TR-2008-315

Hydrology, Salinity, and Salinity Control Possibilities of the Middle Pecos River: A Reconnaissance Report

S. Miyamoto and Shilpa Anand
Texas AgriLife Research and Extension Center at El Paso

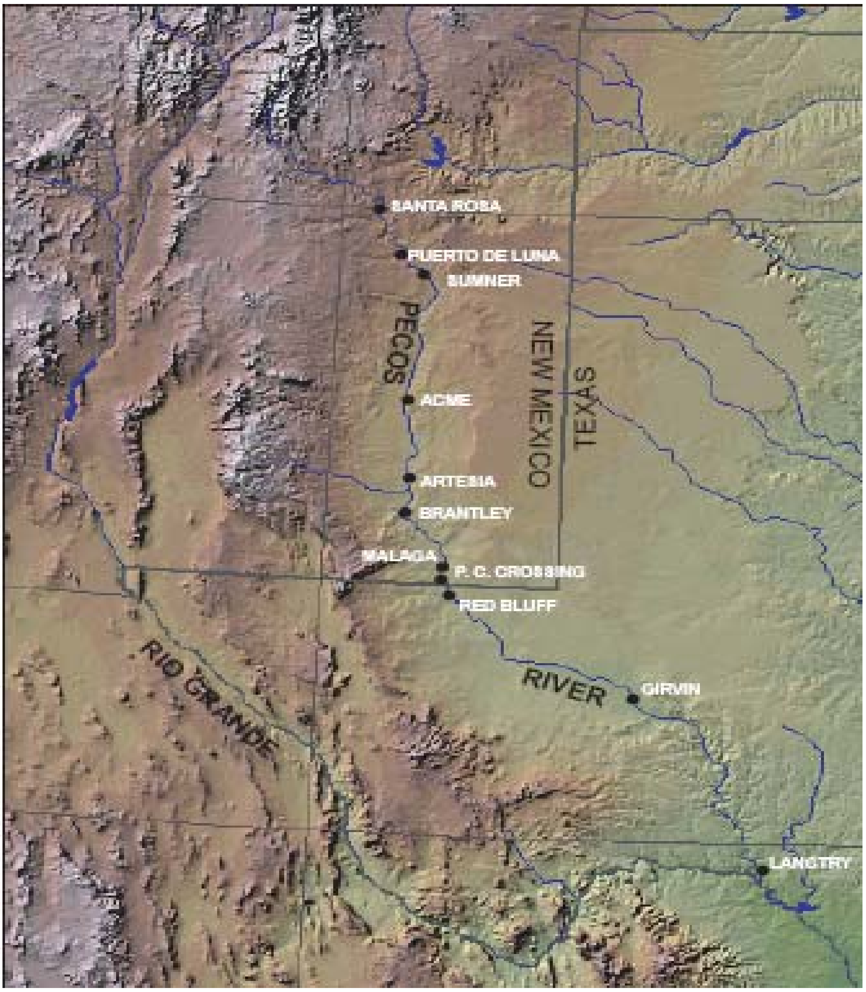
Will Hatler
Texas AgriLife Research and Extension Center at Stephenville

May 2008

Texas Water Resources Institute
make every drop count

HYDROLOGY, SALINITY, AND SALINITY CONTROL POSSIBILITIES OF THE MIDDLE PECOS RIVER: A RECONNAISSANCE REPORT

S. Miyamoto, Shilpa Anand, and Will Hatler



Texas Water Resources Institute
Technical Report TR - 315

May 2008

Texas Water Resources Institute
make every drop count

AgriLIFE RESEARCH
Texas A&M System

Texas Cooperative
EXTENSION
The Texas A&M University System

ACKNOWLEDGEMENT

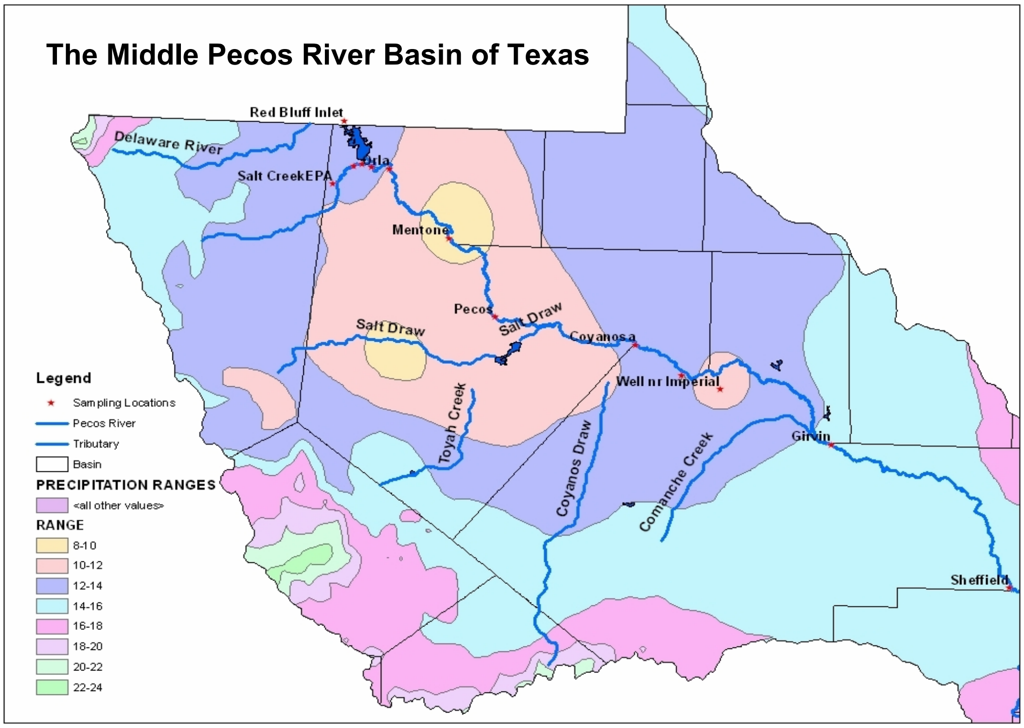
The information presented in this report was gathered primarily for a U.S. Environmental Protection Agency project, “Basin-wide Management Plan for the Pecos River in Texas,” under contract No. 4280001. The cost of analyses and document preparation was defrayed in part by the Cooperative State Research, Education, and Extension Service, U.S. Department of Agriculture, under Agreement No. 2001-45049-01149, and by Texas Agrilife Research, Texas A&M University System. Document preparation was assisted by Nancy Hanks, Research Associate, and Pramod Pandey, Student Trainee at the Texas A&M University Agricultural Research Center at El Paso.

Contents

Abstract..1
Introduction...2
Basin and Reach Characteristics........2
Sources of Salts....................................2
Flow and Salinity.................................2
Water Management 2
Floodplains and Riparian Zones.........2
Salinity Control Needs........................2
Potentials for Reducing Salinity 2
References..2
Attachments.......................................30

Unit Conversion

1 ft = 30.5 cm
1 km = 0.621 miles
1 ha = 2.47 acres
1 acre = 0.405 ha
1 km^2 = 247 acres
1 m^3 = 35.3 ft^3
1 ft^3 = 28.3 L
1 Mm^3 = 811 acre-ft
1 m^3/s = 35.3 cfs
= 22.8 million gpd
1 m = 3.3 ft



HYDROLOGY, SALINITY, AND SALINITY CONTROL POSSIBILITIES FOR THE MIDDLE PECOS RIVER: A RECONNAISSANCE REPORT

S. Miyamoto[1], Fason Yuan[2], Shilpa Anand[3], and William Hatler[4]

Abstract

The Middle Pecos River between Malaga, New Mexico, and Girvin, Texas, is known for high salinity. Streamflow salinity during the last decade (1991-2000), for example, averaged 3,500 and 6,150 mg L^{-1} at Malaga and at the Red Bluff release, and upwards of 12,000 mg L^{-1} at Girvin. These high levels of streamflow salinity not only reduce the economic uses of the water, but also limit the biodiversity of aquatic and riparian species along the river. This report outlines the hydrology, geochemistry, and water management practices of the Middle Pecos River in order to explain the reasons for the high salinity, and to discuss the potential for salinity control.

The main causes of high salinity between Malaga and Red Bluff are brine intrusion at Malaga Bend and Bottomless Lakes and a drastic reduction in flow since the late 1930s that does not adequately dilute the intrusion. The amount of salts entering the Pecos River from these two sites is estimated at 450,000 tons/year while freshwater flow at Malaga has decreased from 260 Mm^3 (210,000 acre-ft) per year from 1929 through 1937 to 81 Mm^3 (66,000 acre-ft) per year from 1959 through 2001.

The causes of high salinity between Red Bluff and Girvin are saline water intrusion from both surface and subsurface sources, low runoff into the river, and the evaporative concentration of the stream. The amount of salts entering this reach is estimated at 250,000 tons/year, primarily from Salt Creek, Salt Draw, Toyah Creek, and shallow saline groundwater. The sources of the shallow saline groundwater which enters the Pecos River between Coyanosa and Girvin are suspected to be groundwater flow from adjacent areas, but details are yet to be investigated. Diversion for irrigation, high seepage loss above Pecos, and low runoff resulted in inadequate flow to prevent intrusion or to dilute saline water entering the Pecos below Coyanosa. The annual flow at Coyanosa decreases below 30 Mm^3 (24,000 acre-ft) per year.

There are interests to lower the salinity of the Middle Pecos River for preserving its biodiversity, protecting groundwater quality, and encouraging the regrowth of native riparian species after ongoing saltcedar control activities, besides increasing the economic value of this water for irrigation. A regional level of concern is its impact on Amistad International Reservoir, located downstream along the Texas/Mexico border. The salinity of this huge reservoir (6.8 billion m^3 or 5.5 million acre-ft) has increased from 560 mg L^{-1} to about 1000 mg L^{-1}, the upper limit of the Texas drinking water standard. The Pecos River accounts for nearly 30 percent of the salt loading into Amistad International Reservoir while providing about 10 percent of the flow, thus raising the background salinity of the reservoir. In addition, historical records from 1941 and 1942 indicate that a high precipitation event between Roswell and Red Bluff can cause the Pecos River to send enough saline water to Amistad to raise the salinity level of the reservoir well above the Texas drinking water standard.

Since the potential for additional freshwater inflow from runoff appears to be limited, salinity management strategies must incorporate ways to reduce saline water intrusion and percolation losses from reservoirs and river beds. Streamflow salinity can be restored closer to the original level by reducing saline water intrusion roughly in proportion to the reduction in fresh water flow caused by diversion and percolation losses. Potential control options include saline water intrusion control upstream at Malaga Bend and Bottomless Lakes, and possibly in the segment between Pecos and Girvin.

---

[1] Professor, [2] Formerly Research Associate, [3] Formerly Research Technician, Texas A&M University Agricultural Research Center at El Paso, 1380 A&M Circle, El Paso, Texas, [4] Extension Assistant, Texas A&M University Research and Extension Center, Stephenville, Texas.

The methods of salt source control at each of these sites are yet to be addressed. Preliminary estimates show that salt source control at Malaga Bend and/or Bottomless Lakes will result in a significant reduction of salinity of Red Bluff Reservoir. The control of brine intrusion at Malaga Bend alone can lower salinity of the Red Bluff release from 6150 to 4800 mg/L, the level comparable to the level that existed shortly after the construction of Red Bluff Reservoir in 1936. However, its impact on Amistad International Reservoir is yet to be analyzed, and it requires good understanding of the hydrologic connection between the middle and the lower reaches. If the connection is weak, salt sources below Pecos should be evaluated for control as a part of the salinity control plan for Amistad International Reservoir. Streamflow salinity below Coyanosa can be lowered simply by reducing the percolation losses from the reservoir and river beds above Pecos, provided that the water saved is left in the river. However, this option will increase salt transport to the Lower Pecos River unless implemented in conjunction with salt source control. Impacts of water management and salt source control options on monthly or daily salinity of the middle and the lower reaches are yet to be evaluated.

Introduction

The Pecos River originates in northeastern New Mexico, travels through the semi-arid part of New Mexico and West Texas, and eventually merges into the Rio Grande just below the historic town of Langtry. An aerial view of the Pecos Basin along with the adjacent Middle Rio Grande Basin is shown on the cover sheet. This report addresses the middle reach of the Pecos from Malaga, New Mexico, to Girvin, Texas (which extends 400 km or 250 river miles). The Pecos River in this reach winds through a desert of rich oilfields, and the river becomes increasingly serpentine as it passes Coyanosa, the approximate midpoint of the reach (Fig. 1). The Pecos is the only perennial river in this dry area of West Texas and is vital for maintaining the region's ecological heritage.

The condition of the Pecos River below the Texas-New Mexico state line has deteriorated significantly. Although various hydrological maps show numerous tributaries flowing into the Pecos (such as the map on the back cover), none of them provide perennial flow any longer, except for Salt Creek. With the exception of flood events, the flow and water quality of the Middle Pecos River in Texas are largely controlled by inflow from upstream above the state line, and the flow has decreased drastically due to a series of diversions for irrigation. Historically, the flow of the Pecos River increased downstream (dotted line, 1929-1937, Fig. 2). The construction of reservoirs such as McMillan (1908), Avalon (1907, 1912, and 1936), Red Bluff (1936), and Sumner (1937) has drastically altered the stream flow to the present day situation shown by the solid line in Fig. 2. Additional reservoirs have since been built: Santa Rosa in 1981 and Brantley (which replaced

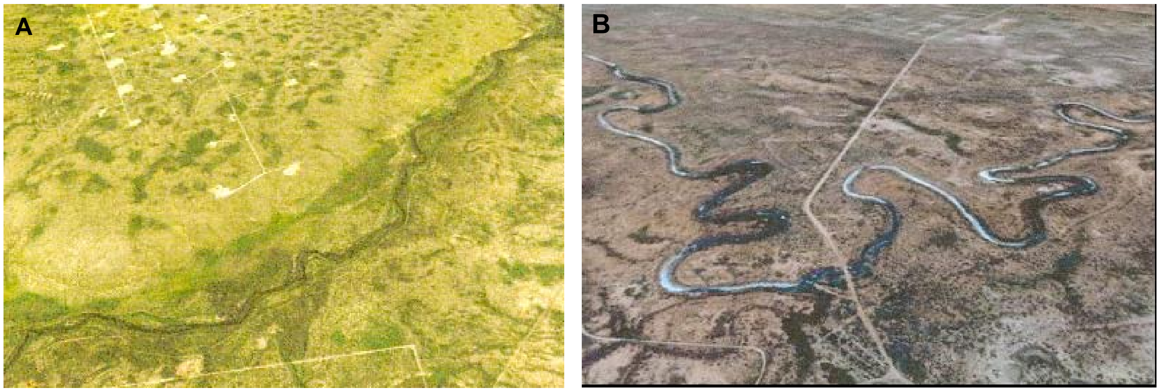


Fig. 1. Aerial view of the Pecos River near Mentone (1A) and Girvin (1B).

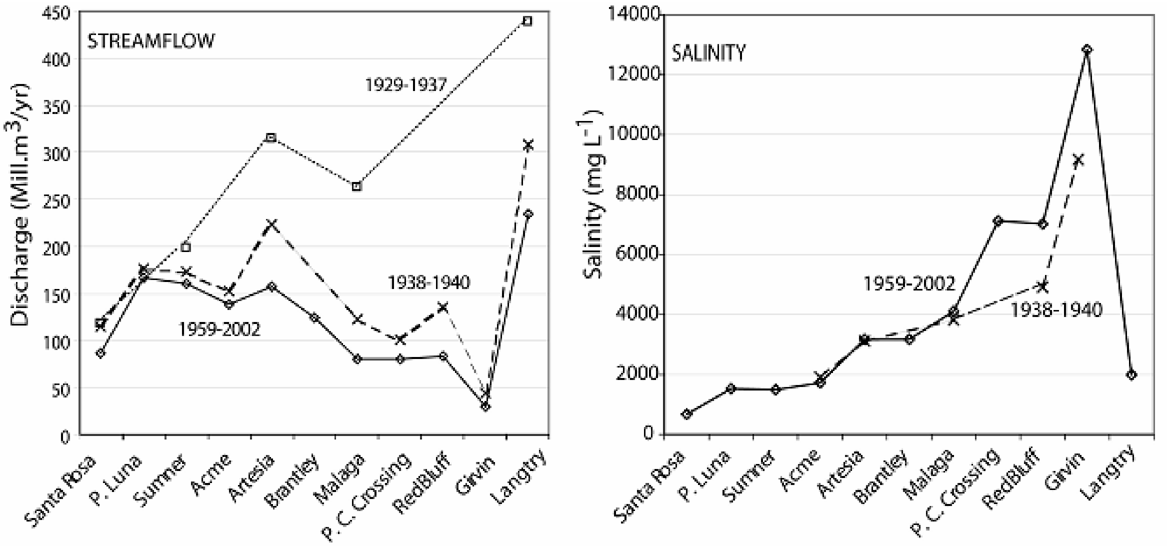


Fig. 2. Flow of the Pecos River at selected gauging stations; dotted line 1929-1937, dashed line 1938-1940, solid line 1959-2002. Salinity data prior to 1937 are not available.

