TR- 298
2007

Water Balance, Salt Loading, and Salinity Control Options of Red Bluff Reservoir, Texas

by

S. Miyamoto, Fasong Yuan, and Shilpa Anand

Agricultural Research and Extension Center at El Paso

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ACKNOWLEDGEMENTS

This material is based on work supported in part by the Rio Grande Basin Initiative Cooperative State Research, Education, and Extension Service, US Department Agriculture under Agreement NO. 2005-34461-15661. The data presented were originally gathered for a previous project funded by the Texas State Soil and Water Conservation Board and the US Environmental Protection Agency under contract No. 4280001. Administrative support to the project was provided by the Texas Water Resources Institute and the Texas Agriculture Experiment Station. Data processing was assisted by Fasong Yuan and Shilpa Anand, and the preparation of the report by Jessica White and Olivia Navarrete of the Texas A&M University, Agricultural Research Center at El Paso.

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Unit Conversion

1 m = 3.3 ft
1 ft = 30.5 cm
1 km = 0.621 miles
1 ha = 2.47 acre
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 A-F
1 m^3/s = 35.3 cfs = 22.8 million gpd

WATER BALANCE, SALT LOADING, AND SALINITY CONTROL NEEDS OF RED BLUFF RESERVOIR, TEXAS

S. Miyamoto, F. Yuan and S. Anand
Texas A&M University, Agricultural Research Center at El Paso

SUMMARY

Red Bluff is the main reservoir of the Pecos River in Texas, and its maximum storage capacity adjusted to sediment accumulation is estimated at 357 million m^3 (289,600 acre-ft.). Aside from the shortage of water entering the reservoir, high salinity has been a concern. This report was prepared with three main objectives: i) to outline water balance of the reservoir, ii) to establish salt loading trends over the past several decades, and iii) to evaluate the impact of salt loading on salinity of the reservoir and its outflow. We also outlined the needs for salinity control, and briefly discussed salinity control options.

The data used in this report were gathered through an EPA project entitled “Basin-wide Management of the Texas Pecos River”, and consisted of flow and salinity data from various agencies. Flow data are fairly reliable as the discharge is measured daily at a number of stations. Salinity data have been taken several times a month to several times a year, and may be considered “sketchy” at best. However, an effort was made to establish salinity and flow relationships, so that salinity measured under a certain flow condition can be extrapolated to the monthly flow. Flow and salt loading analyses were performed since 1959, and the water balance analyses from 1991 through 2001 during which a complete set of flow, storage, and salinity data was available.

The analyses of flow balance indicate that the inflow into Red Bluff from 1991 through 2001 averaged 95 million m^3 (77,000 acre-ft.) per year from the Pecos, and 31 million m^3 (25,000 acre-ft.) from the Delaware River (DWR). These flow means are higher than the long-term (1959-2001) averages of 84 and 21 million m^3 from the Pecos and the DWR, respectively. The reservoir storage during 1991-2001 fluctuated widely between 47 to 186 million m^3 with a mean of 100 million m^3 (81,000 acre-ft). The recorded annual surface outflow averaged 59 million m^3, the estimated evaporation losses, 35 million m^3, and the estimated percolation loss, 41 million m^3 per year or 33% of the total inflow. About 8.7 of the 41 million m^3 appears to be returning to the River above Orla. Ignoring the high percolation loss estimated in two out of eleven years, the seepage losses appear to have averaged 37 million m^3 (30,000 acre-ft) per year. This estimate of percolation losses is subject to the reliability of reservoir outflow measurements.

Salinity of the Pecos River at Malaga (NM) averaged 4100 mg L^{-1} in arithmetic mean, and 3320 mg L^{-1} in flow-weighted during 1959 to 2001. Since 1991, the flow-weighted mean at this location averaged 3500 mg L^{-1}. Salinity of the DWR was estimated at 2600 mg L^{-1}, and the flow-weighted salinity of the composite flow which enters Red Bluff was 4425 mg L^{-1} since 1991. Salinity of outflow from the reservoir since 1991 averaged 6150 mg L^{-1}, thus registering an annual mean salinity increase of 1700 mg L^{-1} in flow-weighted, and 650 mg L^{-1} in arithmetic mean between the inflow and the outflow since 1991.

Salt loading into Red Bluff averaged 478,000 tons per year since 1991, and is stable. The best loading estimate from the Pecos and the DWR combined is 560,000 tons per year or somewhat higher. Salt loading from Malaga Bend is estimated at 150,000 tons per year since 1991, as compared to the long-term mean of 172,000 tons/year. Salt load of the reservoir outflow since 1991 is estimated at 410,000 tons/year which includes seepage returning back to the river.

Salinity of the reservoir release (6150 mg L^{-1} on the average) is too high for irrigated production of most crops, except for highly salt tolerant types, such as cotton and hay. It is not acceptable for poultry, and is marginal for livestock. It also limits biodiversity of both aquatic and riparian species. Salt loading from the Pecos measured at Langtry, (where the Pecos enters the Rio Grande) has averaged 429,000 tons per year since 1986. This accounts for 26% of salt loading (or 30% of gauged inflow) into Amistad, while providing only 9% of the total inflow into the reservoir. This is not an ideal situation as salinity of the Amistad International Reservoir located downstream is nearing 1000 mg L^{-1}, the upper limit of drinking water standard in Texas.

The proposed control of brine intrusion at Malaga Bend seems to be the most effective option for lowering salinity of the Pecos River entering Red Bluff. When this source is controlled, salinity of the reservoir outflow can be reduced to the salinity level reported during 1937 to 1940, which is 4710 mg L^{-1}. Salinity can be lowered even more if saline water intrusion near Chain Lakes (east of Roswell, NM) is controlled. Saline water intrusion controls not only reduce salinity, but can also reduce salt load of the Pecos River entering the Rio Grande, then Amistad Reservoir. The reduction of seepage losses at reservoirs upstream should also help reduce salinity of the Pecos River downstream.

INTRODUCTION

The Pecos River 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). Unfortunately, salinity of this river became among the highest in North America with streamflow salinity fluctuating from 5000 to 7000 mg L^{-1} at the New Mexico – Texas stateline, and eventually reaching over 12,000 mg L^{-1} at Girvin, TX. High salinity of the river has adversely affected the economic use of this water resource as well as stability and diversity of the riparian ecosystem (e.g., Hart, 2004). In addition, the flow of this river accounts for a large portion of salts entering the Amistad International Reservoir located approximately 64 km (40 miles) south of Langtry (Miyamoto, et al., 2006). Salinity of the Amistad Reservoir reached 1000 mg L^{-1} (the upper limit of secondary drinking water standard in Texas) in February 1988, and there is a concern that such an incident may occur with greater frequency unless salinity control measures are implemented at some point.

The primary cause of this high salinity is the dissolution of gypsum, halite, and epsomite into the flow of the Pecos. These salt sources are the evaporites of the Permian Sea which once occupied this area in a geological time (Fig. 2). The flow and salinity data of USGS recently ex-

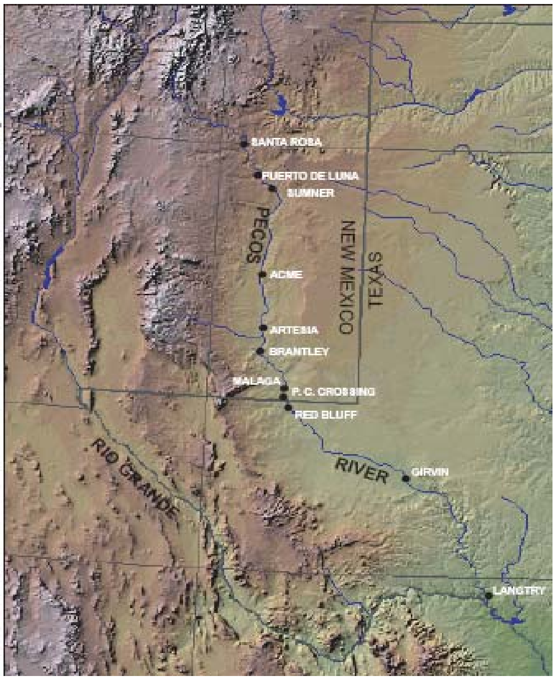

Fig. 1 An aerial view of the Pecos River Basin of New Mexico and Texas.

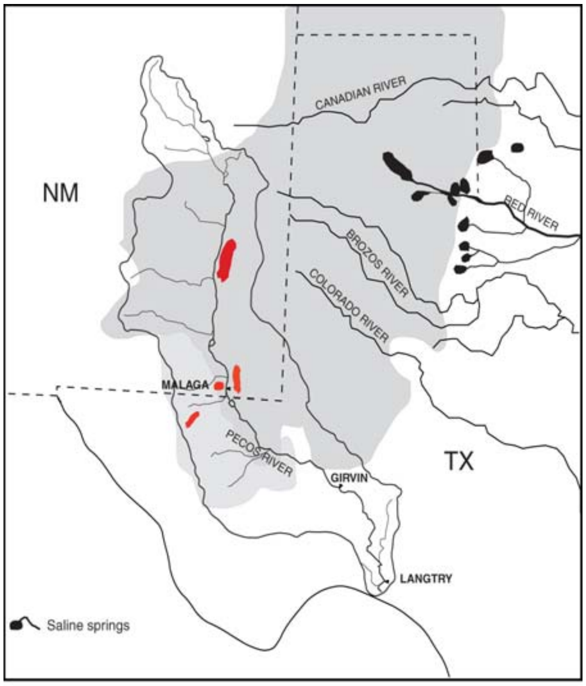

Fig. 2 Permian evaporite deposit of west Texas and southeastern New Mexico.

amined at eleven gauging stations along the Pecos River (Miyamoto et al., 2005) show a progressive increase in streamflow salinity as the riverflow travels down to Texas (Table 1). The positive changes in salt load between the gauging stations indicate a gain in salt load, and are occurring in three segments: between Santa Rosa and P. Luna, Acme and Artesia, and Malaga and P.C. Crossing. The salt gains amount to approximately 683,000 tons per year above Red Bluff. The highest salt concentration and the lowest flow are at Girvin, TX. Salinity then decreases with increasing freshwater inflow into the Pecos below Girvin.

Table 1. Flow, annual mean salinity, flow-weighted long-term salinity, and salt load of the Pecos River averaged over 1959 - 2002 (Miyamoto et al., 2005).

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 salt load increase observed between Santa Rosa and P. Luna is caused by the dissolution of gypsum, whereas the salt gains observed between Acme and Artesia, and between Malaga and P.C. Crossing are associated with the dissolution of halite and gypsum (Miyamoto et al., 2005). Saline water intrusion at the reach between Acme and Artesia seems to be from the Chain Lakes or Bottomless Lakes located east of Roswell, NM. There are a dozen of sinkholes filled with water along the fault zone. Many of these sinkholes are artesian, and salinity ranges from 15 to 30 g L^{-1}. Saline water from these sinkholes flows out into wetlands, then into the Pecos River. The gain in flow between Acme and Artesia is substantial, 21 Mm^3 per year (Table 1), and salinity jumps from 1700 to 3170 mg L^{-1} with an increase in salt load by 261,000 tons per year. The control of this salt source appears to be complicated, as the area has established land uses, including wetlands and wildlife refuges to the north.

Saline seepage, which appears in the Malaga Bend area, has been known for decades, and has been a subject of control through pumping and evaporation (e.g., Havens and Wilkins, 1979). Deep well injection was also considered, but was found to be costly, and probably not sustainable (Cox and Kunkler, 1962). There is a continuing interest to control this salt source, and the Red Bluff District is reportedly negotiating with a private sector for salt production. The estimate of brine discharge rate varies, but 12.5 L per second (0.44 cfs) is often quoted (e.g., Havens and Wilkins, 1979).

