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FLOW, SALTS, AND TRACE ELEMENTS IN THE RIO GRANDE: A REVIEW

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together along the narrow strip of the Rio Grande waterway. Salts and trace metals have been flowing into this waterway from adjacent deserts, farmlands, and nearby communities. In effect, the flow of the Rio Grande has served as a means for disposing of wastewater and environmental contaminants. Separation of saline or wastewater streams from the main flow is certainly a desirable management option that must be explored. Hence, research into the development of saline water and wastewater utilization and disposal away from the Rio Grande waterway may become increasingly important in the future. Otherwise, salts and possibly certain trace elements may continue to accumulate along the narrow strip of the Rio Grande.

VI. ACKNOWLEDGEMENT

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SUMMARY

There are increasing concerns that water quality of the Rio Grande (or Rio Bravo) may be deteriorating mainly due to the recent expansion of the maquilas program and associated population relocation into the Border area. This review was conducted to assess the state of flow, salts, and trace elements in the Texas/Mexico portion of the Rio Grande and its tributaries. The data used included published and unpublished reports by federal, state, and some local sources.

The total inflow into the Texas/Mexico portion of the Rio Grande (El Paso to Brownsville) since 1969 has averaged 4.51 billion m^3 (3.65 million acre-ft) annually. Approximately 60 percent of the inflow is estimated to originate from the Mexican side. The largest flow of the Rio Grande occurs below Falcon Dam at an annual rate of 3.0 billion m^3 (2.43 million acre-ft). No significant yearly trend of annual flow was detected either by a linear regression or the autocorrelation analysis for the last 21 years. The Rio Conchos, the Rio San Juan, and the Rio Salado are the major tributaries from the Mexican side and account, respectively, for 20, 10, and 10 percent of the total inflow into the Rio Grande. The Devils River and the Pecos River are two of the major tributaries from Texas and account, respectively, for 7.8 and 6.1 percent of the total inflow into the Rio Grande.

The highest salinity of the Rio Grande occurs in the section from Fort Quitman to Presidio (2000 to 5000 mg L^{-1}) and at the Pecos River (2000 to 4000 mg L^{-1}). Salinity of the Rio Grande decreases below Presidio due to the confluence of the Rio Conchos, and it currently averages 860 mg L^{-1} at Amistad International Reservoir. However, salinity in this segment of the Rio Grande is increasing at an annual rate of 15 to 18 mg L^{-1}. If these trends continue, salinity at Amistad Reservoir will exceed 1000 mg L^{-1} by the year 2000 or will become twice the salinity level of 1969 by 2004. Salinity below Amistad has been increasing at lower rates (9 to 10 mg L^{-1}). Salinity of the Rio Conchos, the Rio San Juan, and the Pecos River has also been increasing at an annual rate of 8.5, 21, and 38 mg L^{-1}, respectively. Salinity is flow-dependent at the upper reach and at Brownsville. Elsewhere, salinity is largely independent of the annual flow and has not yet attained the steady state.

Sodicity of the main flow of the Rio Grande is at the range where soil particle dispersion begins (SAR of 3 to 4), and that of saline tail water below Fort Quitman and the Pecos River well exceeds the stability guideline. The sodicity of the Rio Grande water usually increases with increasing salinity, and the sodium adsorption ratio reaches close to 10.

The annual salt inflow into the Rio Grande between Fort Quitman and Amistad Dam is estimated at 1.84 million tons, and that between Amistad and Falcon Dam at 1.17 million tons. Saline tail water of the Federal Middle Rio Grande project and the Pecos River contributes 48 percent of the salt load to the Rio Grande above Amistad Dam, while contributing only 21 percent to the flow. These two streams plus the Rio Salado contribute 50 percent of the salt load of the Rio Grande above Falcon Dam, while contributing 26 percent to the flow of the Rio Grande. Salts have been accumulating, especially in the segments above Amistad Dam.

Existing database for trace elements is rather sketchy and is often inaccurate for some elements (e.g., Hg, Ag, and Cd). Nonetheless, most data indicate that dissolved concentrations of trace elements measured for the last 10 years at six monitoring stations along the main flow of the Rio Grande are low enough to meet the EPA primary drinking water standard, the proposed EPA criteria for livestock water supply, as well as guidelines for irrigation uses. However, dissolved concentrations of Cu, Pb, Hg and Ag often exceed the EPA chronic criteria for aquatic species protection, which are considerably more stringent than those for drinking water. Elevated levels of dissolved Hg concentrations are found in the upper reach (Elephant Butte down to Presidio) and elevated levels of dissolved Cu, Pb and V in salt marshes of the Lower Rio Grande. The concentrations of Cd, Cu, and Cr in pore water of the sediments in the upper reach appear to be many times higher than those in free water. The concentrations of many metals in fish samples collected from various locations along the Rio Grande often exceed the 85th national percentile established by the U.S. Fish and Wildlife Service. There is, however, no indications of Se problems along the Rio Grande.

With few exceptions, the concentrations of total recoverable metals found in the sediment samples from the Rio Grande main stream are below or at the average values established for soil samples from the western states, except for Hg and Pb. Acid digestible contents of metals in sediments appear to be poorly correlated with dissolved metals or the metal concentrations in fish. The concentration of acid-digestible trace elements (Zn, Cu, Cd, Pb, Ni, Cr, and V) in soil samples from irrigated fields in the El Paso and the Juarez Valleys show some indications of Cu, Pb, and Zn accumulation. Even so, the levels of these metals are well below toxic levels for plant growth or for animal health concerns. The alkaline nature of the Rio Grande seems to help maintain relatively low dissolved concentrations of metals in water, but metals are probably accumulating in soils and sediments.

Overall, this review indicates salts to be the major constraint for full utilization of water resources in the Rio Grande and that salinity is steadily increasing, especially above Amistad Dam. In these areas, salinity of the Rio Grande already exceeds the primary drinking water standard as well as the guidelines for production of high value horticultural crops. The continuing increase in salinity of Amistad Reservoir is of a special concern, as it may exceed the primary drinking water standard by as early as the year 2000 and could adversely affect high value crop production in the Lower Rio Grande. Trace element problems in the Rio Grande are sporadic and do not seem to be wide-spread at present, except from the view of aquatic species protection. There is a need to carry out a detailed salinity projection analysis, and to improve the accuracy of trace element monitoring and assessment of bioavailability indices for various ecosystems, especially in aquatic systems. Future research should also include water management options which target reuse of saline drainage water and disposal of wastewater away from the primary waterway of the Rio Grande to curtail salinization and trace element accumulation.

its, the removal of vegetation is known to increase the mobility of saline water, and thus can compound salt problems. Artificial planting of trees or agroforestry is actually being promoted as a way to reduce drainage water handling problems in several irrigated areas (Westcot 1988). Likewise, planting of deep rooted salt tolerant trees and shrubs can reduce the mobility of saline seeps by reducing recharge into saline formations (Greenwood, 1986). Future research should include the investigation of vegetation modifications especially in high saline areas with sufficient considerations to habitat protection.

2. Sodicity Control

Sodicity of the main flow of the Rio Grande is in the range where soil particle dispersion begins. In saline areas, however, sodicity already exceeds the threshold for soil structural stability (Table 7). Sewage water from some communities, including the one from El Paso, and shallow well water also exceed the threshold. The rainfall infiltration is severely curtailed under high SAR, and this has been a widespread problem, especially in irrigated fields between El Paso and Fort Quitman. Aside from potential crop damage, poor water infiltration increases the potential for runoff from irrigated land. This is a known process by which pesticides and some nutrient elements flow into surface water resources.

The control of sodicity of irrigation water is similar to the control strategy used for salinity control, because the primary source of Na is of geochemical origins. Saline water of the Morillo Drain and saline seeps at Malaga Bend of the Pecos Basin are some of the examples where the composition of the water is dominated by Na and Cl. Saline seeps originating from halite formations of the Pecos Basin have NaCl concentrations many times greater than seawater. Future research should include the identification of these concentrated Na sources as well as improved handling of Na from municipal, industrial and cooling sources.

On-farm control of sodicity involves the use of chemical amendments such as gypsum, sulfuric acid and acidulating fertilizers. These methods, however, will not reduce sodicity of the Rio Grande, but rather transfer the problem from one's field to downstream. Future research should include the development of environmentally sound on-farm management of sodic water, and improved handling of sodic drainage water.

3. Trace Element Monitoring and Bioavailability

The existing database on trace elements in the Rio Grande is preliminary at best. Nonetheless, it is apparent that one of the most probable impacts of trace elements is on aquatic species, especially relative to Hg and Cd in the upper reach and Cu, Pb, and possibly Ag in the Lower Rio Grande. Within this subject area, however, there is a great deal of uncertainty as to the level of contamination that different aquatic species can tolerate, especially at the chronic level (Miyamoto and Mueller, 1994). There is an even greater uncertainty as to how to quantify bio-availability (Alden, 1992, Alden and Rule, 1992, Chapman, 1986). This task can be further complicated by heterogeneity in parent material as well as by the large spatial variation in sediment quality and trace element concentration existing in the Rio Grande system. These fundamental questions must be addressed before the question of levels of the control can be addressed.

The analysis of dissolved trace elements in water, which has been used routinely for water quality appraisal, seems to have a limited value in assessing their impact on aquatic species, as alkali streams usually provide low readings. The analysis of sediment metal levels provides an indication of contamination levels, but it does not seem to be the credible indicator of bio-availability. This is partly evidenced by the poor correlation observed between metal levels in sediments and fish (Table 17). Dissolved metals in pore water of the sediments seem to be a somewhat better indicator of assessing bio-available metals for some species. The actual processes through which fish or other aquatic organism assimilate metals are complex, involving physical, chemical, and biological interactions (Burton, 1991). Future research must provide improved methods of assessing bio-availability, especially Hg, Cd and Cu which are detected at elevated concentrations in several sections of the Rio Grande, notably at Elephante Butte and Caballo Dam.

4. Water Management

Aside from monitoring, future research should include an evaluation of overall water management schemes, backed by a sound water quality model. To a large extent, both salinity and trace element problems are induced by the fact that water supply and wastewater streams are bunched the steady-state, and future research should include the examination of this trend and the projection for the future.

Dilution has been the most pragmatic method of dealing with salt problems. Undoubtedly, this is the process which keeps salinity under control below Amistad Dam. Even above Amistad, dilution is an important process. If fresh water inflow from the Devils River and small streams were absent, the salinity of Amistad Reservoir would be as high as 1,200 mg L^{-1}, instead of the current level of 860 mg L^{-1}. A potential may exist to enhance water yields and small stream flow for dilution. Realistically, however, economic developments have traditionally curtailed opportunities for dilution by increasing utilization of fresh water resources. This is likely to be the scenario along the Rio Grande, as already evidenced in the El Paso/Juarez section. Future research should include evaluation of minimal base flow required to achieve economic control of salinity of the Rio Grande.

Assuming that opportunities for dilution are likely to be limited in the future, strategies to control salinity must then focus on either increasing salt removal, minimizing salt inflow into the Rio Grande, or reducing evaporative losses of water, which concentrate salts. Although techniques to remove salts such as reverse osmosis and electrodialysis exist, they are not suitable for a basin-wide salinity control objective. The quantities of salts that must be removed are in an order of a million tons every year in the upper reach alone (Table 12). Therefore, the solution to increasing salinity of the Rio Grande may have to rely more on reducing salt inflow.

The source of salts is mostly of geochemical origins. In addition, some salts (especially Na and Cl) are added to the watershed through the atmospheric fallouts of salts (either rain wash or dry fallouts) of the ocean aerosol from the coast to as far as Laredo (Junge and Werby, 1958). These sources are diffused and are not easy to control. However, many of the saline inflows are confined to certain geo-topographical formations. In the case of the Pecos River, for example, saline seeps that enter the river in the Malaga Bend area are considered among the major sources of salts (Hale et al., 1954). Likewise, irrigation return flow is to some extent a point source of discharge, and some of these sources are also controllable. Future research should include the identification of salt sources having a potential for control and their impact on salinity of the Rio Grande.

Salinity control through diversion of saline water or through transport of saline drainage water away from the main flow has been used effectively in many water quality control projects. This option is used only to a limited extent in the Rio Grande Basin; e.g., the disposal of the Morillo drain into the Gulf and an experimental pumping and transport of saline seeps at Malaga Bend (Hale et al., 1954). The diverted saline water must be disposed of in a manner consistent with environmental protection objectives. This usually means evaporation, recharge, and/or deep well injection, unless ocean or inland lake disposals are feasible. Future research should include the development of cost-effective and ecologically sound saline water disposal options, including such options as saline solar ponds and salt mining.

Another challenge is the control of irrigation return flow. Substantial quantities of return flow can be reused through dilution or blending (Rhoades et al., 1988). However, as salinity of the blend becomes high enough to exceed salinity limits for crop production, it must be viewed as the case of water contamination. The saline tail water from Fort Quitman, the Pecos River, and many return flow streams fall into this category. The diversion of these saline water sources which are currently entering the Rio Grande can reduce the salt load of Amistad Reservoir by a significant proportion. A practical problem is that salinity of most return flow is not high enough to justify disposal by evaporation or injection, especially when considering a widespread grower sentiment that salty water is better than no water. The reuse of saline agricultural drainage water without dilution requires the development of highly salt tolerant crops (e.g., Miyamoto, 1993) and/or saline aquaculture, plus disposal options for the concentrated saline water.

Salinity control through modification of evaporation or evapotranspiration is another potential measure. The long stretch of the Rio Grande and its tributaries is infested with a thick stand of Tamarix and other vegetation. When salinity of water is low, the removal of such vegetation can potentially help maintain low salinity by reducing transpiration which increases salinity. However, eradication of river bed vegetation is costly, and is accompanied by an increase in evaporation from waterways. In some cases, it may conflict with game and wildlife preservation interests. When salinity of the water already exceeds economic lim-

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The State of Texas also provides the criteria for public water supply, which are adjusted to local water quality (Table 23). These criteria are similar to the federal secondary drinking water standards. Again, the total dissolved salt concentrations of the Rio Grande often exceed the criteria.

3. Livestock Water Supplies

The proposed EPA criteria for livestock water supply are similar to those of human drinking water supply, except that limits for As, Hg and Pb are lower in livestock water supply (Table 24). The reported quality of the Rio Grande (Table 13) meets these criteria.