McMillan) in 1991. The flow at Malaga has been reduced from 260 Mm^3 (210,000 acre-ft) per year in the 1930s to 81 Mm^3/year for the period from 1959 to 2001. The flow at Red Bluff had decreased to 84 Mm^3 for the same period.

Salinity of the upper Pecos River in New Mexico is elevated due to gypsum dissolution. Below Acme, New Mexico, however, another source of geological salts, halite (NaCl), comes into the stream from Bottomless Lakes and elevates salinity far beyond the solubility of gypsum. When compared to its salinity during 1938 through 1940 (dashed line of Fig. 2) given by Howard and Love (1943), salinity of the Pecos River increased mainly below Malaga, New Mexico, and is now averaging 6,150 mg/L at the outlet from Red Bluff. When reaching Girvin, Texas, salinity increases to as high as 14,000 mg/L, which is a significant increase over the period of 1938 to 1940. Unfortunately, salinity data prior to 1937 do not exist, but it could have been an order of 2,000 to 3,000 mg/L below Acme, New Mexico.

The increase in streamflow salinity first impacted aquatic species. Hoagstrom (2003), for example, reported that only nine out of twenty-seven native species presently appear in the Pecos River below the Brantley Dam. The dominant fish species found today in the Pecos are those of saltwater species, such as puff fish (El-Hage and Moulton, 1998, Linam and Kleinsasser, 1996). There are many species of wildlife along the Pecos (Huser, 2000). The impact of salty water on their well-being is yet to be examined. According to Wauer (1973) and Wuerthner (1989), the native riparian vegetation included cottonwood (*Populus sp.*) and willows (*Salix sp.*). Today, none of these species can be found anywhere between Red Bluff and Girvin.

A regional concern over salinity includes the Amistad International Reservoir located 61 km (38 miles) south of Langtry. This reservoir, with a capacity 6.8 billion m^3 (or 5.5 million acre-ft) is the main reservoir for the Lower Rio Grande Valley, and its salinity has increased from 560 mg L^{-1} to a range of 800 to 900 mg L^{-1} after having reached 1,000 mg L^{-1} in February 1988. The upper limit of dissolved salt concentration for drinking water in Texas is 1,000 mg L^{-1}. Our earlier study indicates that the Pecos River accounts for nearly 30 percent of the salts entering the Amistad International Reservoir, while contributing only about 10 percent of the flow (Miyamoto et al., 2006).

The Pecos River and some tributaries were once heavily infested with saltcedar. Saltcedar was apparently noted as early as 1912 along the Pecos River (Eakin and Brown, 1939), and became the dominant species by 1958, occupying 11,200 ha (28,000 acres) of the 16,400 ha (41,000 acres) of the floodplain (Mower et al., 1964). The first major saltcedar control of the Pecos River took place during the period of 1967 through 1974 in 8,700 ha (21,500 acres) of the floodplain between Acme and Artesia (Weeks et al., 1987). The control on the Texas side, using the chemical treatment, "Arsenal," began in the fall of 1999, and 5,170 ha (12,767 acres) along the 436 km (271 miles) of the Pecos River reach and its tributaries were treated (Hart, 2004). The area treated from Red Bluff to Girvin is estimated at 3,000 ha. There is an expectation that native species may reestablish after the chemical treatment.

There is an interest and the desire to lower the salinity of the Middle Pecos River among a majority of stakeholders and those who care about maintaining the native ecosystem. However, this task is a challenge, covering over 500 miles encompassing the two states. Although there are many geological and groundwater availability reports, none has addressed the causes of high salinity and potentials for lowering salinity, except for the brine intrusion control at Malaga Bend located above the state line.

This report is intended to introduce basin hydrology, salinity, salt sources, and water management practices. An additional objective is to outline the potential for salinity control which may be considered for developing a river management plan. The methods of salt source control at various sites are yet to be addressed.

Basin and Reach Characteristics

Climate: The climate of the Pecos River Basin is semi-arid with annual precipitation around 30 cm (12 inches) per year in the reach between Red Bluff and Girvin, Texas (Table 1). The driest part is near Girvin where the annual precipitation is only 20 cm (8 inches). It then increases towards Langtry where annual precipitation averages 37 cm (15 inches). Rainfall in this basin occurs mostly between May and October, and ordinarily peaks in September (Table 1) as a consequence of Mexico's monsoon season. Pan evaporation at Red Bluff since 1990 is estimated at 294 cm (114 inches) per year which is among the highest in Texas. It decreases somewhat towards Pecos and Langtry (Table 1).

The combination of low precipitation and high evaporation prevalent in this reach of the Pecos provides a limited opportunity for dilution and excellent opportunities for evaporative salt concentration. Dilution by local runoff or springs is significant only below Sheffield, where salinity decreases to below 2,000 mg L^{-1}. Additional information on the climate of this region can be obtained from http://www5.ncdc.noaa.gov/climatenormals/clim81/NMnorm.pdf.

Table 1. Precipitation at three locations and the annual pan-evaporation at Pecos and Langtry in the Pecos River Basin.

Month	Artesia NM	Pecos TX	Langtry TX	Pecos TX	Langtry TX
	precipitation (cm)			pan evap. (cm)	
Jan.	1.0	1.2	1.2	10.8	9.3
Feb.	1.1	1.1	2.1	12.7	11.4
Mar.	0.7	0.9	1.7	21.2	18.4
Apr.	1.3	1.2	2.6	27.4	23.0
May	3.1	3.2	4.8	33.1	26.1
June	4.8	3.2	4.2	33.3	29.6
July	3.5	3.4	3.5	33.4	34.1
Aug.	5.6	4.1	3.9	30.1	30.7
Sept.	6.4	5.7	6.0	22.8	22.3
Oct.	3.3	2.8	4.0	17.0	16.7
Nov.	1.8	1.2	1.9	12.6	11.0
Dec.	1.4	1.6	1.4	10.5	8.8
Total	**34.0**	**29.5**	**37.3**	**265.0**	**241.7**

Precipitation data 1971-2000 National Climatic Data Center (NCDC)

Drainage Basins: The total drainage area of the Pecos River Basin in New Mexico is 50,609 km^2 (19,000 square miles) and in Texas, 40,505 km^2 (15,600 square miles). The drainage basin near Red Bluff consists of gypsic soils, such as Reeves and Holloman soil series. The majority of Reeves and Pecos counties consist of either shallow Aridisols (e.g., Del Norte, Nikel, Reakor) or calcareous silty clay loam, such as Hoban series. The soils in the east bank of the river are predominantly Simona and Sharvana series, both of them are shallow calcareous soils developed over caliche. Permeability of these soils is moderate to high. The soils along the Pecos River consists of alluvial soils, namely Pecos, Patrole, Toyah, and Gila series which have textures ranging from silty to loamy. The Arno series is the only soil which has montmorillonitic clayey textures with low permeability. Additional details on soil types can be found in STATSGO soil classes, or through the soil survey report published by the U.S. Department of Agriculture/Texas Agricultural Experiment Station.

There are numerous creeks and draws in the Middle Pecos River Basin and some are listed in Table 2. The Delaware River, which has salinity of about 2500 mg L^{-1}, enters the Pecos north of the state line. Salt Creek (or Screwbean Creek) is the only perennial tributary above Girvin which enters the Pecos, and this flow is saline. Salt Draw is another saline flow entering the Pecos River below the town of Pecos, along with the occasional flow from Toyah Creek. Coyanosa Draw, which enters the Pecos at Coyanosa, is the largest tributary below Red Bluff. The flow is highly variable, and can yield as high as 5 m^3/s (180 cfs) during storm events. The last significant entry is Comanche Creek which enters the Pecos near Girvin. This creek, fed by springs, once provided over 35 Mm^3/year, but the discharge decreased to the current level of 1.6 Mm^3/year since the early 1950s. The sum of the flow from the creeks and draws listed in Table 2 amounts to a range of 24 to 32 Mm^3/year, excluding one high flow reported at Coyanosa. Additional information on springs or their disappearance is available in Brune (2002).

Table 2. Annual mean flow from the main surface inflow into Malaga and Girvin reach of the Pecos River.

Name	Periods Measured	Average Flow	Salinity
		Mm^3/y	dS m^{-1}
Delaware	1937 - 04	9.51	3.9
Salt Creek	1939 - 57	3.30	19.0
Salt Draw	1939 - 45	3.94	-
Toyah Creek	1939 - 45	4.25	-
Barilla Draw	1924 - 04	0.69	-
Coyanosa Draw	1964 - 77	31.0^1-	-
Comanche Creek	1956 - 64	1.65	-

^{1}- Include occasional high flow. Otherwise 9 million m$^{3/}$year.

The limited runoff from watersheds to the Pecos is partly related to the highly permeable nature of the soil types. Table 3 shows the typical permeability of the main soil series in the Pecos Basin, and the USDA classification related to runoff potential. When CN values are less than 60, no runoff is likely to occur unless the rainfall per occurrence reaches 50 mm (2 inches). The upland soils on this reach of the river consist of the soils with the CN value less than 60 with a few exceptions, such as Del Norte series with a calcic horizon and river bed soils such as the Pecos and Patrole series. We estimate that only 1.4 percent of the annual precipitation makes it to the Pecos River, mostly below Sheffield (Miyamoto et al., 2005). In comparison, the drainage area above the state-line yield runoff equivalent to 2.4 percent of the precipitation.

Table 3. Permeability of the top soil of soil series and USDA runoff classification.

Soil Groups	Permeability mm/hr	Soil Class	CN Number
TX 133 Upland	Low High		
Del Norte (TX)	50 ~ 152	D	77
Nickel, Reakor	50 ~ 152	B	56
TX 230 Upland			
Hoban, Reeves	15 ~ 50	B	56
Reeves, Orla	15 ~ 50	B	56
TX 407 Bottomland			
Pecos	1.5 ~ 5.1	D	77
Patrole	5.1 ~ 15	C	70
Gila, Toya	15 ~ 50	B	56

CN: This is a parameter to estimate water runoff from the soil type.

Groundwater: The main aquifer in Reeves, Pecos, and Ward counties is in the Cenozoic Alluvium which lies above the Rustler Formation. This aquifer was formed through infiltration of runoff water into the basin, including the water from the Pecos River. The aquifer provides over 90 percent of the water used in these counties. The salinity levels of this aquifer are shown in Fig. 3.

The depth to the water table averages 9 m (30 ft) near Red Bluff and becomes shallower to 4.5 m (15 ft), as approaching Coyanosa (Table 4). These average depths to the water table apply to the wells located within 5 km (3.1 miles) from the river stream. The water table away from the river varies, ranging from 45 m (150 ft) to as deep as 90

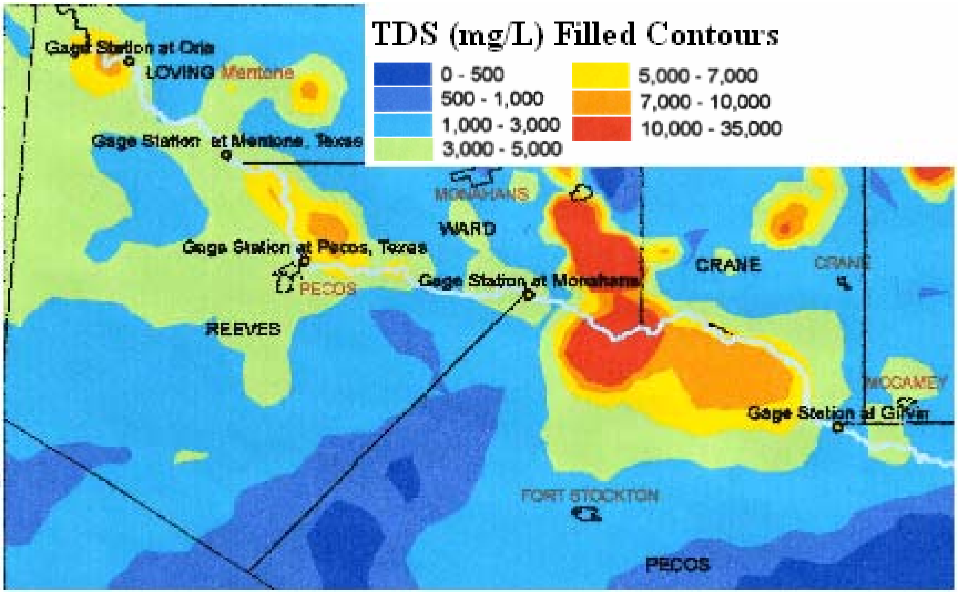


Fig. 3. The distribution of the Pecos Alluvium aquifer, and their salinity levels. (Original chart from Texas Water Development Board.)

m (300 ft), depending on locations and the extent of pumping (Boghici et al., 1999). The elevation difference between Red Bluff and Pecos is 69 m (228 ft), whereas the difference in the depth to a water table is only 8.1 m (27 ft). This aquifer is a typical bolson of the semi-arid southwest except that it is underlined by the salt or oil containing formations.

Salinity of this aquifer is usually less than 3,000 mg L^{-1} in the western reaches of the Middle Pecos River (Fig. 3). However, salinity increases towards Girvin, exceeding 10,000 mg L^{-1}. It is yet to be determined if this aquifer enters into the Pecos between Coyanosa and Girvin. In the reach above Coyanosa towards Red Bluff, this aquifer is charged by saline stream of the Pecos River as well as by area runoff (Grozier et al., 1966).

The sodium adsorption ratio (SAR) of this aquifer is generally low above Pecos and ranges from 2 to 8.9 (Table 4). However, it increases to as high as 17 towards Girvin. Likewise, the concentrations of Na, Cl, and SO_4, increase towards Girvin. The concentration of Cl ranges from 0.3 to 2.0 g/L above Coyanosa and increases to 4.7 g/L below Coyanosa. The concentration of SO_4 remains 1.6 to 1.9 g/L until Coyanosa and then increases to 2.9 g/L below Coyanosa. The Toyah Basin above Coyanosa contains both Cl and SO_4 salts (Uliana and Sharp, 2001), some of which may be entering the Pecos below Coyanosa.

A classic report on the groundwater in the Pecos County (Armstrong and McMillan, 1961)

Table 4. Depth to and quality of ground water wells within 5 km (3.1 miles) from the Pecos River between Malaga and Girvin.

	Water		Salinity		Sodicity		Cl		SO_4	
	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range
	----Depth (m)----		--------(g/L)--------		------SAR-------		---------(g/L)-------		---------(g/L)-------	
Malaga - Red Bluff	12.64	3-30	-	-	-	-	-	-	-	-
Red Bluff - Mentone	9.14	3-15	3.3	3.1-3.5	2.0	1-3	0.3	0.2-0.6	1.8	1.7-2.1
Mentone - Pecos	5.79	3-12	4.4	2.8-6.4	8.9	4-12	0.1	0.7-2.3	1.7	1.3-2.3
Pecos - Coyanosa	4.5	3-8	5.6	2.4-8.4	10.0	5-15	2.0	0.7-3.1	1.9	0.8-2.8
Coyanosa - Girvin	6.71	3-11	9.3	2.1-15.9	17.2	13-21	4.7	2.8-7.4	2.9	2.6-3.6

Source: http://www.twdb.state.tx.us/publications/reports/GroundWaterReports/GWDatabaseReports/GWdatabaserpt.htm indicates that salinity of most well waters in the county prior to 1961 were less than 1,000 mg/L except in the north-central part near the Imperial Reservoir where salinity was in excess of 5,000 ppm. Today, some of these wells have salinity as high as 10,000 mg/L. The causes of this salinity increase are yet to be investigated.

