INFLUENCE OF TRIBUTARIES ON SALINITY OF AMISTAD INTERNATIONAL RESERVOIR

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CONTENTS

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 = 0.811 A-F

INTRODUCTION

Amistad International Reservoir is located at the Texas–Mexico border, and is fed by four main tributaries; the middle Rio Grande (MRG), the Pecos, the Devils, and the Rio Conchos from Mexico (Fig. 1). This reservoir is among the largest reservoirs in the western USA, and it can hold 6.7 billion m^3 (5.5 million acre-ft.) of water. The structure was completed in 1968, and the Reservoir was filled near its capacity by 1972 (Fig. 2b). The storage declined to 3.1 billion m^3 by 1985, backed up to over 4.0 billion m^3 for most parts of '86 through '92, then depleted to as low as 1.5 billion m^3 during the last decade, following the drought which started in 1994.

Salinity of the Rio Grande at Amistad prior to reservoir construction averaged 560 mg L^{-1} (Fig. 2a). Starting in 1975, salinity reached 700 mg L^{-1}, and has remained at the level through 1983. This was followed by a steep increase in salinity which peaked in 1988, and again in 1996. Salinity of the outflow increased to 945 mg L^{-1} during 1988, and during February of that year, it reached the federal secondary drinking water standard of 1,000 mg L^{-1}. There is a concern that salinity may exceed the limit with a greater frequency in the future. This problem of salinity increase at Amistad was noted a decade ago (Miyamoto et. al., 1995).

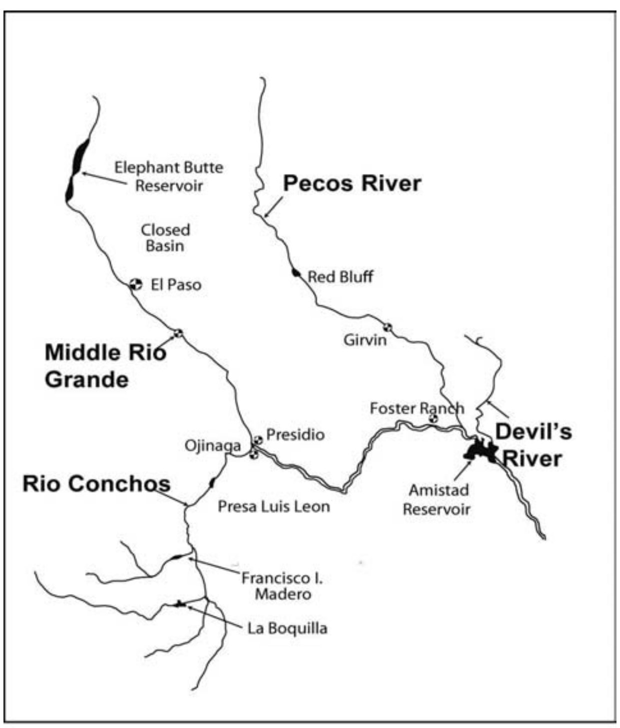

Fig. 1. Watershed of the Rio Grande above Amistad.

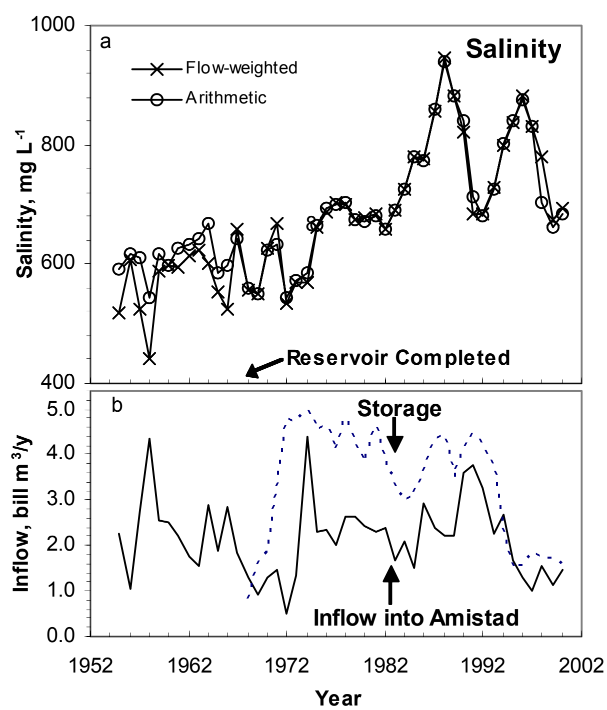

Fig. 2. Changes in salinity, inflow into and storage at Amistad Reservoir.

Meantime, a reconnaissance survey was carried out for identifying salt sources which are entering the Pecos River (Miyamoto et al., 2005). The report indicates that the Pecos River had largely been salinized due to saline water intrusion, and through the reduction in streamflow that is needed for diluting the saline water intrusion. The flow of the MRG below El Paso has also declined after the construction of Elephant Butte, and saline irrigation returnflow has deposited large quantities of salts in the reach between El Paso and Presidio. Consequently, bank salinity is extremely high in the MRG below El Paso. The Rio Conchos from Mexico has historically provided the largest inflow into Amistad. According to the data from the US section of the International Boundary and Water Commission (US-IBWC), salinity of this flow when enters the Rio Grande has been steadily increasing in the recent decades. These are not good signs from the view of maintaining low salinity at Amistad.

This study was conducted to identify the influence of tributaries on salinity fluctuation at Amistad. This type of assessment may be useful for developing salinity control and water management strategies. The data shown in Fig. 2 indicate that the first peak appeared during the high storage period under a seemingly normal inflow situation, and will be the focus of this study. The second peak appeared in 1996 during a low flow and low storage period. This increase is certainly drought-related.

STUDY AREA

The area above Amistad is semi-arid with annual rainfall ranging from 20 cm (7.8 inches) at El Paso to 37 cm (14.5 inches) at Langtry, and 43 cm (17 inches) at the Reservoir. Pan evaporation ranges from 270 cm (108 inches) per year at El Paso to 230 cm (91 inches) at Langtry, and 220 cm (87 inches) at the Reservoir. Most rainfall occurs in warm months of May through September. The monsoon rain usually comes in July and August in El Paso, and September in most other areas of the Basin.

The Rio Conchos is by far the largest feeder, accounting for 33% of the inflow into the Reservoir since its construction in 1968 (Table 1)[1] -. The watershed is the Mapimi Basin of Mexico, and the flow fluctuates widely as this watershed is in the warm monsoon climatic zone. The River enters into the Rio Grande just below Presidio (or Ojinaga, MX). The Pecos River was once the large feeder of the Rio Grande, but now provides only 9.5% of the total inflow into

[1] - This inflow figure includes the reduced flow from fresh water creeks, whereas an earlier report (Miyamoto et al., 1995) is based strictly on gauged flow.

Table 1. Flow and storage characteristics of Amistad Reservoir (IBWC data for 1969-2000).

