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Reconnaissance Survey of Salt Sources and Loading into the Pecos River

by

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Texas Agricultural Experiment Station

The Texas A&M University Agricultural Research and Extension Center at El Paso

In cooperation with

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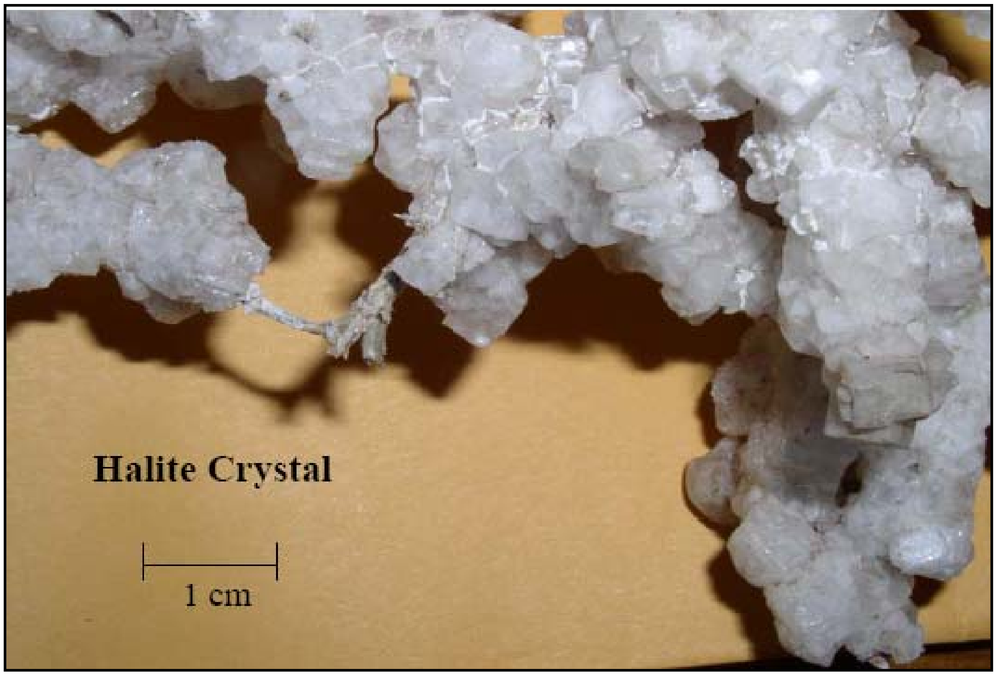

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Unit Conversion

1 m = 3.3 ft
1 ha = 2.47 acre
1 m^3 = 35.3 ft^3
1 ft = 30.5 cm
1 acre = 0.405 ha
1 ft^3 = 28.3 L
1 km = 0.621 miles
1 km^2 = 247 acres
1 Mm^3 = 0.811 A-F

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SUMMARY

The Pecos River of southeastern New Mexico and west Texas is among the saltiest rivers in North America with streamflow salinity regularly exceeding 7,000 mg L^{-1} at the state border and eventually exceeding 12,000 mg L^{-1} at Girvin, Texas. High salinity of the river has adversely affected stability and biodiversity of the riparian ecosystems as well as the economic uses of this water resource. In addition, a recent study shows that the flow of this river system accounts for nearly one-third of the salts entering the Amistad International Reservoir located at the border to Mexico. These circumstances prompted various attempts to lower salinity, including control of saline water intrusion into the river, and eradication of salt cedars (*Tamarix* sp). This study was conducted for identifying additional salt sources and river reaches where saline water sources are entering the Pecos River.

We first reviewed the historical flow and salinity data of the Pecos River at Malaga and Pierce Canyon (P.C.) Crossing, NM (located near the state border), Girvin and Langtry, TX (the confluence to the Rio Grande). The records show that salinity of the Pecos was around 3,000 mg L^{-1} at Malaga prior to 1950, and since 1959 averaged 4,100 mg L^{-1} with greater fluctuation. Salinity at P.C. Crossing during 1938 – 1940 was 4,800 mg L^{-1}, but increased to 7,100 mg L^{-1} after 1954 due to the reduced streamflow. A historical record also indicates that a major storm, if occurs above Girvin, TX, can flush salts in large enough quanties to elevate salinity of Amistad Reservoir above the drinking water standard of 1,000 mg L^{-1}.

We then analyzed streamflow and salinity data of the United States Geological Survey (USGS) at eleven gauging stations along the main stream from the northern watershed to Girvin, TX. This analysis revealed that the main salt loading is occurring in three reaches: between Santa Rosa and Puerto de Luna, Acme and Artesia, and Malaga and Pierce Canyon Crossing, all located north of the state border. The total annual salt loading into these reaches is estimated at 683,000 tons per year. The main ions entering through the first reach are Ca and SO_4; through second and third reaches, Na and Cl ions are entering.

We subsequently analyzed flow and salinity data obtained by the Texas Clean Rivers Program (CRP). This program is primarily for water quality monitoring for the Texas portion of the River, and frequency of monitoring is only 4 to 6 times per year. Nonetheless, it has shown that the salt load is reduced between Red Bluff and Pecos, due to diversion for irrigation and high seepage losses. The increase in salt load between Coyanosa and Girvin was tentatively estimated at several hundred thousand tons per year, mainly through the inflow of shallow saline

ground water. Streamflow salinity below Girvin decreases due to inflow of fresh water from the Lower Pecos watershed. Streamflow salinity at Langtry where the Pecos River merges into the Rio Grande was found to be dictated by the flow of the saline water near Girvin.

The field task undertaken was to collect water samples below Artesia but above Sheffield, and to analyze for major cations, anions, and stable isotope $\delta^{18}O$. These tasks were conducted on March 8, and May 7, 2005. Results indicated that salinity of the stream above Pecos can change as much as 30% or more, depending on the season, and that salinity below Pecos is more stable. The isotope analyses have shown that the concentration of $\delta^{18}O$ was lowest in a sample collected shortly after rain at Salt Creek, and it increased below Pecos to a level typical for shallow ground water of west Texas, -3‰ in SMOW (standard mean ocean water). The isotope measurements conducted on May 7, 2005 indicated higher $\delta^{18}O$ (< -4‰) throughout the sampled reach, presumably because the water which had been stored or exposed for a long time was released upstream. Also included in the fieldwork was exploratory sampling of bank soil samples and testing for salinity. Salinity of the bank soil samples to a depth of 30 cm ranged from 4 to 27 dS m^{-1} in March sampling after bank overflow, and 8 to 16 dS m^{-1} in May, 2005. Soil salinity at the depth 30 to 60 cm was slightly higher, 10 – 15% on the average. These soil salinity levels indicate that bank salt storage is not a significant source for salt flushing as long as the current frequency of bank overflow can be sustained. An exception may apply to certain reaches between Coyanosa and Girvin, TX.

The primary sources of salts entering the Pecos River are geological deposits of gypsum above Puerto De Luna in the northern watershed; geological deposits of evaporites, mostly halite and some epsomite below Acme down to Red Bluff; and shallow saline ground water between Coyanosa and Girvin. Saline water intrusion into the Pecos River at Malaga Bend and the reach between Coyanosa and Girvin has a pronounced impact on salinity of the streamflow, mainly because the flow in these segments declined drastically since the late 1930s due to reservoir construction and diversion upstream. Other potential sources include saline creeks and draws, such as Salt Creek, and Salt Draw which enter the river between Pecos and Coyanosa as subsurface seepage. The most controllable salt source appears to be brine intrusion from Malaga Bend, which is estimated at 172,000 tons per year or less in quantity. Saline water intrusion from shallow ground water below Grandfalls towards Girvin is another source, and a detailed study is needed for assessing feasibility for control. The salts stored in riparian zones are not a significant source. The largest source of salts, which can enter into overland runoff when flooded, is halite deposits near Roswell, and the reach below Carlsbad but above Girvin.

For developing water management plans, three basic features of the middle reach of the Pecos (Malaga, NM to Girvin, TX) should be taken into consideration: i) salinity of the stream can be reduced if saline water intrusion is reduced, ideally in proportion to the reduction in the natural flow. ii) there is a massive amount of evaporites present below the surface layer throughout the middle reach of the Pecos River, and iii) salts are exposed to the surface in several reaches, which can enter into the Pecos River during flood. The exact locations of salts which are exposed and may dissolve into flood flow are not known at present.

INTRODUCTION

The Pecos River of southeastern New Mexico and west Texas is among the saltiest rivers in North America with streamflow salinity regularly exceeding 7,000 mg L^{-1} at the New Mexico and Texas border, and eventually exceeding 12,000 mg L^{-1} at Girvin, Texas. It originates in northeastern New Mexico, flows through the semi-arid part of New Mexico and west Texas, and merges into the Rio Grande just below the historical town of Langtry (Fig. 1). The diversion from this river, estimated at 224 million m^3 (180,000 acre-ft.) per year, is mostly above Red Bluff, mainly for irrigating an estimated 25,000 ha (60,000 acre) of crop lands in New Mexico. The water stored in Red Bluff is also used for irrigating comparatively small areas (less than 4,000 ha) in west Texas. The area irrigated with ground water is much greater.

High salinity of the river has adversely affected stability and diversity of the riparian and aquatic ecosystem (e.g., Hart, 2004; El-Hage and Moulton, 1998; Davis, 1987) as well as the economic use of this water resource, especially in the reach below Red Bluff Reservoir. Degradation of ground water quality along the streamflow is also a concern, as the saline stream percolates through highly permeable alluvium (Boghici, 1999). In addition, one study shows that the flow of this river accounts for nearly one-third of salts entering Amistad International Reservoir located approximately 64 km (40 miles) south of Langtry (Miyamoto, 1996). Salinity of the Amistad Reservoir reached 1,000 mg L^{-1} (the upper limit of secondary drinking water standard) in February 1988, and there is a concern that such an incident may occur with greater

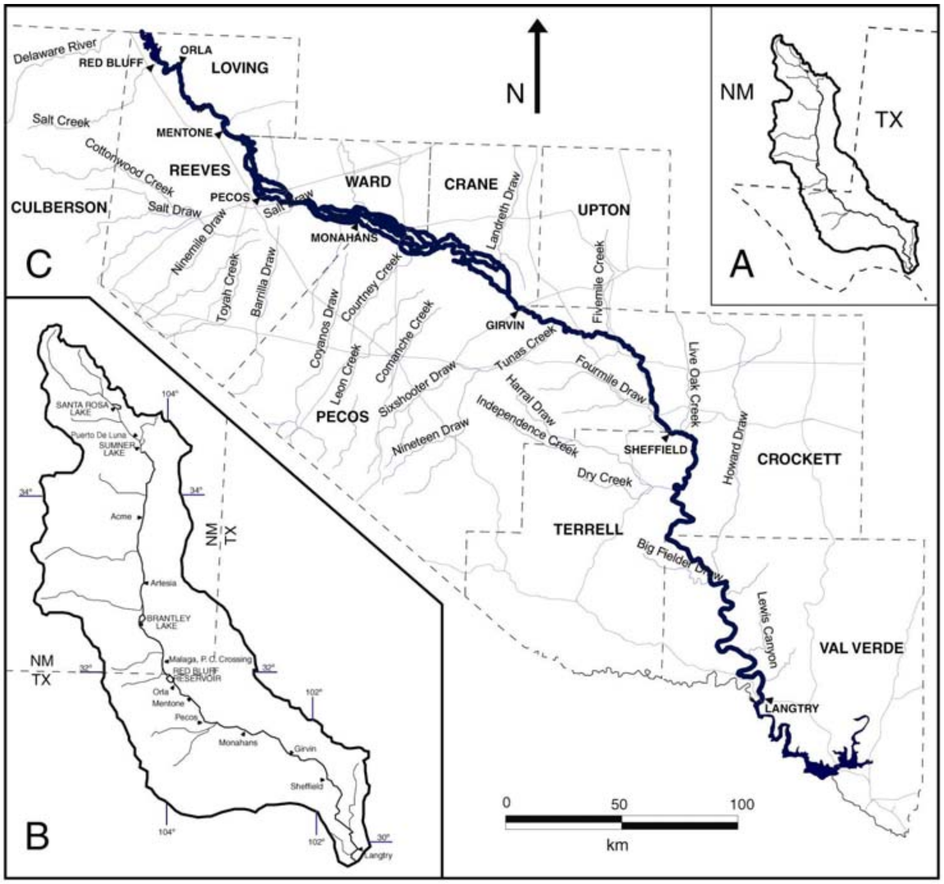

Fig. 1 Sketches of the Pecos River Basin of New Mexico and west Texas (original maps taken from the U.S. Geological Survey).

frequency unless salinity control measures are implemented at some point.

Several measures to lower salinity have been proposed. Pumping of saline seepage below Malaga, which otherwise enters the Pecos, is among the options tried (e.g., Hale et al., 1954). The saline water is saturated brine consisting of common salts (NaCl). The brine once pumped into a nearby depression was evaporated, but the leakage from the ponding area made this option ineffective or unattractive (Havens and Wilkins, 1979). Deep well injection was also considered, but was found to be costly and probably not sustainable (Cox and Kunkler, 1962). The latest effort has been to evaporate the brine and to harvest salts (Personal Communication with the Red Bluff District). Another attempt which has been implemented in recent years is the eradication of salt cedar which invaded the bank of the Pecos River (Hart, 2004). The idea is to maintain the flow by reducing the evapotranspiration, and hopefully streamflow salinity as well by lowering evaporative concentration of salts (Weeks, et al.,1987; Hart, 2004).

This study was conducted for identifying additional sources of salts and river reaches where saline water sources are entering the Pecos River, and was proposed as Subtask 1.5. Identification of saline tributaries is covered under Subtask 1.4.