4. Aquatic Species Protection

Water quality criteria for aquatic species protection are considerably more stringent than those for drinking water, especially the chronic criteria for Hg and Ag (Table 25). Compared with the reported data (Tables 13 and 14), dissolved concentrations of Cd, Cr, Ni, Se and Zn appear to meet the criteria with no difficulty. The concentrations of Cu also meet the fresh water standard in most parts, except in the salt marsh areas of the Lower Rio Grande. The salt water criteria for Cu is 2.9 µg L^{-1} for both acute and chronic standards and the reported values clearly exceed this limit as well as the fresh water chronic criteria. The dissolved concentrations of Pb (Table 13 and 14) also often exceed the criteria. The standards for Hg and Ag are extremely stringent, and it is very possible that the concentrations of Hg (Table 14) frequently exceed these limits. Additional discussion on trace element effects on aquatic species is given elsewhere (Miyamoto and Mueller, 1994).

Table 24. The proposed EPA criteria for water supply to livestock.

As	B	Cd	Cr	Co	Cu	Pb	Hg	Se	Zn
....					µg L^{-1}	....			
20	5000	50	1000	1000	50	10	1	50	2500

Although the dissolved concentration of most elements are either below the limits or somewhat above the criteria, many reported concentrations of metals in fish tissue (Table 17) exceed the 85th national percentiles (e.g., Hg = 0.18 mg kg^{-1}, Pb = 0.33 mg kg^{-1},) and some measurements show occasional extremes. These elevated concentrations of metals in fish tissue may be partly associated with metal release from the sediments. The metal concentrations in pore water of the sediments (Table 14) exceed the criteria set for free water by manyfold, except for Mo and Se. However, the reported concentrations of total metals in sediments (Tables 16 and 17) are close to the mean values for the western region (Shackett and Baernaen, 1984), except for Pb and Hg. The total Hg for the western soil average is 0.046 mg kg^{-1}. (Those western standards are determined based on the total digestion.)

Table 25. Water quality criteria for protection of fresh water aquatics.

	As	Cd	Cr	Cu	Hg	Ni	Pb	Ag	Se	Zn
	....				µg L^{-1}	....				
Fresh Water Acute Criteria: Inorganic										
EPA	—	3.9	16	18	2.4	1800	82	4.1	260	320
Fresh Water Chronic Criteria: Inorganic										
EPA	190	1.1	11	12	.012	96	3.2	0.12	35	47
Texas										
Current	—	2.3	438	28	.012	342	10	0.12	35	230
Proposed	—	2.3	438	28	1.3	342	10	0.12	5	230

V. IMPLICATION TO FUTURE RESEARCH

1. Salinity Control

This review indicates that salinity is a major constraint for full utilization of water resources in the Rio Grande Basin. The finding is consistent with the statewide statistics, indicating salts to be the second most common contaminants after microbial pathogens (TWC, 1990). High salt problems are most pronounced in the upper reach where the rainfall is minimal. What is most disturbing is the fact that salinity of the main flow of the Rio Grande as well as many tributaries is increasing at significant rates: e.g., 15 mg L^{-1} at Amistad Dam and 38 mg L^{-1} per year at the Pecos River. Salinity in the Rio Grande has not reached exceed 20 and 10 μg L^{-1} in irrigation water, respectively. However, they suggested raising the allowable limits of Se and Mo to 100 and 50 μg L^{-1}, respectively, for waters high in SO_4. (The presence of SO_4 ions usually reduces the uptake of Se and Mo). When we compare Se levels in the Rio Grande (1 μg L^{-1} or less) with the guidelines, the potential for Selenosis appears to be remote. The concentrations of Mo in whole water samples are, however, within the range that can allow toxic levels of accumulation in plants, especially in halophytic species.

Chaney (1987) has recently summarized trace element uptake and plant barriers that limit uptake of toxic trace elements (Table 22). According to his review, Cd and Co should be added to the potential food chain contaminants, besides Se and Mo. Both elements, especially Cd are highly toxic to animals, but not to forage crops. Therefore, the uptake of these elements by plants can continue to the level toxic to animals without causing phytotoxicity. However, both Cd and Co concentrations detected in the Rio Grande are low, and it is unlikely that these elements accumulate in plant tissue to the level of causing animal toxicity. Metal levels reported in alfalfa fields irrigated with a mixture of sewage and the Rio Grande water seem to show some indication of Cu, Zn and Pb accumulation in soils (Table 18). However, these values are within the typical values for the soils of the western United States, and well below the levels that are considered to cause toxic effects (Table 18). These guidelines are based on the total metal concentrations in soils (Kabata-Pendias and Pendias, 1992). This, however, does not rule out the possibility of toxic levels of accumulation in plant tissue if high levels of metal are accompanied by high levels of organic matter under low pH. Cajuste et al. (1991), for example, reported toxic levels of Cr and Pb accumulation in alfalfa when irrigated with raw sewage water contaminated with industrial wastes in Mexico. In their case, sewage water used for irrigation contained 112 and 68 μg L^{-1} of dissolved Cr and Pb, respectively, and 680 and 188 μg L^{-1} in whole water. Such conditions, however, rarely exist in the Rio Grande Basin, except in areas where illegal dumping may have occurred. Another potential case for trace element accumulation may include uptake by halophytes which grow in saline areas and salted-ditch banks, and are consumed by ruminants. These plant species have special cell structures which allow high levels of salt accumulation in plant tissue (up to 30 to 40 percent of the dry plant biomass). Several exploratory studies indicate that halophyte species can accumulate high concentrations of Se (Banuelos and Meek, 1990) and even Cu (Reboredo, 1991).

2. Public Water Supplies

The primary drinking water standards for inorganics were established by the EPA as the Federal Standard (Table 23). The Texas State Standards conform to the EPA standards, except for Hg (Table 23). Dissolved trace elements in the Rio Grande (Table 13) appear to be well below these standards.

The secondary drinking water standards established by the State of Texas are shown in Table 23. The quality of the Rio Grande often exceeds the TDS limit of 1000 mg L^{-1}. Salinity of Amistad Reservoir may exceed this standard as early as the year 2000 if the current salinity increase trend continues (Table 8). The concentrations of Cl and SO_4 come close to the limit, but seldom exceed. The concentrations of Cu and Zn in the Rio Grande are well below the standards.

Table 22. Maximum tolerable levels of dietary minerals for domestic livestock comparison with levels in conventional forages (Chaney, 1989).

	Levels in plant foliage		Maximum levels chronically tolerated			
Element	Normal	Phytotoxic	Cattle	Sheep	Swine	Chicken
	(mg kg^{-1} dry foliage)		(mg kg^{-1} dry diet)			
As	0.01-1	3-10	50	50	50	50
B	7-75	75	150	(150)	(150)	(150)
Cd	0.01-1	5-700	0.5	0.5	0.5	0.5
Cr	0.01-1	20	(3000)	(3000)	(3000)	(3000)
Co	0.01-0.3	25-100	10	10	10	10
Cu	3-20	25-40	100	25	250	300
Mo	0.1-3.0	100	10	10	20	100
Ni	0.1-5	50-100	50	(50)	(100)	(300)
Pb	2.5	—	30	30	30	30
Se	0.1-2	100	(2)	(2)	2	2
V	0.1-1	10	50	50	(10)	10
Zn	15-150	500-1500	500	300	1000	1000

Table 23. Drinking water and public water supply criteria.

Primary Drinking Water Standards: Inorganics

	As	Ba	Cd	Cr	Pb	Hg	Se	Ag
	μg L^{-1}							
Texas	50	1000	10	50	50	12	10	50
EPA	50	1000	10	50	50	2	10	50

Secondary Drinking Water Standards: Inorganics

	TDS	Cl	SO_4	Cu	Zn	F	Mn
	mg L^{-1}						
Texas	1000	300	300	1.3	5	2	.05

Texas Public Water Supply Criteria

	Salinity	C	SO_4
	mg L^{-1}		
El Paso - Riverside	1500	300	550
Riverside - Amistad	1200	200	500
Amistad	500	150	250
Amistad-Falcon	1000	200	300
Falcon	700	200	250
Below Falcon	880	270	350

I. INTRODUCTION

The Rio Grande (or El Rio Bravo) is among the longest rivers in North America and constitutes the international border to Mexico in the stretch from El Paso to Brownsville, Texas or Cd. Juarez to Matamoros, Mexico (Figure 1). Undoubtedly, this water resource is what makes the Texas-Mexico portion of the Border a highly productive area in otherwise largely semi-arid desert. There are, however, increasing concerns that quality of this river may be deteriorating mainly due to the recent economic development through the expansion of the maquila program and associated population inflow into the Border area. This review, largely preliminary, was carried out in order to outline the flow of the Rio Grande and the state of water quality focusing on inorganic pollutants: salts and trace elements.

Historically, the area along the Rio Grande had been sparsely populated by various Indian tribes, then by Mexican refugees who fled from Spanish rule. The major development of the Rio Grande began after the passage of the Reclamation Act in 1902. The construction of the first major reservoir, Elephant Butte Dam, was completed in 1916, and this was followed by the construction of two additional large international reservoirs, Falcon Dam and Amistad Dam in 1954 and 1968, respectively. These water projects have transformed the Rio Grande flood plains into a major agricultural area of Texas. Starting at the mid '50s, the population inflow into the Border region began to accelerate. Textile and apparel industries and retailing along with agricultural sectors have provided much of the increased employment opportunities. In some areas, such as El Paso and Harlingen, increased military installation helped economic developments and employment opportunities, especially during the '60s and the '70s.

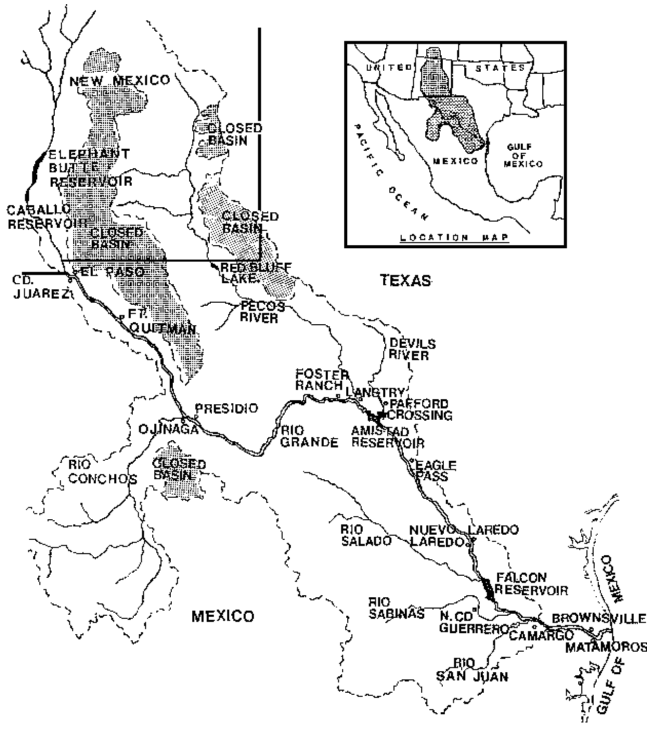

Figure 1. The Rio Grande, its tributaries, and drainage basins.

Starting at the beginning of the '80s, manufacturing became a strong addition, especially to the El Paso/Juarez, Laredo/Nuevo Laredo, McAllen/Reynosa, and Brownsville/Matamoros areas. This trend was accentuated by the sweeping trade liberation policy of Mexico instituted in 1986. Maquila plants, which assemble U.S. made parts on the Mexican side of the Border, have sharply increased since 1986 and reached 534 plants by 1989 along the Texas-Mexico Border alone (Table 1). The maquila development on the Mexican side of the Border also impacted economic developments on the U.S. side. The 1988 report by the Bureau of Economic Statistics indicates that the gross revenue of El Paso County (1.8 billion dollars) was accounted for 30 percent by manufacturing, 27 percent retailing, 27 percent services, and 4 percent by crop and livestock with respective employments of 32, 36, 31, and 0.4 percent. El Paso County is the most urbanized county along the Rio Grande and has clearly evolved from an agricultural county to a county of manufacturing and services. Elsewhere along the Rio Grande, similar trends have begun to appear, although the stage of development varies.

Table 1. Number of maquilas in Mexico as of 1989 (Twin Plant News).

Border to Texas		
Cd. Juarez		290
Matamoros		72
Nueva Laredo		67
Reynosa		43
Cd. Acuna		32
Piedras Negras		30
	Total	534
Border to Calif. & Arizona		
Tijuana		334
Mexicali		131
Nogales		64
Tecate Ensenada		33
Others		79
	Total	641
Interior Mexico		
	Total	285
	Grand Total	1460

One of the most obvious consequences of the economic development has been the massive population inflow into border communities on both sides, but especially on the Mexican side. In 1980, the population of border cities on the Texas side was estimated at 1.2 million, and one-third of this population resided in El Paso (Table 2). By 1990, the population has increased to nearly 1.6 million which is a 32 percent increase during the decade. The population of border communities along the Mexican side (border to Texas) was estimated at 1.5 million in 1980, only slightly greater than the Texas side at the time. By 1990, the population on the Mexican side soared to 2.2 million, some 51 percent increase in the ten year period. The population growth at the border is expected to continue toward the year 2000 at a rate of 5 to 7 percent in Cd. Juarez and 2.7 to 3.8 percent in El Paso (Planning Department, the City of El Paso).

The rapid economic development and population growth elevated the level of concern over the management of water resources, especially of the Rio Grande. The population growth, for example, has increased the water demand from municipalities, notably in the El Paso/Juarez portion of the Border. Fortunately, much of the new demand from municipalities has been met through exploitation of relatively clean and inexpensive ground water resources. There is, however, a strong indication that the surface water withdrawal from the Rio Grande has to increase in time to meet the increasing water demand from municipalities (Eaton and Andersen, 1990). Even so, the overall quantity of inflow into the Texas/Mexico Border portion of the Rio Grande is large: 3.3m^3 per capita per day or 870 gallons/capita/day as compared to a typical water use rate of 100 gallons/capita/day in urban sectors of U.S. cities. Although quantity shortages already exist in some areas, e.g. the El Paso/Juarez section, the availability of water is large enough to sustain traditional irrigated agricultural activities, while allowing additional municipal and industrial developments. A greater problem has been the deterioration of water quality which has placed various constraints for full utilization of water resources.

Table 2. Population changes in the major cities and adjacent areas along the Texas-Mexico Border (U.S. and Mexican census).

	Actual		Projected	Increase
	1980	1990	2000	1980- 90
	................thousands	....		percent
U.S.				
El Paso (city)	425	535	645	26
Laredo	99	139	169	40
McAllen	66	93	113	41
Harlingen	52	64	73	23
Brownsville	33	35	37	6
Others[1]	519	710	842	37
Texas total	1194	1576	1879	32
Mexico				
Cd. Juarez areas[2]	751[3]	1330[3]	2354	77
Matamoros areas	239	303	—	27
Reynosa areas	211	281	—	33
Nuevo Laredo areas	203	217	—	5
Piedras Negras areas	67	96	—	43
Mexico total	1471	2227		51
Border total	2665	3803		42

[1] These include Del Rio/Eagle Pass, and many small communites in the lower Rio Grande.