Storage	(billion m^3)
Maximum Capacity	6.83
Mean (1969-2000)	3.43
Surface Area	(thousand ha)
at high storage (4.5 billion m^3)	27.7
at medium storage (3.0 billion m^3)	20.3
at low storage (1.5 billion m^3)	11.2
mean surface area	22.1
Pan Evaporation (mm/year)	2200
Rainfall (mm/year)	430
Residence time[1]	(years)
at high storage (4.5 billion m^3)	1.5
at medium storage (3.0 billion m^3)	1.1
at low storage (1.5 billion m^3)	1.0
Inflow sources	(million m^3/y)
Rio Conchos	844
Devils	351
Pecos	245
Middle Rio Grande	188
Others[2]	943
Total	2571

[1] - Based on the actual inflow data.

[2] - "Others" denote measured, and unmeasured fresh water inflow estimated by the annual water balance.

the Reservoir[1]. This river originates in northeastern New Mexico, and is impounded by a series of reservoirs in New Mexico, and Red Bluff Dam in Texas. Dissolution of geological evaporites (mainly gypsum, halite, and epsomite) into the deep canyon flow of the Pecos makes it among the saltiest (Miyamoto et al., 2005). The bank of this river was once infested heavily with Tamarisk (salt cedars), but the riparian zones in the Texas portion were cleared through the recent eradication efforts extending from 1999 to 2004 (Hart, 2004). The Pecos River enters the Rio Grande near Langtry.

The middle Rio Grande starts at Elephant Butte Reservoir, and is used extensively for irrigation and municipal water supply. The flow below El Paso is low, and riverbank had been salinized due to lack of bank overflow (Unpublished data, this laboratory). Salt cedar became the dominant riparian vegetation below El Paso down to Presidio, and its control is being discussed.

The Devils River originates from the Edward Plateau, and provides fresh water along with several other creeks and arroyos into the Reservoir. This river has not been developed for any major irrigation activities. The fresh water inflow into the Reservoir, excluding the Devils River, is estimated to be as high as 943 million m^3 (760,000 acre-ft) per year through water balance calculations. The estimate by the US-IBWC is slightly larger, 1,030 million m^3 (830,000 acre-ft) per year. If there is no fresh water inflow into the Reservoir, the mean salinity would top 1,050 mg L^{-1}, which is the mean salinity of the three main tributaries. With the inflow of fresh water, the mean salinity, as will be shown later, decreases to 643 mg L^{-1}[1].

The salinity measured in outflow usually exceeds the inflow salinity because of evaporative concentration. However, this does not explain why salinity of the Reservoir suddenly increased to nearly 1,000 mg L^{-1} during 1988 when storage was above the average. The second salinity peak appeared in 1996, when both inflow and Reservoir storage were declining. The following analyses were made to understand the causes of the salinity increase and fluctuation.

DATA SOURCES AND PROCESSING

Data Sources

The International Boundary and Water Commission (IBWC) is the primary organization engaging in monitoring and reporting flow and water quality of the Rio Grande. Most of the data used came from their annual water bulletin entitled "Flow of the Rio Grande and Related Data", which is now available in a digital form through http://www.ibwc.state.gov/CRP/monstats.htm. We used the IBWC data collected at Presidio for the MRG, at Ojinaga for the Rio Conchos, Langtry for the Pecos, Patford Crossing for the Devils River, and the Amistad gauging station located just below the Reservoir. In addition, flow and salinity data recorded at Foster Ranch station were used to cross-check the combined flow of the MRG and the Conchos.

The streamflow data at Caballo (below Elephant Butte) were made available by the Bureau of Reclamation (BOR) for a period of 1980 through 1994. These data were manually keyed in for analyzing the salt balance along the middle Rio Grande. Additionally, we used an old USGS record (Howard and Love, 1943), when there were large flood events in 1941 and 1942 in the MRG as well as in the Pecos River Basin. The flow and salinity data at Caballo also came from the Reclamation, and the data at Langtry from IBWC.

Soil salinity of riverbanks and floodplains is being assessed as part of a separate project for the reach between Caballo and Ft. Quitman (unpublished data, this laboratory). The data consisted of soil salinity measured at the surface 0 to 1 cm, and for subsurface samples taken to a depth of 120 cm at 30 cm intervals from five sites around El Paso and eight sites below El Paso. The reach above El Paso frequently receives bank overflow, and the reach below does not. At each site, soil samples were taken at 16 holes, 8 each per transect placed across floodways. Salinity of riverbank for the Pecos River was obtained on March 8 and May 7, 2005, and exploratory data were reported earlier (Miyamoto et al., 2005). In addition, soil salinity was measured by Clayton (2002) in the same reach of the Pecos in August 1999, then 2001 and 2002.

Data Processing

Flow, Salinity and Salt Load: The streamflow measured daily was simply added to figure monthly flow. Salinity has been measured weekly or bi-weekly, and was averaged by using the flow-weighted mean.

$$\mathbf{C_m = \Sigma C_i\, q_i / \Sigma q_i} \tag{1}$$

where C_m is the flow-weighted monthly salinity, C_i is the salinity of water samples when taken at the momentary flow rate of q_i.

The annual flow-weighted salinity was then computed as

$$\mathbf{C_A = \Sigma C_m\, Q_m / \Sigma Q_m} \tag{2}$$

where C_A is the flow-weighted annual salinity, C_m is the monthly salinity, and Q_m is the monthly flow. Flow-weighted salinity is usually smaller than arithmetic means, since salinity during high flow tends to be lower. In the case of the Rio Grande at Amistad, the flow-weighted means were similar to arithmetic means (Fig. 2a), because water stored is equalized through mixing.

Salt Balance and Salt Flushing: The annual salt balance between two gauging stations was computed as

$$\mathbf{\Delta S = C_{A2}Q_{A2} - C_{A1}Q_{A1}} \tag{3}$$

where C_A is the flow-weighted annual salinity, and Q_A is the cumulative annual flow, ΔS is the annual salt balance; a positive value indicating a gain in salt load as streamflow travels from locations from 1 to 2. When ΔS is positive following exceptionally large flood events, it is commonly referred to as salt flushing. The salt balance along the MRG was computed for the reach between Caballo and El Paso, and another reach between El Paso and Presidio for the period since 1970. For a comparison, the data from a large flood event of 1941 – 42 (Howard and Love, 1943) were also analyzed.

We experienced difficulties in estimating the salt balance at the lower reach of the Pecos as well as the Rio Conchos. Salinity measurements at Girvin, TX along the Pecos River were discontinued since 1982, and the next USGS station measuring streamflow salinity is near Red

Bluff, some 640 km (400 miles) upstream from Langtry. In addition, the reservoir release is diverted for irrigation, thus yielding a negative salt balance. Nonetheless, salt balance calculations were made between Artesia and Malaga, and Malaga and Langtry since 1970, and the period of 1941 and ’42. We were not able to access water quality data of the Rio Conchos. Therefore, the following alternative method was used for estimating the salt balance of the Rio Conchos, based on the measurement at confluence.

$$\mathbf{C_{ob}Q_{ob} = C_BQ_B + C_IQ_I + \Delta S} \quad (4)$$

where Q_{ob} is the observed flow, and C_{ob} is the corresponding salinity, C_B and C_I are salinity of the baseflow and reservoir release, respectively, and Q_B and Q_I are the baseflow and the reservoir release or stormflow, respectively. Equation 4 simply indicates that the observed salt load is a sum of the salt load of the baseflow and that of the reservoir release or stormflow, plus salt flushing.