Reach Dimension: The Middle Pecos River winds through a semi-arid desert. The course of the river tends to be less winding between Red Bluff and Pecos and become increasingly winding especially below Coyanosa, as shown earlier in Fig. 1. The longitudinal slope of the river between Red Bluff and Pecos averages 0.053 percent (68.4 m drop over 130 km or 228 ft/80.7 mil) whereas the slope between Coyanosa and Girvin is 0.037 percent (52 m over 141 km). The river miles between Red Bluff and Girvin are 346 km (215 miles).

The Pecos River in Texas was carved through water erosion and has a cross–section resembling a sliced section of a bowl (Fig. 4). The size of the cross–section varies by location. The smallest section is from Red Bluff to Mentone where the width of the river top averages 30 m (Table 5). This section has the steepest slope. The second section is between Mentone and Coyanosa where the river top extends to 44 m, and becomes deeper. This section is a transition from the first to the third section where the river top enlarges to 54 m.

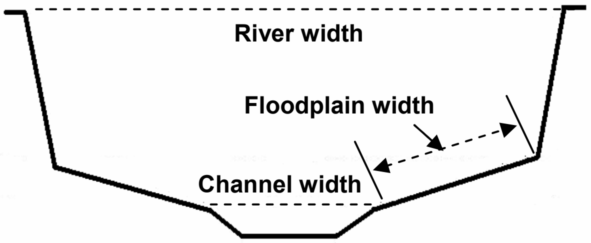


Fig. 4. Schematic of typical cross-section of the Pecos River between Red Bluff and Girvin.

The progressive increase in river dimension undoubtedly reflects the large river flow of the distant past. Today the channel width decreases rapidly beyond Mentone due to declining flow. The surface area of the channel between Red Bluff and Girvin is estimated at 370 ha (914 acres). The water evaporation from the stream is estimated at 6.9 Mm^3/year, assuming the pan coefficient of 0.7.

Table 5. The channel width, the floodplain width measuring along the slope, and the river width of the Middle Pecos.

Reach	Reach Length	Channel Width	Floodplain one side[1┘]	River Width	Channel Area
	km	**m**	**m**	**m**	**ha**
Orla	23	17.0	3.7	30.0	39.1
Menton	53	14.6	4.8	30.0	77.4
Pecos	47	11.0	8.4	34.0	51.7
Coyanosa	62	9.0	14.0	44.0	55.8
Girvin	161	9.0	17.4	54.0	144.9
Total	346				368.9

[1┘] Measured along the slope

Sources of Salts

The Pecos River Basin was once under an ancient sea and is the western edge of the Permian Basin. Upon evaporation of the sea, salts, mostly halite (NaCl), and gypsum ($CaSO_4$, $2H_2O$), were formed. Some of these salts appear near or on the ground as saline springs or saline seeps, not only in the Pecos River Basin, but also in neighboring river basins as shown in Fig. 5 (Johnson, 1981).

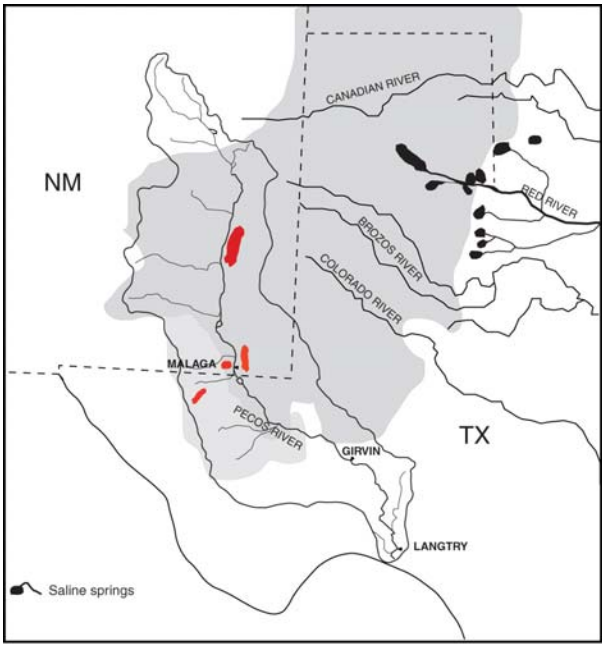


Fig. 5. Permian evaporite deposit of West Texas and southeastern New Mexico.

The flow entering the Pecos River above Acme, New Mexico, is nearly saturated with gypsum (solubility of 2,200 mg L^{-1} as $CaSO_4$,

$2H_20$) after it passes through the gypsum formation. Below Acme, halite becomes the dominant salt. The first major entry of halite into the Pecos River occurs in the area near Bottomless Lakes, located east of Roswell. Groundwater from the west percolates to the ground surface through sinkholes created by the dissolution of gypsum and halite (McAda and Morrison, 1993). The sources of salts which enter the Pecos in the reach between Malaga, New Mexico, and Girvin, Texas, may involve four types: brine from the Salado Formation, shallow saline groundwater, saline creek or draw, and oil-field brine (Miyamoto et al., 2005).

Brine from Salt Formation: Brine intrusion into the Pecos River from Malaga Bend (Fig. 6) has been observed for decades. Surface water is believed to enter through the Rustler Formation (which lies on the Salado Formation) about 50 km (31 miles) northeast of Malaga Bend (Havens and Wilkins, 1979). The infiltrated water moves laterally, then upward towards the Pecos River through a boundary between the two formations. The saturated brine with the salt concentration nearly equaling the solubility of NaCl (360 g L^{-1}) enters the Pecos near USGS Well 11 and, to a lesser extent, near USGS Well 8 (Fig. 6). The discharge rate of brine seepage is estimated at 12.5 L/s (0.44 cfs) which yields an annual salt loading of 140,000 tons into the Pecos River (Hale et al., 1954). In addition, saline seepage seems to enter the Pecos through sinkholes or depressions during high flow or when irrigation activities raise the water table near the discharge points (Hale et al., 1954; Miyamoto et al., 2007). Prior to 1991, the brine intrusion occurred to a greater extent, especially during irrigation seasons, but has declined to the current level of approximately 150,000 tons/year as irrigation activities diminished at Malaga Bend.

When flooding occurs between Roswell and Red Bluff, where salts are exposed near the surface or are accessible through sinkholes, historical records show that the flood water had elevated salinity. An example is given in a later section.

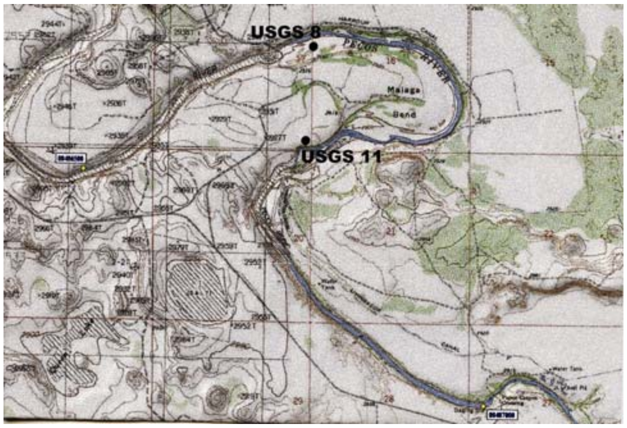


Fig. 6. An aerial view of Malaga Bend to P. C. Crossing segment of the Pecos River near Red Bluff.

Shallow Groundwater: The study conducted by Grozier et al. (1966) indicates that there was continuous flow below Coyanosa (north of Grandfalls) all the way to Girvin when reservoir release or runoff into the Pecos River was minimal. As shown earlier, the depth to the shallow groundwater varies and in places is shallower than the depth to the streambed of the Pecos River. Salinity of the flow was around 17,000 mg L^{-1} except for one entry from Grandfalls (Fig. 7). This highly saline water entering at Grandfalls was oilfield brine and has since been controlled. Salt load, excluding the seepage from Grandfalls, increased almost in proportion to the flow and amounted to 187,000 tons at Girvin, excluding the oilfield brine. The flow-weighted salinity of the shallow saline water intrusion is lower, thus yielding a lower estimate of salt load 136,000 tons, as shown in Table 6. These numbers should be considered a tentative estimate since the existing data are too sketchy to arrive at definitive figures. The additional seepage into the Pecos River was noted below the town of Pecos, and is probably subsurface flow from Salt Draw.

Some believe that the shallow groundwater feeding the Pecos comes from the Monument Draw Trough in Winkler, Ward, and Crane Counties. However, the groundwater in these counties is lower in salinity (mostly less than 3000 ppm) than the water in the river. Jones (2001) pointed out that salinity of the Cenozoic Pecos Alluvium tends to be higher towards the ground surface, especially at a depth less than 75 m (250 ft). White (1971) seems to believe that the shallow portions of the aquifer are concentrated by evapotranspiration prior to discharge into the Pecos. Ashworth (1990) and Ashworth and Hopkins (1995), however, indicate that there are potentials for recharge by agricultural drainage water and contamination by oilfield brine. Salt bearing aquifers and formations located under the Pecos Alluvium can also contribute to elevated salinity. There are also unconfirmed reports, indicating the presence of the secondary salt formation at a depth of 60 to 90 m (200 to 300 ft) in parts of Pecos County (personal communication with drilling contractors). If this is true, wells can potentially dissolve the salt layer. There are also salt pits where oilfield brine was once disposed. It is also possible that the shallow saline groundwater is, in part, the recharge from the Pecos River upstream. This is a fairly complex situation and requires detailed study.

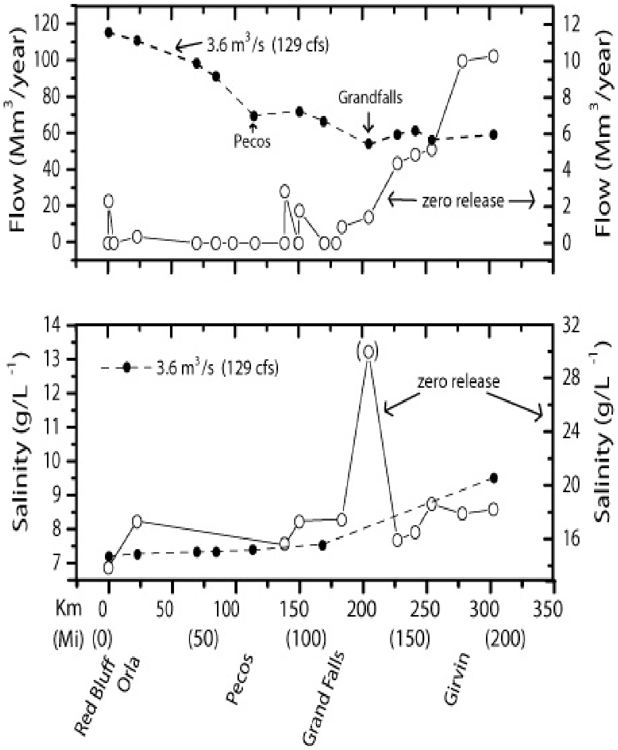


Fig. 7. Spatial changes in flow, and salinity along the Pecos River below Red Bluff: -----discharged at 3.5 m3/s (129 cfs); ——zero release.

Salt Creek: There are a few other entries of saline water into the Pecos River below Red Bluff, which are not widely known. The first is Salt Creek, located immediately below Red Bluff. This is the only perennial creek between Red Bluff and Girvin. Salt Creek carries an annual flow of 3.3 Mm^3 with an estimated salinity range of 12,500 to 15,000 mg/L. The estimated salt load is no less than 41,000 tons/year (Table 6). The source of salts entering Salt Creek has not been investigated but is likely to be a saline spring from the Rustler formation. This formation contains an appreciable amount of soluble salts. There are a few other creeks or draws which appear to carry salts into the Pecos River. One of them is Salt Draw which enters the Pecos River below the town of Pecos and above Coyanosa. The flow of Salt Draw does not reach the Pecos very often, but it enters as subsurface flow. These subsurface sources are significant and are estimated to yield a salt load of 75,000 tons/year (Grozier, 1966), though it is doubtful that this subsurface saline flow occurs at a constant rate throughout the year.

Table 6. Tentative estimates of saline water inflow into the Pecos River and stream flow salinity.

	Salt Load	Flow Wt. Salinity	Arithmetic Means
	kt/y	---------- mg/L	----------
The Upper Reach		488	675
Gypsum dissolution	179	1312	1527
Bottomless Lakes	271	3060	3170
The Middle Reach			
Malaga Bend	150	5400	7100
Salt Creek	41[1]-	6150	6150
Salt Draw	75[2]-		
Saline Groundwater	136	12100	12800
	402		
The river total[3] -	852	-	-

[1] - Estimated, and approximation only.

[2] - Based on one observation, and depending on flow.

[3] - Excluding any dissolution below Girvin.

Oilfield Brine: The Permian Basin is also known for its rich oilfields. Oil and gas are currently produced at depths ranging from 270 m (900 ft) to as deep as 1,800 m (6,000 ft). Salt water is also produced in varying proportions with oil and gas. In early years, oilfield brine was disposed onto the ground surface or into infiltration basins; since 1969 it has been disposed into injection wells. There have been incidences of groundwater contamination with oilfield brine (e.g., Richter et al., 1990; Richter and Kreitler, 1987). Grozier et al. (1966) also noted that the saline water entering the Pecos near Grandfalls was oilfield brine. The extent of oilfield brine intrusion directly into the Pecos River appears to be very limited, at least in the reach to Girvin. However, it is unclear if oilfield brine may have leaked into the shallow saline water along the Pecos River. There are many oil wells along the Pecos, as shown earlier in Fig. 1. The situation below Girvin is beyond the scope of this report, but oil which flows naturally near Iraan is reported to enter the Pecos occasionally.

