mesilla Valley Unit, Franklin Canal below Ysleta	4/22 1971	2	3	3	Hueco-Mesilla Bolson	-0.6	-0.3	USGS (1972)
11	Elephant Butte - Mesilla Valley Unit, Franklin Drain below Sorocco	4/22 1971	2.4	3	3	Hueco-Mesilla Bolson	2.3	0.958	USGS (1972)
12	Elephant Butte - Mesilla Valley Unit, Nemexas Drain near Anthony	4/21 1971	2	3	3	Hueco-Mesilla Bolson	1.81	0.905	USGS (1972)
13	Elephant Butte - Mesilla Valley Unit, West Canal near Anthony	4/21 1971	2.7	4	3	Hueco-Mesilla Bolson	-6.21	-2.3	USGS (1972)
14	Elephant Butte - Mesilla Valley Unit, West Drain near Anthony	4/21 1971	1.8	3	3	Hueco-Mesilla Bolson	5.0	2.778	USGS (1972)
15	Lajitas to Del Rio	2/7-20 1925	293	11	8	Edwards-Trinity (Plateau)	783.0	2.671	TBWE (1960)

The first five of the seven sub-reaches presented in Table 7 are adjacent to Big Bend National Park. Results for the first sub-reach (from Lajitas to Sublet, Texas, located ½ mile downstream from the Terlingua Creek—Rio Grande confluence) indicate a streamflow loss of 20 ft^3/s, whereas neither gain nor loss was recorded in the second sub-reach (Sublet, Texas downstream to the Mariscal dam site). Streamflow gains ranging from 30 to 50 ft^3/s were recorded in the following two sub-reaches, from Mariscal dam to Stillwater Crossing; moreover, gains increased with distance downstream from Boquillas, Mexico (30 ft^3/s) to Amistad International Reservoir (403 ft^3/s; Table 7). Tributaries to the Rio Grande in this area are small, thus it is likely that the source of these substantial gains is from ground-water discharge (springs) and (or) agricultural return flow. The three sub-reaches downstream from Boquillas are proximate to the Edwards-Trinity (Plateau) aquifer. Large gains in streamflow (100—400 ft^3/s) along the lower Wild and Scenic River segment presumably are associated with discharge from this aquifer.

Table 7. Streamflow gains and losses for measurement sites on the Rio Grande reach from Lajitas to Del Rio, Texas.
[dd, degrees; mm, minutes; ss, seconds; ft^3/s, cubic feet per second; mi, miles; --, not applicable]

Study no.	Latitude of upstream end of subreach (dd mm ss)	Longitude of upstream end of subreach (dd mm ss)	Major aquifer outcrop	Gain or loss (-) in subreach (ft^3/s)	Length of subreach (river mi)	Location of upstream end of subreach (river mi)	Descriptive location of upstream end of selected subreaches
15	29 15 20	103 46 30	--	-20.0	17.3	280	at Lajitas, mean discharge for period
15	29 09 34	103 36 18	--	0.0	43.2	297	at Sublet Texas, 1/2 mile below mouh of Terlingua Creek
15	28 59 05	103 11 52	--	50.0	19.0	340	near Mariscal damsite
15	29 11 03	102 58 55	--	30.0	14.5	359	at Boquillas, Coah.
15	29 16 54	102 53 45	--	100.0	24.9	374	at Stillwell Crossing
15	29 32 11	102 47 27	Edwards-Trinity Plateau	220.0	100.9	399	at Reagan Canyon
15	29 47 22	101 34 22	Edwards-Trinity Plateau	403.0	73.3	500	at Langtry, Texas

Temporal Trends in Streamflow

Streamflow changes over time were evaluated using a graphical model, LOWESS (Cleveland 1979, 1981; Cleveland and Devlin 1988). LOWESS, also known as locally-weighted regression analysis or locally-weighted scatterplot smoothing, is a modeling method based on linear and nonlinear least squares regression. LOWESS combines much of the simplicity of linear least squares regression with the flexibility of nonlinear regression. It does this by fitting simple models to localized subsets of the data to derive a function that describes the deterministic part of variation in the data, point by point. One of the primary attractions of this method is that a global function is not required to fit a specific LOWESS model to the data. A polynomial function is fit to the data using weighted least-squares regression, giving greater weight to data points near where the response is being estimated and lesser weight to data points further away. For the trends produced in this report a “tension factor” of 0.5 was used (SYSTAT Software, Inc. 2004) LOWESS requires large, densely sampled, data sets in order to produce reliable and meaningful results. All statistical and graphical results were produced with SYSTAT v. 11 (SYSTAT Software, Inc. 2004).

The LOWESS model was used to produce temporal trends based on annual mean discharge. Results are presented for the Rio Grande above Rio Conchos (Fig. 4), Rio Conchos (Fig. 5), Rio

Grande below Rio Conchos (Fig. 6), Rio Grande at Johnson Ranch (Fig. 7), Rio Grande at Foster Ranch (Fig. 8), and the Rio Grande below Amistad (Fig. 9). Annual mean discharge in the Rio Grande above Rio Conchos decreased from the beginning of record (1900) until about 1960, when the discharge began slowly increasing (Fig. 4). Mean discharge in the Rio Conchos increased from the beginning of record (1954) through about 1975 when discharge began to decrease, particularly during the 1990s through present (2008) (Fig. 5). Mean discharge in the Rio Grande below Rio Conchos has decreased from the beginning of record (1900) until the mid 1950s, following which time mean annual discharge increased slightly until about 1980 when discharge began decreasing through the present time (Fig. 6). Annual mean discharge in the Rio Grande at Johnson Ranch decreased from the beginning of record (1936) until about 1955, when values began to increase until about 1980 (Fig. 7). Mean discharge values have declined since that time. Annual mean discharge in the Rio Grande at Foster Ranch gradually increased from the beginning of record (1961) until the mid 1980s when values began to decrease (Fig. 8). Mean discharge in the Rio Grande below Amistad Reservoir decreased from the beginning of record (1954) until the late 1960s when discharge increased until the mid 1980s, decreasing since then (Fig. 9).

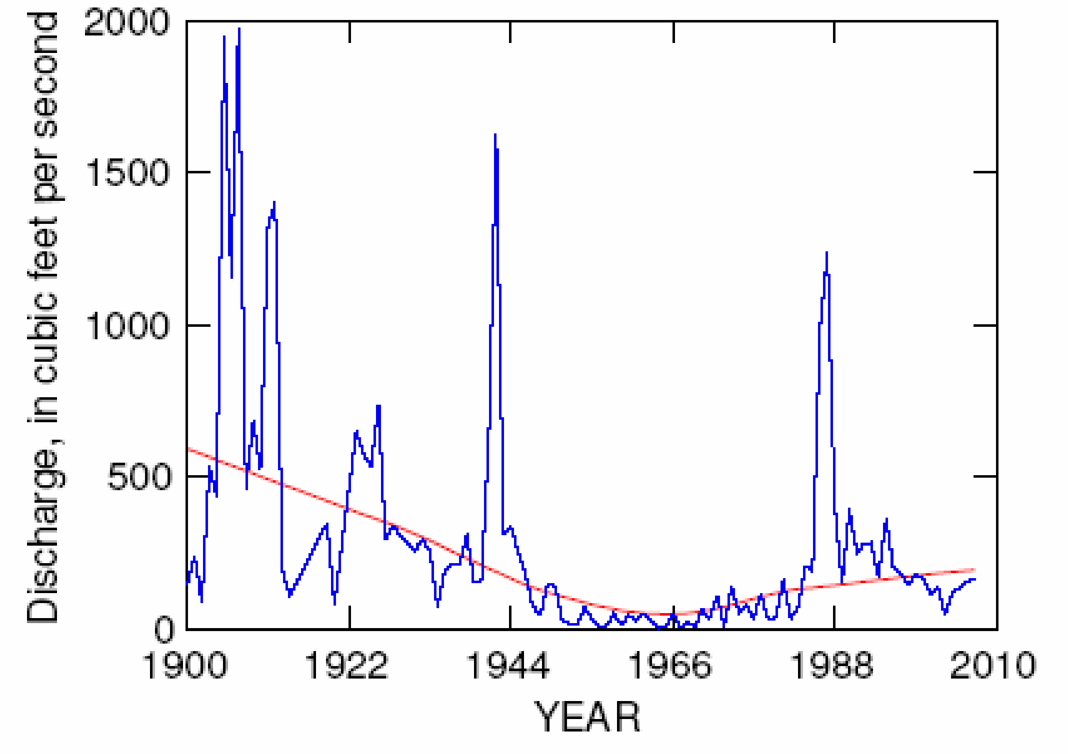


Figure 4. Temporal trends for the Rio Grande above the Rio Conchos.
(Note: Red line represents trend from LOWESS model based on annual mean discharge values)

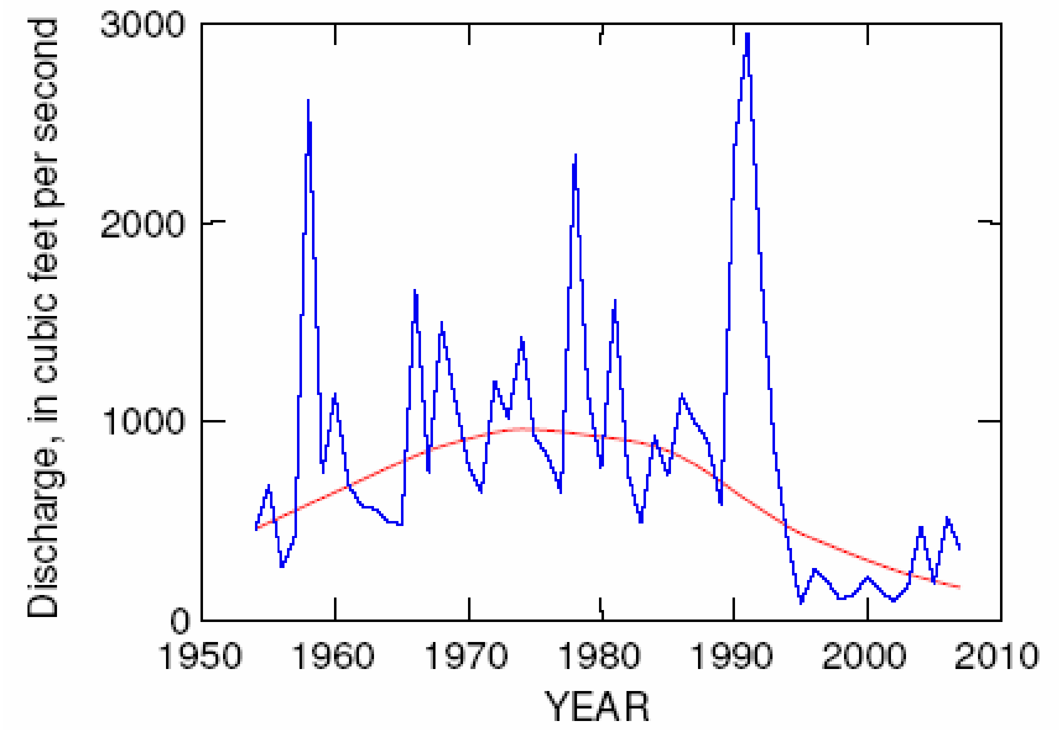


Figure 5. Temporal trends for the Rio Conchos. (Note: Red line represents trend from LOWESS model based on annual mean discharge values)

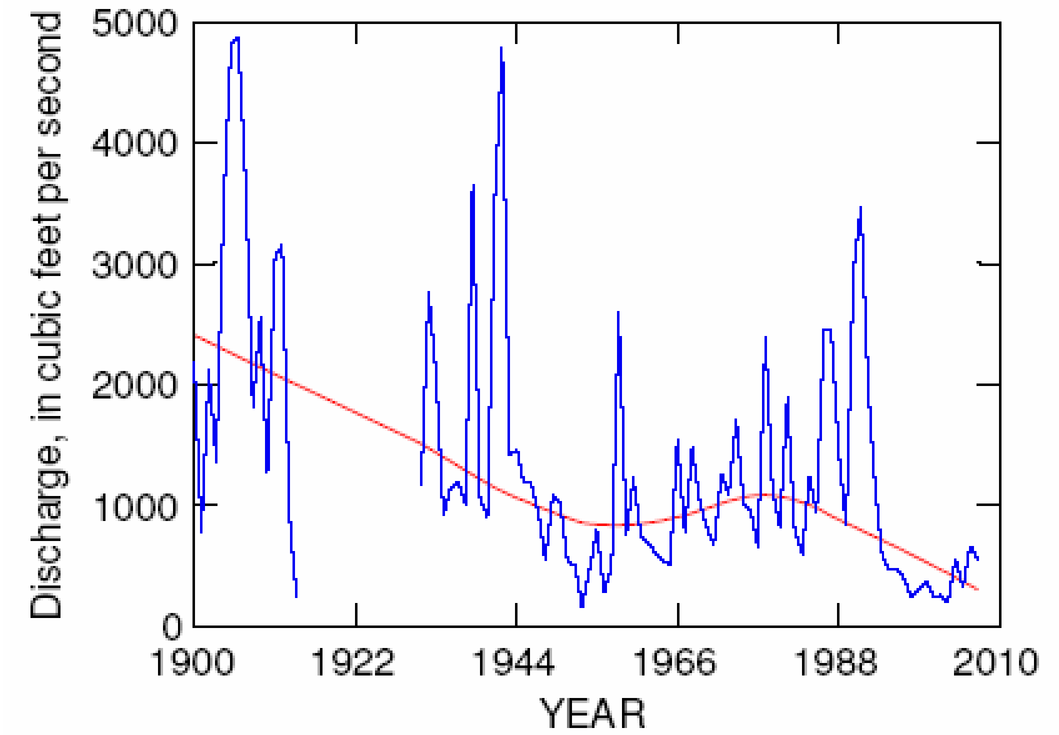


Figure 6. Temporal trends for the Rio Grande below the Rio Conchos.
(Note: Red line represents trend from LOWESS model based on annual mean discharge values; No data reported from 1914 through 1930)

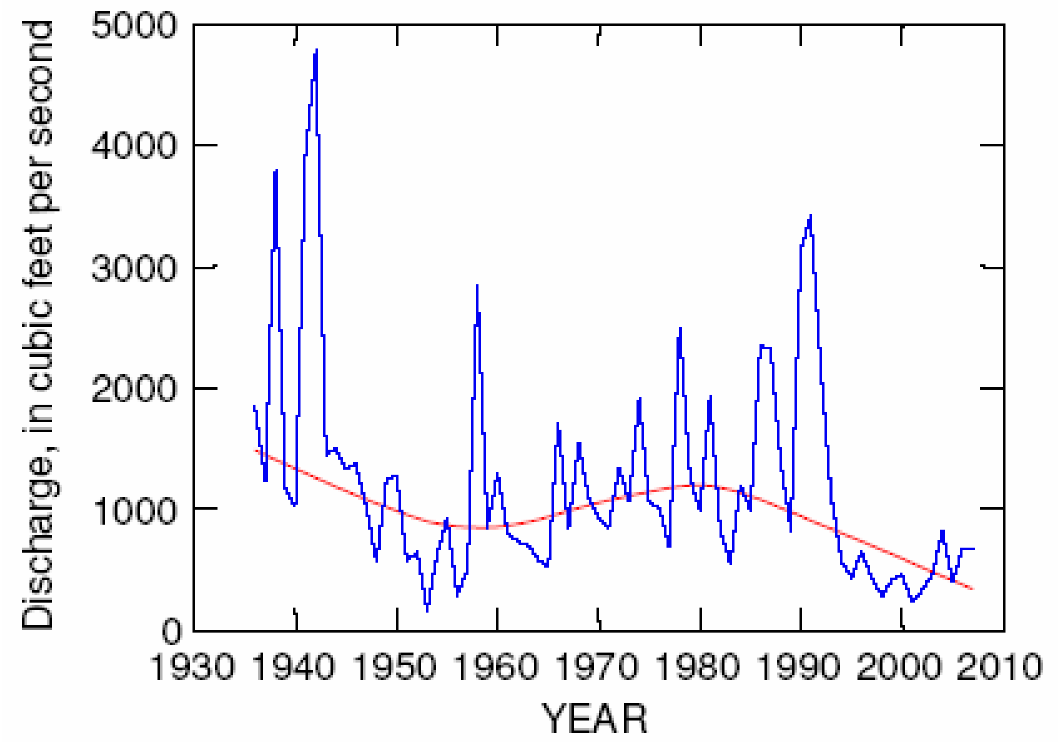


Figure 7. Temporal trends for the Rio Grande at Johnson Ranch.
(Note: Red line represents trend from LOWESS model based on annual mean discharge values)

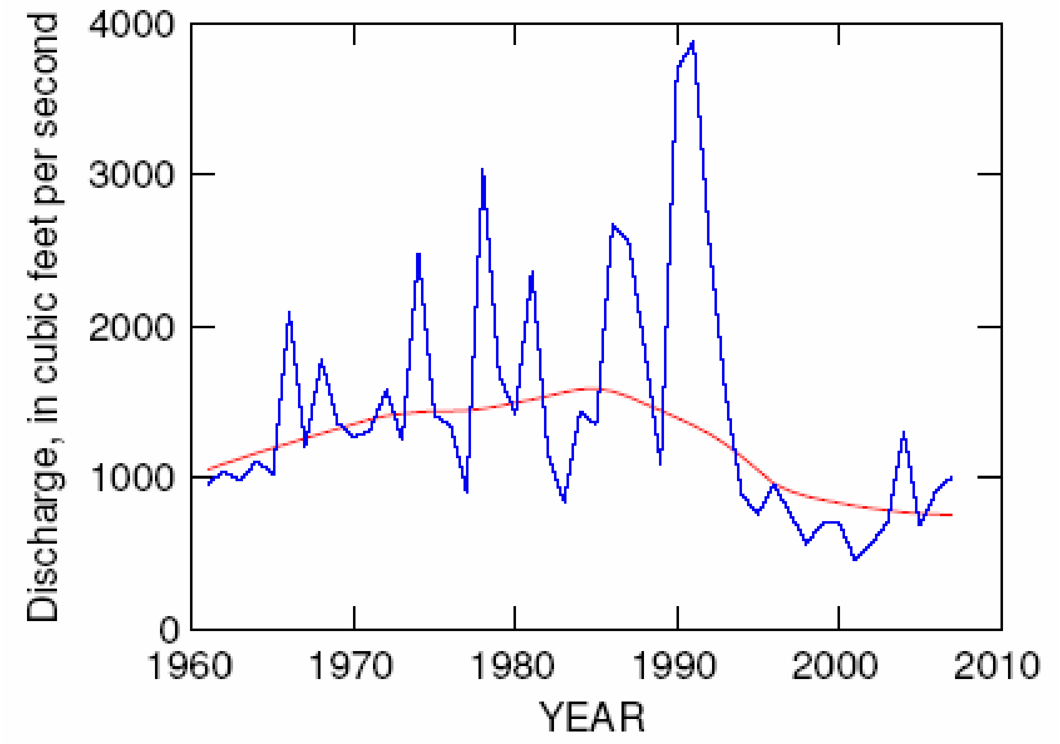


Figure 8. Temporal trends for the Rio Grande at Foster Ranch.
(Note: Red line represents trend from LOWESS model based on annual mean discharge values)

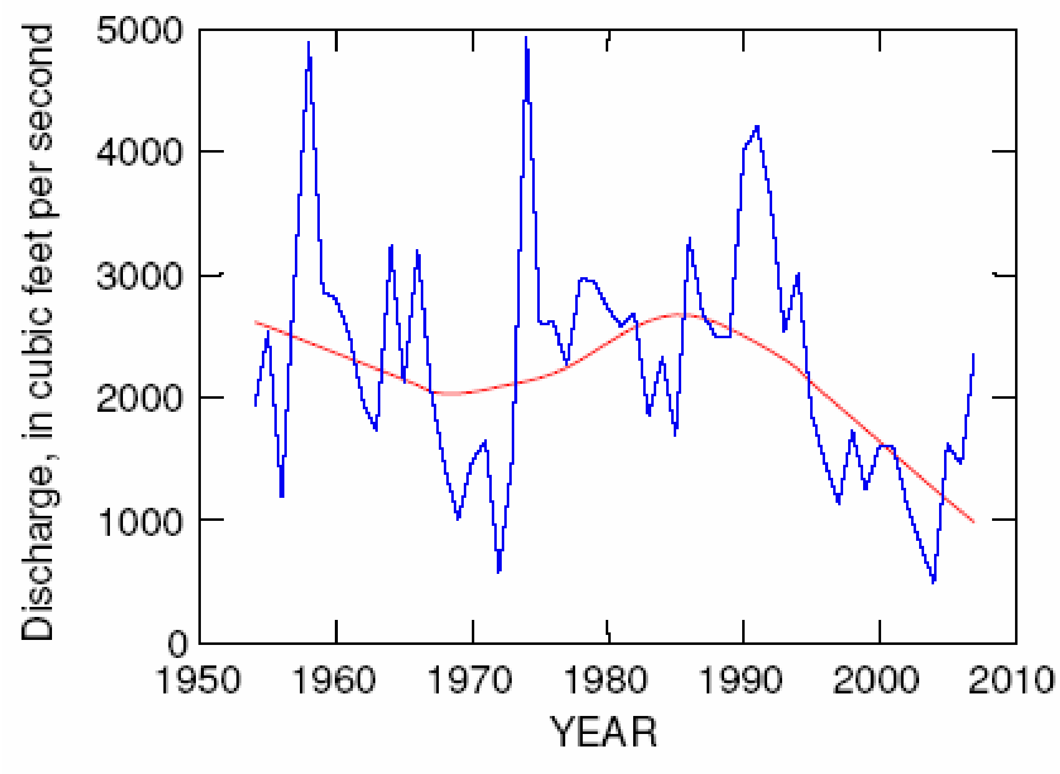


Figure 9. Temporal trends for the Rio Grande below Amistad Reservoir.
(Note: Red line represents trend from LOWESS model based on annual mean discharge values)

Common Patterns in Trends

For the two gaging stations with data since 1900, (Rio Grande above and below the Rio Conchos), the common streamflow trend is decreasing annual mean discharge from 1900 until the late 1950s. For all six stations, annual mean discharges increased from about 1950 until about 1980, when discharges began decreasing until the present time (2008). The general trend indicates that mean discharge in the Rio Grande has been decreasing during the past 25 years, with lower-than-average annual discharges recorded between 1950 and the 1980s. In addition to reductions in annual mean discharge, peak (flood) flows have been attenuated in the Rio Grande since the construction of Elephant Butte Reservoir (refer to hydrographs in Figures 4 and 6). Increases of agricultural and urban water withdrawals in the El Paso – Juarez valley (U.S. Army Corps of Engineers 2008) and, presumably, decreases in water releases from major reservoirs in the Rio Conchos basin (refer to Fig. 5), during the past 25 years have contributed to reduced streamflow in the Rio Grande downstream from Presidio, Texas. A prime factor in reductions of streamflow, however, is a decline in annual-mean precipitation during the period.

Figure 10 shows estimated rainfall for Presidio since 1895 and measured precipitation for three one-degree quadrangles (portions of Texas counties west of Presidio) since 1940. A map showing the boundaries for the quadrangles is presented online at http:/hyper20.twdb.state.tx.us/Evaporation/bigmap.html. Declines in regional precipitation, indicated by LOWESS trend lines on Figure 10, since 1980 are apparent for Presidio as well as for two of the three quadrangles for which long-term data were available. Increases in rainfall variance (range of high to low annual-precipitation values and departure from the LOWESS long-term median value) also are noted during the past 30 years in relation to conditions prior to the 1930s (Fig. 10).

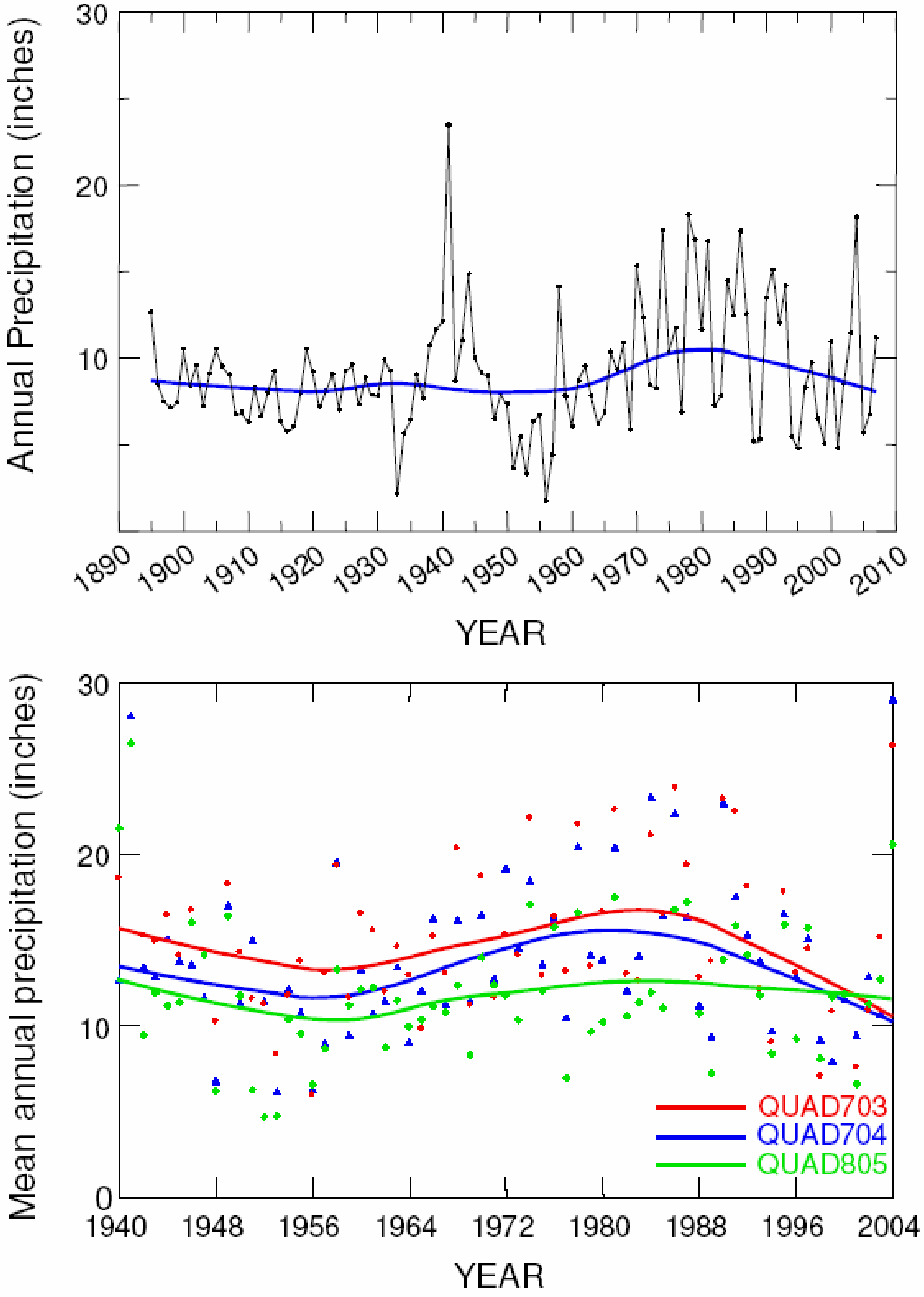


Figure 10. LOWESS trend lines for annual precipitation for Presidio, Texas and three one-degree quadrangles representing Texas counties west of Presidio.

Influence of Flow Regulation on Habitat Structure in the Rio Grande

Prior to regulation, periodic floods controlled sediment and vegetation on the banks and floodplain of the Rio Grande. Since the completion of Elephant Butte Dam, the total annual volume of water has been reduced by 77 percent (US Army Corps of Engineers 2008). The change in flow conditions has critically reduced the Rio Grande's capacity for sediment transport, resulting in aggradation of sediment in the main river channel, deposition of large sediment bars at the mouths of arroyos and other tributaries, and floodplains that are disconnected between xeric plant communities and the present river channel. The Rio Grande between El Paso and Presidio has become an aggrading river segment whose bed is substantially higher than prior to the construction of main-stem reservoirs and tributary flood and sediment detention dams (U.S. Army Corps of Engineers 2008). Historical biannual peak flows during spring and summer have been replaced by a low, steady flow regime linked to the irrigation season.

Modification of river flow regimes and channel geomorphology has contributed to excessive growths of invasive plants, notably salt cedar (*Tamarisk* spp.). During the early 1900s, the Rio Grande system was characterized by broad floodplains with large groves of cottonwood, willow, and mesquite trees, extensive areas of native grasses, and a diversity of wetland plants such as cattails, rushes, sedges, and submerged aquatic macrophytes (U.S. Corps of Engineers 2008). *Tamarisk* was introduced as an ornamental plant and for erosion control in the upper Rio Grande basin (New Mexico) during the 1920s; by the late 1930s, salt cedar had immigrated downstream to the Presidio valley. Since the 1940s, a combination of sediment aggradation in the river channel and along the Rio Grande floodplain, considerable seed production and rapid growth rates of *Tamarisk*, and a relative lack of scouring flood events has resulted in dense growths of exotic floodplain vegetation (Fig. 11) which have largely replaced native trees and grasslands. Concurrent with changes in floodplain characteristics, the river channel has become much narrower and entrenched into the aggradated sediment that has been deposited on to the historic floodplain.

Figure 11. Rio Grande near Langtry, Texas showing upstream view of floodplain vegetation.

Water Quality Conditions and Trends in the Rio Grande

The CHDN has identified 7 protocols that will be used to guide long-term monitoring of 25 ***vital signs*** that represent a comprehensive monitoring program for ecosystems in the network park units (Reiser et al. 2006; 2008). Trends and/or changes of conditions in surface water quality and invertebrates in aquatic systems, two of the CHDN vital signs, are discussed in this section. Seasonal and annual trends in primary surface-water constituents (water temperature, dissolved oxygen, pH, fecal-indicator bacteria, and specific conductance) and common inorganic constituents (major ions, nutrients, metals) are summarized and compared among 6 Rio Grande monitoring sites. Macroinvertebrate-community indicator metrics (taxa richness and the number of sensitive taxa) are compared among 9 Rio Grande sites in relation to water quality and stream-habitat conditions.

Methods

Water quality data were retrieved for Segment 23 (Rio Grande basin in Texas) from the on-line TCEQ data base (http://www.tceq.state.tx.us/compliance/monitoring/crp/data/samplequery.html) during October 2007. The data base includes water quality and quantity records from a variety of water-resource agencies such as the Texas Commission on Environmental Quality (TCEQ), U.S. Geological Survey National Water Information System (USGS-NWIS), U.S. Environmental Protection Agency (USEPA STORET), and others. Water quality results were downloaded, linked relationally with associated site and event tables, and incorporated into a MS Access data base (TCEQ_23.mdb), from which analytical data sets were prepared. In addition to hydrology and water chemistry, limited macroinvertebrate results also were available in the TCEQ data base; however, various literature sources, metrics provided by TCEQ (Bill Harrison, TCEQ, digital communication), and several graduate-research theses primarily were used to evaluate the condition of benthic macroinvertebrate communities in the Rio Grande.

Various tables (MS Excel spreadsheet files) were created to examine the distribution of data and to eliminate quality-control and other samples not relevant to condition or trend analyses. Censored water-quality data, those reported as less than a laboratory method reporting level (MRL) were reset to a value equal to one-half the MRL. Seasonal analyses were in accordance with NPS (1995) which defined two seasons on the basis of Rio Grande hydrology, (1) November 1 – April 30 (hereafter, “low flow”) and (2) May 1 – October 31 (hereafter, “high flow”). Previous publications reporting water quality conditions in the Rio Grande (e.g. International Boundary and Water Commission (IBWC) 1997; 2004; Texas Natural Resource Conservation Commission (TNRCC) 1992, 1997, 2002; National Park Service (NPS 1995a-b; Smith and Alexander 1985; Smith et al. 1982; Lambert et al. 2008) also were reviewed and discussed where appropriate.

Differences in water quality conditions among sites were compared using boxplots, summary statistics, and nonparametric correlation and other statistical procedures. Water-quality trends or dynamics over time were evaluated with LOWESS models of constituent values relative to the period of record, generally 30 to 40 years depending on the constituent. All statistical and graphical results were produced with SYSTAT v. 11 (SYSTAT Software, Inc. 2004).

Water Quality Sites

Sufficient data were available to estimate water-quality conditions and trends at 6 Rio Grande locations (Fig. 12; sites A, B, D/E, G, H, and I); all sites except G are stream-flow gaging stations with continuous records (see previous section). Water-quality data for Site F (Rio Grande above Boquillas Canyon and Rio Grande at Rio Grande Village) were limited to eight years of record (1999 – 2007); statistical summaries of data from this site are presented in this report but not trend analyses. Historic water-quality data from the gaged sites primarily are a legacy of the USGS National Stream Quality Accounting Network (NASQAN); water-quality monitoring at many of the sites has been assumed by TCEQ. Because of incomplete water-quality records, data from sites D (1968 – 76) and E (1974 – 2007) were compared during the common period of record (1974 – 76) and a decision was made to combine those results into a single station (D) with a 1968 – 2007 period of record. A similar decision was made for TCEQ sites 13226 (Rio Grande at Stillwell Crossing; (1977 – 81) and 13225 (Rio Grande at FM 2627; (1986 – 2007). Data from those sites were combined and the site was designated Site G, Rio Grande near La Linda, Mexico (Fig. 9).

Site	Site Name	River Km	TCEQ ID	USGS gage
A	Rio Grande near Presidio, TX (upstream from Rio Conchos)	1551	13230	08371500
B	Rio Grande below Rio Conchos	1529	13229	08374200
C	Rio Grande above Lajitas, TX	1464	18441	-------------
D	Rio Grande at mouth of Santa Elena Canyon$_1$	1425	13228	-------------
E	Rio Grande at Johnson Ranch, TX$_1$	1388	13227	08375000
F	Rio Grande above Boquillas Canyon	1260	--------	-------------
G	Rio Grande near LaLinda, MX$_2$	1219	13225-6	-------------
H	Rio Grande at Foster Ranch, TX	1058	13223	08377200
I	Rio Grande above Del Rio, TX (below Amistad Reservoir)	920	13209	08450900

$_1$Water-quality record for site D compiled from TCEQ 13227 (1968-76) + TCEQ 13228 (1974-2007)
$_2$Water-quality record for site G compiled from TCEQ 13226 (1977-81) + TCEQ 13225 (1986-2007)

Figure 12. Location of surface water quality monitoring sites in the Rio Grande study area.