Another cause of high salinity is the reduction in streamflow which dilutes saline water. According to the monitoring data of USGS (http://waterdata.USGS.gov), the flow of the Pecos during the early period of 1929 through 1937 increased downstream (Fig. 3). The streamflow at Artesia during 1929 – 1937 reportedly averaged 320 million m^3 (259,000 acre-ft.) per year. The gain in flow beyond Malaga appears to be about 175 million m^3 (142,000 acre-ft.) per year prior to 1937, much of which occurs below Girvin. The construction of reservoirs such as McMillan (completed in 1908), Avalon (1907, 1912, and 1936), Red Bluff (1936), and Sumner (1937) has drastically altered the streamflow to the present day situation. Additional reservoirs were constructed later; Santa Rosa in 1981 and Brantley in 1991. The flow entering Texas has declined from 350 million/year to a mere 84 million m^3 (68,000 acre-ft.) annually. Salinity of the Pecos River entering Red Bluff has increased from 4800 mg L^{-1} (recorded during the 1938 –

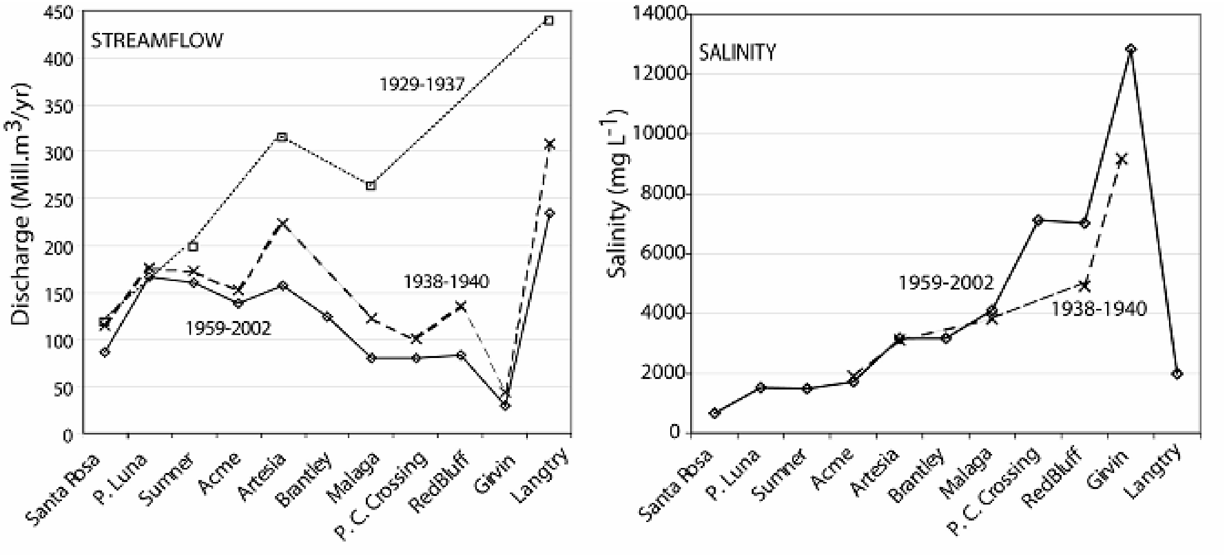

Fig. 3 Flow of the Pecos River at selected gauging stations; dotted line 1929 – 1937, dashed line 1938 – 1940, solid line 1959 – 2002. Salinity data prior to 1937 are not available.

1940 period) to an average concentration of 7000 mg L^{-1} (Fig. 3).

The increase in salinity of the flow at P.C. Crossing above Red Bluff since 1937 is significant as shown in Fig. 4B. The salt load of the flow at P.C. Crossing decreased and became stable. Salinity at Malaga has fluctuated greatly, but does not seem to show a definitive increase trend (Fig. 4A). The salt load of the flow at Malaga seemed to have decreased during the same period, 1937 – 1980. Since the salt load at P.C. Crossing does not show a pattern of increase, the salinity increase at this location has to be attributed largely to the reduction in incoming flow.

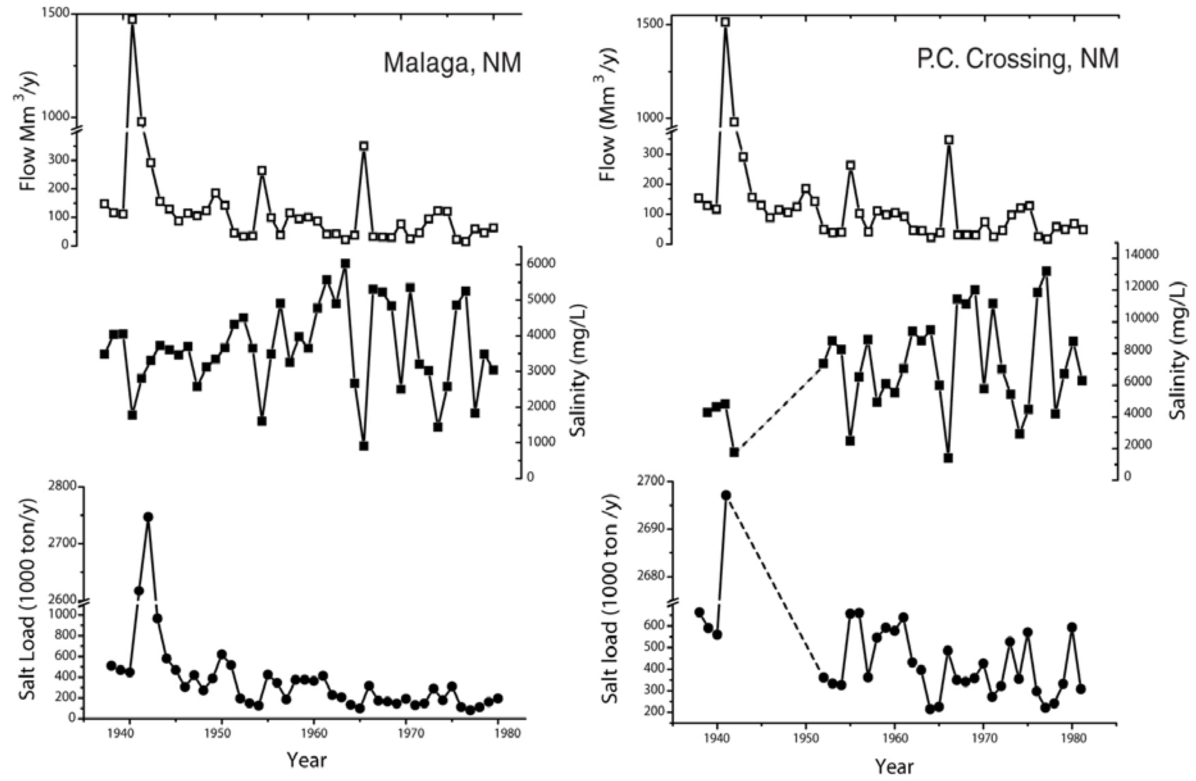

Fig. 4 Historical changes in annual flow and flow – weighted salinity recorded at Malaga and P.C. Crossing, NM (the data from US Bureau of Reclamation).

Red Bluff is currently the only large reservoir which stores the flow of the Pecos on the Texas side. According to the TWDB Reservoir Information sheet, this reservoir was constructed in 1936 at an initial storage capacity of 382 million m^3 (310,000 acre-ft.), and the current capacity is estimated at 357 million m^3 (289,600 acre-ft.). The actual storage obviously fluctuates and has averaged 100 million m^3 (81,000 acre-ft.) since 1991. Since the average rate of current inflow is 126 million m^3 per year, the mean residence time is less than one year. This reservoir is owned and operated by the Red Bluff Water Power Control District (RBWPCD), and water is released upon the requests from the irrigation districts downstream.

High salinity of the water, in addition to the reduced inflow, has been a concern. This water resource has been used for irrigation, but salinity of the supply exceeds all existing recommendations for irrigation uses, except for irrigating highly salt tolerant crops (Ayers and Westcot, 1978). A larger area of croplands has been irrigated with ground water with lower salinity. This resulted in lowering water tables in many areas. There is also a concern that high salinity of streamflow below Red Bluff (6000 to 14000 mg L^{-1}) may limit restoration of the ecosystem along the river bank as well as in the streamflow. Salt cedars in this reach were sprayed with "Arsenal", and there is an expectation that some of the native species will re-establish. This may be possible if bank salinity is low enough for native species to come back. Salt cedars are among the most salt-tolerant species, and tend to dominate other species under high salinity and high soil moisture.

There is also a concern over the reservoir leakage which appears primarily in the southeast corner of the reservoir. Reservoir leakage is a common feature in any reservoirs in the Pecos Basin, and usually accounts for about 10% of the inflow in several reservoirs along the Rio Grande (Inosako et al., 2006). The leakage of the reservoirs in the Pecos Basin is suspected to be larger, because of the leaky geological formation containing soluble salts. Old McMillan Lake, for example, apparently has developed sinkholes and severe leaks. There is a potential that seepage can dissolve salts from the Rustler and the Salado Formation, both of which contain halite (Lucas and Anderson, 1993). Fortunately, McMillan Lake was replaced by the Brantley Dam in 1990, which presumably has less seepage losses.

The study reported here was conducted i) for examining the reservoir water balance of Red Bluff over the past several decades, ii) for establishing salt loading trends, and iii) for evaluating the impact of salt loading on monthly salinity of the reservoir outflow. Salinity of reservoir release was simulated by using a simple two–layer model described in Inosako, et al., (2006). In addition, salinity control needs were discussed briefly.

METHODS

Data Sources

There are three USGS flow monitoring stations along the Pecos River near Red Bluff. These are at Malaga, Pierce Canyon (P.C.) Crossing, and above Delaware River (DWR), which is designated as "Red Bluff" by the USGS. In addition, the USGS maintains flow monitoring at the Delaware River and at Orla, TX located below the reservoir (Fig. 5). The USGS used to monitor the flow of Salt Creek at the Screwbean Draw station. The USGS streamflow data (recorded daily) were downloaded from NWIS.waterdata.USGS.gov. The inflow into the Reservoir was assumed to be a sum of the gauged flow at the USGS stations "Above the DWR" and on the DWR. The record of reservoir storage was obtained from TWDB for a period of 1990 through 2001. The outflow from the Reservoir is recorded by the Control District at the outflow gate, and occasionally by the Clean Rivers Program (CRP) which is administered jointly between the Texas Commission on Environmental Quality (TCEQ) and the U.S. Section of the International Boundary and Water Commission (US – IBWC). We used the monthly release records from the Red Bluff District, and the outflow from the emergency spillway was considered zero as the reservoir storage was well below the capacity. We also used the flow data from Orla and Salt Creek to check the water balance below the Reservoir.

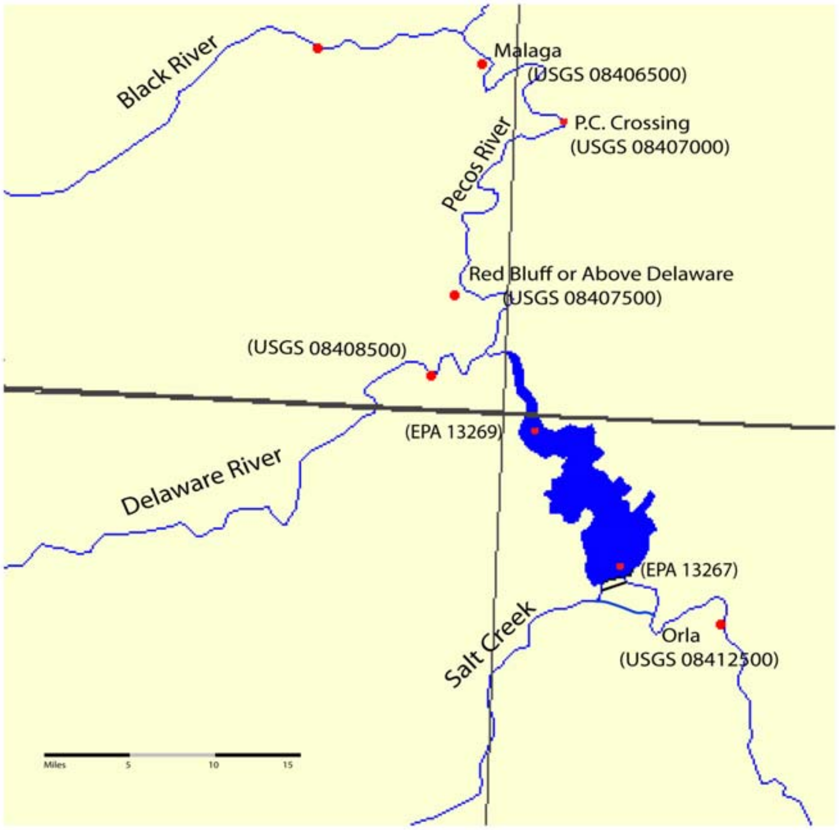

Fig. 5 Drainage map showing locations of the USGS gauging stations near the reservoir.