Flow and Salinity

Historical Data: It was noted in the introduction that one of the most significant changes that took place in the reach below Malaga was a drastic reduction in flow throughout the reach. Historical data show widely fluctuating flow and annual mean salinity at Malaga (Fig. 8A). The overall trend at Malaga is a decline in flow and increasing fluctuation in salinity, especially after the 1950s. Note that the flow during the period of 1937 through 1940 was already reduced by 70 percent as dam construction upstream proceeded mostly in the years 1908 and 1937. Brine intrusion at Malaga Bend into the reduced flow caused streamflow salinity to increase as recorded at Pierce Canyon (P.C.) Crossing (Fig. 8B). Nonetheless, the occasional high flow events still

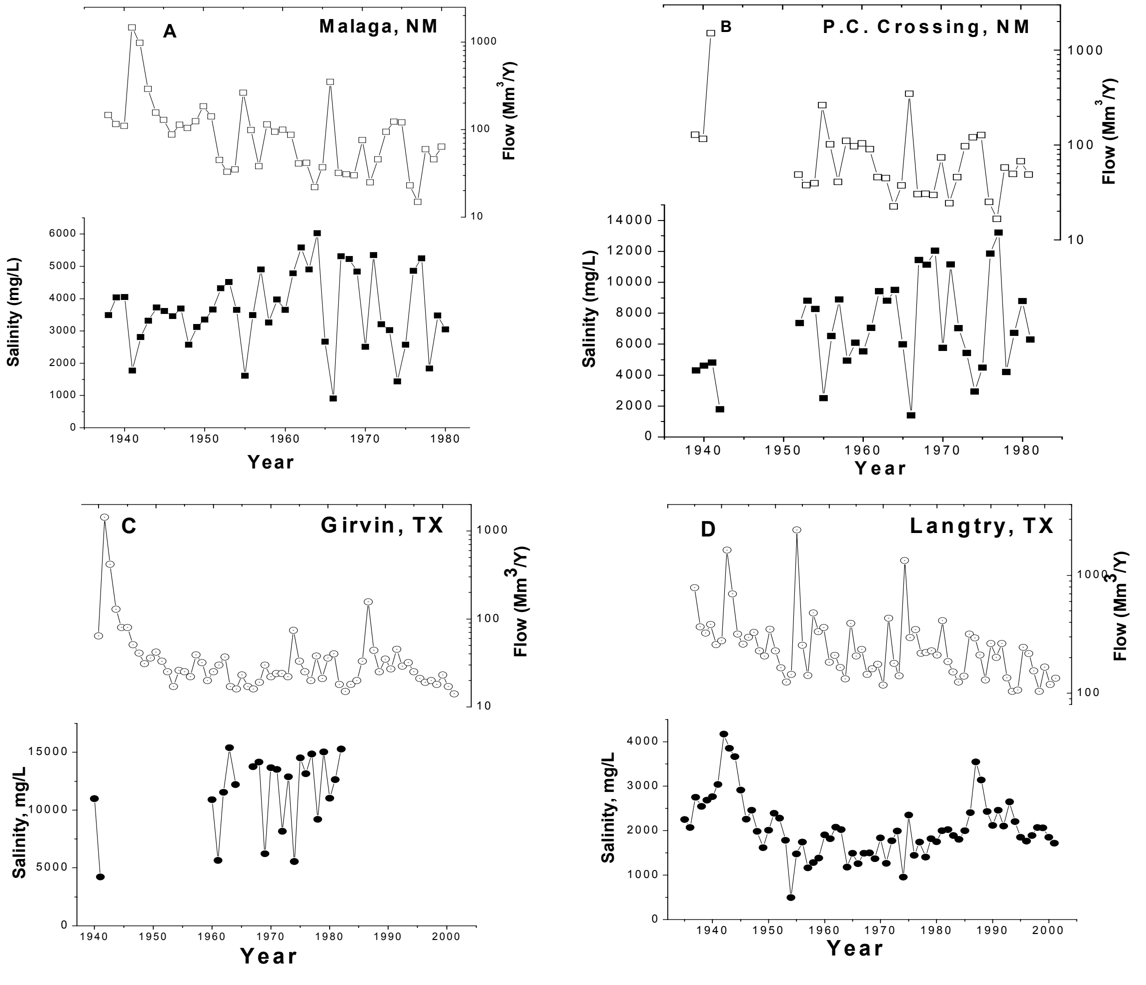


Fig. 8. Historical changes in annual flow and flow-weighted salinity recorded at Malaga and P.C. Crossing, New Mexico, and Girvin and Langtry, Texas (original data from USGS and U.S. Bureau of Reclamation).

lower salinity to as low as 2,000 mg L^{-1}. Salinity data are not available prior to 1937.

Streamflow salinity at Girvin has also increased since 1941 (Fig. 8C). No salinity data are available at Girvin after 1982 except for occasional measurements through the Texas Clean Rivers Program (CRP). The flow has decreased to a range of 20 to 30 Mm^3/year since the 1950s. Salinity reported at Langtry (Fig. 8D) does not follow the salinity pattern at P.C. Crossing or Girvin. Instead, it follows the flow pattern at Girvin. The saline water passing through Girvin is the main source of salts, although it is diluted through tributary inflow below Girvin. Salinity at Langtry is around 2000 mg L^{-1}, and exceeds the Texas drinking water standards.

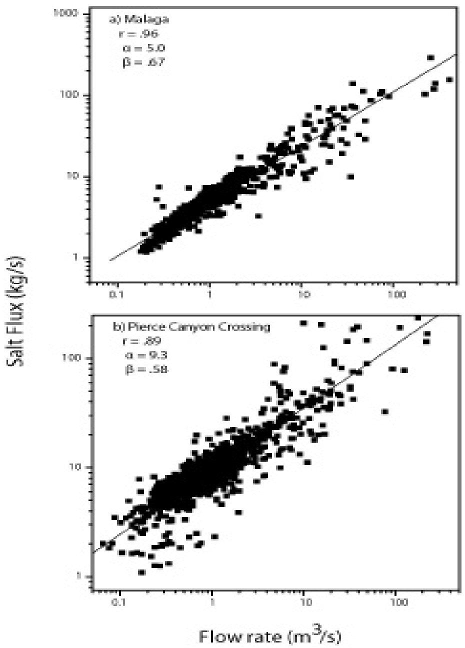


Fig. 9. The historical relationship between salt flux and momentary flow rate at the time of water sampling (Miyamoto et al., 2005).

The correlation between streamflow and salt flux is shown in Fig. 9 at Malaga and P.C. Crossing. The high degree of correlation was found at all gauging stations. The salt flux increases with flow, but salinity usually decreases with increasing flow. When there is no change in salinity with increasing or reducing flow, the coefficient β is equal to 1.0. When the stream is to be diluted with no change in salt load or salt flux, β approaches zero. In other words, salinity decreases inversely with flow. The value for β averages 0.67 in this reach, except at P.C. Crossing where a slightly lower value of 0.58 is more appropriate (Table 7). This type of equation is also useful for adjusting salinity measured at momentary flow to the monthly mean flow. It can also be used to estimate salinity changes associated with the changes in projected flow. Also included in Table 7 is the conversion coefficient from the conductivity to the total dissolved salts (Miyamoto et al., 2005).

Table 7. The empirical coefficient to estimate total dissolved salt contents (TDS), and the conductivity (EC), and to describe the relationship between salt flux (Cq) and flow rate (q).

Location	a	α	β	r
		g/L		
Sumner	0.87	1.48	0.95	0.96
Artesia	0.70	5.01	0.67	0.92
Malaga	0.71	5.01	0.67	0.96
P.C. Crossing	0.67	9.33	0.58	0.89
Red Bluff	0.66	8.71	0.65	0.89
Girvin	0.71	11.48	0.69	0.89
Langtry	0.62	2.24	0.91	0.88

[1] TDS (g/L) = a EC (dS m^{-1})

[2] $Cq=\alpha q^{\beta}$, C=g/L, q=m^3/sec

[3] r value for α and β

Salinity and Ionic Composition: The ionic composition of streamflow should reflect the kinds of salts being dissolved into the stream. The concentration of dissolved salts measured in the stream near Santa Rosa show low salinity, but high proportions of Ca and SO_4 ions (Table 8). This reflects the dissolution of gypsum in the upper watershed. Gypsum dissolution is a prevalent feature throughout the upper reach. When the flow of the Pecos reaches Bottomless Lakes, the dissolution of halite (NaCl) occurs, and affects the stream concentration of Na and Cl at Artesia and below. The concentrations of Ca and SO_4 in the stream near Artesia approach the solubility limit of gypsum, which is approximately 30 meq/L in fresh water.

There is no major known salt inflow between Artesia and Malaga. However, salinity of the stream increases from 3,200 to 4,100 mg/L or by factor of 1.28. The ionic concentrations shown in parentheses in Table 8 were obtained by

Table 8. Salinity and ionic composition of the Pecos River (USGS, 1999-2000).

Location	TDS	Na	Ca	Mg	Cl	SO_4
Recorded	g/L	-------------------	-------------------	meq/L	-------------------	-------------------
Santa Rosa	0.5	0.5	5.0	1.1	0.3	4.5
Sumner	1.3	2.2	14.9	2.8	1.8	15.8
Artesia	3.2	17.6	23.7	8.2	17.5	28.7
Malaga	4.1	29.0	23.9	12.1	31.0	31.0
(Estimate)[1]	(4.1)	(22.5)	(30.5)	(10.5)	(22.4)	(36.0)
Red Bluff	7.0	73.1	26.8	14.8	78.2	32.8
Girvin	12.8	145.1	36.6	32.4	143.7	64.8
(Estimate)[1]	(12.8)	(133.8)	(49.0)	(27.1)	(143.7)	(60.0)
Gains	g/L	-------------------	-------------------	meq/L	-------------------	-------------------
Sumner	0.8	1.7	9.9	1.7	1.5	11.3
Artesia	1.9	15.4	8.8	5.4	15.7	12.9
Malaga	0.9	11.4	0.2	3.9	13.5	2.3
(Estimate)[1]	(0.9)	(11.0)	(6.6)	(2.3)	(4.9)	(8.0)
Red Bluff	2.9	44.1	2.9	2.7	47.2	1.8
Girvin	5.8	72.0	9.8	17.6	65.5	32.0
(Estimate)[1]		(60.7)	(22.2)	(12.3)	(65.5)	(27.2)

[1] Ionic concentration when the release from Red Bluff is assumed to be concentrated through evaporation.

assuming that the ion concentration increases in proportion to the salinity increase caused by the evaporative concentration. The measured data show that the concentrations of both Na and Cl are substantially higher than the estimated. This indicates halite dissolution, possibly into return flow or agricultural drainage water. The measured Ca and SO_4 concentrations were lower than the estimated (Table 8), indicating precipitation of Ca and SO_4. The sharp increase in salinity and the concentration of Na and Cl between Malaga and Red Bluff reflects halite dissolution at Malaga Bend.

Water quality monitoring stations by the USGS are sparse below Red Bluff. Girvin, located 340 km below, was the next station, but water quality monitoring was discontinued in 1983. Thus, the next station is now at Langtry. The available data show large increases in Na and Cl concentrations between Red Bluff and Girvin (Table 8). There is also a significant increase in SO_4 concentration, but not Ca. The dissolution of halite and/or Na_2SO_4 containing minerals is likely. There are also indications of Ca precipitation, and some gains in Mg concentrations. The shortage of water quality data at Pecos and Coyanosa makes it difficult to establish the connection between the salt sources and streamflow water quality.

Reservoirs and Flow Regulation: The flow of the Pecos River above Malaga is now regulated by the Brantley Dam constructed in 1991. This dam is a replacement for the McMillan Dam which suffered silting and sinkhole developments. Brantley Dam has a maximum storage capacity of 1.2 billion m^3 (970,000 acre-ft), and is located 16 km (10 miles) north of Carlsbad, and stores water mainly for the Carlsbad Irrigation District above the state line. The water allocated to Texas is usually released once or twice a year as a lump sum from this reservoir.

Red Bluff Dam, constructed in 1936, has been the major water storage facility on the Texas side. The storage capacity adjusted to sediment accumulation is estimated at 357 Mm^3 (289,600 acre-ft). However, the actual storage since 1991 averaged 100 Mm^3 (81,000 acre-ft), while the inflow averaged 126 Mm^3 (70,000 acre-ft) per year, including the flow from the Delaware River (Table 9). The outflow averaged 59 Mm^3 (48,000 acre-ft) per year for the same period. If the outflow reported is correct, it appears that slightly more than half of the water entered into the reservoir was lost. The evaporative loss from the reservoir water surface is estimated at 35 Mm^3 (28,000 acre-ft) per year, the rainfall which falls on the surface, 5.7 Mm^3/year. This leaves the percolation loss to be 41 Mm^3/year, which is 33 percent of the inflow. However, the flow records at Orla suggest that about 9 out of the 41 Mm^3 may be returning back to the river.

The annual salt loading into Red Bluff for 1991-2001 is estimated at 558,000 tons at the flow-weighted salinity of 4,425 mg L^{-1} from the Pecos plus the inflow from the Delaware River (Table 9). The salt leaving the reservoir, estimated at 579,000 tons/year is roughly comparable to the salt loading, as it should be. The outflow salinity has averaged 6,150 mg L^{-1} since 1991. Salinity data for the outflow prior to

Table 9. Flow-weighted salinity and the estimated salt load entering and leaving Red Bluff Reservoir for a long-term (1959 - 2001) and short-term (1991 - 2001) durations.

	1959 - 2001			1991 - 2001		
	Flow	Salinity	Load	Flow	Salinity	Load
	Mm^3/y	mg/L	1000 t/y	Mm^3/y	mg/L	1000 t/y
Inflow						
The Pecos	84	5390	453	95	5030[2]	478
The DWR	21	2677[1]	56	31	2572	80
Composite (USGS)	105	4810	505	126	4425	558
(EPA)	-	6160[3]	-	-	5495[3]	
Reservoir Storage				storage		
EPA data	-	-	-	-3.6	-	24[4]
				(Subtotal)		(582)
Outflow						
Gauged (Dist./EPA)	-	-	-	59	6150[3]	363
Percolation (EPA)			-	41	5310	216
				(Subtotal)		(579)

[1] Estimated by using the salinity and flow relationship.

[2] This concentration is at P.C. Crossing, and probably lower than those at the station below (Above DWR).

[3] Arithmetic means.

[4] An estimate based on EPA data. Salinity at the beginning and ending was reported to be 6480 and 6640 mg L^{-1}, respectively.

1991 are not available. The concentration difference between the inflow and the outflow since 1991 is 655 mg/L in arithmetic mean and 1,700 mg/L in flow-weighted mean. This salinity increase is caused mainly by the evaporative salt concentration. The water surface area of Red Bluff averaged 17 km^2 (4,200 acre) for 1991 through 2001, and the average water depth during the period was reported to be 6.6 m (19 ft).

Red Bluff—and any reservoir for that matter—contributes to an increase in salinity as water evaporates from the stored water. However, reservoirs also serve to equalize salinity of incoming flow. This is particularly important at Red Bluff, as salinity of the streamflow is highly variable due to intrusion of saturated brine at Malaga Bend. There was widely held notion that saline water is settling at the bottom. We found no data to confirm it. Instead, a model analysis seems to indicate that the reservoir water is mixed, and that salinity is slightly higher at the surface due to water evaporation (Miyamoto et al., 2007).

Fig. 10 shows examples of annual flow and annual mean salinity during normal flow years (2000 and 2001) and during low flow years (2002 and 2003) for the reach between Red Bluff and Langtry. These figures were drawn using the data obtained by the Texas Clean Rivers Program (CRP). Flow and salinity are measured through this program three to four times a year. The outflow from Red Bluff has salinity of 5,000 mg L^{-1} during normal years and around 7,000 mg L^{-1} during low flow years. Salinity of the release increased by about 100 mg L^{-1} due to the inflow of Salt Creek below the reservoir. Salinity at Coyanosa increases probably because of the inflow from Salt Draw. It also increases towards Girvin due to shallow groundwater intrusion.

Water and Salt Balance: The tentative water and salt balance estimate for the reach between Red Bluff and Girvin is shown in Table 10. These estimates were made based on CRP data from 1995 through 2004, supplemented by the USGS data and the report by Grozier et al. (1966). The reservoir release data were obtained from the Red Bluff district from 1990 through 2001 along with the diversion data. The percolation loss was estimated based on the earlier reports by Grozier et al. (1966). The evapotranspiration loss was

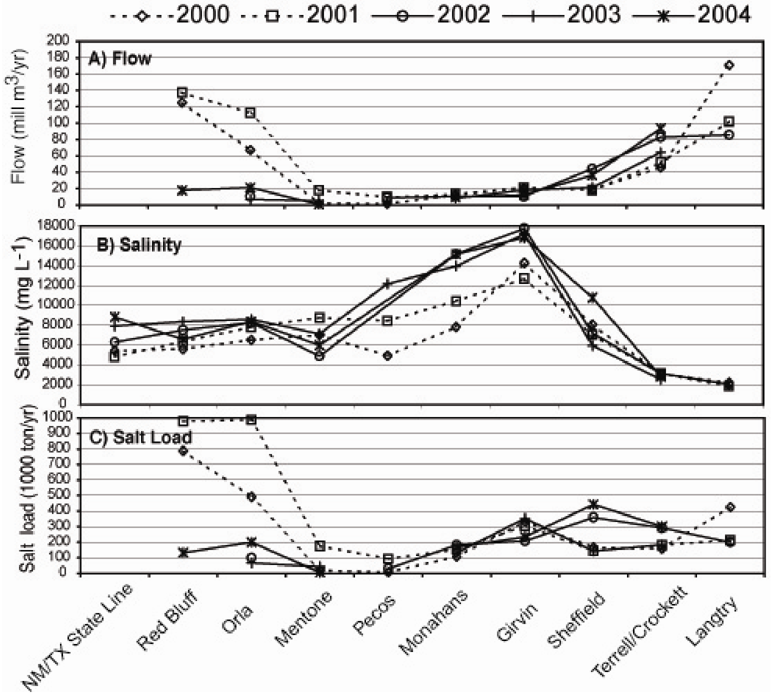


Fig. 10. Flow, salinity, and salt balance in different reaches of the Pecos River during the last four years (original data from CRP).

estimated by assuming a 1:4 ratio for flooded and non-flooded riparian zones. As will be discussed later, Cleverly et al. (2002) reported the evapotranspiration loss of 1.20 m for flooded areas and 0.74 m for non-flooded areas per year in New Mexico. The weighted mean of 83 cm (32 inches) was used for the annual evapotranspiration. The riparian area subject to the evapotranspiration losses for the reach between Red Bluff and Girvin was assumed to be 3,000 ha (7,410 acres) as estimated by Hart (2004). The gauge near Coyanosa is located more or less at a midpoint of the Red Bluff-Girvin reach, thus the estimated evapotranspiration loss of 25 Mm^3 (20,200 acre-ft) was apportioned.