Macroinvertebrate data were available from all sites shown on Figure 12. The earliest publication of macroinvertebrate data from the Rio Grande appears to be Davis (1980a), who collected at sites A, B, D, H, and I during 1976 – 77. Similar historical macroinvertebrate data were collected from the Pecos River (Davis 1980b) and Lower Devil's River (Davis 1980c) around the same time period. Those rivers are tributaries that enter the Rio Grande upstream from Amistad Reservoir. With the exception of several macroinvertebrate-sample results in the TCEQ data base (from unknown sources or protocols), the most recent (since the mid-1990s) macroinvertebrate data has been collected by TCEQ (IWBC 2004; Bill Harrison, TCEQ, written communication), USGS (Moring 2002), and as graduate research studies (e.g. Ordonez 2005; Fordham 2008). Recent (2007-08) data available from TCEQ consisted primarily of metric scores; full data sets were not available for analysis or comparison with other published results. Because of uncertainty with differences in collection protocols and taxonomic resolution among studies, two common USEPA/TCEQ metrics were calculated for all samples: (1) **taxa richness**, the number of "species" in a sample identified at multiple taxonomic levels ranging from order to family, and/or genus (sometimes species), depending on the study, and (2) **E+T richness**, the number of mayfly (Ephemeroptera) and caddisfly (Trichoptera) taxa (generally identified to family and/or genus) in a sample. No stonefly (Plecoptera) taxa have been reported from the study area, so the common EPT richness metric (e.g. Barbour et al. 1999) was simplified to E+T. Taxa richness provides an estimate of the diversity of species present in benthic-community samples, whereas E+T richness provides an estimate of the number of "sensitive" (relatively intolerant to pollution) species in the sample. Both metrics tend to increase with improvements in water-quality and/or stream-habitat conditions, however, water-quality assessments made solely on the basis of these two metrics (or even multi-metric indices of "biotic integrity") should be viewed with caution. Metrics are not a substitute for understanding. Full data sets for all Rio Grande macroinvertebrate samples would have enhanced analyses of stream condition and potential trends in macroinvertebrate-community structure over time.

Primary Surface-Water Constituents

Water Temperature

Median water temperature in the Rio Grande ranged from 18.3 ^{O}C at site I (below Amistad Reservoir) to 23.3 ^{O}C at site G (Table 8; Appendix C), downstream from hot-spring discharges into the river (Fig. 3). Median temperature was highest in the middle portion of the Wild and Scenic River segment, downstream from Santa Elena Canyon (site D) at sites G—H, during both the high-flow (Fig. 13, shaded boxplots) and low-flow (unshaded boxplots) seasons. Median temperature was significantly lower at site I than other sites during the hot season, most likely a result of discharge from Amistad Reservoir upstream from this site. Relatively little change in water temperature has been recorded over the past 35 years (Fig. 14). Higher water temperature in the middle Wild and Scenic River segment of the Rio Grande appears to have been a constant condition over the period of record, as indicated by the LOWESS trend lines for sites G and H (Fig. 14).

Table 8. Distribution of primary surface-water constituents: water temperature, dissolved oxygen, pH, and specific conductance.

MIN, minimum; 10%, 10th percentile; 25%, 25th percentile; 50%, 50th percentile (= median); 75%, 75th percentile; 90%, 90th percentile; MAX, maximum, n, number of data records; °C, degrees Celsius; mg/L, milligrams per Liter; μS/cm, microsiemens per centimeter.

SITE	MIN	10%	25%	50%	75%	90%	MAX	n	Period of Record
Water Temperature (^{o}C)									
A	0.8	8.7	12.5	19.3	25.0	27.0	33.0	311	11/1977 - 9/2007
B	5.0	10.5	14.2	20.3	25.7	27.8	35.0	417	5/1969 - 9/2007
D	2.2	10.8	14.7	22.2	26.6	28.5	33.0	244	9/1968 - 9/2007
F	11.2	---	17.3	22.8	26.0	---	33.1	55	11/1999 - 8/2007
G	9.2	12.4	17.0	23.3	28.0	29.5	34.0	108	10/1977 - 9/2007
H	9.5	13.2	17.0	22.5	27.0	28.0	31.0	248	9/1968 - 6/2007
I	0.0	11.5	14.0	18.3	21.0	24.0	32.0	269	1/1972 - 8/2004
Dissolved Oxygen (mg/L)									
A	1.5	5.3	6.2	7.4	8.9	10.1	19.2	306	11/1977 - 9/2007
B	3.9	6.0	6.7	7.8	9.0	10.0	17.2	410	5/1969 - 9/2007
D	3.3	6.1	7.0	8.0	9.7	11.0	16.5	247	9/1968 - 9/2007
F	2.4	---	6.4	7.5	8.9	---	12.5	54	11/1999 - 8/2007
G	0.2	6.2	6.7	7.7	9.2	10.2	13.6	107	10/1977 - 9/2007
H	2.5	6.1	7.0	8.5	9.6	10.6	13.0	243	9/1968 - 6/2007
I	1.3	---	5.5	7.8	9.6	---	12.5	79	1/1972 - 8/2004
pH (standard units)									
A	5.2	6.9	7.3	7.8	8.1	8.4	10.8	305	11/1977 - 9/2007
B	5.4	7.2	7.6	7.9	8.2	8.3	11.0	382	2/1972 - 9/2007
D	6.9	7.6	7.9	8.0	8.2	8.4	9.3	245	9/1968 - 9/2007
F	7.4	---	7.7	7.8	8.0	---	8.9	55	11/1999 - 8/2007
G	6.6	7.2	7.7	8.1	8.2	8.3	8.7	108	10/1977 - 9/2007
H	7.1	7.6	7.9	8.1	8.2	8.4	9.0	244	9/1968 - 6/2007
I	7.1	7.6	7.8	7.9	8.0	8.2	9.5	267	2/1972 - 8/2004
Specific Conductance (μS/cm)									
A	300	1,400	1,883	2,830	3,480	3,900	6,450	306	11/1977 - 9/2007
B	163	1,000	1,300	1,705	2,640	3,261	4,420	358	2/1972 - 9/2007
D	210	809	1,150	1,618	2,620	3,360	4,050	246	9/1968 - 9/2007
F	663	---	1,660	2,211	2,685	---	2,900	56	11/1999 - 8/2007
G	587	1,154	1,300	1,640	1,949	2,470	2,870	107	10/1977 - 9/2007
H	2	266	427	773	1,560	3,435	15,700	186	9/1968 - 6/2007
I	645	972	1,040	1,150	1,255	1,360	1,500	260	1/1972 - 8/2004

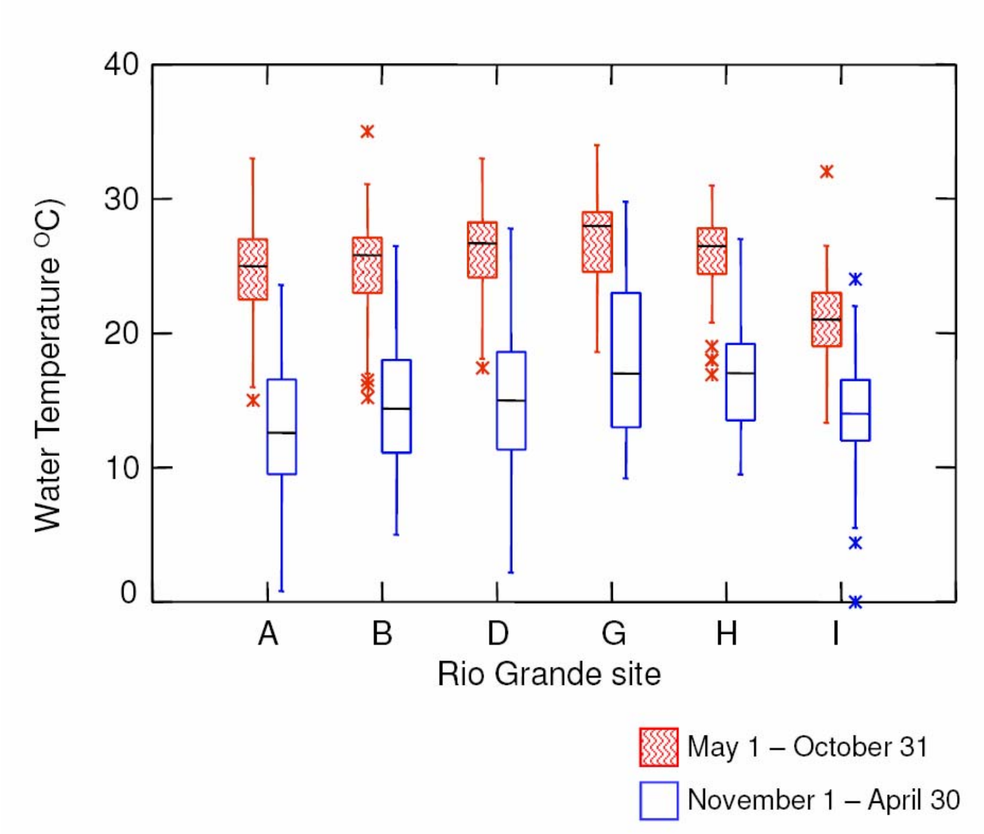


Figure 13. Median water temperature in the Rio Grande during the high-flow (May - October) and low-flow (November - April) seasons.

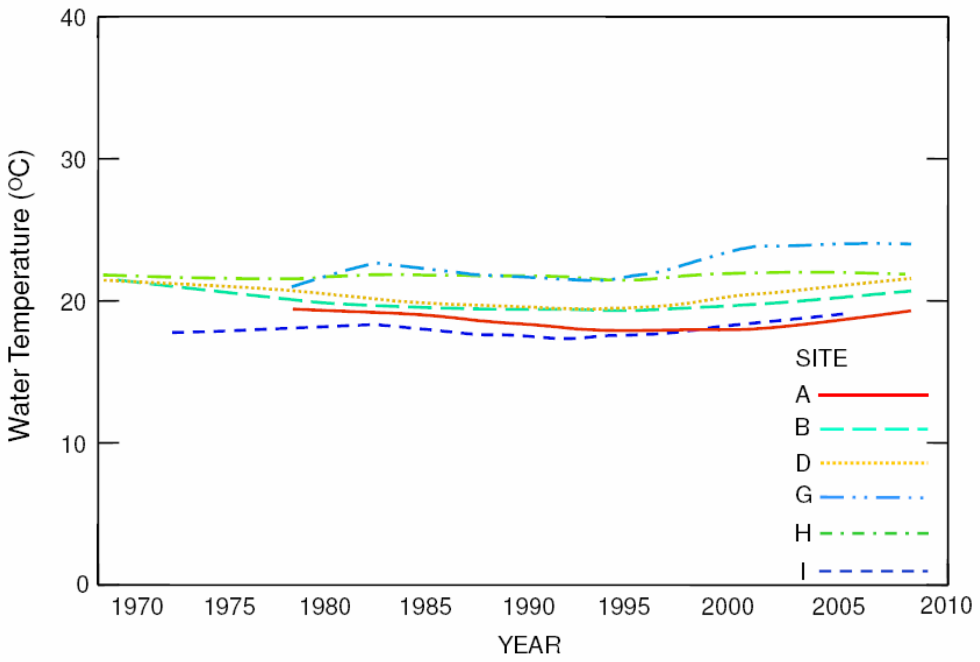


Figure 14. LOWESS trend lines for water temperature in the Rio Grande.

Dissolved Oxygen

Dissolved-oxygen (DO) concentrations were relatively similar among sites, with median concentrations varying from 7.4 mg/L at site A (Rio Grande above the Rio Conchos confluence) to 8.5 at site H (Foster Ranch)(Table 8; Appendix C). As would be expected from physical properties of water (i.e. temperature and DO relations), median DO was significantly higher during the low-flow season (Fig. 15, unshaded boxplots), when the median temperature range was 12—18 ^{O}C, than during the high-flow season (shaded boxplots), when median temperature generally exceeded 25^{O}C (Fig. 13). Relatively lower DO was found in the Rio Grande below Amistad Reservoir, particularly during the high-flow season (Fig. 15, site I). Examining 30-year water-quality trends (Fig. 16), DO at site I decreased considerably from 1972 through the early 2000s; since that time, DO concentrations appear to be improving. Dissolved-oxygen dynamics at site I were likely influenced by the construction of Amistad Reservoir dam and subsequent discharge from the reservoir. Improvements in overall DO concentrations below the dam may be related to improved management of reservoir discharges.

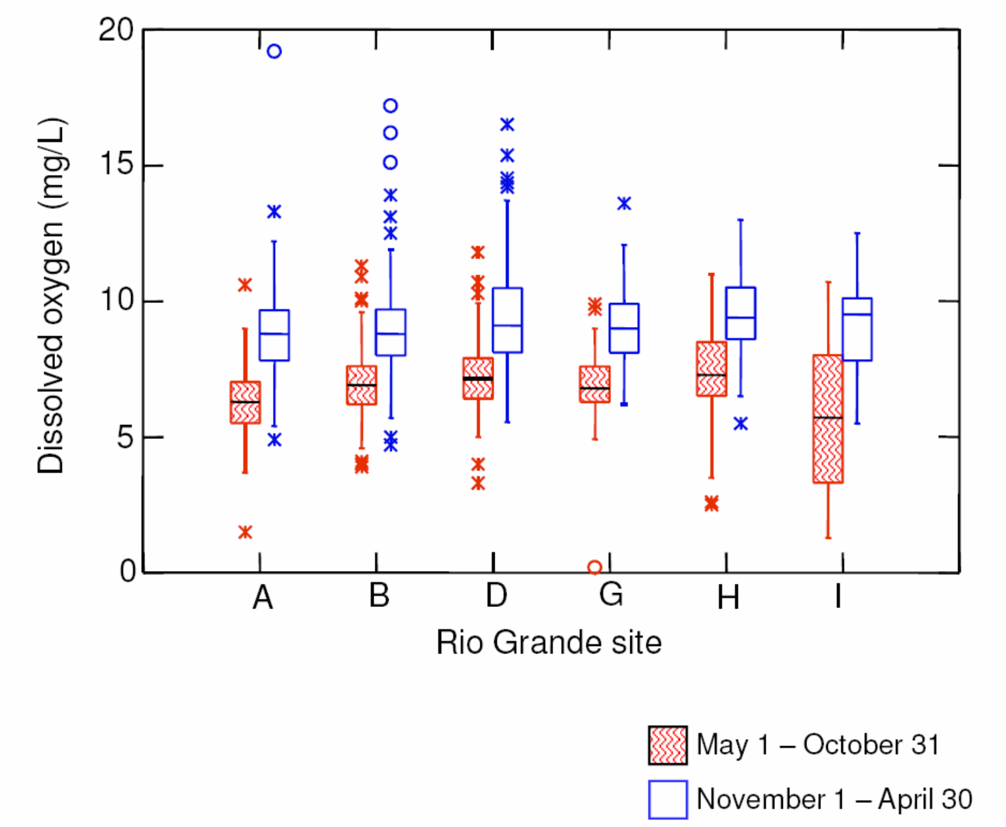


Figure 15. Median dissolved-oxygen concentrations in the Rio Grande during the high-flow (May - October) and low-flow (November - April) seasons.

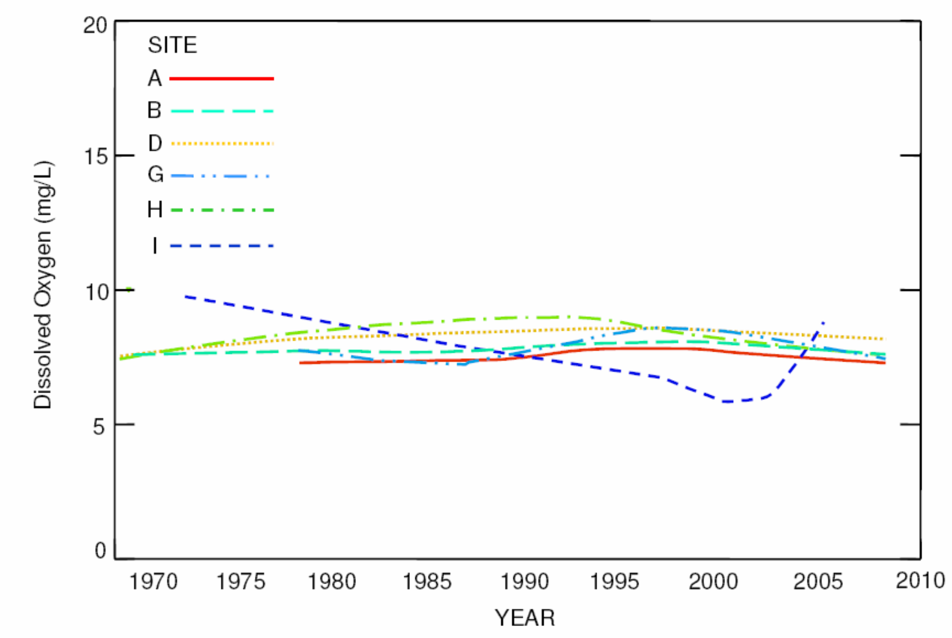


Figure 16. LOWESS trend lines for dissolved oxygen in the Rio Grande.

pH

Median pH values ranged from 7.8 to 8.1 (Table 8; Appendix C) and were similar among sites (Fig. 17). Median pH was slightly higher during the low-flow season than the high-flow season; however, these differences were not significant, statistically. Several pH values in the data base, typically maxima or minima for various sites (Table 8), did not meet water-quality criteria of 6.0 < pH < 9.0, particularly at sites A and B (Fig. 17). Although NPS (1995a) reported that pH values at two sites near site H generally had increased since the early 1980s, no water-quality trends for pH were observed at any site during the previous 30-to-39 year period of record.

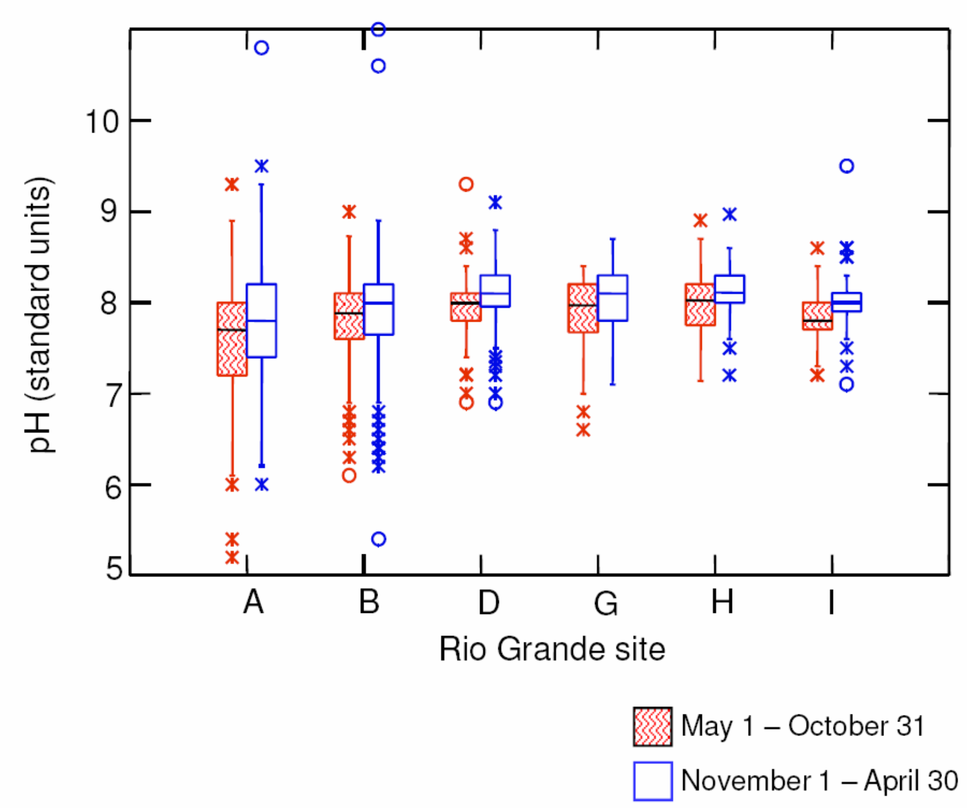


Figure 17. Median pH values in the Rio Grande during the high-flow (May - October) and low-flow (November - April) seasons.

Fecal Indicator Bacteria

Median values for fecal coliform (FC) and *Escherichia coli* (*E. coli*) bacteria generally were similar (same order of magnitude) among sites (Table 9; Appendix C). Values were highest at site B, downstream from the small towns of Presidio, Texas and Ojinaga, Mexico, as well as the Rio Conchos confluence with the Rio Grande. With the exception of sites A and B, median FC values were significantly higher during the high-flow season than the low-flow season (Fig. 18). A similar seasonal pattern was noted for the abundance of *E. coli* bacteria at site H, upstream from Amistad Reservoir. Fecal-indicator bacteria trends in the Rio Grande are complex (figs. 19 and 20). FC bacteria values decreased (or were relatively constant) during the 1980s through early 1990s. FC bacteria values at sites A—D have been increasing since the early 1990s, whereas those at sites G and H have remained relatively constant. Values for *E. coli* bacteria, available since 2001, show increases at sites D, G, and H, but relatively little change at sites A and B (Fig. 20). Some of the variability in fecal-indicator bacteria values may be associated with river flow. Considering the entire Rio Grande data set, *E. coli* values increased significantly with discharge (Spearman $\rho = 0.348$; $p<0.001$; $n = 192$).

Table 9. Distribution of primary surface-water constituents: fecal coliform and *E. coli* bacteria.

MIN, minimum; 10%, 10th percentile; 25%, 25th percentile; 50%, 50th percentile (median), 75%, 75th percentile; 90%, 90th percentile; MAX, maximum, n, number of data records; % exceedance, percentage of samples exceeding 200 colonies per 100 mL (fecal coliform) or 126 colonies per 100 mL *(E. coli).*

SITE	MIN	10%	25%	50%	75%	90%	MAX	n	% Exceedance	Period of Record
Fecal coliform bacteria (colonies per 100 mL)										
A	<1	1	20	67	193	485	25,000	251	22.3	1/1978 - 8/2007
B	<1	4	40	137	440	1,588	32,500	268	**41.0**	11/1974 - 8/2007
D	<1	---	13	25	148	---	8,000	89	20.2	12/1974 - 4/2007
F	<1	---	17	26	61	---	722	50	10.0	11/1999 - 8/2007
G	<2	---	8	43	195	---	65,000	83	22.9	10/1977 - 4/2007
H	<4	---	8	29	126	---	18,000	40	10.0	10/1974 - 3/2004
***Escherichia coli* bacteria (colonies per 100 mL)**										
A	7	---	20	33	101	---	2,400	58	20.7	4/2001 - 9/2007
B	5	---	32	120	726	---	2,419	58	**44.8**	4/2001 - 9/2007
D	<1	---	12	42	79	---	2,419	53	20.8	4/2001 - 9/2007
G	<1	---	4	13	23	---	2,420	16	18.8	4/2001 - 4/2007
H	<4	---	13	40	93	---	580	7	14.3	3/2002 - 6/2007

Currently (2008), the Rio Grande from the confluence of Rio Conchos to Alamito Creek (Area 2306_01) is on TCEQ's 303 (d) Impaired Waters List for exceeding numerical criteria for fecal-indicator bacteria. It is difficult to evaluate potential human health concerns (regarding contact recreation) of fecal-indicator bacteria in this investigation because USEPA and TCEQ water-quality criteria are based on a geometric mean of a minimum number of samples (e.g. six) collected within a specific time period (e.g. month). However, if a 200 colonies per 100 mL guideline (cf. IBWC, 2004) is used to interpret FC results (126 colonies per 100 mL for *E. coli*), over 28 percent of FC samples (and 27 percent of *E. coli* samples) exceeded the guidelines (Table 9). The frequency of exceedance was largest at site B, where nearly 45 percent of *E. coli* results exceeded 126 colonies per 100 mL, and lowest at site H (Foster Ranch) where *E. coli* results exceeded the guideline in about 14 percent of samples. Percentages of exceedance for *E. coli* bacteria generally were similar to those for FC (Table 9).

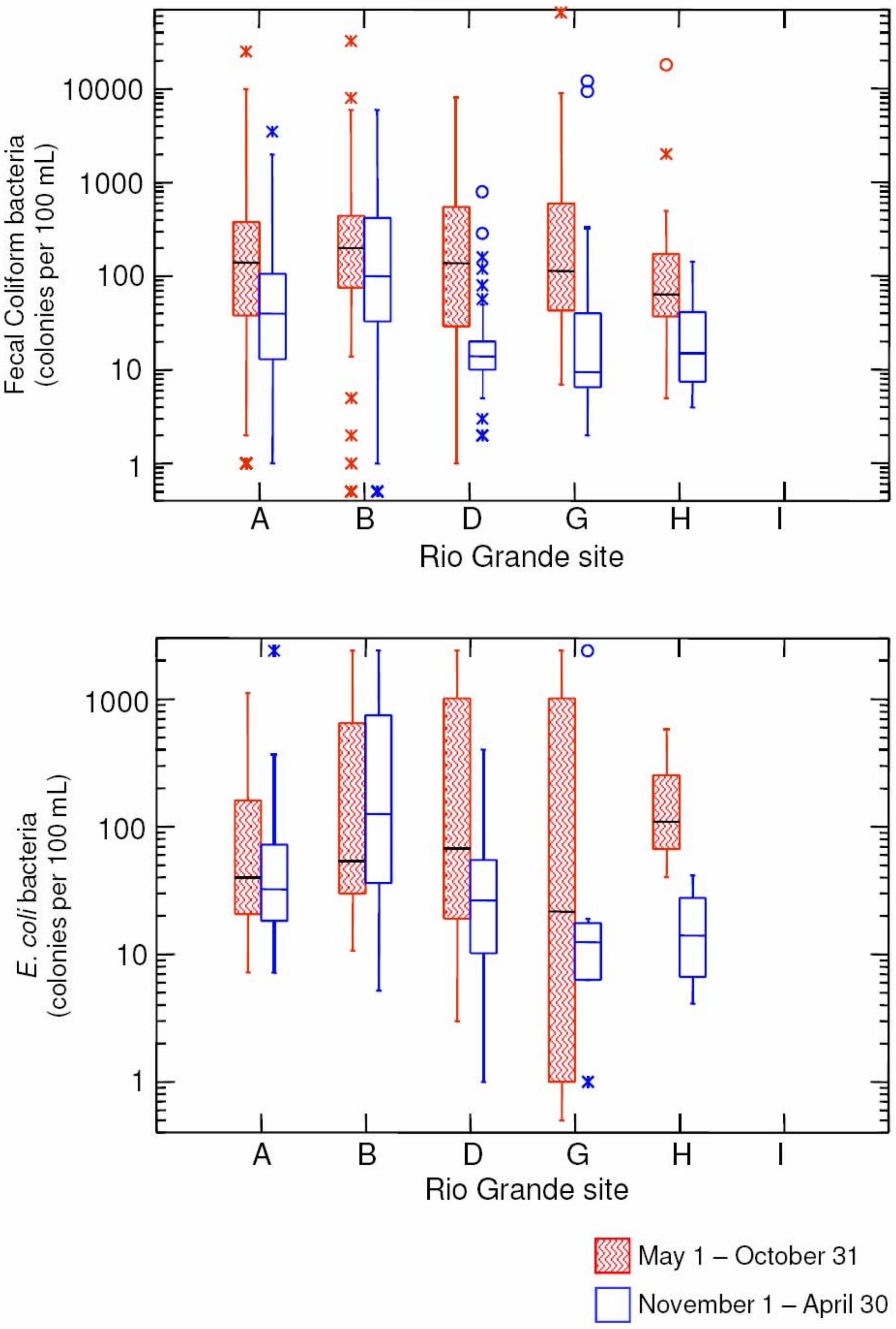


Figure 18. Median fecal coliform and *E. coli* bacteria levels in the Rio Grande during the high-flow (May - October) and low-flow (November - April) seasons.

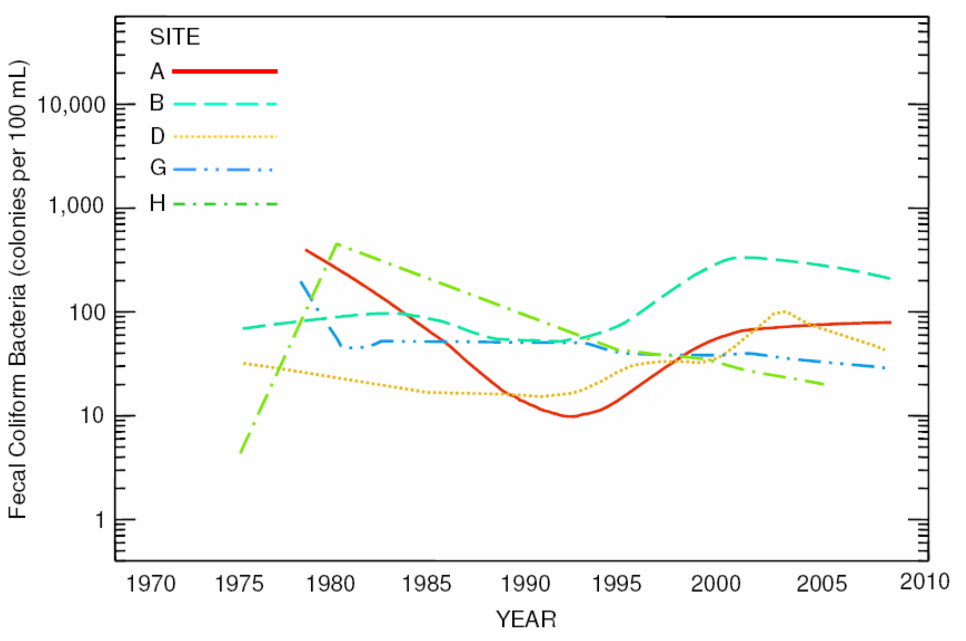


Figure 19. LOWESS trend lines for fecal-coliform bacteria in the Rio Grande.

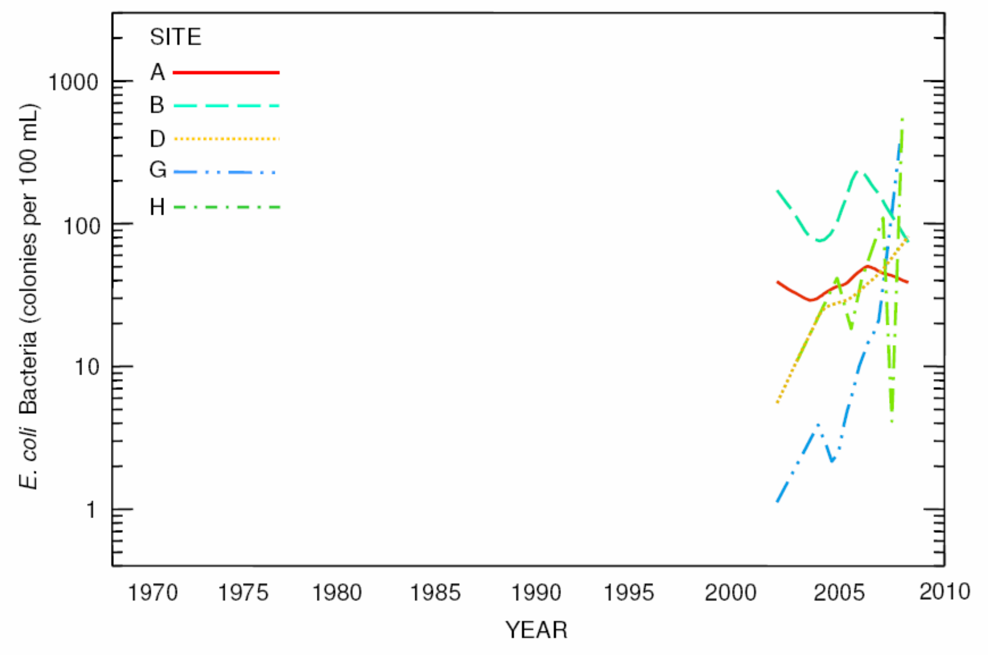


Figure 20. LOWESS trend lines for *E. coli* bacteria in the Rio Grande.

Specific Conductance

Specific conductance (SpC), an indicator of dissolved ions or salinity, varied considerably among sites and over time (figs. 21 and 22). With the exception of site I (below Amistad dam), median SpC values were larger during the low flow season than the high-flow season (Fig. 21). Median SpC was highest (2,830 μS/cm) at site A (above the Rio Conchos confluence) and decreased with distance downstream to site H where median SpC was 773 μS/cm (Table 8; Appendix C). The median SpC value at site B (below the Rio Conchos confluence) was appreciably lower than at site A, suggesting that dilution of the Rio Grande from the Rio Conchos discharge was an important water-quality process, at least prior to the mid-1990s (figs. 21 and 22). Since then, an upward trend in SpC values at site B has recently (2007) resulted in values similar to site A. A similar increase of SpC values was observed at site D (Fig. 20; Santa Elena Canyon), however, SpC has remained relatively constant over time at the downstream sites G—I.

Although specific conductance can be influenced by natural differences in fluvial geochemistry among drainage basins, increases in SpC values over the past 30 to 40 years at sites A - D most likely are attributable to increases in irrigated agriculture along the Rio Grande corridor and Rio Conchos basin. Increases in salinity and nutrient concentrations from agricultural return flows to these rivers have adversely affected water-quality and aquatic-life conditions. IBWC (2004) reported chronic toxicity of ambient water quality at sites B and D, attributing the toxicity to elevated chloride and total dissolved solids concentrations from irrigation practices, oil and gas wells, wastewater discharges, and natural occurrences of salts in soils. Currently (2008), Rio Grande Segment 2307, including (and upstream from) site A, is on TCEQ's 303 (d) Impaired Waters List for exceeding numerical criteria for chloride and total-dissolved solids concentrations. Reductions in SpC values downstream from site D, and perhaps the lack of upward temporal SpC trends at sites G—I, most likely are associated with dilution from high-quality ground-water discharges to the Rio Grande (e.g. from the Edwards-Trinity aquifer; Fig. 3). Although specific conductance is a useful, relatively inexpensive, indicator of salinity, improved understanding usually can be gained by examination of common inorganic constituents: major ions, nutrients, and metals.

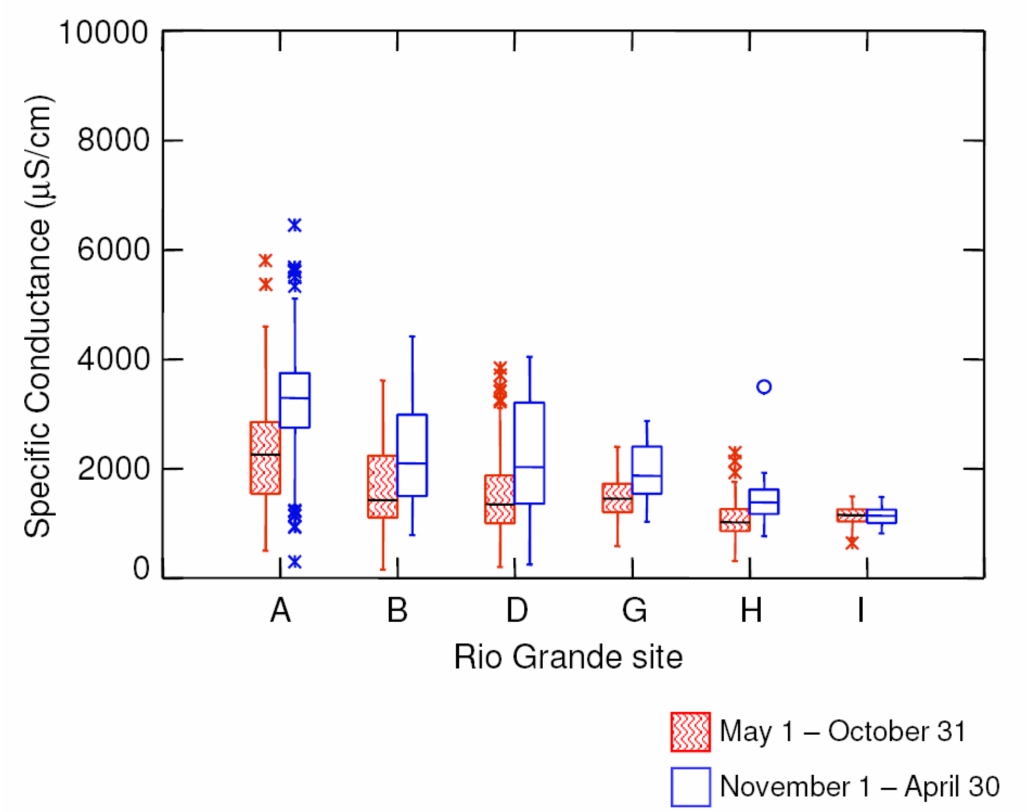


Figure 21. Median specific conductance values in the Rio Grande during the high-flow (May - October) and low-flow (November - April) seasons.