Streamflow salinity had been measured for varying durations (Table 2). Whenever possible, we used stream salinity data by the USGS, which can be downloaded from NWIS.waterdata.USGS.gov. Salinity measurements along the Pecos consisted of one to four times per month during 1959 to 1981, and every other month since 1982. Missing salinity data were estimated from the flow data using the flow and salinity relationship given in Appendix I. There was no routine water quality monitoring for the Delaware River which accounts for ¼ of the flow into Red Bluff. However, the USGS posted water quality data taken in August 24, 1966, and we measured salinity and flow on March 7 and May 6, 2005. Since no other data were available at this site, these data were used to construct salinity and flow relationships with the methods described in Appendix.

No official gauging station is available for monitoring salinity at the outflow gate. However, water samples were collected four times a year at a depth of 30 cm (1 ft.) in the reservoir near the outflow gate by the Texas Water Commission (TWC) for a period of 1972 to 1996. These data were accessed through www.epa.gov/storet. This monitoring program was then transferred to the Clean River's Program (CRP). We measured salinity of Salt Creek on March 7, May 6, and July 12, 2005. Both the monthly pan evaporation and the rainfall data were obtained from http://hyper20.twdb.state.tx.us/Evaporation/evap.html for Quad 604 (Orla).

Table 2. The list of gauging stations near Red Bluff Reservoir

Station Location		**Data Source**		**Data Available**	
Official Name	**Our Designation**	**Organization**	**Station No.**	**Flow**	**Salinity**
Pecos River at Malaga	Malaga	USGS	(8406500)	1937-02	1959-02
at P.C.Crossing	P.C. Crossing	USGS	(8407000)	1937-02	1959-02
at Red Bluff	Above DWR	USGS	(8407500)	1937-02	1959-94
Delaware River Near Red Bluff	DWR	USGS	(8408500)	1937-02	1966
Salt Screwbean Draw	Salt Creek	USGS	(8411500)	1939-57	
Pecos River at Orla	Orla	USGS	(8412500)	1937-02	1967-02
Red Bluff Reservoir Storage		TWDB-USGS		1990-02	
Outflow		RBWPCB-USGS		1959-02	
Red Bluff Reservoir near Stateline	Inlet	EPA-TWC[a]	13269		1979-96
Red Bluff Reservoir above Dam	Outflow	EPA-TWC	13267		1972-96
Salt Creek near Reservoir	Salt Creek	EPA-TWC	13171	1989	1989
Red Bluff Reservoir 1/2 mile South of TX-NM border	Inlet	CRP-IBWC[b]	13269	1994-02	1994-02
Red Bluff Reservoir above Dam, North of Orla	Outflow	CRP-IBWC	13267	1994-02	1994-02

[a] EPA STORET Data collected by Texas Water Commission available online at http://www.epa.gov/STORET/dw_home.html.

[b] Clean Rivers Program data available at IBWC website http://www.ibwc.state.gov/CRP/monstats.htm.

Data Processing

Detailed procedures used to analyze the data are shown in Appendix I. The analyses consisted of; i) water balance at Red Bluff, ii) inflow and salt loading over the past several decades, and iii) salinity equalization in the reservoir. All of the calculations dealing with the salt balance were conducted by using flow-weighted salinity. Some data sets did not have the information on flow or discharge at the time of sampling. These data were used to compute arithmetic means to show the level of total dissolved salts, and these data are designated as “arithmetic means”. Other details are shown in Appendix I.

Outflow Salinity Projection

Once salt loading and salinity equalization were validated, several salinity control options were evaluated. These included i) effects of increased or reduced inflow on reservoir salinity, ii) impact of brine intrusion control, and iii) combination of the two scenarios. Additionally, we examined a potential impact of delaying water delivery to Texas until April of the following year on water evaporation and outflow salinity. These option analyses are merely scenarios, and do not imply endorsement or opposition to one method over another.

RESULTS

Water Balance

The flow of the Pecos measured at the station above the Delaware River fluctuated widely with three large flow events during 1966 through 1986 (Fig. 6). These high flow events raised the mean annual flow to 84 million m^3 (68,000 acre-ft.). If these high flow events are excluded, the annual flow averaged 60 Mm^3/year. The flow became relatively stable since 1991, and increased to 95 million m^3 per year for the last decade (Table 3). We suspect Brantley Dam (constructed in 1991) had a significant impact on the flow control capability.

The flow of the Delaware River (DWR) averaged 21 million m^3 (17,000 acre – ft.) per year, which is 25% of the flow of the Pecos. Since 1991, however, the flow has increased to 31 million m^3. The reservoir storage data prior to 1991 were not available. The mean storage since 1991 averaged 100 million m^3 or 81,000 acre-ft. (Table 3), less than ⅓ of the initial storage capacity of the Red Bluff Dam.

The inflow into Red Bluff (sum of the flow of the Pecos and the DWR) during the period of 1991 through 2001 averaged 126 million m^3 (102,000 acre-ft.) per year (Table 3). The outflow during the same period was reported by the District to be 59 million m^3 (49,000 acre-ft.) per year. The reservoir storage averaged 100 million m^3 (81,000 acre-ft.), and the storage change per year amounted to a reduction of 3.4 million m^3 per year for the period studied; 1991 – 2001. The inflow minus the outflow averaged 67 million m^3 per year. After adjusting to the storage change and rainfall, it appears that half of the water that flowed into the reservoir, 75 Mm^3 (61,000 acre-ft), was lost, presumably due to evaporation and percolation.

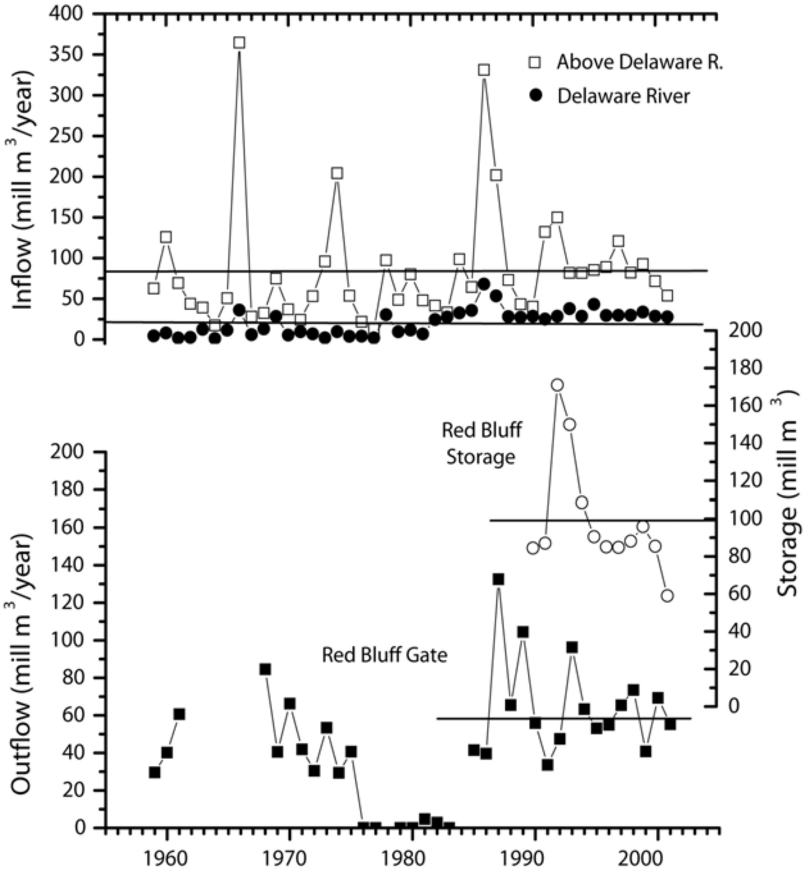

Fig. 6 The annual inflow, the storage, and the outflow from Red Bluff Reservoir (original data from USGS).

The mean water surface area since 1991, computed by Eq. (3) of Appendix I, was 17 km^2 (4,200 acres). The evaporation losses estimated by using a pan coefficient of 0.70 are shown in Table 3, and the pan evaporation averaged 294 cm (114 inches) per year during the period of 1991 through 2001. The estimate of water evaporation from the reservoir was corrected for the surface area, and averaged 35 million m^3 (28,000 acre-ft) per year.

The percolation losses estimated by Eq. (1) of Appendix I averaged 41 million m^3 (33,000 acre-ft.) per year or 32% of the inflow. (The percolation loss decreases to 35 million m^3 per year if the contribution of rainfall on the water surface is ignored). The percolation loss reached 60 million m^3 when the reservoir storage was large (186 million m^3). If the high percolation loss estimate for 1992 and 1995 is ignored, the percolation losses averaged 37 million m^3 (30,000 acre-ft). The accuracy of percolation estimates depends on the reliability of outflow records.

Table 3. The annual inflow, annual outflow, reservoir storage, surface area, rainfall, evaporation and percolation losses for a period of 1991 - 2001.

	Inflow		Outflow	Storage		Surf Area	Rainfall	E_{VAP}	Evap	Percol Loss
Year	Above DWR	DWR	Red Bluff	Red Bluff		Red Bluff	Red Bluff	Red Bluff	Red Bluff	Red Bluff
	Mm^3/y		Mm^3/y	Mm^3		km^2	Mm^3	cm/y	Mm^3	Mm^3
1990	(40)[1] -	29	56	-[2] -	84[3] -	15	3.7	130	19	-
1991	132	25	34	87	147	15	6.8	210	32	36
1992	150	29	47	171	186	26	13.5	170	45	61
1993	82	37	96	150	124	24	10.4	226	54	42
1994	82	29	63	109	100	18	4.4	236	43	32
1995	85	43	53	90	90	16	3.8	205	32	58
1996	89	30	55	85	98	15	7.0	218	32	37
1997	121	30	65	85	114	15	4.0	195	29	37
1998	82	30	73	88	85	15	4.7	230	35	38
1999	93	34	41	96	107	16	3.2	191	31	35
2000	72	29	69	85	80	15	3.4	196	29	32
2001	54	28	55	59	47	11	1.6	161	18	44
Avg.	**95**	**31**	**59**	**100**		**17**	**5.7**	**204**	**35**	**41**

[1] - Incomplete data.

[2] - Average storage for 1991 - 2001.

[3] - End of year storage.

The mean annual flow measured at the outflow gate and at Orla during 1991 – 2001 was 59 and 71 million m^3, respectively. In other words, there has been a gain in flow by 12 million m^3 per year. The inflow from Salt Creek during the period of 1939 through 1957 was reported to be 3.3 million m^3 per year or 3% of the flow of the Pecos at Orla. (There are no records of Slat Creek flow since 1958). The flow gain between the reservoir and Orla may be mainly due to return of reservoir seepage. If so, about ¼ of the estimated percolation losses may be returning to the River. The elevation difference between the water level in the reservoir and the streambed of the Pecos River is over 6 ft. This elevation difference also exists between the reservoir and Salt Creek, and seepage flow can enter into Salt Creek. We found that the flow of Salt Creek increased near the reservoir before entering the Pecos, and salinity decreased from 19 to 8 dS m^{-1} when measured on July 12, 2005. At the same time, the remaining ¾ of the estimated percolation loss seems to be not recovered at Orla. The fate of this seepage water is unknown.