Rewriting Eq. (4) for ΔS

$$\mathbf{\Delta S = C_{ob}Q_{ob} - [C_BQ_B + C_I (Q_{ob} - Q_B)]} \quad (5)$$

When ΔS is zero, the observed salt load equals the base salt load plus salt load associated with stormflow or reservoir release. The term $C_I (Q_{ob} - Q_B)$ represents salt load of flow greater than the baseflow.

The salt balance in the reservoir was computed as the difference between salt loading and unloading. The unloading components considered were outflow (or reservoir release) from the Reservoir, seepage losses, and salt storage in the stored water as well as in the bank of the Reservoir. Seepage losses were estimated by multiplying the mean salinity of the Reservoir to the seepage losses estimated as a sum of the spring flow below the Reservoir. The salt storage in the reservoir bank was estimated as the evapotranspiration losses from the bank when the shoreline receded.

Reservoir Processes: Salinity of composite flow was estimated by the flow-weighted average.

$$\mathbf{C_C = \sum C_iQ_i / \sum Q_i} \quad (6)$$

where i denotes individual flow.

Salinity of the inflow is buffered by reservoir storage. The salt balance in reservoir was first described as

$$\mathbf{C_S = (C_{SO}V_0 + C_CQ_C) / (V_0 + Q_C)} \quad (7)$$

where V_0 is the initial storage with its salt concentration C_{SO}, and Q_C is the inflow into the reservoir. The value for V_{SO} is updated by Eq. (10), and C_S became C_{SO} in subsequent calculations.

Once C_S is estimated, the reservoir water storage was assumed to consist of two layers; the top layer which is subject to evaporation and rainfall, and the second layer subjected to percolation losses (Killworth and Carmack, 1979). At the top layer,

$$\mathbf{C_{TOP} = d_{TOP}AC_S / (d_{TOP}A - V_E + V_R)} \quad (8)$$

where d_{TOP} is the depth of the top layer subject to evaporative concentration, A is the water surface area, V_E is the volume of water evaporated, and V_R the volume of rain fallen on the reservoir. The depth of the top layer (d_{TOP}) was calibrated by solving Eq. (8) for d_{TOP} and by substituting the measured outflow concentration C_{OUT} for C_{TOP}.

$$\mathbf{d_{TOP}A = C_{OUT} (V_E - V_R) / (C_{OUT} - C_S)} \quad (9)$$

where V_E, the volume of water evaporated, and is to be calculated by multiplying the water surface area and the pan coefficient to the pan evaporation data. The pan coefficient of 0.70 was used, following the calibration data of Texas Water Development Board (Unpublished). This pan coefficient was also found to be suitable in some other studies (e.g., Khan and Bohra, 1990).

The new reservoir storage was then calculated as

$$\mathbf{V_i = V_{i-1} + Q_C - V_{OUT} - V_E + V_R - V_P} \quad (10)$$

where V_P is the percolation loss, estimated from perennial springs which appear below the reservoir, and V_{OUT} is the outflow from the reservoir.

RESULTS AND DISCUSSION

Inflow Salinity and Salt Load

The mean salinity of the Pecos, the MRG, and the Rio Conchos since 1969 was 1753, 1558, and 735 mg L^{-1}, respectively (Table 2). Salinity of the Devils River averaged 248 mg L^{-1} for the same period, and was assumed to represent, for simplicity, all other sources of fresh water inflow into the Reservoir. The actual salinity of a dozen of small fresh water creeks near the Reservoir was found to average 240 mg L^{-1}. Salinity of inflow into the reservoir is determined by the flow of different tributaries, as indicated by Eq. (6). The mean salinity of the composite inflow during the period of 1969 and 2000 was found to be

Table 2. The average annual salt loading, sink, and salt balance of Amistad Reservoir 1969 - 2000

	Flow	Salinity	Load	
Inflow	Mm^3/y	(mg/L)	million/tons	%
Rio Conchos	844	735	0.621	37
Pecos	245	1753	0.429	26
MRG	188	1558	0.293	18
Devils	351	248	0.087	5
Others	943	240	0.224	14
Total	2571	643	1.654	100
Outflow and Sinks				
Outflow	2075	723	1.500	92
Seepage	131	723	0.095	6
Storage	22	727	0.016	1
Lake Bank	23	723	0.017	1
Total			1.628	100

[1] - These percentage figures are based on the total inflow including the estimated fresh water draws categorized as "others". Our earlier report lists the percentage figures based on the gauged flow.

$$C_c = (735Q_{CON} + 1558Q_{MRG} + 1753Q_{PCS} + 248Q_F) / (Q_{CON} + Q_{MRG} + Q_{PCS} + Q_F) \quad (11)$$

where Q_{CON}, Q_{MRG}, Q_{PCS} and Q_F are the annual flow from the Conchos, the MRG, the Pecos, and the fresh water from all other sources, respectively. The mean annual flow from these sources was 844, 188, 245, and 1,298 million m^3, respectively (Table 1). The mean salt concentration of the composite inflow consisting of the three salt-carrying tributaries (the Conchos, the MRG, and the Pecos) was found to be 1,050 mg L^{-1}. Inflow of fresh water near the Reservoir, estimated at 1,298 million m^3 (1,049,000 acre-ft.) per year, including the Devils River, lowered the mean inflow salinity to 643 mg L^{-1}.

The total salt loading into the Reservoir averaged 1.65 million tons annually (Table 2). The large salt loading came from the Rio Conchos at 621,000 tons/year, which is 37% of the total salt loading, mainly because of its large inflow into Amistad. The Conchos provided 884 million m^3 of flow every year, which is 33% of the inflow into the Reservoir. Salt loading from the Pecos and the MRG were 26 and 18%, respectively. The Pecos River accounted for 9.5% of the total inflow, and the MRG 7.3% of the inflow. These two tributaries provided 16.8% of the total inflow into the Reservoir, yet 44% of the salt loading. The three tributaries account for 81% of the total salt loading into the Reservoir. The contribution of flow and salt loading from the main tributaries shown in Table 2 is smaller than the figures reported earlier by Miyamoto et al. (1995), mainly because the previous estimate was based on gauged inflow only, excluding the estimated freshwater inflow obtained through the mass balance calculation.