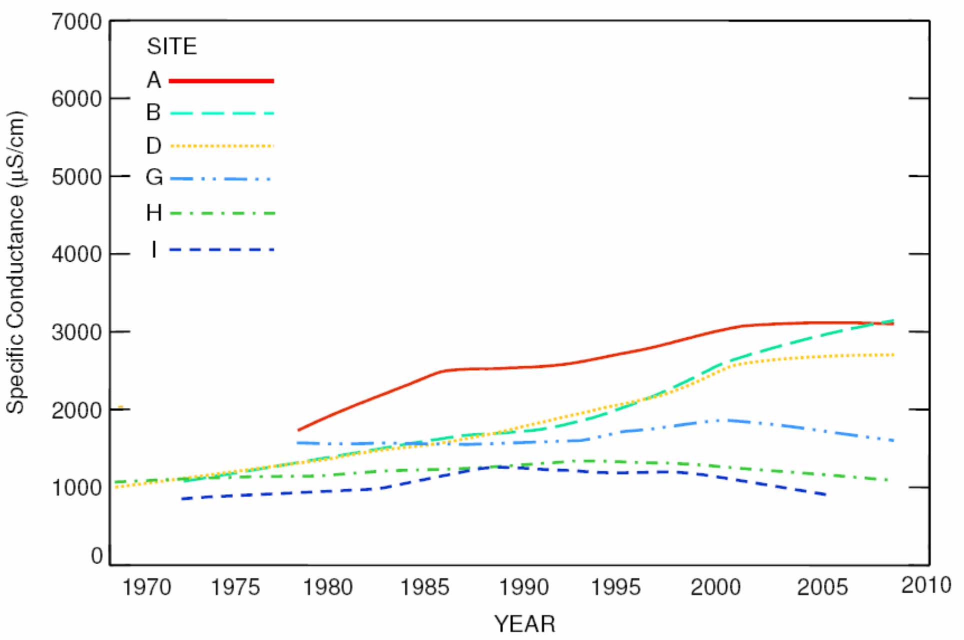


Figure 22. LOWESS trend lines for specific conductance in the Rio Grande.

Common Inorganic Constituents

Major Ions

Major-ion results for concentrations of chloride, sulfate, and total-dissolved solids (TDS) are available for extended periods of record (30 to 40 years). No water-quality criteria are applicable for sulfate or TDS concentrations (IBWC 2004); however, TCEQ-segment specific criteria are available for chloride concentrations based on presumed acute or chronic toxicity to aquatic life. The acute aquatic-life value is 860 mg/L whereas the chronic value is 230 mg/L (IWBC 2004). Based on those criteria, about 35 percent of all sample results exceeded the chronic value while only 2.3 percent of samples exceeded the acute criterion. The percentage of acute and chronic exceedances of chloride criteria was largest at site A (11.5 percent and 76.9 percent of samples, respectively; Table 8). No exceedances of acute aquatic-life values were observed downstream from site B, and the percentage of chronic aquatic-life exceedances decreased from 43.5 percent at site B to 7.6 percent at site H. No exceedances of aquatic-life criteria were observed at site I, downstream from Amistad Reservoir (Table 10).

Median chloride concentrations decreased in a downstream direction, from 523 mg/L at site A to 89 mg/L at site H (Table 10; Appendix C). Similar to specific conductance values, median chloride concentrations generally were larger during the low-flow season than the high-flow season (Fig. 23). Relatively higher median chloride concentrations in the Rio Grande below Amistad Reservoir (Fig. 23; site I), in comparison with the previous site H (Foster Ranch), probably is associated with discharges from the Pecos River and subsequent limnological processes in Amistad Reservoir (e.g. Fang et al. 2007; Groeger et al. 2008). Chloride concentrations increased at all sites from the late 1960s through the early 1990s (Fig. 24). Since the mid 1990s, chloride concentrations have continued to increase in upper portions of the study area (e.g. sites B and D); however, concentrations have been relatively constant to declining at sites G—I (Fig. 24). Chloride concentrations at sites B and D (downstream from the Rio Conchos confluence) have continued to increase since the early 1990s, whereas median chloride concentrations have remained relatively unchanged at site A (upstream from the Rio Conchos confluence) over the past 20 years. Increases in chloride concentrations at sites B and D, relative to site A, suggest increasing chloride trends in the Rio Conchos, perhaps associated with increases in agricultural activities (or other potential sources of chloride) in the Rio Conchos basin. A similar pattern was observed for sulfate concentrations.

Median sulfate concentrations decreased in a downstream direction, from 552 mg/L at site A to 230 mg/L at site I (Table 10; Appendix C). With the exception of site I, median sulfate concentrations during the low-flow season were relatively larger than those during the high-flow season (Fig. 25). Sulfate concentrations at site A did not vary over time (Fig. 26); however, concentrations at sites B—G have increased since the early 1990s, whereas concentrations at sites H and I decreased over the same time period. Since the late 1990s, sulfate concentrations at sites B and D have remained larger than those upstream of the Rio Conchos confluence (Fig. 26), suggesting that the Rio Conchos basin may be a primary source of sulfate in the Rio Grande, presently.

Table 10. Distribution of major ions in the Rio Grande.

MIN, minimum; 10%, 10th percentile; 25%, 25th percentile; 50%, 50th percentile (median), 75%, 75th percentile; 90%, 90th percentile; MAX, maximum; n, number of data records; % exceedance, percentage of samples exceeding chronic USEPA chloride criterion for protection of aquatic life (230 mg/L).

SITE	MIN	10%	25%	50%	75%	90%	MAX	n	% Exceedance	Period of Record
				Chloride (mg/L)						
A	20	109	243	523	707	888	1,600	276	76.9	11/1977 - 8/2007
B	25	63	103	189	362	566	880	361	43.5	5/1969 - 8/2007
D	7	50	88	181	412	530	680	203	41.4	9/1968 - 8/2007
F	0	---	97	219	395	---	620	48	48.0	5/2000 - 8/2007
G	16	48	73	120	207	350	515	106	19.8	10/1977 - 12/2006
H	3	33	51	89	165	213	322	221	7.6	9/1968 - 12/2006
I	61	110	120	140	160	180	220	260	0.0	1/1972 - 8/2004
				Sulfate (mg/L)						
A	84	284	396	552	703	841	1,985	273		11/1977 - 8/2007
B	79	276	363	460	623	846	1,322	356		12/1969 - 8/2007
D	45	275	360	491	629	808	1,100	197		9/1968 - 8/2007
G	60	251	334	412	497	574	705	106		10/1977 - 12/2006
H	31	170	239	297	340	380	521	215		9/1968 - 12/2006
I	94	178	210	230	260	275	310	260		1/1972 - 8/2004
				Total Dissolved Solids (mg/L)						
A	10	886	1,200	1,942	2,360	2,875	24,300	210		11/1977 - 8/2007
B	11	826	1,023	1,509	2,048	2,352	3,370	239		9/1977 - 8/2007
D	---	---	---	---	---	---	---	---		---
G	17	690	885	1,120	1,488	1,700	9,400	71		11/1977 - 12/2006
H	318	512	646	824	1,000	1,124	1,470	161		8/1977 - 12/2006

Long-term total dissolved-solids data were available for 4 sites (Table 10) with median concentrations varying from a high of 1,942 mg/L at site A, downstream to a low of 824 mg/L at site H. Seasonal and temporal patterns for TDS concentrations were very similar to those for specific conductance (figs. 21 and 22) and chloride (figs. 23 and 24). NPS (1995a) reported that surface waters in the BIBE area study area were moderately high in dissolved solids, including sodium, sulfate, and chloride. Smith and Alexander (1985) reported no significant trends for TDS concentrations in the Rio Grande at or near sites H and I.

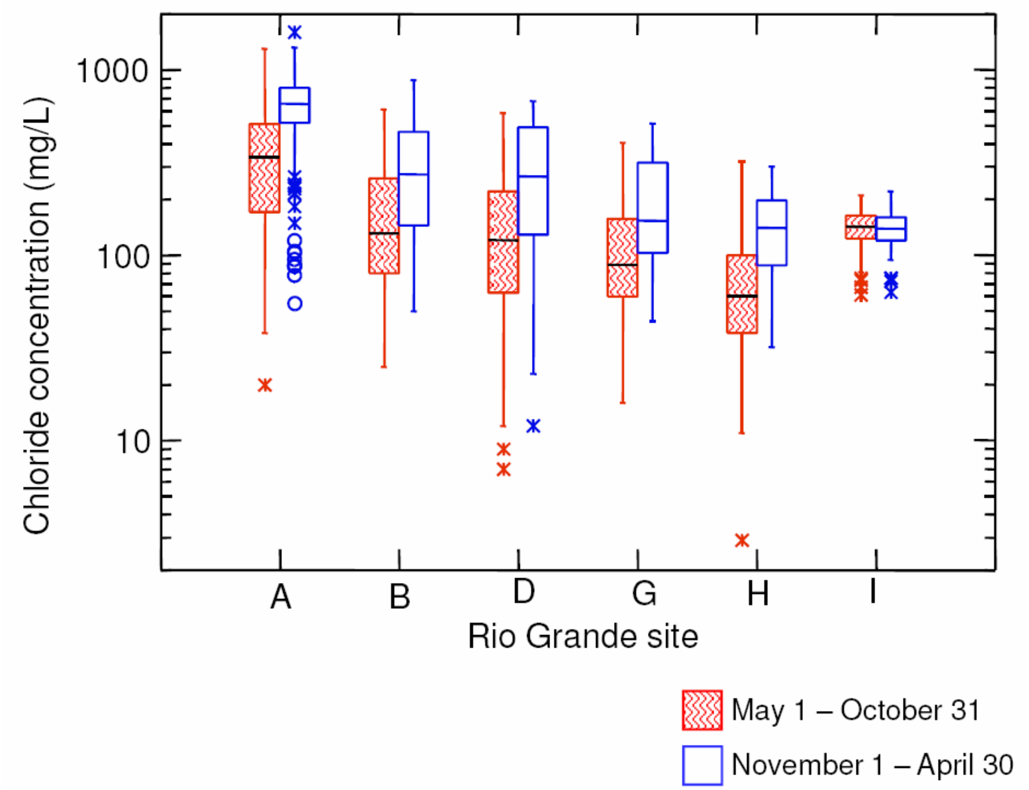


Figure 23. Median chloride concentrations in the Rio Grande during the high-flow (May - October) and low-flow (November - April) seasons.

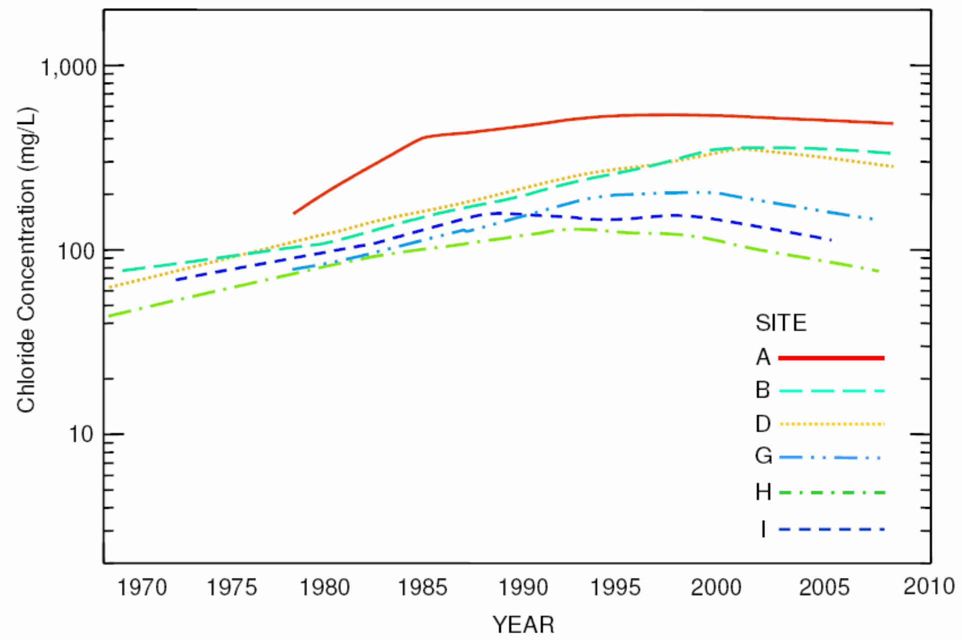


Figure 24. LOWESS trend lines for chloride concentrations in the Rio Grande.

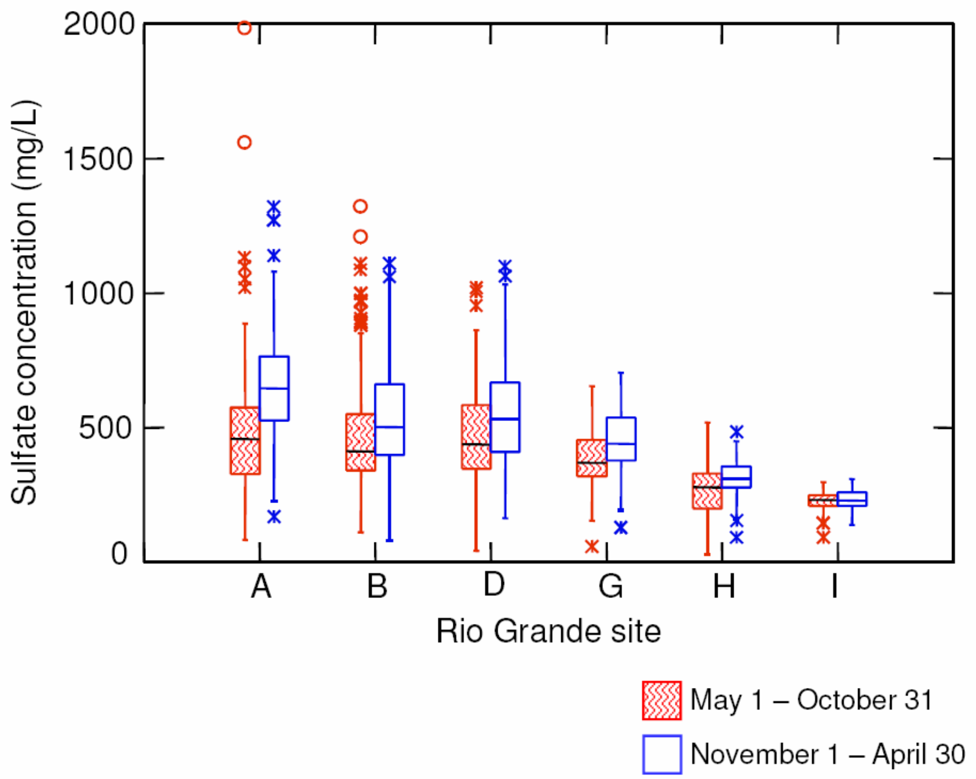


Figure 25. Median sulfate concentrations in the Rio Grande during the high-flow (May - October) and low-flow (November - April) seasons.

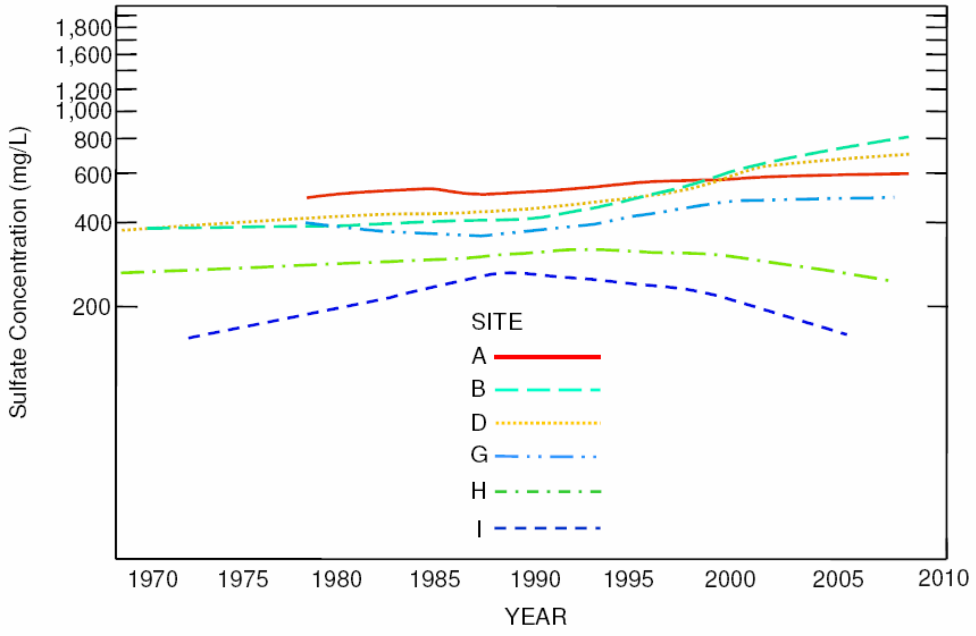


Figure 26. LOWESS trend lines for sulfate concentrations in the Rio Grande.

Nutrients and Other Indicators of Eutrophication

Nutrients are forms of nitrogen and phosphorus that can stimulate the growth of algae and other aquatic plants, contributing to a process known as eutrophication. Algae are primary producers in aquatic systems, providing food resources for many aquatic macroinvertebrates (e.g. mayflies, midges, snails, etc.) and certain fish (e.g. stonerollers). Decomposition of excessive algal growths can result in adverse water-quality effects, including low dissolved-oxygen concentrations that may result in fish kills. Although algal-community data have not been reported for the Rio Grande, samples for phytoplankton chlorophyll *a* (CHLa), a photosynthetic pigment present in all algae, have been collected since the 1970s. The CHLa concentration is proportional to the biomass of the algal population that was sampled (Porter 2000). Algal biomass and (or) growth potential can be restricted or "limited" by low nutrient concentrations and (or) light availability (e.g. Stevenson et al. 1996).

Water-quality criteria presently (2008) are not available for nutrients or CHLa in Texas streams and rivers; however, screening levels adopted by IBWC and TCEQ have been used to interpret historic nutrient and CHLa data from the Rio Grande (e.g. IBWC 2004; refer to Table 12). In addition, USEPA technical guidance for establishing nutrient criteria for rivers and streams (USEPA 2000) recommended a screening level equivalent to the value observed at the 75th percentile of large monitoring data sets. Although TCEQ has not formally established nutrient criteria for the Rio Grande, the USEPA 75th percentile approach commonly is used to provide a context for establishing nutrient criteria for streams and rivers within individual states (USEPA 2000). Both approaches were used in this investigation. For each approach, sites with more than 25 percent of values exceeding one or more of the screening levels were designated "concern" and those with less than 25 percent exceedances were designated "no concern" (cf. IBWC 2004).

Median ammonia-nitrogen concentrations (NH4) were relatively low, varying from 0.01 mg/L at site F (Fig. 12, Rio Grande above Boquillas Canyon/Rio Grande Village) to about 0.02 mg/L downstream at sites G and H (Table 11; Appendix C). Exceedances of the IBWC 0.16 mg/L screening level ranged from about 9 - 15 percent at sites upstream of site F, decreasing to 3.4 – 3.8 percent at sites H and G, respectively (Table 12). Using the USEPA approach, the 75th percentile value for NH4 is 0.6 mg/L (n=953). Using this screening level, sites F (33 percent exceedance), A (31 percent exceedance) and D (30 percent exceedance) should be considered of concern (at risk) for accelerated rates of eutrophication (Table 12). No temporal trends were noted for NH4 data.

Median nitrite+nitrate-nitrogen concentrations (NO23) were lowest (0.06 mg/L) at site F (Fig. 12, Rio Grande above Boquillas Canyon/Rio Grande Village) and varied from 0.19 – 0.78 mg/L at other sites in the study area (Table 11). Median NO23 concentrations were similar between seasons, and did not change appreciably from site B downstream to site H (Fig. 27). Exceedances of the IWBC 3.5 mg/L screening level were low; 2.6 percent at site A, 1.4 percent at site B, and zero to less than 0.5 percent exceedances at sites downstream from site B (Table 12). The 3.5 mg/L level of concern identified by IBWC (2004) may be too high to avoid adverse effects of eutrophication. Using the USEPA approach, the 75th percentile value for NO23 is 0.9 mg/L (n = 622). With this screening level, sites B (40 percent exceedance) and G (28 percent exceedance) should be considered of concern for accelerated rates of eutrophication (Table 12).

Table 11. Distribution of nutrient concentrations in the Rio Grande.

MIN, minimum; 10%, 10th percentile; 25%, 25th percentile; 50%, 50th percentile (median), 75%, 75th percentile; 90%, 90th percentile; MAX, maximum; <, less than; n, number of data records.

SITE	MIN	10%	25%	50%	75%	90%	MAX	n	Period of Record
Ammonia nitrogen (mg/L)									
A	<0.005	<0.010	<0.010	0.040	0.090	0.200	3.790	273	11/1977 - 9/2007
B	<0.005	<0.010	<0.010	0.030	0.060	0.140	1.340	296	6/1972 - 8/2007
D	<0.010	0.020	0.020	0.050	0.100	0.182	4.140	161	6/1972 - 8/2007
F	<0.002	---	<0.010	0.010	0.100	---	0.940	45	5/2000 - 8/2007
G	<0.005	<0.010	0.020	0.025	0.050	0.079	0.410	106	10/1977 - 12/2006
H	<0.002	<0.006	<0.010	0.020	0.030	0.060	0.410	117	10/1981 - 7/2004
Nitrite + Nitrate nitrogen (mg/L)									
A	<0.005	<0.010	0.030	0.190	0.560	1.078	35.60	194	11/1977 - 8/2007
B	<0.005	0.100	0.438	0.780	1.070	1.372	28.00	219	6/1972 - 8/2007
D	<0.010	0.020	0.139	0.520	0.780	1.100	2.100	123	6/1972 - 8/2007
F	<0.005	---	0.020	0.060	0.292	---	9.300	41	5/2000 - 8/2007
G	<0.005	---	0.400	0.655	0.935	---	1.330	68	10/1977 - 9/2005
H	0.065	---	0.360	0.630	0.720	---	1.300	18	11/1990 - 3/1998
Total Kjeldahl nitrogen (mg/L)									
A	0.420	---	1.167	1.400	1.965	---	8.450	57	6/1984 - 7/2007
B	0.380	---	0.861	1.100	1.560	---	11.900	84	6/1984 - 8/2007
D	0.470	---	0.780	1.015	1.280	---	12.800	54	6/1993 - 8/2007
F	<0.100	---	---	1.240	---	---	6.300	7	11/2006 - 8/2007
G	---	---	---	---	---	---	---	---	---
H	0.160	0.291	0.400	0.600	1.060	3.427	23.11	146	10/1981 - 12/2006
I	0.100	---	0.184	0.216	0.237	0.278	---	56	5/1996 - 8/2004
Total phosphorus (mg/L)									
A	0.025	0.120	0.200	0.330	0.535	1.081	18.60	268	11/1977 - 6/2007
B	<0.015	0.050	0.090	0.180	0.348	0.737	10.45	311	6/1972 - 6/2007
D	<0.010	0.050	0.100	0.190	0.360	1.212	15.50	161	6/1972 - 7/2007
F	<0.010	---	0.075	0.140	0.385	---	18.30	48	5/2000 - 7/2007
G	<0.010	0.040	0.087	0.140	0.630	2.500	14.00	105	10/1977 - 12/2006
H	<0.004	0.020	0.050	0.100	0.276	1.609	14.51	181	4/1972 - 12/2006
I	<0.002	---	<0.005	0.009	0.013	---	0.080	66	4/1972 - 8/2004
Dissolved orthophosphate (mg/L)									
A	<0.005	<0.005	<0.010	0.030	0.100	0.246	1.900	194	11/1977 - 12/2006
B	<0.004	<0.005	<0.010	0.020	0.060	0.162	4.800	213	12/1973 - 4/2006
D	<0.007	<0.010	<0.010	0.058	0.100	0.175	4.100	120	12/1973 - 8/2007
F	<0.001	---	0.020	0.040	0.100	---	4.140	22	5/2000 - 8/2004
G	<0.005	<0.005	<0.010	0.030	0.030	0.080	0.410	101	10/1977 - 4/2006
H	<0.001	<0.001	<0.007	<0.010	0.010	0.020	0.070	119	10/1981 - 12/2006

Table 12. Comparison of IBWC and USEPA approaches for determining screening values for nutrients, phytoplankton chlorophyll *a*, and total suspended-sediment concentrations.

NH4, ammonia nitrogen; NO23, nitrite + nitrate nitrogen; TKN, total Kjeldahl nitrogen; DOP, dissolved orthophosphate; TP, total phosphorus; CHLa, chlorophyll *a*; TSS, total suspended sediment; IBWC, International Boundary Waters Commission (2004); USEPA, U.S. Environmental Protection Agency (2000); *, value at 75th percentile of data distribution; n, number of samples used to determine data distribution; mg/L, milligrams per Liter; µg/L, micrograms per Liter.

			Percentage of samples exceeding screening value					
			Rio Grande site					
Constituent (method)	**Screening value**	**n**	**A**	**B**	**D**	**F**	**G**	**H**
NH4 (IBWC)	0.16 mg/L	---	12.5	9.1	10.6	15.5	3.8	3.4
NH4 (USEPA)	0.06 mg/L *	953	**30.8**	23.3	**29.8**	**33.3**	11.3	7.7
NO23 (IBWC)	3.5 mg/L	---	2.6	1.4	0	0.5	0	0
NO23 (USEPA)	0.9 mg/L *	622	13.4	**40.2**	16.3	12.2	**27.9**	11.1
TKN (IBWC)	---	---	---	---	---	---	---	---
TKN (USEPA)	1.31 mg/L *	397	**56.1**	**30.9**	**26.3**	**42.9**	19.9	19.9
DOP (IBWC)	0.90 mg/L	---	1.0	1.4	1.7	0.4	0	0
DOP (USEPA)	0.06 mg/L *	747	**35.0**	22.1	**30.0**	**36.4**	12.9	1.7
TP (IBWC)	1.10 mg/L	---	9.0	7.4	10.6	16.7	15.2	12.2
TP (USEPA)	0.41 mg/L *	1092	**37.3**	21.2	21.7	20.8	**27.6**	20.4
CHLa (IBWC)	30 µg/L	---	**31.2**	15.2	17.2	11.1	9.1	2.2
CHLa (USEPA)	23 µg/L *	745	**45**	23.2	21.8	15.5	11.1	3.6
TSS (IBWC)	---	---	---	---	---	---	---	---
TSS (USEPA)	438 mg/L *	799	22.1	17.1	---	---	**31.8**	**43.1**

Although Smith and Alexander (1985) reported significant upward trends in NO23 concentrations at or near sites H and I, concentrations of NO23 have declined since the late 1980s at most sites (Fig. 28), particularly at site I (below Amistad Reservoir). Concentrations may be increasing slightly over time at site A.

Median total nitrogen concentrations (TKN) were largest at site A (1.4 mg/L) and decreased at sites downstream to site I (0.216 mg/L; Table 11; Appendix C). Median TKN values were similar between seasons (Fig. 29). Using the USEPA 75th percentile approach to determining screening levels, the screening value for this data set is 1.31 mg/L (n = 397). With this screening level, sites A (56 percent exceedance), F (43 percent exceedance), B (31 percent exceedance), and D (26 percent exceedance) should be considered of concern for accelerated rates of eutrophication (Table 12). TKN concentrations generally have remained similar over the period of record (since the mid-1980s). Significant declines in TKN concentrations were observed during 1984-94 at site B, downstream from the Rio Conchos confluence (Fig. 30).

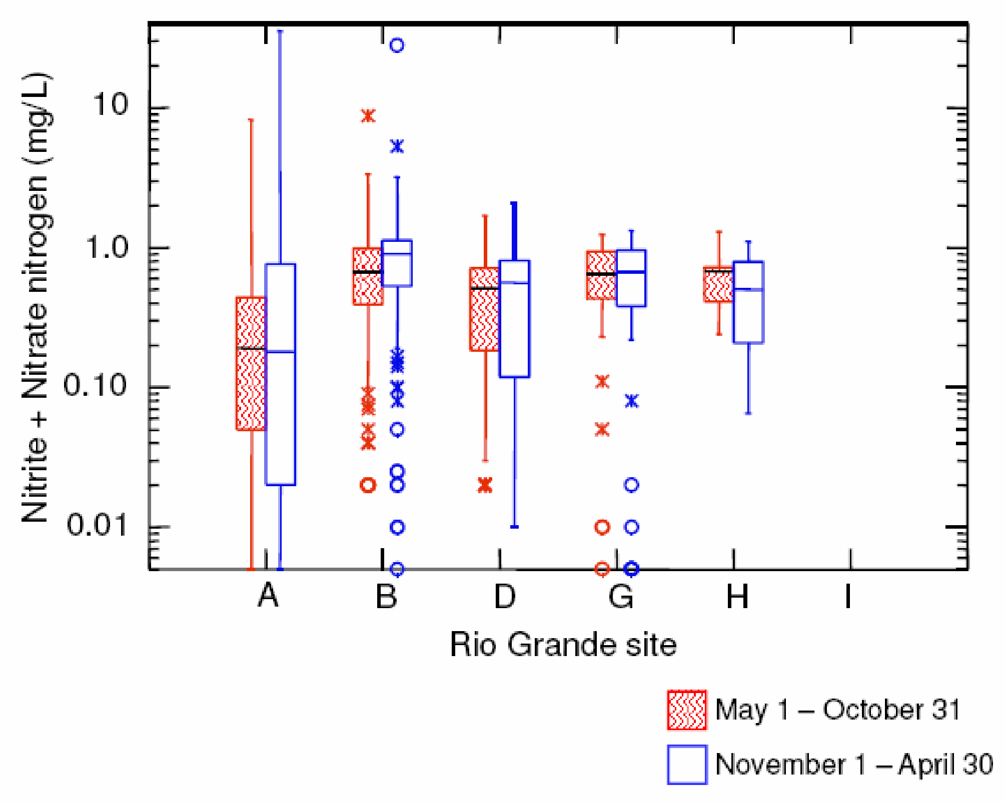


Figure 27. Median nitrite + nitrate nitrogen concentrations in the Rio Grande during the high-flow (May - October) and low-flow (November - April) seasons.

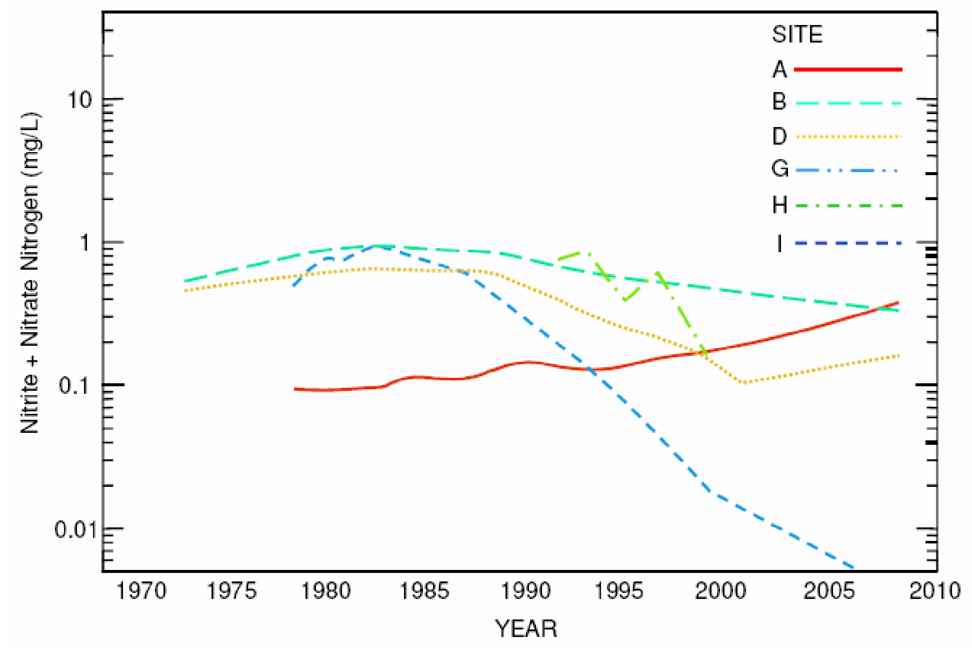


Figure 28. LOWESS trend lines for nitrite + nitrate nitrogen concentrations in the Rio Grande.

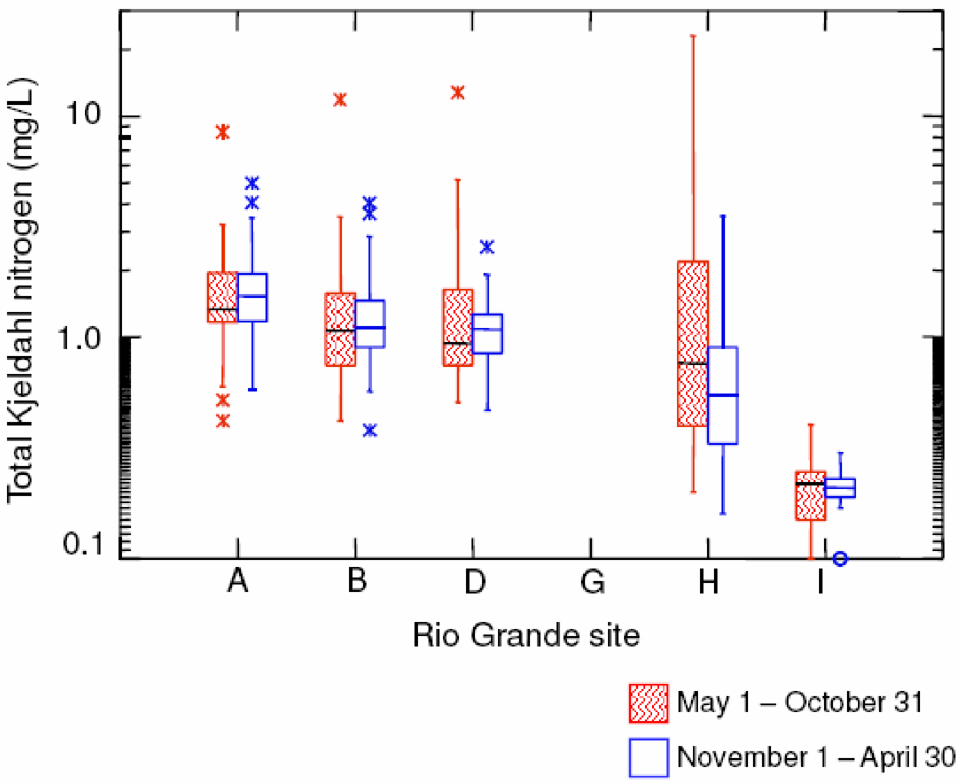


Figure 29. Median total nitrogen concentrations in the Rio Grande during the high-flow (May - October) and low-flow (November - April) seasons.