STUDY AREA

The Pecos River originates in the Sangre de Cristo Mountains of New Mexico and flows south for approximately 805 km (500 miles) into Texas (Fig. 1). The study area is semi-arid with the annual precipitation of 34, 29, and 37 cm at Artesia, NM, Pecos, TX, and Langtry, TX, respectively (Table 1). The month of September is the wettest at all locations with monthly rain exceeding 5.5 cm (2.2 inches). Most rainfall occurs during warm months. Pan evaporation is many times greater than precipitation, and ranges from 280 cm (110 inches) at Quad 604 (Orla) to 230 cm (91 inches) at Langtry, TX (Table 1).

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.	1.02	1.19	1.24	10.81	9.33
Feb.	1.12	1.14	2.06	12.72	11.45
Mar.	0.71	0.86	1.68	21.19	18.44
Apr.	1.32	1.19	2.59	27.36	22.98
May	3.12	3.18	4.75	33.14	26.14
June	4.75	3.15	4.24	33.33	29.62
July	3.51	3.43	3.51	33.40	34.15
Aug.	5.56	4.11	3.94	30.15	30.73
Sept.	6.38	5.69	5.97	22.79	22.34
Oct.	3.30	2.79	4.04	17.01	16.70
Nov.	1.75	1.19	1.88	12.58	11.01
Dec.	1.42	1.55	1.37	10.54	8.85
Total	**33.96**	**29.47**	**37.27**	**265.03**	**241.73**

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

The total drainage area of the Pecos River Basin in New Mexico is 50,609 km^2 (19,000 square miles), which is based on the estimate by the United States Geological Survey (USGS) and is available from http://waterdata.USGS.gov. In Texas, the river flows southeast, and angles across Val Verde County to its mouth on the Rio Grande between Comstock and Langtry, approximately 61 km (38 miles) northwest of Del Rio (Fig. 1C). The total river mile in Texas is estimated at 640 km (400 miles), and the drainage area is 40,505 km^2 (15,600 square miles). Most of its tributaries flow from the west. Some, especially those above Coyanosa, are know to be saline, but details are unknown.

The drainage area consists mostly of well-drained Aridisols and Entisols (USDA/TAES), and supports sparse desert shrubs. The drainage basin near Red Bluff consists of gypsic soils such as Reeves and Holloman soil series. The majority of the soils in Reeves and Pecos counties are either shallow Aridisols (Del Norte, Nikel, Reakor) or calcareous silty clay loam, such as a 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. The permeability of these soils is moderate. The soils along the Pecos River are alluvial soils, namely Pecos, Patrole, Toyah and Gila series which have textures ranging from silty to loamy. Arno series, also an alluvial soil, is the only series which has montmorillonitic clayey textures with low permeability. Additional details on soils can be obtained through STATSGO soil classes (http://www.fri.sfasu.edu/pages/ archives/gis_data/html/gis_data.html) or through the soil survey map published by USDA/TAES. Soil permeability along the Pecos River can be high. A field study shows percolation losses as high as 40% in reaches below Red Bluff and above Pecos (Clayton, 2002). The same results were also reported earlier by Grozier et al. (1966). This high permeability is not limited to the river bed. Avalon Dam and old McMillan Lake (constructed in 1908), upstream of Red Bluff, have suffered excessive percolation losses through sinkholes. McMillan Dam was breached and replaced by Brantley Dam in 1991. A report by US Bureau of Reclamation (US BOR) and TWDB (1991) indicates the presence of minor sinkholes in Red Bluff Reservoir as well.

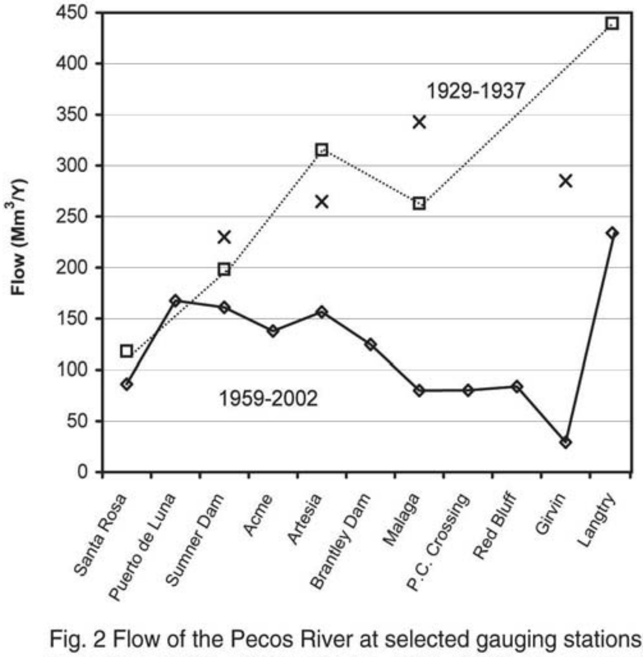

Fig. 2 Flow of the Pecos River at selected gauging stations; dotted line 1929 - 1937, solid line 1959 - 2002. The symbols x are the current flow plus diversion: the horizontal axis is not to scale.

The limited rainfall and highly permeable soils of this region yield low runoff from the watershed to the Pecos River. According to the USGS streamflow data, the streamflow at Artesia during 1929 – 1937 is reported to be 320 million m^3 (259,000 acre-ft.) per year. This annual flow amounts to 2.5% of the precipitation which falls on the drainage area above Artesia in New Mexico. On the Texas portion, the gain in flow beyond Malaga appears to be about 175 million m^3 (142,000 acre-ft.) per year prior to 1937. This flow amounts to 1.4% of the precipitation in the basin.

The construction of reservoirs such as McMillan (1908), Avalon (1907, 1912, and 1936), Red Bluff (1936), and Sumner (1937) has drastically altered the streamflow to the present day situation (Fig. 2).

Additional reservoirs were constructed later: Santa Rosa in 1981 and Brantley in 1991. Note that the flow below Puerto de Luna has declined, and it is reduced to a mere 29 million m^3 (23,500 acre-ft.) annually at Girvin, TX. The flow then increases with confluence of freshwater tributaries before discharging into the Rio Grande. Figure 2 also includes four data points which represent the current flow plus the diversion for irrigation. These points closely follow the original flow of the Pecos River prior to irrigation developments.

The water diverted from the river has been used for irrigated crop production (Table 2). The data of irrigated areas in four counties in New Mexico (Guadalupe, De Baca, Chaves, and Eddy) are unclear. The water used for irrigation shown in the right columns of Table 2, (downloaded from the New Mexico Office of the State Engineers website, http://www.ose.state.nm.us) may be a better indicator of croplands irrigated with the surface water of the Pecos River. The total irrigated area estimated from the annual water use from the Pecos River is 25,000 ha (60,000 acres) at the water allocation of 90 cm (3 acre-ft. per acre). Many areas in the New Mexico reach are also irrigated with ground water. Irrigated areas in the counties along the Pecos on the Texas side peaked during the early 1960s, then declined to the current level of 23,000 ha (57,000 acres), which includes the croplands irrigated with ground water. The cropland irrigated with the surface water on the Texas side was 21,000 ha (53,000

Table 2. Irrigated areas and surface water use along the Pecos River.

	Irrigated area[1] Thousand Ha						**Irrigation use[2]** Million m^3				
New Mexico	1940	1960	1970	1980	1990	2000	1960	1970	1980	1990	2000
To Sumner (Guadalupe & De Baca)											
Total[1]	0.4	0.9[3]	1.6[3]	2.0[3]	1.7[3]	2.8[3]	-	-	-	65	65
Sumner to Artesia (Chaves)											
Total[1]	2.2	0.3[3]	14.6	12.2	31.2	34.6	-	-	-	49	30
Artesia to Malaga (Eddy County)											
Total[1]	10.6	9.6	17.2	18.5	18.5	18.7	-	-	-	102	129
Total	**13.2**	**10.9**	**33.4**	**32.8**	**51.4**	**56.2**	-	-	-	**216**	**223**
Texas	1940	1958	1964	1979	1989	2000	1958	1964	1979	1989	2000
Red Bluff-Pecos (Loving, Reeves, and Ward)											
Total[1]	-	41.2	50.1	15.5	9.2	11.8	474	534	167	109	109
Surface	13.0	4.5	3.0	0.2	1.6	2.9	42.1	15.4	1.2	21.3	26.8
Pecos-Girvin (Pecos and Crane)											
Total[1]	-	47.5	48.3	11.0	10.2	11.0	426	453	117	91	92
Surface	8.0	0.0	0.0	0.0	0.7	0.5	0.0	0.0	0.0	9.3	2.2
Below Girvin (Crockett, Terell, and Val Verde)											
Total[1]	-	1.3	1.1	0.8	0.6	0.5	6.0	7.9	4.0	3.5	2.2
Surface	-	0.0	0.1	0.3	0.3	0.4	0.6	1.3	1.5	2.0	1.7
Total	**-**	**90.0**	**99.5**	**27.3**	**20.0**	**23.3**	**906**	**995**	**287**	**203**	**203**
Surface	**21.0**	**4.5**	**3.1**	**0.5**	**2.6**	**3.8**	**42.7**	**16.7**	**2.7**	**32.6**	**30.7**

[1] Include ground water irrigated areas. To convert to 1000 acres, multiply by 2.47

[2] Data published on www.seo.state.nm.us/water-info/water-use/wateruse.html for New Mexico and http://www.twdb.state.tx.us/publications/reports/Reports.asp for Texas. The data for 1940 are from NRPB,1942.

[3] Incomplete data.

acres) in 1940, and has fluctuated widely depending on the year (Table 2). The data for 1940 came from a survey report by the National Resources Planning Board (1942). The cropland irrigated with the surface water is found mostly above the town of Pecos.

Any figures related to water use or irrigated acreages have been a contested issue between the two states. Texas, for years, considered that New Mexico has not been living up to the terms of the Compact Agreement of 1948, to allow for equitable distribution of this water resource: 43% for Texas and 57% to New Mexico. In 1987, the U.S. Supreme Court ruled in favor of Texas claims, and the effort has been made to deliver additional water to Texas (e.g., Hamilton, et al., 2002). It is unclear how the delivery of additional water may affect salinity. The compact agreement does not address salinity of water to be delivered to Texas.

The Pecos River and some tributaries were once heavily infested with salt cedars. Salt cedar 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 flood plain (Mower et al., 1964). The first major salt cedar control of the Pecos River riparian 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 chemical treatment "Arsenal" began in the fall of 1999, and 544 ha (1,344 acres) of 106 km (66 river miles) reach below Red Bluff was implemented with 84 to 90% mortality (Hart, 2004). In 2001, an additional 580 ha (1,440 acres) over 57 river miles was treated, making the total treated area to 1,100 ha (2,774 acres). During 2002, 1,444 ha (3,567 acres) were treated, and in 2003 and 2004, an additional 1,080 ha (2,667 acres) along the Pecos main stem, and 430 ha (1,063 acres) of tributaries were treated. During 1999 through 2004, the total treated area amounted to 5,170 ha (12,767 acres) over 436 km (271 miles) of the Pecos River reach and its tributaries (Hart, 2004).

There are several significant ground water resources along the Pecos River. The Roswell Basin near Roswell, NM, for example, has the San Andres Limestone aquifer of the Permian age with an estimated thickness of 1,000 feet (Bean, 1949). The southern part of the Basin has the Grayburg Formation of the Artesia group which is known as a leaky artesian aquifer. According to Theis (1965), the natural discharge as springs at Roswell is estimated at 190 million m^3 (155,000 acre-ft.) per year. The San Andres Formation contains gypsum, especially in north Roswell. A shallow water aquifer is also present in the vicinity of Roswell at the south end of the Valley. Pumping in the Roswell Basin was estimated to have averaged 530 million m^3 (430,000 acre-ft.) per year in the 1950s. This resulted in a drop of water tables at a rate of more than 30 cm (1 ft.) per year. We made no attempt to digest more recent reports of ground water resources in New Mexico (e.g., McAda and Morrison, 1993), as it is beyond the scope of this study.

On the Texas side, the Cenozoic Pecos Alluvian is the principal aquifer and consists of up to 450 m (1,500 feet) thick alluvial sediments. This aquifer was once used for irrigation of large areas of the croplands in the Pecos Valley of Texas. During the peak irrigation era of the 1950s, pumping by wells was estimated to have reached as much as 900 million m^3 (730,000 acre-ft.) per year. Pumping from this alluvium declined drastically after the 1960s, and water tables have dropped as much as 60 m (200 feet), according to a report by TWDB (Ashworth, 1990). However, recent data show that water tables in the west of Pecos have risen as much as 9 m (30 feet) between 1989 and 1998 (Boghici, 1999). Perched water tables near the Pecos River are usually between 3 and 6 m, and deepen to 15 m away from the River. The depth fluctuates depending on the flow of the Pecos (www.twdb.state.tx.us).

Salt Bearing Formation

The Pecos River Basin is located in the southwestern edge of the Permian Basin which extends all the way to western Oklahoma. The Permian Basin was once an inland sea, and upon evaporation, salts, mostly halite and gypsum, have precipitated as much as 300 m (1000 ft.) thick. Salts deposited in this fashion are now found in several salt units that underlie a vast area as shown in Fig. 3. This figure, based on the rock salt distribution map (Brune et al., 1981), is an approximation, and detailed information on the salt bearing formation near Malaga is available in Havens and Wilkins (1979) and in Austin (1980).

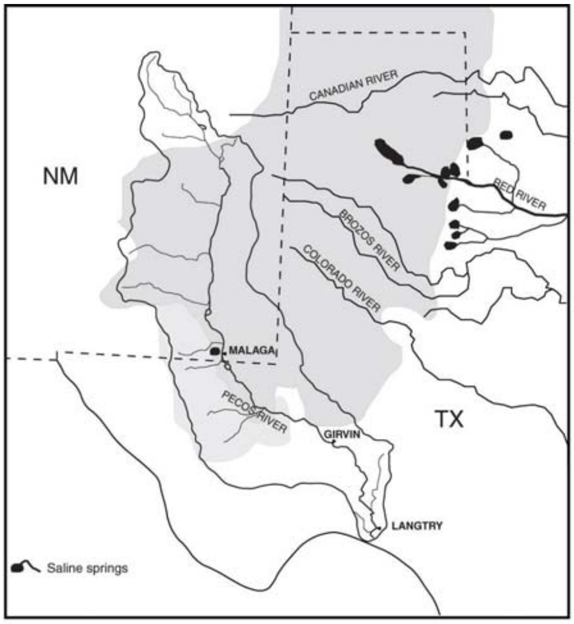

Fig. 3 Permian evaporite deposit of west Texas and southeastern New Mexico and the river basins affected by salt dissolution.