Equation (11) and associated discussion are based on the data for 1969 through 2000. The current situation is somewhat different. First, salinity of the Conchos had increased steadily until the end of 1980s (Fig. 3). Thereafter, salinity declined with the flood of 1990 and 1991, then, due to drought, it climbed up above 1,000 mg L^{-1}. The trend of salinity increase experienced during 1969 through 1989 was extrapolated to year 2000 to express the present salinity, assuming that the flow is near normal from the Conchos. The rate of increase has been 8.6 mg L^{-1} per year, and the extrapolated salinity to year 2000 was estimated as 1,030 mg L^{-1}. (The actual salinity is considerably higher due to low flow condition). Salinity of the MRG has increased to 1,874 mg L^{-1} during 1991 through 2000, which is considerably higher than the long-term average of 1,558 mg L^{-1}. The long-term salinity of the Pecos is 1,753 mg L^{-1}, and increased to 2,107 mg L^{-1} since 1991. Thus, equation (11) was rewritten for the current situation as

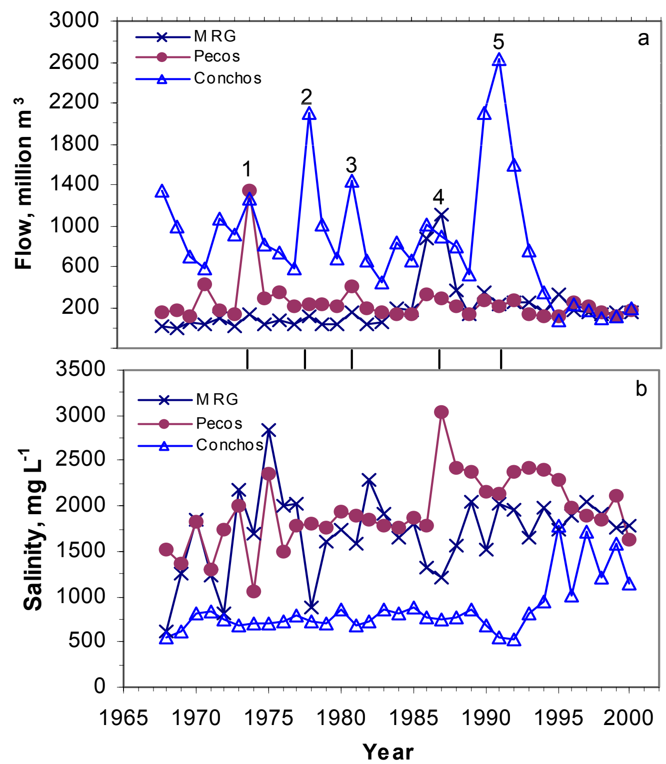

Fig. 3. Flow and salinity of the main tributaries entering Amistad Reservoir.

$$C_c = (1030Q_{CON} + 1874Q_{MRG} + 2170Q_{PEC} + 248Q_F) / (Q_{CON} + Q_{MRG} + Q_{PEC} + Q_F) \qquad (12)$$

The average salinity of the three salt-carrying flow is estimated at 1,383 mg L^{-1} for the decade of 1990s, which is a significant increase over the long term mean of 1,050 mg L^{-1} for 1969 through 2000. We assumed that the flow stayed the same, and salinity of the fresh water flow has not changed. Salinity of the composite flow was estimated to be 807 mg L^{-1}, which is a significant increase over 643 mg L^{-1} estimated for 1969 through 2000.

Salt loading into Amistad Reservoir from the three salt-carrying tributaries has fluctuated over the period examined (Fig. 4). The major loading occasions are numbered in the figure. The first large salt loading, nearly 1.4 million tons of salts occurred in 1974 from the Pecos when the annual flow registered 1.3 billion m^3, as marked by numeral 1 in Fig. 4. This was followed by two large loading events from the Conchos in 1978 and 1980 (as marked 2 and 3), and in 1990/91 (marked by 5). The large salt loading from the MRG (1.1 and 1.35 million tons) occurred in 1986/87 (marked by 4), followed by comparatively small loading in 1995. These high loading events have coincided with the high flow events as shown in Fig. 3. In most cases, streamflow salinity decreased with increasing flow; e.g., during the high flow event of 1974 from the Pecos (marked by numeral 1 in Fig. 3); during the high flow event of 1987 from the MRG (numbered as 4 in Fig. 3). However, salinity did not decrease enough to make the salt load equal to the level prior to the high flow. In all other cases, salinity did not decrease sufficiently during high flow, thus causing salt load to increase during high flow events. In the case of the Rio Conchos, high flow events were seldom accompanied by reduced salinity (Fig. 3). Salinity

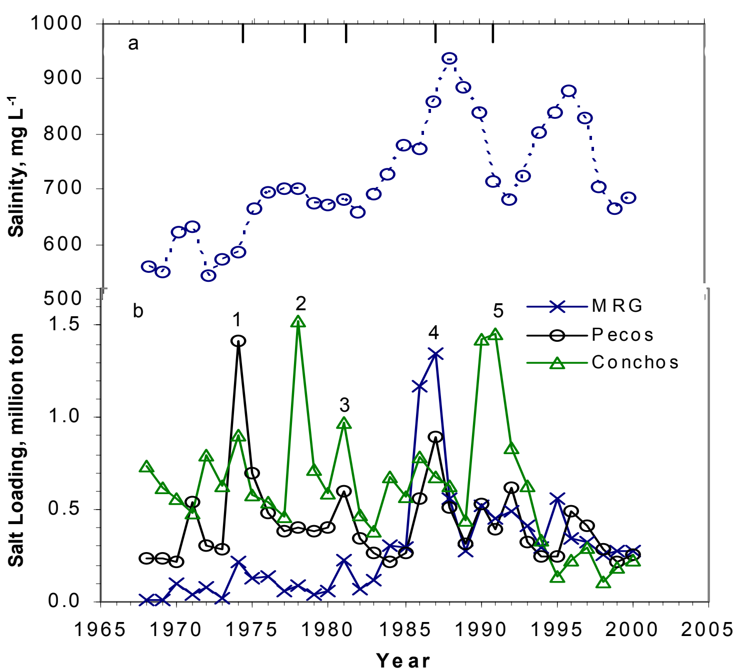

Fig. 4. Salt loading from the main tributaries, and salinity of the reservoir.

of the Reservoir has not necessarily coincided with these large salt-loading events. Reservoir processes must have affected salinity of the Reservoir.

Salt Balance and Salt Flushing

The total quantity of salt which entered into the reservoir averaged 1.65 million tons per year, and the salt unloaded during the same period through outflow (or reservoir release) amounted to 1.63 million tons per year (Table 2). The outflow accounted for 92% of the total salt unloading. Deep percolation accounted for 6%, and the salt storage gain in the reservoir amounted to only 1% of the salt inflow. However, the quantity of salts stored in the reservoir at a mean storage of 3.43 billion m^3 amounted to 2.2 million tons or 1.3 times the total annual mean salt loading. The total salt loading exceeded the unloading only by a percentage point, thus providing a degree of quality assurance for the data used.