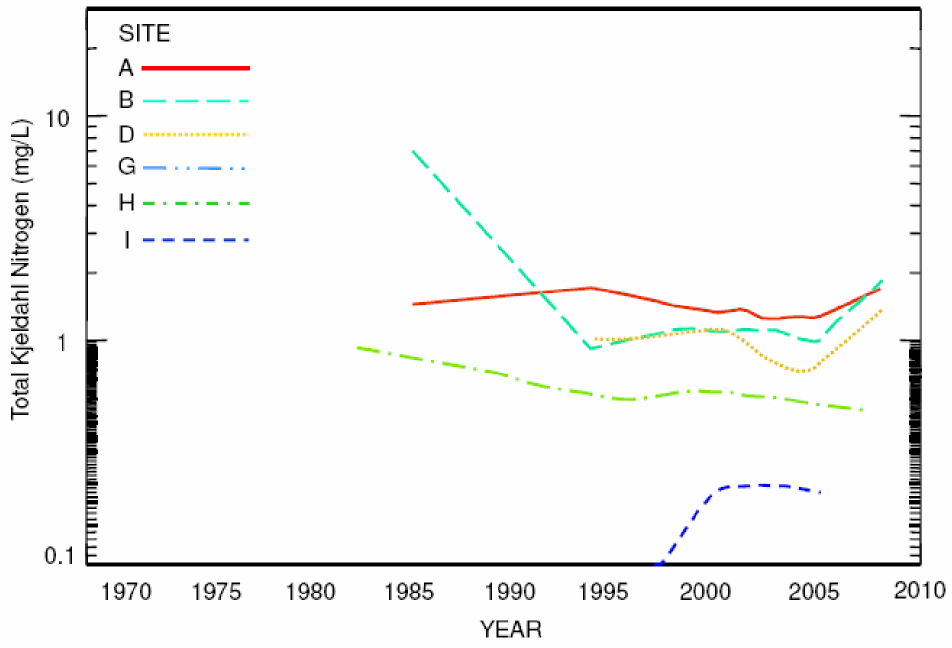


Figure 30. LOWESS trend lines for total nitrogen concentrations in the Rio Grande.

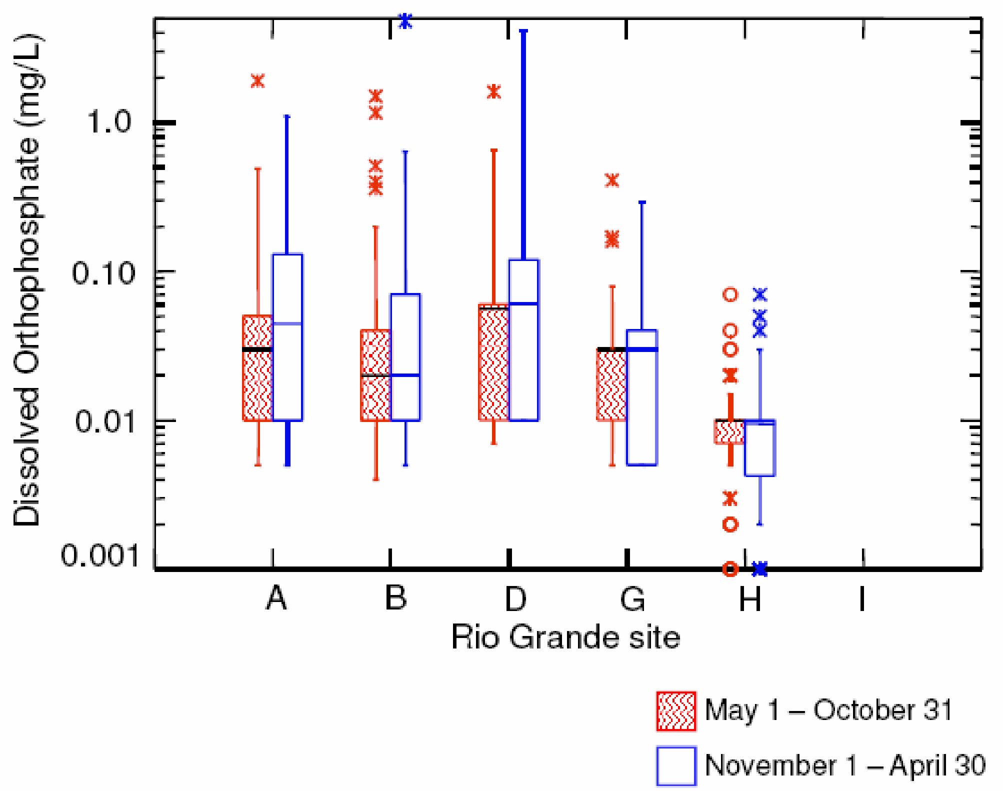


Figure 31. Median dissolved orthophosphate concentrations in the Rio Grande during the high-flow (May - October) and low-flow (November - April) seasons.

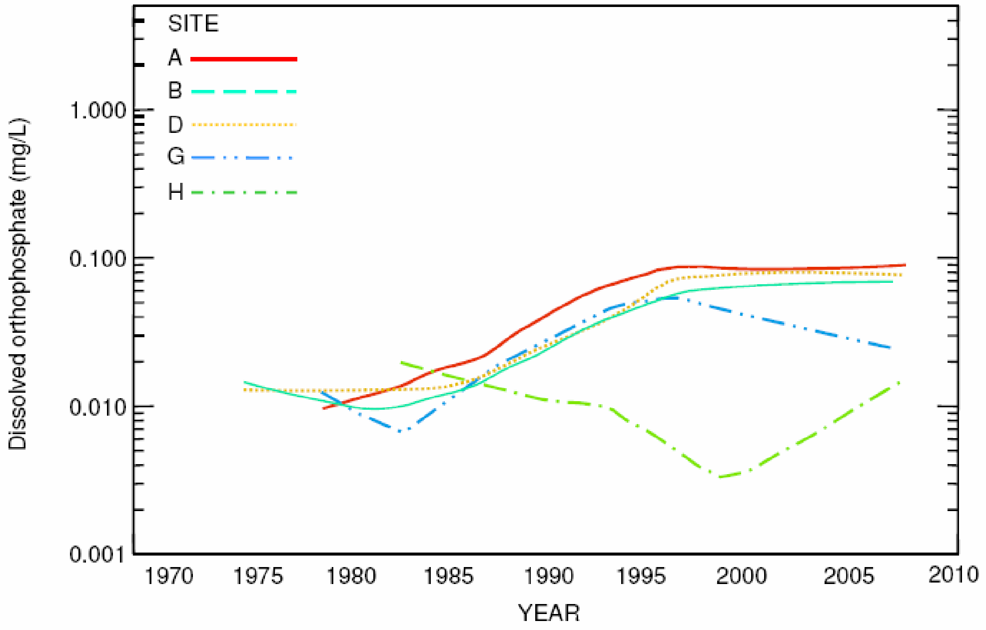


Figure 32. LOWESS trend lines for dissolved orthophosphate concentrations in the Rio Grande.

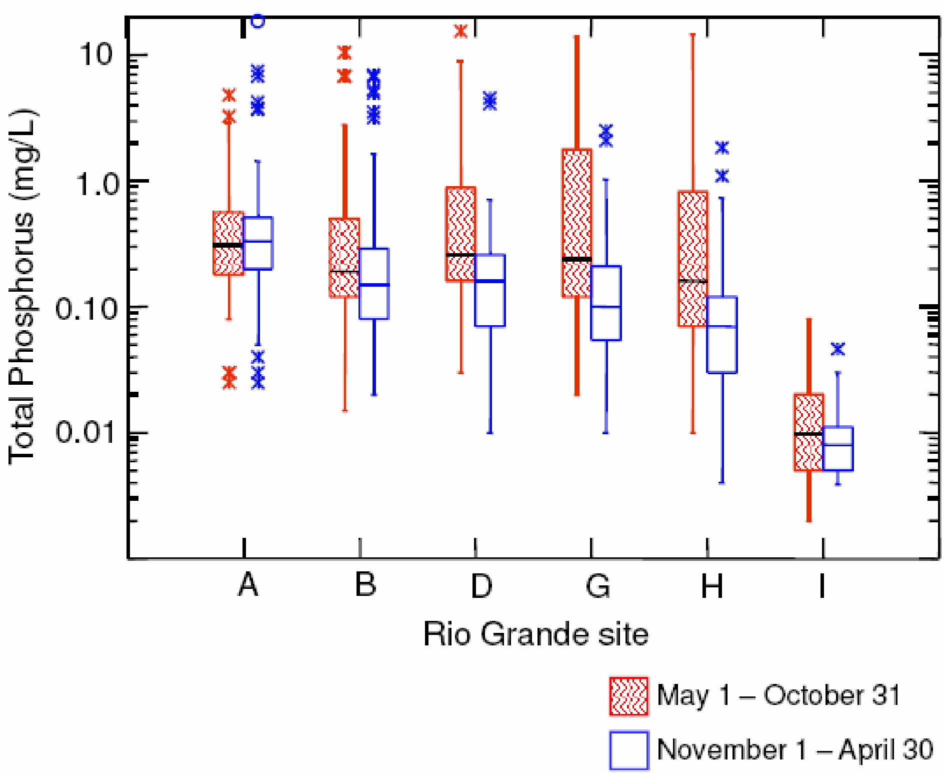


Figure 33. Median total phosphorus concentrations in the Rio Grande during the high-flow (May - October) and low-flow (November - April) seasons.

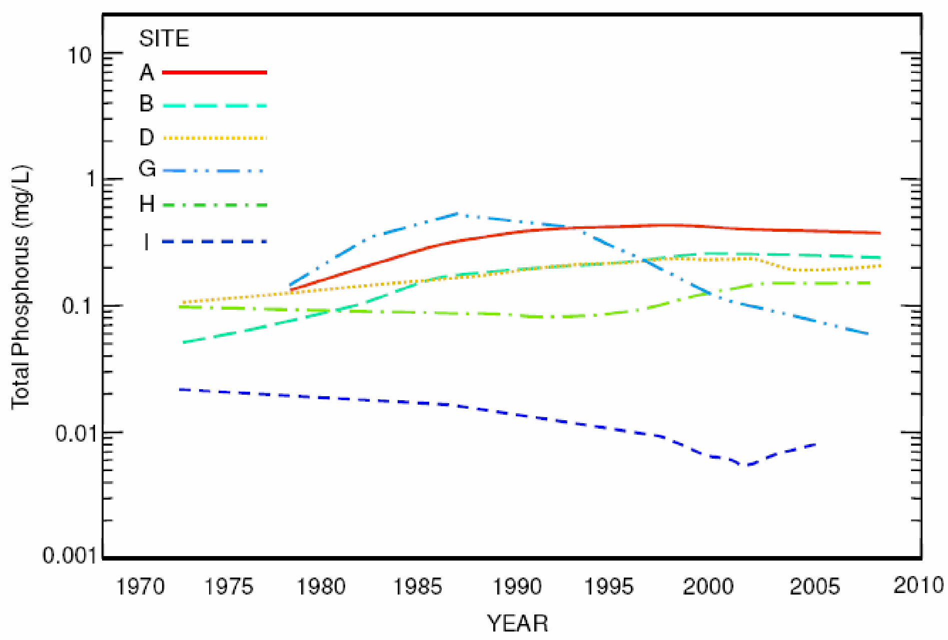


Figure 34. LOWESS trend lines for total phosphorus concentrations in the Rio Grande.

Median dissolved-orthophosphate concentrations (DOP) generally were low, ranging from 0.058 mg/L at site D to less than 0.010 mg/L at site H, where median concentrations were significantly lower than at other sites (Table 11; Fig. 31). Median DOP values were similar between seasons (Fig. 31). Using the IWBC screening level of 0.90 mg/L, the percentage of exceedance varied from 1.0% to 1.7% at sites A, B, and D, with few to no exceedances found at sites downstream (Table 12). Using the USEPA 75th percentile approach to determine screening levels, the screening value for this data set is 0.06 mg/L (n = 747). With this screening value, sites F (36 percent exceedance), A (35 percent exceedance) and D (30 percent exceedance) (Table 12) should be considered of concern for accelerated rates of eutrophication, particularly given upward trends for DOP observed since the early 1980s (Fig. 32). Although DOP dynamics at sites G and H have been variable over time (Fig. 32), DOP concentrations near the beginning and end of the period of record were similar.

Median total phosphorus concentrations (TP) were largest (0.33 mg/L) at site A and decreased in a downstream direction to 0.009 mg/L at site I, where median TP concentrations were significantly lower than at other sites (Table 11; Fig. 33). Median TP concentrations were relatively higher during the high-flow season at sites B—H; however, median concentrations at sites A and I were similar between seasons (Fig. 33). Using the IBWC screening level (1.1 mg/L), exceedances varied from none (site I) to 16.7 percent (site F); no water-quality concern is indicated throughout the study area (Table 12). However, using the USEPA 75th percentile approach (screening value = 0.41 mg/L), sites A (37 percent exceedance) and G (28 percent exceedance) should be considered of concern for accelerated rates of eutrophication (Table 12). TP concentrations have increased at sites A, B, and D during the past 35 years (Fig. 34). Concentrations at site G increased during 1977-87, however, TP concentrations have declined since then. Concentrations at site I have declined, generally, since 1972, whereas TP concentrations at site H have been relatively constant throughout the period of record. Smith and Alexander (1985) reported no significant trends for TP in the Rio Grande at or near sites H and I. Smith et al. (1982) previously reported significant downward trends in TP concentrations and loads of total phosphorus; however, no trend was apparent for flow-adjusted TP concentrations during the same time period (i.e. TP concentrations increase with stream flow).

As mentioned previously, the concern about nutrient concentrations in rivers relates to potential eutrophication; the development of nuisance algal blooms provides visible evidence of water-quality degradation to the public. Water samples have been collected for chlorophyll *a* (CHLa) analyses for 30—35 years in the Rio Grande (Table 13). These data provide an estimate of the abundance of phytoplankton (algae suspended in the water column) in the river but do not reflect the dense growths of attached algae (benthic algae or periphyton) that were observed during a field visit to BIBE in early April 2008. Median CHLa values were highest at site A (18.6 μg/L) and decreased in a downstream direction, with the lowest value observed at site I (2 μg/L; Table 13; Fig. 35). In lakes and reservoirs, median CHLa values observed at sites A—H would be classified “mesotrophic,” whereas the median value at site I would be classified “oligotrophic.” Using the IBWC screening level (30 μg/L), the frequency of exceedance ranged from 31 percent (site A) to no exceedances at site I (Table 12). Using the USEPA 75th percentile approach to determine screening levels, the screening value for this data set is 23 μg/L (n = 745). With this approach, the frequency of exceedance ranged from 45 percent (site A) to no exceedances at site I. The frequency of exceedance decreased with distance downstream from site A (Table 12).

Table 13. Distribution of phytoplankton chlorophyll *a* and total suspended-sediment concentrations in the Rio Grande.

MIN, minimum; 10%, 10th percentile; 25%, 25th percentile; 50%, 50th percentile (median); 75%, 75th percentile; 90%, 90th percentile; MAX, maximum; n, number of data records; μg/L, micrograms per Liter; mg/L, milligrams per Liter.

SITE	MIN	10%	25%	50%	75%	90%	MAX	n	Period of Record
				Chlorophyll *a* (μg/L)					
A	0.5	4.0	7.0	18.6	36.0	53.6	144	202	11/1977 - 8/2007
B	0.5	1.9	3.0	8.0	22.0	40.2	125	224	3/1973 - 8/2007
D	1.0	3.0	5.0	10.0	19.0	43.4	366	151	12/1973 - 12/2005
F	0.0	---	2.5	8.0	14.6	---	65	45	5/2000 - 8/2007
G	0.5	1.1	3.0	6.0	12.0	29.8	157	99	10/1977 - 12/2005
H	1.0	---	4.0	6.0	10.0	---	13	56	4/1972 - 12/2006
I	0.5	---	1.0	2.0	4.0	---	13	13	4/1972 - 3/1997
				Total Suspended Sediment (mg/L)					
A	5	73	112	213	406	736	24,970	272	11/1977 - 8/2007
B	3	43	71	130	288	824	13,000	297	6/1972 - 8/2007
D	---	---	---	---	---	---	---	---	---
G	6	38	84	180	652	3,294	100,000	107	10/1977 - 12/2006
H	25	61	107	326	1,860	8,522	24,300	123	10/1981 - 8/2004

Both approaches classify site A as being of concern for accelerated rates of eutrophication. Maximum values observed at sites A—G (Table 13; 125 μg/L—366 μg/L) would be considered "hypereutrophic" if they occurred in a lake or reservoir (e.g. Carlson 1977). Phytoplankton CHLa values have increased at sites B, D, and G, and remained about the same at sites A and H, during the past 30—35 years (Fig. 36). Values at site I decreased significantly from 1972 through 1997.

In addition to nutrients, algae and other aquatic plants require light to supply energy for metabolism, growth, and reproduction. The abundance of algae can be low in turbid rivers with poor water clarity, particularly during high-flow seasons. Concentrations of total suspended solids (TSS; Table 13) were used as a surrogate for water clarity; high TSS concentrations increase water turbidity, thereby reducing water clarity and light penetration into the water column to support algal metabolism. During the high-flow season (but not during the low-flow season) median concentrations of TSS at sites G and H were relatively higher than other sites (Fig. 37), consistent with relatively lower median CHLa values at those sites. During the past 30 years, TSS concentrations have remained relatively constant at sites A and B; however, TSS concentrations have decreased since the mid-1990s (Fig. 38) at site G (near La Linda, Mexico), whereas CHLa values at this site (also at site H) have increased during this time period. Phytoplankton biomass in the Rio Grande appears to be stimulated by nutrient enrichment from agricultural and other human sources upstream from Big Bend National and State Parks (Rio Grande and Rio Conchos basins) and is limited by light (water turbidity) in the Wild and Scenic

River segment of the Rio Grande. The timing and duration of nuisance algal conditions in the Rio Grande likely are a function of antecedent river discharge and sediment transport.

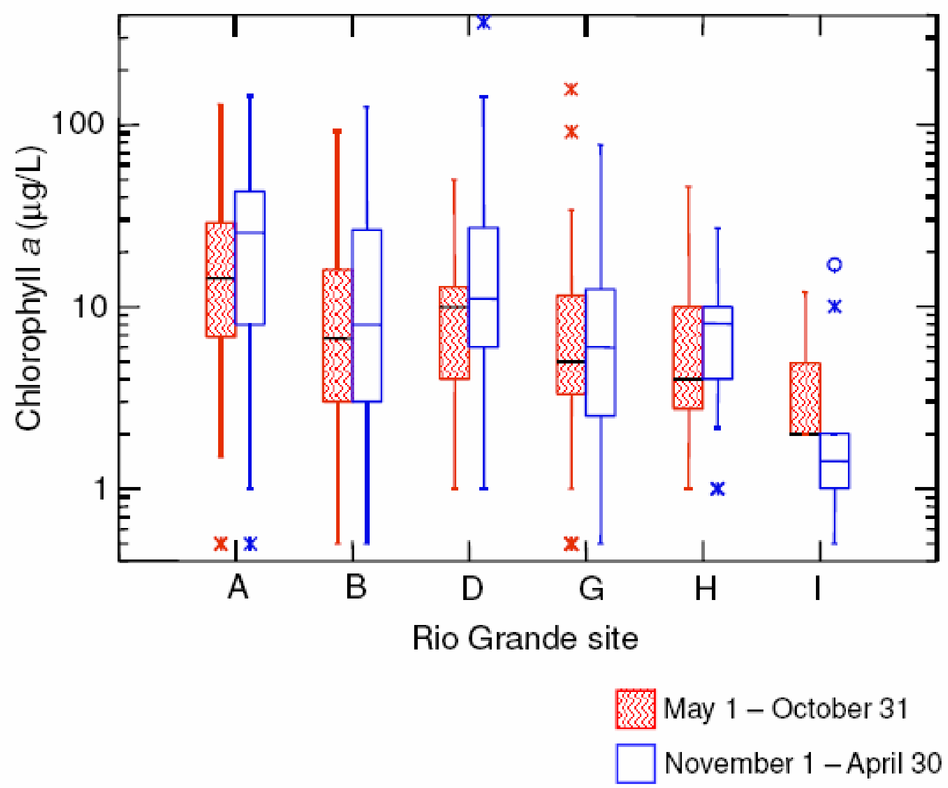


Figure 35. Median phytoplankton chlorophyll *a* values in the Rio Grande during the high-flow (May - October) and low-flow (November - April) seasons.

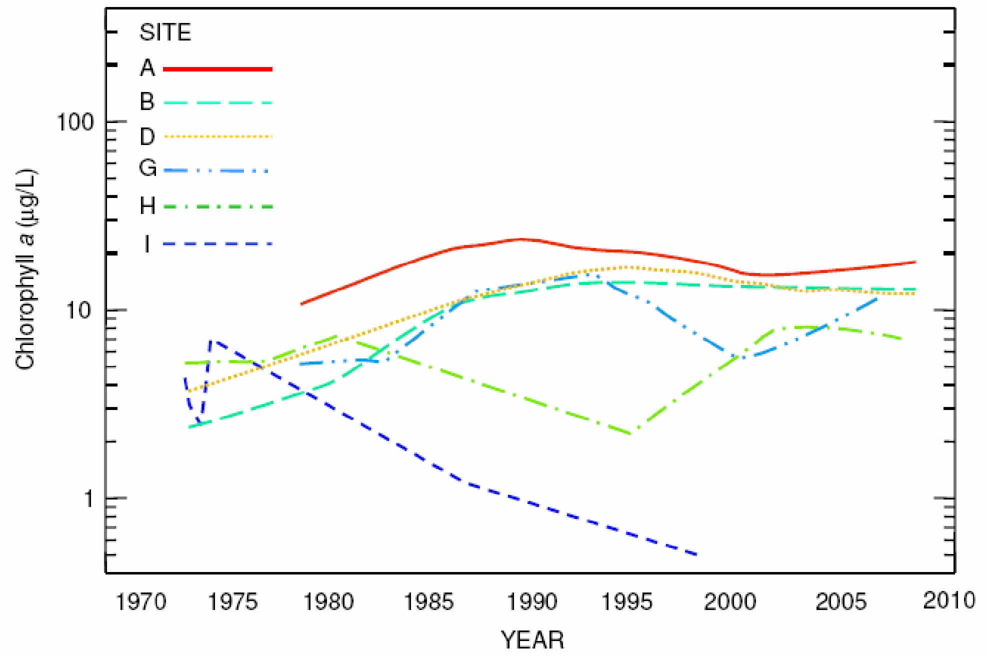


Figure 36. LOWESS trend lines for chlorophyll *a* values in the Rio Grande.

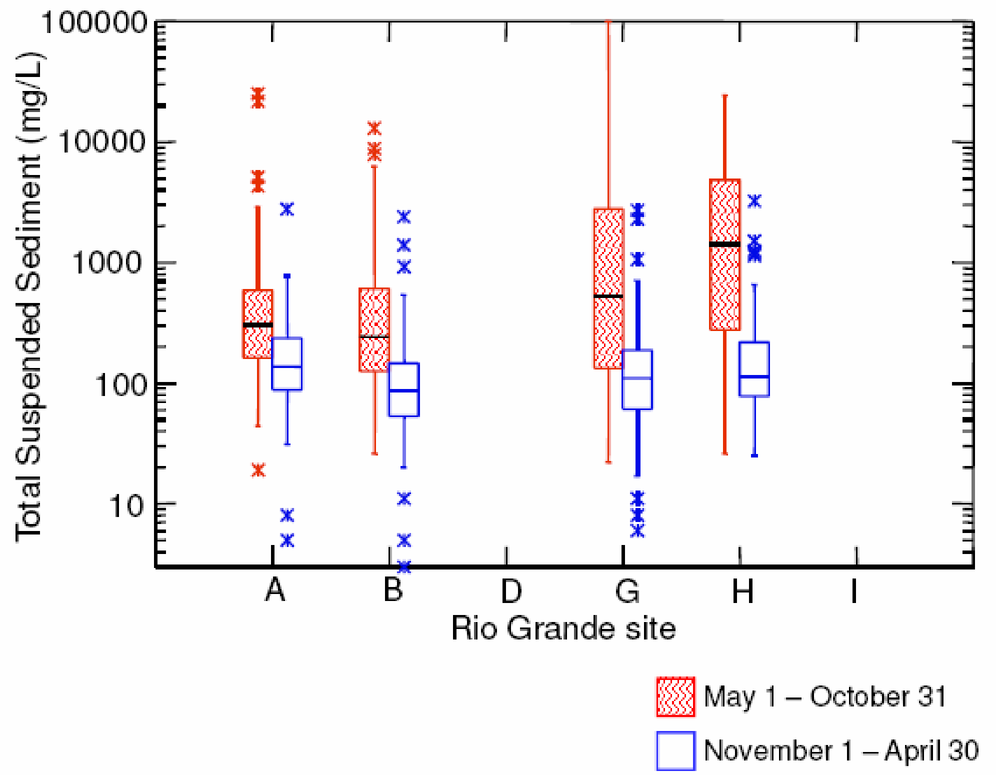


Figure 37. Median suspended sediment concentrations in the Rio Grande during the high-flow (May - October) and low-flow (November - April) seasons.

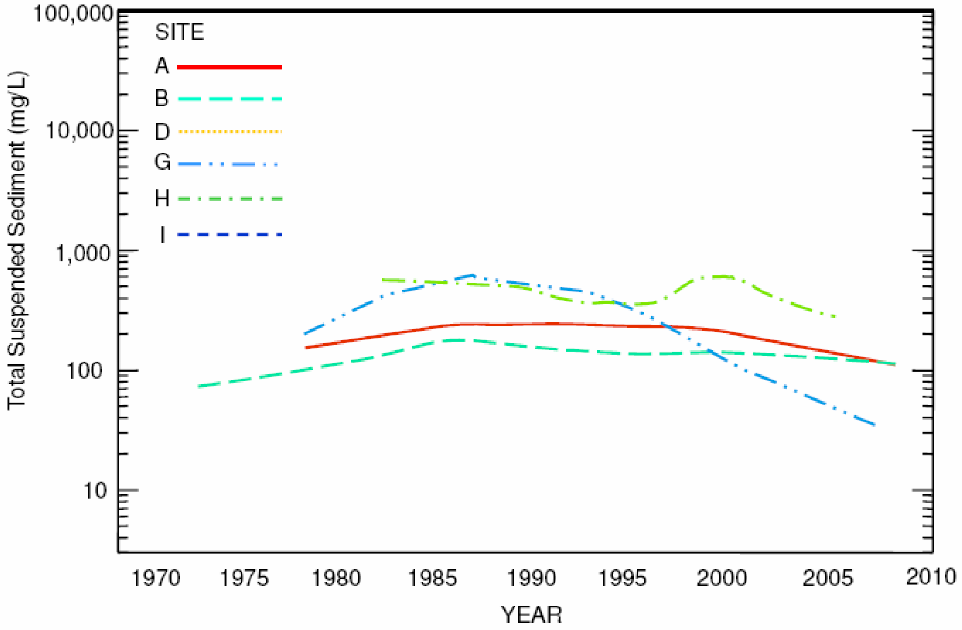


Figure 38. LOWESS trend lines for suspended sediment concentrations in the Rio Grande.

Metals

Despite historic mining activities in the region, particularly mercury mining in the Terlingua mining district and adjacent areas in Brewster and Presidio Counties during 1899-1970 (see review by Lambert et al. 2008), concentrations of metals in water and sediment samples generally were low at all sites, consistent with natural background levels. Many sample results for metal concentrations were censored (less than laboratory reporting limits) in the TCEQ data base, and those with detectable concentrations were less than water quality criteria for protection of aquatic life and human health, consistent with independent findings by Lambert et al. (2008). An intensive synoptic study of toxic substances in water, sediment, and fish tissue was conducted in the El Paso/Ciudad Juárez - Big Bend National Park segment of the Rio Grande during 1998, following previous, larger-scale studies in 1992-93 (IBWC 2004). Arsenic was detected in all water samples; however, levels did not exceed aquatic-life or human-health criteria. Concentrations of cadmium, chromium, copper, lead, nickel, and zinc were detected in Rio Grande sediment samples; however, the range of concentrations found generally represented background levels for the region (IBWC 2004).

The IBWC (2004) reported total-recoverable mercury concentrations exceeding the TCEQ human health criterion in water samples collected during November 1998 from the Rio Grande above Presidio/Ojinaga (Fig. 12, site A) and Santa Elena Canyon (site D). Lambert et al. (2008) reported detectable concentrations of mercury (0.0007 to 0.198 μg/L; median = 0.0975 μg/L) in all water samples collected from the Rio Grande and tributary streams during 2002. With the exception of Terlingua Creek and Arroyo del Fortino (where mercury concentrations were among the <u>lowest</u> in the study), mercury concentrations were larger than the TCEQ human health criterion for fish consumption (0.0122 mg/L), however, all concentrations were considerably less than criteria for acute and chronic aquatic-life protection (Lambert et al. 2008).

Although concentrations of mercury were low in water and sediment samples, concern has been raised about biomagnification of mercury concentrations through the aquatic food web (IBWC 2004; Mora and Wainwright 1997; Smith 2009) and in terrestrial invertebrates (e.g. Khan and Richerson 1982) near the historic mining areas and in the Rio Grande. Becker and Groeger (submitted) reported tissue concentrations of mercury ranging from 400 to 1,200 parts per billion in largemouth bass collected recently (2006) from Amistad International Reservoir The USEPA screening level is 300 ppb (Becker and Groeger, submitted).

Few long-term data sets for metals are available for the Rio Grande. A 20-year record of dissolved arsenic and zinc concentrations was found in the TCEQ data base for site H (Rio Grande at Foster Ranch). Dissolved arsenic concentrations generally were low (< 16 μg/L) throughout the period of record (early 1980s through 2003), however the LOWESS trend line shown in Figure 39 suggests an upward trend during the 1980s (with considerable variance) followed by a population of less variable, low arsenic values (less than 5 μg/L, the current USEPA drinking-water standard) since the mid 1990s. By contrast, concentrations of zinc at this site exhibited a downward trend during the 1980s, followed by relatively little change since the mid 1990s (Fig. 40). All concentrations of zinc at site H were considerably less than acute or chronic aquatic life criteria, and concentrations observed since the mid 1990s (< 8 μg/L) are considered background levels.

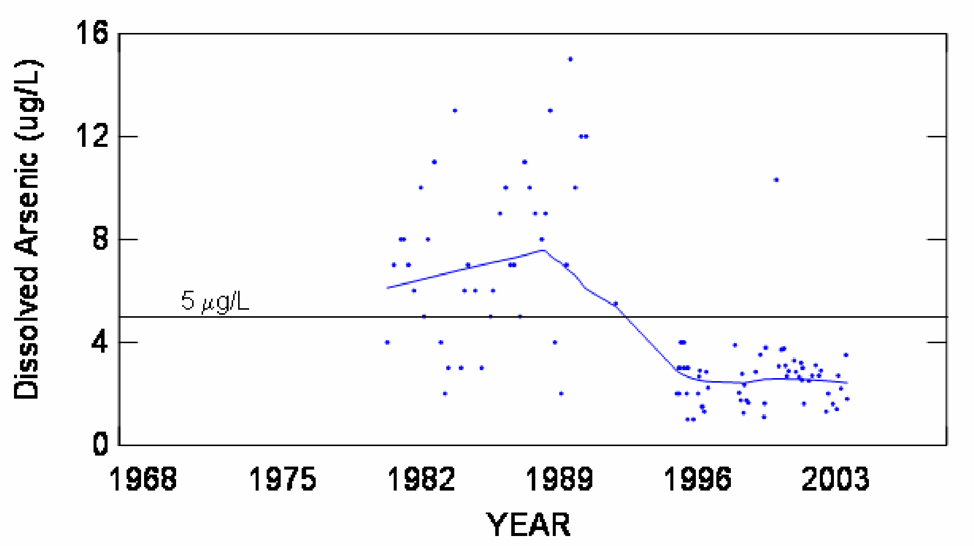


Figure 39. LOWESS trend line for dissolved arsenic concentrations at site H (Rio Grande at Foster Ranch).

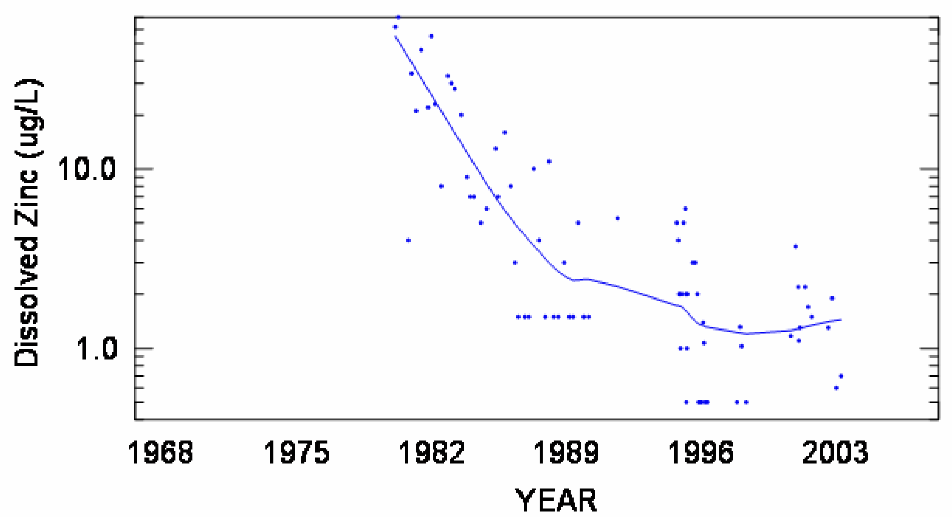


Figure 40. LOWESS trend line for dissolved zinc concentrations at site H (Rio Grande at Foster Ranch).

Concentrations of metals (arsenic, chromium, copper, lead, mercury, nickel, vanadium, and zinc) in age-dated sediment cores from the Rio Grande arm of Amistad International Reservoir increased significantly from the late 1960s through 1995 (Van Metre et al. 1997). Results from the Devils River arm of Amistad International Reservoir, receiving drainage from a largely undeveloped basin, were similar to the Rio Grande arm except for chromium (no trend) and lead (downward trend). Concentrations of arsenic, chromium, and nickel in upper layers of the sediment cores (more recent years) exceeded biological threshold effect levels published by USEPA and Environment Canada (refer to Van Metre et al. 1997), whereas concentrations of copper, lead, mercury, and zinc were below the threshold levels, indicating no immediate cause for concern. Increases in concentrations of metals through time were attributed primarily to atmospheric fallout of contaminants (from fossil fuel combustion (especially coal) and solid waste incineration (Van Metre et al. 1997)). The transport of sediment and adsorbed metals from historic mining areas occurs primarily during large rainfall and runoff events (cf. Lambert et al. 2008) so the accumulation of metals in river and lake sediments may reflect the timing of extreme hydrologic events more than gradual accumulation over time. In addition, average rates of sediment deposition in Amistad International Reservoir are high (45 centimeters per year), possibly diluting the load of metals and other contaminants associated with sediments (Van Metre et al. 1997).