[2] The population in Mexican communities includes those within city limits plus adjacent areas.

[3] Data from the El Paso Planning Department. The Mexican census shows lower figures; 567 and 787 thousands for 1980 and 1990, respectively.

The discharge of poorly treated (or untreated) sewage effluents has already caused extensive contamination of both surface and shallow groundwater resources by pathogens (Eaton and Hurlbut, 1992). The incidents of water-borne diseases such as Hepatitus A and Sigaria along the border are many times higher than the respective national averages. In addition, there is an increasing fear that chemical pollution of surface water may increase with increased industrial activities (Lewis and Ormsby, 1990). In addition to the impacts of deteriorating water quality on human health, the preservation of wildlife, especially aquatic species and waterbird has been an issue, especially in the Lower Rio Grande (Gamble et al., 1988; White et al., 1983; White and Cromartie, 1985; Wells et al., 1988). The Lower Rio Grande is a habitat for some 86 species which are on the endangered list. Many fish and waterbird samples collected in the area have shown elevated levels of various metals and pesticides (mostly organochlorine type).

Meantime, infrastructure developments along the border have lagged behind the rate of population growth. In fact, most communities along the Mexican side still lack sewage treatment facility, and raw sewage and industrial effluents are discharged into irrigation water supplies or into drain ditches. There are, however, efforts to built sewage water treatment facility, especially in large population centers such as Cd. Juarez and Nuevo Laredo. On the U.S. side, rural communities along the Rio Grande are also in need of upgrading their sewage treatment capabilities as well as industrial effluent pretreatments. Yet, this area is anticipating additional economic activities through the North American Free Trade Agreement (NAFTA). This agreement is widely believed to stimulate economic activities beyond the immediate border areas, especially on the Mexican side of the Rio

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fects of sodicity. The soils with minimal tillage and those having sod covers are less susceptible to the dispersing effect of sodium. Under sodded conditions, the primary water conduction occurs through macropores, and structural cracks developed by swelling and shrinking. Table 20 shows the relative reduction in infiltration rates into three typical soils of the Rio Grande after mechanical pulverization down to less than 2 mm in size (Miyamoto, 1989). The reference infiltration is taken when no Na is present as well as when the ratio of SAR to EC (in dS m^{-1}) or SAR is unity. The latter may be a more realistic point of reference. The primary cause of this severe reduction in infiltration rate is usually related to rapid disintegration of weak soil aggregates at the soil surface, which forms an effective seal in fine-textured soils. The SAR/EC ratios or SAR of the Rio Grande in most part range from 3 to 5. This range of sodicity should be viewed as a factor of reducing water infiltration when the soils are pulverized excessively with disking. Poor water infiltration not only affects crop production, but also increases surface ponding and/or runoff.

c. Trace Elements

Trace elements in irrigation water are of concern for both phytotoxicity and toxic element accumulation in plants. Boron is the most common trace element which causes phytotoxicity to many crops (Ayers and Westcot, 1985). Pecans, grapefruits, oranges, peaches, and several vegetable crops are susceptible to B phytotoxicity at dissolved B concentrations as low as 0.5 to 0.75 mg L^{-1} (Ayers and Westcot, 1985; Picchioni et al., 1991). The boron concentration in the main flow of the Rio Grande water is usually less than 0.5 mg L^{-1} (Table 13), and B phytotoxicity is not a significant problem in cropland irrigated with the main flow of the Rio Grande.

Table 20. Relative infiltration rates of irrigation or rain water into three typical soils of the Rio Grande as affected by salinity (EC) and sodium adsorption ratio (SAR): The reference infiltration rates were taken at SAR = 0 and SAR = 1.0 (Miyamoto, 1988).

	Gila loam		Sanali S. C. loam		Glendale C. Loam	
SAR/EC[1]	Irrigation water infiltration					
0	1.00	—	1.00	—	1.00	—
1	0.85	1.00	0.76	1.00	0.59	1.00
2	0.72	0.85	0.59	0.78	0.35	0.59
3	0.62	0.73	0.47	0.62	0.21	0.36
4	0.52	0.61	0.37	0.49	0.13	0.22
5	0.45	0.53	0.29	0.38	0.08	0.14
6	0.38	0.49	0.23	0.30	0.05	0.09
7	0.32	0.38	0.18	0.24	0.03	0.05
SAR	Rainwater infiltration					
0	1.00	—	1.00	—	1.00	—
1	0.66	1.00	0.62	1.00	0.15	1.00
2	0.55	0.83	0.52	0.84	0.14	0.93
3	0.47	0.71	0.46	0.74	0.14	0.93
5	0.36	0.99	0.36	0.58	0.13	0.87
7	0.26	0.39	0.28	0.45	0.13	0.87
10	0.15	0.23	0.19	0.31	0.12	0.80
15	0.0062	0.0094	0.08	0.13	0.11	0.73

[1] The unit for SAR in (mmol L^{-1})$^{-1/2}$ and EC in dS m^{-1}.

The toxic effects of other trace elements on plant growth have been studied mostly in nutrient solutions. Based on these results, several guidelines were recently developed by Pratt and Suarez (1990) for evaluating the maximum allowable concentrations of trace elements in irrigation water for protection of plant growth as well as potential toxicity to animals (Table 21). Trace element concentrations of the Rio Grande water (e.g., Table 13) are well below these guidelines. It is unlikely that trace elements become a source for phytotoxicity. This assessment stands even when the trace element concentrations in whole water samples (Table 14) are used for the assessment. One exception appears to be V and B, both of which appear at high concentrations in the salt marsh of the Lower Rio Grande (Table 13). However, these waters are not used for irrigation because of high salinity.

The accumulation of trace elements in plants and subsequent contamination of the animal food chain is of another concern. Molybdosis and Selenosis are two of the most common diseases associated with excessive plant uptake of Mo and Se, respectively. Pratt and Suarez (1990) recommended that the maximum concentration of Se and Mo should not

Table 21. Guidelines for the maximum concentrations of trace elements in irrigation water for protection of animal health and plants (Pratt, and Suarez, 1990).

Protection from phytotoxicity		
	µg L^{-1}	
As	100	Phytotoxicity may occur above this concentration
B	750	Phytotoxicity to sensitive tree crops
Cd	10	Phytotoxicity at 100 µg L^{-1} in sensitive plants in nutrient culture
Co	50	Phytotoxicity at 100 µg L^{-1} in some plants in nutrient culture
Cr	100	Phytotoxicity at 500 µg L^{-1} in some plants in soil culture
Cu	200	Phytotoxicity at 100-1000 µg L^{-1} in plants in nutrient culture
V	100	Phytotoxicity at 500 µg L^{-1} in plants in nutrient culture
Protection of animal health		
	µg L^{-1}	
Se	20	Protection from Selenosis
	100	For water with high SO_4
Mo	10	Protection from Molybdosis
	50	For water with high SO_4
Cd	10	Considering potential effects on human food chain contamination

peaches which are economically important crops on both sides of the border. However, even at irrigation water salinity of 1 dS m^{-1}, salt damages have occurred to pecans and citrus planted in clay textured soils (Miyamoto et al., 1984; Miyamoto et al., 1986). Erratic stands of many vegetable crops, especially pepper and onions under furrow irrigation have also been observed (e.g., Miyamoto, et al., 1986). If salinity of the Rio Grande continues to increase at the current rates, the salinity at Amistad Reservoir will exceed 1.5 dS m^{-1} (1,000 mg L^{-1}) by the year 2000 and at Falcon by the year 2010. This can have a significant impact on production of salt sensitive crops in the Lower Rio Grande.

Field and forage crops can be grown satisfactorily at higher levels of salinity (Table 19). However, their cash outputs per unit quantities of water used are usually a fraction of those of vegetable and tree crops. Cropping patterns in high saline areas such as Pecos, Presidio, and Fort Quitman areas have already changed to forage, cotton, and grains. However, this has caused a significant reduction in farm revenue and a severe reduction in irrigated acreage (TDA, 1990). In addition, the use of high salinity water for irrigation results in higher salinity in drainage water. Under the existing system of drainage water handling in most parts of the Rio Grande, agricultural drainage water becomes a major portion of irrigation return flow which is a significant source of both surface and subsurface water contamination. This process of water salinization is especially evidenced in the upper reach where saline agricultural drainage water from the El Paso Valley and the Hudspeth Irrigation District flows back into the Rio Grande.

In addition to salt stress, several crops are known to suffer from specific ion toxicity involving Na and Cl (e.g., Ayers and Westcot, 1985). The toxic effect of Na appears primarily in tree crops, especially in pecans (Miyamoto et al., 1985). Likewise, Cl toxicity often appears in tree crops, but Cl concentrations in the majority of the Rio Grande water (less than 200 mg L^{-1}) are below the threshold with the exception for citrus and prunus species.

b. Sodicity

Sodicity of irrigation water has a major impact on structural stability of soils and permeability. The structural degradation of soils increases with increasing sodicity, but is also influenced by soil types, salinity levels, and soil management practices. In general, soil structural degradation is at maximum when soils are mechanically pulverized and brought into contact with water of low salinity such as rain water. Figure 6 shows an increase in suspended solids in drainage water with increasing sodicity. Three typical alluvial soils of the Rio Grande were leached with rain water, and suspended solids measured (Miyamoto, 1989). Coarse-textured soils such as Gila loam tend to disperse more readily than fine-textured soils, and the dispersed particles are transported by water. The dispersion increases rapidly when the sodium adsorption ratio (SAR) exceeds 3 to 4.

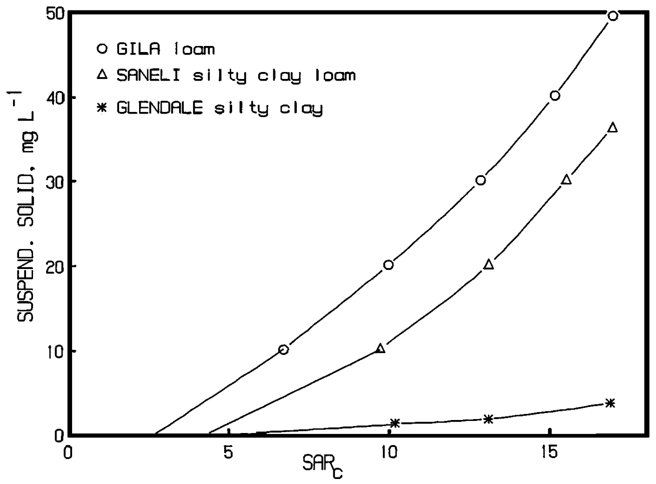

Figure 6. The concentration of suspended solids in leachates when three soils from the El Paso Valley having initially different sodium adsorption ratios (SAR) were leached with distilled water (original data from Miyamoto, 1989).

The sodicity of the main flow of the Rio Grande is in the range of 3 to 4 in SAR (Table 7), whereas the sodicity of some tributaries (e.g., the Pecos river) and of the flow between Fort Quitman and Presidio is considerably higher, reaching 8 to 10 in SAR. Municipal sewage water from El Paso also has SAR values of 6 to 8. Irrigation with the sewage water has caused soil dispersion, soil hardening, and crop establishment problems in the El Paso Valley (Miyamoto et al., 1984). The principal problem occurs at the soil surface where salts accumulate following upward capillary flow and water evaporation. During this process, Ca precipitates, and salt concentrations increase. Both of these processes cause a sharp increase in SAR at the soil surface (Miyamoto and Pingitore, 1993). A recent field measurement in the surface of the crop beds shows that the SAR can reach 10 to 25 even when irrigated with the Rio Grande water having SAR of as low as 3.1 (Miyamoto and Cruz, 1987). This is the range where soil particle dispersion becomes a major problem (Figure 6).

The effect of sodicity on water infiltration depends on salinity levels, soil types, and soil management. In general, reducing salinity increases the adverse effects of Na. Thus, sodicity has the greatest impact on infiltration of rain water. Also, the soils that are mechanically pulverized, e.g. by excessive disking, are most subject to the adverse ef-

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Grande drainage basins. This can have a significant impact on quantity and quality of the inflow into the Rio Grande from the Mexican side. The majority of the surface inflow into the Texas portion of the Rio Grande originates from Mexico (Sullivan and Critendon, 1986).

It is quite obvious that management of the Rio Grande is now entering a new era, and must satisfy not only the traditional agricultural interest, but also must meet increasing needs from municipalities, industrial sectors, and for the preservation of wildlife. To meet these diverse uses of water, there is an increasing need to develop water quantity and quality management strategies for the Rio Grande and its tributaries (EPA/SEDUE, 1992). This document was prepared mainly to provide the background information on the Rio Grande, with emphasis on flow, salinity, and trace elements. The information on water contamination by poorly treated or untreated sewage is already available (Eaton and Hurlbut, 1992; EPA/SEDUE, 1992). The information presented here is largely preliminary. However, it is hoped that this review will help outline the state of water quality relative to inorganic contaminants, delineate some of the data gaps, and define the priority areas for research.

II. FLOW OF THE RIO GRANDE

1. Hydrology

The Rio Grande Basin consists of two major watersheds. One originates from the southern slopes of the Colorado Mountains and northern New Mexico, another from the mountain ranges of Chihuahua, Mexico and the Pecos Basin of southern New Mexico and far west Texas. Although the Rio Grande is shown as a continuous river, the flow from the Colorado Mountains at times diminishes near Fort Quitman approximately 125 km (78 miles) south of El Paso. The new perennial flow begins at the confluence of the Rio Conchos from the Mexican side, approximately 454 km (284 miles) downstream from El Paso (Figure 1).

The flow of the Rio Grande that originates from the watershed in the southern slopes of the Colorado Mountains and the mountain ranges of northern New Mexico is stored at Elephant Butte Dam (design capacity 3.25 billion m^3 or 2.64 million acre-ft) located in New Mexico. The water is used to irrigate the Mesilla, the El Paso and the Juarez Valleys. The Rio Grande below the El Paso-Hudspeth county line consists mostly of the return flow and occasional excess water and runoff from the adjacent areas. The Bureau of Reclamation designates the Rio Grande between Elephant Butte Dam and Fort Quitman as the middle Rio Grande, whereas in Texas, this section is considered as a part of the Upper Rio Grande reach. In any case, the El Paso to Fort Quitman segment of the Rio Grande consists largely of the tail water of the water supply from Elephant Butte Dam. The annual rainfall in this segment of the Rio Grande Basin averages 200 mm (7.8 inches), the lowest in Texas.