The salt balance analyses performed using Eq. (5) at the two reaches of the MRG show a large quantity of salt pick-up from the reach between El Paso and Presidio during the high flow period of 1986 and 1987 (Fig. 5). As shown in Table 3, there was a large increase in salt load as the flow traveled through the MRG; from 0.75 to 1.16 million tons in 1986, and from 0.74 to

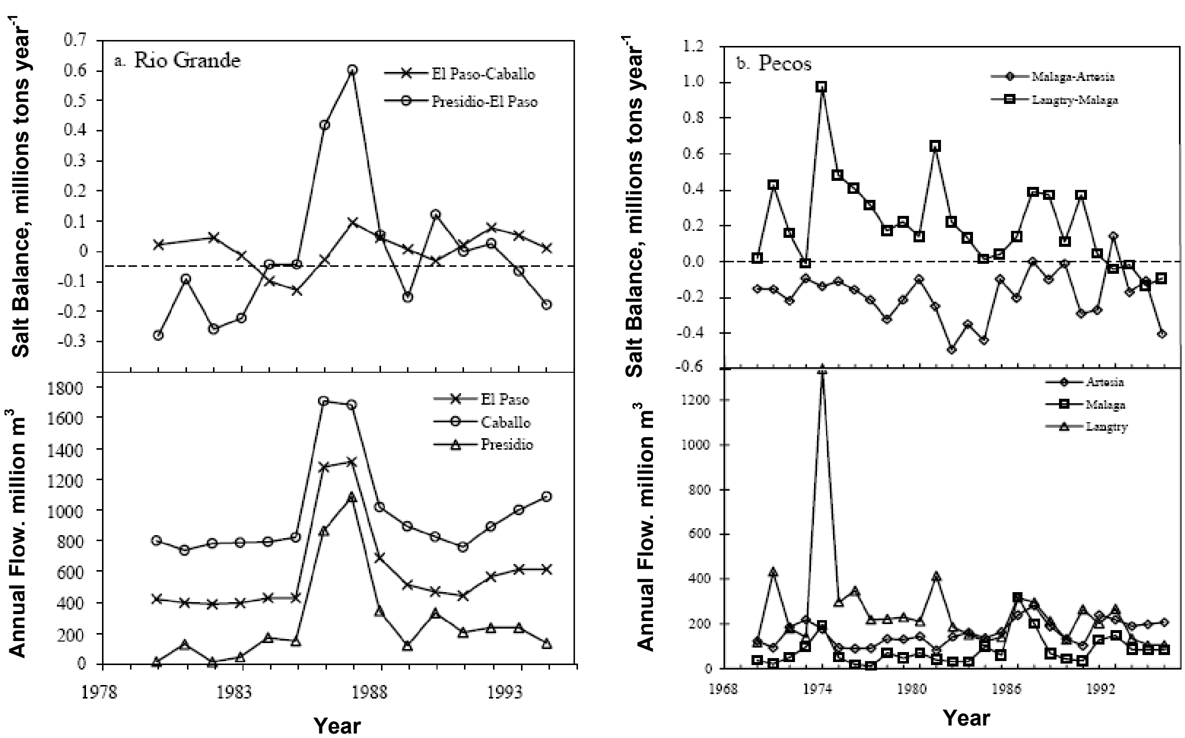

Fig. 5. The annual salt balance and the streamflow measured at three locations.

1.34 million tons in 1987 (Table 3). These data indicate that salt flushing has occurred from the reach between El Paso and Presidio, but not significantly in the reach above El Paso. The quantity of salts flushed from the reach, approximately 1 million tons for the two-year period, is large, yet it amounts to less than a three-year release of salts from Elephant Butte. During average-flow years, the annual salt release from Elephant Butte is approximately 425,000 tons (Miyamoto et. al., 1995).

The IBWC records show that there was also high flow in 1941/42 in the MRG. It produced the annual flow 2.0 billion m^3 for the two-year period, which is comparable to the flood events of 1986/87 (Table 3). However, the quantity of salts flushed during the flood events of 1941/42 was 0.72 million tons in total, which is less than the flushing recorded during the 1986/87 events. The time interval between the construction of Elephant Butte Reservoir and the flood event of 1941 -

Table 3. Salt flushing during high flow events of 1941/42 and 1986/87 from the MRG,and 1941/42 and 1974/87 for the Pecos

	The Rio Grande				The Pecos		
	Caballo	El Paso	Presidio	Year	Artesia	Malaga	Langtry
Flow (M m^3/year)[1]							
(41)	870	630	572	(41)	1667	2001	1641
(42)	2215	1920	1450	(42)	631	570	698
(86)	1722	1294	881	(74)	177	194	1342
(87)	1697	1327	1101	(87)	280	200	295
Salinity (mg L^{-1})[2]							
(41)	605	857	1542	(41)	-	1775	3036
(42)	421	560	1002	(42)	-	2802	4169
(86)	379	578	1319	(74)	-	1327	1057
(87)	411	560	1222	(87)	2344	3295	3034
Salt Load (million tons/year)							
(41)	0.52	0.54	0.88	(41)	-	3.55	5.00
(42)	0.93	1.08	1.45	(42)	-	1.60	2.90
(86)	0.65	0.75	1.16	(74)	-	0.257	1.42
(87)	0.70	0.74	1.34	(87)	0.66	0.66	0.89
Salt Flushing (million tons/year)							
(41)	-	0.01	0.34	(41)	-	-	1.43
(42)	-	0.14	0.38	(42)	-	-	1.31
	-	0.15	0.72				2.74
(86)	-	0.10	0.41	(74)	-	-	1.16
(87)	-	0.05	0.60	(87)	-	0.00	0.23
		0.15	1.01				1.39

[1] - The average river flow at Caballo, El Paso, and Presidio are 838, 499, and 164 million m^3/year.

[2] - The average salinity of the river at Caballo, El Paso and Presidio are 482, 770, and 1464. mg L-1 for the period of 1938 through 2000.

42 was 25 years, whereas the interval between the two flood events (1941 vs. 1987) was 45 years. It is possible that salts accumulated in floodways were greater in quantity prior to the flood event of 1986/87 than the previous case.

Large salt loading from the Pecos has occurred more frequently than did from the MRG: 1974, 1981, and 1987. This was followed by a series of smaller loading events (Fig. 4). The salt loading during 1974 from the Pecos was 1.43 million tons, which is as large as the loading from the MRG during 1986 and 1987. The analysis of historical data show that the salt loading during 1941 came at an unprecedented quantity of 5 million tons at Langtry, along with 1.6 billion m^3 flow at salinity of 3,000 mg L^{-1} (Table 3). The precipitation during 1974 occurred mostly below Girvin, whereas the precipitation during 1941 flood occurred above Girvin where geological salts are present. The USGS data also show that during the high flow event of 1941, salinity at Langtry was higher than at Malaga, indicating potential salt pick-up below Malaga. Unfortunately, the exact locations or reaches of salt entry into the Pecos during flood remain unknown.