Dissolution of this salt into percolating water created saline seepage and springs along the Brackish water clastics. Both the Red River and the Arkansas River to the north are also affected by saline water intrusion (Johnson, 1981). Saline water intrusion into the Pecos River reportedly occurs in two areas; east of Roswell and east of Malaga. The site east of Roswell consists of Chain Lakes or Bottomless Lakes (Attachment I). These lakes are saline (15,000 – 35,000 mg L^{-1}) and overflow into the Pecos River (McAda and Morrison, 1993). Saline water intrusion also occurs at Malaga Bend in the southeastern part of New Mexico through dissolution of halite contained in the Salado formation which lies below the Rustler formation (Havens and Wilkins, 1979). Stratigraph extending from Northwestern Shelf (Northeast of Carlsbad) to Nash Draw (southeast of Carlsbad) is given by Austin (1980) and is cited in Fig. 4. Brine intrusion into the Pecos River at Malaga Bend (Attachment I) is believed to occur at the boundary between the Rustler and the Salado Formation. McNutt Member contains K (KCl, K_2SO_4, and KNO_3) which is being mined near Nash Draw (Barker and Austin, 1993). Detailed hydraulic head distribution is available in Corbet and Wallace (1993). A recent testing report shows that salinity of this brine is as high as 338,000 mg L^{-1}, and consists of NaCl with a small fraction (4.8% in chemical equivalent) made of $MgSO_4$. The solubility of halite is 370,000 mg L^{-1}. An additional small saline spring is also reported upstream of the Salt Creek below Red Bluff. The Delaware Creek located just above Red Bluff is not saline.

There are several other geologic formations containing rock salts. For example, the upper Triassic Santa Rosa formation consists of conglomerates, mudstones, and sandstones with gypsum pellets (Sidwell and Warn, 1953; Bodine Jr. and Jones, 1990). This formation occurs primarily in the upper basin near Santa Rosa. In the Roswell Basin, the San Andres formation of Permian Age provides a considerable amount of spring flow into the Pecos River (Fiedler and Nye, 1933; Theis, 1965). This formation contains gypsum. Both of these formations, as will be shown later, add a significant quantity of Ca and SO_4 to the upper portion of the Pecos River.

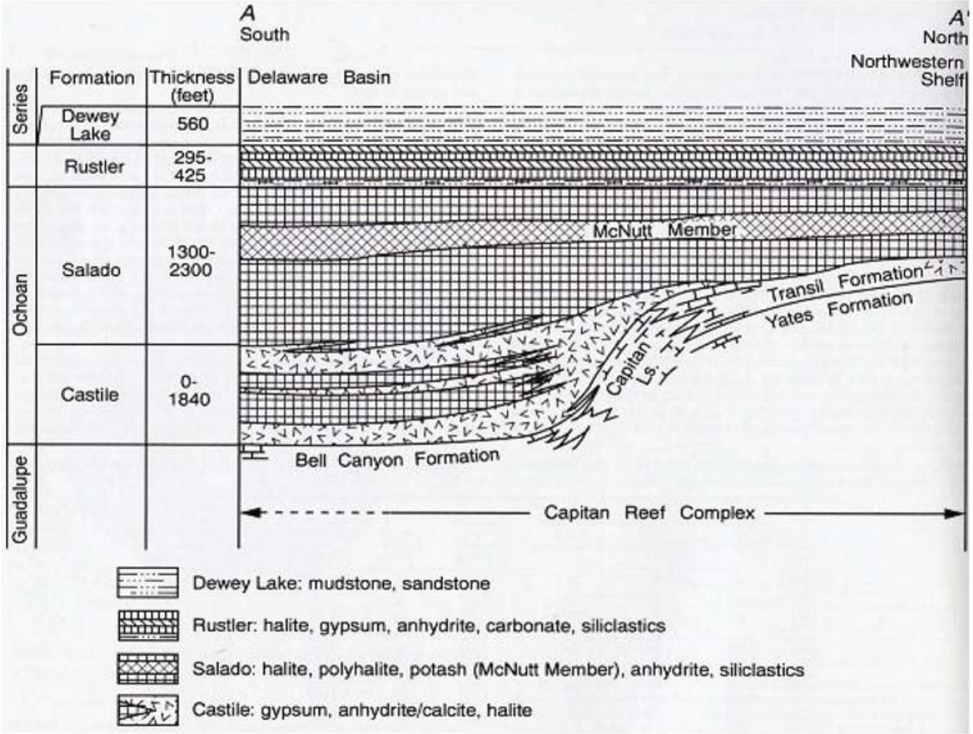

Fig. 4 Stratigraph of the North – South cross section from the Northwestern Shelf to the east of Loving, NM (Austin, 1980).

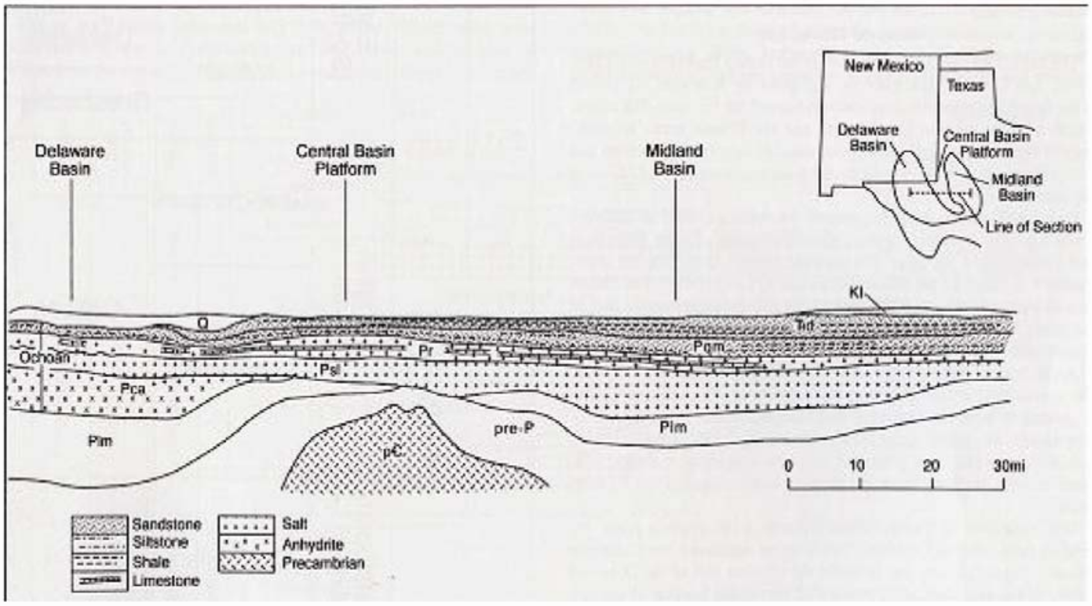

Fig. 5 Stratigraph of the East – West cross section across the Delaware, the Central Basin and the Midland Basin of west Texas (Lucas and Anderson, 1993).

There is a report indicating the formation of sinkholes as a result of dissolution of gypsum in the Pecos River Basin (Harrington, 1957).

The Rustler and the Salado Formations extend into west Texas and its stratigraph is shown in Fig. 5 (Lucas and Anderson, 1993). The Pecos River runs through the Delaware Basin of which the North – South cross-section in New Mexico was shown earlier in Fig. 4. Figure 5 presents the East – West cross-section covering the three basins in west Texas. Note that the Rustler Formation (P_r) and the Salado (P_{sl}), both of which contain salts, extend well into far west Texas, including the Midland/Odessa area. The depth to the Rustler Formation increases towards the east, as the Dockum Formation (T_{rd}) of the Triassic age provides an additional overburden. The subsurface brine of the Permian Guadalupian series has salinity ranging from 50,000 to 200,000 mg L^{-1}, and has the potentiometric gradient to the east towards the Midland Basin (McNeal, 1965).

The Permian Basin is also known for rich oilfields, and in some localities (e.g., Iraan, TX), oil once appeared on the ground surface naturally (Blackwell, 1974). Drilling and production of oil began in the area in the 1890s. 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, as the oil-bearing formation (the Pennsylvanian age) is located below the salt bearing formation (the Rustler and Salado). The paper by Broadhead and Speer (1993) discusses oil and gas fields in southeastern New Mexico and west Texas. In previous years, field operators discharged salt water into the surface and infiltration basins, and since 1969 into injection wells. Oil and gas field brines have long been considered a source of water contamination (e.g., Rold, 1971; Richter and Kreitler, 1987, Richter et al., 1990), but details are unclear.

METHODS

Analysis of Existing Data

Four sets of monitoring data were analyzed. The first set of monitoring data was sought, mainly to observe historical salinity data prior to the development of extensive crop irrigation. Two sets of the historical records were found; one at Malaga and the inlet to Red Bluff by U.S. Bureau of Reclamation (US BOR), and another for Langtry by the International Boundary and Water Commission (IBWC). The data set by the US BOR was apparently developed as a part of the Malaga Bend salinity control study and is given in an unpublished report by Wayne Cheney, Technical Service Center, US BOR at Denver. The data for a few additional years were found in Howard and Love (1945), and Hale et al., (1954) which was prepared as a contract report by the U.S. Geological Survey (USGS). The data for Girvin came from the USGS. These data provided monthly flow and salinity or salt load. In the case of the IBWC data set for Langtry, total dissolved salt (TDS) concentrations were estimated from the electrical conductivity (EC), using the calibration given in Table 3.

$$\mathbf{TDS = aEC} \tag{1}$$

where a is the conversion factor shown in Table 3.

The annual flow-weighted salinity was computed as

$$C_A = \Sigma C_m\, Q_m / \Sigma Q_m \qquad (2)$$

where C_A is the flow weighted annual salinity, C_m the monthly salinity, and Q_m the monthly flow. Flow-weighted salinity is usually smaller than arithmetic means, since salinity during high flow tends to be lower. This is especially true in the reach with limited flow. Unless stated otherwise, flow-weighted annual salinity, instead of arithmetic means, will be used for estimating salt load and balance.

Table 3. Correlation between the electrical conductivity (EC) and the total dissolved salts (TDS) at various gauging stations.

Location	a	r^2	n
Puerto De Luna	0.88	0.98	105
Sumner	0.87	0.99	11
Acme	0.78	0.98	145
Artesia	0.70	0.99	385
Malaga	0.71	0.99	272
P.C. Crossing	0.67	0.99	325
Red Bluff	0.66	0.86	169
Girvin	0.71	0.94	96
Langtry	0.62	0.99	115

TDS (mg/L) = a EC (dS m^{-1})

Table 4. The empirical coefficients to describe the relationship between salt flux and flow rates.

	α	β	r
Santa Rosa	1.00	0.62	0.98
Puerto Luna	3.62	0.49	0.88
Sumner	1.48	0.95	0.96
Acme	2.51	0.83	0.96
Artesia	5.01	0.67	0.92
Brantley	3.55	0.88	0.94
Malaga	5.01	0.67	0.96
P.C. Crossing	9.33	0.58	0.89
Red Bluff	8.71	0.65	0.89
Girvin	11.48	0.69	0.89
Langtry	2.24	0.91	0.88

The second set of monitoring data consisted of flow and salinity data maintained by the USGS at eleven gauging stations along the main channel of the Pecos River. The flow data at some locations date back to 1905, but water quality data were available mostly after 1959. These data were downloaded from the National Water Quality System (NWIS, http://waterdata.usgs.gov/nwis). The water quality data were first screened by using the cation and anion balance, and the TDS and EC relationship mentioned earlier. The data which deviated more than 30% from the estimate were omitted. The streamflow data at each of the gauging stations were reported daily, thus the monthly flow was computed simply as a sum. Water quality data were reported for water samples collected one to four times a month, and may or may not represent the true quality of the month. We noted that flow rates at the time of sampling usually do not coincide with the mean flow rate computed from the daily flow records. In order to adjust the water quality records to the actual flow, we used the following equation.

$$C_i q_i = \alpha q_i^{\beta} \qquad (3)$$

or

$$\log (C_i q_i) = \beta \log q_i + \log \alpha \qquad (4)$$

where C_i is the measured ionic concentration or TDS, q_i is the flow rate at the time of water sampling, and α and β are empirical coefficients. The term $C_i q_i$ will be referred to as salt flux.

Examples of the relationship between salt flux ($C_i q_i$) and flow rate (q_i) obtained at various stations are shown in Fig. 6. Also included in Table 4 are the regression coefficients (α and β) with the coefficient of correlation (r). With an exception of the data set at Pierce Canyon

Crossing and the inlet to Red Bluff, Eq.(4) was found suitable for describing the salt flux and flow rate relationships. The data at Pierce Canyon Crossing and the inlet to Red Bluff were somewhat scattered due to brine intrusion into the Pecos River. The data from these gauging stations should be used with caution. (The Red Bluff station was removed after 1995, but an effort is being made to install an automated gauging station through a joint effort of several agencies.)