Inflow and Salt Load

The flow measured at Malaga, P.C. Crossing, and above the Delaware River (DWR) was nearly identical (Fig. 7), as it should be. The annual flow prior to 1991 was mostly below 60 million m^3 (49,000 acre-ft.) per year, and it increased to a level of 95 million m^3 (77,000 acre-ft.) since 1991. The long-term average flow at Malaga and P.C. Crossing is 81 million m^3 per year (Table 1), which is affected by sporadic high flow.

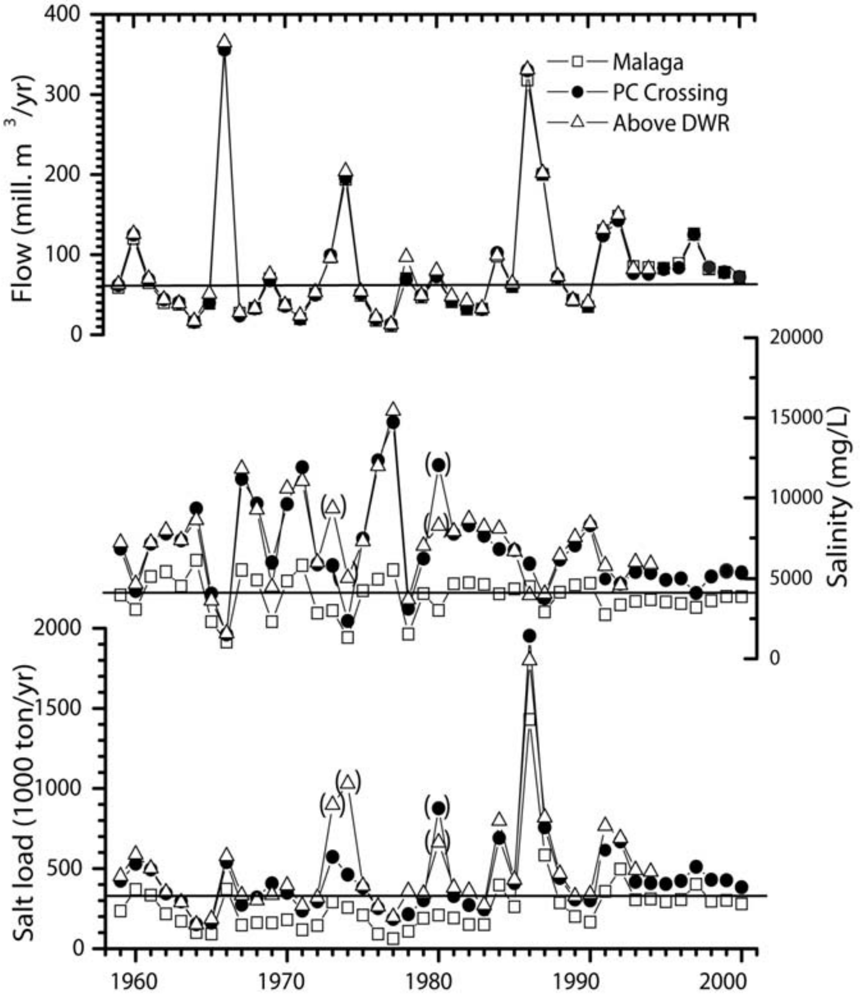

Fig. 7 The inflow, the salinity, and the salt load recorded at Malaga, P.C. Crossing, and above the Delaware River (DWR). The data in parenthesis are not credible.

Streamflow salinity at Malaga averaged 4,100 mg L^{-1} in arithmetic mean, and 3,320 mg L^{-1} in flow-weighted for a period of 1959 to 2001 (Table 1), and has fluctuated mostly between 2,000 to 6,000 mg L^{-1} until the end of the 1980s (Fig. 7). The fluctuation decreased in the decade of the 1990s, and salinity has not changed greatly, 3940 and 3500 mg L^{-1} in arithmetic and flow–weighted mean, respectively. The long term salt load at Malaga averaged 265,000 tons per year at the flow-weighted concentration of 3,315 mg L^{-1} (Table 1), and since 1991, increased to 333,000 tons/year at the flow-weighted salinity of 3,500 mg L^{-1}.

Streamflow salinity readings at P.C. Crossing and "Above the DWR" were similar, except for the years 1973, 1974 and 1980. During 1973 and 1974, several high flow events (which lower salinity) were not registered at the station "Above the DWR". As a result, the annual flow-weighted salinity was computed to be artificially higher than the actual, and these data are shown in parenthesis (Fig. 7). During 1980, the data set contained a high salinity reading (EC of 28 dS m^{-1}) during high flow at P.C. Crossing, whereas the high flow was not recorded at the station above the DWR. The high salinity reading at P.C. Crossing was probably related to sampling at the onset of the high flow events which flushed brine and salt deposits from the river bed. Both of these data points are placed in parenthesis, as they are questionable. The flow–weighted mean salinity at P.C. Crossing averaged 5390 mg L^{-1} for 1959 – 2001, and decreased to 5,030 mg L^{-1} since 1991. Salinity data at the station "Above DWR" are not available after 1994, but are probably similar to or slightly higher than the data from P.C. Crossing. The salt load at P.C. Crossing was 456,000 tons/year for 1959 – 2000, and has increased to 478,000 tons/year since 1991, largely due to the increase in flow, as shown later in Table 4.

High salt load events at P.C. Crossing and "Above the DWR" occurred almost always during high flow years, except for 1966 (Fig. 7). During the year, salinity decreased to the lowest level. The record shows that significant rain occurred in the Black Creek Watershed. This creek originates in the Guadalupe Mountains and flows into the Pecos just above Malaga (Fig. 5). The creek is a fresh water creek, and high flow from the creek seems to have diluted salinity of the Pecos.

The difference in salinity and salt load between Malaga and P.C. Crossing (Fig. 8) may reflect the magnitude of saline water intrusion into the river segment between the stations. The difference in salinity between the stations was large during the period of 1966 through 1984, then declined, especially after 1991. The increase in flow–weighted salinity between these stations is approximately 1500 mg L^{-1} or slightly greater since 1991. In terms of salt load, it was below the mean gain of 172,000 tons per year until 1983. Then, there was a period of increased salt loading between 1984 and 1991, which is related to the high (or elevated) flow events of 1984, 1986 and 1991 shown in Fig. 7. These salt loading spikes may be related to a combination of increased brine intrusion and washout of the salts present on the riverbeds. The fluctuating salt load prior to 1983 reflects low flow conditions, and the data in parenthesis are due to infrequent water sampling for salinity measurements. The salt load difference between Malaga and P.C. Crossing decreased from 172,000 to 150,000 tons/year since 1991.

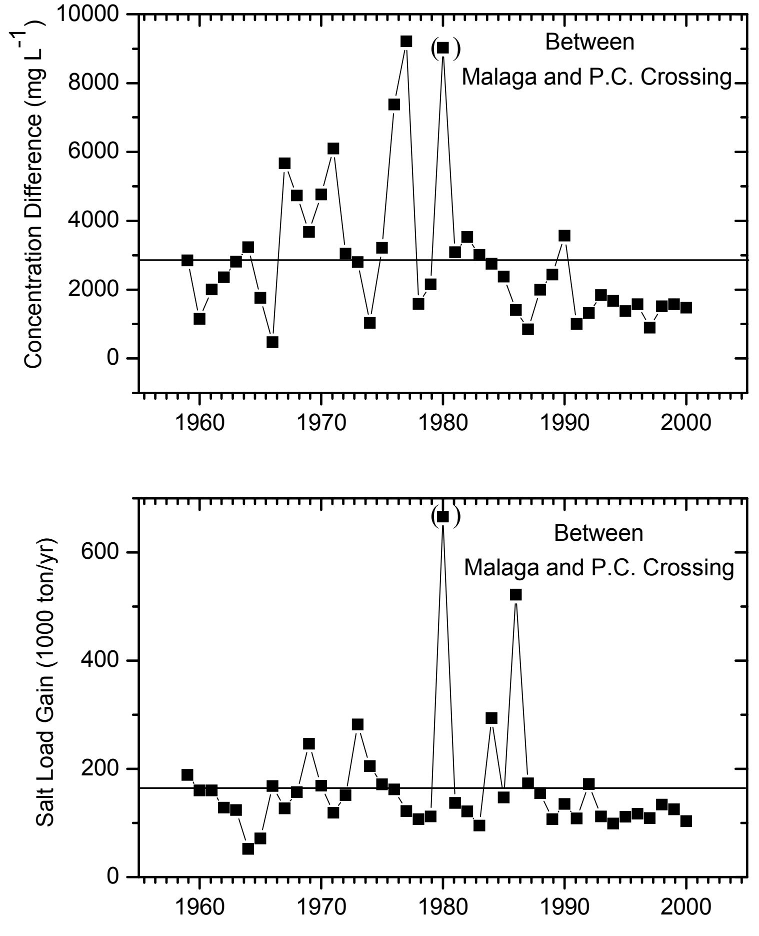

Fig. 8 Differences in salinity and salt load between Malaga and P.C. Crossing. Data in parenthesis not credible.

The seasonal changes in flow and salinity difference between Malaga and P.C. Crossing present an interesting picture (Fig. 9). The flow at P.C. Crossing has not changed greatly, except for the timing of water release between the two periods, yet there is a notable difference in salinity and salt gains between the two periods; 1959 – 1990 and 1991 – 2000. The salt gain has occurred most during irrigation seasons prior to 1990, but not necessarily after 1991. An aerial photo taken in 1970 shows that there was irrigated land right in the Malaga Bend. When visited in 2005, local experts indicated that the irrigated farm was over 1,200 acres in the Malaga Bend area, and was in production in the 1960s and 1970s. We suspect that irrigation activities have once accentuated brine intrusion. Hale et al. (1954), who conducted a geohydrology investigation, also indicated that irrigation may be a factor of increasing saline seep into the Pecos. The lack of flood events since the construction of the Brantley Dam might have also helped reduce saline water intrusion.

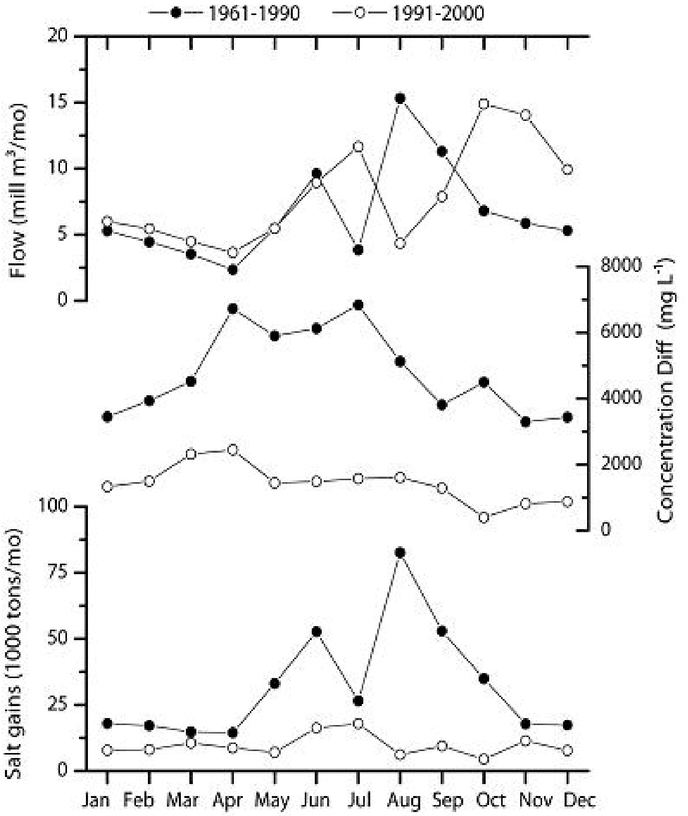

Fig. 9 Seasonal changes in averaged flow at Pierce Canyon Crossing and Above Delaware, concentration differences and salt gains between Malaga and Above Delaware for the past four decades.