The inflow from creeks and draws was back-calculated, as the existing records are sketchy or do not exist. The estimated annual salt loading of 194,000 tons from Creek and Draws in Table 10 seems to be too large, since the combined salt loading from the two known sources, Salt Creek and Salt Draw, amounts to 116,000 tons (Table 6). However, recall that 9 out of 41 Mm^3 of the reservoir percolation loss seems to be returning back to the river. This accounts for 52,000 tons/year, although it is placed in the wrong category. The salt balance of 26,000 tons/year can come from Toyah Creek and others.

The water and salt balance shown in Table 10 is a crude estimate. However, it does point out that the salt load of the Pecos River at Coyanosa, 149,000 tons/year, is comparatively small as the

Table 10. Tentative water and salt balance estimate for the Pecos River between Red Bluff and Girvin.

	Flow	Salinity	Load
	Mm^3/y	mg L^{-1}	1000 t/y
Red Bluff - Coyanosa (180 km, 115 miles)			
Incoming	59	5805	+342
Creek & Draws	(31)[1] -	(6260)	(+194)
Diversion	32	6150	-197
Percolation	31	6150	-191
Evap-Trans	13	(11507)	0
Outflow	14	10650	-149
Coyanosa - Girvin (166 km, 100 miles)			
Incoming	14	10650	+149
Creek & Draws	(10)[1] -	(900)	(+9)
Subsurface	11	12100	+136
Diversion	0	0	0
Evap-Trans	12	(14800)	-
Outflow	21	14010	-294

Data from the CRP since 1995.

[1] - Numbers in parenthesis are estimated.

water is diverted for irrigation or lost through percolation. The salt load of the stream nearly doubles when reaching Girvin. The saline water intrusion of 136,000 tons/year mostly accounts for the increase. It is unknown at this stage if this intrusion is fed by the recharge from the Pecos stream or from the Monument Draw Trough. If the salt load increase is originating solely from the percolation loss, it amounts to 70 percent of the salt loss from the percolation loss. In terms of water balance, the saline water intrusion of 11 Mm^3/year (or 22 Mm^3/year adjusted to the evapotranspiration) loss amounts to 70 percent of the percolation loss above Coyanosa. This, however, does not indicate that the percolation loss above Coyanosa is the source. It merely indicates that the quantity of percolation loss is large enough to account for the saline water intrusion. Detailed studies of groundwater flow are needed to clarify these uncertain figures.

Water Management

The Pecos River was originally developed for irrigation, mostly during the period of 1908 through 1936. The Red Bluff and Carlsbad Districts are two of the oldest irrigation districts along the Pecos River. Declined flow, combined with increased salinity, is believed to have caused a shift in crop irrigation to groundwater in the 1950s (Table 11). Irrigated crop production in the Texas counties has eventually declined starting in the 1970s. The cropland irrigated with the river water is now less than 8,000 acres in Texas counties. Prior to the 1970s, the area irrigated with the river water was well above 11,000 acres. The cropland irrigated with groundwater is holding at around 50,000 acres.

Water Storage and Delivery: Water storage and delivery operations are managed by the Red Bluff Water Power Control District (RBWPCD). Water losses associated with water storage were already mentioned earlier. Water transmission losses along the river were also introduced earlier in Fig. 3. According to the data of Grozier et al. (1966), the transmission losses amount to 40 percent of the reservoir release between Red Bluff and Pecos, and an additional 12 percent percolation loss occurs before reaching Grandfalls. Thereafter, the river gains flow because of groundwater intrusion to the tune of 0.16 m^3/s (5.6 cfs). These figures were obtained under a constant release of 3.6 m^3/s (129 cfs), and the diversion was kept at minimal.

The diversion for irrigation takes place mostly between Orla and Pecos (Fig. 11). The Pecos Irrigation District obtains water from the Imperial Reservoir rather than directly from the river. For the period of 1991 through 2001, the reservoir release averaged 59 Mm^3 (48,000 acre-ft) per year. The average diversion was reportedly 32 Mm^3 (26,000 acre-ft) per year. This means that 54 percent of the water released from the reservoir was diverted. However, if we add 9 Mm^3/year of the seepage return, the diversion rate falls below 50 percent. Recall that the percolation loss from Red Bluff to Grandfalls (near Coyanosa) was estimated at 52 percent. These figures, which came from different sources, seem to be consistent.

Water from the reservoir is released upon the requests from individual irrigation districts.

Table 11. Irrigated areas and surface water use along the Pecos River.

	Irrigated area (acres)[1] -			
Texas	1958	1964	1979	2000
	------------------------------acres--------------------------------------			
Red Bluff-Pecos (Loving, Reeves, and Ward)				
Total[1] -	15,460	123,747	38,320	29,095
Surface	11,200	7,300	375	7,080
Pecos-Girvin (Pecos and Crane)				
Total[1] -	117,413	119,113	27,291	27,083
Surface	0	0	0	1,199
Below Girvin (Crockett, Terell, and Val Verde)				
Total[1] -	3,116	2,827	1,973	1,167
Surface	111	207	658	808
Total	**135,989**	**245,687**	**67,584**	**57,345**
Surface	**11,311**	**7,507**	**1,033**	**9,087**

[1] - Data published on and http://www.twdb.state.tx/us/publications/reports/Reports.asp for Texas.

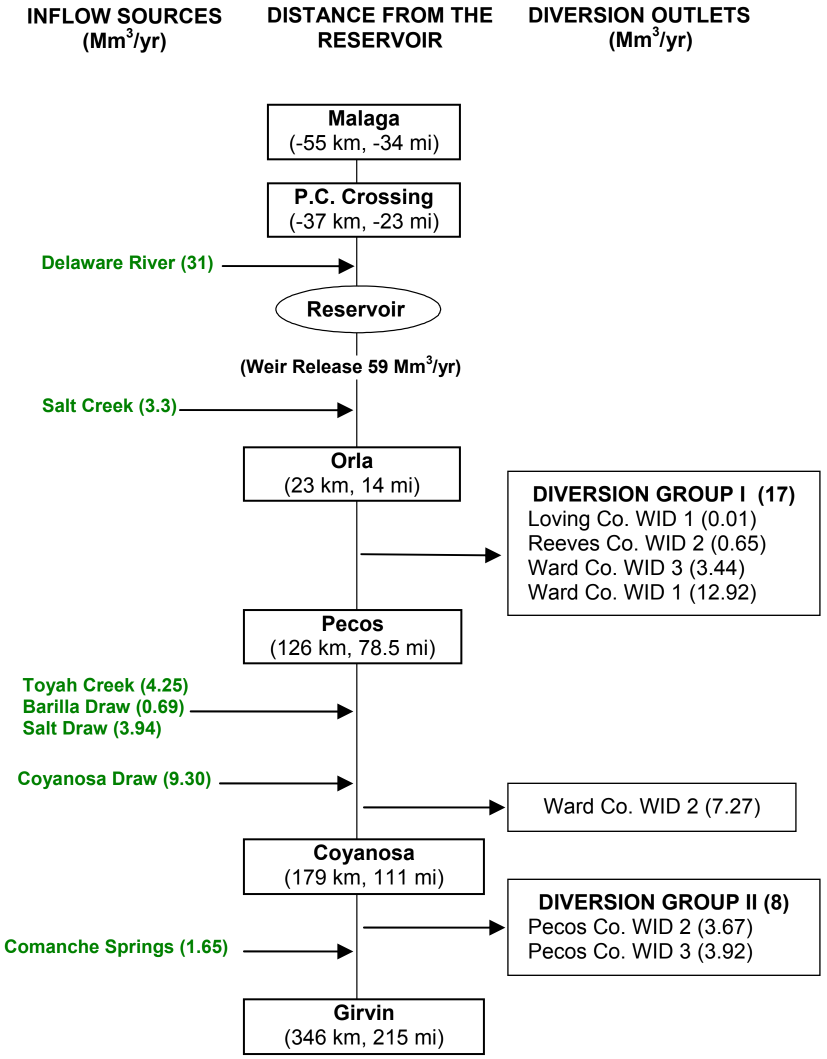


Fig. 11. Inflow and diversions along the Pecos River between Malaga and Girvin (the means of 1991 through 2001).

Since the primary crops grown are cotton and hay (or pasture), the demand is concentrated during summer months, April through August. However, if available, water is released until as late as November.

The flow of the Pecos River which finally reaches irrigated land is about half of the reservoir release. Since the water loss at Red Bluff (evaporation and percolation losses) was also about half of the inflow, only ¼ of the water entering Red Bluff appears to reach irrigated fields. Since the inflow varies with year, the diversion, and the irrigated areas also vary. The diversion since 1991 averaged 32 Mm^3/year, which is sufficient to irrigate 3,200 ha (7,900 acres) of croplands at an assumed annual water application of 1 m (40 inches) per ha.

On-Farm Water Management: This topic was beyond the scope of this study. However, there has been an interest in improving the water distribution efficiency by changing from the surface method to pressurized systems, such as drip and drop-tube methods. The use of sprinklers with saline water causes foliar salt adsorption and associated damage in broadleaf plants such as cotton (e.g., Moore and Murphy, 1979). Because of the high salinity of irrigation water, certain amounts of water have to be drained in order to maintain the necessary salt balance. This will depend on the salinity of the irrigation water, salt tolerance of crops to be grown, as well as irrigation methods and management.

Conservation Release: Whenever water is available in Red Bluff Reservoir, a small amount of the water is said to be released for sustaining aquatic life. Because of highly permeable streambeds, the water tends to be lost through percolation. Fortunately, the reach below Coyanosa usually has some flow, even when the reservoir release is low. A problem is that salinity of the flow is very high, as mentioned earlier in Table 5.

Floodplains and Riparian Zones

Floodplains: The floodplains of the Middle Pecos River are narrow and sloped, especially above Mentone. Floodplains—but not necessarily channel width—become wider downstream, reflecting the river flow of the distant past. Bank overflow is easier to attain with the narrow and confined floodplains. The floodplain of the Middle Pecos, especially above the town of Pecos, consists of loamy sediments which are moderately to highly permeable. These two factors are likely to facilitate salt leaching from the floodplains.

Salinity and Moisture of Floodplains: Soil salinity and moisture have a direct impact on growth of riparian vegetation. Soil salinity is measured in the soil saturation extract, and if it exceeds 4 dS m^{-1}, it is classified as saline soil (USSL Staff, 1954). However, this criterion is for crop production, and may not have a great deal of meaning for growth of highly salt-tolerant riparian vegetation. We measured soil salinity and field soil moisture in May, July, September, and November of 2005 at the CRP Pecos River monitoring sites. Soil samples were taken at 0.7 and 4.5 meters (2.5 and 15 ft) from the stream edge at three depths: 0-30, 30-60, and 60-90 cm (1, 2 and 3 ft) and were analyzed for the field soil moisture, the saturation water content, and salinity of the saturation extract by the method described in Rhoades and Miyamoto (1990).

Results have shown that soil salinity and moisture data did not change significantly over the season of the measurements except at Pecos where salt leaching seems to have occurred after July. The data obtained in July and September were averaged and are shown in Table 12. The most notable trend was that soil salinity increased downstream, especially below Coyanosa. This pattern can be attributed to the increase in streamflow salinity. The ratio of soil salinity over stream salinity was less than 1.0 at Orla and Mentone, and increased towards 2.0 below Pecos. This ratio was greater for the samples taken at the

Table 12. Soil salinity measured at .75 m (2.5 ft) and 4.5 m (15 ft) from the stream at the three depths (average of 7/13 and 9/20, 2005).

Location	Soil	Soil Salinity		ECe / ECw		Field Moisture		SWC[3]
(ECw)[1]	depth	0.75m	4.5 m	0.75m	4.5 m	0.75m	4.5 m	0.75m
dS m^{-1}	cm	-----dS m^{-1}-----				---------------g/100g-----------------		
Orla (10.7)	0-30	4.4	-[2]	0.4	-[2]	10	-	32
Menton (8.6)	0-30	6.2	-[2]	0.7	-[2]	21	-	40
	30-60	6.6	-[2]	0.8	-[2]	25	-	30
Pecos (9.6)	0-30	19.4	20.8	2.0	2.2	20	16	40
	30-60	15.0	13.4	1.6	1.4	21	17	33
	60-90	10.0	13.7	1.0	1.4	24	20	23
Coyanosa (15.6)	0-30	19.7	22.7	1.3	1.7	27	20	42
	30-60	18.7	19.1	1.2	1.5	27	28	50
	60-90	18.2	22.4	1.2	1.4	29	30	50
Girvin (19.3)	0-30	24.0	29.0	1.2	1.2	20	13	42
	30-60	18.3	33.0	0.9	1.7	24	14	40
	60-90	17.0	28.0	0.9	1.5	30	29	43

[1] ECw is the electrical conductivity of streamflow.

[2] No soil samples were collected either because of the presence of a hard calcic horizon or the sampling location exceeded the active floodplain.

[3] SWC: the saturation water content

4.5 m distance from the stream than at the 0.7 m distance. We attributed this pattern to the reduction in bank overflow as it departs away from the stream. In any case, the observed range of ratios would not be considered as the case of significant salt accumulation.

The soil moisture readings were somewhat more variable, but overall they had a trend of increasing downstream. This trend is probably related to the textural transition and the shallowing water table. The soil textural classes shown in Table 12 were inferred from the saturation water content (Miyamoto, 1988). The soil moisture at the 4.5 m distance was significantly lower, especially at the shallow depth.

These soil salinity and moisture data imply that the floodplain, at least up to a 4.5 m distance from the stream, has been receiving bank overflow. Fig. 12 illustrates daily streamflow at Girvin averaged over the past two decades. According to the flow rate shown in Fig. 12, bank overflow is likely to occur, starting sometime at the end of April through the beginning of May (or about 150 days of the year), then late August through early September (or around the 270th day of the year). The first peak is most likely caused by a combination of the first or the second water release and the spring (or early summer) monsoon. The second peak is undoubtedly related to the monsoon which usually arrives in late August through September from Mexico (Table 1).

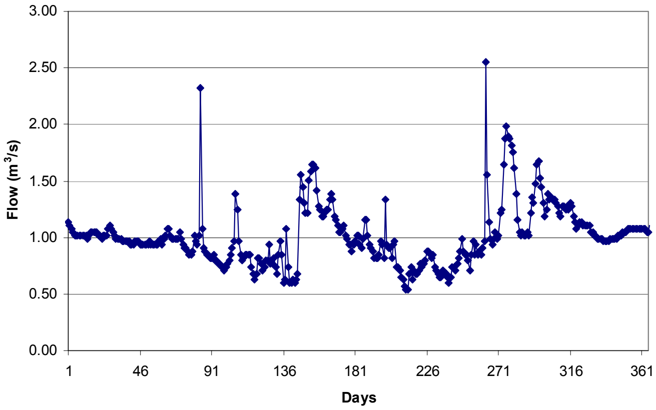


Fig. 12. The daily flow of the Pecos River at Girvin (1969-2001) (USGS data).