The Rio Conchos from Mexico is the major entry into the Rio Grande below Fort Quitman and flows in just below Presidio (or Ojinaga, Mexico) which is located 454 km (284 miles) south of El Paso. This flow continues to Amistad Dam (design capacity 6.27 billion m^3 or 5.1 million acre-ft), located 500 km (312 miles) below Presidio. There is no major tributary that flows into the Rio Grande from the U.S. side, until the inflow of the Pecos River at Langtry, TX, and the Devils River at Amistad Reservoir. The flow of the Pecos River is regulated at Red Bluff Lake at the New Mexico-Texas border, and it consists mostly of saline irrigation return flow. The flow of the Pecos River that enters the Rio Grande is a mixture of return flow and runoff from far west Texas. The Bureau of Reclamation designates this segment of the Rio Grande as a part of the lower Rio Grande system, whereas in Texas, this segment is commonly referred to as the Upper Rio Grande reach. The annual rainfall in this section of the Rio Grande averages 250 to 300 mm (10 to 12 inches).

The Rio Grande between Amistad Dam and Falcon Reservoir (capacity 3.94 billion m^3 or 3.2 million acre-ft) is a long stretch extending 481 km (299 miles). There is no major tributary, but there are numerous creeks and draws that flow into the Rio Grande after storms. In Texas, this segment of the Rio Grande is commonly referred to as the Middle Rio Grande reach. The annual rainfall in this section increases to 500 mm (20 inches).

The Rio Grande below Falcon Reservoir to the Gulf of Mexico is the heart of the Lower Rio Grande, and extends 442 km (275 miles). The Rio Salado from Mexico is a major tributary that flows directly into Falcon Reservoir, and the Rio San Juan flows into the Rio Grande below Falcon. There are two major drainways on the U.S. side: the Main Floodway and the Arroyo Colorado. The later is of special importance, because it flows directly into the

Laguna Atascosa National Wildlife Refuge. The natural drainage flow is away from the Rio Grande eastward toward the Laguna. This area is outside the Rio Grande Basin, and is a part of the Nueces River Coastal Basin.

2. Main Flow of the Rio Grande

The International Boundary and Water Commission (IBWC) maintains excellent records of the main flow of the Rio Grande at various gauging stations. Table 3 shows the records of means, maximum and minimum annual streamflows at selected locations averaged over the periods of 21 years, starting at 1969, one year after the construction of Amistad Dam.

The water released from Elephant Butte Dam has averaged 842 million m^3 (682 thousand acre-ft) annually. A large portion of this flow is diverted to irrigate crop lands in New Mexico. The remainder and return flow then reach El Paso at an annual rate of 547 million m^3. As the flow reaches American Diversion Dam, 332 million m^3 has been diverted annually to the American canal which is the main supply canal for the El Paso Valley. The diversion to Mexico has amounted to 65 million m^3 annually, which is used to irrigate the Juarez Valley along with shallow groundwater and municipal sewage. After diversion, the flow of the Rio Grande is reduced to 155 million m^3 annually. The flow gradually increases again due to the collection of return flow and municipal sewage water discharged from several plants from El Paso and adjacent communities. The sewage water from Cd. Juarez is discharged into irrigation canals and to a limited extent to drainage ditches, but not directly into the Rio Grande. When the flow reaches Fort Quitman, storm runoff from small creeks is added to the flow of the Rio Grande.

The Rio Conchos that originates from the Mapimi drainage basin of the State of Chihuahua carries an average annual flow of 909 million m^3 at the point of inflow into the Rio Grande near Ojinaga, Mexico (Table 3). This flow is slightly greater than the annual release from Elephant Butte Dam, and forms the main flow of the Rio Grande in the stretch between Presidio and Amistad Dam. The Pecos River and the Devils River contribute 274 and 353 million m^3 annually to the flow of the Rio Grande, respectively. All of these flows are stored at Amistad International Reservoir.

The discharge from Amistad Dam has averaged 2.06 billion m^3 annually since its construction in 1968 (Table 3). About half of this release is taken into the Maverick Canal located 28 km south

Table 3. Annual flow of the Rio Grande and tributaries at selected gauging stations between 1969 and 1989 (original data from IBWC).

Stations	River or canal	Annual flow Ave.	Max.	Min.
		..... million m^3/year*		
Elephant Butte Release, NM	Rio Grande	842	1,769	370
El Paso, TX	Rio Grande	547	1,615	165
American Canal, TX	Diversion	-332	-528	-131
Mexican Canal, TX	Diversion	-65	-82	-18
El Paso after Diversion	Rio Grande	155	814	26
Fort Quitman, TX	Rio Grande	169	884	11
Near Ojinaga, Chihuahua	Rio Conchos	909	2,094	439
Presidio, TX	Rio Grande	1,125	2,184	595
Foster Ranch, TX	Rio Grande	1,468	2,709	754
Langtry, TX	Pecos River	274	1,342	117
Pafford Crossing, TX	Devils River	353	872	89
Amistad Dam Release, TX	Rio Grande	2,063	4,399	514
Maverick Canal, TX	Diversion	-1,117	-1,337	-566
Power Plant Return, TX	Return flow	829	1,096	208
Maverick Extension, TX	Diversion	-174	-263	-52
Eagle Pass, TX	Rio Grande	2,516	4,629	870
Laredo, TX	Rio Grande	2,863	4,799	1,209
Las Tortillas, Tamaulipas	Rio Salado	472	2,961	60
Falcon Dam Release, TX	Rio Grande	3,046	5,181	1,411
Camargo, Tamaulipas	Rio San Juan	434	2,123	8
Rio Grande City, TX	Diversion	-292	-425	-186
Anzalduas Canal, Tamaulipas	Diversion	-1,192	-1,903	-681
Anzalduas Dam, TX	Diversion	-254	-398	-149
Progreso, TX	Diversion	-532	-868	-329
San Benito, TX	Diversion	-133	-199	-88
Brownsville, TX	Rio Grande	1181	3,263	165

*The negative sign indicates diversion.

in the Juarez Valley and another in the El Paso Valley (Johnson, 1993). In the Juarez field, untreated municipal sewage water from Cd. Juarez has been used routinely to supplement irrigation up to about 25 percent, whereas the field in the El Paso Valley had been irrigated mostly using the water from the Rio Grande with occasional uses of treated sewage water. Soil samples were collected from the top 0 to 3 cm (but excluding the thin layer of a filter cake present at the soil surface) and 3 to 30 cm, and were analyzed for concentrated HNO_3 and H_2O_2 digestible Cd, Cr, Cu, Co, Ni, Zn and V (EPA method 3050). The concentrations of Cd and Co were below the detection limit of 1 mg kg^{-1}. The results from the El Paso field (Table 18) were relatively uniform throughout the length of water run which extends 300 m. Elevated concentrations of Cu and Pb were found near the irrigation ditch at both fields. These data may indicate accumulation as a result of irrigation with untreated municipal sewage water. The concentration of Zn was highly variable, but was often higher in the surface layer.

Table 18. Acid digestible trace elements in two irrigated fields in the El Paso and Juarez valleys. The samples were collected along the transect set perpendicular to the irrigation ditch (Johnson, 1993).

	Cr	Cu	Pb	Ni	Z n	V
	..... mg kg^{-1}					
0-100 m from the irrigation water check-in.						
El Paso						
0-3 cm	15	10*	12	10	35	23
3-30 cm	14	6	10	10	31	23
Juarez						
0-3 cm	13	17*	13*	9	46	20
3-30 cm	18	11	12	10	50*	38
100 - 200 m from the irrigation water check-in.						
El Paso						
0-3 cm	14	11*	10	12	43	21
3-30 cm	12	5	9	10	36	20
Juarez						
0-3 cm	13	10*	7	9	40*	21
3-30 cm	13	5	7	8	30	28
Mean Std.Dev.	2	4	2	2	9	4
Phytotoxic[1]	50-100	50-125	50-500	20-100	70-300	50-150

*Values significantly higher than those in the second layer or in the position away from the ditch.

[1] Total metal concentrations in soils which may cause phytotoxic effects (Kabata-Pendias and Pendias, 1992).

IV. COMPARISON WITH WATER QUALITY STANDARDS

1. Irrigation Uses

No enforceable standard is available for regulating quality of water for irrigation, as the suitability for irrigation varies with types of crops and soils involved and irrigation management. However, several guidelines are available for assessing suitability of water for irrigation (e.g., Ayers and Westcot, 1985; Pratt and Suarez, 1990).

a. Salinity

The adverse effect of salts on crop production varies with salt tolerance of crops, salinity control in the root zone, and several other factors. Table 19 shows appraisal of irrigation water salinity for production of crops which are commonly grown in the Rio Grande Basin. The leaching fraction (LF) is assumed to be 15 percent or more. In heavy clay soils of the Rio Grande, the leaching fraction can be lower than 15 percent and if so, given crops may be adversely affected when irrigated with water of the specified salinity.

The majority of water in the Rio Grande below Amistad Dam has the salinity range of 1 to 1.5 dS m^{-1} as reviewed earlier. This level of salinity allows production of high value crops, namely chile peppers, green peppers, onion, citrus, pecans, and

Table 19. Crops which can be grown satisfactorily with the specified ranges of salinity in permeable soils with the leaching fractions greater than 15 percent (Ayers and Wilcox, 1985).

	Threshold Salinity ..... dS m^{-1}				
Crops	<1	1 - 1.5	1.5 - 2.0	2.0 - 3.0	>3.0
Vegetables					
	bean	pepper lettuce onion	corn potato	cucumber tomato spinach	beet squash asparagus
Tree and fruits					
	strawberry	pecans plum almond peach citrus		pistachio	date palm
Field crops					
	bean		corn sugarcane	peanuts soybeans	wheat sorghum sugarbeet cotton barley
Forages					
			trefoil alfalfa	cowpea sudan	fescue rye wheatgrass bermuda

concentrations observed in fish tissue. The concentration of metals in the sediment is in noncrystalline forms (no HF treatment), and the value for Hg at Elephant Butte and Caballo Dams are not available. However, the total analyses (Table 17) show Hg concentrations to be 2.9 to 3.3 mg kg^{-1} at Elephant Butte, and 2.5 mg kg^{-1} at Caballo. Even if the noncrystalline form is assumed to be 10 percent, Hg concentrations are very high, and are believed to be caused by inflow of mine sediments. A comparatively high concentration of Hg in sediment is also reported in Presidio (Table 17). Hg concentrations below Amistad are low, but increase somewhat near the Gulf. Pb concentrations range from 5 to 15 mg kg^{-1}, except for a high reading at the Main Floodway, 33 mg kg^{-1}. The concentrations of Cu and Cr are similar to Pb, except for elevated concentrations at the confluence of the Rio Salado.

The metal concentrations in fish tissue vary widely. However, there seem to be higher Hg levels in Elephant Butte, Laguna Atascosa, and Laguna Madre. Pb and Cu concentrations in fish tissue appear to be higher in the Upper Rio Grande reach, while Cr and Cd in fish tissue appear to have no geographical patterns. The correlation between metal levels in sediments and fish is very poor (the last row of Table 17).

There are additional data on metal levels in sediments as well as metal levels in biota samples collected from different parts of the Rio Grande and its tributaries (TWC Water Quality file, USFWS records). However, the database consisting of simultaneous measurements of both sediments and biota is currently very limited. In addition, one may find considerable discrepancy in metal level among different sources, some of which can be attributed to the difference in the analytical procedures employed and/or sampling methods.

f. Trace Elements in Irrigated Soils

Intensive soil sampling and analysis of the soil samples were recently made in two alfalfa fields; one

Table 17. Heavy metal concentrations in bed sediments (S) and fish (F) in selected locations in the Rio Grande Basin.

Sources	Hg		Pb		Cu		Cr		Cd	
	S	F	S	F	S	F	S	F	S	F
	mg kg^{-1}									
Elephant Butte[1]	(3.1)*		9.5		9.0		5.7		0.12	
Shad		<.01		0.16		0.45		0.87		0.21
Carp		0.61		0.82		2.3		2.8		0.20
Bass	*	0.63		7.50		0.08		0.53		0.30
Caballo Dam[1]	(2.50)*		2.3		7.0		0.8		0.09	
Shad		0.19		3.3		0.33		1.2		0.21
Carp		0.47		0.10		0.25		2.5		0.54
Bass		<0.00		0.12		0.57		1.6		<0.00
Presidio Rio Grande[2]	0.29	0.41	11.0	1.5	10.0	2.6	9.8	0.62	0.4	0.3
Foster Ranch Rio Grande[2]	0.017	0.28	11.0	1.5	11.0	1.2	10.0	0.64	0.3	0.35
Shuma Pecos[2]	0.028	0.10	6.6	1.7	4.9	0.7	8.5	1.24	0.6	0.4
Amistad Dam[3]										
Bay-Rio Grande	0.04	—	14	—	16	—	23	—	<1	—
Bay-Devils River	0.02	—	10	—	14	—	19	—	<1	—
Near Spillway	0.04	—	15	—	14	—	25	—	1	—
Del Rio Rio Grande[4]	0.076	0.25	15	<1.5	10	1.3	11	<0.6	<0.6	<0.3
Laredo Rio Grande[2]	0.065	0.065	18	<1.6	14	0.75	17	0.7	0.6	0.4
Falcon Dam[5]										
Bay-Rio Grande	0.02	—	5.7	—	10	—	7.6	—	<1	—
Bay-Rio Salado	0.03	—	14	—	21	—	21	—	<1	—
Bay-Arroyo Salinilas	0.03	—	5.5	8.1	—	7.0	—	<1	—	
Near spillway[5]	0.05	—	10	—	12	—	12	—	<1	—
Near spillway[6]	—	<0.2	15	<0.8	10	1.3	(57)*	2.6	<2	<0.37
Anzalduas Dam[6]	—	<0.2	16	<0.8	16	1.6	(47)*	0.5	<2	<0.4
Main Floodway[6]	—	<0.37	33	<0.8	28	0.4	(46)*	1.1	<2	<0.4
Laguna Atascosa[6]										
Bay-Arroyo Colorado	—	0.48	16	<0.8	11	0.9	(52)*	1.1	<2	<0.4
Bay-Cayo Atascosa	—	—	13	—	17	—	(40)*	—	<2	—
Laguna Madre[6]		0.87	15	<0.8	13	2.8	(42)*	0.4	<2	0.4
Baca Chica Rio Grande[2]	0.42	0.04	9.9	1.7	17	0.95	6.6	1.5	0.3	0.4
Correlation r	-0.037		-0.56		-0.28		0.31		0.463	

*Total Hg or Cr concentration

[1]Popp et al. (1983), [2]TWC Data file (unpublished), [3]TWDB (1973) IMS 21, [4]TWC (1990) IS 90-03, [5]TWDB (1974) IWS II, [6]Wells et al 1988

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of Del Rio for hydraulic power generation and irrigation. The return flow from the power plant goes right back into the Rio Grande, and the remainder is used for irrigation through the Maverick Extension Canal. The combination of the base flow, return flow, and the inflow from creeks bring the flow of the Rio Grande back to over 2 billion m^3 annually at Eagle Pass. The diversion below Eagle Pass but above Laredo is minimal, and the Rio Grande gains flow and reaches 2.8 billion m^3 annually at Laredo. Below Laredo, there are several rivers and streams that flow into the Rio Grande. The Rio Salado from Mexico is one of the larger rivers and has contributed to the flow of the Rio Grande at an annual rate of 472 million m^3. The combined flow reaches 3.0 billion m^3 annually at Falcon International Reservoir.