Outflow Salinity and Salt Balance

Salinity of the outflow simulated by Eq. (11) of Appendix I is shown by the solid line in Fig. 10. The depth of a top layer where salinity is affected by evaporation and rainfall (d of Eq.

11) was found to be 0.8 m through numerical matching. Salinity of the inflow computed from the USGS data at the Pecos and the DWR is shown by the dotted line, and averaged 5360 mg L^{-1} (arithmetic mean) or 4425 mg L^{-1} (flow-weighted mean). The arithmetic mean of the EPA data taken at the inlet to Red Bluff was 5495 mg L^{-1}, which is close to the data of USGS. The simulation of outflow salinity by the model produced an arithmetic mean salinity of 6300 mg L^{-1}, as compared to the measured salinity of 6150 mg L^{-1} by EPA. However, salinity of the reservoir near the outlet gate reported by EPA deviated from the simulated for the years of 1993, 1998, and 1999. During 1993, the measured salinity was higher than the projected, and was similar to the projected salinity of 1992. The records shown in Fig. 6 show that the reservoir storage peaked in 1992, then decreased sharply in 1993 and 1994. It is entirely possible that the salinity measured in 1993 near the outflow gate was salinity of the water stored in 1992 which had not been mixed well with the incoming flow during 1993. In the case of 1998 and 1999, the measured salinity was lower than the projected. The salinity of the reservoir measured at the surface near the outflow gate is similar to the salinity of inflow measured by the USGS. As shown in Fig. 11, a large amount of water was transferred once from the Brantley to Red Bluff at end of 1987. This large flow might have reached the outflow gate with poor mixing. The quantity of water released in one month was half of the reservoir storage. Otherwise the prediction was reasonable.

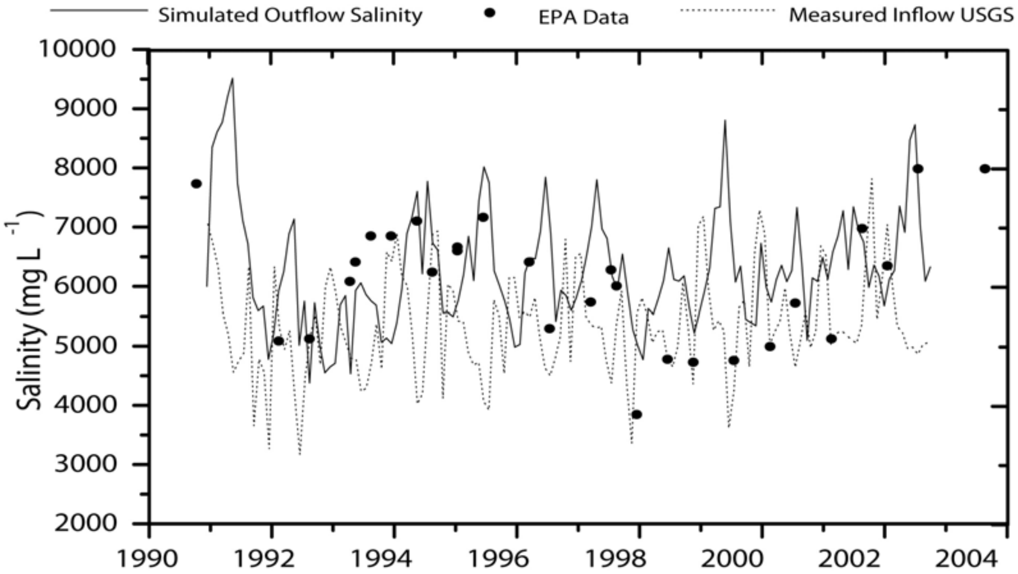

Fig. 10 Simulated reservoir outflow salinity, measured reservoir salinity by EPA, and measured inflow salinity by USGS.

Figure 11 shows the relationship between inflow, inflow salinity, and evaporation on a monthly time scale for the period of 1994 through 1997. Note that salinity of the inflow decreased with increasing monthly inflow. Salinity fluctuation in inflow is quite large, ranging from 4,000 to 7,000 mg L^{-1}. The low salinity corresponds approximately to salinity of reservoir release from the Brantley. The high inflow salinity may correspond to salinity of the low flow which includes irrigation returnflow and brine intrusion. Included in the figure is the salinity estimated by Eq. 10 prior to the evaporative concentration. It shows stable salinity as a result of inflow mixing with reservoir storage, as observed in other reservoirs, such as Elephant Butte, Amistad and Falcon (Inosako, et al., 2006). Salinity of inflow often decreased in the middle of each year, as reservoir release commences mostly from May through October or November.

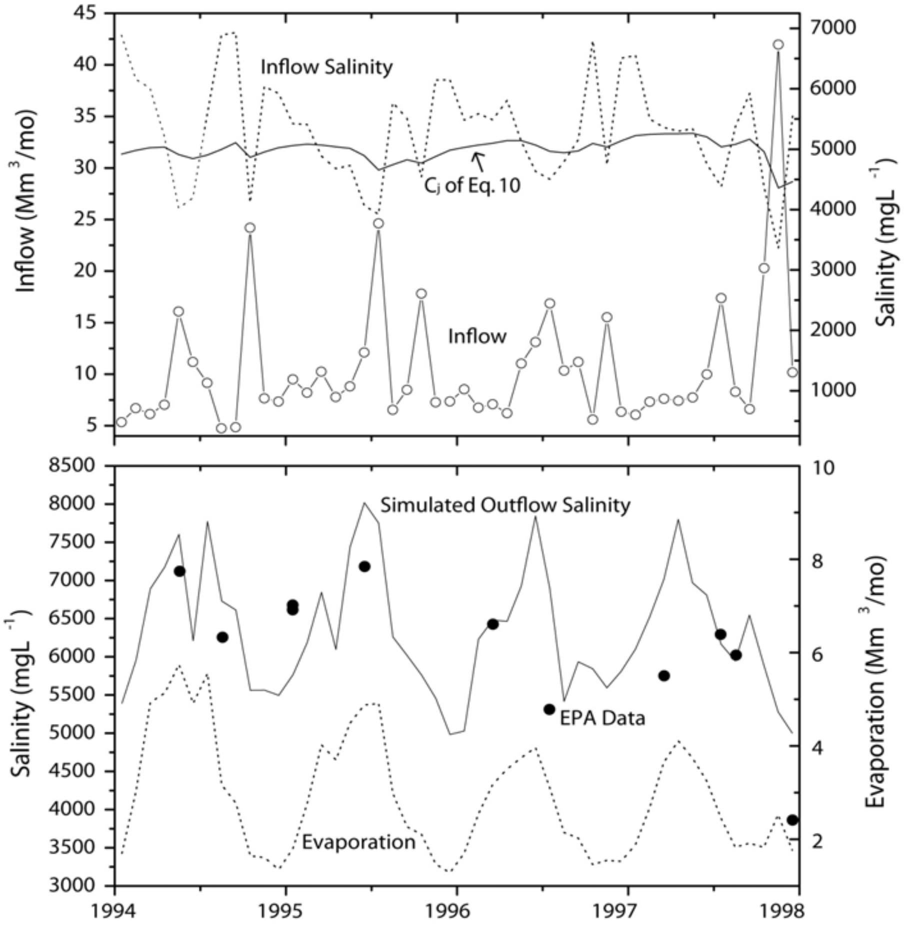

Fig. 11 Inflow, inflow salinity, outflow, and simulated outflow salinity during 1994 through 1997 with the measured salinity noted by closed circles.

Nonetheless, salinity of the outflow from Red Bluff tends to be highest during summer months due to evaporative concentration at the reservoir surface.

The salt balance for 1991 through 2001 indicates that the salt load from the Pecos and the DWR combined was 558,000 tons per year (Table 4). As mentioned earlier, this estimate is based on the salinity measurements at P.C. Crossing. According to the EPA data, the salinity of the outflow given by the arithmetic mean averaged 6150 mg L^{-1}. This value should be close to the flow-weighted mean, as the outflow had been subjected to equalization in the reservoir. Salt load of the outflow is estimated at 363,000 tons/year. Salinity of percolated water was assumed to be the mean of inflow salinity (flow-weighted) and the outflow salinity. The salt unloading through percolation losses was estimated at 216,000 tons/year, of which 21% may have returned to the River. The salt load discharged to the Pecos was estimated at 409,000 tons annually, including the return of seepage.

Table 4. 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.

The net evaporative water losses (evaporation minus rainfall) from the reservoir were estimated earlier as 29 million m^3 per year (Table 2.4). Since the inflow averaged 126 million

m^3 per year, the salt concentration should have increased by 126/(126-29) or 1.30 times. The ratio of outflow and inflow salinity (6150/4425) is 1.39. This indicates that salinity of the reservoir release was slightly greater than the estimate. This finding is consistent with the two–layer model assumed. The increase in salinity between inflow and outflow was 1720 mg L^{-1} in flow-weighted mean, or 650 mg L^{-1} in arithmetic means. The large difference in salinity between the arithmetic and the flow–weighted is caused by the fact that the flow–weighted salinity measured above the reservoir is lowered by the occasional release of low salt water from the Brantley. In terms of frequency, streamflow salinity is more often than not close to the arithmetic means of 5495 mg L^{-1}.

The salt balance between the inflow, the outflow, and the storage change turned out to be reasonable, 582,000 against 579,000 tons/year (Table 4). However, analyses of water samples taken occasionally are inherently problematic. It is desirable for accurate salt loading and unloading analyses to have continuous flow and salinity measurements. The accurate measurement of reservoir outflow is also critical for a reliable estimate of percolation losses, using the water balance method.

Salinity Control Options[1] -

Increasing Inflow: It is a fundamental rule that salinity of streamflow receiving saline water intrusion increases with a reduction in incoming flow of low salinity water. This rule applies to the Pecos River below Malaga. During 1927 though 1937, the USGS data show that the flow into Red Bluff was around 260 million m^3/year, the same level recorded at Malaga (Fig. 3). No record of salinity is available prior to 1937, but it was assumed to be similar to those recorded at P. C. Crossing during 1937 through 1940, which was 4800 mg L^{-1} (Fig. 3). Through back-calculation, the flow–weighted salinity at Malaga during the period was estimated to be 3300 mg L^{-1} (Table 5).

During the period of 1927 through 1940, the flow of the Pecos decreased from 260 to 104 million m^3/year at Malaga and P.C. Crossing. This caused salinity of the stream (flow–weighted) to increase by approximately 1000 mg L^{-1}, while brine intrusion was occurring at a

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[1] - These option analyses are merely scenarios, and do not imply endorsement or opposition to one method or another by the authors or the associated organizations.

rate of 150,000 to 172,000 tons/year. There was a further decrease in flow to 80 million m^3 per year, which increased salinity to 5465 mg L^{-1} in estimate, and 5393 mg L^{-1} in flow–weighted actual salinity. During the last decade (1990 – 2001), however, the incoming flow has increased, and salinity has decreased accordingly (Table 5).

Table 5. The estimated and the measured salinity of the Pecos River as related to flow and brine intrusion.[1]-

Period	Malaga			P.C. Crossing			
	Flow	Salinity	Load	Flow	Load[1]-	Salinity	Measured
	Mm^3/y	mg L^{-1}	1000 tons/y	Mm^3/y	1000 tons/y	mg L^{-1}	mg L^{-1}
1927-1937	260	(3300)	858	260	1008	3870	(3870)[2]-
1937-1940	104	(3300)	343	104	493	4742	4900
1959-2002	80	3315	265	80	437	5465	5393
1991-2001	95	3500	333	95	483	5079	5030
2001-	113	(3080)	388	113	538	4760	-
	113	(3500)	396	113	546	4831	-
		Delaware			Red Bluff		
2001-	31	2572	80	126	563	4428	4425
				144	618	4290	-
				144	626	4350	-

[1]- Assumed to be 150,000 tons/year, except for 1959-2001 during which 172,000 tons/year was used.