Macroinvertebrate Communities

The condition of macroinvertebrate communities at 9 Rio Grande sites was evaluated with two common (e.g. Barbour et al. 1999) water-quality metrics, taxa richness and E+T (modified from EPT) richness. Macroinvertebrate data from known publications and academic theses were entered into Excel spreadsheets; taxa richness, E+T richness, and the percentage of EPT taxa were calculated for samples with species lists. The TCEQ macroinvertebrate data were limited to metrics, therefore, the common denominator variables evaluated among studies were limited to taxa and E+T richness. Published data sets with high taxonomic quality are available for a number of Rio Grande sites collected during certain years (for example, 1976-77 (Davis 1980a) and 1999 (Moring 2002); however, such data were not available for all sites and years. Taxa and E+T richness values from some data sources appeared depauperate, possibly reflecting differences in collection methods (or effort) and (or) differences in taxonomic resolution in macroinvertebrate samples, for example, whether midges were identified at taxonomic levels lower than “Chironomidae.” Because of the importance of macroinvertebrate data as a vital sign, the CHDN network should consider a process for developing a high-quality macroinvertebrate data base to document baseline aquatic-life conditions at sites associated with BIBE and the Wild and Scenic River segment. Taxonomic harmonization among studies (and/or the use of a consistent set of “rules” for calculating metric scores) would improve understanding of ecological conditions among sites and potential changes in water-quality or habitat conditions. A taxonomic survey recently was completed for mayfly and caddisfly species in the Big Bend area (Baumgardner and Bowles 2005).

Taxa richness reported from Rio Grande samples ranged from 2 to 59, whereas E+T richness varied from 0 to 18. Median richness values for both variables were lowest at sites A, D, and G (Fig. 41). Specific samples collected during 1976 (Davis 1980a) and 1999 (Moring 2002) are plotted on Figure 41 to provide comparisons between years and sites. Taxa and E+T richness increased significantly between sites A and B, possibly associated with improvements in water-quality and habitat conditions associated with discharge from the Rio Conchos into the Rio Grande. Taxa and E+T richness decreased appreciably at site D compared with upstream sites sampled in both 1976 and 1999 (Fig. 41). Thereafter, overall taxa richness increased in a downstream direction, whereas E+T richness was relatively unchanged to declining (e.g. Fig. 41; Moring 1999). This appears to indicate increases in the number of tolerant organisms rather than improvements in water quality. Based on similarities in taxa and E+T richness between the 1976 and 1999 samples, there is no compelling evidence to suggest that the condition of macroinvertebrate communities had changed appreciably during that time period.

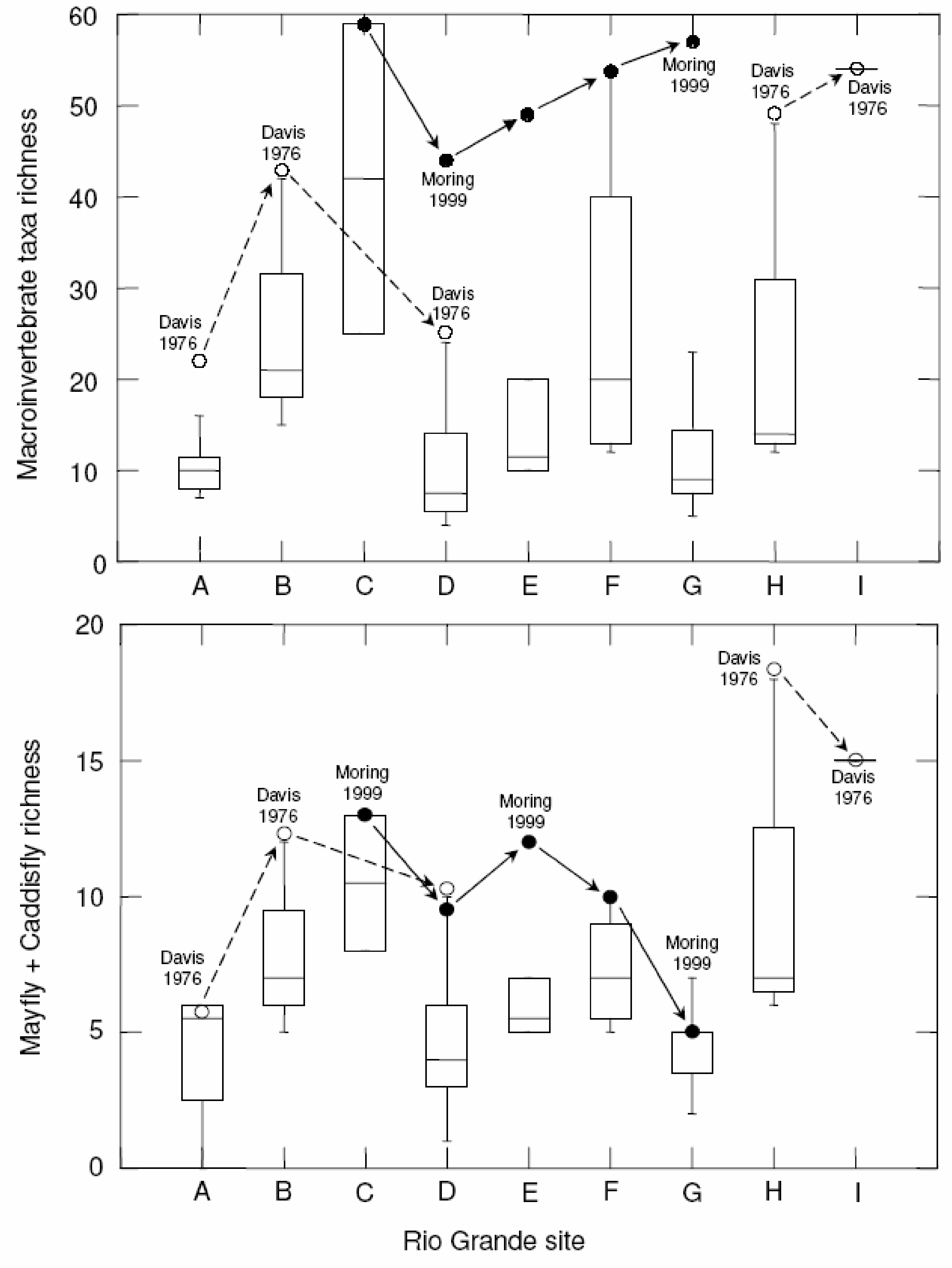


Figure 41. Macroinvertebrate taxa and E+T richness in the Rio Grande.

A TCEQ study conducted in 1998 reported taxa richness in the Rio Grande ranged from 10 (site A) to 14 (sites B and D) with E+T richness of 7 at site B and 6 at other sites in the study area (IBWC 2004). Benthic Macroinvertebrate Rapid Bioassessment Index of Biotic Integrity (BRBIBI) scores were in the "intermediate" aquatic-life use category. The TCEQ-designated aquatic-life use for Rio Grande segments 2306 and 2307 is "high;" therefore, macroinvertebrate IBI scores are indicating that the designated use is not being met (IBWC 2004). Ongoing macroinvertebrate monitoring in the Rio Grande (e.g. Harrison 2007) should improve understanding of factors that influence community composition and structure along the Rio Grande.

Water Quality Conditions in Selected Tributary Streams

Relatively little water-quality or macroinvertebrate data were found for Rio Grande tributaries in or near BIBE or the Wild and Scenic River segment of the Rio Grande. Bane and Lind (1978) reported seasonal macroinvertebrate distributions in Tornillo Creek during 1973-74. Taxa richness ranged from 14 (summer) to 39 (fall), and mean invertebrate biomass varied several orders of magnitude, from 1.1 mg/m^2 during late summer to over 1,000 mg/m^2 during the spring and fall. A few water-quality sample results are available during the 1970s for Terlingua Creek near Terlingua, Texas (USGS gage 08374500) and during the early 1990s for Terlingua Creek above the Rio Grande confluence (TCEQ site 13107). Dissolved oxygen concentrations reported for Terlingua Creek varied from 7.6 to 9.0 mg/L, pH from 6.4 to 8.2, SpC from 1,305 to 1,848 µS/cm, and water temperature from 17.5 to 37.3 ^{O}C. Chloride concentrations in Terlingua Creek were relatively low (7 – 17 mg/L), however, sulfate concentrations were high (490 – 620 mg/L). Nutrient concentrations also were relatively low, with maximum values for NH4, NO23, TP, and DOP not exceeding 0.04 mg/L, 1.0 mg/L, 0.06 mg/L, and 0.01 mg/L, respectively. TCEQ macroinvertebrate results for Terlingua Creek upstream from the Rio Grande (site 13107) indicated stressed conditions; only 5 taxa occurred in samples collected during 1993 and only one mayfly taxon was reported (*Baetodes* sp.). Terlingua Creek near Terlingua, Texas was nearly dry during the field visit in late April 2008. The primary stress to most streams in the Park is simply lack of stream flow during substantial portions of the year. Extended periods of drought functionally re-set benthic communities in these systems, and taxa richness likely is a function of the time since flow returned to the stream since the last zero-flow disturbance.

Water-quality and macroinvertebrate data also are available for Alamito Creek near FM 170 (USGS gage 0837400), generally about 8 to 12 samples collected during 1977-93. Dissolved oxygen concentrations ranged from 1.8 – 14.7 mg/L, pH from 7.2 – 8.7, and SpC from 432 – 840 µS/cm. Concentrations of chloride and sulfate were low (3 – 46 mg/L and 34 – 98 mg/L, respectively). Concentrations of nutrients and fecal-coliform bacteria were more variable. For example, NO23 concentrations ranged from 0.02 – 3.0 mg/L and TP concentrations varied from 0.02 – 3.61 mg/L. Fecal-coliform levels ranged from 2 to over 19,000 colonies per 100 mL, with a median of 160 colonies per 100 mL representing relatively few (10) samples. Three macroinvertebrate samples were collected during 1988-89 and one sample was collected during August 1993 (TCEQ data base). Taxa richness varied from 4 – 5, whereas E+T richness ranged from none to 2 (median = 1).

Macroinvertebrate richness metrics at these Rio Grande tributary sites suggest poor water quality and (or) habitat conditions (including lack of stream flow). TCEQ data from other tributaries in the region (Devil's and Pecos Rivers; Independence and Live Oak Creeks) reveal taxa richness ranging from 15 – 29 and E+T richness ranging from 3 – 10 taxa.

Water Quality and Macroinvertebrate Conditions at Other CHDN Parks

Carlsbad Caverns National Park (CAVE)

Rattlesnake Spring is a substantial groundwater resource that discharges to an un-named tributary of the Black River. According to park personnel, several State-listed fish species of concern are known from the Rattlesnake Springs system; however, invasive species also are becoming an issue in the area (Paul Burger, NPS, personal communication). Concern has been expressed about oil and gas production activities in the area and potential hydrocarbon contamination of ground-water resources.

We have been unable to obtain long-term water quality data for Rattlesnake Spring. A summary of results from the treated water supply (Carlsbad Caverns National Park Water System 2008) indicates excellent water quality with no violations of water-quality criteria. Nuisance growths of algae and (or) aquatic plants have been reported in Rattlesnake Spring, particularly during the spring season; moderate growths of benthic algae and macrophytes were observed during a field visit in early April 2008. Water quality and ecological conditions in the small stream maintained by the Rattlesnake Spring outflow are unknown. This un-named tributary to the Black River appears to be a high-quality resource.

Fort Davis National Historic Site (FODA)

The only surface water resource associated with FODA is Limpia Creek, located on the northern boundary of the Historic Site. Green (1986) wrote that Limpia Creek and a spring at the post furnished most of the garrison's water needs during the 1870s, when Limpia Creek was described as "always clear, pure, and cool, not very hard,…" During the 1880s, a water system was developed to deliver water from Limpia Creek to the post; however, an extended period drought during the late 1880s apparently reduced both the quantity and quality of Limpia Creek water, threatening the existence of the fort (Green 1986). Over the next few years until the fort was abandoned the quality of the water did not markedly improve. More recently, a local resident reported to us that Limpia Creek traditionally supported Rio Grande cutthroat trout; however, there has been less flow in the stream since the early 1960s (Henry Sanchez, personal communication). Observations of Limpia Creek during early April 2008 revealed an, essentially, intermittent stream with several pools separated by considerable distances of dry stream bed.

Although water-quality and macroinvertebrate data were found in the TCEQ data base, water chemistry records were available from 1972—1986, and only two macroinvertebrate sample results are available, one from 1975 and the other from 1986. From the same water-quality results, NPS (1999) previously reported several exceedances of DO, pH, lead, and fecal-coliform criteria or screening levels. During the period of record, water-quality conditions generally were good. Median water temperature, DO, pH, SpC, and fecal coliform values were 16.1^{O}C, 7.7 standard units, 370 µS/cm, and 5 colonies per 100 mL, respectively. Median concentrations of chloride (12 mg/L), sulfate (26 mg/L), NH4 (<0.1 mg/L), NO23 (<0.3 mg/L, and CHLa (<4 µg/L) were low. Median concentrations of TP (0.1 mg/L) and DOP (0.07 mg/L) were typical for small streams. Benthic macroinvertebrate taxa richness ranged from 10 (1986) to 20 (1975), whereas E+T richness varied from 3 (1986) to 4 (1975). Water quality and ecological conditions since 1986 are unknown.

Guadalupe Mountains National Park (GUMO)

Although no reports of water quality or macroinvertebrate data were found in the TCEQ data base, NPS (1997a) discussed water quality results from four sites on McKittrick Creek, two sites on North McKittrick Creek, and 12 sites on South McKittrick Creek. Results also are presented for Choza Spring, Manzanita Spring, Frijole Spring, Guadalupe Spring, and several other springs within the park boundary. Most data were collected in the McKittrick Creek basin during 1978-97. More recent data were not available for analysis in this report.

According to results presented by NPS (1997a), median dissolved oxygen concentrations in McKittrick Creek appears to have decreased from over 8.5 mg/L in 1978 to about 6.5 mg/L in 1997 (NPS 1997a, p. 71). Median concentrations of nitrate nitrogen and DOP increased during the period of record; however, nutrient concentrations were relatively low. Median chloride (< 5 mg/L) and sulfate (< 15 mg/L) were very low, probably representing background conditions in the region. Median dissolved-oxygen concentrations in South McKittrick Creek were relatively constant during the period of record, about 8 mg/L (NPS, 1997a, p. 93). Although DOP concentrations appear to be increasing slightly over time, concentrations of nutrients, as well as chloride and sulfate concentrations, generally, were low with no apparent water-quality trend.

Published macroinvertebrate studies in the McKittrick Creek basin include Lind (1979; data collected over a 5-year period from 1967—1972), Meyerhoff and Lind (1987a-b; data collected during the early 1980s), Green (1993; data collected during the late 1980s), and Fullington (1979). Macroinvertebrate taxa richness and E+T richness were calculated from species data listed in Green (1993; Table 1). Taxa richness increased from 35 (Lind 1979) to 41 (Meyerhoff and Lind 1987b) to 82 (Green, 1993); however, these differences may have more to do with differing levels of taxonomic resolution among investigators than improvements in water quality and (or) habitat conditions. Similarly, E+T richness varied from 10-11 (Lind 1979; Meyerhoff and Lind 1987b) to 18 (Greene 1993). The distribution of common species was similar among studies. This work provides an excellent baseline ecological data set from which subtle changes in condition associated with natural or human factors can be evaluated.

White Sands National Monument (WHSA)

Located in the Tularosa Basin of south-central New Mexico, surface-water resources in the WHSA study area include Lucero, Garton, Foster, and other lakes, Lost River and other intermittent stream channels, Holloman Lake and other smaller reservoirs and ponds, and several springs (NPS 1997b). Limited water quality data were available for Lake Lucero, Lake Stinky, Garton Lake, and a number of unidentified sites listed by NPS (1997b). Surface water quality in

WHSA could be characterized as hypersaline and of poor quality for freshwater aquatic life. Concentrations of chloride exceeded USEPA drinking-water and acute-freshwater criteria in all samples (NPS 1997b). Concentrations of sulfate also exceeded the USEPA drinking-water criterion in all samples. The highest concentrations of chloride and sulfate (126,000 mg/L and 39,000 mg/L, respectively) were reported from South Lake Lucero in April 1993 (NPS 1997b). Elevated concentrations of metals were reported in water and sediment samples. Data for the headwater segment of the Lost River (south of the WHSA park boundary and not generally accessible to the public) were limited to concentrations of metals in streambed sediments (1985) and lists of benthic macroinvertebrates and diatoms from 1993 collections by the New Mexico Environment Department (David Bustos, WHSA, written communication). Macroinvertebrate taxa richness was 7, dominated by *Trichocorixa* sp., a tolerant water bug. No E+T taxa were found. The diatom community consisted of halophilic (tolerant of salts) species found typically in coastal estuaries. Although Garton Pond, historically, was a significant water resource used by the public, over the past 10-20 years the water level in Garton Pond has decreased (possibly in association with local increases in aquifer withdrawals) to the current (2008) level where surface water appears in isolated, stagnant pools and the area resembles a wetland.

Groundwater Quantity

Every CHDN park is dependent on groundwater to satisfy its potable water needs. This groundwater either discharges from onsite springs or is pumped from local aquifers—sources that are continually adjusting to the effects of weather, area pumping, and land use. Understanding the nature and net effect of these changing conditions is important toward maintaining viable sources of sufficient and potable groundwater. The effects of groundwater recharge and discharge can be monitored through the observation of water levels in representative wells and discharge from local springs and seeps. The tracking of groundwater levels and springflow over time (groundwater-quantity monitoring) is vital to understanding the long-term sustainability of any given aquifer or spring.

Aquifers are replenished by recharge from the infiltration of precipitation, leakage from surface-water bodies, subsurface inflow of groundwater from adjacent aquifers, and irrigation return flow. Recharge to the aquifers within CHDN is limited by the relatively limited and sporadic nature of precipitation, and some of the U.S.'s highest rates of evaporation outside Death Valley, California. As a result, the wells upon which CHDN relies for water supply are vulnerable to the long-term effects of climatic change and (or) shorter-term (seasonal) water-level fluctuations that –if unabated–can evolve into longer-term decline. For this reason, a systematic program of groundwater observation is essential toward evaluating both the short- and long-term trends of relevant aquifers, and providing a means of effectively managing the various aspects of any park's water resources.

This section of the report provides groundwater (including water well) information for each of the CHDN parks (except for the Rio Grande Wild and Scenic River, where specific well and water-level data are unavailable). With the exception of continuous water-level data for 1997-2008 from WHSA monitoring wells and shorter-term (2004-2008) information from more recently installed monitoring wells in BIBE, the water-level data for CHDN parks are limited and mostly of a miscellaneous nature. Consequently, hydrographs are provided for only water levels measured from the observation wells at BIBE and WHSA. For the other parks, where long-term water-level data are unavailable, hydrographs are provided of water levels in the closest State- or USGS-operated observation wells that track water levels in aquifers considered most relevant to the groundwater resources and future water supplies at each park.

Amistad National Recreational Area (AMIS)

Hydrogeologic Setting

The rocks that underlie the Amistad National Recreational Area (AMIS) and provide a stark-white backdrop to Amistad Reservoir's shoreline are composed of Cretaceous limestone (calcium carbonate) and dolostone (calcium-magnesium carbonate). The predominant groundwater source in the area, as well as that supporting AMIS operations, is the Edwards aquifer (Maclay and Small 1984) of Early Cretaceous age. In the area of Amistad Reservoir, the Edwards aquifer is comprised of the Devils River and Salmon Peak Formations on the north and south, respectively (Lozo and Smith 1964). Although not as karstically and structurally altered—and, therefore, not as permeable—as their Cretaceous-age counterparts toward the east in the Balcones fault zone, the Devils River and Salmon Peak strata are, nevertheless, permeable where fractured. For electronic storage and retrieval purposes, the Texas Water Development Board (TWDB) classifies these water-bearing strata as "218EDRD" in the AMIS area.

Groundwater Wells and Water Levels

The following table provides data regarding AMIS–owned and –operated groundwater wells. This table contains the shallowest (highest) and deepest (lowest) water levels on record for these wells, where such information is available. Other than the typical seasonal range of roughly 30 feet (ft) between shallowest and deepest water levels, as indicated by the new Diablo East well, most of the apparent water-level differences reflect adjustments in aquifer levels to changes in the stage of Amistad Reservoir. The water levels in most Edwards aquifer wells in hydraulic communication with Amistad Reservoir underwent rises coincident with the late-1960s filling of this reservoir (Boghici 2004).

Table 14. Information for selected wells in the Amistad National Recreation Area (AMIS).

AMISTAD NATIONAL RECREATION AREA (AMIS)								
Well Name	**Northing** (Zone 14)	**Easting** (Zone14)	**Land Surface Altitude (ft amsl)**	**Well Depth (ft)**	**Aquifer**	**Shallowest Water Level (ft)**	**Deepest Water Level (ft)**	**REMARKS**
Diablo East	3261692	304369	1178	480	Edwards	118.1	218.1	Salmon Peak Fm.
Diablo East, New	3261635	304634	1,160	600	ditto	40	71.35	Ditto
Rough Canyon	---	---	---	300	ditto	51.00	---	Ditto
Pecos River	---	---	---	625	ditto	153.5	---	Devils River Ls.
Governors Landing	---	---	1,150	390	ditto	35.80	312.68	Salmon Peak Fm.

The prevailing hydraulic gradient in the region slopes from the Edwards Plateau, north of AMIS, toward the topographically lower Rio Grande drainage and the more deeply entrenched tributaries, such as the Pecos and Devils Rivers (Barker and Ardis 1996, Fig. 16). It is noteworthy that since the reservoir first filled, during the early-1970s, the highest groundwater elevations (land surface minus depth to groundwater) are roughly 10 ft higher than Amistad Reservoir's conservation level of 1,117 ft amsl. In other words, any groundwater level in the AMIS vicinity that is below lake stage is probably a short-term response to a local pumping event and, therefore, of temporary consequence.

Historical Trends

As no water-level data other than that shown in the above table are available for AMIS wells, no park well is supported by enough water-level record to permit construction of a groundwater hydrograph. For this reason, Figure 42 is provided to show the long-term trends in the groundwater records of other, privately owned wells that tap the Edwards aquifer near AMIS.

The dominant pattern of water-level change reflected in either hydrograph (Fig.42) relates to the post-impoundment rise of Lake Amistad, which began during late 1968. Following a relative stabilization of reservoir levels (during the early 1970s), both hydrographs appear to reflect the aquifer's response to area recharge and discharge, particularly that of nearby pumping. Whereas toward the north, on the Edwards Plateau, water levels in the Edwards-Trinity aquifer generally varied between 50–75 ft during the early-1970s through early-1990s (Bush et al. 1993), the water levels in most wells within roughly five miles of Amistad Reservoir were restricted to fluctuations of less than 50 ft during this same period. The relatively stable nature of groundwater levels near AMIS is no doubt linked to the buffering influence of the large body of surface water contained behind Amistad Dam.

Other than a couple of relatively low readings presumably caused by short-term pumping conditions, the lowest groundwater elevations indicated in the hydrographs (Fig. 43) correspond to the lake's lowest stages during the mid-1990 through early-2000 period. The 1993 through late-2003 interval of generally decreasing or comparatively low groundwater levels in Well 70-25-502 (Fig. 42) corresponds to the 1993-2002 timing of a 10-yr drought in the area (Appendix B1). Surface-water inflow to the reservoir obviously was reduced during the drought, which directly impacted the pool level and eventually the water levels in nearby, hydraulically connected wells—including those whose hydrographs are shown in Figure 42.

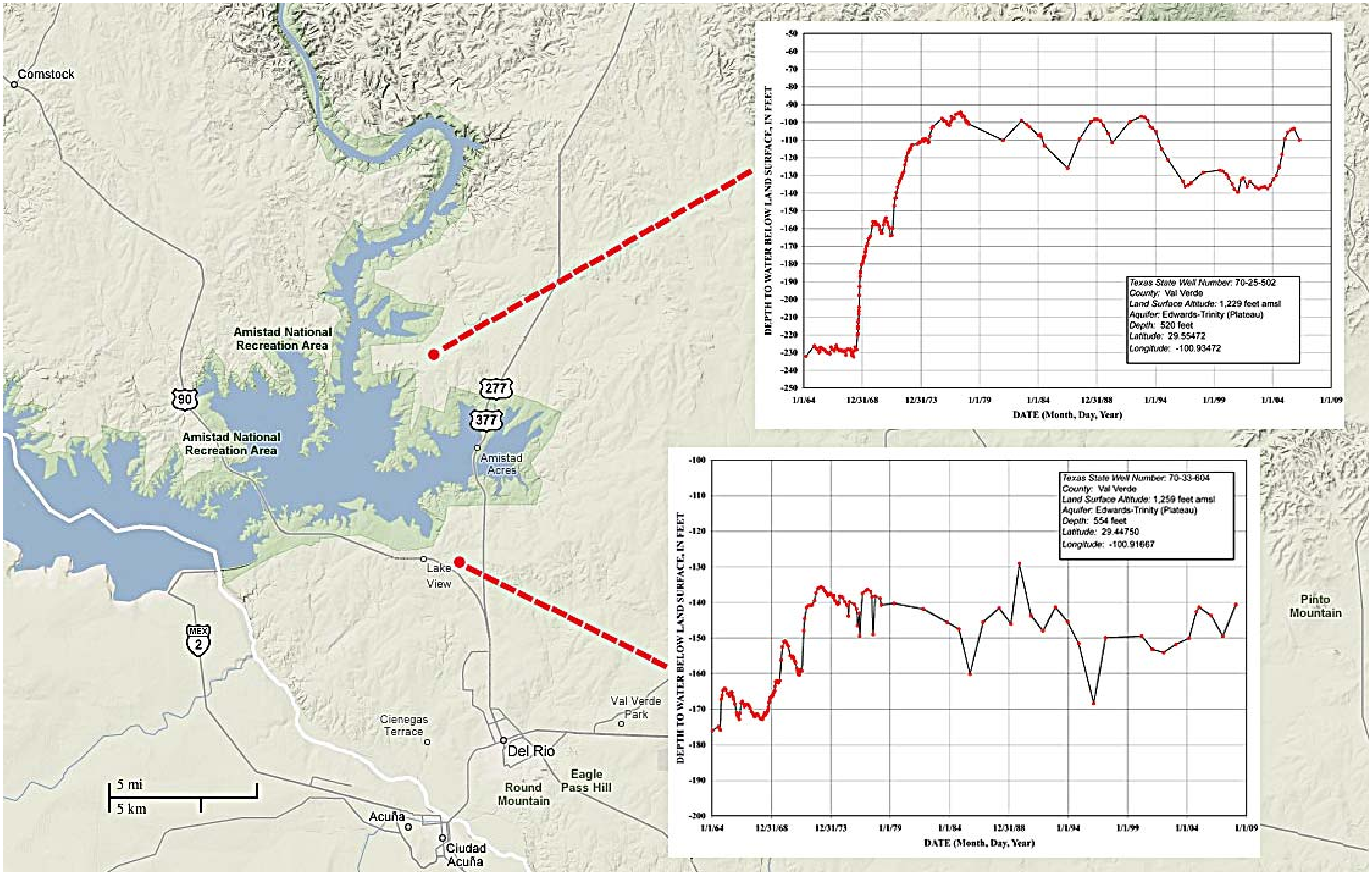


Figure 42. Groundwater hydrographs for Val Verde County observation wells, showing depths to water level in Edwards-Trinity aquifer near Amistad National Recreational Area.

Big Bend National Park (BIBE) and Rio Grande Wild and Scenic River (RIGR)

Hydrogeologic Setting

From the oldest, 500 million-year-old rocks at Persimmon Gap to the present-day windblown sand at Boquillas Canyon, the geologic formations in Big Bend National Park (BIBE) exhibit the diverse effects of variable depositional patterns and extreme tectonic events over the last three eras of geologic time (Maxwell et al. 1967). The geology of the region qualifies as some of the most complex in Texas (LBG-Guyton 2001). After being inundated by ancient seas for more than a billion years, the region was subjected to tectonic uplift and crustal buckling that folded, faulted, and fractured the older marine strata. Following sporadic volcanic episodes that spewed lava and ash over thousands of square miles, a system of bolsons (downfaulted basins between adjacent mountains) developed. Material eroded from the adjacent mountains was redistributed as basin-fill deposition within the bolsons. The net effects of the above-described and subsequent geologic activity serve to characterize the hydrogeologic framework of today's aquifers.

The Tertiary Volcanics (Igneous) aquifer in the BIBE area occurs in igneous rocks of Tertiary age similar to those that form much of the Davis Mountain region of Jeff Davis County and extend southward into Brewster County (LBG-Guyton 2001; Ashworth and Hopkins 1995). This somewhat loosely defined collection of groundwater bodies occurs as a series of lava flows, ash flows, and discontinuous basin-fill deposits that are linked through varying degrees of hydraulic connectivity. For data storage and retrieval purposes, the Texas Water Development Board (TWDB) designates wells tapping these strata as belonging to their “120VLCC” category.

The Tertiary Volcanics (Igneous) aquifer is characterized by fractures, crevices, and vesicular zones within upper parts of congealed lava flows that comprise most of this aquifer. The tops and bottoms of the lava layers are generally the most permeable because they typically comprise highly fractured rubble zones caused by the rapid cooling of originally molten lava. Because central parts of the lava flows cool relatively slowly, they remain comparatively dense and, therefore, exhibit less permeability. The general freshness of the water quality, as indicated by its typically low dissolved solids (DS) content, indicates that water is transmitted relatively quickly between land surface and the aquifer. Recharge occurs also from rainfall that infiltrates coarse-grained alluvial fans that skirt many of the mountain flanks. However, due to the hydrologically-disconnected nature of the Volcanics aquifer, the actual amount of water that might be recovered is typically problematic.

Carbonate (limestone and dolomitic) rocks in the area comprise water-bearing zones classified by the Texas Water Development Board (TWDB) as the “Upper Cretaceous Series” or what is known locally as the “Cretaceous Limestone” or “Santa Elena” aquifer. This southern extension of the regionally extensive Edwards-Trinity aquifer (Barker and Ardis 1996) apparently underlies much of the Big Bend area, where it extends westward at least as far as Lajitas, Texas (Far West Texas Water Planning Group 2006). In support of electronic data storage and retrieval systems, the TWDB considers wells completed in these strata in the Big Bend area to be of the “211CRCSU” category. Several of the “K-Bar” wells at BIBE (see Table 15 below) are finished in this carbonate-rock aquifer, which provides most of the park’s well water.

Although both the younger Boquillas Formation and Buda Limestone in Coahilla (Mexico) typically produce limited quantities of (generally) poor quality water, the Santa Elena Formation contains “an undetermined, but apparently significant quantity of good quality water between 1,200 and 1,500 [mg/L] TDS,” according to the Brewster County Groundwater Conservation District. The Santa Elena Formation (Maxwell et al. 1967) is probably the source of most spring discharge into the Rio Grande from Mexico, in addition to being the major groundwater source for recent development near Lajitas and the sole source of water for the Study Butte/Terlingua system (Far West Texas Water Planning Group 2006). The stratigraphic equivalents of the Cretaceous strata that comprise the Edwards-Trinity aquifer system north of the Rio Grande also are major contributors of groundwater inflow to the river and adjacent springs, including that which supports the endangered *Gambusia* at Rio Grande Village (Jeffery Bennett, NPS Science and Resource Manager, written communication, 2008).

Groundwater, including that which issues through the land surface as spring or seep flow, provides the most reliable water supply for Big Bend National Park (MacNish et al. 1996). Much of the aesthetic beauty and biological diversity within the park and along downstream reaches of the Rio Grande Wild and Scenic River (RIGR) depends on the temporal and spatial distribution of these springs and seeps. In addition to being extremely variable over time, spring discharge in the region is sensitive to small variations in the hydrologic balance between recharge and discharge.

Spring inflows to the Rio Grande in western Brewster County and Big Bend National Park “constitute a majority of flow for the Rio Grande through the [park] and Rio Grande Wild and Scenic River...the only substantial section with dependable flows for approximately 900 river miles,” according to Jeffery Bennett (NPS Science and Resource Manager, written communication, 2008). Indeed, stream discharge measurements by the USGS and NPS indicate that such groundwater inflow exceeded 200 cubic feet per second along an interior reach of the Wild and Scenic River during 2006 (William Wellman, Superintendent, Big Bend National Park, written communication, 2008).

Regional potentiometric maps indicate that the deeply entrenched Rio Grande drainage in southern Terrell and Val Verde Counties is a discharge area for the Edwards-Trinity and equivalent aquifers on both sides of the international border (Barker and Ardis 1996, Fig. 16; Boghici 2004, Fig. 7). Steep groundwater gradients toward the river from both sides have historically sustained an outflow of groundwater through a complex of hot and cold-water springs (Boghici 2004; Fig. 3), as well as diffuse upward leakage to the river through permeable parts of the Rio Grande streambed.

The permanency of groundwater discharge from springs and seeps along the Rio Grande is dependant on the long-term stability of aquifers that are hydraulically connected to surface water in the region. A continuation of groundwater discharge to surface-water bodies depends on the maintenance of groundwater gradients toward the areas of spring and streambed discharge. If aquifer water levels are lowered as a consequence of drought or excessive well pumpage, then the gradients will decrease and downgradient reductions in springflow and streamflow can be expected to occur.

The spring complexes along the Rio Grande are threatened by “increased unregulated groundwater pumping in Terrell County,” according to William Wellman (Superintendent, Big Bend National Park, written communication, 2008). Indeed, the results of recent computer modeling (Andrew Donnelly, hydrologist, Texas Water Development Board, 2007) support the possibility of significant water-level declines in the Edwards-Trinity aquifer of Brewster and Terrell Counties associated with the pumpage of groundwater that would otherwise discharge to springs and streams within the Rio Grande drainage system. According to assessments in Mr. Wellman’s recent report to the Far West Texas Water Planning Group, “the long-term response of the Edwards-Trinity (Plateau) aquifer to large-scale groundwater development will be depletion of groundwater discharge to springs and streams.” Not surprisingly, the NPS and BIBE are seeking the protection of these springs and streams from the impacts of future groundwater development.

Groundwater Wells and Water Levels

Table 15 below provides a summary of available well and water-level information for BIBE. In addition to water-level measurements obtained by EARDC personnel during their April 2008 reconnaissance of CHDN parks, this table contains a subset of well and water-level records maintained by BIBE’s staff (Jeffery Bennett, NPS Science and Resource Manager, written communication, 2008). This abbreviated version of the park’s entire database contains information on only 29 of more than 100 wells known to have been dug or drilled within BIBE’s boundaries during the last century. However, it presumably represents the wells that are currently the most important sources (or potential sources) of water and (or) hydrogeologic information relevant to park managers, water-resource planners, and hydrologists. All water-level observation wells at BIBE are highlighted in this table with yellow.