Below Falcon, the Rio San Juan (434 million m^3/year) flows into the Rio Grande from the Mexican side at Camargo. The Rio Grande water is diverted between Rio Grande City and Anzalduas Dam at a rate of 292 million m^3/year for irrigation (Table 3). The major diversion to Mexico is at Reynosa. The U.S. side of the diversions are at Anzalduas Dam, Progreso and San Benito at a combined diversion flow of 919 million m^3 per year. When the Rio Grande reaches Brownsville, the flow decreases to 1.18 billion m^3/year, which includes erratic flood water after a storm.

3. Surface Inflow into the Rio Grande

The records of the surface flow that enters the Rio Grande are also maintained by the IBWC. A summary of the surface flow (averaged over 1969 through 1989), including springs, is shown in Table 4. In the El Paso-Ft. Quitman segment, the main inflow is the Rio Grande entering from New Mexico and municipal sewage from El Paso. There is no recorded inflow from the Mexican side in this segment of the Rio Grande.

The Fort Quitman to Amistad Dam segment has four inflows from the U.S. side and the Rio Conchos from the Mexican side (Table 4). The

Table 4. Annual surface inflow (recorded and estimated) into the Rio Grande from Texas and Mexico between 1969 to 1989, including irrigation return flow (original data from IBWC).

Inflow from the US	million m^3/year
El Paso - Fort Quitman	
Rio Grande, NM	547
El Paso sewage	30
	577
Fort Quitman - Amistad	
Above Presidio	0
Alamito Creek	18
Terlingua Creek	56
Pecos River	274
Devils River	353
Recorded total	701
Unaccounted	160
Estimated total	861
Amistad - Falcon	
Springs & Creeks near Del Rio	21
San Felipe Springs & Creeks near De. Rio	202
Pinto Creek below Del Rio	14
Return flow	
above Eagle Pass	51
below Eagle Pass	86
Estimated subtotal	374
Sewage	
Eagle Pass	2
Laredo	12
Estimated total	388
Falcon - the Gulf	
Brownsville Sewage	9
TOTAL	
(El Paso - the Gulf)	1835

Inflow from Mexico	million m^3/year
Cd. Juarez - Col Luis Leon	
Cd. Juarez sewage	0
	0
Col Luis Leon - Amistad	
Above Col Luis Leon	0
Rio Conchos	909
Subtotal	909
Unaccounted	124
Estimated total	1033
Amistad - Falcon	
Arroyo de Los Jabocillos	47
Springs & Creeks near Cd. Acuna	48
Rio San Diego near Jimenez	218
Rio San Rodrigo at El Moral	153
Rio Escondido at Villa de Fuente	76
Rio Salado near Las Tortillas	472
Estimated Total	1014
Falcon - the Gulf	
Rio Alamo at Cd. Mier	120
Rio San Juan at Camargo	434
San Juan return flow	74
	628
TOTAL	
(Cd. Juarez - the Gulf)	2695

Rio Conchos accounts for 56 percent of the recorded inflow, and the Devils River 22 percent and the Pecos River 17 percent in this segment of the Rio Grande. There is a net increase in flow of the Rio Grande between Presidio and Amistad Dam by 284 million m^3 which is not accounted for by these recorded inflows. The unaccounted flow was divided in proportion to the drainage areas for the Texas side (20,000 km^2) and the Mexican side (15,600 km^2) between Fort Quitman (or Colonia Luis Leon) and Amistad. The total annual inflow from the U.S. side was estimated to be 861 million m^3, and that from the Mexican side 1,033 million m^3 in this section of the Rio Grande.

The Amistad-Falcon segment starts with the inflow of Arroyo de Los Jaboncillos, four springs and three creeks near Cd. Acuna from the Mexican side, followed by the inflow of four Mexican rivers, which include the Rio Salado (Table 4). The recorded total surface inflow from the Mexican side amounts to 1.01 billion m^3 annually in this segment of the Rio Grande, and the Rio Salado accounts for 47 percent of the inflow. The recorded inflow from the Texas side, which includes irrigation return flow from the Maverick Irrigation District, amounts to 374 million m^3 annually. In addition, municipal sewage from Eagle Pass and Laredo provides an additional inflow of 12 million m^3 per year. Sewage water is also discharged from the Mexican side into the Rio Grande (e.g., from Nuevo Laredo). The exact quantities are unknown, but are probably comparatively small in quantity.

The Rio Grande gains flow between Amistad and Falcon Dams by 983 million m^3 (Table 3). The net diversion at the Maverick power plant is 288 million m^3, which is then channeled into the Maverick Irrigation District. Additional diversions to Eagle Pass and Laredo are estimated at 12 million m^3. The diversion to Mexico is not recorded, but is estimated at 26 million m^3 based on irrigated acreages. The gain in flow plus the diverted quantity is estimated at 1.31 billion m^3, which approximately equals the estimated total inflow of 1.40 billion m^3/year (Table 4). Seventy-two percent of the inflow in this segment of the Rio Grande originates from the Mexican side.

The Falcon to the Gulf Coast segment has a topographical slope where a large portion of the Rio Grande river bed is higher than the elevation of the drainage basin on the Texas side. The general direction of surface flow is toward the Laguna Atascosa and the Laguna Madre away from the Rio Grande. The inflow into the Rio Grande is thus from the Mexican side, (chiefly from the Rio San Juan, and San Juan drainage), and is recorded to be 628 million m^3 annually. The reduction in flow of the Rio Grande between Falcon Dam and Brownsville averages 1.865 billion m^3 annually (Table 3), while the recorded plus some estimated diversion amounts to 2.477 billion m^3 annually (Table 5). The recorded diversion exceeds the total inflow (637 million m^3, Table 4) by 1.84 billion m^3, which coincides with the measured reduction in flow.

Overall, the recorded surface inflow in the Texas side amounts to 1.835 billion m^3 and that from the Mexican side 2.675 billion m^3 annually, which is roughly 1 to 1.5 ratio in favor of the Mexican side. This ratio, however, excludes subsurface inflow into the Rio Grande.

4. Water Use

The quantity of water diverted from the Rio Grande surface flow is also recorded by the IBWC. The figures presented herein do not include groundwater use, but only the direct withdrawal from the Rio Grande.

a. Agricultural Use

Irrigated crop production dominates the use of the Rio Grande surface flow. The water released from Elephant Butte Dam is used to irrigate 35,200 ha of crop land in New Mexico (Table 5). The remainder plus return flow from New Mexico is then used to irrigate crop land in the El Paso and Juarez Valleys. The reported irrigated crop land area for the El Paso Valley in 1989 was 17,200 ha which is about two-thirds of the irrigable lands. Some lands are now classified as residential areas, or commercial lots, and others have salted out or are not being cropped. Low density residential areas with the holding of one ha or greater actually receive allocation of the Rio Grande water, as the water right is tagged to the ownership of the land within the district boundary. The source of irrigation water below Acala (Hudspeth County) is predominately return flow, and occasional excess spills from the El Paso Irrigation District. When these water supplies are curtailed, shallow groundwater is used to supplement irrigation.The use of the Rio Grande water for agricultural purposes is limited to about 2,000 ha between Fort Quitman and Amistad (Table 5). However, an estimated area of 129,000 ha in Mexico is irrigated by the Rio Conchos before the water reaches the Rio Grande. Likewise, the Pecos river water is used to irrigate 5,400 ha in Texas and additional unlisted areas of 14,164 ha in New Mexico. Agricultural uses of the Rio Grande water between Amistad and Falcon are concentrated in the Maverick Irrigation District (16,300 ha) on the Texas side. On the

stable crystalline. Popp et al. (1983) analyzed sediment samples from the Rio Grande at San Marcial, from Elephant Butte and Caballo Dams, using sequential extractions involving 1 M ammonium acetate (which supposedly extracts the exchangeable form), 0.04 M hydroxylamine hydrochloride in acetic acid (which presumably extracts hydrous metal oxides and possibly those incorporated into calcites), 30 percent H_20_2 digestion followed by ammonium acetate in HNO_3 (which presumably removes organically complexed metals), and the total digestion by HF, HNO_3 and $HCl0_4$. Results indicate that noncrystalline fractions range typically from 10 to 40 percent in the case of As, Cd, Cr, Cu and Pb, and 40 to 60 percent in the case of Mo, Se and V (Table 16). There are, however, large variations in trace element concentrations in both crystalline and noncrystalline phases among the sediment samples analyzed. These high variations may again indicate that the sediments are composed of heterogeneous parent materials. Even the fractions that are retained in organic matter ranged widely from 4 to 50 percent, depending on elements and sediment types.

The noncrystalline fraction of trace elements has been viewed as an indication of contamination levels, and it may be better correlated with dissolved concentrations than the crystalline form. A linear regression analysis between the concentrations of noncrystalline forms and the concentration of dissolved metals in pore water of the sediments shown in Table 14, however, revealed no significant correlation (r = -0.309 for As, 0.20 for Cd, -0.14 for Cr, and 0.11 for Cu).

e. Trace Elements in Bed Sediments and Fish

The concentration of trace elements in bed sediments observed in various locations along the Rio Grande are shown in Table 17 along with the metal

Table 16. Trace element retention in bed sediments of the Rio Grande by different categories (Popp et al., 1983) and the average concentrations in the soils of the western states (Shackett and boernanen, 1984).

Element	Rio Grande at San Marcial		Elephant Butte Dam		Caballo Dam		Western States Average[1]
	mg kg^{-1}	percent	mg kg^{-1}	percent	mg kg^{-1}	percent	mg kg^{-1}
As							
Noncrystalline	3.0	46	1.4	25	2.0	24	55
Crystalline	3.6	54	4.2	75	6.3	76	
Cd							
Exchangeable	0.04	5	0.12	6	0.09	4	
Oxides	0.15	18	0.62	30	0.88	41	
Organics	0.07	8	0.40	20	0.09	4	
Crystalline	0.59	69	0.91	44	1.10	51	
	0.85	100	2.05	100	2.16	100	
Cr							
Noncrystalline	7	25	5.7	14	0.8	2	
Crystalline	21	75	35.0	86	41.2	98	41.
Cu							
Noncrystalline	8	40	9.0	37	7.0	19	
Crystalline	12	60	15.3	63	30.0	81	21
Pb							
Noncrystalline	5	15	9.5	19	2.3	18	
Crystalline	28	85	40.7	81	54.7	82	17
Mo							
Exchangeable	0.06	9	.32	16	0.10	5	
Oxides	0.01	1	.27	14	0.05	3	
Organics	0.10	15	.38	19	0.86	50	
Crystalline	0.51	75	1.01	51	0.72	42	
	0.68	100	1.98	100	1.73	100	0.9
Se							
Exchangeable	0.02	7	.03	10	—	—	
Oxides	0.07	22	.03	10	—	—	
Organics	0.02	7	.12	40	—	—	
Crystalline	0.20	64	.12	40	—	—	
	0.31	100	.30	100	—	—	0.2
V							
Noncrystalline	1.0	77	0.75	55	0.04	52	

As, Mo and Se are not. The concentration of Cd and Cr in filtered water averaged 0.57 and 5.7 $\mu g\ L^{-1}$ and that of pore water 13 and 26 $\mu g\ L^{-1}$, respectively, indicating 20 and 4.6 fold greater values. The concentrations of Cu and Pb in free water averaged 20 and 5 $\mu g\ L^{-1}$ and those in pore water 44 and 17 $\mu g\ L^{-1}$, respectively, indicating several fold increases (Table 14). High concentrations of metals in pore water of the sediments are probably caused by the reduction in pH and redox potential (e.g., Lindsay, 1979), and formation of organo-metal complexes (e.g., McBride, 1989). There seems to be no consistent pattern in pore water trace element concentrations among the different sampling locations, except for As and Cu. The As concentrations in pore water seem to increase with the distance from the head water location, while the Cu concentrations appeared to have decreased with the distance (Table 14).

c. Trace Elements in Whole Water

The Rio Grande water, as most other surface water in the arid Southwest, contains high levels of suspended solids. Because of high affinity of most metals to sediments, analyses of whole water samples after acid digestion generally yield higher metal concentrations than those in filtered water.

The analyses by Popp et al. (1983) at San Marcial and by USGS (unpublished) at Fort Quitman show higher concentrations of Cd, Cr, Cu, Mg and Pb in digested whole water samples, whereas the concentrations of As, Mo and Se in the digested whole water were similar to those in free water (Table 15). At the Fort Quitman station, the ratios of the concentrations in the whole water to those in filtered water ranged from 3 to 6 for Cu and Pb and 1.3 to 3 for Cd and Hg. At San Marcial and Elephant Butte, this ratio was somewhat greater than these at Fort Quitman, and above all, it was highly variable. This high variability may be associated with the highly variable nature of the suspended solids at these locations which receive sediments from various abandoned gold, silver and uranium mines (Popp and Laguer, 1990). The concentrations of Hg and As appear to be higher in water samples collected near the lake bottom as exemplified by the data from Caballo Dam. There was no significant correlation between metal concentrations in whole water and the concentrations in suspended solids.

d. Trace Elements in Sediment Extracts

Trace elements are present in sediments in various forms, including exchangeable, oxides, organic complexes, and those incorporated into calcites and

Table 15. The concentration of dissolved metals in filtered water (D) and in digested whole water (W) at several locations along the Rio Grande.