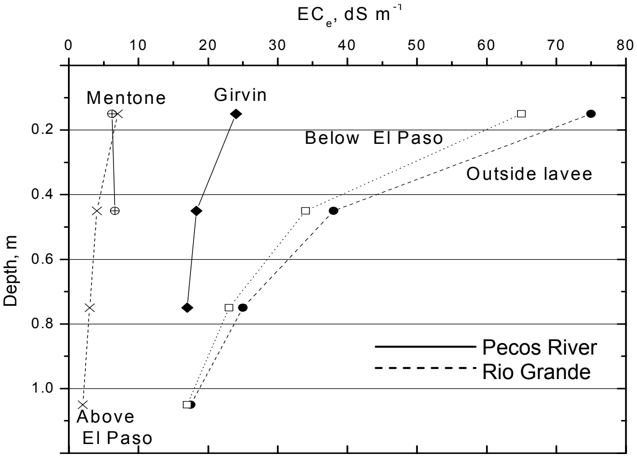


Fig 13. The vertical distribution of soil salinity at Mentone and Girvin (solid lines) along the Middle Pecos, and above and below El Paso along the middle Rio Grande.

In order to illustrate the importance of bank overflow, salinity of the riparian zone from the Middle Rio Grande is shown in Fig. 13. The high soil salinity is reported outside the levee where bank overflow is absent. The water table in the sampled area was 3 m (9 ft), and salinity of the shallow groundwater was 3500 mg L^{-1}, which is greatly lower than the case of the Pecos. Salinity of the soil samples collected inside the levee below El Paso was also elevated with the high concentration toward the ground surface. This reach of the Middle Rio Grande seldom receives bank overflow as the flow is diverted to the irrigation canal at and near El Paso (Miyamoto, 1996). Salinity of the riparian zone above El Paso is similar to salinity at Mentone; both locations receive bank overflow.

Salinity of the river bank as high as that reported in the Rio Grande below El Paso not only reduced biodiversity, but also become salt pools which can be flushed during occasional flood. The surge of salinity at Amistad International Reservoir during 1986 through 1989 was caused mainly by salt flushing from the Rio Grande reach between El Paso and Presidio (Miyamoto et al., 2006). Although salt loading from the Pecos River into Amistad is normally greater than that from the Rio Grande, the quantity of salts currently stored in the floodplains of the Middle Pecos River within 4.5 m (14.8) from the stream is sufficiently low not to cause salinity surge at Amistad.

Fig. 14. Aerial photographs of the riparian zone along the Pecos River near Orla (14A), near Girvin (14B and 14C).

Riparian Zones: Aerial photographs show that the width of the riparian zones extends more or less 50 m (165 ft) on either side of the Pecos River, including its stream (Fig. 14A). This led to the estimate of the riparian zones to be 2960 ha (7322 acres) along the main flow of the Pecos between Red Bluff and Girvin. However, the plant density of the riparian zones becomes low as the river approaches Girvin (Fig. 14B). In some areas, the ground surface is salt-crusted (Fig.14C). Salt crusts are usually formed when the water table is shallow (especially less than 1 m or 3.3 ft) and/or the ground surface does not permit runoff or bank overflow.

As indicated in the introduction, the riparian zones between Red Bluff and Girvin were sprayed with “Arsenal” mostly during the fall of 1999 through 2004. Saltcedar which received the spray was defoliated, but many developed new sprouts. A biological control using leaf-eating beetle (*Diorhabda elongata*) is being considered for saltcedar control.

A riparian survey conducted by Dr. Hart and his associates indicates that the width of saltcedar bands averages 8.9 m on one side of the river bank or 17.8 m on both sides of the stream. For the length of the river between Red Bluff and Girvin (346 km in river miles), the area affected by saltcedar canopy amounts to 616 ha (1430 acres). Beyond the saltcedar canopy, there are salt-tolerant native vegetation, such as saltbush (*Atriplex sp.*) and Mesquite (*Prosopis sp.*). These species generally occupy higher grounds of the floodplain where bank overflow may rarely reach. The same survey also indicates that the floodplain below Pecos consists of as much as 50 percent bare grounds within the 30 m (100 ft) strip. The bare ground is probably as a result of high soil salinity and/or low available soil moisture.

We assumed that the saltcedar band adjacent to the stream transpires 1.20 m/year, and the second or the third band away from the stream transpires at a rate of 0.75 m/year as reported by Cleverly et al. (2002). Transpiration loss from these saltcedar bands is estimated at 6.3 Mm^3 (5,100 acre-ft) per year, which can be compared to water evaporation from the stream surface (6.9 Mm^3/year). The evaporative water loss for this reach seems to be 13.2 Mm^3/year, which is smaller than an earlier estimate shown in Table 9. However, this estimate excludes the transpiration from other species of riparian vegetation, and the evaporation from the soil surface. The evaporation from the soil surface can be substantial in the presence of shallow water table (e.g., Jolly et al., 1993; Warrick, 1988).

Salinity Control Needs

The majority of stakeholders along the Middle Pecos River expresses interests to lower streamflow salinity. However, the specific needs depend on locations and water use objectives. In the reach between Red Bluff and Coyanosa, the desire to lower salinity is for improving crop production. In the reach between Coyanosa and Girvin, the saltiest reach, some ranchers are concerned about re-growth of native vegetation after saltcedar control as well as the suitability of water quality for livestock and wildlife. Below Girvin, especially below Sheffield, salinity of the stream decreases, thus high salinity does not seem to be a great deal of concern, even though it exceeds the Texas drinking water standard of 1000 mg L^{-1}. However, salt load is an issue because of salt loading to Amistad International Reservoir.

Economic Use of Water: The primary use of the Pecos River has been for crop irrigation. Because of its high salinity, the crops which can be irrigated effectively are limited to salt-tolerant types, namely cotton and hay (or pasture) grown in permeable soils. However, salinity of Red Bluff release exceeds the threshold salinity for both cotton and hay, which is 5 dS m^{-1} in irrigation water or 7.5 dS m^{-1} in the soil saturation extract (Attachment 1). There is a potential for a yield increase of these crops if the salinity of the release is lowered. In addition, lowering the salinity of irrigation water lowers crop establishment failure. If groundwater of lower salinity is available, the river water could be used conjunctively, either for blending or for irrigating crops during certain times of the year.

The Pecos River was once a vital watering hole for transporting cattle and livestock. Salinity of the Pecos River below Pecos reaches 7,000 to 14,000 mg/L, levels unsuitable for livestock water supply (Table 13). Lowering salinity to below 5,000 mg/L makes it reasonably safe for consumption by livestock, except for poultry.

There have been interests to culture shrimp and algae, using saline water. The optimum salinity for algae production is usually around 10,000 mg/L, which is the current salinity of the Pecos River below Pecos. A concern was also expressed that salinity control may adversely affect shrimp production. Ponding elevates salinity due to water evaporation. Lowering salinity may help reduce the water requirement for growing shrimp and/or saline algae. Blending with saline groundwater offers another option if salinity adjustments are required.

Recreational uses of the Pecos River, including Red Bluff Reservoir, have been limited as compared to other river systems, such as the Rio Grande. One of the constraints has been fish-kills by golden algae (*Prymnesium parvum*). Salinity of the water is implicated as one of several causes of allowing explosive growth (Sager et al., 2007). This strain of algae is more salt tolerant than most fresh water algae. Salinity control may be necessary along with other measures to reduce the incidences of fish-kills.

Ecological Considerations: One of the concerns is vegetative composition after chemical treatments of saltcedars along the riparian zones. As shown in Attachment 2, salt tolerance of riparian vegetation varies widely. Salinity values shown apply to the soil saturation extract as well as to streamflow when the leaching fraction is

Table 13. Salinity guidelines for livestock water supply (National Research Council, 1974).

Total soluble salts (mg/l)	Comments
Less than 1,000	These waters have a relatively low level of salinity, and should present no serious burden.
1,000 to 2,999	These waters should be satisfactory. They may cause temporary and mild diarrhea in livestock unaccustomed to them, but they should not affect their health or performance.
3,000 to 4,999	These waters should be satisfactory, although they may cause temporary diarrhea or be refused at first by animals unaccustomed to them. Unfit for poultry. Often causes watery feces, increased mortality, and decreased growth, especially in turkeys.
5,000 to 6,999	These waters can be used with reasonable safety. It may be well to avoid using those approaching the higher levels for pregnant or lactating animals. Not acceptable for poultry.
7,000 to 10,000	Considerable risk may exist in using these waters for pregnant or lactating livestock, the young of these species, or for any animals subjected to heavy stress or water loss. In general, their use should be avoided, although older livestock may subsist on them for long periods under conditions of low stress.
More than 10,000	The risks with these highly saline waters are so great that they cannot be recommended for use under any conditions.

approximately 30 percent or higher. The predominant vegetation, such as saltcedar, grows well at streamflow salinity of 1 to 5 g/L. When salinity reaches 10 and 15 g/L, such as the case of the Middle Pecos River below Coyanosa, the growth rates decrease by 30 to 50 percent depending on the species (Glenn et al., 1998).

There is an expectation that some native species will re-establish once saltcedars are treated. In fact, saltbushes (*Atriplex sp.*) which have equal or higher salt and drought resistance have been residence vegetation along the drier part of the riparian zones. Honey mesquite (*P. glandulosa*), which is less salt-tolerant than saltbush, is also residence vegetation along the drier part of the riparian zones. These salt-tolerant species are likely to thrive. Although not native, there is some common Bermuda grass (*Cynodon dactylon*) growing at the bank above Pecos. This moderately tolerant species is replaced by a sparse stand of saltgrass (*Distichlis sp.*) below Pecos. In some areas below Coyanosa, salinity of the riparian zones is high enough to encourage growth of highly salt-tolerant succulent halophytes. Unfortunately, succulent halophytes which are commonly found below Coyanosa do not hold sediments as well as does saltgrass. Likewise, we can not expect to have willows and cottonwood unless salinity of the Pecos River is reduced well below the current level. These species are salt-sensitive (Attachment 2).

There are many species of wildlife along the Pecos River. Mule deer (*Odocoileus hemionus*), for example, is native to this region and occasionally found along the Pecos (Fig. 15). It is a matter of conjecture if the Pecos River water below Coyanosa is good for these species.

Aquatic species also have preferred salinity ranges. Linam and Kleinsasser (1996), for example, reported that seven fish species, including pupfish (*Cyprinodon sp.*) dominated the habitat near Girvin. This may lead to a notion that salinity of the stream makes no difference, as aquatic species which prefer saline water will simply replace salt-sensitive species. However, this transition is accompanied by a reduction in biodiversity. Hoagstrom (2003), for example, points out that only nine out of 27 native fish species appear in the Pecos River below the Brantley. A reduction in the diversity of benthic micro-invertebrates was also reported in the section between Orla and Girvin by Davis (1987). Salinity of the streamflow must be kept much lower than the current level if biodiversity of freshwater aquatic species is to be achieved.

Fig. 15. Mule deer (*Odocoileus hemionus*) along the Middle Pecos River.

Although salt tolerance of both agricultural crops and native vegetation is fairly well known, the target level of salinity for the Pecos River below Red Bluff is yet to be determined. This is a challenging task, as water quality requirements vary with types of use. One option may be to use the salinity recorded from 1937 to 1940 at Orla, Texas (4710 mg L^{-1}), as a tentative target for initial salinity control efforts.

Protecting Groundwater Quality: Salinity of the groundwater in the Pecos Alluvium is mostly less than 3000 mg L^{-1}. There are, however, sizable areas along the Pecos River where salinity ranges from 3,000 to 10,000 mg L^{-1} as shown earlier in Fig. 3; salinity of the Pecos River is frequently higher, from 6000 to 14,000 mg L^{-1}. Percolation of this type of water increases the salinity of the groundwater. The transmission loss is estimated at 30 Mm^3 (24,000 acre-ft) per year or half of the reservoir release. If this situation is allowed to continue for a long time, the area affected may increase. Fortunately, the impact is likely to be confined to near the river, as the general direction of the groundwater movement is toward the river at least in the reach above

Coyanosa (Fig. 16). Exceptions are where a cone of depression has formed due to excessive pumping, such as near Coyanosa.

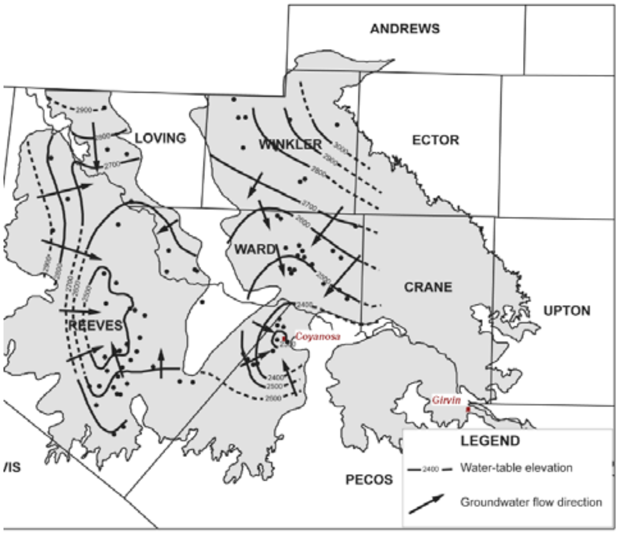


Fig. 16. The potentiometric map of the Pecos Alluvium aquifer (Boghici, 1999).

Protecting Water Quality of Amistad Reservoir: Salinity of the Amistad International Reservoir located downstream has been increasing (Fig. 17). The impact of the Pecos River on the salinity of Amistad is a concern, because this reservoir is used for municipal water supply, in addition to crop irrigation. The drinking water standard for dissolved salts has been 1000 mg L^{-1} in Texas, although many other states, including Arizona and New Mexico, use a tougher standard of 500 mg L^{-1}.

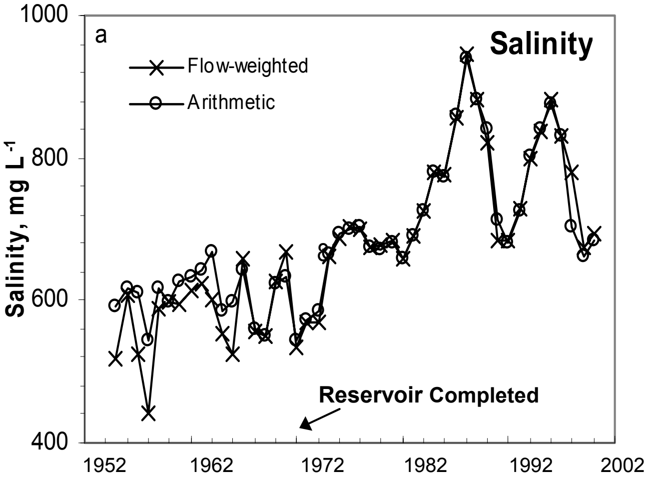


Fig. 17. Changes in salinity at Amistad International Reservoir (Miyamoto et al., 2006).

The salt load of the Pecos River measured at the confluence of the Rio Grande (near Langtry) averaged 429,000 tons/year since 1968 (Miyamoto et al., 2006). The salt loading from the Pecos River into the Amistad International Reservoir accounts for 26 percent of the total salt loading (or 30 percent of the gauged inflow), while providing only 9 percent of the inflow (Table 14). The mean salinity of composite inflow is 643 mg L^{-1} since 1969, or 807 mg L^{-1} since 1991. Salinity of the outflow from Amistad has been averaging approximately 1.1 times the inflow salinity or 888 mg L^{-1} since 1991 (Miyamoto et al., 2006).

An increase in salt loading from any of these salt-carrying tributaries can cause the salinity of the Amistad International Reservoir to exceed the upper limit of the drinking water standard. As long as area growers continue to use surface water from the Pecos River, no additional salt is likely to pass Girvin. If not, additional quantities of salts are likely to enter into the Rio Grande, and into Amistad. An estimate indicates that the reservoir release currently used for irrigation contains salts in sufficient quantity to raise the salinity of Amistad by about 10 percent if they are left unused and flow into Amistad (Miyamoto et al., 2006). A similar impact may also result if percolation loss control is put in effect without first lowering streamflow salinity.