High salt loading from the Conchos has also occurred frequently: 1978, 1981, 1990, and 1991 (Fig. 4). The salt load ranged from 1.0 to 1.5 million tons per year. However, the large quantity of salt loading from the Rio Conchos did not cause an increase in streamflow salinity of the Rio Grande, because the salt concentration of the flow from the Conchos has been low, except after 1995 (Fig. 3).

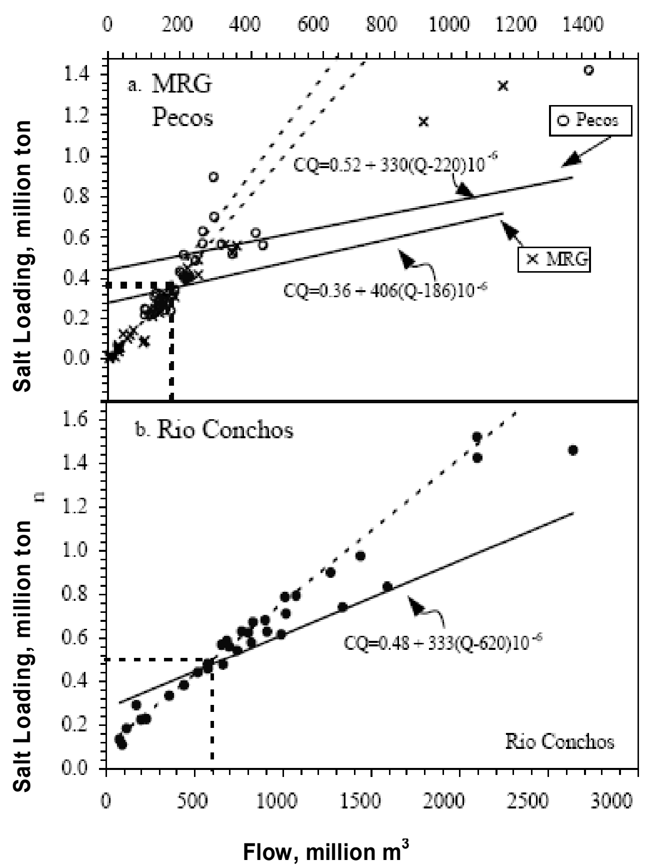

Fig. 6. The relationship between salt loading and flow at these tributaries.

The relationship between annual salt load and flow (Fig. 6) was indeed linear up to certain flow rate as assumed in Eq. (5). In other words, salinity of the flow within the flow limit was more or less constant. In the case of the MRG, for example, the flow limit was 186 million m^3/year or an average daily flow rate of 509,000 m^3, which was considered to be the baseflow. The data point then deviated from the linear relationship, due to dilution of the baseflow with flood water or reservoir release. The concentration of flood water or reservoir release, C_I was assumed to be the lowest monthly salinity reading reported. The difference between the measured and the estimated salt load by the equation shown in the figure is, in theory, the salt load gained by salt flushing. In the case of the MRG, the quantities of salt flushing estimated in this manner were roughly equal to the estimates by Eq. (3).

The relationship between salt load and flow of the Pecos River should be considered tentative as the data points were insufficient to draw a definitive line. The lowest monthly salinity recorded, 330 mg L^{-1}, was considered to be salinity of the storm runoff into the reach below Girvin. This value could be somewhat higher than the actual, as salinity of the Devils, an adjacent river, is lower, 248 mg L^{-1}. An important feature is that salt loading from the 1974 flood came well above the dilution line as shown by an open circle on the far right of Fig. 6. During the flood events of 1941 and 1942 (not shown in the figure), salt loading was even higher (Table 3). As noted earlier, the precipitation in 1941, and 1942 occurred above Girvin where halite deposits are present, whereas the precipitation in 1974 was recorded mostly below Girvin.

During the second major salt flushing in 1978, the Conchos loaded 1.5 million tons, of which 0.55 tons were estimated to have come from salt flushing. During the third major salt loading in 1981 from the Conchos, salt flushing accounted for only 25% of the total salt loading. Note that the Conchos was flushed in 1978 or 3 years prior to this event. During the major salt loading from the MRG in 1986/87, 45% of the salt loading came from salt flushing. During the last major salt loading from the Conchos in 1990 and 1991, 32 and 21 % of the salt loading came from salt flushing, respectively. Salt flushing occurs as an addition to high salt load carried through high flow.

A question arises as to the quantity of salts present on and in the floodway between El Paso and Presidio prior to bank overflow. A survey of bank salinity being conducted for the MRG between Caballo and Ft. Quitman shows that the average salt accumulation at the surface 1 cm was 10 tons/ha in the reach with no regular overflow, and only 0.3 tons/ha in the reach with regular overflow (Table 4). When the samples were taken to a depth of 120 cm, the salt storage below El Paso amounted to 144 tons / ha. The previous major flood in these reaches occurred in 1986 or 16 years prior to sampling. Soil salinity analyses made for an area outside the levee have shown that salt storage to a depth of 120 cm was 152 tons/ha. It was estimated, based on tree ring counts, that the area outside the levee was abandoned probably 22 years ago from irrigated farming. The water table there was in the range of 150 to 180 cm, and has supported good growth of salt cedars. If the salt accumulation prior to the flood of 1986 was comparable to what was observed during the survey, the salt stored in the floodway (8,240 ha) to a soil depth of 120 cm is more or less equal to the quantity of salts flushed. The streamflow records show that during 1987, there was localized flood below Ft. Quitman and above Presidio. This flood may have flushed salts accumulated in the watershed beyond the floodway. In any case, the salts stored in river bank and floodways would have been adequate to provide the salt source for flushing between El Paso and Presidio along the MRG.

Table 4. The average soil salinity and salt storage of the Rio Grande and the bank of the Pecos.

	Rio Grande			Pecos			
Soil Depth	No Overflow	Overflow	Difference	August '00		March '05	
Conductivity of the saturation extract (dS m^{-1})							
0 - 1 (cm)	200	10	190	0 - 5 (cm)	13	-	-
1 - 120 (cm)	35	5	30	5 - 15 (cm)	9	0 - 60 (cm)	8
Salinity of soil extract (g L^{-1})							
0 - 1 (cm)	200	6	194	0 - 5 (cm)	9	-	-
1 - 120 (cm)	24	3	21	5 - 15 (cm)	6	0 - 60 (cm)	6
Salt storage (tons/ha)[2] -							
0 - 1 (cm)	10	0.3	10	0 - 1 (cm)	0.5	-	-
1 - 120 (cm)	144	18	126	0 - 120 (cm)	36	1 - 120 (cm)	36
Salt storage for the area (thousand tons)							
area (ha)	8240 ha[2] -	2800 ha			2000 ha[3] -		2000 ha[3] -
0 - 1 (cm)	80	0.84	80	0 - 1 (cm)	-	0 - 1 (cm)	-
1 - 120 (cm)	1,186	50	1,130	0 - 120 (cm)	72	0 - 120 (cm)	72

[1] - The saturation water content averaged 0.50 ml/cm^3.

[2] - Include the area (2000 ha) between El Paso and Ft. Quitman.