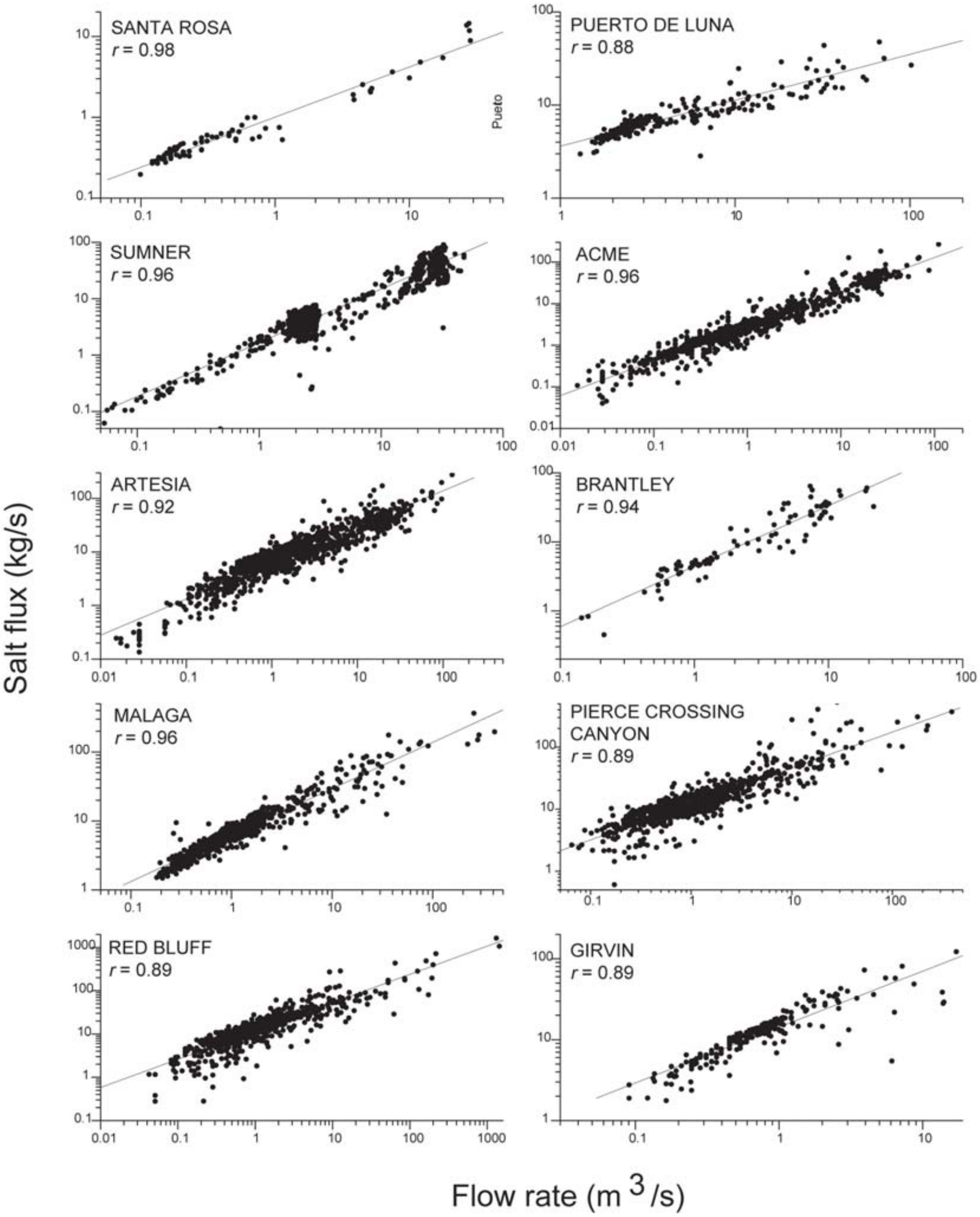

Fig. 6. The relationship between salt fluxes and flow rates at ten USGS gauging stations.

Examples of the plots when Eq.(4) was applied to ionic concentrations at Artesia are shown in Fig. 7. The relationship given by Eq.(3) worked well with all ions except for Na and Cl ions which did not follow the log-linear relationship for the entire range of the flow rates encountered. We used two lines for the best fit in these cases.

Water quality data were then converted to the concentration applicable to the actual flow condition.

$$\mathbf{C_m = [\Sigma C_i q_i/\Sigma q_i]\ [q_m/(\Sigma q_i/n)]^{\beta-1}} \tag{5}$$

where C_m is the flow-weighted monthly concentration adjusted to the actual flow condition, q_i is the flow rate at the time of sampling with n denoting the number of sampling per month, and q_m is the actual mean flow rate from the flow monitoring. The term $\Sigma C_i q_i/\Sigma q_i$ indicates the flow-weighted concentration, and the term $[q_m/(\Sigma q_i/n)]^{\beta-1}$ represents the conversion factor from the average flow rate during sampling ($\Sigma q_i/n$) to the monthly flow rate given by the flow monitoring, (q_m).

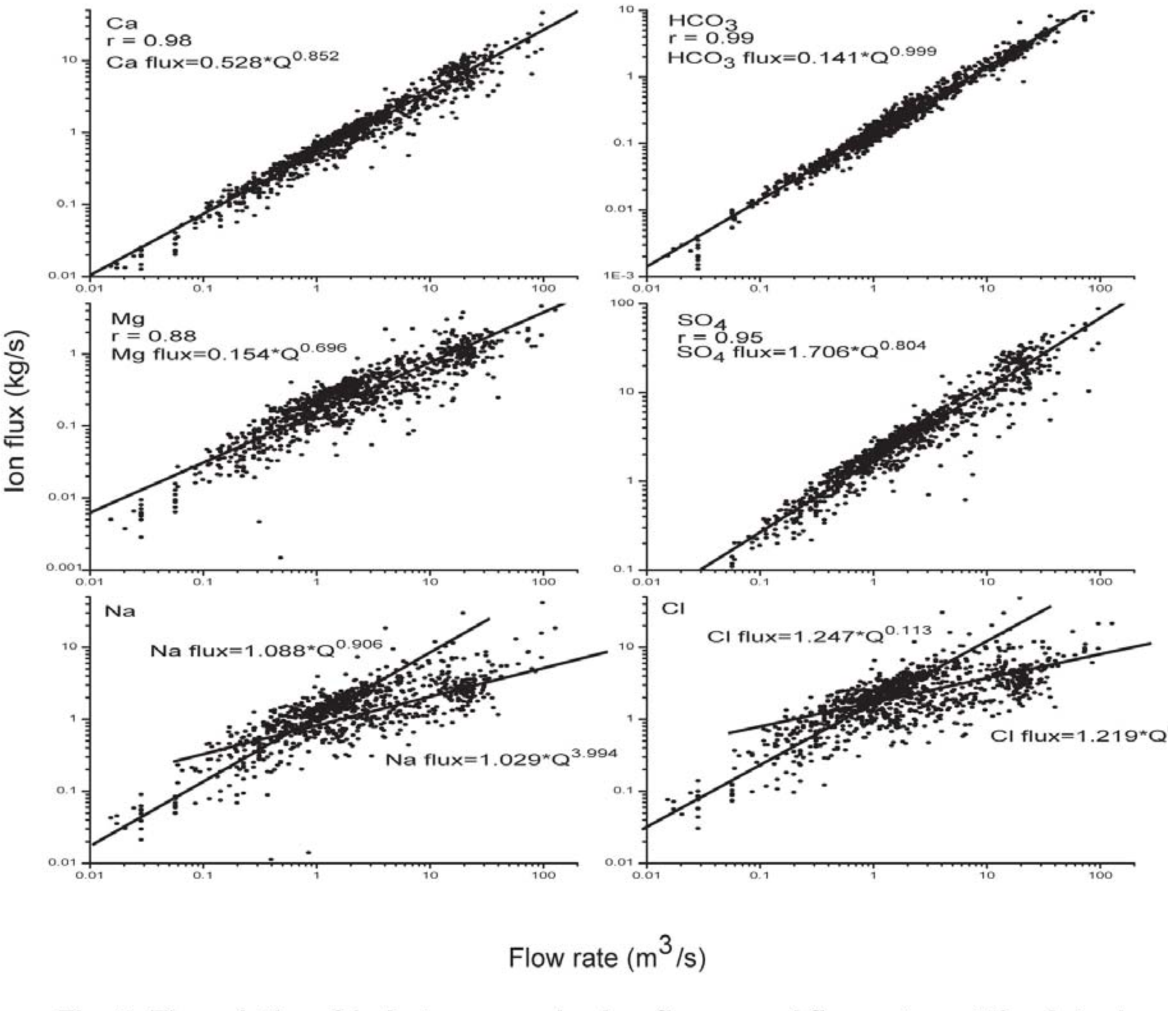

Fig. 7. The relationship between major ion fluxes and flow rates at the Artesia gauging station.

Once C_m was adjusted to the actual flow condition, the annual flow-weighted salinity was computed by Eq.(2) mentioned earlier. The annual mean salinity was then computed as an arithmetic mean.

$$\mathbf{C_A = \Sigma C_A/N} \tag{6}$$

where C_A is the annual mean salinity which is flow-weighted up to twelve months, and N is the number of years. The annual mean salinity estimated by Eqs.(5), (2), and (6) may correspond to salinity of the reservoir with a residence time of about one year. The residence time of the reservoirs in this basin seems to be around one year, except for dry years.

If the total mass balance computation for an extended period is desired, the mean dissolved salt concentrations (C_d) should be computed as the flow-weighted means across the years of interest.

$$\mathbf{C_d = \Sigma C_A Q_A/\Sigma Q_A} \tag{7}$$

where C_A is the annual salinity estimated by Eq.(2) with the corresponding annual flow, Q_A. The flow-weighted annual mean salinity is considerably lower than the salinity estimated by Eq.(6), as the large flow events yield low salinity. The annual mean salt loading (AMSL) can be computed as

$$\mathbf{AMSL = C_d\ \Sigma Q_A/N} \tag{8}$$

where N is the number of years.

The salt balance in river segments was computed as salt outflow minus salt inflow. The positive value indicates the net increase in salt load, and the negative value a reduction in salt load in the river segment.

The third set of monitoring data analyzed came from the Texas Clean River Program (CRP), and was retrieved from an IBWC data file (http://www.ibwc.state.gov/CRP/monstats/htm). Flow and water quality monitoring for the Texas portion began in 1993, and has been carried out at Red Bluff, Orla, Mentone, Pecos, Coyanosa, Girvin, Sheffield and several other locations. Unfortunately, the frequency of measurements was low, 4 to 6 times a year, and the measurements consisted, in most cases, of the flow rate, conductivity, Cl and SO4 concentrations. The data since 1995 were used for this study, and were screened by using the relationship between the sum of anions against electrical conductivity readings. Since there is no record of daily measurements of flow, except at Girvin and Langtry, we simply took the average of the flow rates measured at the time of sampling to compute the annual flow rate. The flow computed in this manner may be meaningful as an indicator of relative flow rates across the gauging stations, and is usually lower than the actual, because no water sampling is made during flood. (Two continuous flow monitoring stations were recently installed, and are expected to partially fill this data gap). Annual salinity was estimated as the flow-weighted salinity. The annual salt load was computed as the flow times the annual flow-weighted salinity at each gauging station.

The last set of the data was obtained from a report by Grozier et al. (1966). The study measured flow and salinity of the Pecos River when the reservoir release was kept at 3.65 m^3/s (129 cfs) in March 1965, and in May, 1965 when the release was nearly zero. The measurements were performed at 26 sites within the stretch between the reservoir and Girvin. During the measurements, inflow from creeks and tributaries was minimal, and diversion amounted to 2% of the release. In other words, the measured flow reflects largely the seepage loss during the constant release, and ground water intrusion during no reservoir release.

Exploratory Water and Soil Testing

Water samples were collected at the sampling sites previously selected by the CRP, and included Red Bluff, Orla, Mentone, Pecos, Coyanosa, Girvin, and Sheffield. Water was sampled on two occasions: March 8 and May 7, 2005. The first sampling on March 8 was to collect water samples prior to reservoir release. However, because of unusual rain in January through February, Red Bluff storage was near its capacity, and a small quantity of water had been released, in addition to fresh runoff from nearby creeks. The USGS streamflow monitoring shows that the flow recorded at Orla and Girvin on March 7 was 0.79 and 1.33 m^3/s (28 and 47 cfs), respectively. There was also high flow in July and November of 2004 which caused bank overflow in most parts of the Pecos River.

The second sampling was conducted on May 7, one week after reservoir release was temporarily shut-down. The flow recorded on May 7 was 0.79 and 0.48 m^3/s (29 and 17 cfs) at Orla and Girvin, respectively. Limited data indicated that the baseflow at Girvin (when there is no reservoir discharge) is 0.35 m^3/s (e.g., Grozier et al., 1966). The flow measured on May 7 at Girvin is within the range of the baseflow variability. The water samples collected on March 7 were icepacked, sent out to a contract laboratory, and analyzed for Na, Ca, Mg, and K with an ICP (EPA method 200.7), SO_4 with a turbidimetric method (EPA method 375.4), and Cl with a tritrimetric method (EPA method 325.3), all described in the US EPA methods of water analyses (1983). Water samples taken on May 7 were not analyzed for ionic composition, because of a question related to QAPP. Additional water samples were collected on July 14, 2005, and were analyzed for TDS, pH, Cl, and SO_4. A separate set of the samples collected on March 8 and May 7 was analyzed for isotope $\delta^{18}O$ by a mass spectrometer at the Stable Isotope Laboratory at the University of Colorado and Duke University. The concentration of $\delta^{18}O$ reflects the degree of water evaporation, although other factors also affect the readings. Results of the reference samples from both laboratories were compatible.

Soil samples were also collected on March 8 and May 7, 2005 from the river bank at 60 cm away from the stream towards the floodplain to a depth of 0 to 30, and 30 to 60 cm using a drill-type power auger. The sampling holes were geo-referenced, and soil samples during subsequent sampling were taken within the circle of 30 cm (1 ft.) from the first sampling hole. Bank soil samples were air-dried, passed through a 2 mm screen, and analyzed for field moisture contents, the saturation water content, and salinity of the saturation extract by the method described in Rhoades and Miyamoto (1990). The saturation water content is an indicator of soil textural classes.