The incident of the 1941 and 1942 floods points out that Amistad International Reservoir is vulnerable to salt washout from watershed in southern New Mexico and West Texas where geological salt deposits are exposed or present at or near ground level. In the case of the flood of 1941, which hit the area from Roswell to Artesia, the Pecos River sent 4.8 million tons of salts to the Rio Grande at a concentration of 3,000 mg L^{-1}, and additional 3.0 million tons in 1942 (Miyamoto et al., 2006). If the Amistad International Reservoir, with the storage capacity of 6.8 billion m^3 (5.5 million acre-ft), had been in existence at the time, the salinity of the water would have well exceeded the drinking water standard of 1,000 mg L^{-1} for an extended period, possibly up to 2 or more years (Miyamoto et al., 2006). The flow control capability of Red Bluff and Brantley combined is about half a billion m^3, while the

Table 14. Inflow quantity and salinity entering the Amistad International Reservoir during 1969 - 2000 (Miyamoto, et al., 2006).

Tributaries	Inflow	Salinity		Salt load	Inflow		Salt load	
Years →	69-00	69-00	91-00	69-00	A	B	A	B
	Mm^3	$mg\ L^{-1}$		1000 t/y	-----------------%-----------------			
Rio Conchos	844	735	1030	621	33	52	37	43
Devil's	351	248	248	87	14	22	5	6
Pecos	245	1753	2170	429	9	15	26	30
MRG	188	1558	1874	293	7	11	18	21
Others	943	240	248	224	37	-	14	-
Total	2571			1654	100	100	100	100

[A]- Percentage based on the total inflow commonly refered to as deduced or estimated flow

[B┘] The gauged or measured flow into the Amistad Reservoir.

flood of 1941 is recorded to be 1.5 billion m^3. There is no salinity control plan in place to deal with this type of unusual event.

Potentials for Reducing Salinity

This reconnaissance study was conducted for obtaining a broad picture of the Middle Pecos River with an emphasis on hydrology, salt sources, salinity, and water management. In-depth study of salt sources and their entry processes into the Pecos, which is needed for developing specific salinity control plans, is yet to be carried out. However, it may be appropriate to evaluate the following broad options for reducing streamflow salinity: 1) increase the inflow of fresh water, 2) reduce evaporative concentration, 3) reduce percolation losses, and 4) reduce salt loading into the Pecos. These are simply potential options which can be evaluated further.

Increase Fresh Water Inflow: An increase in flow above Red Bluff is likely to lower salinity of the incoming flow. However, this would depend on the type of water delivered. If all of the additional flow, assumed to be 18 Mm^3 (15,000 acre-ft) per year, comes directly from the Brantley Reservoir, the flow-weighted salinity would be around 3,080 mg/L, which has been the mean salinity since 1991. If the added flow has salinity similar to the ongoing flow, it would be around 5,030 mg/L. The flow-weighted salinity of the combined flow (the existing mean flow plus 18 Mm^3/year) would be 4,290 mg/L for the direct release from Brantley, as compared to 4,350 mg/L for the second scenario. Both salinity figures are a modest improvement over the salinity of the past decade: 4,425 mg/L. The measures which can be used to increase incoming flow include seepage control at reservoirs and streambeds, besides pumping of groundwater.

Watershed management which can help increase runoff into the Pecos was beyond the scope of this reconnaissance study. However, there are interests among range management experts to evaluate this potential. There are also thoughts to keep storm runoff from seeping into the ground by providing a clay liner. This idea may help increase runoff into the Pecos River as well as reduce the salinity of the runoff if used in a situation like Salt Draw and Toyah Creek. The upland soils along the Middle Pecos River have moderate to high permeability (Table 3). However, it is uncertain if private land owners universally endorse this type of idea. The reality seems to be that the reduction in spring flow resulted in a decline in inflow into the Pecos, except for the case of saline springs.

Decrease Evaporative Water Losses: The water evaporation from shallow reservoirs not only reduces water storage, but also increases salinity. It may be possible to adjust delivery schedules from Brantley to Red Bluff in a way to reduce water evaporation and evaporative salt concentration. The evaporative water losses from 17 km^2 (4,200 acres) of water surface of Red Bluff are estimated at 35 Mm^3 (28,000 acre-ft) per year or 27 percent of the average inflow for the last decade. A detailed analysis of the impact of withholding water transfer until April indicates that the quantity of holding has to be large enough to reduce the surface area of Red Bluff Reservoir storage if this strategy is to be effective in reducing evaporative concentration (Miyamoto et al., 2007). In addition, the quantity of the holding when released in April has to be large enough to lower salinity of the stored water. Otherwise, this option does not seem to change salinity status of Red Bluff greatly, although it may be worth considering during drought years. A more effective option would be to lower the salinity of the streamflow entering Red Bluff. The effect of evaporation is magnified with increasing salinity of inflow.

Saltcedar control is another measure which can potentially reduce the transpirational loss of water. However, a report complied by Hart et al. (2005) seems to indicate that water salvage resulting from saltcedar control is difficult to quantify, and the eradication has not so far affected streamflow salinity. The reason for this apparent lack of concrete response is yet to be investigated. Nonetheless, the initial estimate of the transpiration rate of saltcedar, 210 cm (7 ft) per year, could have been over-estimated. This rate of water loss is equal to 0.8 times the pan evaporation rate shown in Table 1. More recent data seem to show that transpiration losses from saltcedar are not greatly different from other riparian vegetation (e.g., Glenn and Nagler, 2005). A recent observation in New Mexico indicates 120 cm (4 ft) per year when flooded, and 74 cm (2.4 ft) when not flooded (Cleverly et al., 2002). Additionally, the area infested with saltcedar may also have been over-estimated. A new estimate of the saltcedar affected area within 30 m of the stream appears to be on an order of 620 ha (1,580 acres), instead of the initial estimate of 3000 ha (7,400 acres) which include other riparian species. The annual transpiration losses, assuming a 120 cm loss for the first band and a 74 cm loss for the second and the third bands, totals 6.3 Mm^3/year or slightly more than 10 percent of the current reservoir release. If the data from New Mexico and Arizona are used, water salvaging potential from saltcedar control seems to be rather small. An alternative interpretation is that the impact of saltcedar control appears on reduced recharge to groundwater, but probably not on the surface water flow. The presence of vegetation can increase water uptake from a water table (Thorburn et al., 1995), provided that the water table is deeper than at least 1 m (3.3 ft). The depth of the water table has a significant impact on evaporative water losses (Jolly et al. 1993; Thorburn et al., 1995).

The impact of saltcedar on salinity is less clear. There was and still is a notion that saltcedar primes salts from the soil and secretes them to the ground. This type of salt secretion process has been known not only for saltcedar but also for saltgrass. However, the magnitude is poorly understood. If we assume, as a potential maximum, that saltcedar can uptake all the salts in a soil solution without any exclusions, salinity of the stream can increase by around 10 percent. This estimate, however, is not constant with soil test results which show high soil salinity (e.g., Table 12 and Fig. 13).

Evaporation from the stream was estimated at 6.9 Mm^3/year, based on the channel width and the reach length. This water surface area of 370 ha (914 acres) is fairly small as compared to the water surface area of Red Bluff–1,700 ha (4,200 acres). The water evaporation from the stream, however, is comparable to the estimated transpiration from saltcedar and is probably a conservative estimate. If saltcedars hanging over the stream are removed, the evaporation from the stream as well as the river bank will increase. An increase in soil surface salinity was indeed reported after saltcedar removal (Clayton, 2002), but salinity increases associated with water evaporation cannot be controlled easily, except for discharging the water at a faster rate but less frequently.

Reduce Percolation Losses: The average percolation loss from Red Bluff is estimated at 41 Mm^3/year or 33 percent of the inflow for a period of 1991 trough 2001. Since 9 out of 41 Mm^3/year seems to be returning back to the Pecos, the net percolation loss appears to be 32 Mm^3/year or 25 percent of the inflow. Reducing this percolation loss may not have a significant impact on the salinity of the reservoir release, but it can lower the salinity below Pecos if the salvaged water is left in the river. According to the U.S. Bureau of Reclamation (US BOR and TWDB, 1991), the percolation loss seems to be occurring mostly through sinkholes. If so, a standard method of plugging with quick cement may be feasible.

Transmission losses between Red Bluff and Pecos are estimated at 40 percent of the reservoir release at a discharge rate of 3.6 m^3/s (129 cfs). These percent losses increase with reducing the rate of discharge (e.g., Boroughs and Abt, 2003). Assuming the transmission loss of 40 percent, 36 Mm^3 (29,000 acre-ft) per year of the water can be saved if both percolation and transmission losses are controlled. Note that the discharge from the reservoir is estimated to increase to 93 Mm^3/year through the percolation loss control. Controlling transmission losses may not affect salinity of the stream above Pecos, but might lower it below Pecos if the water saved is left in the river.

The idea to control percolation and transmission losses is not new. In fact, this idea was proposed by U.S. Bureau of Reclamation in 1991 (US BOR and TWDB, 1991). The question which has been debated is the cost vs. benefit, because of the poor quality of the reservoir release. In addition, it should be kept in mind that this type of loss control can increase salt loading into Amistad. If the water saved is left in the river, the flow at Girvin will double. This will lower salinity, but will increase the quantity of salts passing through Girvin to Amistad. However, both of these shortcomings can be overcome if salinity is lowered through an appropriate salt source control upstream.

Reduce Inflow of Saline Water: Brine intrusion control at Malaga Bend is widely regarded as the most cost-effective option. The brine is concentrated, thus requiring a minimum of evaporation to form halite. An extraction well has already been installed, and salt processing facility is available within a 30 mile distance. If implemented successfully, salt load of up to 150,000 tons can be removed per year. This can lower streamflow salinity at P.C. Crossing and below, from the current level of 5.1 g/L to 3.5 g/L as shown in Table 15 (note that g/L is used for expressing salinity which is equal to 1000 mg L^{-1}). This flow will be diluted somewhat with the flow from the Delaware River (31 Mm^3/yr at 2520 mg/L) which carries 80,000 tons of salts per year. The use of a simple mixing equation yields an inflow concentration of 3.3 g/L into Red Bluff (Table 15). The salinity of the outflow from the reservoir is estimated to be 4.6 g/L using a mass balance equation. This figure is similar to the two-layer model estimate of 4.8 g/L (Miyamoto et al., 2007), and is approximately equal to the salt level of the reservoir release shortly after the construction of the Red Bluff Reservoir in 1936.

The estimate of salinity below Red Bluff is

Table 15. Tentative estimate of salt load and salinity changes upon hypothesized salt source control scenarios; O: current (1991-2001), I: brine control at Malaga Bend, II: plus salt dissolution control at Bottomless Lakes at 130,000 tons/year, III: bypass Bottomless Lakes area to avoid salt load of 261,000 tons/year, in addition to salt control at Malaga Bend.

Location	Flow	Salinity				Salt Load			
		O	I	II	III	O	I	II	III
	M m^3/y	-g/L-				-1000 tons/year-			
Samner	162	1.3	1.3	1.3	1.3	210	210	210	210
Artesia	159	3.1	3.1	2.3	1.4	489	489	359	228
Malaga	95	3.5	3.5	2.7	1.8	332	332	255	173
P.C. Crossing	95	5.1	3.5[1┘]	2.7	1.8	482	332	255	173
Red Bluff	126	4.4	3.3[2┘]	2.6	2.0	554	416	335	251
Out	59	6.2	4.6[3┘]	3.7	2.8	363	271	218	164
Girvin	29	12.1	10.5[4┘]	9.6	8.7	351	304	279	253
Langtry	234	1.8	1.6[5┘]	1.5	1.4	421	374	349	322

Estimated as [1┘] (482-150)/95; [2┘] (332+80)/126; [3┘] 3.3x1.39; [4┘] (351-363 (29/59) + 4.6(29)/29 = (172+133)/29 = 105; [5┘] (304+70)/234 problematic. We assumed that no salt will be removed except at Malaga Bend. We also assumed that the salt entering the Pecos in the reach is coming from external sources, but not from the percolation from the Pecos River. The salt load gain in the reach plus salt loading from the incoming flow yields a salt load of 305,000 tons/year at an average flow rate of 29 Mm^3/year. This yields a projected salinity level of 10.5 g/L, which is a slight reduction from the current level of 12.1 g/L. The estimate of salinity at Langtry was made with an assumption that the saline water which passes through Girvin is diluted with fresh water (205 Mm^3/year) with a salt load of 70,000 tons/year. It is only a slight reduction, from 1.8 to 1.6 g/L. The hypothesized salt source control at Malaga Bend is likely to have only a limited impact on salinity below Girvin, including Amistad International Reservoir, unless saline water entering Pecos is originating from the percolated water from the reach above Coyanosa.

The control of the salt source at the Bottomless Lakes area is strictly hypothetical, as it was not investigated for its feasibility. (This area contains a wildlife refuge, and is ecologically sensitive.) Two scenarios were assumed: salt removal of 130,000 and 261,000 tons/year. The higher figure may be obtained through re-routing or lining the Pecos in the reach. The estimate of salinity shows a significant reduction in streamflow salinity at Artesia and Malaga. This benefit is carried onto Red Bluff where the inflow salinity is estimated to decrease to 2.6. g/L from the current level of 4.4 g/L at the hypothesized removal of 130,000 tons/year at the Bottomless Lakes, in addition to the removal of 150,000 tons/year at Malaga Bend. However, the impact on salinity at and below Girvin appears to be small.

There are several implications of these estimates. First, the removal of salt sources at Malaga Bend alone can lower stream salinity from 5.1 to 3.5 g/L at P.C. Crossing above Red Bluff. This salt level is roughly comparable to the salt level recorded at Malaga during a period of 1937-40, or shortly after the construction of Red Bluff Dam. The flow at Malaga and P.C. Crossing during the period was 104 Mm^3/year, which is 60 percent of the flow during 1927-37 (Fig. 2). Salt loading at P.C. Crossing is 482,000 tons/year which includes 150,000 tons/year from Malaga Bend. If it is removed, the salt load decreases to 68 percent. In other words, a salt load reduction in proportion to a reduction in fresh water flow can restore the salinity of Red Bluff, although it is still subject to high rates of evaporation and percolation losses.

The second implication of the salinity estimates shown in Table 15 is that the salt source control at Malaga Bend and/or Bottomless Lakes will have minimal effects on salinity at or below Girvin, including that of Amistad. In other words, additional salt control has to be made in the reach between Red Bluff and Girvin if the salinity control target is Amistad. The largest source of salts in this reach is the saline water intrusion between Coyanosa and Girvin. If this salt source turns out to be the water percolation from the Pecos River above Coyanosa, the estimates and assessment will change. A detailed study is needed to find the hydrologic connection between the Middle and Lower Pecos River, along with identification of salt sources. There is an increasing concern over potential leakage of oilfield brine into shallow aquifer, partly due to renewed oil well drilling activities.

The third implication is that the salt source control at Bottomless Lakes can provide water of excellent quality to the southeastern New Mexico, chiefly to the Carlsbad Irrigation District. This is a sharp contrast to the salt source control at Malaga Bend, which offers little incentive to the state of New Mexico because of its location.

The salinity projection shown above is based on the average flow condition which rarely exists in reality. The estimate of monthly or daily salinity under various flow or water management scenarios requires simulation of water and salt transport processes. Several models are available for simulating the streamflow, but not stream salinity (e.g., Boroughs and Abt, 2003). A model to simulate both water and salt transport is currently being developed. It can provide a more definitive picture of salt control options on salinity of the Middle Pecos River.

References

Armstrong, C.E., McMillan, L.G., 1961. Geology and ground-water resources of Pecos County, TX. Texas Board of Water Engineers. Bull. 6106, Austin, TX.

Ashworth, J.B., 1990. Evaluation of groundwater resources in parts of Loving, Pecos, Reeves, Ward and Winkler Counties, Texas. TWDB Report 317, p. 51.

Ashworth, J.B., Hopkins, J., 1995. Aquifers of Texas. TWDB Report 345, p. 69.-

Ayers, R.S., Westcot, D.W., 1985. Water quality for agriculture. FAO Irrigation and Drainage Paper, 29. UN. Rome.

Boghici, R., Coker, D., Guevara, M., 1999. Changes in groundwater condition in parts of Trans-Pecos Texas, 1988-1998. TWDB Report 348.