[2]- Numbers in parenthesis are estimates

As a scenario, we assumed that an additional flow of 18 million m^3 (15,000 acre-ft.) may be added to the current flow of 126 million m^3/year. The main uncertainty is salinity of the additional flow. If all the added flow comes from the Brantley Reservoir, the flow-weighted salinity of the inflow would be around 3,080 mg L^{-1}, which has been the mean salinity at the Brantley since 1991. This will increase salt load by 55,440 tons/year. If the added flow has salinity similar to that of the current inflow, salinity of the inflow is likely to be around 5,030 mg L^{-1} (Table 4), which provides an added salt load of 90,540 tons/year. The flow-weighted salinity of the combined inflow (including the DWR) would be 4,290 mg L^{-1} for the first scenario, and 4,350 mg L^{-1} for the second scenario, which can be compared against the current flow-weighted salinity of 4,425 mg L^{-1} (or the arithmetic salinity of 5,495 mg L^{-1}). This example calculation shows that salinity of Red Bluff is unlikely to change significantly with the additional flow of 18 million m^3/year, as it accounts for a comparatively small proportion of the current total inflow. Salt loads, however, would increase substantially. If the entire flow into Red Bluff is replaced by the direct delivery from the Brantley, it will have a significant impact. However, the existing water law counts returnflow as a part of the allocation, regardless of its quality.

Reduce Brine Intrusion: Figure 12 shows the current and projected salinity of outflow when salt loading at or above Malaga Bend is assumed to be reduced by 100,000 and 200,000 tons/year. Since the current estimated salt loading at Malaga Bend is 150,000 tons/year, any higher rates of salt removal, such as 200,000 tons/year would require salt removal in a reach above Malaga Bend. The projection was made with an assumption that the flow experienced in 1991 – 2001 will be maintained. With a removal of 200,000 tons per year, the estimated salinity of the outflow is between 3950 and 4045 mg L^{-1}, depending on the choice of the current outflow concentration; 6150 mg L^{-1} (measured) or 6300 mg L^{-1} (simulated). When 100,000 tons are removed per year, the outflow concentration would be 5010 to 5160 mg L^{-1}. In any case, salt removal at Malaga Bend and low incoming salt load from Malaga will have a positive and significant effect on salinity of the Red Bluff release, especially during a period of low flow.

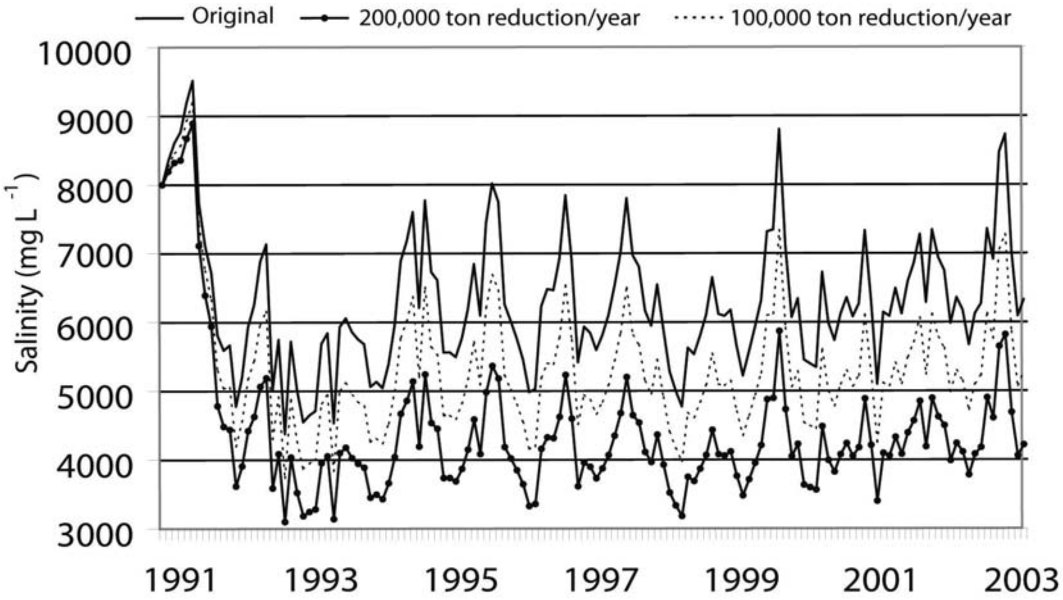

Fig. 12 The simulated outflow salinity and the projected salinity of the outflow when the salt load is assumed to be reduced in 200 and 100 thousand tons/y.

Modifications of Water Management Practices: Water evaporation from reservoirs is a significant factor for increasing salinity, especially when the reservoir is shallow, or having a large surface to depth ratio, like Red Bluff and Brantley. The mean depth of Red Bluff at the average storage of 100 million m^3 is only 6.6 m (19 ft), while the annual water evaporation rate is as high as 2 meters (6.6 ft or 80 inches). As noted in Table 3, the reservoir evaporation accounts for 28% of the inflow. Although the difference in measured salinity of inflow and outflow is comparatively small (655 mg L^{-1}), the flow–weighted salinity which governs the salt balance is being raised by as much as 1700 mg L^{-1}. This degree of salinity increase was not observed in the deeper reservoirs located along the Rio Grande, such as the Elephant Butte, and the Amistad (Inosako, et al., 2006).

Under the current prevailing water delivery practices, the allotment seems to be transferred during and shortly after the irrigation season. The water transferred shortly after the irrigation season is then subjected to evaporation for as long as 5 to 6 months prior to the release for irrigation for the next season. Although there may be various contractual constraints, holding water in deep reservoir upstream until the beginning of the irrigation season may reduce percolation losses, evaporation losses, and associated increase in salinity of the receiving reservoir. However, the quantity of holding must be large enough to reduce the water surface area, and to cause significant dilution of the reservoir storage at the onset of the irrigation season. Figure 13 shows examples of salinity changes when water transfer after an irrigation season is

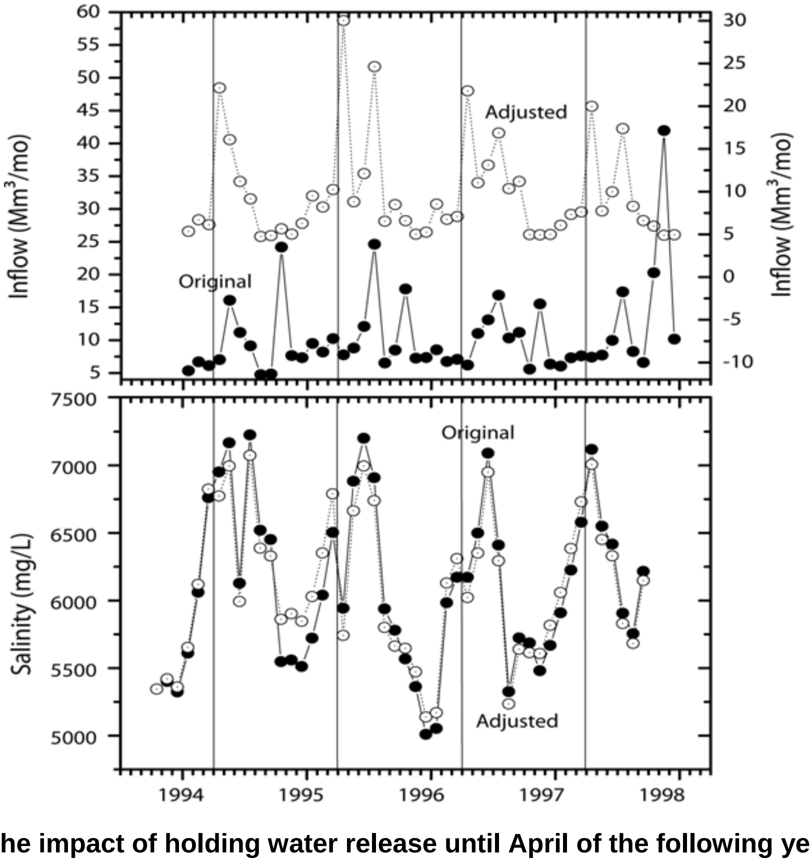

Fig. 13 The impact of holding water release until April of the following year on salinity of Red Bluff.

held back until April of the following year. Note that salinity during the irrigation season was reduced somewhat, but overall changes were relatively small, mainly because the quantity of water which was assumed to be held back was relatively small as compared to the reservoir storage. For this option to be effective, a greater portion has to be held back. It is unlikely that this idea receives overwhelming support from stakeholders.

Reducing percolation losses at reservoirs upstream would be another way to reduce streamflow salinity when the streamflow receives saline water intrusion. Seepage control at Red Bluff is, however, unlikely to affect salinity of the outflow from the reservoir, as seepage loss is merely a form of outflow. Any reductions in reservoir seepage, however, can help reduce salinity below Pecos or Coyanosa where shallow saline ground water enters the Pecos, provided that part of the water saved through seepage control will be left in the river. The control of percolation loss should be an integral part of water management in this basin, and a detailed investigation of seepage losses would be helpful.

DISCUSSION

Causes of High Salinity

At the onset of this study, a question was raised as to the causes of high salinity at Red Bluff. The principal reason is saline water intrusion at Malaga Bend and near the Chain or Bottomless Lakes located east of Roswell. The quantity of salts currently entering the Pecos River at these locations is estimated at 150,000 and 271,000 tons/year, respectively (Miyamoto, et al., 2006). These saline water intrusions are capable of increasing flow–weighted salinity by 2600 mg L^{-1} at the current flow rate of 160 million m^3 per year (Table 5).

Brine seepage at Malaga Bend was studied several times by the USGS (e.g., Hale et al., 1954; Cox and Kunkler, 1962; Havens and Wilkins, 1979) and by the State of New Mexico. Brine has been entering the Pecos, mainly near USGS Well No. 11, and some near Well No. 8 (Fig. 14). Salinity of the brine is close to the saturated brine (360 g L^{-1}). A geological study indicates that this brine seems to be an upward leakage of saturated brine from the boundary between the Rustler Formation and the Salado Formation (Havens and Wilkins, 1979).

The saline water intrusion between Acme and Artesia includes the outflow from the Chain Lakes. As mentioned in the introduction, salinity of the Chain Lakes varies from 15 to 35 g L^{-1}. Assuming that the salt concentrations of these lakes averages 20 g L^{-1}, the discharge

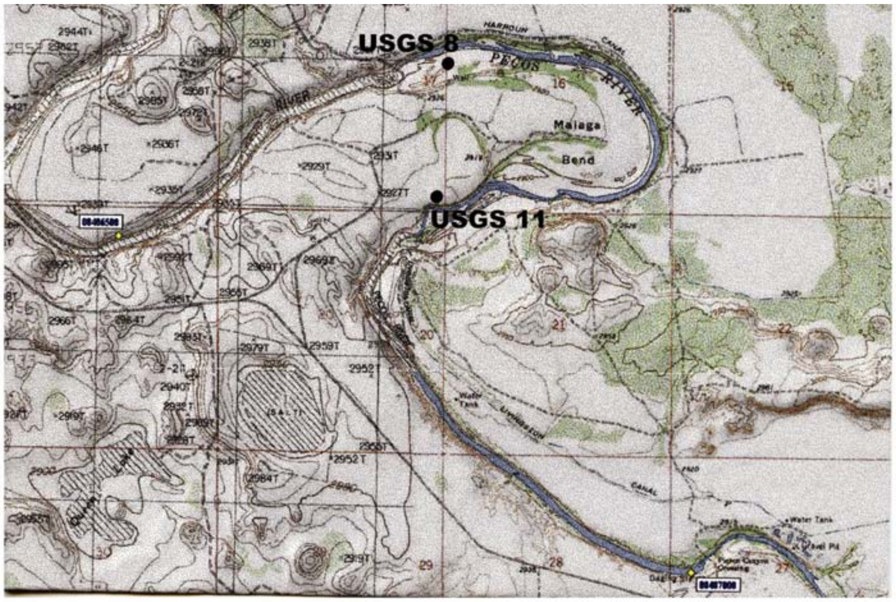

Fig. 14 An aerial view of Malaga Bend to P. C. Crossing segment of the Pecos River near Red Bluff.

rate has to be at least 13 million m^3 per year to add 261,000 tons of salts to the Pecos. The recorded flow increase in this area is 17 million m^3 per year between Acme and Roswell, and an additional 21 million m^3 between Acme and Artesia. These lakes appear to be a major source of salts. However, there is a sizeable area, possibly as large as 20,000 ha (50,000 acres) of cropland irrigated with ground water west of the Pecos. Some suggest that subsurface flow into these lakes is coming from the west rather than from the north.