RESULTS

Historical Flow and Salinity

The historical records at Malaga show widely fluctuating flow and annual salinity (Fig. 8). The overall trend is declining flow, especially since 1950. Salinity of the streamflow fluctuated around 3,000 mg L^{-1} during the period of 1938 through 1943. The long term salinity at Malaga since 1959 is 4,100 mg L^{-1}. Salinity of the Pecos River was evidently elevated before the extensive irrigation developments, and the fluctuation in salinity became greater with reducing streamflow.

The historical flow at the inlet to Red Bluff was almost identical to that at Malaga or P.C. Crossing. There is no perennial flow in this segment. Streamflow salinity at P.C. Crossing, however, was substantially greater during the period of 1938 through 1940 (Fig. 8), due to brine intrusion. The difference in streamflow salinity became even greater during the 1960s through the 1980s as the incoming flow from Malaga had declined.

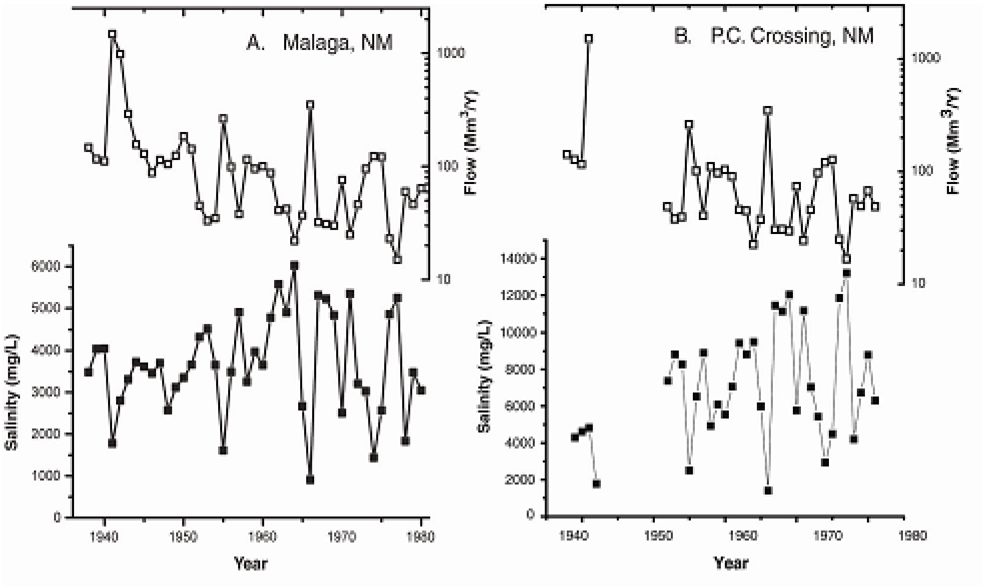

Fig. 8 Historical changes in annual flow and flow-weighted salinity recorded at Malaga and P.C. Crossing, NM (the data from US Bureau of Reclamation).

The historical records at Girvin and Langtry are shown in Fig. 9. As the case of Malaga, the overall pattern of flow at these locations is one of declining. Salinity of streamflow prior to the flood of 1941 was 11,000 mg L^{-1} at Girvin, and 2,800 mg L^{-1} at Langtry. Neither reading is greatly lower than salinity readings of subsequent years. The pattern of salinity variation at Langtry closely resembled the pattern of flow fluctuation at Girvin. Since 1935, salinity of the Pecos River at Langtry increased when the flow at Girvin increased. This observation can be explained by the fact that the flow from Girvin is the principal provider of salts to the lower reach of the Pecos. However, there were two cases which did not follow this trend, and occurred in 1954 and 1974. In these years, the flow at Langtry was either exceptionally high or substantially higher than the average flow, and this may have lowered salinity. Saline flow at Girvin seems to have played a key role in controlling salinity of the lower Pecos River in all other years examined.

The historical records presented in Figs. 8 and 9 show that there was high flow in 1941, which was registered at all locations: Malaga, Girvin, and Langtry. Most of this flow, 1.6 billion m^3, was probably caused by the precipitation that had fallen near or above Malaga towards Roswell. This high flow caused streamflow salinity to decrease at Malaga, but not at Langtry, indicating possible salt pick-up below Malaga and, to a lesser extent, from the reach between Roswell and Malaga. This is a contrast to the two other high flow events with the flow exceeding

1 billion m^3, recorded in 1954 and 1974 at Langtry, but not at Girvin. It appears that streamflow salinity is higher when rain falls near Malaga or above, but not near Langtry.

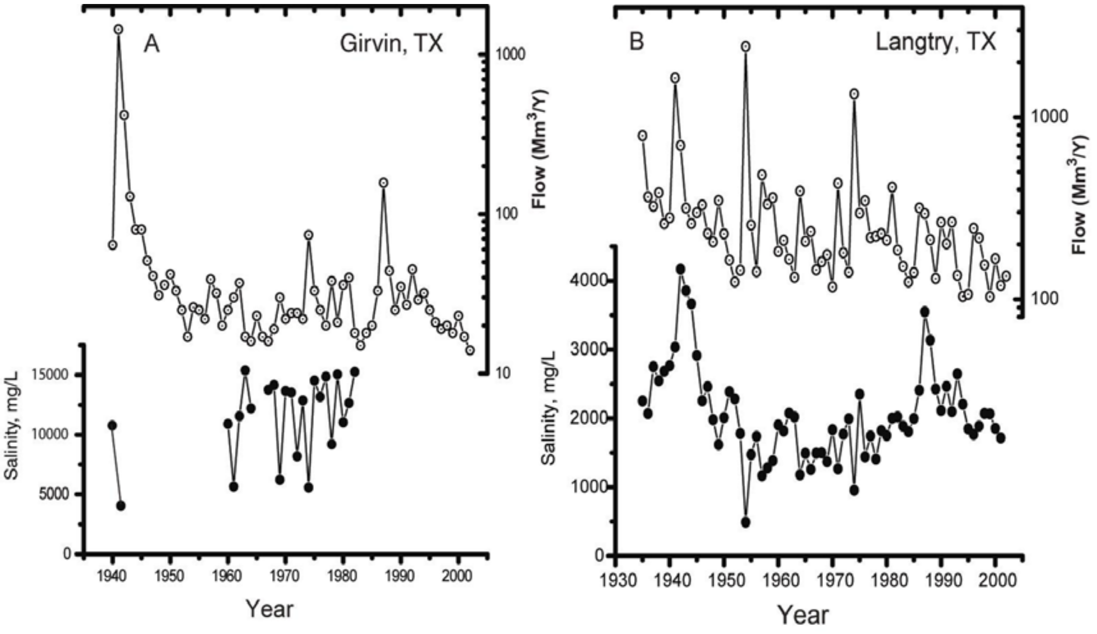

Fig. 9 Historical records of flow and salinity at Girvin and Langtry (original data at Girvin from USGS, these at Langtry from IBWC).

Spatial Changes in Flow and Salt Load

Annual Flow and Salinity: The decade average flow between Puerto de Luna and Artesia did not change greatly over the distance, and averaged about 160 million m^3 (130,000 acre-ft.) per-year (Fig. 10A). The flow then decreased as approaching Malaga, then became stable at about 80 million m^3 per year through Red Bluff. The flow at Girvin decreased to 29 million m^3 per year. There are several diversions for irrigation below Red Bluff. The annual mean streamflow during the last three decades (61-70, 71-80, and 81-90) below Red Bluff has been fairly consistent, except at Langtry. The variable flow at Langtry is caused by inconsistent precipitation associated with monsoon weather patterns.

Streamflow salinity, the arithmetic mean of annual salinity estimated by Eq.(6) averaged around 600 mg L^{-1} in the northern watershed, and increased to 1,500 mg L^{-1} at Sumner Dam, and 3,000 mg L^{-1} before reaching Artesia. Salinity increased from 4,000 to 7,000 mg L^{-1} as the streamflow traveled from Malaga to Pierce Canyon Crossing, and eventually reached in excess of 12,000 mg L^{-1} at Girvin (Fig. 10B). Salinity declines again below Girvin as runoff enters the lower reach where annual mean precipitation amounts to 38 cm. Table 5 includes the salinity computed by Eq. (7), which is the long-term flow-weighted value. These values are significantly lower than the arithmetic average of the annual salinity. (The annual salinity is flow-weighted monthly estimated by Eq.(2) for 12 months). The reduction in flow-weighted salinity occurs when occasional flood events occur, as salinity of these high flows is typically low. The measured salinity is closer to the arithmetic mean, except for the period of high flow.

The annual flow of the Pecos below Red Bluff (Fig. 11A), which came from the CRP, varied, and was minimal during the period of drought which extended from 2002 to 2004.

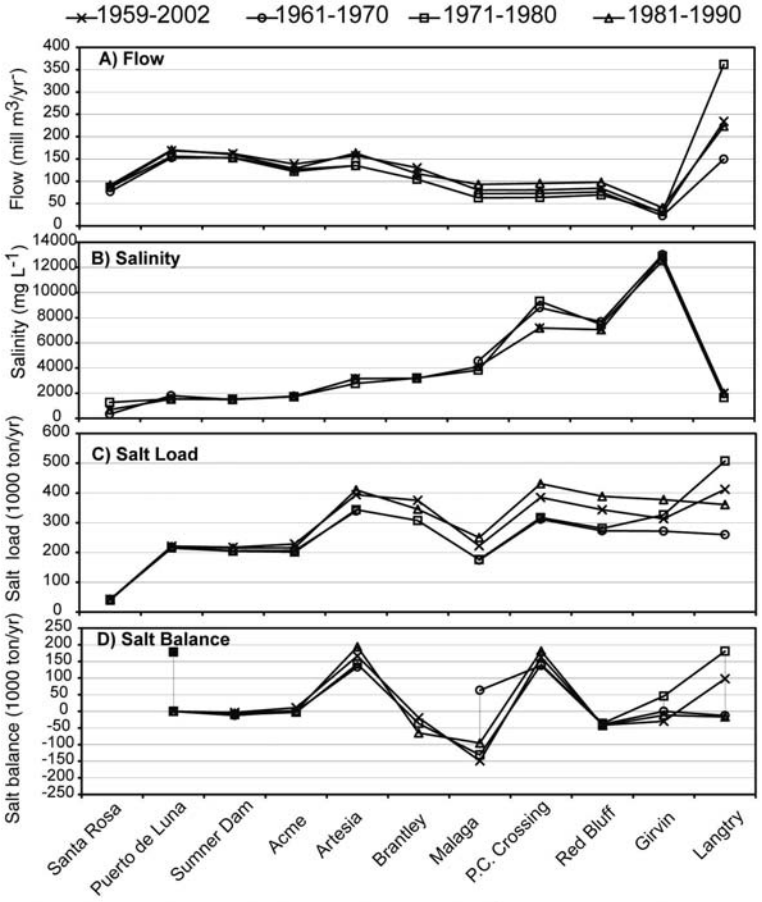

Fig.10 Flow, salinity, salt load, and salt balance in different reaches of the Pecos River over the last four decades. Note that numbers for salt balance were calculated by subtracting salt loading downstream from station upstream.

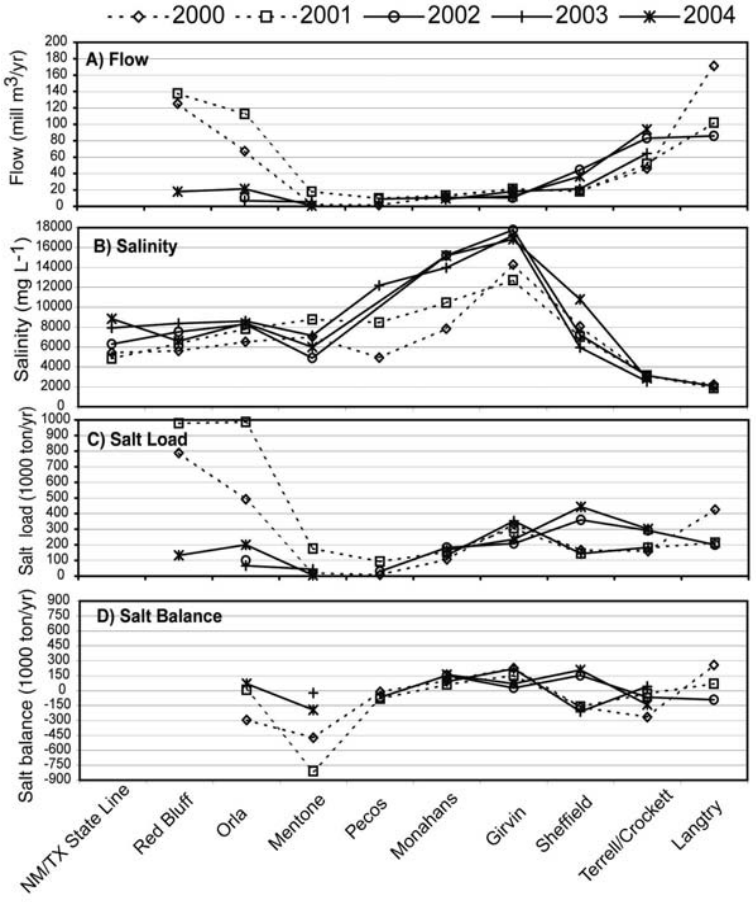

Fig.11 Flow, salinity, salt load, and salt balance in different reaches of the Pecos River during the last four years. Note that numbers for salt balance were calculated by subtracting salt loading downstream from station upstream.

However, the base-flow increased steadily towards Girvin, and almost exponentially thereafter. The reservoir release did not seem to affect the flow below Coyanosa greatly, probably because the release is diverted for irrigation upstream. The flow recorded at Girvin ranged from 18 to 30 million m^3 (14,600 to 24,000 acre-ft.) per year. This can be compared against the long-term mean streamflow of 29 million m^3 (23,500 acre-ft.) per year recorded at the USGS station.