Location	Suspended Solids	As		Cd		Cr		Cu		Hg		Mo		Pb		Se	
	mg L^{-1}	D	W	D	W	D	W	D	W	D	W	D	W	D	W	D	W
		……… $\mu g\ L^{-1}$ ………															
San Marcial, Rio Grande(1)																	
Average	950	25*	14	.73	1.3	1.4	53	6	71*	1.5	2.0	13	4*	5	30	1	<1
(Std. Dev.)		(11)	(8)	(.56)	(1.5)	(1.7)	(0.2)	(3)	(71)	(2.7)	(3.0)	(10)	(2)	(4)	(35)	(1)	—
Ratio (W/D)		—	—	—	1.8	—	38	—	—	—	1.3	—	—	—	6	—	—
Fort Quitman, Rio Grande(2)																	
Average (3/15-9/15)		5.9	7.4	.38	.25*	—	—	3.0	8.4	.04	.12	—	—	1.8	7.5	.57	.57
(Std. Dev.)		(2.7)	(4.1)	(.52)	(.46)	—	—	(1.7)	(5.5)	(.05)	(.08)	—	—	(1.7)	(7.9)	(.53)	(.53)
Ratio (W/D)		—	1.3	—	—	—	—	—	3.7	—	3.0	—	—	—	4.3	—	1.0
Average (9/16-3/14)		5.3	6.0	.40	.80	—	—	1.6	6.8	.15	.10*	—	—	1.3	8.4	.67	.67
(Std. Dev.)		(3.4)	(3.1)	(.7)	(1.0)	—	—	(1.3)	(5.2)	(.24)	(.08)	—	—	(1.6)	(6.6)	(.5)	(.5)
Ratio (W/D)		—	1.1	—	2.0	—	—	—	4.2	—	—	—	—	—	6.5	—	1.0
Elephant Butte Dam(1)																	
1	160	11	12	.29	2.2	6.4	36	28	33	.7	.4	5.3	6.4	4.4	27	1.2	1.0
2	6	9	12	.90	6.6	4.6	19	18	135*	1.0	.5	5.0	86*	4.3	12	0.9	.58
3	3	9	58*	.85	6.3	3.3	154*	17	121*	.5	1.2	4.4	9.0	5.0	20	0.7	.55
4	3	9	32*	.48	5.2	4.9	31	22	53	.7	1.2	5.0	12	4.6	25	0.9	.10*
mean	—	9.5	12.0	.63	5.1	4.8	29	21	43	0.7	0.8	4.9	7.0	4.6	21	0.9	0.71
(Std. Dev.)	—	(4)	(15)	(.59)	(3.5)	(5.9)	(21)	(20)	(31)	(0.7)	(1.2)	(3)	(8)	(5.0)	(18)	(1)	(1)
Ratio (W/D)	—	—	1.3	—	8.1	—	6.0	—	2.0	—	1.1	—	1.4		4.6	—	0.80
Caballo Dam(1)																	
Surface	20	12	11	.32	1.5	7.1	171*	16	17	.62	1.2	3.7	10	7.2	86*	2.1	<1.0
(Std. Dev.)		(8)	(11)	(.19)	(2.9)	(6.7)	(99)	(11)	(26)	(.87)	(1.2)	(4.1)	(8)	(11)	(.56)	(2.6)	(<1.0)
Ratio (W/D)		—	0.9	—	5.6	—	10.0	—	11	—	1.9	—	2.7	—	—	—	—
Bottom	—	41	37	.35	1.4	12	88*	12	30	.57	2.0	5.2	11	6.3	20	.07	<1.0
(Std. Dev.)		(60)	(52)	(.25)	(1.9)	(14)	(84)	(4.6)	(33)	(.58)	(1.1)	(3.5)	(8)	(6.2)	(7.1)	(.06)	(<1.0)
Ratio (W/D)		—	0.9	—	4.0	—	7.3	—	2.5	—	12	—	2.1	—	3.2	—	—

* Analytical values of questionable quality or geochemical extremes.

(1)Popp et al, 1983, (2)USGS File (unpublished).

Table 5. Recorded or estimated diversions from the Rio Grande for agricultural purposes between 1969 and 1989, and reported irrigated areas in 1989 (original data from IBWC).

	Diversion (million m^3/year)			Irrigation (1000 ha)		
	Texas	Mexico	Total	US	Mexico	Total
Elephant Butte - El Paso	—		0	—	(35.2)[1]	0
(35.2)						
El Paso - Fort Quitman						
El Paso-Acala	332	65	393	17.2	5.5	22.7
Acala-Fort Quitman	—	—	—	7.1	0	7.1
Fort Quitman-Amistad						
(Rio Conchos above Ojinaga)	—	—	—	0	(129)	(129)
Presidio	10[2]	0	10[2]	1.0	0	1.0
Presidio-Langtry	3[2]	7[2]	10[2]	0.3	0.7	1.0
(Pecos River)	—	—	—	(5.4)	0	(5.4)
(Devils River)	—	—	—	(0)	0	(0)
Rio Grande irrigated	13[2]	7[2]	20[2]	1.3	0.7	2.0
Tributary irrigated	—	—	—	(5.4)	(129)	(134.4)
Amistad-Falcon						
(San Felipe Creek)	—	—	—	(0.7)	0	(0.7)
(Rio San Diego)	—	—	—	0	(3.3)	(3.3)
(Rio San Rodrigo)	—	—	—	0	0	0
Del Rio-Laredo	263	26[2]	289	16.3	1.6	17.9
Laredo-Falcon	34[2]	10[2]	44[2]	2.1	0.9	3.0
(Rio Salado)	—	—	—	0	(25.5)	(25.5)
Rio Grande irrigated	297	36[2]	333[2]	18.4	2.5	20.9
Tributary irrigated	—	—	—	0	(28.8)	(28.8)
Falcon-the Gulf						
(Rio Alamo)				0	(3.2)	(3.2)
(Rio San Juan)				0	(79.3)	(79.3)
Falcon-Rio Grande city	12	13[2]	25[2]	1.8	1.9	3.7
Rio Grande City-Anzalduas	292	36[2]	328	72.4	9.2	81.6
Anzalduas Canal	254	1192	1446	65.6	196.1	261.7
Progreso Intake	532	7[2]	539	132.7	1.7	134.4
San Benito Intake	133	3	136	37.5	0.7	38.2
Brownsville Diversion	3	0	3	0.9	0	0.9
Rio Grande irrigated	1226	1251	2477	310.9	209.6	520.5
Tributary irrigated	—	—	—	(0)	(82.5)	(82.5)
Total (El Paso-Tthe Gulf)						
Rio Grande irrigated	1868	1359	3227	354.9	218.3	573.2
Tributary irrigated	—	—	—	(5.4)	(240.3)	(245.7)

[1] Numbers in parentheses indicate irrigated areas before reaching the Rio Grande below El Paso.

[2] Estimated from irrigated areas.

Mexican side, the Rio Salado is used to irrigate 25,500 ha before reaching the Rio Grande.

The major agricultural uses of the Rio Grande are below Falcon, totalling 310,900 ha on the Texas side and 209,600 ha plus 82,500 ha of tributary-irrigated areas on the Mexican side (Table 5). The irrigated area below Falcon accounts for 88 percent of the Rio Grande irrigated area on the Texas side, and 96 percent of the land irrigated directly by the Rio Grande on the Mexican side. The cropped area changes depending on the year, but these changes do not affect the overall picture of the agricultural water uses. The total water use for agriculture from El Paso to the Gulf Coast averaged 1.87 billion m^3 per year on the Texas side, and 1.36 billion m^3 per year on the Mexican side with corresponding irrigated areas of 354,900 and 218,300 ha, respectively. The combined agricultural use of the surface water of Rio Grande is 3.23 billion m^3, as compared to the combined estimated infow of 4.51 billion m^3 per year.

b. Municipal and Industrial Uses

The total municipal water use from the surface flow of the Rio Grande amounts to 98 million m^3 per year on the Texas side, and 49 million m^3 per year on the Mexican side averaged over the last 10 years (Table 6). This amounts to 5 percent and 3 percent of the agricultural uses directly from the Rio Grande, respectively. The major industrial use of the Rio Grande water is at the Laredo Power Plant which consumes 1.5 million m^3 per year.

The actual water use for municipal and industrial purposes is greater due to additional groundwater uses. The city of El Paso, for example, has been using 110 million m^3 per year, of which 24

Table 6. Estimated water uses directly from the Rio Grande for agricultural and municipal/industrial purposes (original data from IBWC).

Segment	Agricultural[1]		Municipal[2]		
	US	Mex.	US	Mex.	
	.... million m³/year		.... million m³/year		Communities
El Paso-Fort Quitman	332	65	24	0	El Paso
Fort Quitman-Amistad	13	7	0	0	
Amistad-Falcon	297	36	13	3	Del Rio-Cd. Acuna
			5	9	Eagle Pass-Pie Negra
			27	34	Laredo-Nuevo Laredo
			45	46	
Falcon-the Gulf	1226	1251	2		New Zapata
			2		Roma
			2		Rio Grande City
			23		Brownsville
			29	3	
Total	1868	1359	98	49	

[1] The data for 1969-1989.

[2] The data for 1979-1989.

million m^3 comes from the Rio Grande. The Texas Department of Water Resources has estimated in 1990 that the total municipal uses along the Texas side of the Rio Grande to be 346 million m^3 per year, or three times the surface water withdrawals directly from the Rio Grande. Municipal water uses are projected to grow with increasing population along the border and/or, with depletion of groundwater reserves (Eaton and Hurlbut, 1992).

c. Recreation and Wildlife Enhancement

There is no simple way to assess the quantity of water used for recreation and wildlife enhancements. All three major reservoirs, Elephant Butte, Amistad, and Falcon are used extensively for outdoor recreational activities. The quantity of water evaporating from these reservoirs alone is substantial; 19, 58, and 79 million m^3 per year at the maximum water surface of 7,500, 27,000 and 36,000 ha at Elephante Butte, Amistad and Falcon, respectively. The evaporation deficit at these dams is 254, 216 and 218 cm per year, respectively. The evaporation from these three reservoirs alone amounts to a quantity greater than the municipal water use from the Rio Grande.

Waterways along the Rio Grande and its tributaries, including drainage ditches, are habitats to many wildlife species. The evapotranspiration losses from these wetlands are likely to reach substantial quantities, although these are not measured as such. In the section of Elephant Butte Dam to El Paso, for example, the densely vegetated areas along the Rio Grande floodways are estimated at 15,000 ha. The unit evapotranspiration rate from these vegetated areas exceeds that of agricultural lands, and is estimated to reach 150 cm per year. The evapotranspiration losses occurring in this segment of the waterways alone can amount to 225 million m^3 per year.

III. STATE OF WATER QUALITY

1. Salts

Several agencies have maintained monitoring of common salts at various locations along the Rio Grande. Records of the IBWC were used for this study as they contain not only monthly measurements of salinity and common salt elements but also of monthly flow data.

a. Salinity, Sodicity and Cl/SO$_4$ Ratios

A review of the current salinity status (using the latest data, 1989) indicates that salinity of the Rio Grande main flow reaching El Paso averaged 1.0 dS m^{-1} with the SAR of 3.1 and the Cl to SO$_4$ ratio of 0.61 in chemical equivalent during the period of March 15 to September 15 (Table 7). This period is the main irrigation season in this area. The concentration of Cl averaged 89 mg L^{-1} (2.5 meq L^{-1}) and that of SO$_4$ 198 mg L^{-1} (4.1 meq L^{-1}). During off-season (September 16 to March 14), irrigation return flow and sewage water constitute the main flow, thus salinity, sodicity and Cl/SO$_4$ ratios increase. Salinity of water at Fort Quitman, as compared to that at El Paso increased by a fac-

evated levels of salts, B, Ba, V, and Cu (Table 13). High salinity of the Arroyo Colorado is caused by the intrusion of seawater from the Laguna Madre. The elevated concentrations of B can also be attributed to the high concentration in seawater, 4.5 mg L^{-1} (Drever, 1982). High concentrations of Ba, V, Cu and Zn are probably the characteristic of the Laguna Madre. Additional data on trace elements in this area are reported by the USFWS (1986). Reported values are highly variable, but the areas below the Main Floodway toward the coast appear to have elevated concentrations of all types of trace elements.

The USGS Water Quality Monitoring file also contains trace element data back to 1981. We could not detect any significant yearly trend of the dissolved trace element concentrations in water during the 10 year period.

Dissolved metal concentrations in Elephant Butte and Caballo Reservoirs were measured by Popp et al (1983), and their findings are cited in Table 14. The samples were collected in May 1981, October 1981, May 1982 and November 1982; one each at San Marcial, four locations in Elephant Butte and a location in Caballo Dam. San Marcial is located at the head water of Elephant Butte, and the Rio Grande water is channeled into Elephant Butte at this location. The major floodway water bypasses this feeder canal. There is irrigation return flow right above San Marcial, and the Rio Puerco (which carries sediments from old mines) about 100 km above San Marcial, which can skew quality of the intake canal water. The locations within the Elephant Butte are numbered from the head water position. The water in Caballo Dam is the overflow from Elephant Butte. Water samples were collected near the surface, and 1 m above the bottom, and the analyses were made in duplicate. The listed values are an average of eight samples collected at two different depths and four different occasions.

Trace element concentrations, especially As and Hg, measured at San Marcial intake canal (Table 14) are generally higher than those reported by the USGS for the Floodway (Table 13). However, these differences are probably not statistically significant because of high variability. At Elephant Butte, the differences in trace element concentration among the four locations are mostly within the mean standard deviation. Also no consistent difference in metal levels at two different depths was reported, except for As of which concentrations tend to increase with depth. Although a rigid comparison is not possible, dissolved concentrations of Cu, Cr, As and Hg appear to be higher in Elephant Butte and Caballo reservoirs than in the main flow of the Rio Grande. The redox potential is probably lower in these reservoirs than in the main flow.

Metal levels in Amistad and Falcon reservoirs were studied by the Texas Water Quality Board in 1974 (TWQB, 1975a/1975b). However, dissolved metal concentrations were not reported. Recently, the TWC has carried out another monitoring study at Falcon (TWC, 1991) and to a limited extent, below Amistad. The detection limits for metals in water were too high for most metal elements.

b. Trace Elements in Pore Water

Dissolved metal concentrations in pore water squeezed out of the bottom sediments are shown in Table 14 (Popp et al., 1983). It is apparent that the concentrations of Cd, Cr, Pb and Cu are substantially higher in pore water, whereas the concentrations of

Table 14. The concentration of trace elements dissolved in free water (D), and dissolved in pore water of the sediments (P) in the Elephant Butte Dam and the Caballo Dam (Popp et al., 1983).

	As		Cd		Cu		Cr		Hg		Mo		Pb		Se	
	D	P	D	P	D	P	D	P	D	P	D	P	D	P	D	P
San Marcial, Rio Grande	25	6	.73	6	6	24	1.4	11	1.5	—	13	3	5	7	1	<1
(Std. Deviation)	(11.0)	—	(.56)	—	(3)	—	(1.7)	—	(2.7)	—	(10)	—	(4)	—	(1)	—
Elephant Butte																
Location 1	11	9	.29	16	28	53	6.4	25	.7	—	5	5	4	13	1	<1
2	9	4	.90	7	18	46	4.6	38	1.0	—	5	4	4	9	1	<1
3	9	10	.85	6	17	30	3.3	16	.5	—	4	5	5	13	1	<1
4	9	22	.48	14	22	27	4.9	21	.7	—	5	3	5	18	1	<1
(Std. Deviation)	(4)	—	(0.59)	—	(20)	—	(5.9)	—	(0.7)	—	(3)	—	(5)	—	(1)	—
Caballo Dam	—	13	.33	22	14	62	9.5	31	.6	—	4	5	7	31	1	<1
(Std. Deviation)	30	—	.22	—	(8)	—	(10.5)	—	(.6)	—	(4)	—	(9)	—	(1)	—
Detection Limits	2	—	0.3	—	—	—	—	—	1.0	—	1.0	—	1.0	—	2.0	1
Mean of Dam Water	9.5	11.3	.57	13	20	44	5.7	26	0.7	—	4.6	4.4	5.0	17	1	<1
Ratio (P/D)	—	1.2	—	23	—	20	—	4.6	—	—	—	0.06	—	3.4	—	<1

Table 13. The concentration of trace elements in the Rio Grande, and several drainage ways in the Lower Rio Grande (original data from USGS).