Boroughs, C.B., Abt, S.R., 2003. Water losses along the reach of the Pecos River in New Mexico. J. American Water Res. Association 39: 1457-1464.

Brune, G., 2002. *The Springs of Texas.* Texas A&M University Press: College Station, TX.

Clayton, L.A., 2002. Saltcedar management strategies and effects on water quality and quantity of the Pecos River. MS Thesis, Department of Rangeland Ecology & Management, Texas A&M University, College Station.

Cleverly, J.R., Dahm, C.N., Thibault, J.R., Gilroy, D.J., Coonrod, J.E., 2002. Seasonal estimates of actual evapo-transpiration from *Tamarix ramosissima* stands using three-dimensional eddy covariance. Journal of Arid Environ. 52: 181-197.

Davis, J.R., 1987. Faunal characteristics of a saline stream in the northern Chihuahuan desert. Contributed papers of the second symposium on resources of the Chihuahuan desert region United States and Mexico.

Eakin, M.E., Brown, C.B., 1939. Silting of Reservoirs. USDA, Tech. Bull. 524: 11-18.

El-Hage, A., Moulton, D.W., 1998. Evaluation of selected natural resources in parts of Loving, Pecos, Reeves, Ward, and Winkler Counties, Texas. Resource Protection Division: Water Resources Team.

Felker, P., Clark, P.R., Laag, A.E., Pratt, P.F.,1981. Salinity tolerance of the tree legumes: mesquite (*prosopis glandulosa* var. *torreyana*, *P. velutina* and *P. articulata*) algarrobo (*P. chilensis*), kiawe (*P. pallida*) and tamarugo (*P. tamarugo*) grown in sand culture on nitrogen-free media. Plant and Soil 61: 311-317.

Glenn E.P., Nagler, P.L., 2005. Comparative ecophysiology of *Tamarix ramosissima* and native tress in western U.S. riparian zones. Journal of Arid Environ., 61: 419-446.

Glenn, E., Tanner, R., Mendez, S., Kehret, T., Moore, D., Garcia, J., Valdes, C., 1998. Growth rates, salt tolerance and water use characteristics of native and invasive riparian plants from the delta of the Colorado River, Mexico. Journal of Arid Environ. 40: 281-294.

Grozier, R.U., Albert, H.W., Blakey, J.F., Hembree, C.H., 1966. Water-delivery and low-flow studies, Pecos River, Texas: Quality and quality, 1964 and 1965. TWDB Report 22.

Hale, W.E., Hughes, L.S., Cox, E.R., 1954. Possible improvement of quality of water of the Pecos River by diversion of brine at Malaga Bend, Eddy County, New Mexico. Pecos River Commission, Carlsbad, NM.

Hart, C.R., 2004. The Pecos River ecosystem project progress report. Texas Cooperative Extension at the Texas A&M University System.

Hart, C.R., White, L.D., McDonald, A., Sheng, Z., 2005. Saltcedar control and water salvage on the Pecos River, Texas, 1999-2003. Jour. of Environ. Manag. 75: 399-409.

Havens, J.S., Wilkins, D.W., 1979. Experimental salinity alleviation at Malaga Bend of the Pecos River, Eddy County, New Mexico. U.S. Geological Survey Professional Paper 80-4.

Hoagstrom, C.W., 2003. Historical and recent fish fauna of the lower Pecos River. Museum of Texas Tech Univ. Special Pub. No. 46.

Howard, C.S., Love, S.K., 1943. Quality of surface waters of the United States, 1943. U.S. Department of the Interior, Water-Supply Paper 970.

Huser, V. 2000. *Rivers of Texas*. 1st Edition. Texas A&M University Press. College Station, TX.

Jackson, J., Ball, J.T., Rose, M.R., 1990. Assessment of the salinity tolerance of eight Sonoran Desert riparian trees and shrubs. Univ. of Nevada System, Biological Sciences Center, Desert Research Institute.

Jolly, I.D., Walker, G.R., Thorburn, P.J., 1993. Salt accumulation in semi-arid floodplain soils with implications for forest health. J. Hydrol. 150: 589-614.

Johnson, K.S., 1981. Dissolution of salt on the east bank of the Permian Basin in the southwestern U.S.A. Journal of Hydrology 54: 75-93.

Jones, I.C., 2001. Cenozoic Pecos alluvium aquifer. Presented in Aquifers of the Edwards TWDB Report 356.

Linam, G.W., Kleinsasser, L.J., 1996. Relationship between fished and water quality in the Pecos River, Texas. River Studies Report No. 9. Resource Protection Division, Texas Parks and Wildlife Department, Austin, TX.

McAda, D.P., Morrison, T.D., 1993. Sources of information and data pertaining to geohydrology in the vicinity of the Roswell basin in parts of Chaves, Eddy, De Baca, Guadalupe, Lincoln, and Otero Counties, New Mexico. U.S. Geological Survey Open-File Report 93-144.

Miyamoto, S., 1988. Sampling irrigated soils for salinity appraisal. The Texas Agricultural Experiment Station, College Station, TX.

Miyamoto, S., 1996. Salinity of the Rio Grande: trend and management implications. Terra, 14(3): 265-278.

Miyamoto, S., Glenn, E.P., Olsen, M.W., 1996. Growth, water use and salt uptake of four halophytes irrigated with highly saline water. Journal of Arid Environ. 32: 141-159.

Miyamoto, S., Martinez, I., Padilla, M., Portillo, A., Ornelas, D., 2004. Landscape plant lists for salt tolerance assessment. Texas A&M University Agricultural Research Center at El Paso and El Paso Water Utilities.

Miyamoto, S., Yuan, F., Anand, S., 2006. Influence of tributaries on salinity of Amistad Reservoir. Texas A&M University Agricultural Research Center at El Paso. Texas Water Resources Institute, Technical Report 292.

Miyamoto, S., Yuan, F., Anand, S., 2007. Water balance, salt loading, and salinity control options of Red Bluff Reservoir, Texas. Texas A&M University Agricultural Research Center at El Paso. Texas Water Resources Institute, Technical Report 298.

Miyamoto, S., Yuan, F., McDonald, A., Hatler, W., Anaya, G., Belzer, W., 2005. Reconnaissance survey of salt sources and loading into the Pecos River. Texas A&M University Agricultural Research Center at El Paso. Texas Water Resources Institute, Technical Report 291.

Moore, J., Murphy, J.M., 1979. Sprinkler irrigation with saline water. In: Proc. Inter. Amer. Conf. on Salinity and Water Management Tech. S. Miyamoto (Ed.) Texas A&M University Agricultural Research Center at El Paso.

Mower, R.W., Hood, J.W., Cushman, R.L., and Galloway, S.E., 1964. An appraisal of potential ground-water salvage along the Pecos River between Acme and Artesia, New Mexico. U.S.

Geological Survey Water-Supply Paper 1659, p.98.

National Research Council, 1974. Nutrients and toxic substances in water for livestock and poultry. National Academy of Sciences, Washington, D. C.

Rhoades, J.D., Miyamoto, S., 1990. Testing soils for salinity and sodicity. *Soil Testing and Plant Analysis*, 3rd ed. Madison, WI: no. 3, p. 299.

Richter, B.C., Dutton, A.R., Kreitler, C.W., 1990. Identification of sources and mechanisms of salt-water pollution affecting ground-water quality: a case study, west Texas. The University of Texas, Bureau of Econ.Geology.

Richter, B.C., Kreitler, C.W., 1987. Sources of ground water salinization in parts of west Texas. Ground Water Monitoring Review, v. 7, no. 4.

Sager, D., Fries, L., Singhurst, L., Southard, G., 2007. Guidelines for Golden Alga Prymnesium parvum management options for ponds and small reservoirs (public water) in Texas. Texas Parks and Wildlife Department.

Thorburn, P.J., Walker, G.R., Jolly, I.D., 1995. Uptake of saline groundwater by plants: an analytical model for semi-arid and arid areas. Plant and Soil. 175: 1-11.

Uliana, M.M., Sharp, J.M., 2001. Tracing regional flow paths to major springs in Trans-Pecos Texas using geochemical data and geochemical models. Chem. Geol. 179: 53-72.

U.S. Department of the Interior, Bureau of Reclamation (US BOR) and Texas Water Development Board (TWDB), 1991. Red Bluff water power control district rehabilitation study: Texas. Special Technical Report.

U.S. Salinity Laboratory Staff (USSL Staff), 1954. Diagnosis and improvement of saline and alkali soils. L.A. Richards (ed.). Handbook 60 U.S. Government Printing Office, Washington D.C.

Warrick, A.W., 1988. Additional solutions for steady-state evaporation from a shallow water table. Soil Science 146, p. 29.

Wauer, R.H. 1973. *Naturalist's Big Bend*. Texas A&M University Press. College Station, TX.

Weeks, E., Weaver, H.L., Campbell, G.S., Tanner, B.D., 1987. Water use by saltcedar and by replacement vegetation in the Pecos River floodplain between Acme and Artesia, New Mexico. U.S. Geological Survey Professional Paper 491-G.

White, D.E., 1971. Water resources of Ward County, Texas. TWDB Report 125, p. 235.

Wuerthner, G., 1989. Texas' Big Bend country. American Geographic Publishing, Helena, MT.

Attachment 1. Yield potential of selected crops when irrigated with water having various salt levels[1]– (Ayers and Westcot, 1985).

Yield Potential	100%		90%		75%		50%	
Salinity[1] - →	EC_e	EC_w	EC_e	EC_w	EC_e	EC_w	EC_e	EC_w
		--------------		dSm $^{-1}$		--------------		
FIELD CROPS								
Cotton (*Gossypium hirsutum*)	7.7	5.1	9.6	6.4	13.0	8.4	17.0	12.0
Sugarbeet (*Beta vulgarius*)[2] -	7.0	4.7	8.7	5.8	11.0	7.5	15.0	10.0
Sorghum (*Sorghum bicolor*)	6.8	4.5	7.4	5.0	8.4	5.6	9.9	6.7
Wheat (*Triticum durum*)[3] -	6.0	4.0	7.4	4.9	9.5	6.3	13.0	8.7
Wheat, durum (*Triticum turgidum*)	5.7	3.8	7.6	5.0	10.0	6.9	15.0	10.0
Soybean (*Glycine max*)	5.0	3.3	5.5	3.7	6.3	4.2	7.5	5.0
Peanut (*Arachis hypogaea*)	3.2	2.1	3.5	2.4	4.1	2.7	4.9	3.3
Corn (maize) (*Zea mays*)	1.7	1.1	2.5	1.7	3.8	2.5	5.9	3.9
FOLIAGE CROPS								
Wheatgrass, tall (*Agropyron elongatum*)	7.5	5.0	9.9	6.6	13.0	9.0	19.0	13.0
Wheatgrass, crested (*Agropyron cristatum*)	7.5	5.0	9.0	6.0	11.0	7.4	15.0	9.8
Bermuda grass (*Cynodon dactylon*)[4] -	6.9	4.6	8.5	5.6	11.0	7.2	15.0	9.8
Barley (forage) (*Hordeum vulgare*)[3] -	6.0	4.0	7.4	4.9	9.5	6.4	13.0	8.7
Sudan grass (*Sorghum vulgare*)	2.8	1.9	5.1	3.4	8.6	5.7	14.0	9.6
Ryegrass, perennial (*Lolium perenne*)	5.6	3.7	6.9	4.6	8.9	5.9	12.0	8.1
Fescue, tall (*Festuca arundinacea*)	3.9	2.6	5.5	3.6	7.8	5.2	12.0	7.8
Wildrye, beardless (*Elymus triticoides*)	2.7	1.8	4.4	2.9	6.9	4.6	11.0	7.4
Alfalfa (*Medicago sativa*)	2.0	1.3	3.4	2.2	5.4	3.6	8.8	5.9
Clover, berseem (*Trifolium alexandrinum*)	1.5	1.0	3.2	2.2	5.9	3.9	10.0	6.8
Orchard grass (*Dactylis glomerata*)	1.5	1.0	3.1	2.1	5.5	3.7	9.6	6.4
VEGETABLE CROPS								
Field Pumpkin (*Cucurbita pepo melopepo*)	4.7	3.1	5.8	3.8	7.4	4.9	10.0	6.7
Beet, red (*Beta vulgarius*)[3] -	4.0	2.7	5.1	3.4	6.8	4.5	9.6	6.4
Tomato (*Lycopersicon esculentum*)	2.5	1.7	3.5	2.3	5.0	3.4	7.6	5.0

[1] - EC_e is salinity of the soil saturation extract, and EC_w is salinity of the irrigation water. Actual yields may vary depending on the leaching fraction attained.

[2] - Beets are more sensitive during germination; EC_e should not exceed 3 dS/m in the seeding area for garden beets and sugar beets.

[3] - Barely and wheat are less tolerant during germination and seeding stage; EC_e should not exceed 4-5 dS/m in the upper soil during this period.

[4] - Tolerance given is an average of several varities; Suwannee and Coastal Bermuda grass are about 20 persent more tolerant, while Common and Greenfield Bermuda grass are about 20 percent less tolerant.

Attachment 2. Relative growth rates of riparian species when grown at the leaching fraction greater than 30 percent, using saline solutions with the specified salt concentrations.

Species salinity of water (g L^{-1}) →	1	5	10	15	20	30	Ref.
				%			
SHRUBS AND TREES							
Pickleweed (*Allenrolfea occidentals*)	71	94	81	77	75	72	(1)
Pickleweed (*Allenrolfea occidentals*)	48	87	84	88	92	95	(2)
Sea blite (*Suaeda esteroa*)	93	98	99	73	45	13	(4)
Turtleweed (*Batis maritima*)	100	91	84	64	51	29	(4)
Saltgrass (*Distichlis spicata*)	91	97	99	77	48	20	(4)
Saltbush (*Atriplex canescens*)	99	95	82	60	40	17	(4)
Quailbush (*Atriplex lentiformis*)	72	98	84	65	48	0	(2)
Salt Cedar (*Tamarix sp.*)	98	89	78	68	57	35	(1)
Salt Cedar (*Tamarix chinensis*)	95	92	72	53	22	0	(2)
Mesquite (*Prosopis sp.*)							
Honey Mesquite (*P. pallida)*	97	87	72	55	39	8	(3)
Honey Mesquite (*P. articulata)*	92	61	38	40	43	48	(3)
Honey Mesquite (*P. glandulosa)*	93	65	42	32	24	5	(3)
Arrowweed (*Pluchea sericea*)	95	77	54	31	7	0	(1)
Mule Fat (*Baccharis salicifolia*)	91	53	6	0	0	0	(1)
Goodding willow (*Salix goodingii*)	89	42	0	0	0	0	(1)
Goodding willow (*Salix goodingii*)	99	13	6	4	3	2	(2)
Cottonwood (*Populus fremontii*)	86	3	0	0	0	0	(1)
GRASS SPECIES							
Fults alkaligrass (*Puccinellia distans*)	95	99	93	92	87	76	(5)
Tall wheatgrass (*Thinopyrum ponticum*)	88	91	95	74	46	33	(5)
Wild rye (*Elymus sp.*)	91	96	66	41	19	0	(5)
Alkali muhly (*Muhlenbergia asperifolia*)	77	89	93	42	0	0	(5)
Buffalograss (*Buchloe dactyloides*)	99	61	33	2	0	0	(5)
Wheatgrass (*Thinopyrum sp.*)	98	53	33	0	0	0	(5)
Bermudagrass (*Cynodon dactylon*)	99	74	15	0	0	0	(5)
Blue grama (*Bouteloua gracilis 'Alma'*)	99	29	13	0	0	0	(5)
Black gramma (*Bouteloua eriopoda*)	99	0	0	0	0	0	(5)

[1] - Assuming the soil moisture range of 0 to 50% depletion at a leaching fraction no less than 30%.

[2] - References: (1): Glenn et al. (1998), (2): Jackson et al. (1990), (3): Felker et al. (1981), (4): Miyamoto et al. (1996), (5): Miyamoto et al. (2004).

[3] –Salinity is expressed in g/L, which can be converted to the electrical conductivity unit of dS m^{-1} through division by 0.66. For example, 10g/L corresponds to 15.2 dS m^{-1}.