There are at least two other factors which increase salinity of Red Bluff. One is the significant reduction in incoming flow of low salinity water, which is needed for dilution. The reduction in incoming flow seems to account for an additional increase of at least 1100 mg L^{-1} (Table 5). The increase of flow–weighted salinity of the Pecos River caused by saline water intrusion, and the reduced inflow of low salt water amounts to approximately 3700 mg L^{-1}. The actual flow–weighted salinity increases from 1600 to 5000 mg L^{-1} between Acme and P.C. Crossing, or an increase of 3400 mg L^{-1}. The evaporation from Red Bluff contributes to an additional salinity increase by as much as 1700 mg L^{-1} (in flow–weighted) or 650 mg L^{-1} (in arithmetic mean). This large increase in flow–weighted salinity is related not only to the high evaporation rate, but also to the high salinity of the inflow. If the salinity of the inflow were, for example, 3315 mg L^{-1} (salinity at Malaga), the increase would have been 990 mg L^{-1}, instead of 1700 mg L^{-1}.

One additional cause of high salinity is washout of salts from the watershed. The historical record of the USGS shows that there was a large flow in 1941 and 1942 (Fig. 4) at Malaga and P.C. Crossing. Although salinity of this huge flow (1.5 billion m^3 in 1941) was lower than normal at Malaga, the total salt load reached 2.7 million tons, and streamflow salinity at Langtry (confluence to the Rio Grande) increased to over 4000 mg L^{-1}. Surface washout of salts is likely to be the cause of the high salinity and the high salt load during flood events.

Salinity Control Needs

Dissolved Salt Levels: From the perspective of the Red Bluff District, it is important to provide water of lower salinity to applicable irrigation districts. The salinity of reservoir release during summer months regularly exceeds 7000 mg L^{-1} (Fig. 10). For appraisal of irrigation water salinity, the electrical conductivity (EC) unit, instead of the dissolved salt concentration is commonly used. In the case of Red Bluff, 660 mg L^{-1} is equal to 1 dS m^{-1} (Table I-1 of Appendix I), or 6150 mg L^{-1} is equal to 9.3 dS m^{-1}. Water of this salt level is usable in well – drained sandy soils for producing highly salt tolerant crops, such as cotton and hay (Appendix II, Table II-1). If salinity is lowered to 4710 mg L^{-1} (7.1 dS m^{-1}), a few other crops can be grown, especially under high leaching fractions (25 to 30%) where EC_e (salinity of the soil saturation extract) equals EC_w (salinity of irrigation water). Water of this level of salinity, however, cannot be used in clayey soils or for production of high value horticultural crops. In addition, sprinkling of cotton leaves with irrigation water having this level of salinity causes severe leaf injuries (Moore and Murphy, 1979).

Salt tolerance of riparian vegetation varies to a greater extent than do agricultural crops. Table II-2 of Appendix II shows examples of growth reduction caused by salinity of the saturation extract expressed in mg L^{-1}. The conversion to dS m^{-1} requires a division by 660. For example, 10,000 ppm corresponds to 15.1 dS m^{-1}. Differences in experimental conditions yield the difference in apparent salt tolerance, even when water of a given salt level is used. The experimental results reported by Miyamoto, et al., (1996) and Miyamoto, et al., (2006) used soil water depletion of 50% prior to irrigation. In addition, the leaching fraction was controlled at 30%. Under this leaching fraction, salinity of the soil saturation extract averaged over the root zone approximately equals salinity of the irrigation water. Salinity of the saturation extract measured along the river bank of the Pecos River was indeed close to salinity of streamflow (unpublished data, this laboratory). The experimental conditions used by other investigators involved daily irrigation with unspecified leaching fraction or soil water depletion. In order to standardize the expression of salt tolerance, salinity of irrigation water was divided by 1.5 to convert to mean salinity of soil solution when the soil water storage was assumed to deplete 50% of the holding capacity.

Pickleweed (*Allenrolfea occidentalis*) is among the most salt tolerant succulent halophytes, and survives sea water salinity (32,000 mg L^{-1}) or higher. Suaeda (*S. esteroa*) and Maritima (*Batis maritima*) are also succulent halophytes, and commonly found in saline basins. Saltbush and saltgrass are also tolerant to salts, along with mesquite (*Proposis sp.).* Salt tolerant of mesquite (*Proposis sp.*), and possibly salt cedar is dependent of species. For example, Screwbean mesquite (*P. pubescens*) is much more tolerant to salt than Honey mesquite (*P.glandulosa*) or salt cedar (unpublished data, this laboratory).

Salt tolerance of cottonwood (*Populus fremontii*) and range grass species native to the Southwest is usually less than 7500 mg L^{-1} of NaCl (Appendix II, Table II-2). Salinity of streamflow in the reach between Coyanosa and Girvin is currently 14000 mg L^{-1}, which is well above the tolerance limits of cottonwood or native range grass species. Salinity of the streamflow in this reach has to be lowered if biodiversity in riparian vegetation is to be achieved. Otherwise, the riparian zones in the salty reach will eventually be dominated by salt tolerant species and a few halophytes.

According to the guidelines complied by the National Academy of Science, livestock can tolerate up to 5000 mg L^{-1} when the water is used for daily consumption (Appendix II, Table II-3). Poultry, however, cannot tolerate this level of salinity. The prevailing salinity of the Pecos River below Red Bluff (6150 to 14000 mg L^{-1}) is unfit for consumption by livestock.

Aquatic species also have preferred salinity ranges. Linman 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 likely to be accompanied by a reduction in native species. Hoagstrom (2003), for example, points out that only nine out of 27 native species appear in the Pecos River below the Brantley. A reduction in 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 of 6000 to 14000 mg L^{-1} if biodiversity of freshwater aquatic species are to be achieved.

Although salt tolerance of both agricultural crops and native vegetation are 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. For a lack of the target salinity that all can agree upon, salinity of 4710 mg L^{-1} recorded during 1937 – 1940 at Orla, TX could be used as a tentative target for initial salinity control efforts.

Salt Load: Salinity of Amistad International Reservoir located downstream has been increasing (Fig. 15). The impact of Red Bluff release on 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 the 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}.

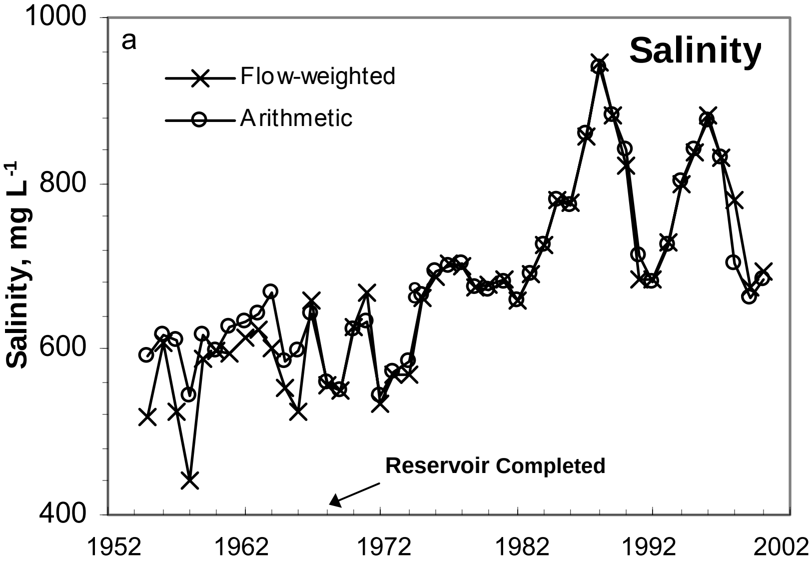

Fig. 15 Changes in salinity at Amistad Reservoir (Miyamoto, et al., 2006

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 Reservoir accounts for 26% of the total salt loading (or 30% of the gauged inflow), while providing only 9% of the inflow (Table 6). The mean salinity of composite inflow is 643 mg L^{-1} since 1969, or 807 mg L^{-1} since 1991. Salinity of outflow from the Amistad has been averaging approximately 1.1 times the inflow salinity or 888 mg L^{-1} since 1991 (Miyamoto, et. al., 2006).

Table 6. Inflow quantity and salinity entering the Amistad International Reservoi during 1969 - 2000 (Miyamoto, et al., 2006).

	Inflow	Salinity		Salt load	Inflow		Salt load	
	Mm^3	mg L^{-1}		1000 t/y	----------	%	----------	
Rio Conchos	844	735	(1030)[1] -	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

[1] - Salinity since 1991

[2] - Percentage based on the total inflow

A major increase in salt loading from any of these salt carrying tributaries can cause salinity of the Amistad Reservoir to exceed 1000 mg L^{-1}, the upper limit of drinking water standards in Texas. 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 the Amistad. An estimate indicates that the reservoir release currently used for irrigation contains salts in sufficient quantity to raise salinity of Amistad by 10%, if they are left unused and flow into Amistad (Miyamoto, et al., 2006).

The incident large floods in 1941 and 1942 points out that the Amistad 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 the ground level. If the Amistad Reservoir were constructed before 1941, the flood would have increased salinity of the Amistad well above 1000 mg L^{-1} (Miyamoto, et al., 2006). If there is a flood event exceeding the flood control capability of Red Bluff and Brantley, salty water can flow directly into the Amistad. The flow control capability of Red Bluff and the Brantley combined is about half a billion m^3, while the 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 events.

Selection of Salinity Control Options

In the case of the Pecos River, there is a need to lower both salinity (salt concentration), and salt load which may reach the Amistad Reservoir. Increasing inflow into Red Bluff can lower salinity, but may also increase salt load. Reducing saline water intrusion can reduce both salinity and salt load. From the view of water quality control objectives, the control of brine intrusion at Malaga Bend and east of Roswell should receive high priority.

According to a report by Havens and Wilkins (1979), pumping of brine from Well No. 8 at a rate of 12.5 L/s (0.44 cfs) at Malaga Bend was sufficient to lower salt-water intrusion from 400 to 66 tons/day. This discharge rate equals 0.394 million m^3 (320 acre-ft.) per year. These daily salt loads correspond to 146,000 and 24,000 tons/year, and the rate of intrusion coincides with the current estimate of 150,000 tons/year. Unfortunately, the brine pumped and piped to nearby unlined depression (the Northeast depression) has leaked, and the brine reappeared in the Pecos River somewhere below USGS Well No. 11. Pumping of this brine has been the primary control measure attempted for decades, and the Red Bluff District has been working with a private sector for salt production. The control of saline water intrusion between Acme and Artesia seems to be viewed as a task for the state of New Mexico. If implemented, it will also affect Red Bluff, and the Texas portion below.