Table 5. Flow, annual mean salinity, flow-weighted long-term salinity, and salt load of the Pecos River averaged over 1959 - 2002 (USGS Data).

Gauging Stations	Annual Flow	Annual[1-] Salinity	Flow-weighted[2-] Long-term	Salt Load	Load[3-] Changes	Loading Contribution[4-] - Girvin	Loading Contribution[4-] - Langtry
	M m^3/y	mg/L^{-1}		1000 ton/y		%	%
Santa Rosa	87	675	488	42	+ 42	6	5
P. Luna	168	1527	1312	221	+ 179	26	24
Sumner	162	1494	1345	218	- 3	-	-
Acme	138	1722	1649	228	+ 10	2	1
Artesia	159	3171	3078	489	+ 261	38	35
Malaga	80	4111	3315	265	- 224	-	-
P. C. Crossing	81	7128	5393	437	+ 172	25	23
Red Bluff	84	7028	5433	456	+ 19	3	2
Girvin	29	12849	12095	351	- 105	-	-
Langtry	234	1995	1823	426	+ 75	-	10

[1-] Annual mean salinity by Eq (6).

[2-] Flow-weighted long-term means by Eq (7).

[3-] The postive values indicate a gain in salt load.

[4-] Percentage of the positive salt loading total above Red Bluff (683,000 tons/year) and that of the total above Langtry (758,000 tons/year).

The analyses of the Texas Clean Rivers Program data indicate that salinity of the stream below Red Bluff averaged 6,000 mg L^{-1} during 2000 and 2001, the years of good water supply (Fig. 11B). This is lower than the long-term salinity at the location, 7,000 mg L^{-1}. Salinity decreased somewhat toward Pecos, then increased towards Girvin where it reached over 12,000 mg L^{-1}. Some of these figures are higher than the long-term average reported by USGS, partly due to the limited number of measurements which tends to miss low salinity during occasional high flow associated with localized rain. During the years of short water supply (2002 through 2003), salinity reached over 14,000 mg L^{-1} at Coyanosa, and ranged from 16,000 to 18,000 mg L^{-1} at Girvin.

Annual Salt Load: There are two ways to estimate salt load; one using the arithmetic mean salinity, and another, flow-weighted mean salinity over a multi-year duration. If the annual flow is determined as the cumulative of daily flow events for multiple years, salt load should be estimated by flow-weighted means, such as shown in Eq.(8). In reality, salt load is often estimated by using the arithmetic mean and the flow at the time of sampling. The salt load estimated in this fashion can be an over-estimation, but not as much as the difference shown in Table 5, because the flow is likely to be underestimated by ignoring occasional high flow events.

Salt loads of the Pecos River estimated by Eq.(8) increased from 42,000 tons per year at Santa Rosa to 221,000 tons per year at Puerto de Luna (Table 5). An additional increase in salt load occurred between Acme and Artesia, which brought the cumulative salt load to 489 thousand tons per year at Artesia. Salt load then declined due to the decline in flow between

Artesia and Malaga. A sharp increase in salt load was noted at Pierce Canyon Crossing at an annual rate of 172,000 tons, even though the flow did not significantly increase. Brine seepage enters into the Pecos River between Malaga and Pierce Canyon. The salt load in the reach below Red Bluff decreased, except for a period of high flow. This pattern is caused by flow diversion for irrigation.

Three reaches were identified, which yield the large salt loading above Red Bluff; between Santa Rosa and Puerto de Luna, Acme and Artesia, and Malaga and Pierce Canyon Crossing. These reaches receive not only large salt load, but also yield the notable increases in salinity, especially at the reach between Malaga and Pierce Canyon Crossing. The salt load from these reaches accounted for 89% of the total loading of 683,000 tons per year above Red Bluff (Table 5). The salt loading estimates from Red Bluff to Pecos show a large reduction, thereafter steady increases below Pecos all the way to Langtry (Fig. 11C). The reduction is caused by flow diversion for irrigation and high seepage losses, mostly above Pecos, and can be misleading. There is significant salt loading below Pecos due to saline shallow ground water intrusion.

Dissolution of Salts: The annual mean loading (AML) of major cations and anions estimated by Eq.(8) from USGS data show significant spatial changes (Table 6). As soon as streamflow reaches Santa Rosa, Ca and SO_4 ions are being dissolved, and this pattern continues until reaching Puerto De Luna. The cations and the anions appeared in these reaches are exclusively Ca and SO_4. As streamflow passes Acme, Na and Cl ions are found in increasing quantities, and the dissolution of Ca and SO_4 slows (Table 6). As streamflow travels down to Red Bluff, Na and Cl load double between Malaga and Pierce Canyon Crossing. There are direct indications that salt sources change from gypsum to halite.

Table 6. Estimated cations and anions loads and their changes between the selected stations (USGS data for 1959 through 2002).

Gaging Station	TDS	Ca	Mg	Na	K	HCO_3	SO_4	Cl	Na/Cl[1]-	CM/S[2]-
			1000 tons/year							
Santa Rosa	42	12	1.5	1.4	0.3	16	26	1.1		1.3
Puerto De Luna	221	56	6.6	8.9	0.5	28	142	12	1.1	1.1
Sumner Dam	218	54	6.1	9.2	0.4	22	137	12	1.3	1.1
Acme	228	45	6.9	17	0.5	17	128	22	1.2	1.1
Artesia	489	74	15.4	62.9	1.0	27.7	214	97	1.0	1.1
Malaga	265	31	9.4	42.8	1.0	12.5	96	71	1.0	1.2
P.C. Crossing	437	33	11.7	101.8	3.0	12.8	111	165	1.0	1.1
Red Bluff	456	35	11.5	108.8	2.8	14.2	102	180	0.9	1.3
Girvin	351	20	10.6	90.1	1.5	3.8	84	138	1.0	1.1
Langtry	426	35	13.7	89.4	2.1	50.6	87	148	1.1	1.9

Changes[2]-

	TDS	Ca	Mg	Na	K	HCO_3	SO_4	Cl	Na/Cl	CM/S[2]-
				1000 tons/year						
Santa Rosa to Puerto De Luna	179	39.4	4.6	6.7	0.2	12.7	103.4	9.6	1.1	1.1
Acme to Artesia	261	30.9	8.8	46.8	0.5	11.8	91.5	75.9	0.9	1.3
Malaga to PC Crossing	172	2.7	2.3	59	2	0.3	15.4	94.2	1.0	1.0

[1]-Ionic ratios based on equivalent weights.

[2]-CM/S = (Ca+Mg)/SO4

Seepage and Shallow Ground Water Intrusion: The flow released from the reservoir at a constant rate of 3.6 m^3/s (129 cfs) decreased to 1.7 m^3/s (60.6 cfs) over the distance of 205 km (127 miles) where the river intercepts Highway 18 near Grandfalls as marked by an arrow in Fig. 12 (Grozier et al., 1966). The reduction in flow over the 205 km stretch was approximately linear, except near Pecos (115 km from the reservoir) where the flow decreased as the permeability of the riverbed suddenly increases. Since the diversion was kept minimal during the study, the reduction in flow can be attributed to percolation losses. The evaporation from the free water surface during March is small; 0.64 cm/day or 0.075 acre-ft. per the estimated surface area of 360 ha (or 900 acres) over the transmission time of 4 days. The bank storage loss would have been minimum, as the measurement of flow began 14 days after the release of water.

During the constant discharge setting, streamflow salinity increased from 7,200 mg L^{-1} to 7,300 mg L^{-1} in the reach between the confluence of the Salt Creek and Orla (14.3 miles), then stayed at the level all the way to Pecos (Table 7). Salinity then increased to 7,500 mg L^{-1} above Grandfalls, and 9,500 mg L^{-1} at Girvin. The major salt inflow seems to be occurring below Grandfalls. Salt load deceased down to 499,000 tons/year at Grandfalls, and then increased to 562,000 tons/year at Girvin. The salt gain between Grandfalls and Girvin appears to be 63,000 tons/year at a flow rate equivalent to 55 Mm^3/year.

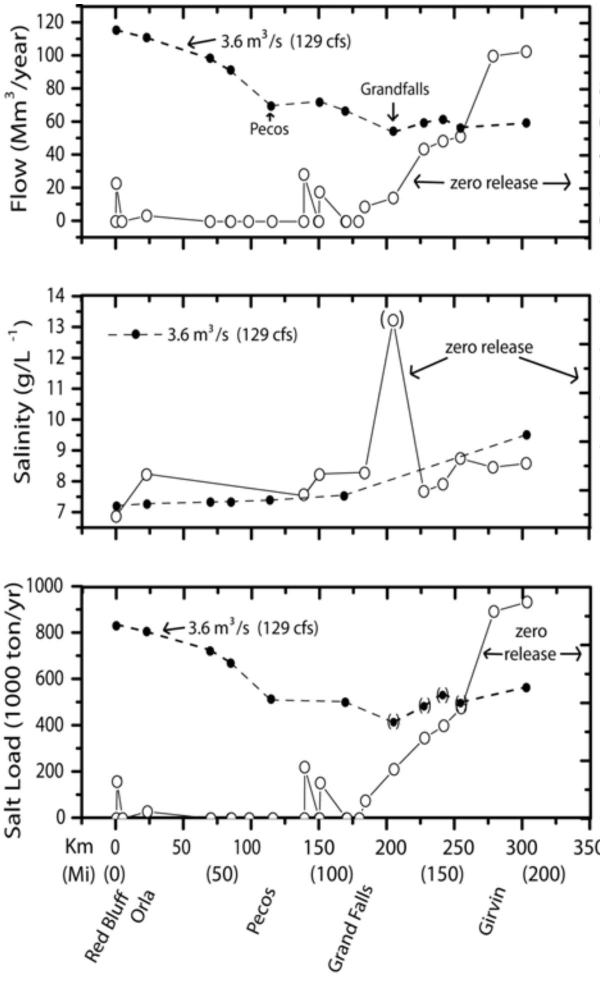

Fig. 12. Spatial changes in flow, salinity and salt load along the Pecos River below Red Bluff: - - - - - discharged at 3.6 m3/s (129 cfs) : ——— zero release.

Prior to the measurement of flow on May 10 – 12, 1965, there was apparently no release or surface runoff for at least 30 days. Therefore, the flow which appeared below Grandfalls (near Coyanosa) is likely to be subsurface inflow, and reached 10 million m^3/year (8,100 acre-ft.) at Girvin. There were two sites where streamflow appeared between Pecos and Coyanosa. This flow was probably originated from Salt Draw and another from Toyah Creek. These surface sources seep into the ground, then flow into the Pecos. The continuous flow begins just north of Grandfalls, or the Coyanosa Station.

During no discharge setting, salinity of the streamflow ranged from 16,000 to 18,500 mg L^{-1}, except for one entry from Grandfalls, which was noted to be contaminated with oilfield brine. Salt load increased to 187,000 tons/year between Grandfalls and Girvin, excluding the salt entry from the Salt Draw and the Toyah Creek. If included, the total salt inflow is estimated at 262,000 tons/year. When the study was conducted in 1965 (Grozier et al., 1966),

Table 7. Flow, annual salinity, salt load during normal, and low flow years (CRP data), and those reported during the controlled flow regimes.

Gauging Stations	Normal flow (2000 - 01)				Low flow (2002 - 03)			
	Flow	Salinity	Load	Change	Flow	Salinity	Load	Change
	Mm^3/y	mg L^{-1}	1000 t/y		Mm^3/y	mg L^{-1}	1000 t/y	
Red Bluff (Outlet)	131	5991	883	-	-	7953	-	-
Orla	90	7184	739	-144	8.8	8449	83	-
Mentone	10	7895	97	-642	5.4	6024	43	-23
Pecos	6	-	-	-	8.9	7616	30	-70
Coyanosa	13	9148	130	80	9.6	14586	157	121
Girvin	21	13504	319	188	14.4	17493	281	123
	Constant Flow (3/1965)[2]-				No Release (5/1965)[2]-			
Red Bluff	115	7190	829	-	2.3	13860	32	-
Orla	110	7320	720	-109	0.3	17292	6	-25
Pecos	69	7320	512	-208	0.0	-	-	-
(Salts Draw[1]-)	-	-	-	-	(4.6)	(16310)	(75)	(75)
Grandfalls	54	7520	499	-13	0.9	17420	15	15
Girvin	56	9500	562	63	10.2	18216	187	172

[1] -Saline flow which appears in two sites between Pecos and Coyanosa, and is believed to originate from the subsurface flow from the Salt Draw. Not considered as steady subsurface inflow.

[2] -Flow and salinity measured under the controlled flow of 55 Mm^3/year by Grozier et al. (1966).

there was no surface flow from the Salt Creek, yet salinity of the reservoir seepage was elevated from 7,200 to 13,860 mg L^{-1}. This seems to indicate that about half of the salt load, 16,000 tons per year might have originated from subsurface flow of the Salt Creek. This estimate is tentative. The location maps and several photographs of the Salt Creek, Toyah Creek, and the reach below Grandfalls are shown in Attachment II.

Exploratory Water and Soil Analyses

Ionic Concentrations of the Streamflow: The concentrations of cations and anions measured by the USGS at selected gauging stations from Artesia to Sheffield are shown in Table 8. Note that both Cl and Na concentrations increased downstream more so than SO_4 or Ca ions. This resulted in Cl/SO_4 ratios (expressed in chemical equivalent) to increase from 0.61 at Artesia to a range of 2.0 to 2.5 at Orla or below. Although not shown, the Salt Creek sample had cation and anion composition similar to that of the Pecos at Orla. Likewise, Na to Cl ratios (in chemical equivalent) also increased from near unity to a range of 1.3 to 1.7 below Orla. Included in Table 8 are the ion concentration data from the USGS, which were adjusted to the TDS at the long-term average flow (1959-2000). The ion concentrations measured in March 2005 at Artesia and Malaga were higher than the annual average, probably due to seasonal changes, whereas the ion ratios, especially Na/Cl and Ca/SO_4 remained constant.