Location	Periods	EC	pH	B	Ba	Sr	Mo	Se	V	As	Cd	Cr	Co	Cu	Pb	Hg	Ni	Ag	Zn
		dS m^{-1}		....	mg L^{-1}	....	....						µg L^{-1}						....
Taos, NM	’88, ’89, ’90																		
	November	0.31	8.2	.05	—	—	7	<1	—	2	<1	2	—	3	2	0.1	—	—	7
	(Std. Deviation)	(0.02)	(0.1)	(0.1)	—	—	(2.1)	—	—	—	—	(1)	—	(2)	(2)	(0.1)	—	—	(3)
San Marcial	’86, ’87																		
	November	0.55	8.0	.1	.06	.54	<10	<1	<6	4	<1	<1	<3	5	—	0.1	3	<1	6
El Paso, TX	’88, ’89, ’90																		
	Mar 15-Sept 15	0.86	8.3	.3	.07	.82	<10	<1	—	3	<1	<1	<3	4	4	—	2	<1	9
	Sept 16-Mar 14	1.89	8.5	—	.09	1.56	11	<1	—	3	<1	2	<3	2	1	—	1	<1	13
	(Std. Deviation)	(0.25)	(0.3)		(0.01)	(0.24)	(2)	—	—	(.5)	—	(.5)	—	(1)	(2)	—	(.5)	—	(7)
Fort Quitman	’88, ’89, ’90																		
	Mar 15-Sept 15	3.56	8.3	—	.08	2.8	11	<1	19	7	<1	<1	<3	3	<1	—	4	<1	22
	Sept 16-Mar 14	3.50	8.2	—	1.25	2.8	8	<1	12	7	1	2	<3	3	<1	—	4	<1	17
Laredo, TX	’88, ’89, ’90																		
	Mar 15-Sept 15	1.11	7.9	—	0.11	1.3	<10	<1	<6	4	2	<1	<3	<1	<5	<.1	1	<1	11
	Sept 16-Mar 14	1.19	8.0	—	0.10	—	<10	<1	<6	3	<1	<1	<3	6	<1	<.1	7	—	11
Brownsville	’88, ’89, ’90																		
	Mar 15-Sept 15	1.41	8.1	—	0.11	1.6	<10	<1	<6	3.7	<1	<1	<3	<3	<3	0.2	<1	<1	12
	Sept 16-Mar 14	1.44	8.1	—	0.10	1.5	<10	<1	<6	3.8	<1	<1	<3	<4	<7	<.1	<4	<1	7
Main Flood Way at Progreso	’86																		
	June	2.09	7.2	0.8	.20	—	18	1	16	7	<1	<10	—	10	<5	<.1	4	<1	20
Arroyo Colorado	’86																		
Above Rio Hondo	June	5.40	7.5	2.1	—	—	18.0)	1	44	8	1	<10	—	20	<5	<.1	2	<1	<10
River Mouth	June	14.3	8.6	2.1	.20	—	10	2	120	9	<1	<10	—	30	<5	<1	16	<1	10
Laguna Madre	June	29.2	8.7	3.4	.30	—	11	<1	270	7	1	20	—	40	<5	.5	4	<1	30
Ocean (average)[1]		57	—	4.5	.002	8.0	10	0.2	2	4	0.05	0.3	0.05	0.5	0.03	0.03	0.5	0.04	2

[1] Data compiled by Drever (1982).

Table 7. Salinity, sodicity, chloride, and sulfate concentrations of the Rio Grande and its tributaries in 1989 (original data from IBWC).

Location	River	March 15 - Sept. 15					Sept. 16 - March 14				
		EC	SAR	Cl	SO_4	Cl/SO_4[1]	EC	SAR	CL	SO_4	Cl/SO_4[1]
		dS m^{-1}		....	mg L^{-1}	....	dS m^{-1}		....	mg L^{-1}	....
El Paso	Rio Grande	1.0	3.1	89	198	0.61	2.0	6.1	227	463	0.66
Fort Quitman	Rio Grande	3.0	8.5	553	520	1.43	3.7	9.5	690	635	1.46
	(CV)[2]	(11)	(10)	(13)	(13)	(14)	(12)	(5)	(13)	(9)	(4)
Above Presidio	Rio Grande	2.9	6.4	467	568	1.11	3.1	8.8	750	642	1.58
Ojinaga	Rio Conchos	1.4	4.0	68	360	0.26	1.4	3.0	45	252	0.24
	(CV)	(35)	(10)	—	—	—	(21)	(6)	—	—	—
Below Presidio	Rio Grande	1.9	—	—	—	—	1.8	—	—	—	—
Foster Ranch	Rio Grande	1.4	4.0	68	360	0.26	1.4	3.0	45	252	0.24
Langtry	Pecos River	3.3	7.5	747	447	2.26	4.3	9.0	977	637	2.07
	(CV)	(6)	(6)	(5)	(6)	(1)	(11)	(9)	(15)	(12)	(2)
Pafford Cross	Devils R	0.4	—	—	—	—	0.4	—	—	—	—
Amistad Dam	Rio Grande	1.3	4.0	178	270	0.89	1.4	4.0	180	277	0.88
Laredo	Rio Grande	1.3	2.7	178	260	1.01	1.3	0	160	253	0.86
Las Tortillas	Rio Salado	1.5	3.2	193	637	0.41	2.6	4.8	358	1320	0.37
	(CV)	(50)	(50)	(14)	(20)	(2)	(20)	(15)	(7)	(8)	(2)
Falcon Dam	Rio Grande	1.2	3.6	158	258	0.83	1.2	3.7	163	270	0.82
Camargo	Rio S. Juan	2.3	—	—	—	—	2.4	—	—	—	—
Camargo	Rio Grande	1.2	3.5	158	262	0.82	1.3	3.8	175	283	0.84
Reynosa	Rio Grande	1.4	4.0	182	288	0.85	1.5	4.6	213	319	0.89
Brownsville	Rio Grande	1.4	4.0	190	287	0.89	1.6	4.3	223	343	0.88
	(CV)	(3)	(0)	(6)	(6)	(1)	(6)	(12)	(16)	(15)	(3)

[1] The Cl/SO_4 ratio is given by chemical equivalent.
[2] CV: Coefficient of variation in percent.

tor of 3.0 during March 15 through Sept. 15, whereas Cl and SO_4 ions increased by a factor of 6.2 and 2.6, respectively. This disproportional increase in Cl concentration is caused by Cl inflow, probably from return flow and sewage water containing high levels of Cl, and by some precipitation of SO_4. The sodicity of the Rio Grande at Fort Quitman ranges from 8.5 to 9.5 in sodium adsorption ratio (SAR), which is greater than the SAR increase caused by the increase in salt concentration, and includes the effect of Ca precipitation. The flow of the Rio Grande at Fort Quitman is among the highest in salinity and sodicity.

High salinity of the Rio Grande continues to Presidio as the inflow of fresh water is limited in this portion of the Rio Grande. The Rio Conchos has the highest salinity during April through July and lower salinity during August through November, coinciding with the seasonal pattern of rainfall. Salinity of the irrigation season (March 15 to September 15) and off-season (September 16 to March 14) thus tends to average out. The inflow of the Rio Conchos dominates salinity as well as the flow of this portion of the Rio Grande, but the effect of saline flow of the Rio Grande above the confluence is apparent as indicated by the increased salinity below the point of the confluence. Salinity of the Rio Grande then decreases with the inflow of surface water in the section between Presidio and the Foster Ranch monitoring station.

The confluence of the Pecos River could increase salinity of the Rio Grande, but this effect is offset by the inflow of the fresh water from the Devils River. During 1989, the flow of the Rio Grande, the Pecos, and the Devils rivers measured at the points of inflow into the Rio Grande was 962, 129 and 235 million m^3, respectively. A simple salt balance calculation projects that salinity of the blend should be 1.42 dS m^{-1}. The actual value measured at Amistad was somewhat lower, 1.36 dS m^{-1}. The high Cl concentration of the Pecos river water (747 ppm Cl or 21 meq L^{-1}) causes a substantial increase in the Cl/SO_4 ratio of the blend; 0.74 in theory and 0.89 in measured. The Pecos River is high in SO_4 above Red Bluff Dam, then SO_4 ions precipitate as gypsum upon water evaporation. The dilution of such water downstream creates water of high Cl to SO_4 ratios. This effect is carried throughout the Rio Grande below Amistad. The Pecos River also has high sodium adsorption ratios (SAR), but this effect is buffered by dilution. (The SAR values decrease with dilution by its definition).

Below Amistad Dam, irrigation return flow is mixed into the Rio Grande above and below Eagle

Pass. This does not seem to affect salinity of the Rio Grande, probably because the quantity of the Rio Grande flow at this location is sufficiently large (2.5 billion m^3 in 1989). Salinity data for the Rio Salado were not taken during 1989, and the record shows low flow, 102 million m^3 as compared to the long-term flow of 472 million m^3 per year. The data of 1988 were used for Rio Salado. During the normal year, the Rio Salado can affect salinity of the Rio Grande.

Below Falcon, salinity of the Rio Grande increases somewhat before reaching Brownsville. The contribution of the Rio San Juan is not readily detectable in this data set. However, the flow from the Rio San Juan was exceptionally low in 1989, 7.6 million m^3 instead of the ordinary flow of 434 million m^3 annually. An intensive salt balance study conducted during 1984 through 1986 (TWC/IBWC, 1993) indicates an average salinity increase of 280 mg L^{-1} between Falcon and Anzalduas Dam (about 9 km north of Reynosa). Readings taken during 1989 indicate a salinity increase of 0.15 dS m^{-1} or 110 mg L^{-1} during March 15 to September 15 and 0.33 dS m^{-1} or 240 mg L^{-1} during September 16 through March 14.

We will now examine the flow and salinity of 1989 against the long-term average (1969-89) recorded at selected stations along the Rio Grande (Figure 2). The flow data (dashed lines) of 1989 are similar to the long-term average, except for the lower flow in most segments of the Rio Grande below Presidio. The salinity pattern (solid lines) was also similar, except for higher readings during 1989 than the long-term average below Presidio and lower readings at Fort Quitman.

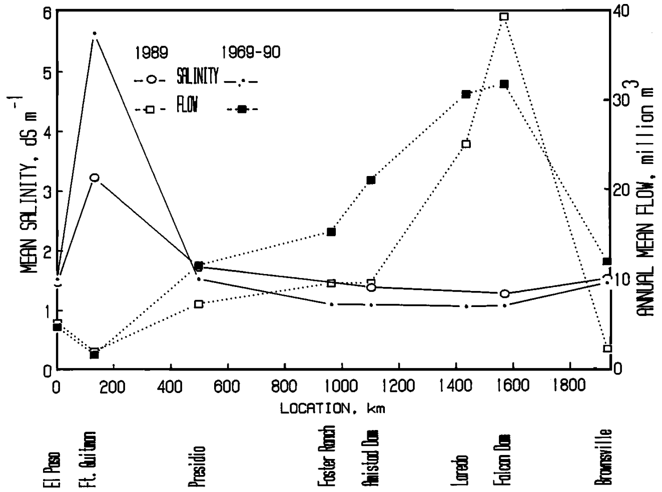

Figure 2. The annual mean salinity (solid lines) and flow (dashed lines) in 1989 and those averaged for a period of 1969 through 1989 (original data from IBWC).

b. Salinity and Flow Trends

To examine the yearly trend, the annual mean salinity values were first computed by taking arithmetic means of monthly salinity records kept by the IBWC since 1969, the year after the construction of Amistad Dam. The annual mean salinity and the annual total flow recorded at two terminal locations (El Paso and Brownsville) and at Fort Quitman are shown in Figures 3A and 3B, respectively. The annual mean salinity at Fort Quitman has fluctuated widely; and high salinity values appeared to have coincided with the years of low flow, and low salinity values with the years of high flow. There seems to be a similar trend at El Paso, although it is less clear. The annual mean salinity at Brownsville, however, has been more stable, even though the flow has varied greatly over the years.

Recall that the flow of the Rio Grande at Fort Quitman is the blend of the tail water of the water supply from Elephant Butte Dam and irrigation return flow. During the years of low flow, the flow at this location consists mostly of agricultural return flow and sewage water, both of which are highly charged with dissolved salts. Also, saline

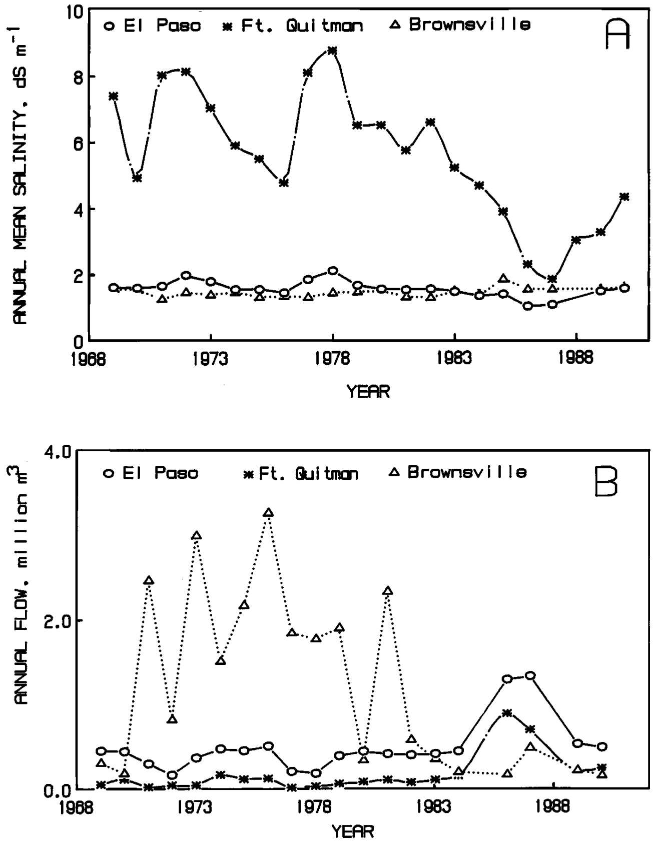

Figure 3. The annual mean salinity (A) and the annual flow (B) of the Rio Grande at El Paso, Fort Quitman, and Brownsville (original data from IBWC).

does provide a broad picture of the flow and the salt load averaged since 1969. For example, approximately 60 percent of the flow as well as salts that flow into Amistad then Falcon Dams originate from the area above Amistad (Table 12). The Rio Conchos is the single largest inflow and salt carrier into the Texas/Mexico portion of the Rio Grande. However, salinity of the Rio Conchos is lower than the salinity of the other sources combined. The saline flow from Fort Quitman and the Pecos River contributes to 48 percent of the salt load into Amistad Reservoir, while these surface streams contribute only 21 percent of the flow into Amistad Dam (Table 12). These two streams plus the Rio Salado contribute to 50 percent of the salt load, while providing 26 percent to the flow of Texas/Mexico portion of the Rio Grande. Salinity control at three major saline inflow sources (the Pecos, the Rio Salado, and the tail water from Fort Quitman) is likely to have a major impact on salinity of the Rio Grande. Likewise, salinity of the Rio Conchos, which has been increasing, is likely to have a major impact in the future.