Historical Trends

The hydrographs in Figure 43 illustrate the temporal distribution of available water-level data for the Tertiary Volcanic (Igneous) aquifer that underlies large parts of BIBE. The TWDB’s observation well near the Panther Junction visitor center is the only installation of its type operating within the boundaries of any CHDN park. Other than the network of eight monitoring wells at WHSA, it is the only installation within CHDN designed to electronically track the status of groundwater quantity over time. Cataloged by the TWDB as Brewster County Well 73-47-404, this 620-feet deep borehole is equipped with a continuous recorder and satellite telemetry. Unfortunately, the relatively recent date (May 2007) of this installation prevents its data from being sufficient lengthy to support conclusions regarding long-term groundwater trends in the area’s Tertiary Volcanics aquifer. Of course, this shortcoming will improve over time.

Table 15. Information for selected wells and springs in Big Bend National Park (BIBE).

BIG BEND NATIONAL PARK (BIBE)								
Well Name	**Northing**	**Easting**	**Land Surface Altitude (ft amsl)**	**Well Depth (ft)**	**Aquifer**	**Shallowest Water Level (ft)**	**Deepest Water Level (ft)**	**REMARKS**
Gambusia Spgs Obs #1	3229622	699027	1,777	---	---	2.93	5.28	---
Gambusia Spgs Obs #2	3229650	699014	1,777	---	---	5.65	7.69	---
South Butterbowl Tank #2	3278638	667526	2,900	---	---	75	76.2	Observation Well
Raven Mill	3271804	671553	2,896	202	Tertiary Volcanics	95	96	Observation Well
Oak Springs #1	3240475	661592	4,135	117	ditto	36	---	Igneous
Oak Springs #2	3240413	661807	4,225	184	---	80	---	ditto
T-3 (W. Lone Mtn #1)	3246756	673035	3,617	300	---	76.75	99.75	Observation Well
T-4 (W. Lone Mtn #2)	3246882	672591	3,653	260	---	101.7	127	Observation Well
TH-1 (I-41)	3246154	669649	4,008	387	---	112.3	114.6	Observation Well
TH-2 (Grapevine #1)	3247736	670296	3,785	600	---	80.7	82.3	Observation Well
TH-3 (I-43)	3247242	668280	3,880	600	---	117	---	---
TH-4 (I-44)	3249280	666631	3,589	600	---	---	---	---
TH-6 (Grapevine #3)	3251172	672649	3,380	600	---	55.5	56.25	Observation Well
TH-7 (I-47)	3245745	674868	3,648	600 (?)	---	160	---	---
TH-10 (N. Lone Mtn #1)	3247872	674388	3,459	455	---	37	40.63	Observation Well
TH-10a (N. Lone Mtn #2)	3247888	674394	3,455	459	---	38.66	43	Observation Well
Panther Junction #4	3244726	673603	3,883	217	Quaternary System	151	204	Alluvium
Panther Junction #5	3244745	673610	3,880	240	ditto	154	---	ditto
Panther Junction #5 Obs	3244741	673598	3,880	250	ditto	163	---	ditto
Panther Junction #10 (State Observation)	3244736	673606	3,880	620	Tertiary Volcanics	145.24	173.13	TWDB Observation Well
K-Bar # 2	3243385	676514	3,503	138	Cretaceous Limestone	92	120	---
K-Bar #5	3242878	676954	3,480	109	ditto	52.5	90	Primary water supply
K-Bar # 6	3243386	676526	3,501	145	ditto	112	---	---
K-Bar # 6 Observation	3243389	676544	3,498	165	ditto	109	---	Observation Well
K-Bar # 7 Observation	3242928	676984	3,470	130	ditto	75	---	Observation Well
Dugout Springs Windmill	3239543	681024	2,970	18	Alluvial	7.85	13	---
Cottonwood #1	324245	643615	2,133	48	Rio Grande Alluvium	22	26	---
Cottonwood #2	3224260	643544	2,130	68	ditto	20	27	---
Cottonwood #3	3224396	643674	2,145	132	ditto	33	---	---

Although inconclusive, it is interesting to note that this well’s seemingly precipitous 26-foot drop in head (water level) between the recorder’s installation (May 2007) and March 2008 occurred while BIBE apparently was receiving greater-than-average rainfall (Appendix B2). The sheer depths of the screened and open intervals (180-340 ft and 340-620 ft, respectively) in Brewster County Well 73-47-404 may prevent its water levels from responding as quickly to precipitation as might be expected in shallower wells that tap the Tertiary Volcanics (Igneous) aquifer.

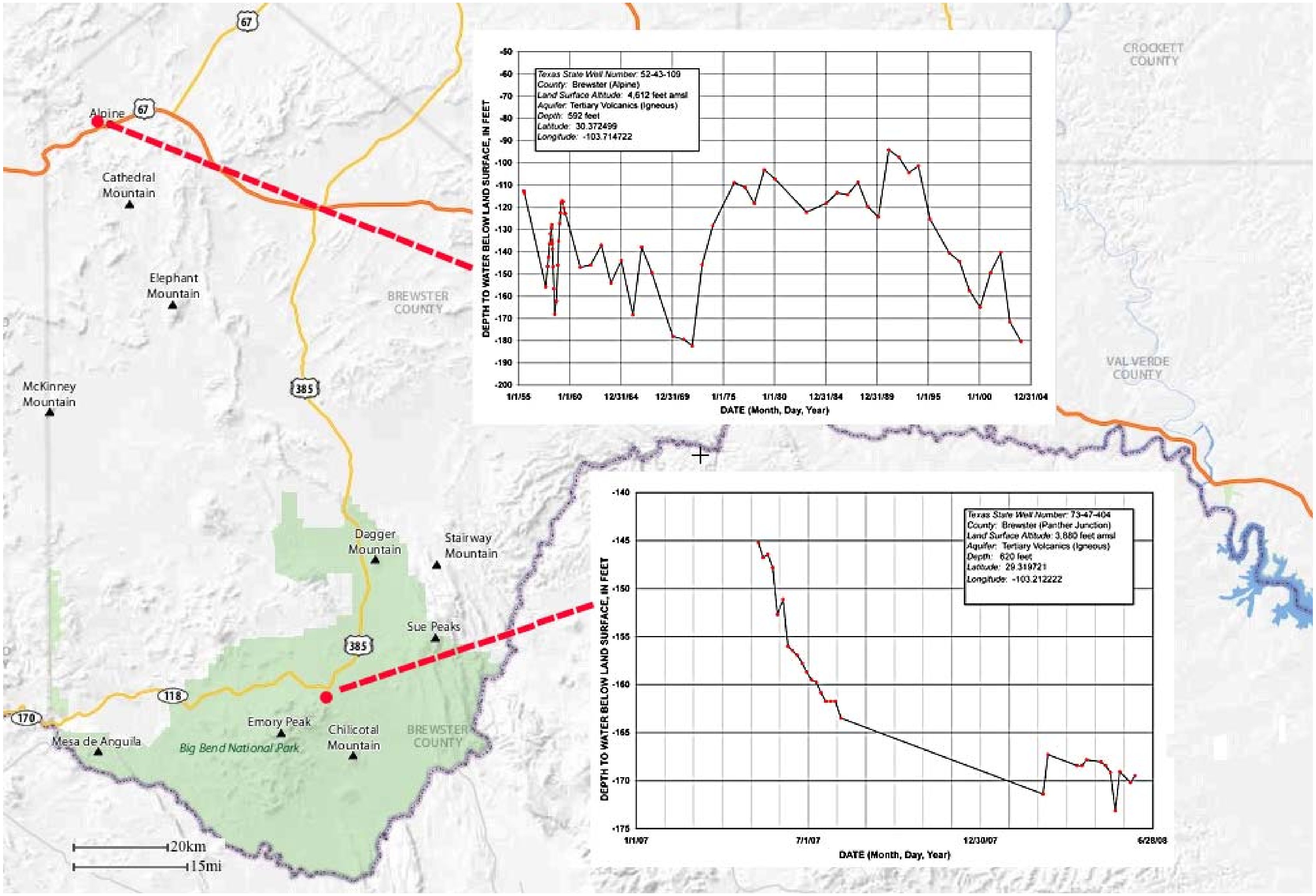


Figure 43. Groundwater hydrographs for Brewster County observation wells, showing depths to water level in the Tertiary Volcanics (Igneous) aquifer in and near Big Bend National Park.

Figure 44 shows the depths to groundwater measured since January 2004 in eleven observation wells inside BIBE (Jeffery Bennett, NPS Science and Resource Manager, written communication, 2008). All wells except for K-Bar #6 and #7 are believed to track water levels in the Tertiary Volcanics aquifer (Table 15). The hydrographs for K-Bar #6 and #7 indicate levels in the Upper Cretaceous (Santa Elena) Limestone aquifer since January 2005. The annual-to-semi-annual frequency of measurement masks the seasonal effects of aquifer recharge and discharge and allows only year-to-year comparisons of groundwater levels below arbitrary datums near land surface. This somewhat limited measurement of frequency and relatively short (4-year) period of observation fails to indicate any significant trend in groundwater quality for BIBE, at least for the time being. Future measurements will afford a longer-term perspective with which to evaluate the status of groundwater resources at BIBE.

To illustrate the effects that comparatively heavy pumping can have in an otherwise similar hydrogeologic setting, a hydrograph is also provided in Figure 43 for an observation well 80 miles away near Alpine, Texas. Both wells penetrate roughly the same thickness of volcanic strata. Being nearly 750 feet higher in elevation than Panther Junction, however, the Alpine area receives roughly six inches, or 55 percent more precipitation on average. Although the additional precipitation and presumed additional recharge might be expected to offset some of the much heavier pumping stress, LBG-Guyton (2007) reports that most wells near Alpine “have experienced some water-level decline since each well’s initial construction.” Indeed, several long-term observation wells near Alpine indicate several tens to hundreds of feet of water-level decline during the last 50 years.

Historical rainfall data for Alpine indicate that the 1970-92 period was one of generally greater-than-average precipitation. This relatively wet interval seems consistent with the pattern of generally increasing water levels in Brewster County Well 52-43-109 during 1970-92. Likewise, the sharp increase in municipal pumpage during 1992-98 (LBG-Guyton 2007) appears to explain the steep decline in Well 52-43-109’s water levels between 1992 and 2000. Based on these historical accounts and the apparent controls on groundwater levels near Alpine, it appears likely that similar associations might exist among precipitation, pumpage, and the resulting water levels in the generically similar Tertiary Volcanics aquifer that underlies large parts of BIBE.

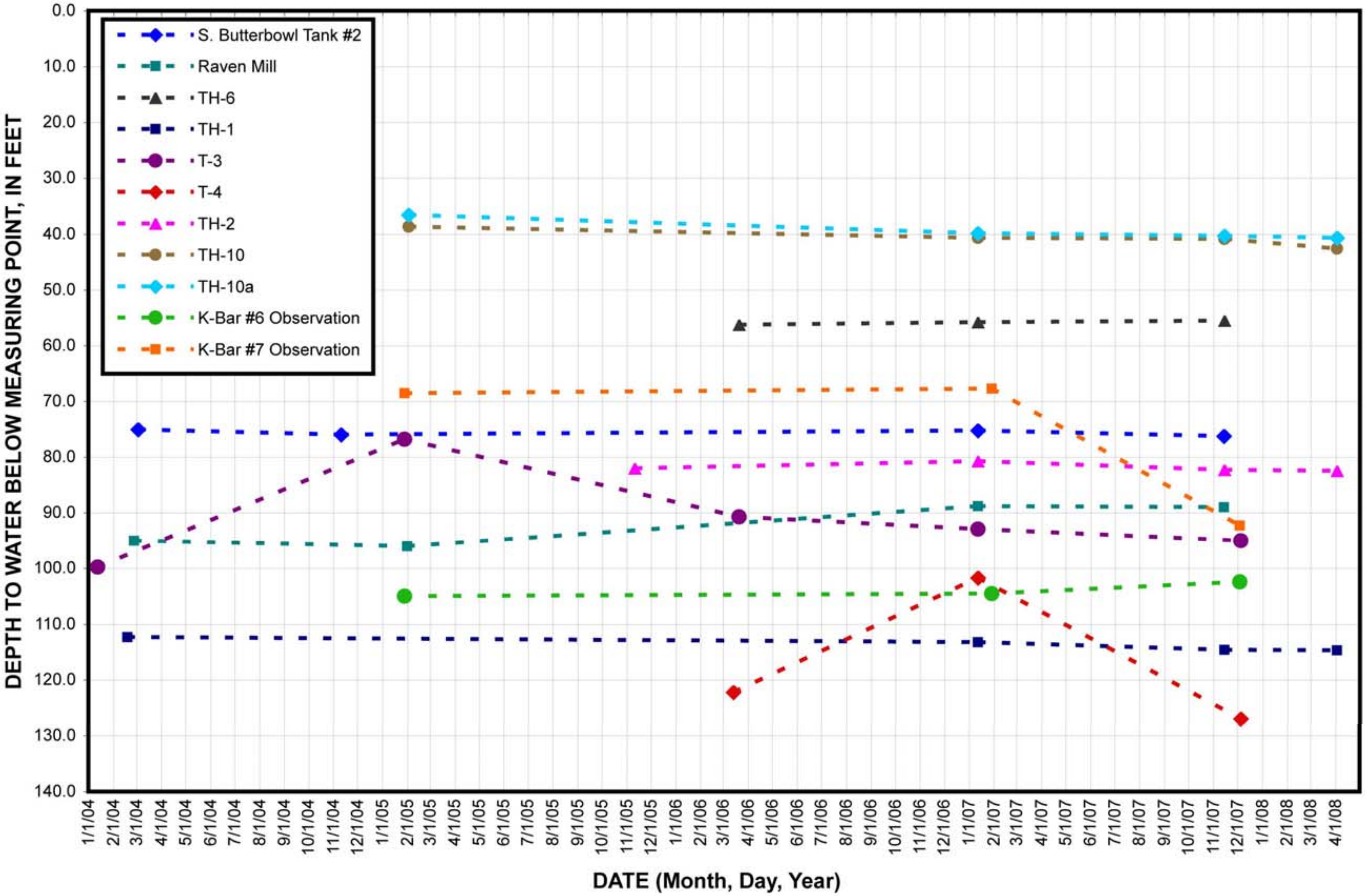


Figure 44. Hydrographs of water levels in Big Bend National Park, showing depths to groundwater in wells tapping the Tertiary Volcanics and Upper Cretaceous (Santa Elena) Limestone aquifers.

Carlsbad Caverns National Park (CAVE)

Hydrogeologic Setting of Rattlesnake Springs

For more than 50 years, Rattlesnake Springs has provided irrigation water for NPS property and for privately owned nearby land, such as Washington Ranch. Water at this site is piped from a water-supply well to park headquarters near the main cavern through a pipeline that was completed in 1935. This 118-ft deep well (see Table 16 below), taps the same coarse alluvial aquifer that sustains the spring. Since 1946, irrigation water for adjacent properties also has been pumped from nearby wells that tap this aquifer.

Since the 1950s, several state and federal agencies and educational institutions have conducted studies to evaluate the origin and conditions of Rattlesnake Springs and the associated aquifer. Since the release of one of the earliest reports of the New Mexico State Engineers Office (Hale, 1955), it was known that the springs represented "the discharge from an aquifer in the alluvium whose source is considered to be southwest of the springs."

As the discharge from Rattlesnake Springs appeared to recede during the 1950s drought, the NPS "became concerned about the diminished flow during the summer months when use of water at Carlsbad Caverns is greatest." Hale (1955) and subsequent investigators recognized that upgradient irrigation wells, when pumping, intercept groundwater that would otherwise discharge at the spring. Litigation involving the hydraulic implications of such capture prompted a cooperative study of the situation during the early 1960s by the USGS, NPS, and New Mexico Department of Game and Fish. The USGS was requested to "prepare a report describing the effects of pumping the three nearby irrigation wells on the flow of Rattlesnake Springs."

The results of this study (Cox 1963), substantiated earlier inferences that the rate of Rattlesnake Springs discharge was lessened as a result of upgradient well withdrawals and further recognized a "common source" of water (from the southwest) that was either pumped from the aquifer or allowed to discharge naturally from the springs. The resulting data also revealed that "some water from the southwest of Rattlesnake Springs must bypass the springs and probably ... discharges at Blue Spring, about 11 miles northeast of Rattlesnake Springs."

Subsequent studies have attempted to quantify the properties of the alluvial aquifer and the degree of interconnection among upgradient wells, including CAVE's own water-supply well, which is located a few hundred feet southwest of the Rattlesnake Springs pool. Mourant and Havens (1964) concluded that "large" yields could be obtained only from wells in the area that "penetrate solution channels in stringers of conglomerate." Their specific conductance measurements of water collected at "various spots in the pool area" lead them to deduce that the water discharging from Rattlesnake Springs is a mixture of water issuing from several openings at the bottom of the spring pool. Interestingly, Mourant and Havens also found that the overall quality of water in the Rattlesnake Springs pool "improves when the pool level is lowered by pumpage of these irrigation wells to the southwest."

A Master Thesis study supported by digital modeling (Bowen 1998) indicated that observed variations in discharge from Rattlesnake Springs were controlled mostly by fluctuations in annual precipitation. According to Bowen, “Fluctuations in annual precipitation are transmitted by the [groundwater-flow] system and observed as seasonal variations in discharge.” The results of model projections led Bowen to further conclude that the effects of 40 years of agricultural development in the area had evolved to the extent that such development “can be considered part of the current equilibrium” such that the current [1998] level of agricultural impact was “minimal.” Bowen continued to conclude, however, that increased rates of well withdrawals could have a “significant” effect on Rattlesnake Springs “either by withdrawing directly from the flow to the springs or by decreasing flow to the Black River and altering the base level of the system.”

Groundwater Wells and Water Levels

Table 16. Well information for Rattlesnake Springs.

CARLSBAD CAVERNS NATIONAL PARK (CAVE)								
Well Name	**Northing**	**Easting**	**Land Surface Altitude (ft amsl)**	**Well Depth (ft)**	**Aquifer Material**	**Shallowest Water Level (ft)**	**Deepest Water Level (ft)**	**REMARKS**
Rattlesnake Springs	3552672	549830	3,640	118	Conglomerate	1	---	Drilled 1963 (?)

Historical Trends

The following set of hydrographs is provided as follow-up to earlier studies of the Rattlesnake Springs area. The upper chart shows the mean daily springflow from Rattlesnake Springs between January 1, 2001 through December 31, 2007 (Paul A. Burger, NPS geohydrologist, written communication, 2008). The lower chart shows three hydrographs of water levels in USGS observation wells that were first monitored during the 1950s and 1960s as part of ongoing hydrogeological studies of the Rattlesnake Springs flow regime. Although the overlapping period of the two charts is limited to 2001-2006, the overall downward trend in both springflow and groundwater levels since at least January 2001 is obvious. Despite not showing springflow rates prior to 2001, the groundwater hydrographs in Figure 45 indicate that recharge to the area’s flow regime was probably decreasing since about 1990. Indeed, the annual precipitation totals for the area also reflect a similar pattern of a significant precipitation deficit in the area beginning about 1989, through at least 2004 (Appendix B3).

The seasonal patterns of springflow variation reflected in the upper chart mirror a description of groundwater patterns provided over 50 years ago by Cox (1963). Cox described groundwater levels in the Rattlesnake Springs area as being generally highest over the winter (October through March), before pre-planting irrigation began, and typically lowest during the summer months, when irrigation demands were greatest. The dominant forces behind the historic relations among precipitation, groundwater levels, and springflow that Cox (1963) and Bowen (1998) noted earlier do not seem to have changed significantly.

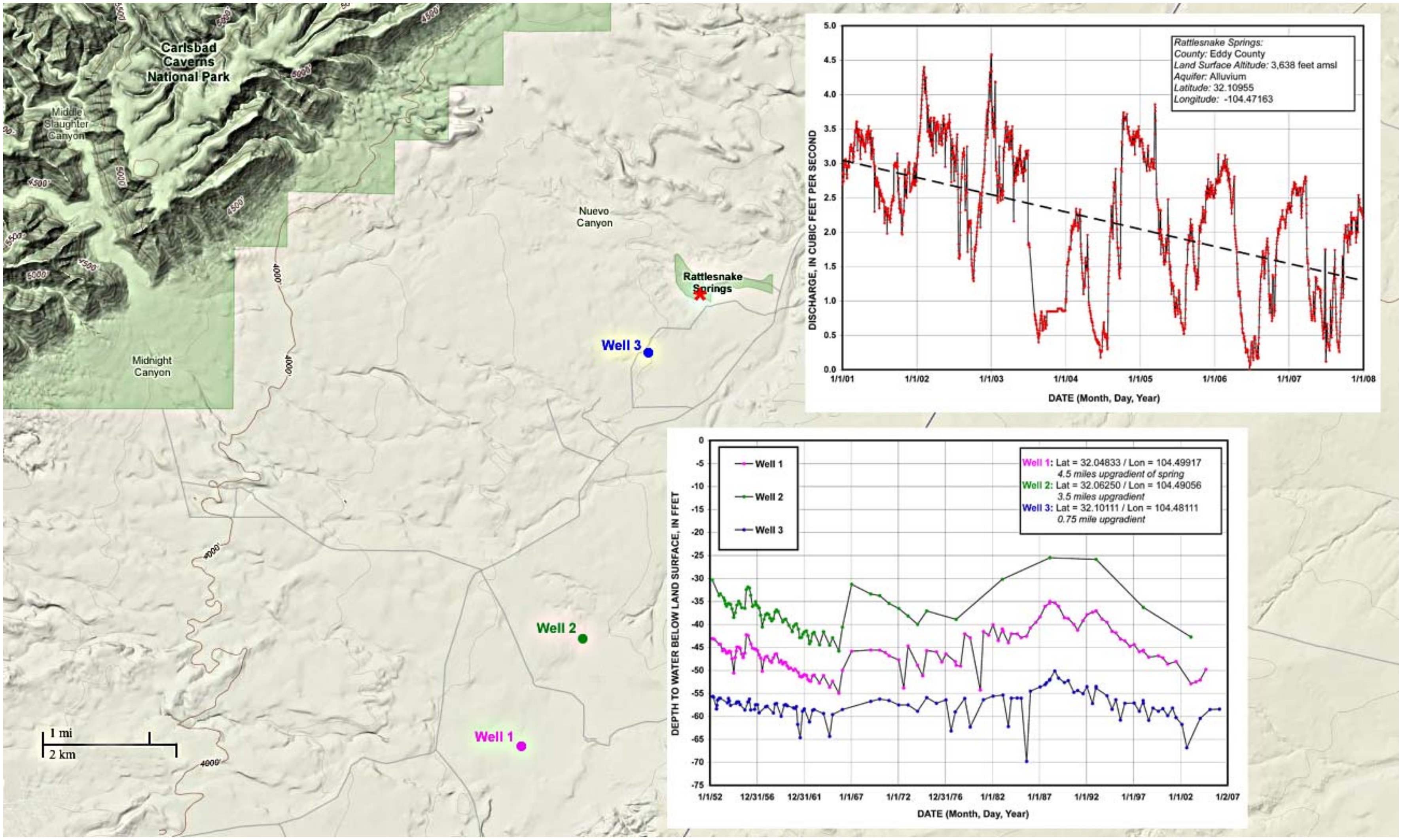


Figure 45. Hydrographs of discharge from Rattlesnake Springs and of water levels in selected alluvial aquifer wells within five miles of Carlsbad Caverns National Park.

Fort Davis National Historic Site (FODA)

Hydrogeologic Setting

The steep, columnar-rock backdrop to the Fort Davis National Historic Site (FODA) is comprised of the same igneous strata of Tertiary age that crop out over most of Jeff Davis County and form impressive buttes in the surrounding Davis Mountains. Most of these igneous rocks are represented by intrusions that cut through—or volcanic flows that overlie—thick sequences of younger carbonate rocks deposited in marine settings during the Cretaceous Period. Because the centers of volcanic activity shifted from place to place across the Trans-Pecos landscape over long intervals of geologic time, the terrain today is dominated by massive occurrences of volcanic material (Chastain-Howley 2001).

During the latter part of Tertiary time, as igneous activity began to wane, tensional forces in the earth's crust produced a series of downfaulted basins across wide expanses of igneous and older carbonate strata. During a particularly violent period of crustal instability and extension, blocks of igneous material dropped downward relative to adjacent blocks that remained relatively elevated (Muehlberger and Dickerson 1989). As the down-dropped blocks settled into lower positions, streams draining the structurally higher areas deposited thick sequences of eroded sedimentary and volcanic detritus in the basins, or bolsons. These bolsons are now filled or partly filled with Quaternary alluvial deposits, which—depending on their interconnectivity and proximity to recharge—may or may not represent viable aquifers with potential sources of potable groundwater.

Regardless of whether an alluvial-filled boson is relevant to the local groundwater-flow system, the Tertiary Volcanics (Igneous) aquifer is far more complicated than that expected from a simple collection of typical lava flows (Chastain-Howley 2001). This aquifer generally consists of spatially variable, somewhat discontinuous, permeable zones within a "complex layering of vents, flows, and interbedded volcanic-sedimentary units, which were deposited in the many intervals between eruptions." Because the different physical components are not necessarily linked hydraulically, the resulting hydrogeologic framework and associated aquifer characteristics can be extremely complex.

Although the history of faulting and fracturing in the region tends to increase the potential for connection among the various components, the distribution of groundwater near FODA is affected by three-dimensional aspects of the local hydrogeologic framework. Due to both lateral and vertical facies changes and structurally dislocated water-bearing strata, groundwater levels can vary by several hundreds of feet between closely spaced wells. Similar water-level discordance can result also from the rugged topography and (or) the highly variable porosity and storage capacity of the dominant volcanic-rock types (LBG-Guyton 2001).

Groundwater generally occurs within and migrates through fractures and rubble zones typically associated with the tops and bottoms of lava flows. Considerable recharge to the Tertiary Volcanics aquifer results from precipitation infiltrating land surface and percolating deeper through fractures—especially in areas where fractures intersect streambeds that drain mountain watersheds. Recharge also results from the infiltration of rainfall through coarse-grained alluvial fans that border the mountains. However, due to the hydrologically-disconnected nature of this aquifer, the actual amount of recoverable water is likely much less than that originally recharged.

The principle directions of groundwater flow near FODA radiate away from the higher-elevation mountainous terrain toward the topographically lower areas (LBG-Guyton 2001, Fig. 9). Most discharge results from well withdrawals and springflow. There is little indication of prolonged groundwater discharge to perennial streams.

Some wells in the Fort Davis area penetrate and withdraw water from the alluvial-filled bolsons or erosional channels that breach the lateral continuity of individual lava flows. The TWDB classifies the collective nature of the producing strata in such cases as “110AVTV,” which relates to the Alluvium and Tertiary Volcanics aquifer. This aquifer has been monitored in the FODA area since 1967 through water-level measurements in the Jeff Davis County (observation) Well 52-25-309 (Fig. 46).

The Tertiary Volcanics (Igneous) aquifer is the sole source of water for the residents of Fort Davis. The city relies on water for its municipal supply from the locally known Davis Mountains aquifer, which includes the Barrel Springs Formation and associated alluvium (LBG-Guyton 2001).

According to LBG-Guyton (2001), sufficient groundwater exists within the Tertiary Volcanics (Igneous) aquifer system to meet projected water-supply needs in most parts of Jeff Davis County. However, unpublished reports, letters, and notes regarding well installations at FODA indicate a history of concern regarding the long-term dependability of potable water sources for the park. A key management issue is the need to avoid excessive pumpage from existing well fields. For this reason, LBG-Guyton recommends the spreading of wells over as wide an area as possible in order to minimize the cumulative effects of well-field drawdown.

Table 17. Information for selected wells at Fort Davis National Historic Site (FODA).

FORT DAVIS NATIONAL HISTORIC SITE (FODA)								
Well Name	**Northing**	**Easting**	**Land Surface Altitude (ft amsl)**	**Well Depth (ft)**	**Aquifer**	**Shallowest Water Level (ft)**	**Deepest Water Level (ft)**	**REMARKS**
Church Camp, Original	---	---	---	48	---	38.4	---	---
Church Camp # 2	3385305	605321	4,965	240 (?)	Tertiary Volcanics	93.06	---	Well depth unresolved
Oak Grove	3385485	605979	4,915	---	ditto.	77.37	---	Well depth unresolved
Maintenance Area	3385738	606696	4,870	---	---	30.65	---	Well depth unresolved

Groundwater Wells and Water Levels

Table 17 contains a summary of available information on water wells at FODA. Although no historical water-level data are available, the shallowest water levels listed in this table were measured by EARDC personnel during their April 2008 reconnaissance of CHDN parks. From minimal available records, it appears that FODA has experienced a varied history of groundwater sources, particularly from wells of different depths in different places. Without information that could not be recovered for this report (John Heiner, NPS Chief of Interpretation, written communication, 2008), there is no way of knowing how "shallow" or "deep" these April 2008 measurements might be compare to actual historical conditions.

Historical Trends

The water-level hydrographs in Figure 46 reflect groundwater trends in wells both east and west of FODA. Compared to the two eastern wells with depths of less than 100 ft, the western installation (Jeff Davis County Well 52-25-209) maintained by Davis Mountains State Park, is comparatively deep with a depth of 392 ft below land surface. The much higher land surface elevation (5,080 ft) associated with the State Park well might explain why it is nearly 200 ft deeper than even its deepest eastern counterpart (Jeff Davis County Well 52-25-308). Likewise, the east-to-west difference of more than 100 ft in the depths to groundwater is probably explained by the associated differences in surface elevation.

Despite several examples of similar water-level disparities in central Jeff Davis County, LBG-Guyton (2001) concluded "most of the largest differences in the depth to groundwater between nearby wells are attributable to differences in surface elevation." Considering the differences in construction related to their different locations and land surface elevations, all three observation wells represented in Figure 46 likely penetrate the same permeable zone and, thus, are likely hydraulically connected.

Although none of the hydrographs in Figure 46 indicates a water-level change exceeding +/- 5 ft, all three hydrographs appear to track a slightly downward trend since the beginning of their periods of record. Despite different time scales, the hydrographs for all three wells appear to track a remarkably similar pattern of water-level response to aquifer conditions, most notably those related to recharge from precipitation and pumping from nearby wells. The sharpest drop of water in (aquifer) storage is indicated in the hydrograph for Jeff Davis County Well 52-25-309 during the 1991-2003 interval. This water-level decline mirrors the drop in the 10-year moving average rate of precipitation during 1991-2003 at Fort Davis, as illustrated in Appendix B4. The fate of groundwater contained in the Tertiary Volcanics aquifer near FODA is obviously very closely related to departures from the area's long-term average rate of precipitation.

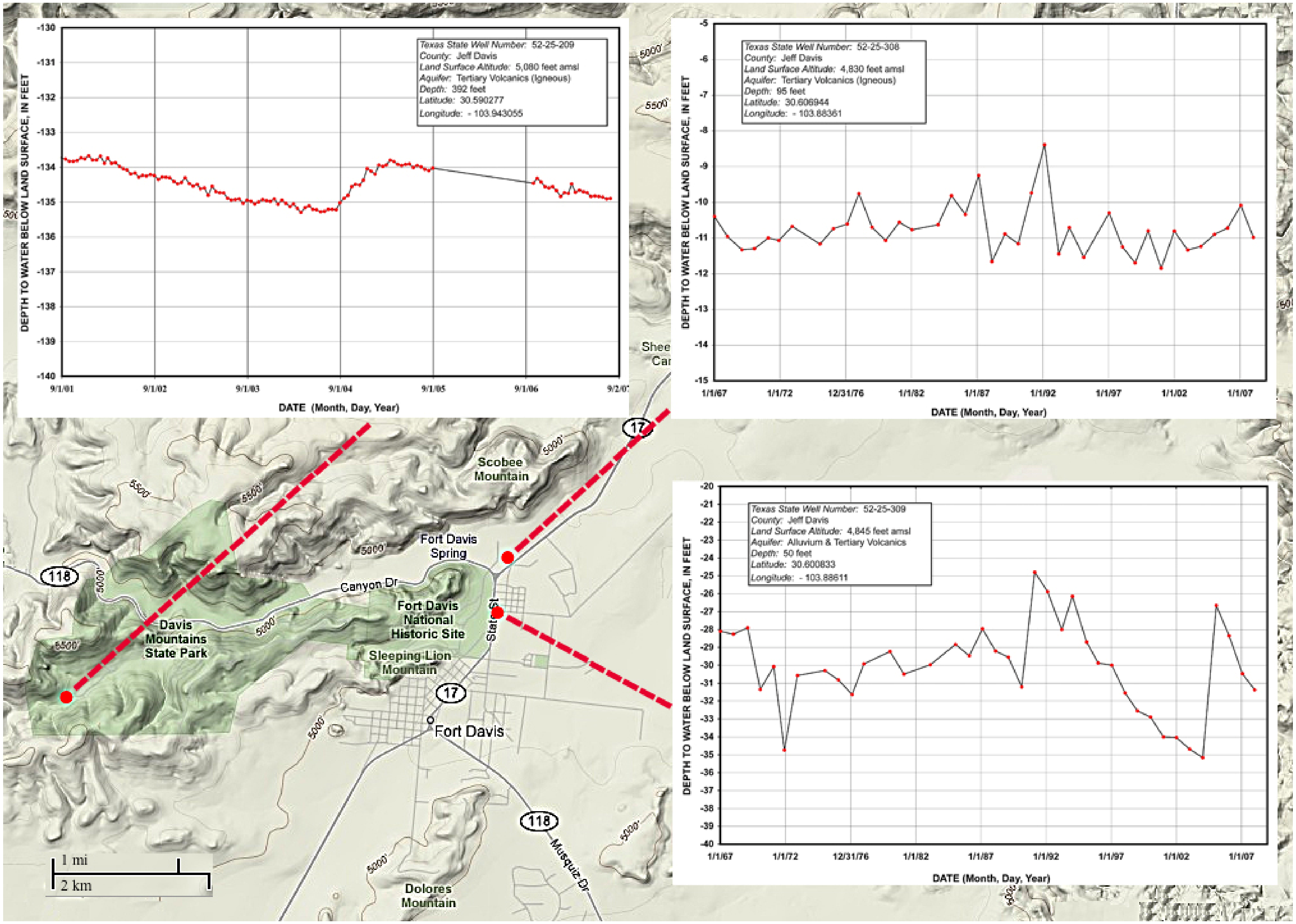


Figure 46. Groundwater hydrographs for Jeff Davis County observation wells, showing depth to water in Igneous and Igneous and Alluvial aquifers near Fort Davis National Historic Site.

Guadalupe Mountains National Park (GUMO)

Hydrogeologic Setting

Roughly 250 million years ago, decaying marine organisms accumulated upon a shallow shelf that nearly encircled the Delaware Basin, a marine embayment that persisted throughout most of the Permian Period. The proliferation of organisms (predominantly coralline algae, sponges, and byrozoans) associated with this buildup evolved into a reef several hundreds of feet thick. Continued sedimentation and tectonism buried the reef as the ocean subsequently withdrew (Uliana 2001). The area was subsequently uplifted by massive compressional forces. Within the past ten to twelve million years, erosion has worn down the softer sedimentary rock and exposed large blocks of the Permian limestone that comprise the Capitan Reef. In a process that continues today, detrital material eroded from the reef was transported downgradient to form the expansive salt flats west of today's park boundaries.