Table 8. The major anions and cations measured at various locations by USGS and TCRP in year 2000 - 2001 (Normal year), 2002 - 2004 (Dry year), and in 2005.

	EC	PH	TDS	Cl	SO_4	Cl/SO_4	Na	Ca	Mg	Na/Cl	Ca/SO_4
	dS m^{-1}		g/L				meq L^{-1}				
Artesia											
USGS[1] -		7.6	3.2	17.5	28.7	0.60	17.6	23.7	8.2	1.0	0.80
3/8/05	9.5	8.4	6.9	64.8	39.7	1.6	77.6	32.0	17.8	1.2	0.80
Malaga											
USGS		7.7	4.1	31.0	31.0	1.0	29.0	23.9	12.1	0.9	0.80
3/8/05	8.1	8.4	5.2	54.7	40.0	1.4	58.9	23.9	13.6	1.1	0.60
7/14/05	-	8.7	7.6	74.0	40.0	2.0	-	-	-	-	-
Red Bluff											
USGS		7.6	7.0	78.2	32.8	2.4	73.1	26.8	14.8	0.9	0.82
2000 - 01	9.1			65.6	45.5	1.4	-	-	-	-	-
2002 - 04	10.7			88.5	45.5	2.0	-	-	-	-	-
3/8/05	8.4	7.9	5.2	53.1	29.4	1.8	64.8	20.0	11.7	1.2	0.68
7/14/05	6.6	8.2	6.0	60.0	34.4	1.7	-	-	-	-	-
Orla											
3/8/05	17.3	8.5	11.4	138.4	48.6	2.9	187.4	27.5	17.8	1.6	0.60
7/14/05	7.6	7.6	5.4	50.0	29.8	1.7	-	-	-	-	-
Mentone											
3/8/05	16.5	9.1	10.9	133.7	47.5	2.8	182.8	25.8	18.6	1.4	0.54
7/14/05	7.5	7.9	5.4	53.0	31.3	1.7	-	-	-	-	-
Pecos											
2000 - 01	11.5			75.7	47.6	1.6	-	-	-	-	-
2002 - 04	13.5			87.5	31.2	2.8	-	-	-	-	-
3/8/05	9.6	8.5	6.9	74.1	37.3	2.0	96.3	23.6	15.3	1.3	0.63
7/14/05	7.3	8.0	5.3	48.9	51.4	0.95	-	-	-	-	-
Monahans (Coyanosa)											
2000 - 01	16.0			131.0	60.2	2.2	-	-	-	-	-
2002 - 04	21.7			189.5	71.7	2.6	-	-	-	-	-
3/8/05	15.8	8.3	10.5	120.6	47.1	2.6	164.6	28.3	21.5	1.4	0.60
7/14/05	14.2	7.5	10.5	107.7	52.5	2.1	-	-	-	-	-
Girvin											
USGS		7.4	12.8	143.7	64.8	2.2	145.1	36.6	32.4	1.0	0.56
(Estimate)[2] -			(12.8)	(143.7)	(60.0)	(2.4)	(133.8)	(49.0)	(27.1)	(0.9)	(0.8)
2000 - 01	19.7			155.1	77.6	2.0	-	-	-	-	-
2002 - 04	26.3			214.8	85.8	2.5	-	-	-	-	
3/8/05	22.0	8.1	14.5	162.3	62.9	2.6	219.6	31.8	32.2	1.4	0.51
7/14/05	18.5	8.0	14.8	146.1	65.1	2.2	-	-	-	-	-
Sheffield											
2000 - 01	10.7			79.4	39.6	2.0	-	-	-	-	-
2002 - 04	12.6			97.7	39.9	2.4	-	-	-	-	-
3/8/05	14.6	7.9	10.0	112.3	44.3	2.5	156.5	24.8	24.8	1.7	0.56
7/14/05	6.7	7.9	4.4	48.8	18.9	2.6	-	-	-	-	-

[1] - Long-term average of USGS data (1959-2000) adjusted to the long-term mean flow.

[2] - Estimated ion concentrations by assuming proportional increases to TDS, which is 1.83 .

[3] - Water samples collected on May 8, 2005 were not analyzed due to a question on QApp. Water samples were re-taken on July 14, 2005 and were analyzed for EC, TDS, Cl, and SO_4.

Table 8 also includes the increase in ionic concentrations (estimated by assuming the proportional increase in ionic elements as total dissolved salts) using a factor of 1.83 which is the ratio of TDS at Girvin and that at Red Bluff. The quantity of Ca dissolved were lower than those of the estimated, whereas the quantities of dissolved Mg and Na exceeded the estimates. These trends are consistent with a pattern usually associated with evaporative concentration (e.g., Miyamoto and Pingitore, 1992), but intrusion of saline water can also yield a similar result.

Isotopes: The isotope analysis revealed the lowest $\delta^{18}O$ reading in fresh runoff from the Salt Creek (-8.2‰), followed by the reading (-6.3‰) from Delaware Creek (Table 9). The readings from the Pecos River between Artesia and Malaga were in the range of -5.9 to -6.6‰. The readings below Mentone declined to an order of -3 ‰ with the lowest reading of -2.9‰ at Girvin. Just for a comparison, Phillips et al., (2003) reported $\delta^{18}O$ for the middle Rio Grande to be -14 to -5‰ which is lower than those from the Pecos Basin. The Rio Grande originates from snow pack of the Colorado which has a lower $\delta^{18}O$ concentration. Note that the concentration of $\delta^{18}O$ is expressed in comparison with $\delta^{18}O$ in SMOW (the standard mean ocean water) as indicated in the footnote of Table 9. This means that water rich in $\delta^{18}O$ yields isotope readings closer to zero, the reference value for ocean water. Water evaporation is usually a common mechanism which causes $\delta^{18}O$ to enrich in the remaining water body (e.g., Drever, 1982). However, the inflow of ground water which has elevated $\delta^{18}O$ also presents the same results.

Table 9. Instream conductivity, pH, temperature, and isotope concentrations measured on March 8, and May 7, 2005

	EC		pH		Temp.		$\delta^{18}O$	
	3/8	5/7	3/8	5/7	3/8	5/7	3/8	5/7
	dS m^{-1}				C		‰ SMOW	
Artesia	9.5	10.2	8.4	8.1	14.2	24.1	-6.0	-4.8
Brantley	7.7	7.2	8.2	-	13.1	17.5	-6.6	-4.9
Malaga[1] -	8.1	6.8	8.4	8.2	16.2	21.7	-5.9	-4.1
(DW Creek)	(3.7)	(3.7)	(8.2)	-	(16.8)	(22.7)	(-6.3)	(-5.7)
R.B. Inlet	6.3	7.3	8.6	-	16.4	23.4	-5.2	-3.2
R.B. Outlet	8.4	9.8	7.9	7.8	14.7	20.6	-4.2	-2.1
(Salt Creek)[1] -	(16.6)	(>20)	(8.1)	-	(18.7)	(23.1)	(-8.2)	(-2.2)
Orla	17.3	13.9	8.5	8.1	17.1	24.1	-5.2	-2.6
Mentone	16.5	9.7	9.1	9.3	18.2	22.2	-4.8	-2.4
Pecos	9.6	12.0	8.5	8.5	18.8	22.1	-3.1	-2.0
Coyanosa	15.8	16.9	8.3	8.5	18.0	22.9	-3.3	-1.2
Girvin	22.0	>20.0	8.1	8.2	15.2	19.3	-2.9	-0.4
Sheffield	14.6	11.8	7.9	7.9	15.7	20.1	-3.9	-3.1

$\delta^{18}O = [(\delta^{18}O \text{ of sample} - \delta^{18}O \text{ of ocean}) / \delta^{18}O \text{ of ocean}] \times 1000$

[1] - There are arroyos entering the Pecos River

The $\delta^{18}O$ concentration determined in May 7, 2005 was greater than the values reported on March 8 by 1 to 2.4‰. It appears that saline water with an EC of 10.2 dS m^{-1} was released above Artesia. It is unknown if this saline water was irrigation returnflow or release from one of the reservoirs upstream. The Salt Creek also registered higher readings, as this small flow is subjected to evaporation. The higher $\delta^{18}O$ content persisted all the way to Girvin.

Salinity of River Bank: Salinity of river bank was highly variable, ranging from 4.4 to 28 dS m^{-1} in the samples collected from a depth of 30 cm (Table 10). The range of salinity variation in the depth (30 – 60 cm) was equally wide, and soil salinity in the second depth was often higher than in the first depth by 10 – 15%. There was no systematic pattern or a definitive relationship between salinity of streamflow and bank salinity. The highest salinity was observed with the samples collected at Coyanosa, and the lowest salinity with the samples collected at Mentone. Soil salinity measured in May was equally variable, and at some locations, it nearly doubled in a matter of 2 months. Soil salinity at Coyanosa decreased in May sampling. These sites might have received bank overflow prior to sampling on May 7, as the bank clearance was low. These results are consistent with an earlier report (Clayton, 2002), indicating high levels of variability in bank salinity. Measurements of bank soil salinity are continuing.

Table 10. Salinity of streamflow and of the soil saturation extract of the soil samples collected on March 8 and May 7, 2005 at the Texas Clean Rivers Program monitoring stations along the Pecos River.

	Orla	Mentone	Pecos	Coyanosa	Girvin	Sheffield
Stream EC (dS m^{-1})						
3/8	17.3	16.8	9.6	15.8	22.0	14.6
5/7	13.9	9.7	12.0	16.9	>20.0	11.8
7/13	7.6	7.5	7.3	14.1	18.5	6.7
Soil EC_e (dS m^{-1}): 0 - 30 cm[1] -						
3/8	10.9	4.4	8.5	27.8	10.5	4.1
5/7	-	7.9	13.1	15.4[2] -	15.8	-
7/13	4.4[2] -	6.8	29.0	19.3	27.0	12.8
Soil EC_e (dS m^{-1}): 30 - 60 cm						
3/8	9.9	3.1	9.8	26.0	13.3	5.1
5/7	-	6.7	16.7	15.4	18.4	-
7/13	6.9	6.8	13.4	17.2	18.3	8.7
Field Moisture (g/100 g): 0 - 30 cm						
3/8	26.0	31.0	33.0	19.0	31.0	29.0
5/7	-	14.9	22.6	22.9	32.0	-
7/13	10.5	16.3	22.4	29.6	20.5	27.4
Saturation Water (g/100 g): 0 - 30 cm						
Ave.	35.7	42.5	49.0	37.5	59.0	53.7
Texture	loam	silt loam	clay loam	loam	silty clay loam	silty clay loam

[1] - EC_e: the electrical conductivity of the saturation extract.

[2] - The decline in salinity was caused by bank overflow.

DISCUSSION

Salt Sources

One of the interesting descriptions of the Pecos River Basin appeared in The Scientific Monthly in 1957. It is titled, "Sinkholes, Bottomless Lakes, and the Pecos River," by Harrington (1957). He wrote, "In the summer of 1956, a cattleman near Vaughn, New Mexico heard a great booming and roaring, and the windows of the ranchhouse rattled. He ran out and found that surface rock layers, 100 yards across, had dropped 50 feet. The horizontal rock stratum that had been yesterday's surface lay in jumbled pieces at the bottom." The cattleman just witnessed the birth of a new sinkhole developed through dissolution of salts present beneath the western bank of the Pecos River, called the Sacramento Plain. This plateau lays about 300 m (1,000 ft.) above the canyon floor of the Pecos River and is presumably positioned along the ancient shore line of the Permian Sea. Some believe that the Pecos River was carved through a series of sinkholes, some holding water and others being dry until the coming of the next flood. One of the sinkholes holding water is Bottomless Lake located near Roswell along the Pecos River (Attachment I). This is where the Permian evaporite, halite, appears along with gypsum near the ground level, and salt concentrations of the Pecos River jump from 1,700 to 3,200 mg L^{-1} (Table 5). The flow of the Pecos decreases in the section between Brantley Dam and Malaga, partly due to deep percolation losses, besides the diversion for irrigation. Further down the river, brine enters at Malaga Bend (Attachment I), just above Pierce Canyon Crossing, and salt concentrations there jump from 4,000 to 7,000 mg L^{-1}. This type of salt dissolution and salinization of stream is also reported in the Wichita/Red River Basin, and the Arkansas River Basin to the north located in the same Permian Basin (Johnson, 1981).

This geological background dictates hydrochemistry of the Pecos River Basin. Gypsum, halite, and epsomite dissolve into water to different degrees. The solubility of gypsum, halite and epsomite is 0.028, 5.78, and 6.16 eq L^{-1}, respectively. At the reach between Santa Rosa and Puerto De Luna, the elements which increased most were Ca, SO_4, and to a lesser extent Mg. What is significant is that the increases in Ca plus Mg load equaled the increase in SO_4 loading in chemical equivalent (Table 6). This indicates that the source of the salts was gypsum (or anhydrite), and possibly epsomite ($MgSO_47H_20$). The elements which increased most between Acme and Red Bluff were Na and Cl ions. Both Na and Cl ions have increased almost equally, and halite (NaCl) is likely to be the source. A significant amount of Mg along with SO_4 also accounted for the increases. This is not unusual as epsomite appears in both gypsum and halite deposits, and Mg concentrations usually increase with that of Na and Cl.

Saline water intrusion into the Pecos appears to be the cause of high salinity of the Pecos River below Grandfalls. The water table in this reach is shallow, ranging from 3 to 21 m (10 to 70 ft.) while the streambed of the Pecos River at this reach is deep enough to permit ground water entry. The quantity of salts entering the river amounts to 187,000 tons/year under no reservoir release (Table 7). When the flow was maintained at 54 million m^3/year, however, the gain in salt load was less than half, 63,000 tons/year, probably because of an increase in hydro-static pressure. If the salt inflow from the Salt Draw below the town of Pecos is included, the total salt inflow into this segment increases by 75 thousand tons per year.