From a historical perspective, it is interesting to note that salinity of the outflow from Red Bluff for 1937 – 1940 was reported to be 4710 mg L^{-1}, instead of the current salinity of 6150 mg L^{-1} when measured at Orla (Howard and Love, 1943). A graphic presentation was given earlier in Fig. 3. Note that both flow and salinity reported for "Red Bluff" was actually measured at Orla below the reservoir, but not at the inlet. By the period of 1938 to 1940, most major reservoirs along the Pecos had been constructed, thus presenting the flow pattern which is similar to the one observed today. A brine intrusion control if fully implemented at Malaga Bend (assuming that 150,000 tons/year removal) may lower mean salinity of the reservoir outflow, on the average, to a range of 4470 to 4600 mg L^{-1}. This projected salinity range is comparable to salinity of the reservoir outflow during 1938 through 1940.

Benefits of lowering salinity of Red Bluff are yet to be articulated, along with some of the data related to streamflow and salinity, which were used for this study. Unfortunately, irrigated acreage has declined along with the reduction in water supply, both in quantity and quality. Nonetheless, lowering salinity of the Red bluff release may benefit local agriculture, and possibly may reduce salt loading into the Amistad. An additional value of salinity controls may have to be evaluated based on ecosystem restoration, and improvements of water quality at Red Bluff and the Amistad. If ecological benefits are the central objective, other constituents, besides salts, which affect aquatic and riparian species, need to be evaluated. These include nutrient elements, metals, and pesticide residues.

APPENDIX I

Data Processing Methods Used

***Water Balance*:** The water balance involving the Reservoir was computed annually as

$$\mathbf{Q_P = Q_{IN} - Q_{OUT} - \Delta S - E + R} \tag{1}$$

where Q_P is the percolation loss, Q_{IN} the inflow total, Q_{OUT} the outflow total, ΔS the changes in reservoir storage with an increase expressed by positive values, R the rainfall, and E the evaporation losses estimated as

$$\mathbf{E = 0.70E_{pan}\,A} \tag{2}$$

where E_{pan} is the pan evaporation with a pan coefficient of 0.70 recommended by the Texas Water Department Board, and A is the free water surface area of the reservoir adjusted to the depth or storage. Based on the information provided, we developed the following equation to estimate the water surface area, A.

$$\mathbf{A = 75.6 - 74.5\ Exp\ (-V_S/414)} \tag{3}$$

where V_S is the reservoir storage in million m^3 adjusted to the volume of sediments surveyed and A is in km^2 (which is equal to 247 acres).

***Inflow and Salinity*:** Salt balance calculations involving reservoir are usually carried out in mass per unit volume of water. We used the following equation to convert the electrical conductivity (EC) to total salt concentration (C).

$$\mathbf{C = a\ EC} \tag{4}$$

where a is the empirical coefficient which varies with ionic compositions as well as the range of concentrations. The coefficient may be determined through calibration against the data set with known cation and anion concentrations, and the results are shown in Table I-1.

The monthly flow was computed simply as a sum of daily flow. Water quality data are reported for water samples collected one to four times a month, and may or may not represent the true quality of the month because the flow rates at the time of sampling may or may not coincide with the daily 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.

$$\mathbf{C_i q_i = \alpha q_i^{\beta}} \tag{5}$$

or

$$\mathbf{\log (C_i q_i) = \beta \log q_i + \log\alpha} \tag{6}$$

where C_i is the measured salinity or the ionic concentration, q_i the momentary flow rate at the time of water sampling, and α and β are empirical coefficients (Table I-2). The term C_iq_i will be referred to as salt flux, and is plotted against the momentary flow (Fig. I-1). The data points available for the DWR are limited to three, thus the reliability can be questioned. However, it will not affect the salt balance calculation greatly, because both salt concentrations and streamflow are comparatively low. In addition, the coefficient β is close to unity, indicating salinity of this flow is nearly constant.

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

$$\mathbf{C_m = [\Sigma C_i q_i/\Sigma q_i]\, [q_m/(\Sigma q_i/n)]^{\beta-1}} \tag{7}$$

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 $\Sigma C_iq_i/\Sigma q_i$ 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). This equation can also be used to estimate missing salinity data from adjacent data sets.

The annual flow-weighted salinity was estimated as

$$C_A = \Sigma C_m Q_m / \Sigma Q_m \quad (8)$$

When multiple streams enter into the reservoir, the composite flow salinity is computed as the flow-weighted mean.

$$C_m = \Sigma C_{mi} Q_{mi} / \Sigma Q_{mi} \quad (9)$$

where i designates the number of streams entering the reservoir.

***Salinity Equalization*:** Reservoir storage helps buffer salinity fluctuation, as inflow blends with storage. We used a two-layer model (Inosako et al., 2006) for computing salinity of the outflow. This method assumes a complete mixing of reservoir storage with outflow, then the top layer was assumed to be subject to evaporation and rainfall, the second layer the percolation losses.

$$C_j = \frac{C_{j-1} S_{j-1} + C_{INj} Q_{INj} - C_{j-1} Q_{Pj}}{S_{j-1} + Q_{INj} - Q_{Pj}} \quad (10)$$

$$C_{OUTj} = dA_j C_j / (dA_j - E_j + R_j) \quad (11)$$

where C_{OUTj} is the outflow salinity, d is the depth of the reservoir subject to evaporative concentration, A the water surface area, and E, R, and Q_P are defined by Eqs. (1) and (2). The evaporation (E) and the rainfall (R) were assumed to affect the top layer of a thickness of d. The resulting storage S_j is then estimated by incorporating the evaporation, the rainfall, the percolation loss and the outflow. The thickness of the top layer is to be estimated by solving Eq. (11) for d, by applying available historical data or through curve fitting. In the case of Red Bluff, we found that 0.8 m (2.6 ft) provides the best fit.

Table I-1. Correlation between the electrical conductivity (EC) and the total dissolved salts (TDS) at various gauging stations.

Location	a	r^2	n
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
Delaware River			

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

Table I-2. The empirical coefficients to describe the relationship between salt flux (kg/s) and flow rates (m^3/s) by Eq. (5).

	α	β	r
Artesia	5.0	0.67	0.92
Malaga	5.0	0.67	0.96
P.C. Crossing	9.3	0.58	0.89
Red Bluff	8.9	0.65	0.89
Delaware River	2.6	0.92	0.99

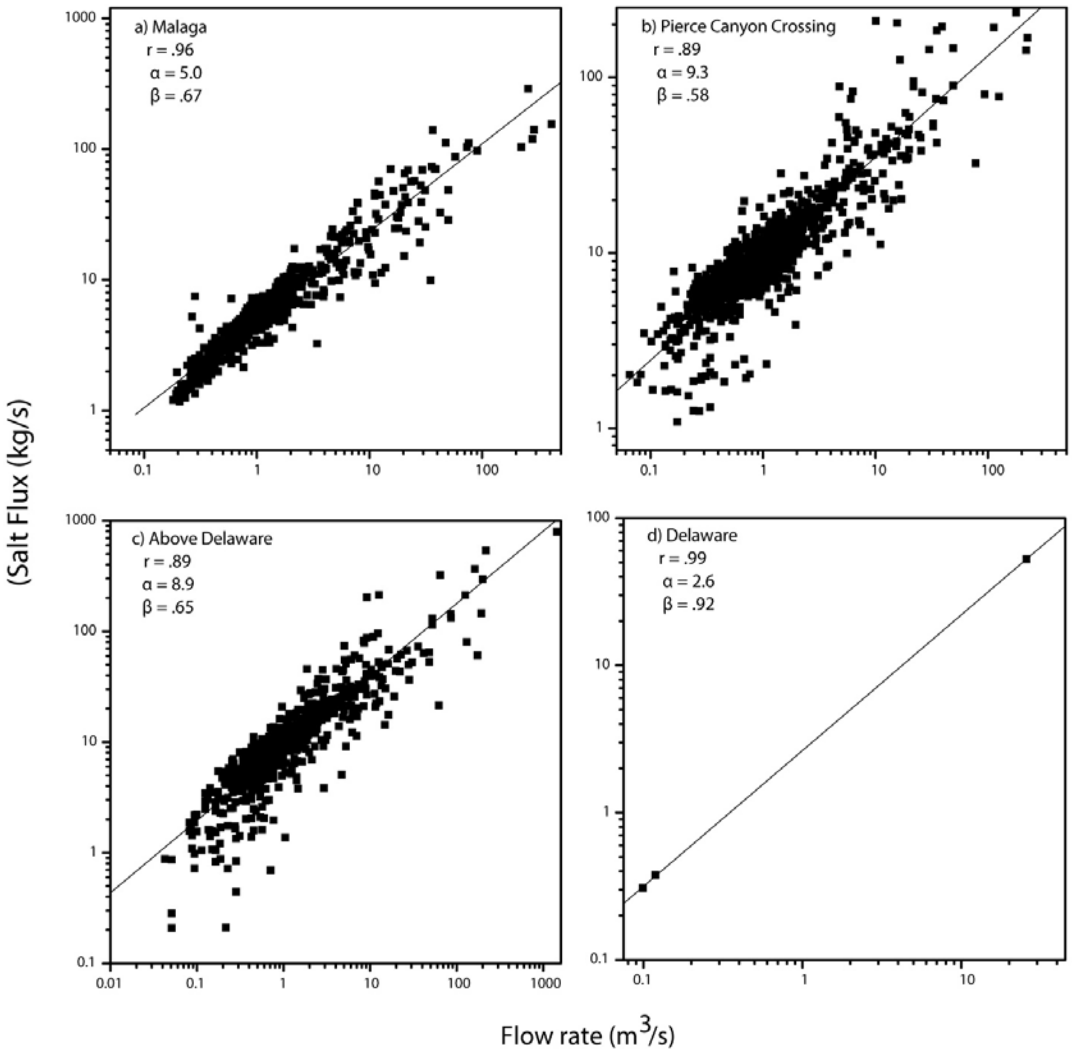

Fig. I-1 The historical relationship between salt flux and momentary flow rate at the time of water sampling.

APPENDIX II

Guidelines for Appraisal of Water Quality

Table II-1. Yield potential of selected crops when irrigated with water having various salt levels[1]- (Ayers and Westcot, 1989).

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 aestivum*)[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 elatior*)	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								
Squash (*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.

Table II-2. Relative qrowth rates of riparian species when grown at the leaching fraction greater than 30%, 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 occidentalis*)	71	94	81	77	75	72	(1)
Pickleweed (*Allenrolfea occidentalis*)	48	87	84	88	92	95	(2)
Suaeda (*Suaeda esteroa*)	93	98	99	73	45	13	(4)
Maritima (*Batis maritima*)	100	91	84	64	51	29	(4)
Saltgrass (*Distichlis palmeri*)	91	97	99	77	48	20	(4)
Saltbush (*Atriplex nummularia*)	99	95	82	60	40	17	(4)
Quailbush (*Atriplex lentiformis*)	72	98	84	65	48	0	(2)
Salt Cedar (*Tamarix ramosissima*)	98	89	78	68	57	35	(1)
Salt Cedar (*Tamarix chinensis*)	95	92	72	53	22	0	(2)
Mesquite (*Proposis 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 (*Tessaria sericea*)	60	72	40	24	18	0	(2)
Arrowweed (*Pluchea sericea*)	95	77	54	31	7	0	(1)
Sheepwillow (*Baccharis salicifolia*)	91	53	6	0	0	0	(1)
Goodding willow (*Salix goodingii*)	89	42	0	0	0	0	(1)
Goodding willow (*Salix gooddingii*)	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 and White, (2006).

Table II-3. Salinity guidelines for livestock water supply (National Academy of Science, 1974).

Total soluble salts content of waters (mg/l)	Comments
Less than 1,000	These waters have a relatively low level of salinity, and should not present no serious burden.
1,000 to 2,999	These waters shold 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 faeces, increased mortality and decreased growth, especially turkeys.
5,000 to 6,999	These water 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.

From: NAS, *Nutrients and Toxic Substances in Water for Livestock and Poultry*

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