West of the Permian Reef Complex, the Salt Bolson forms a closed alluvial basin that extends from just north of the New Mexico border into Hudspeth and Culbertson Counties of Texas, and southward into Jeff Davis County (Angle 2001). This basin is a downfaulted block (graben) filled or partly filled with Tertiary and Quaternary alluvial and lacustrine deposits that separate the Permian rocks underlying Dell Valley from the exposed Permian Reef Complex to the east (Ashworth 1995). The municipality of Dell City is situated over the central part of Dell Valley (Fig. 47).

The Permian rocks that directly underlie Dell Valley (on the west) and the Capitan Reef Complex (on the east) are called the Bone Spring and Victorio Peak Limestones. The Bone Spring Limestone grades upward into the younger Victorio Peak unit. Together, these limestone formations are probably at least 1,500 feet thick. Both units exhibit the karstic effects of solution cavities that formed along bedding planes, joints, and fractures (Ashworth 1995). Groundwater is pumped in the Dell City area from these cavities associated with the dissolution of limestone and dolomitic carbonate strata. These strata provide most of the irrigation water pumped in the Dell City area, as well as being the major source of municipal water supply.

Groundwater supplies at GUMO are potentially affected by at least three widespread aquifers in addition to locally important permeable zones within the expansive alluvial fan complex that skirts the eastern front of the Guadalupe Mountains. Listed in order of distance from and decreasing relevance to the current sources of water at GUMO (Gordon L. Bell, NPS Geologist, verbal communication, 2008), these aquifers are (1) the Capitan—or Capitan Reef Complex—aquifer, (2) Bone Spring-Victorio Peak aquifer, and (3) Salt Bolson and Delaware Mountain Group aquifer. The hydrographs presented below show the effects of recharge to and pumping withdrawals from these aquifers. Recharge to all these aquifers is minimal due to the region's limited precipitation and high rates of evaporation.

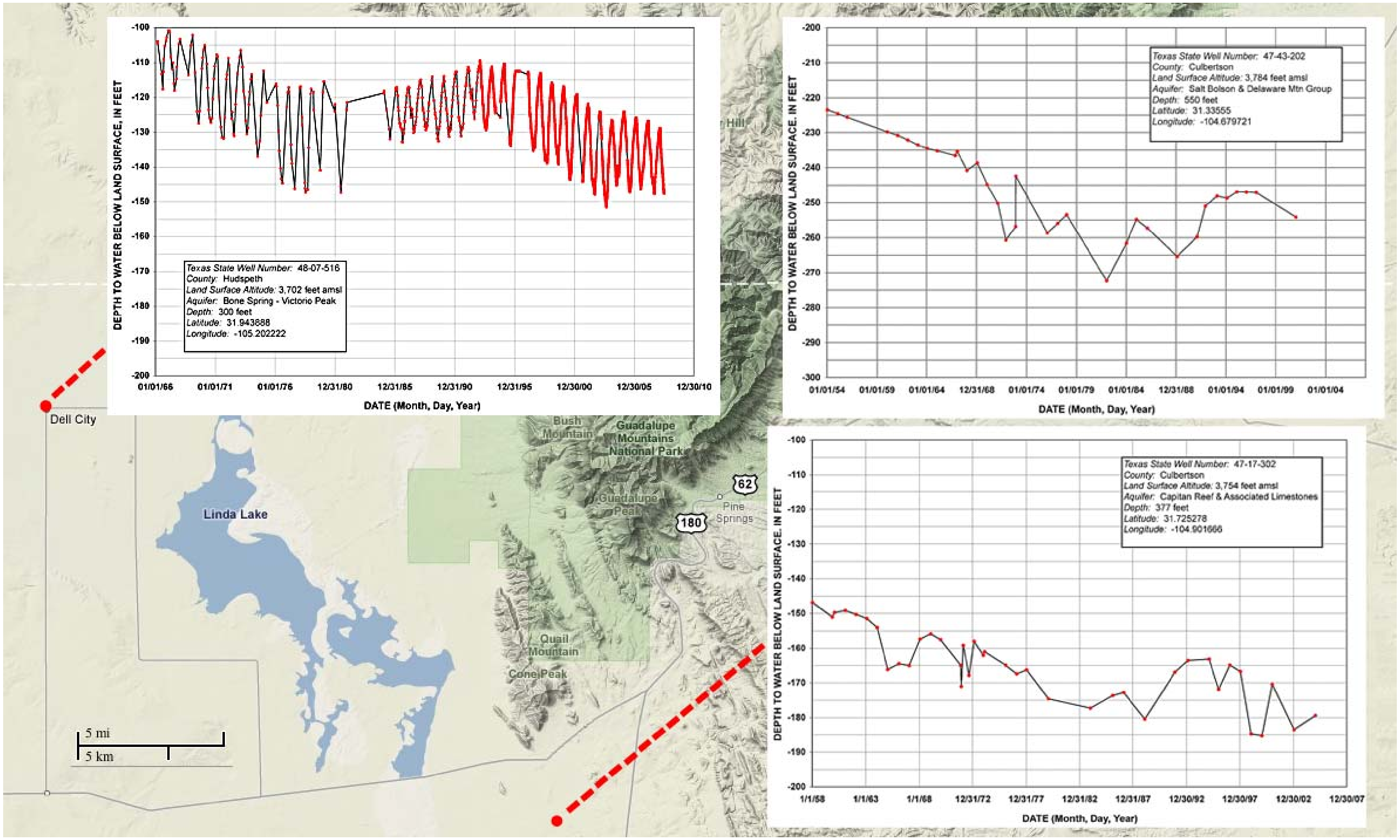


Figure 47. Groundwater hydrographs for Culbertson and Hudspeth County observation wells, showing depths to water in selected aquifers near Guadalupe Mountains National Park.

The Capitan (Reef Complex) aquifer comprises the saturated remains of a vast reef that wrapped around the Delaware Basin between 280-225 million years ago. The aquifer is composed of up to 2,360 feet of dolomite and limestone strata that was deposited within reef, fore-reef, and back-reef facies. Permeability and well yields are generally high, but the water quality typically is too poor for municipal or irrigation use (Ashworth and Hopkins 1995). The water primarily is sodium-chloride-sulfate water with an average TDS greater than 3,000 mg/L. Water of the freshest quality is found near areas of recharge, where the reef is exposed at the surface, such as in the higher elevations of southeastern New Mexico.

The regional patterns of groundwater flow have been altered as a result of Pecos River down cutting and by the development of groundwater and petroleum resources (Hiss 1980). Although higher-permeability zones within the Capitan aquifer result in a concentration of flow along the trend of the reef, generally toward the north and northeast, the prevailing pattern of regional flow is away from GUMO, toward the east (Uliana 2001).

Most of the groundwater pumped from the aquifer in Texas is used for oil reservoir water-flooding operations in Ward and Winkler counties. A small amount is used for irrigation of salt-tolerant crops in Pecos and Culberson counties. The aquifer is potable enough to provide an abundance of freshwater to the city of Carlsbad, New Mexico. The Capitan Reef Complex is also tapped by GUMO’s Pine Springs (Glover #13) well, the park’s “main water supply,” according to Gordon Bell (NPS Geologist, verbal communication., 2008).

The Bone Spring-Victorio Peak aquifer is tapped almost exclusively for irrigation purposes where it occupies the eastern edge of the Diablo Plateau west of the Guadalupe Mountains in northeast Hudspeth County, Texas and extends northward into the Crow Flats area of New Mexico. The Bone Spring and Victorio Peak Formations that comprise this aquifer are composed of as much as 2,000 feet of Early Permian limestone strata that contain groundwater in joints, fractures, and solution cavities.

The occurrence and availability of groundwater is highly variable (Uliana 2001), resulting in well yields that range from about 150 gallons per minute (gpm) to more than 2,000 gpm (Ashworth 2001). Dell City is the only community that withdraws water from the aquifer for public supply. This aquifer also underlies GUMO at depths greater than the Capitan Reef Complex of Late Permian age that the park currently uses as one of its potable water sources.

According to Ashworth and Hopkins (1995), groundwater from the Bone Spring-Victorio Peak aquifer commonly contains between 2,000 mg/L and 6,000 mg/L dissolved solids. However, the water is generally acceptable for irrigation. Because the water does not meet drinking-water standards, the community of Dell City must use a demineralization process before distributing it to domestic customers. The quality of groundwater has deteriorated over time as evaporites and other salty compounds (leached from shallow soil horizons by irrigation return flow) have percolated deeper into the saturated zone.

The West Texas Bolsons aquifer system of far-west Texas comprises several alluvial aquifers situated in deep basins filled with Quaternary-age sediments of both igneous and sedimentary origin. These physically-connected basins contain significant quantities of groundwater in the bolson deposits and potentially in underlying, fractured volcanic rocks. The deposits in each basin differ, depending on the type of rock material that was eroded from the adjacent uplands and on the manner in which this material was deposited. According to Ashworth and Hopkins (1995), these sediments range from coarse-grained volcanic and limestone remnants that were redeposited as alluvial fans to fine-grained silt and clay lacustrine (lakebed) deposits. Although some well yields reportedly exceed 3,000 gpm, most wells produce less than 1,000 gpm. Water quality differs from basin to basin, ranging from fresh to slightly saline.

The northernmost segment of this aquifer complex with permeable zones potentially important to GUMO is classified as the Salt Bolson and Delaware Mountain Group (aquifer code: “112SBDM”) by the TWDB. This aquifer underlies the Salt Flat area described above. Unfortunately, despite rare exceptions, most groundwater pumped from the alluvial fill is too highly mineralized to be suitable drinking water. Accordingly, most wells in the Salt Flat area penetrate entirely through the alluvial overburden and are completed in the underlying Capitan Formation or Delaware Mountain Group of Permian age (Angle 2001). Although this aquifer has been considered as a potential water supply for GUMO, the aquifer likely is susceptible to future water-level declines due to the area’s increasing demand for irrigation and potable drinking water.

Groundwater Wells and Water Levels

Table 18. Information for selected wells in or near Guadalupe Mountains National Park.

GUADALUPE MOUNTAINS NATIONAL PARK (GUMO)								
Well Name	**Northing**	**Easting**	**Land Surface Altitude (ft amsl)**	**Well Depth (ft)**	**Aquifer**	**Shallowest Water Level (ft)**	**Deepest Water Level (ft)**	**REMARKS**
Pine Springs (Glover #13)	3528920	516304	5,840	2,577	Capitan Reef Complex	2,186	---	Main Park Supply Well
McKittrick Canyon RS	3538148	523156		76.5	---	57.5	---	Coarse Alluvium
Sara Ann (Dog Canyon)	3539709	515635		2,970	---	2,484	---	Limestone
Ship of the Desert	3536372	521690	5,550	155	Capitan Reef Complex	---	---	Permian Limestone
Pratt Cabin	3538608	520740	5,400	27		---	---	Coarse Alluvium
Signal Peak	3523404	516029	4,565	1,240 (?) 1,500(?)	Capitan Reef Complex	357.6	---	Permian Limestone
PX	3537298	504882	3,867	250-300	---	234.4	---	---

Historical Trends

Because none of the GUMO-operated wells (Table 18) afford water-level histories, hydrographs of water levels in the three closest wells with long-term water-level records are presented in Figure 47. None of the wells is located closer than six miles from a GUMO park boundary. The westernmost observation well (Hudspeth County 48-07-516) is a former public supply well that is currently owned and maintained by the Dell City Community Center. Both of the other privately owned wells lie south of GUMO; one (Culbertson County Well 47-17-302) is located on the provided map and the other (Culbertson County 47-17-302) is 39 miles further south, too far to be shown on Figure 47. The Dell City well, which monitors activity affecting the Bone Spring-Victorio Peak aquifer, has been retrofitted with a continuous recorder; thus, the thickly clustered nature of its hydrograph trace. The closest well (Culbertson County 47-17-302) penetrates and presumable reflects conditions the Capitan Reef and Associated Limestones aquifer--of the same Permian aquifer complex supporting GUMO's Pine Springs (Glover #13) supply well, and other wells within the park (Table 18). Despite tapping three different aquifers and presumably reflecting the effects of different stresses, none of the water levels in any of these wells indicates a span between the highest and lowest of water levels that exceeds +/- 20 ft.

Despite being 30 miles apart and apparently tapping different aquifers, the hydrographs for the two wells south of GUMO reflect similar patterns of water level behavior. Although direct correlations to area precipitation (Appendix B5) are not necessarily obvious in either of the southern-well hydrographs, the water levels track rather similarly during the course of the common period of record (1958-2000). Both hydrographs indicate a sharp rise in water levels beginning in 1989, following a "leveling-out" period over the preceding 15 years or so. This "leveled-out" interval appears consistent with Angle's (2001) assessment that "pumping has been fairly steady at about 2,600 acre-ft/yr from 1974 through 1994."

The highest water levels since the early 1970s in any of the three wells occur during the mid-1990s. This most-recent period of water-level highs, shared among three hydrographs, appears to correspond to the three consecutive years of sharply increasing precipitation in the GUMO area during 1994-96 (Appendix B5). Although the measurement frequencies associated with the water levels observed in the two southern wells are not sufficient to show the seasonal effects of pumping, the continuously recorded levels in Dell City's (Hudspeth County 48-07-516) well show a striking similar year-to-year pattern of seasonal pumping cycles as a result of irrigation-well pumpage in support of this community's farming economy.

White Sands National Monument (WHSA)

Hydrogeologic Setting

According to Huff (2005), an assortment of basin-fill deposits collectively form what is conveniently called the "basin-fill aquifer" within the larger Tularosa Basin of south-central New Mexico. The basin fill results from the re-deposition of material eroded from the surrounding mountains and fluvial sedimentation within the ancestral Rio Grande basin. Unconsolidated coarse- to fine-grained coalescing alluvial-fan deposits skirt the basin and grade basinward into progressively finer-grained fluvial and lacustrine deposits. The thickness of this aquifer ranges from less than 100 feet in areas overlying uplifted blocks of bedrock to as much as 4,000 ft elsewhere.

In contrast to the brackish-to-briny quality of the groundwater in central parts of the basin, Huff reports that the deepest fresh groundwater is located along the margins of this basin, in areas remote from the downgradient concentration of salts. Evaporite minerals, principally selenite, are continuously precipitating from the briny water associated with Lake Lucero, which occupies the lowest elevations in this closed basin. The selenite crystals eventually break into sand-size grains that are picked up and redistributed throughout WHSA's dune field by prevailing southwest winds.

Although no "areally extensive confining unit" was recognized in the basin-fill aquifer by Huff (2005), an unpublished account by Bill Conrod (former WHSA Natural Resource Specialist) indicates the existence of an "organic-smelling" clay layer that appears to underlie the gypsum dunes in the picnic-loop area at a depth of about 25 ft below land surface. Mr. Conrod describes this clay as a lakebed remnant of Pleistocene age associated with ancient Lake Otero that predates Lake Luceno and "shrank with modern climate drying." The shoreline and bed deposits of the former Lake Otero presumably retreated horizontally and vertically to a lower elevation now conforming to the present-day Lake Lucero. According to Mr. Conrod, "The clay formation underlying the dunes acts as an aquatard (impermeable layer), probably isolating the sand above from the general aquifer." Mr. Conrod continues to conclude that the "abundant moisture in the sand above the clay is most likely rain water."

Indeed, a comparison of water-level elevations in Huff's (2005, Fig. 10) publication (scope associated with entire Tularosa Basin of south-central New Mexico) with those measured since 1997 in WHSA's network of relatively shallow observation wells (see Table 19 below) indicates water elevation differences on the order of 80 ft. This difference (between shallow water levels beneath the dunes and the deeper, regionally-distributed potentiometric heads) supports Mr. Conrod's conclusion regarding the existence of a perched, shallow aquifer that directly underlies the dune field—at least where monitored by the clustered sets of observation wells near the picnic loop and park headquarters.

It is significant to note that water levels measured in WHSA's Lake Lucero monitoring well (Fig. 48)—unlike those measured from wells to the northeast—do appear to conform to the same potentiometric level depicted in Huff's Figure 10 for the deeper, basin-fill aquifer. This circumstance suggests that the 80-ft water-level disparity between the perched and deeper zones (near the picnic loop and park headquarters) likely decreases—if not disappears altogether—away from the dune field, toward the lowest-lying part of the basin currently occupied by Lake Lucero.

Table 19. Information for selected wells in White Sands National Monument.

WHITE SANDS NATIONAL MONUMENT (WHSA)								
Well Name	**Northing**	**Easting**	**Land Surface Altitude (ft amsl)**	**Well Depth (ft)**	**Aquifer**	**Shallowest Water Level (ft)**	**Deepest Water Level (ft)**	**REMARKS**
WHSA MW - 001	3632406	381332	3,994	25	Shallow, perched aquifer	1.20	3.89	Lacustrine deposits
WHSA MW - 002	3631479	381382	3,996	30	ditto	1.75	5.54	ditto
WHSA MW - 003	3628269	389221	4,002.94	40	ditto	18.17	19.95	ditto
WHSA MW - 004	3627424	390014	3,991.52	37	ditto	8.55	12.41	ditto
WHSA MW - 005	3626565	389404	3,991.24	29	ditto	8.62	11.39	ditto
WHSA MW - 006	3631373	382087	3,998	29.5	ditto	0.67	3.44	ditto
N L. Lucero	3618672	363992	3,895	---	ditto	2.75	5.30	ditto
NE Boundary	3637808	392159	4,045	---	ditto	11.65	13.55	ditto

Groundwater-Monitoring Network of Observation Wells

From the unpublished account by Mr. Conrod:

> *In the early 1990s, monument resource management staff attempted construction of improvised water monitoring wells by using a motorized post hole auger to bore holes and placing stainless steel pipe. These wells did not conform to state monitoring well requirements, such as a concrete collar at ground level, bentonite backfill around the pipe to prevent surface water contaminating ground water, and a lockable cap. ...Two of these non-conforming wells (NE boundary and north Lake Lucero) are still used for monitoring of depth to ground water.*
>
> *In 1997, a grant administered by the NPS Water Resource Division funded construction of six monitoring wells (three in the picnic loop and three around headquarters). These were constructed by a well service to comply with New Mexico monitoring well standards. ...These have been used for obtaining water samples for organic (looking for potential solvent contaminants-none detected) and inorganic chemical analysis in the late 1990s, and for measuring depth to ground water for ongoing monitoring. ...Depth to ground water data has been collected since 1997, with a goal of quarterly measurements at eight wells.*

Table 19 summarizes the locations and other key information regarding the monitoring wells described by Mr. Conrod. The distributions of water levels collected from these installations between November 1997 and January 2008 (David Bustos, NPS Biologist, written communication, 2008) are illustrated in the form of hydrographs in Figure 48.

Historical Trends

Despite a slightly downward track of water levels that appears to have rebounded since the summer of 2004, there is not much to describe regarding obvious trends in the groundwater hydrographs in Figure 48. Despite the indication of an overall east-to-west decrease in the depths to water, the water levels in all eight monitoring wells appear, for the most part, to reflect the effects of similar phenomena within a common hydrologic framework. Water levels observed in MW-03 might reflect an exception to this generalization, because this well's depths to water far exceed those of any other monitoring well in the network. It is possible that the relatively deep water levels in MW-03 are the result of higher evapotranspiration rates related to comparatively lengthy tap roots of specific vegetation types that do not subsist in the dune field.

All wells, except for possibly NL Lucero (as explained above), presumably tap a perched flow regime that is not subjected to pumping. The observed water-level fluctuations must, therefore, reflect the net effect of evapotranspiration and recharge from precipitation that vertically infiltrates the overlying soil or sand. The long-term rates of annual (1895-2007) precipitation (extrapolated to vicinity of NPS visitor center) are shown in Appendix B6. Rather than being the result of east or west positioning, the apparent westerly decrease in the depth to groundwater might relate more to whether a given well is located within or outside the dune area—which would likely entail entirely different water budget considerations.

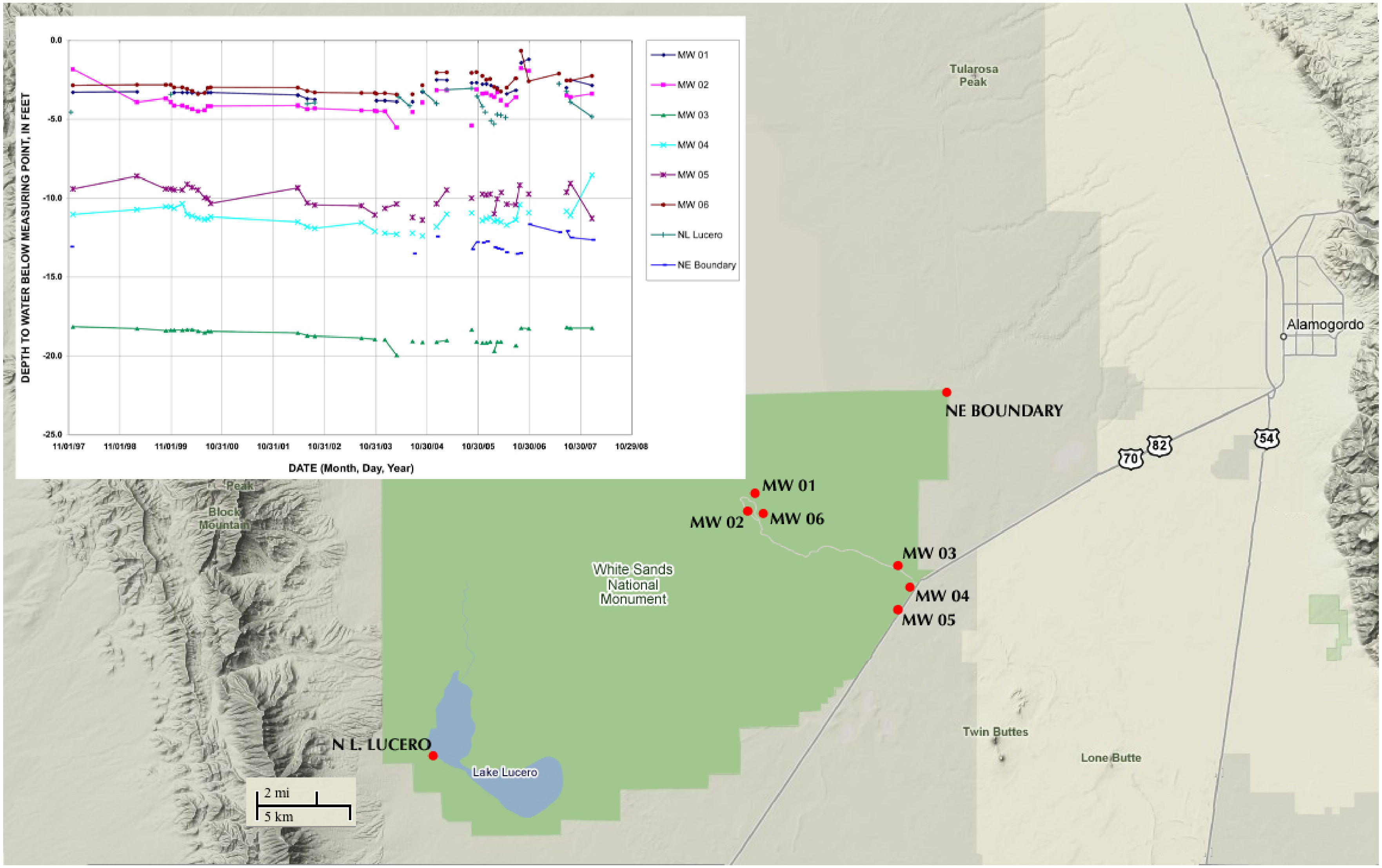


Figure 48. Hydrographs of groundwater levels in White Sands National Monument monitoring wells, 1997 – 2008.

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Appendices

Appendix A- 1. Manuscripts for streamflow stations Rio Grande above Rio Conchos and Rio Conchos near Ojinaga.

08371500 RIO GRANDE ABOVE RIO CONCHOS NEAR PRESIDIO, TEXAS AND OJINAGA, CHIHUAHUA

DESCRIPTION: Cableway, bubbler gage, and water-stage recorder (graphic and digital), DCP with GOES high data rate telemetry, located on the left bank at latitude 29 36'15", longitude 104 27'05", and river kilometer 1,551; 8.0 river kilometers upstream from the international highway bridge between Presidio, Texas and Ojinaga, Chihuahua and 3.8 river kilometers upstream from the confluence with the Rio Conchos. The zero of the gage is 784.29 meters above mean sea level, U. S. C. & G. S. datum.

RECORDS: Based on 26 current-meter measurements during the year and a continuous record of gage heights. Computations by shifting control methods. Records available: 1889 through 2003.

REMARKS: Reservoirs, diversions, and drainage returns modify the river flow at this station. Prior to 1978 the zero of the gage was 785.37 meters above mean sea level, U. S. C. & G. S. datum.

EXTREME FLOWS FROM RECORDS: Momentary: Max. 396 CMS on June 14, 1905. Highest flow recorded since 1924 was 146 CMS, with a gage height of 3.22 meters, on May 26, 1942. Min. frequently no flow.

08373000 RIO CONCHOS NEAR OJINAGA, CHIHUAHUA

DESCRIPTION: Cableway, gravity well, and water-stage recorder located on the right bank at latitude 29 34'57", longitude 104 25'52", 1.0 river kilometer from the confluence with the Rio Grande, 4.0 kilometers northwest of Ojinaga, Chihuahua, and 6.0 kilometers northwest of Presidio, Texas. This stream enters the Rio Grande at river kilometer 1,547, 18.7 river kilometers upstream from the "Rio Grande below Rio Conchos" Gaging Station. The zero of the gage is 780.40 meters above mean sea level, U. S. C. & G. S. datum.

RECORDS: Based on 166 discharge measurements during the year. Records available: 1896 through 1913; 1924 through 2003. Prior to April 4, 1954, flow records were determined from records of the Rio Grande at stations located upstream and downstream from the Rio Conchos confluence.

REMARKS: Reservoirs, diversions, and drainage returns modify the river flow at this station. La Boquilla Reservoir, La Colina Reservoir, and Luis L. Leon Reservoir are located 405, 393, and 183 river kilometers, respectively, upstream from this station. Francisco I. Madero Reservoir is located on the Rio San Pedro, a tributary which enters the Rio Conchos 283 river kilometers upstream from this station. Power generation facilities: La Boquilla 14,647 kw., La Colina 3,620 kw., Francisco I. Madero and Luis L. Leon, none. The station was relocated on January 20, 1978 incident to the Rio Grande channel rectification in the Presidio-Ojinaga area.

EXTREME FLOWS FROM RECORDS: Momentary: Max. (period 1968-2000) 2,020 CMS, on September 30, 1978 with a 7.53 meter gage height. The greatest recorded flow occurred September 11, 1904 with a peak flow estimated at 4,590 CMS. Min. 0.21 CMS on June 12, 1995 with a 0.46 meter gage height. During the period 1996 to 1998, it is very probable that a minimum momentary flow smaller than the referenced one occurred; however, that data is not available.

Appendix A- 2. Manuscripts for streamflow stations Rio Grande below Rio Conchos and Rio Grande at Johnson Ranch

08374200 RIO GRANDE BELOW RIO CONCHOS NEAR PRESIDIO, TEXAS AND OJINAGA, CHIHUAHUA

DESCRIPTION: Cableway, bubbler gage, water-stage recorders (graphic and digital), DCP with GOES high data rate telemetry, located on the left bank at latitude 29 31'10", longitude 104 17'10", and river kilometer 1,529; 0.6 river kilometer downstream from Alamito Creek and 14.4 river kilometers downstream from the international highway bridge between Presidio, Texas and Ojinaga, Chihuahua. The zero of the gage is 771.75 meters above mean sea level, U. S. C. & G. S. datum.

RECORDS: Based on 26 current-meter measurements during the year and a continuous record of gage heights. Computations by shifting control methods. Records available: 1955 through 2003. Records are also available from 1896 through June 13, 1932 for a station located about 19.5 river kilometers downstream from the Rio Conchos and 2.1 kilometers upstream from Alamito Creek; and from June 14, 1932 through 1954 for a station about 3.2 river kilometers downstream from the Rio Conchos and 18.3 river kilometers upstream from Alamito Creek.

REMARKS: Reservoirs, diversions, and drainage returns modify the river flow at this station. Prior to December 1, 1979 the zero of the gage was 772.97 meters above mean sea level, U. S. C. & G. S. datum. A concrete control weir at this station was partially removed in December 1991.

EXTREME FLOWS FROM RECORDS: Momentary: Max. 1,730 CMS on September 30, 1978, with a gage height of 4.70 meters. The greatest recorded flow occurred September 11, 1904, with a peak flow estimated at 4,590 CMS at a station 19.0 kilometers upstream. Min. 0.01 CMS several days in July 1955 and June 30, 1958.

08375000 RIO GRANDE AT JOHNSON RANCH NEAR CASTOLON, TEXAS AND SANTA ELENA, CHIHUAHUA

DESCRIPTION: Cableway, gravity well, DCP with GOES high data rate telemetry, water-stage recorder (graphical and digital), located on the left bank at latitude 29 02'05", longitude 103 23'25", and river kilometer 1,388; 2.2 river kilometers upstream from the old Johnson Ranch headquarters, 9.7 river kilometers downstream from Smoky Creek, and 14.8 river kilometers upstream from Chizos Crossing and the Chihuahua-Coahuila state line. The zero of the gage is 623.41 meters above mean sea level, U. S. C. & G. S. datum.

RECORDS: Based on 21 current-meter measurements during the year and a continuous record of gage heights. Computations by shifting control methods. Records available: April 1936 through 2003.

REMARKS: Reservoirs, diversions, and drainage returns modify the river flow at this station.

EXTREME FLOWS FROM RECORDS: Momentary: Max. 2,040 CMS, on September 30, 1978 with a gage height of 8.66 meters. A flow estimated at 2,750 CMS with a stage of 7.50 meters occurred at this station site on October 3, 1932. Min. no flow several days in 1953, 1955, 1957, and 1958.

Appendix A- 3. Manuscripts for streamflow stations Rio Grande at Foster Ranch and Rio Grande below Amistad Reservoir

08377200 RIO GRANDE AT FOSTER RANCH NEAR LANGTRY, TEXAS AND RANCHO SANTA ROSA, COAHUILA

DESCRIPTION: Cableway, bubbler gage, DCP with GOES high data rate telemetry, concrete control weir, and water-stage recorder (graphic and digital) located on the left bank at latitude 29 46'50", longitude 101 45'30", and river kilometer 1,058; 152 meters downstream from the Terrell-Val Verde County line, 8.8 kilometers downstream from Lozier Canyon, and about 19.8 kilometers west of Langtry, Val Verde County, Texas. The zero of the gage is 352.71 meters above mean sea level, U. S. C. & G. S. datum.

RECORDS: Based on 36 current-meter measurements during the year, 28 by the United States Section and 8 by the Mexican Section of the Commission, and a continuous record of gage heights. Computations for medium and high flows by shifting control methods. Low flow computations based on a stable control weir rating curve defined by current-meter measurements. Records available: September 1961 through 2003.

REMARKS: Reservoirs, diversions, and drainage returns modify the river flow at this station. The concrete control weir was placed in operation on February 21, 1967.

EXTREME FLOWS FROM RECORDS: Momentary: Max. 4,190 CMS on November 5, 1978 with a gage height of 11.63 meters. Min. 2.54 CMS on October 12, 2000.

08450900 RIO GRANDE BELOW AMISTAD DAM NEAR CD. ACUNA, COAHUILA AND DEL RIO, TEXAS

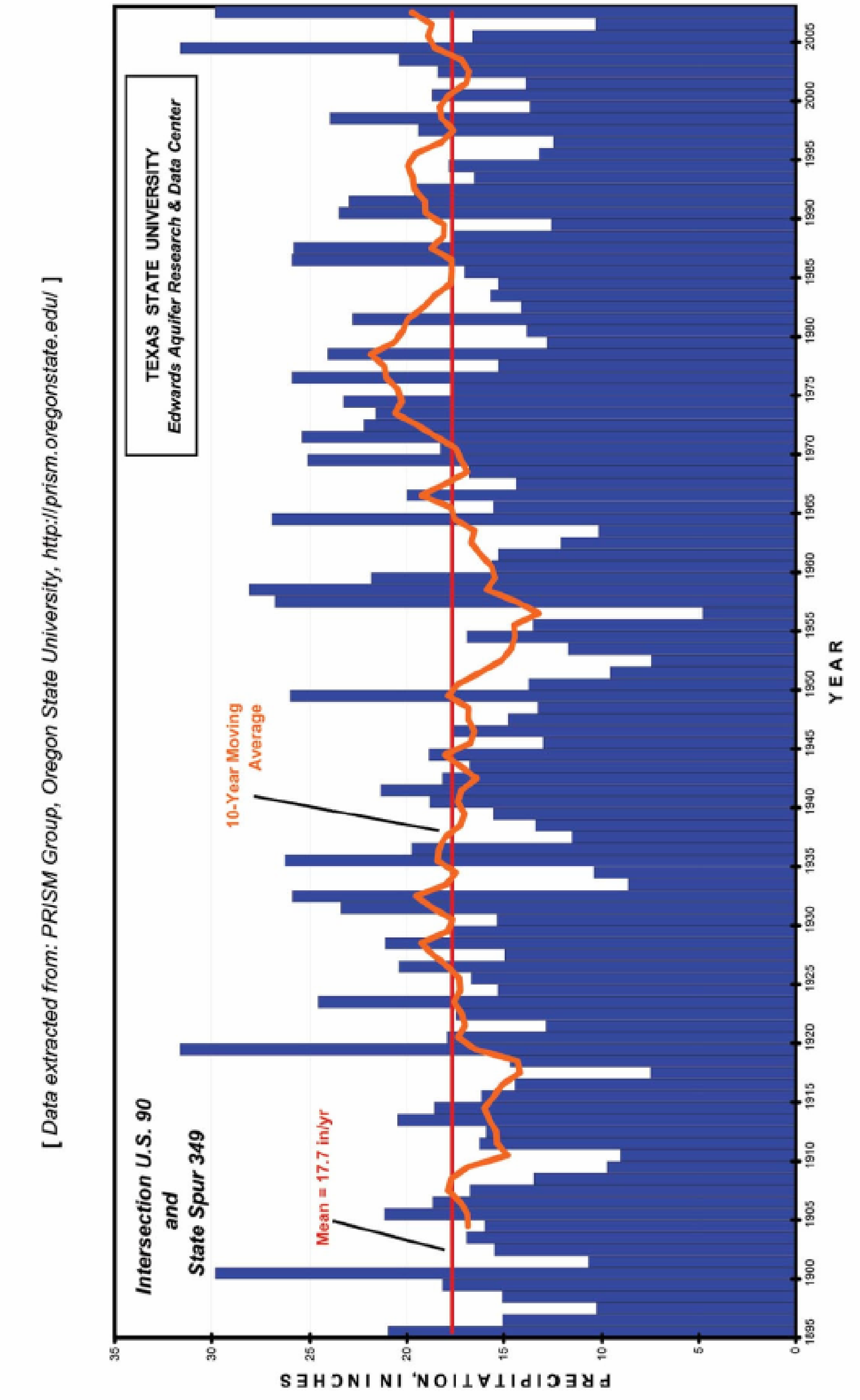
DESCRIPTION: Cableway, gravity well, concrete control weir, and water-stage recorders (graphic and digital), located on the left bank at latitude 29 25'30", longitude 101 02'25", and river kilometer 920, 3.4 river kilometers downstream from Amistad Dam and 17.4 river kilometers upstream from the international highway bridge between Del Rio, Texas and Cd. Acuna, Coahuila. The zero of the gage is 274.00 meters above mean sea level, U. S. C. & G. S. datum.