[3] - Riparian area of the Pecos River between Red Bluff and Girvin (Hart, 2004).

The quantity of salts stored in the riparian zone of the Pecos River was estimated at 36 tons/ha, when measured in March, 2005 (Table 4), several months after the flood of November 2004. When measured again in May, 2005, bank salinity increased at some locations and decreased at other locations due to localized bank overflow associated with reservoir release. For an estimated riparian area of 2,000 ha between Red Bluff and Girvin, the salt stored is estimated at an order of 70,000 tons, based on the measurements made in March, 2005. When the bank salinity was measured in 1999 and 2000 in the same reach prior to the flood of 2004, bank salinity was in the same range (Clayton, 2002). The difference in bank salt storage between these years is too small to account for the salt flushing estimated for the reach. Salt gains noted in this reach might be a result of saline water intrusion, resulting from dissolution of geological salts (Miyamoto et al., 2005).

Salinity of Reservoir Release

Salinity of the composite flow estimated by Eq. (6) is shown in Fig. 7. The salinity pattern of the composite flow resembled, but was not identical to the measured outflow (dotted lines with open circles). The first major salt loading, which occurred in 1974 from the Pecos, did not cause any increase in salinity of the composite inflow, mainly because of the surge of fresh water flow during the year (Table 5). If the flow of the fresh water sources were at the normal level of 1.3 billion m^3, instead of 2.4 billion m^3, salinity of the reservoir could have been as high as 728, instead of 606 mg L^{-1}. In fact, when the fresh water flow settled to the normal level in 1975, salinity of the inflow increased to 703 mg L^{-1} (Fig. 7).

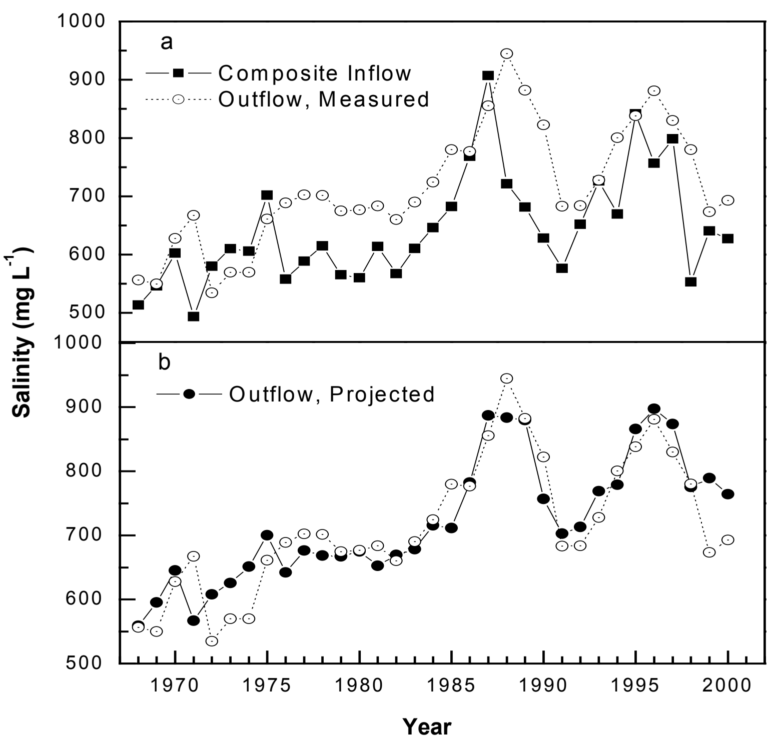

Fig. 7. Estimated salinity of the inflow, the estimated and the recorded salinity of the outflow from Amistad International Reservoir.

Salinity of the composite flow, according to the calculation by Eq. (6), has remained around 610 mg L^{-1} for a period of 1976 through '83, including years of large salt loading; 1978 and '81 (Table 5). During these years, the inflow was dominated by the Conchos plus fresh water flow which lowered salinity of the Conchos (typically around 700 mg L^{-1}) down to 600 mg L^{-1}. Nonetheless, salinity of the composite flow during the period reached a level higher than the period of 1968 through 1972, because of the combination of increased flow from the Pecos and the MRG, and the steady increase in salinity of the Conchos as well as the MRG. Fresh water flow has essentially remained at the normal level or slightly higher during this period.

The most significant salt loading from the MRG, amounting nearly twice the normal loading, did increase the concentration of inflow to 770 mg L^{-1} in 1986, and 907 mg L^{-1} in the following year. Salinity of the outflow reached 945 mg L^{-1} in 1988. Salt loading in 1986 came

Table 5. Flow, salt loading and storage status during the periods of high salt loading years and of average conditions.

	1974	1978	1981	1986	1987	1990	1991	1995	Ave[1]-
Inflow Volume (million m^3/year)									
Conchos	1269	2095	1437	1010	898	2097	2637	75	1439
MRG	125	104	144	881	1102	348	222	326	407
Pecos	1342	222	413	317	295	264	201	106	395
Fresh Water	2377	1411	1560	1543	1262	1872	1566	853	1555
Total	5113	3832	3554	3751	3557	4581	4626	1360	3797
Salinity of Inflow Sources (mg L^{-1})									
Conchos	709	726	679	780	759	679	553	1784	834
MRG	1653	887	1579	1319	1222	1349	1950	1726	1461
Pecos	1057	1820	1461	2049	3034	2018	1976	2295	1964
Fresh Water	240	240	240	240	240	240	240	240	240
Salt loading (million tons/year)									
Conchos	0.900	1.521	0.976	0.788	0.682	1.424	1.458	0.134	0.985
MRG	0.207	0.092	0.227	1.162	1.347	0.469	0.433	0.563	0.562
Pecos	1.418	0.404	0.603	0.650	0.895	0.533	0.397	0.243	1.643
Fresh Water	0.570	0.339	0.374	0.370	0.303	0.449	0.376	0.205	0.373
Total	3.096	2.356	2.181	2.970	3.226	2.876	2.664	1.144	2.563
Salt Flushing (million tons/year)									
Conchos	0.204	0.550	0.224	0.178	0.109	0.453	0.308	0	0.253
MRG	0	0	0	0.520	0.615	0.044	0.058	0.145	0.173
Pecos	0.528	0	0.020	0.098	0.350	0	0	0	0.125
Total	0.732	0.550	0.244	0.796	1.074	0.497	0.366	0.145	0.551
Salinity of Composite Flow (mg L^{-1})									
Estimated	606	615	614	792	907	628	576	842	698
Storage at Amistad (billion m^3 or mg L^{-1})									
Volume	4.97	4.82	4.66	3.58	4.34	4.10	4.49	1.51	4.06
Salinity (est)	586	605	596	711	809	680	625	734	668
Salinity of the outflow (mg L^{-1})									
Measured	570	701	683	777	855	822	683	838	741

[1]- Average of the listed events. The long-term averages are shown in Tables 1 and 2.

primarily from the MRG, and '87 from a combination of the MRG and the Pecos. Salt flushing of 1986 and '87 contributed to the salinity increase at the Reservoir (Table 5). While the loading from the Conchos was at the average, fresh water inflow in 1986 was above normal, and 1987, it was at the normal level (Table 5). If the fresh water inflow were below normal, salinity of the Reservoir would have exceeded 1,000 mg L^{-1} throughout the year.