The source(s) of this shallow ground water is not known for certain, except for the conventional idea of percolation of area rainfall. The aerial photograph given in Attachment II seems to indicate that the seepage from the river itself cannot be ruled out as a source of the shallow ground water entering the Pecos. The isotope readings obtained on March 8 and May 7, 2005 are, for example, consistent with this hypothesis. If the shallow ground water is a separate source, the isotope readings below Coyanosa should not change greatly, when reservoir release was kept at a minimum. Neither the ionic composition, Cl to SO_4 ratios nor Na to Cl ratios changes greatly below Pecos (Table 8). However, bankflow may account for some portion of the flow (perhaps less than 25%), and can present apparent similarity in chemical make-up between streamflow and ground water intrusion. Nonetheless, these are the early indications that the shallow ground water entering the Pecos below Coyanosa is charged at least in part by seepage from this winding river. As mentioned earlier, the reach below Coyanosa consists of the Del Norte Series which has a petrocalcic horizon having low subsurface permeability.

Another source of salts entering the Pecos is surface inflow. This is a subject of Task 1.4. Current indications are that the Salt Creek, the Salt Draw, and possibly Toyah Creek are potential sources. The salt inflow from the Salt Creek is estimated at 45,700 tons per year at the annual flow of 3.3 million m^3 as given by the USGS for a period of 1939 through 1957. The Salt Draw can add 63,600 tons per year at an annual inflow of 3.9 million m^3 if the concentration observed in 1966 (16,310 mg L^{-1}) holds. Both the Salt Draw and Toyah Creek enter into a shallow depression (Attachment II), then seep into the Pecos River underground. Salt loading from these surface sources could be reduced in principle by providing floodway directly to the Pecos River, although there may be other constraints, including the elevation difference.

Another source of salts often mentioned in the literature is oilfield brine. Richter et al., (1990) indicates three types of formation water: Permian, Pennsylvanian, and Walfcampain. Subsurface brine from the Permian and the Pennsylvanian formation is isotropically similar to shallow ground water of the meteoric origin. The typical range of $\delta^{18}O$ reported in their study of west Texas oil patches is between -5.5 and 0‰ for the formation water, and -5.5 to -3.0‰ for shallow ground water with a few data points yielding $\delta^{18}O$ close to that of the ocean water (Ritcher et al., 1990). A report from the Illinois Basin brine also shows $\delta^{18}O$ readings of -8.0 and 0‰ (Clayton et al., 1966). Thus, isotropic data do not seem to be useful for separating oilfield brine from shallow ground water. An exception may be the brine samples from the Walfcampain formation. They apparently have exceptionally high $\delta^{18}O$ concentrations (as high as +6‰), because of their extreme evaporative concentration.

The ionic composition of oilfield brine is dominated by Na and Cl. Richter et al., (1990) have shown that the Cl/SO_4 ratios of shallow ground water in west Texas range from 0.1 to 10 with a mean of about 2, whereas the Cl/SO_4 ratio of oilfield brine from the Permian and the Pennsylvanian formation ranged from 10 to 10,000. The Cl/SO_4 observed in the Pecos River ranged from 1.0 to 2.8, a range typical for shallow ground water (Table 8). The Cl/SO_4 ratio of the well entering the Pecos River near Grandfalls was estimated at 6.9, which is still lower than that of the formation water. However, this finding does not necessarily indicate that oilfield brine is not contaminating the shallow ground water. The Cl/SO4 ratio lower than 10 for example, may be a result of blending. There are reported historical cases of ground water contamination by brine (e.g., Richter and Kreitler, 1987), and some entering creeks along with crude oil (e.g., Blackwell, 1974). However, the data given by Grozier et al. (1966) do not seem to indicate that oilfield brine is the wide-spread source directly entering the Pecos, at least in the segment between Red Bluff and Girvin.

Salt Loading

Three reaches were identified above the stateline, where salts are entering the Pecos River in large quantities. These are the reaches between Santa Rosa and Puerto Luna, Acme and Artesia, and Malaga and Pierce Canyon Crossing (Table 5). The quantity of salts being dissolved into the stream is estimated at a total of 683,000 tons per year for the reach above Red Bluff. Additional salt loading takes place between Coyanosa and Girvin in Texas at a magnitude of several hundred thousand tons per year (Table 7).

The identification of exact locations and salt loading or pathways at each of these locations is beyond the scope of this study. However, loading of Ca and SO_4 from the northern watershed is probably occurring through old or developing sinkholes, and gypsum dissolution into agricultural drainage water in irrigated areas. This loading process is difficult to control as gypsum is found widely throughout the Pecos Basin. Fortunately, dissolution of gypsum into streamflow is not nearly as damaging as dissolution of NaCl for irrigated crop production. The situation becomes worse in the second reach (Acme to Artesia) where Na and Cl are the dominant ions which enter into the flow of the Pecos.

The river segment between Acme and Artesia receives 261,000 tons of salts per year from various sources, including, the outflow from Chain Lakes and Bottomless Lakes. Salinity of Chain Lakes varies from 15 to 35 g L^{-1}, based on our spot check. Assuming that the salt concentrations of these lakes average 20 g L^{-1}, the discharge rate has to be at least 13 million m^3 per year to add 261,000 tons of salts to the Pecos. The actual flow increase in this area is 17 million m^3/year from Acme to near Roswell, and 21 million m^3/year between Acme and Artesia. These saline lakes appear to be a major source of water and salts. However, there is a sizeable area, possibly as large as 20,000 ha (50,000 acres) of cropland irrigated with ground water nearby in the westbank of the Pecos. Some suggest that subsurface flow into these lakes is coming from the west, rather than from the north (McAda and Morrison, 1993). In addition, there is a National Wildlife Refuge just to the north, and wetlands between these lakes and the Pecos River (Attachment I). The control of salts in this area appears to be complicated.

Salt loading into the Pecos between Malaga and Pierce Canyon Crossing is in the form of brine seep into river beds. Brine seep in this part of the Pecos Basin was studied several times primarily by USGS (e.g., Hale et al., 1954; Cox and Havens, 1961; Cox and Kunkler, 1962; Havens and Wilkins, 1979) and by the State of New Mexico. Salinity of the brine is close to the saturated brine (360 g L^{-1}). A geological study indicates that this brine is an upward leakage of saturated brine from the boundary between the Rustler Formation and the Salado Formation (Havens and Wilkins, 1979). Pumping of this brine at a rate of 12.5 L/s (0.44 cfs) was apparently sufficient to lower the salt water intrusion from 400 to 66 tons/day. These daily rates correspond to 146,000 and 24,000 tons/year, and the intrusion prior to pumping roughly coincides with the estimate of 172,000 tons/year (Table 5). Unfortunately, the brine pumped and piped to nearby depression (the Northeast depression) did not hold, and the brine reappeared in the Pecos somewhere downstream. Pumping of this brine, although temporarily ceased, appears to offer a cost-effective option, and the Red Bluff District has been working with a private sector for salt production.

Salt flushing from the Pecos River is likely to come from halite dissolution from the floodplain around Malaga and east of Roswell (Attachment I), as well as the reach between Red Bluff and Girvin (Attachment II). The flood of 1941, for example, produced 1.6 billion m^3 of water, and salinity of 3,000 mg L^{-1} when measured at Langtry. This means that 4.8 million tons of salts were flushed into the Rio Grande. If Amistad Dam were present at the time, reservoir salinity could have increased well above 1,000 mg L^{-1}. The historical storage at the Amistad is 3 billion m^3 with a mean salinity of over 800 mg L^{-1} for the last three decades. The residence time averages approximately 2 years. These historical data indicate that the Pecos River is capable of producing large salt flushing into Amistad Reservoir, depending on where and how much precipitation falls.

The salt loading into the Pecos between Grandfalls and Girvin could be reduced. The data shown in Table 7 seem to indicate that saline water intrusion is reduced under elevated flow, e.g., greater than 50 million m^3/year. Extrapolating this thesis, it may be possible to reduce saline water intrusion by raising the level of streamflow using a check dam. A potential obstacle is the slope of the land which drops 18 m (60 ft.) over this 54 km (34 mile) stretch. Another potential problem is a possibility of excessive leakage when ponded. This could enlarge the area with high water tables and associated soil salinization. Riparian vegetation in this reach is already sparse (Attachment II). Detailed investigation is warranted to examine this check-dam option.

One encouraging aspect of the situation below Red Bluff is the absence of irrigation returnflow. Reduced irrigation activities, excessive pumping, and highly permeable nature of alluvial soils, all seem to contribute to this situation. This is rather unique as we compare to the situation in the middle Rio Grande where irrigation returnflow is the major source of salts (Miyamoto and Mueller, 1994). Irrigation returnflow from the Carlsbad Irrigation District is beyond the scope of this study.

Another encouraging sign is that salinity of the bank in the Pecos is low enough to facilitate regrowth of various riparian vegetation, perhaps with an exception of some areas below Coyanosa. Just for a comparison, salinity of the bank of the Rio Grande below El Paso at a comparable depth is upward of 40 to 80 dS m^{-1} in the saturation extract (unpublished data, this laboratory). The principle difference between the Pecos and the lower reach of the middle Rio Grande is bank overflow -- or the absence of it in the case of the middle Rio Grande below El Paso. Salt flushing from the middle Rio Grande between Ft. Quitman and Presidio was among the causes which raised salinity of Amistad Reservoir from 700 to 1,000 mg L^{-1} in the winter of 1988 (refer to the separate report under Subtask 1.6). During that event, over 1 million tons of salts were flushed upon sudden winter release of water from Elephant Butte. In the short run, eradication of salt cedars can increase salt flushing. However, this does not seem to be a significant concern, as bank salinity of the Pecos River is relatively low due to frequent bank overflow.

Water and Salt Balance

Salt loading into an open streams increases salinity when the streamflow is limited. This is the case with the Pecos River below Malaga. The historical records indicate that over 250 million m^3 of water passed Malaga every year during 1929 – 37 (Fig. 2). Today, the flow has decreased to 81 million m^3 per year, thus resulting in reduced dilution and increased salinity (Fig. 8). The same scenario applies to the situation at Girvin (Fig. 9). The original flow at Girvin was much larger. Saline water intrusion into the reduced flow yields high salinity at Girvin.

In order to reduce streamflow salinity, it is essential to maintain or, if possible, to increase freshwater inflow into the Pecos. Unfortunately, this is not an easy task. One method is to reduce saline water intrusion, ideally in proportion to the reduction in streamflow. In the case of Red Bluff, the inflow decreased from 350 Mm^3/year to 80 Mm^3/year, a reduction of 77%. If the brine intrusion at Malaga Bend is controlled, salinity will be reduced from the current 7,000 mg L^{-1} to 4,100 mg L^{-1} (or from 5,400 to 3,300 mg L^{-1} in flow-weighted salinity). Although usually considered not economical, another method is to reduce percolation losses from reservoirs and leaky streambeds. Reservoirs along the Pecos River are subject to high percolation losses, due to sinkhole developments. As mentioned earlier, McMillan Dam was breached in 1990 because of large sinkhole developments. Percolation losses not only reduce streamflow needed for dilution, but also can dissolve salt deposits. There is an indication that the salinity distribution in the aquifer near Avalon Dam (just below old McMillan Dam) is a reflection of the past leakage (Wallace, 1993). Red Bluff has also developed sinkholes, and seepage losses are suspected to be considerable (US BOR/TWDB, 1991). Evaluation of percolation losses seems to be a priority task.

The Salt Cedar Control Project was implemented, in part to salvage streamflow (Hart, 2004). The riparian area infested by salt cedars between Red Bluff and Girvin was estimated to be 2,000 ha (5,030 acres) over 200 km (120 miles) of river miles with an average width of 105 m (345 ft.). The estimate of water use by salt cedars is variable, but it is assumed to be 122 cm (48 inches) per season based on the recent work conducted in New Mexico (Cleverly et al., 2002). The same report also indicates that the evapotranspiration from salt cedar canopy located in the area receiving no flooding was 61% of 122 cm/year or 74 cm per season. By the same token, the evaporation from the stream surface and the wet zone of the river bank would be higher than 122 cm. Since the riparian survey has not been completed, we tentatively used 122 cm/year as the first approximation of the evaporative water loss. The evapotranspiration loss of water amounts to 25 million m^3 (20,000 acre-ft.) per season. The actual evapotranspiration loss today is likely to be less, because salt cedar has largely been eradicated, and the riparian areas extend far beyond the active flood plain. The evapotranspiration loss will be examined in detail under Task 1.6.

The reservoir release from Red Bluff is estimated at 59 million m^3 (47,800 acre-ft.) per year, since 1991, based on the record provided by the Red Bluff District. The district data also show that the diversion averaged 32 million m^3 (26,000 acre-ft.)/year (Table 11). The river seepage losses were taken as 53% of the reservoir release based on the data shown in Table 7, and the evaporation was apportioned between the upper and lower reach. The outflow was extrapolated from the CRP data along with streamflow salinity. The inflow from creeks and draws was back-calculated, and included all sources above Coyanosa, including subsurface inflow of the Salt Draw. This estimate would vary depending on area rainfall. The impact of evaporation on streamflow salinity was computed as the concentration of residual flow (inflow-diversion-percolation), and was close to the measured. Similar estimates apply to the reach below Coyanosa where diversion is nearly zero. For the reach between Girvin and Langtry, the dilution was the only process considered. The flow at Langtry is the long-term mean from the IBWC station, and it varies with monsoon. These are tentative estimates, and are subject to change.

Table 11. 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 tons/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 (346 km, 215 miles)			
Incoming	14	10650	+149
Creek & Draws	(10)	-800	+8
Subsurface	8	17420	+139
Diversion	0	0	0
Evap-Trans	-12	(14800)	-
Outflow	-20	14010	-280
Girvin - Langtry			
Incoming	20	14010	+280
Creek & Draw	(155)	(450)	(+70)
Outflow	-175	1995	-350

Data from the CRP since 1995.

[1] -Numbers in parenthesis are estimated.

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