RECORDS: Based on 22 current-meter measurements during the year, 12 by the Mexican Section and 10 by the U.S. Section, and a continuous record of gage heights. Computations for high flows by shifting control methods. Low and medium flow computations based on a stable control weir rating curve defined by current-meter measurements. Records available: September 1954 through 2003. Records are also available from May 1900 through April 1915 for a station 3.1 kilometers upstream; from December 1919 through March 1920 for a station 2.7 kilometers downstream near McKee's Switch; from July 2, 1941 through August 1954 and October 1960 through 1967 for a station at the international highway bridge; and from December 1923 through July 2, 1941, and 1968 through 2003 for a station approximately 17.1 kilometers downstream.

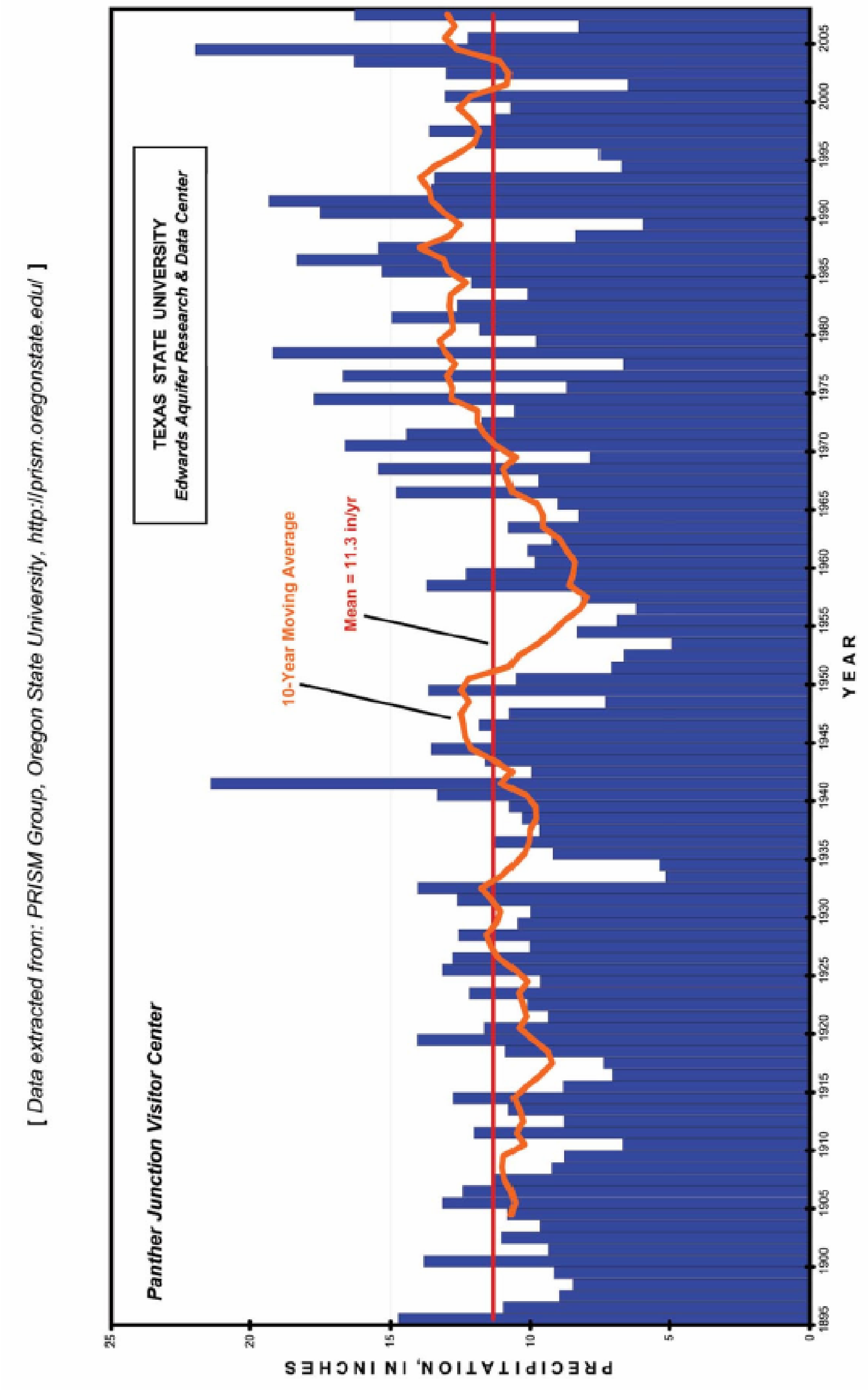
REMARKS: Reservoirs, diversions, and drainage returns modify the river flow at this station. On May 31, 1968 Amistad Dam started impounding water. After this day, flow at this station is controlled largely by releases from Amistad Reservoir, 3.4 river kilometers upstream. A computerized radio telemetry system relays gage height data to the Amistad Dam office.

EXTREME FLOWS FROM RECORDS: Momentary: Max. 32,790 CMS on June 28, 1954, determined by slope-area computation, with a gage height of 16.98 meters at the old station site 152 meters downstream. This is the greatest rate of discharge recorded at any point on the Rio Grande. Max. since Amistad Dam, 1,760 CMS on Sept. 21, 1974. Min. 0.63 CMS on February 14, 1969, with a gage height of 0.33 meters.

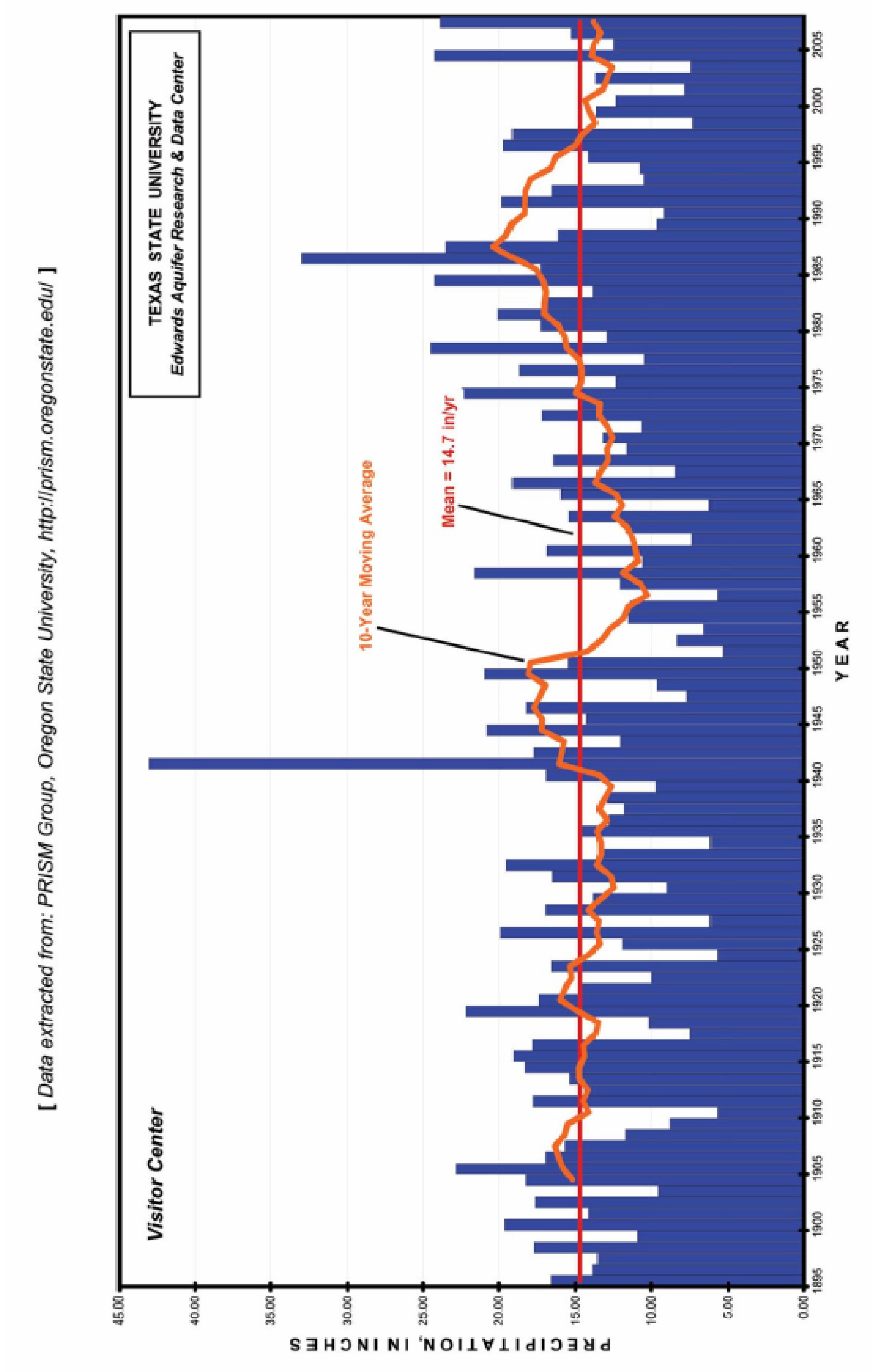
Appendix B- 1. Annual precipitation at Amistad National Recreational Area during 1895 – 2007.



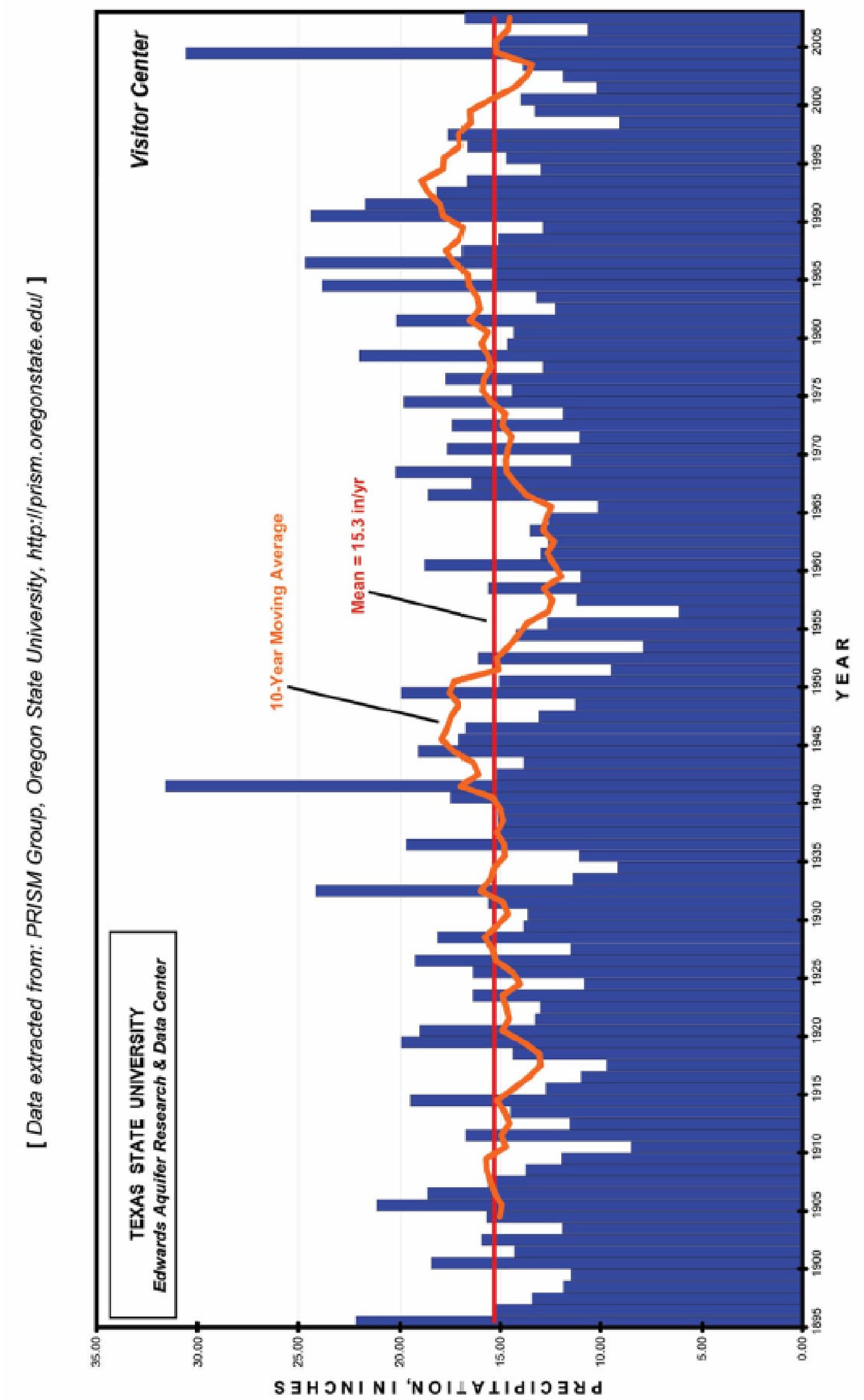
Appendix B- 2. Annual precipitation at Big Bend National Park during 1895 – 2007.



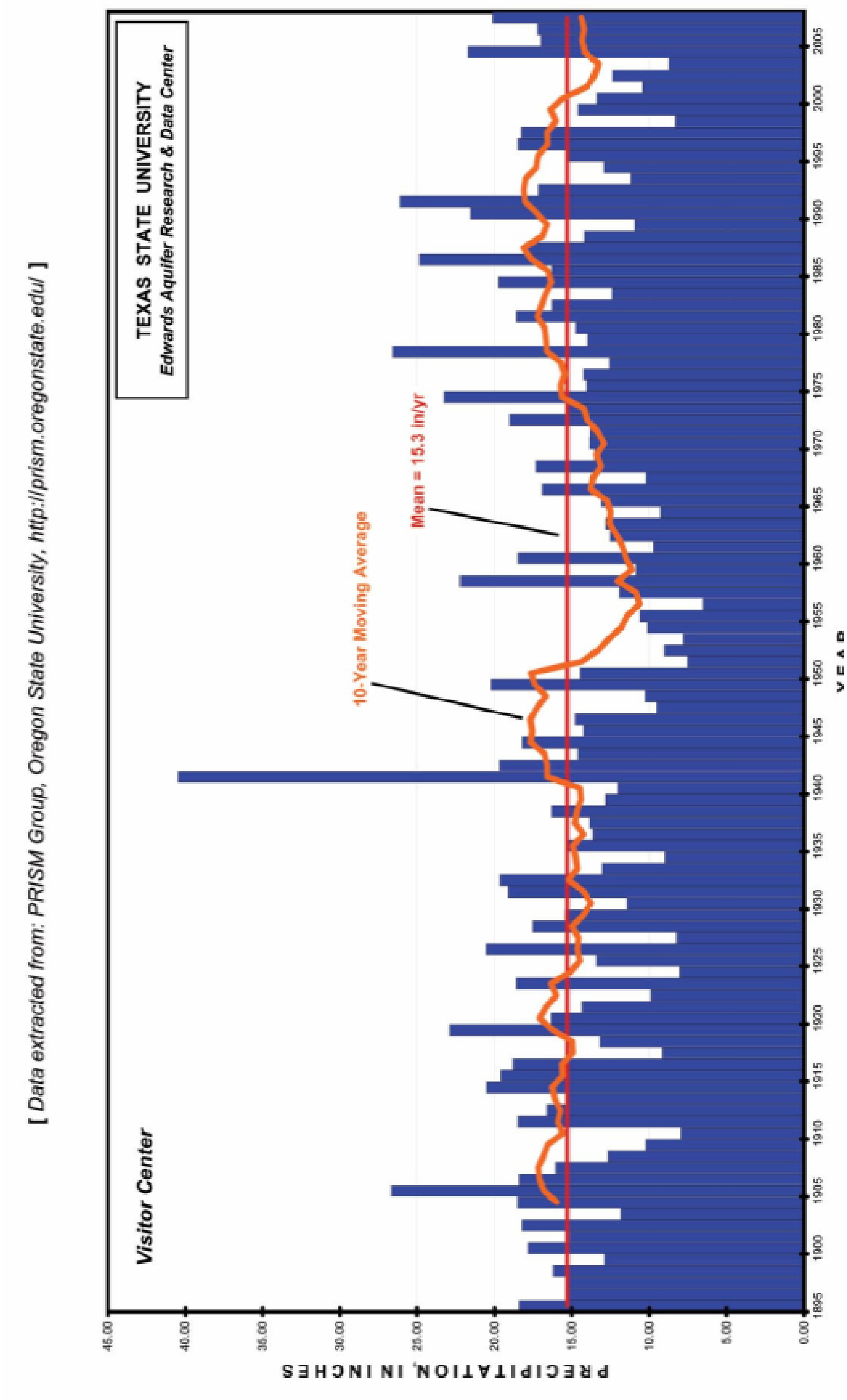
Appendix B- 3. Annual precipitation at Carlsbad Caverns National Park during 1895 – 2007.



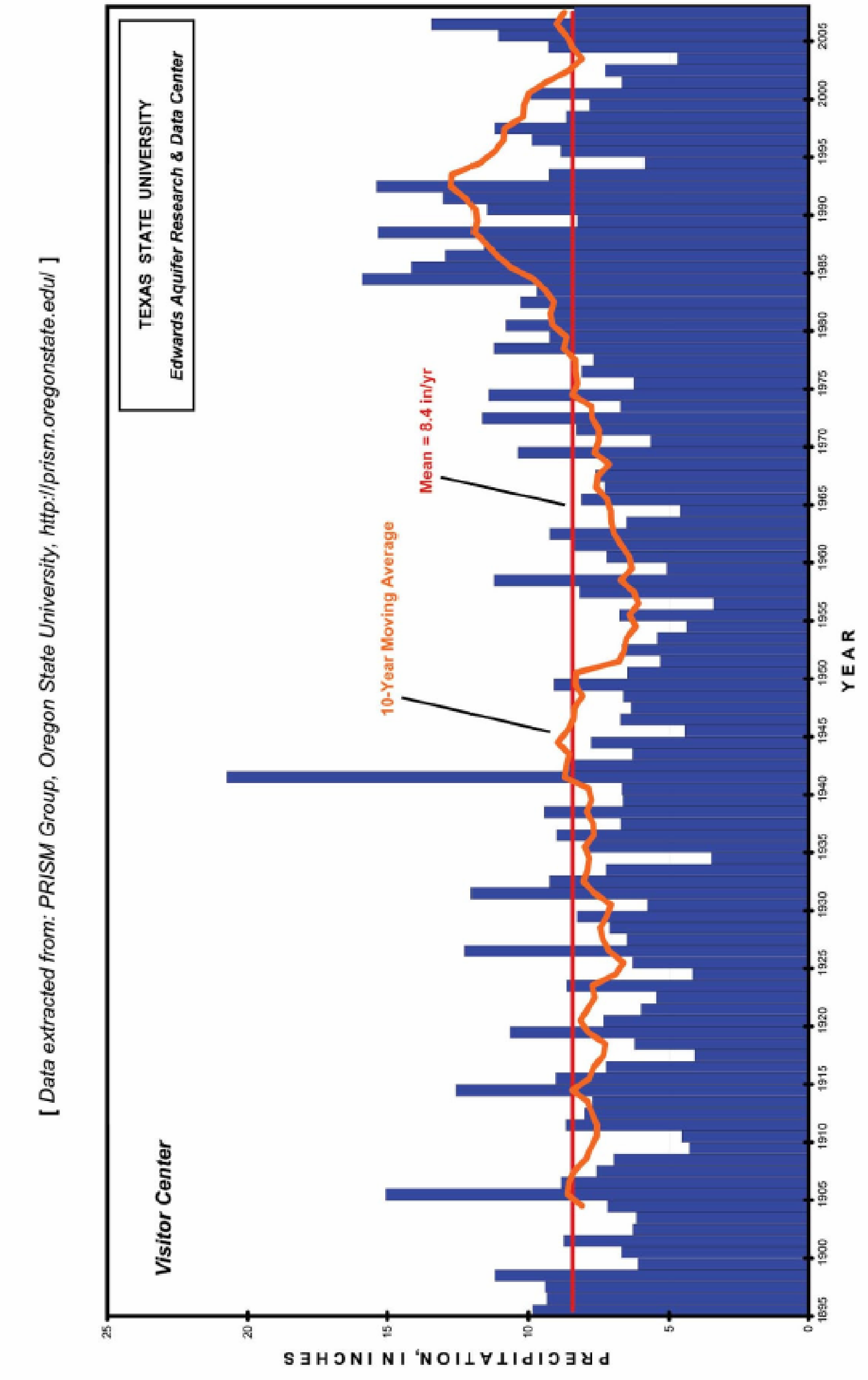
Appendix B- 4. Annual precipitation at Fort Davis National Historic Site during 1895 – 2007.


[Data extracted from: PRISM Group, Oregon State University, http://prism.oregonstate.edu/]

Appendix B- 5. Annual precipitation at Guadalupe Mountains National Park, McKittrick Canyon, during 1895 – 2007.



Appendix B- 6. Annual precipitation at White Sands National Monument during 1895 – 2007.



[Data extracted from: PRISM Group, Oregon State University, http://prism.oregonstate.edu/]

Appendix C- 1. Mean, standard deviation, and number of water quality records for the Rio Grande above Rio Conchos during the period of record, low-flow, and high-flow seasons.

Std. Dev, standard deviation; n, number of data records; WT, water temperature (^{o}C); DO, dissolved oxygen (mg/L); SpC, specific conductance (μS/cm); FC, fecal coliform bacteria (colonies per 100 mL); ECOLI, *Escherichia coli* bacteria (colonies per 100 mL); Cl, choride (mg/L); SO4, sulfate (mg/L); TDS, total dissolved solids (mg/L); NH4, ammonia nitrogen (mg/L); NO23, nitrite + nitrate nitrogen (mg/L); TKN, total nitrogen (mg/L); TP, total phosphorus (mg/L); DOP, dissolved ortho-phosphate (mg/L); CHLa, chlorophyll *a* (μg/L); TSS, total suspended solids (mg/L); SECCHI, Secchi depth (inches).

Rio Grande above Rio Conchos

Variable	Period of Record			Low-Flow Season			High-Flow Season		
	Mean	Std. Dev	n	Mean	Std. Dev	n	Mean	Std. Dev	n
WT	18.4	7.0	311	13.1	4.7	164	24.3	3.5	147
DO	7.6	2.0	306	8.8	1.7	163	6.3	1.3	143
pH	7.7	0.6	305	7.8	0.7	163	7.6	0.6	142
SpC	2770	1108	306	3200	1082	162	2288	926	144
FC	337	1737	251	110	346	138	615	2539	113
ECOLI	143	366	58	132	420	32	157	293	26
Cl	516	301	276	650	282	145	368	250	131
SO4	574	245	273	648	209	145	489	257	128
TDS	1995	1741	210	2372	2202	114	1549	731	96
NH4	0.01	0.325	273	0.124	0.434	148	0.07	0.08	125
NO23	0.774	3.124	194	1.168	4.243	100	0.355	0.861	94
TKN	1.742	1.263	57	1.758	1.019	27	1.727	1.466	30
TP	0.614	1.391	268	0.677	1.780	146	0.539	0.679	122
DOP	0.103	0.214	194	0.136	0.223	94	0.073	0.202	100
CHLa	25.7	25.9	202	30.9	29.7	106	19.9	19.3	96
TSS	535	2051	272	204	258	143	902	2928	129
SECCHI	5.9	3.3	112	7.1	3.6	58	4.6	2.5	54

Appendix C- 2. Mean, standard deviation, and number of water quality records for the Rio Grande below Rio Conchos during the period of record, low-flow, and high-flow seasons.

Std. Dev, standard deviation; n, number of data records; WT, water temperature (^oC); DO, dissolved oxygen (mg/L); SpC, specific conductance (μS/cm); FC, fecal coliform bacteria (colonies per 100 mL); ECOLI, *Escherichia coli* bacteria (colonies per 100 mL); Cl, choride (mg/L); SO4, sulfate (mg/L); TDS, total dissolved solids (mg/L); NH4, ammonia nitrogen (mg/L); NO23, nitrite + nitrate nitrogen (mg/L); TKN, total nitrogen (mg/L); TP, total phosphorus (mg/L); DOP, dissolved ortho-phosphate (mg/L); CHLa, chlorophyll *a* (μg/L); TSS, total suspended solids (mg/L); SECCHI, Secchi depth (inches).

	Rio Grande below Rio Conchos								
Variable	Period of Record			Low-Flow Season			High-Flow Season		
	Mean	Std. Dev	n	Mean	Std. Dev	n	Mean	Std. Dev	n
WT	19.7	6.5	417	14.7	4.5	213	25.0	3.3	204
DO	7.9	1.8	410	8.9	1.7	209	6.9	1.2	201
pH	7.8	0.5	382	7.9	0.6	198	7.8	0.4	184
SpC	1966	852	358	2238	853	185	1676	751	173
FC	649	2220	268	499	1010	149	837	3133	119
ECOLI	412	589	58	405	541	31	421	650	27
Cl	253	185	361	314	196	191	184	145	170
SO4	511	216	356	538	198	189	480	231	167
TDS	1539	607	239	1702	594	129	1348	566	110
NH4	0.068	0.124	296	0.072	0.137	159	0.064	0.107	137
NO23	0.994	2.018	219	1.202	2.665	112	0.777	0.919	107
TKN	1.408	1.362	84	1.306	0.72	44	1.52	1.831	40
TP	0.474	1.11	311	0.39	0.971	169	0.575	1.253	142
DOP	0.093	0.362	213	0.117	0.478	105	0.07	0.191	108
CHLa	16.1	20.5	224	19.2	24.3	120	12.5	14.3	104
TSS	483	1274	297	138	233	158	875	1769	139
SECCHI	8.2	15.2	164	9.2	12.2	87	7.2	17.9	77

Appendix C- 3. Mean, standard deviation, and number of water quality records for the Rio Grande near Santa Elena Canyon during the period of record, low-flow, and high-flow seasons.

Std. Dev, standard deviation; n, number of data records; WT, water temperature (^{o}C); DO, dissolved oxygen (mg/L); SpC, specific conductance (μS/cm); FC, fecal coliform bacteria (colonies per 100 mL); ECOLI, *Escherichia coli* bacteria (colonies per 100 mL); Cl, choride (mg/L); SO4, sulfate (mg/L); NH4, ammonia nitrogen (mg/L); NO23, nitrite + nitrate nitrogen (mg/L); TKN, total nitrogen (mg/L); TP, total phosphorus (mg/L); DOP, dissolved orthophosphate (mg/L); CHLa, chlorophyll a (μg/L); Turb(JTU), water turbidity in Jackson Turbidity Units.

	Rio Grande near Santa Elena Canyon								
Variable	Period of Record			Low-Flow Season			High-Flow Season		
	Mean	Std. Dev	n	Mean	Std. Dev	n	Mean	Std. Dev	n
WT	20.5	6.9	244	15.3	5.1	128	26.1	3.1	116
DO	8.4	2.1	247	9.5	2.0	129	7.2	1.3	118
pH	8.0	0.3	245	8.1	0.3	127	8.0	0.3	118
SpC	1869	962	246	2184	983	129	1521	810	117
FC	545	1521	89	45	122	47	1105	2084	42
ECOLI	238	563	53	54	81	32	518	824	21
Cl	241	184	203	305	193	109	167	140	94
SO4	514	214	197	558	214	106	462	203	91
NH4	0.097	0.342	161	0.064	0.069	86	0.135	0.494	75
NO23	0.537	0.436	123	0.573	0.48	66	0.494	0.378	57
TKN	1.465	1.803	54	1.12	0.459	26	1.785	2.442	28
TP	0.657	1.708	161	0.272	0.643	86	1.099	2.337	75
DOP	0.118	0.403	120	0.143	0.523	61	0.093	0.22	59
CHLa	19.5	35.2	151	25.5	45.8	82	12.3	11.7	69
Turb(JTU)	270	844	101	43.2	36.1	52	511	1169	49

Appendix C- 4. Mean, standard deviation, and number of water quality records for the Rio Grande at Rio Grande village and Rio Grande near LaLinda, Mexico during the period of record, low-flow, and high-flow seasons.

Std. Dev, standard deviation; n, number of data records; WT, water temperature (^{o}C); DO, dissolved oxygen (mg/L); SpC, specific conductance (μS/cm); FC, fecal coliform bacteria (colonies per 100 mL); ECOLI, *Escherichia coli* bacteria (colonies per 100 mL); Cl, choride (mg/L); SO4, sulfate (mg/L); TDS, total dissolved solids (mg/L); NH4, ammonia nitrogen (mg/L); NO23, nitrite + nitrate nitrogen (mg/L); TKN, total nitrogen (mg/L); TP, total phosphorus (mg/L); DOP, dissolved ortho-phosphate (mg/L); CHLa, chlorophyll *a* (μg/L); TSS, total suspended solids (mg/L).

Rio Grande at Rio Grande Village

Variable	Period of Record		
	Mean	Std. Dev	n
WT	21.4	5.6	55
DO	7.7	1.8	54
pH	7.8	0.2	55
SpC	2093	649	56
FC	75	131	50
Cl	248	159	47
SO4	525	188	46
TDS	1342	521	48
NH4	0.101	0.194	44
NO23	0.57	1.631	40
TKN	2.492	2.12	7
TP	1.141	3.19	47
DOP	0.287	0.899	21
CHLa	13.9	20.4	44

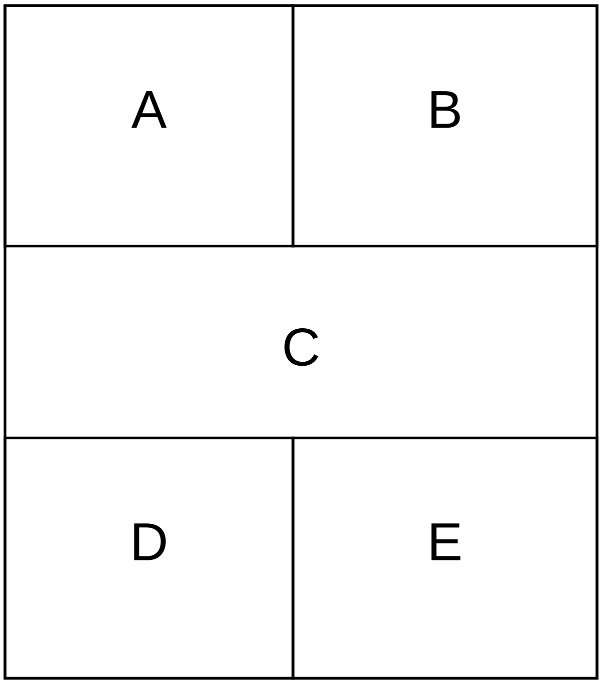
Rio Grande near La Linda, Mexico

Variable	Period of Record			Low-Flow Season			High-Flow Season		
	Mean	Std. Dev	n	Mean	Std. Dev	n	Mean	Std. Dev	n
WT	22.4	6.5	108	17.8	5.6	53	26.8	3.6	55
DO	8.0	1.8	107	9.1	1.5	53	6.9	1.4	54
pH	7.9	0.4	108	8.0	0.4	54	7.8	0.4	54
SpC	1685	504	107	1939	493	53	1436	378	54
FC	1449	7357	83	543	2330	42	2376	10181	41
ECOLI	373	833	16	249	756	10	579	986	6
Cl	157	113	106	202	125	51	115	82	55
SO4	414	129	106	447	130	51	383	121	55
TDS	1262	1057	71	1491	1399	36	1027	417	35
NH4	0.042	0.055	106	0.046	0.067	52	0.039	0.04	54
NO23	0.632	0.379	68	0.631	0.408	34	0.634	0.353	34
TP	0.985	2.337	105	0.251	0.464	51	1.679	3.083	54
DOP	0.038	0.058	101	0.039	0.053	50	0.038	0.063	51
CHLa	12.5	20.9	99	11.9	15.6	48	13.1	25.0	51
TSS	2641	11143	107	254	493	52	4899	15259	55

Appendix C- 5. Mean, standard deviation, and number of water quality records for the Rio Grande at Foster Ranch during the period of record, low-flow, and high-flow seasons.

Std. Dev, standard deviation; n, number of data records; WT, water temperature (^oC); DO, dissolved oxygen (mg/L); SpC, specific conductance (μS/cm); FC, fecal coliform bacteria (colonies per 100 mL); ECOLI, *Escherichia coli* bacteria (colonies per 100 mL); Cl, choride (mg/L); SO4, sulfate (mg/L); TDS, total dissolved solids (mg/L); NH4, ammonia nitrogen (mg/L); NO23, nitrite + nitrate nitrogen (mg/L); TKN, total nitrogen (mg/L); TP, total phosphorus (mg/L); DOP, dissolved ortho-phosphate (mg/L); CHLa, chlorophyll *a* (μg/L); TSS, total suspended solids (mg/L); HARD, water hardness (mg/L); AS, dissolved arsenic (μg/L); CR, dissolved chromium (μg/L); CU, dissolved copper (mg/L); NI, dissolved nickel (mg/L); ZN, dissolved zinc (mg/L); Turb(NTU), water turbidity in Nephelometric Turbidity Units.

	Rio Grande at Foster Ranch								
Variable	Period of Record			Low-Flow Season			High-Flow Season		
	Mean	Std. Dev	n	Mean	Std. Dev	n	Mean	Std. Dev	n
WT	21.6	5.6	248	16.7	3.8	117	25.9	2.5	131
DO	8.3	1.8	243	9.5	1.4	115	7.3	1.5	128
pH	8.0	0.3	244	8.1	0.3	117	8.0	0.3	127
SpC	1225	372	250	1396	348	118	1073	325	132
FC	567	2845	40	36	45	23	1287	4333	17
ECOLI	115	208	7	19	16	4	243	293	3
Cl	111	72	221	145	67	104	80	62	117
SO4	287	84	215	311	63	101	267	94	114
TDS	821	231	161	920	188	76	732	231	85
NH4	0.032	0.051	117	0.028	0.059	50	0.035	0.044	67
NO23	0.597	0.323	18	0.533	0.363	8	0.648	0.298	10
TKN	1.714	3.493	146	0.682	0.535	68	2.615	4.578	78
TP	0.668	1.862	181	0.132	0.246	85	1.143	2.456	96
DOP	0.011	0.011	119	0.011	0.013	52	0.011	0.010	67
CHLa	7.8	7.2	56	8.0	5.4	32	7.5	9.2	24
TSS	2348	4581	123	297	525	53	3901	5588	70
HARD	305	63	27	322	54	15	283	69	12
AS	4.5	3.3	101	4.9	3.6	43	4.3	3.0	58
CR	1.7	2.0	78	1.9	2.1	33	1.6	1.9	45
CU	1.9	0.8	41	2.0	0.9	18	1.9	0.6	23
NI	2.4	4.8	99	2.2	1.9	41	2.5	6.1	58
ZN	8.3	14.1	79	7.2	14.0	33	9.2	14.3	46
Turb(NTU)	1319	2399	38	178	456	15	2063	2843	23



Back cover photos:

A: Guadalupe Mountains National Park

B: Big Bend National Park (Rio Grande at mouth of Santa Elena Canyon)

C: Fort Davis National Historic Site

D: White Sands National Monument

E: Carlsbad Caverns National Park (Rattlesnake Spring)