The last major salt loading which occurred in 1990 from the Conchos caused salinity of the composite flow to decrease. This loading had low salinity (679 mg L^{-1}) due to unprecedented high flow of 2.1 billion m^3 from the Conchos, which is enough to fill half of the reservoir in one year. Salinity of inflow started increasing after the large flow event, and an example of water and salt balance is shown using the 1995 data, in Table 4. Note that the flow from the Conchos diminished: the fresh water flow curtailed, while the flow and salt loading from the MRG have increased well above the average. The inflow from the Pecos was below average, but at higher salinity than normal. These are ingredients ideal for increasing salinity of the composite flow. This type of flow situations persisted until 1998 when salinity was finally lowered due to increased fresh water flow.

Salinity of the reservoir outflow, calculated using Eq. (8) is shown in Fig. 7b. Reservoir storage reduced salinity fluctuation, but also elevated salinity as it is subject to water evaporation. The annual evaporation from the Reservoir is estimated at 340 million m^3 (276,000 acre-ft) by assuming 70% of the pan evaporation rate. The mean water surface area was estimated at 22,000 ha (54,000 acres), based on the storage and surface area relationship provided by the Reservoir operation. This amounts to 13.2% of the annual inflow. Since the precipitation on the water surface averaged 95 million m^3/year, the net evaporation loss was calculated to be 245 million m^3 per year, or 9.5% of the annual inflow. The salinity increase associated with evaporation would be 1.1 times the mean inflow salinity or 710 mg L^{-1}. The measured outflow salinity averaged 734 mg L^{-1}, which is slightly higher than 710 mg L^{-1}, and is consistent with the two-layer model used.

The measured outflow concentration was lower than the estimated during the period of 1972 through 1974. During this period, the fresh water flow from the Devils River was dominant, thus it might have pushed the saline water inflow away from the outflow structure. The spillway is located more or less at the center of the two flow regions (refer to the cover page). The same flow pattern into the spillway may have occurred after 1995 when the flow from the Rio Grande side became low, because of the drought in the Conchos Basin. Otherwise, the estimated salinity of outflow agreed well with the measured.

Potential Scenarios for Elevated Salinity

Equations (11) and (12) indicate that increasing the flow from the Pecos plus the MRG, or decreasing fresh water flow below these mean values can increase salinity of the inflow. Increasing the flow of the Conchos usually lowers salinity of the composite flow, but can also increase it if salinity of the composite flow is initially less than that of the Conchos. Increasing salinity of any of these tributaries, including fresh water, can increase salinity of the composite flow. Obviously, any reductions in inflow of fresh water (which accounts for half of the inflow) would increase reservoir salinity.

There are several scenarios which could further increase salinity of the inflow. The first scenario is that salinity of the tributaries continues to increase. According to Eq. (12), which reflects the current status, the mean salinity of the composite flow has already reached 807 mg L^{-1}. Using a conservative evaporative concentration scenario, the outflow salinity is already at 888 mg L^{-1}. The inflow salinity has increased at a rate of about 10 mg L^{-1} per year during the decade of 1990s. If this trend continues, mean salinity of the composite inflow can reach 1,000 mg L^{-1} in a decade or two, unless fresh water inflow into the Reservoir increases.

Another scenario is a potential reduction in freshwater flow, which is currently estimated to be equal to the combined flow of the Conchos, the Pecos and the MRG. These fresh water streams, including the Devils River have not yet been developed. If this fresh water resource is to be developed, for example, 20% of it, it can increase the current composite inflow salinity by approximately 10% or from 807 to 888 mg L^{-1}. The salinity of the outflow is likely to be very close to 1,000 mg L^{-1}, using the evaporative concentration of 1.1.

Another scenario relates to the future of the Pecos River. If local growers feel that the high saline water from Red Bluff cannot be used economically for crop production, there would be additional salt load of 197,000 tons/year (Table 11 of the Reconnaissance report), which may enter into Amistad (unless the release is left to infiltrate). This will increase the current total salt loading from 2.07 to 2.27 million tons/year. This will cause a salinity increase in inflow another

10%, at least in calculation. Salinity of the outflow will be very close to 1,000 mg L^{-1}. This does not include an anticipated distribution of 12 million m^3 (15,000 acre-ft.) per year from New Mexico, which can add an additional salt load of up to 70,000 tons/year. By the same token, the salt load will decrease by 150,000 tons/year if the brine intrusion at Malaga Bend is controlled.

Other scenarios, such as salt flushing and a short-term drought can push salinity over 1,000 mg L^{-1}, perhaps for a year or two, but not for a long term. Under the elevated background salinity of the inflow, these events can push salinity of the reservoir to 1000 ppm much more easily. Provided that the flow or storage stay the same, the quantity of salts required to raise salinity from 807 to 1000 mg L^{-1} is reduced by 258,000 tons per year. Another way to look at is that salt flushing of 1986/87, if occurs again, can increase salinity of the reservoir to the order of 1100 mg L^{-1}.

A more rigid estimate of future salinity of Amistad can be made by using probability statistics. In order to develop river management options to curve the current increasing trend in salinity, a model analysis is needed. Unfortunately, there is currently no reliable model which can be used to analyze all types of situations occurring on this vast watershed. Salt flushing and salt dissolution are, for example, difficult to model, but they are the prominent features of this basin.

CONCLUSIONS

The analyses presented here indicate that salt flushing from the Middle Rio Grande (MRG) and, to a lesser extent, from the Pecos River was a main cause for the sharp increase in salinity of Amistad Reservoir during 1986-1988. Salt flushing was also a significant factor in other high salt loading events. Salt flushing from the MRG seems to have originated from the salts stored in the floodplain below El Paso, and that from the Pecos River may involve dissolution of geological salts present above Girvin. Limited historical records indicate that large rainfall events in the area of halite deposits in the Pecos subbasin can flush out salts in quantities sufficient to increase salinity of Amistad Reservoir well above 1000 mg L^{-1}. The gradual increase in salinity of the tributaries over the past several decades has contributed to the increase in the background salinity, and the outflow salinity has increased from 560 mg L^{-1}, prior to dam construction in 1968, to 888 mg L^{-1} in the 1990s. Water evaporation from the reservoir increases the background salinity by 10 to 13%. Salinity of the Amistad Reservoir can exceed 1,000 mg L^{-1} under a number of combinations involving high inflow from salt-carrying tributaries (mainly the MRG and the Pecos), and/or low inflow of freshwater, especially when reservoir storage is low, or the inflow is accompanied by salt flushing. A model capable of describing salt flushing and salt dissolution, two of the unique features of this basin, would be useful for predicting future salinity trends and for evaluating river management options to curve the current increasing trends of reservoir salinity.

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