2. Trace Elements

a. Dissolved Trace Elements

Trace element concentrations of the Rio Grande were obtained from the U.S. Geological Survey (USGS) stream water quality monitoring file (unpublished). The USGS has maintained monthly analyses of common salts, trace elements, pesticides and several other constituents at four locations along the Rio Grande (El Paso, Fort Quitman, Laredo, and Brownsville). In addition, the USGS has maintained several other monitoring stations upstream of the Rio Grande in New Mexico. The Texas Water Commission (TWC) has also maintained water quality monitoring for trace elements, yet the detection limits of analytical procedures and/or equipment used did not permit low concentration measurements of trace elements in water.

The USGS data (1988, 1989, and 1990) obtained monthly at six monitoring stations were divided into two periods, March 15 to September 15 (the main irrigation season), and September 15 to March 14. The listed values in Table 13 are the average of six separate measurements per year and were averaged for the three years, except for the data sets at Taos and San Marcial, which consist of annual measurements in November. Table 13 also includes the data for the Main Floodway and the Arroyo Colorado reported in Wells et al. (1988).

In the section above Fort Quitman, the dissolved concentrations of Cd, Co, Ag, and Se were at or below the detection limits at all locations. The concentrations of Cr, Hg, Pb and Mo were also near or slightly above the detection limits. The trace elements which were detected include As, Cu, Ni, Zn, V, Ba, B and Sr. The concentrations of As, Ba and Zn, and especially Sr have shown an increasing trend toward Fort Quitman. Although the available data are sketchy, the concentrations of B and V are probably increasing as these elements usually increase with water evaporation. There appears to be no consistent seasonal trend in trace element concentration between the two periods examined.

The concentrations of trace elements in the Lower Rio Grande (Laredo and Brownsville) were not significantly different from those reported at San Marcial or El Paso, except for some indications of higher concentrations of Cu and Ni at Laredo. These occasional high readings may indicate contamination, probably through discharge of municipal sewage (TWC, 1991).

The water samples from the Main Floodway and the Arroyo Colorado (Wells et al., 1988) show el-

Table 12. Summary of inflow and salt loads into Amistad and Falcon Reservoirs (the average from 1969 to 1989).

	Inflow			Salt load		
Sections Rivers	million m^3	percent (1)	percent (2)	million tons	percent (1)	percent (2)
Fort Quitman-Amistad						
Rio Grande	169	5	8	0.352	12	19
Pecos river	274	8	13	0.544	18	29
Rio Conchos	909	26	44	0.762	25	41
Others	711	21	35	0.187	6	10
Subtotal	2063	60	100	1.845	61	100
Amistad - Falcon						
Rio Salado	472	13	34	0.604	20	52
Others	930	27	66	0.569	19	48
Subtotal	1402	40	100	1.173	39	100
Total	3465	100	—	3.018	100	—

(1) Based on the total inflow into Falcon Dam
(2) Based on the inflow into Amistad or Falcon Dam T able

Table 11. Annual inflow, outflow and salt load balance in three segments of the Rio Grande from El Paso to Falcon Dam (the average from 1969 to 1989).

Location	River	Annual flow	Flow-weighted salinity	Salt concent.	Salt load
		million m^3	dS m^{-1}	mg L^{-1}	million tons
El Paso - Fort Quitman					
Inflow					
El Paso	Rio Grande	547	1.12	777	0.425
El Paso	Sewage	30	2.0[1]	1390[1]	0.042[1]
		577			0.467
Outflow					
American	Diversion	-332	1.12	777	—
Mexican	Diversion	-65	1.12	777	-0.051
Fort Quitman	Rio Grande	-169	3.05	2083	-0.352
		-566			-0.403
Balance		+11			+0.064
Fort Quitman - Amistad					
Inflow					
Fort Quitman	Rio Grande	169	3.05	2083	0.352
Near Ojinaga	Rio Conchos	909	1.27	839	0.762
Langtry	Pecos River	274	3.21	1985	0.544
Pafford Cross	Devils River	353	0.38	264	0.093
Other recorded inflows		74	0.41	264[1]	0.019[1]
Unaccounted		284	0.41	264[1]	0.075[1]
		2063		(894)[2]	1.845
Dam Storage (Annual Equivalent)		-174	1.04	687	-0.120
Outflow					
Various	Diversions	-20[1]	1.07[1]	707	-0.014
Amistad	Rio Grande	-2063	0.993	656	-1.354
		-2083			-1.368
Balance		-194			+0.357
Amistad - Falcon					
Inflow					
Amistad	Rio Grande	2063	0.993	656	1.382
Tortillas	Rio Salado	472	1.940	1280	0.604
Other recorded flow		930	0.92[1]	612[1]	0.569[1]
		3465		(737)[2]	2.555
Outflow					
Various diversions		-424	0.993	656	-0.278
Falcon	Rio Grande	-3046	1.162	768	-2.339
		-3470			-2.617
Balance		-5			-0.062

[1] These values are the estimate and subject to some error.

[2] The values are estimated by the salt balance equation.

soils in this section of the Rio Grande has increased substantially over the years.

The inflow into the Fort Quitman to Amistad Dam section includes the tail water of the Middle Rio Grande, the Rio Conchos, the Pecos River, the Devils River and other minor flows totaling 2.06 billion m^3 per year (Table 11). The salt inflow from various sources in this section was estimated to be 1.84 million tons annually. The outflow includes small diversions for limited areas of irrigation and the Rio Grande flow leaving Amistad Dam. There is also the dam storage which is given as the annual rate equivalent. The recorded inflow is about 10 percent less than the storage plus the outflow, and much of this difference can be accounted for by the unrecorded inflow. The salt balance evaluated at the dam shows that the salt inflow exceeded the outflow plus storage, indicating a possibility of continuing salt accumulation in this segment of the Rio Grande. This estimate is in agreement with the continuing increases in salinity of the Rio Conchos, the Pecos River, and Amistad Reservoir.

The flow-weighted mean salinity of the inflow in the Fort Quitman to Amistad segment is estimated at 894 mg L^{-1}. In theory, this value should coincide with the flow-weighted salinity of Amistad Reservoir, which is 687 mg L^{-1} based on the salinity and the volume of the discharge. This observed value is, however, considerably lower than the estimated salinity, and may suggest that the steady-state condition has not yet been achieved.

The Amistad to Falcon segment of the Rio Grande has the recorded total inflow of 1.4 billion m^3 per year from both the U.S. and Mexican sides combined (Table 4) in addition to the main flow of 2.06 billion m^3 per year. The recorded outflow, including diversion (Table 6), is similar to the recorded inflow. The lake water storage is ignored here as Falcon Dam was filled prior to 1969. The long-term salinity readings from various tributaries are not available, thus the mean value obtained during the 1988 survey (TWC/IBWC, 1993) is substituted. The salt balance (inflow minus the outflow) in this segment is only slightly negative, when the diverted flow is assumed not to return back to the Rio Grande. This assumption is probably not realistic, as some return flow does exist in this segment of the Rio Grande. If we assume that the salt diverted will return quantitatively, the salt balance is positive, but not by a large margin.

The segment below Falcon Dam receives inflow almost all from the Mexican side, and some of these tributaries (e.g., the Rio San Juan) are quite saline. However, this segment is dominated by diversion (1.2 billion m^3 to the Texas side and 1.3 billion m^3 to Mexico annually, Table 6), while the inflow is estimated to be 0.64 billion m^3 per year. The diverted water, especially that delivered to the Texas side, drains away from the main flow of the Rio Grande toward the Laguna. A short-term intensive salt balance study conducted by the TWC in cooperation with the IBWC (TWC/IBWC, 1993) indicates some increases in salinity in the segment between Falcon and Anzalduas Dams during the periods of low flow. The increases seem to have been caused by both subsurface seepage intrusion and the salt inflow mostly from the Mexican side of the river.

The salt balance discussed above is a simplified version of complex systems. Nonetheless, it

well waters are used to supplement irrigation during the years of low flow. This practice yields return flow of high salinity. All of these factors contribute to high salinity readings at Fort Quitman. The flow of the Rio Grande at the Brownsville location is the excess spill from Falcon Dam, thus salinity readings should be stable. However, when the flow is severely curtailed as in recent years, return flow and saline seepage from the surrounding areas can constitute a considerable portion, thus causing some increase in salinity.

The annual mean salinity and the annual flow were also detrmined at Presidio below the confluence of the Rio Conchos, and for the release from Amistad and Falcon Dams (Figures 4A and 4B) as well as three key tributaries at the points of confluence: the Rio Conchos, the Pecos River and the Rio San Juan (Figures 5A and 5B). The annual mean salinity and the annual flow at Laredo (above Falcon Dam) were also determined, but the data are not shown, because they were essentially identical to those at Falcon Dam. The annual mean salinity as well as the annual flow of the Rio Grande at Presidio is influenced most significantly by the conditions of the Rio Conchos, and, to a limited extent, by the flow conditions of the Rio Grande below Fort Quitman. The flow from the Rio Conchos dominates the flow of the Rio Grande. In fact, the annual mean salinity and the annual flow pattern recorded at the Presidio location (Figure 4) are similar to those of the Rio Conchos (Figure 5), but not to those recorded at Fort Quitman (Figure 3). The annual mean salinity of Amistad Dam release has been lower than at Presidio, even though the saline water from the Pecos flows into the Rio Grande above Amistad. It was indicated earlier that significant dilution is taking place in this segment of the Rio Grande, especially by the inflow of fresh water from the Devils River and small streams. The annual mean salinity of Falcon Dam release has been similar to that of Amistad, even though the annual flow has been considerably larger at Falcon (Figure 4).

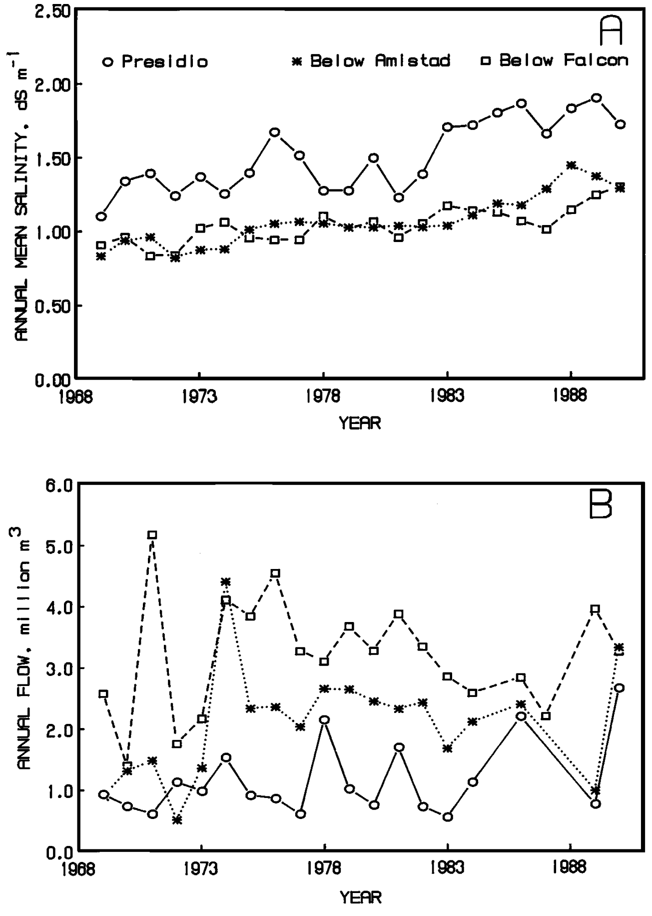

Figure 4. The annual mean salinity (A) and the annual flow (B) of the Rio Grande at Presidio (below the confluence of the Rio Conchos), and the release from Amistad and Falcon Dams (original data from IBWC).

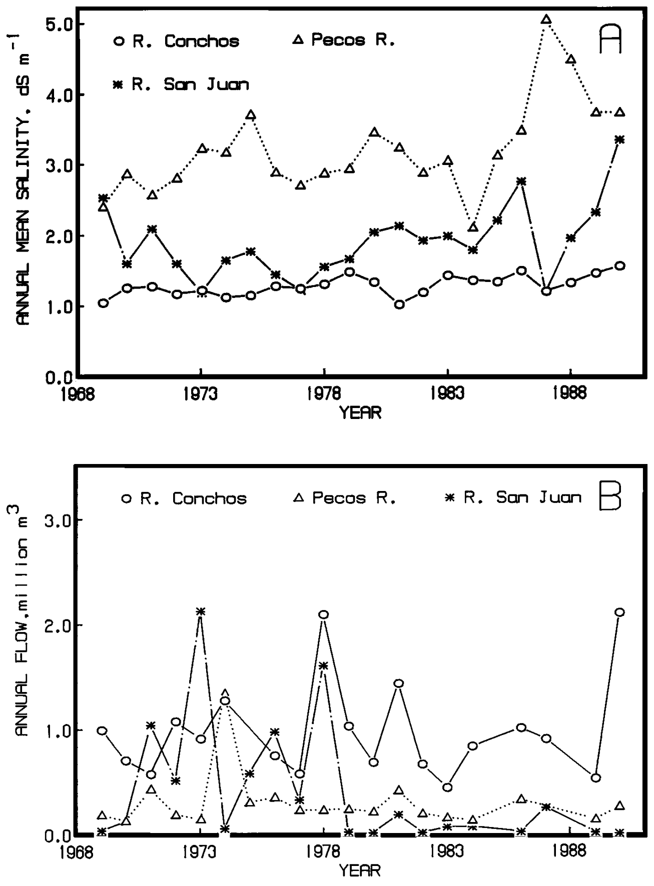

Figure 5. The annual mean salinity (A) and the annual flow (B) of the three tributaries at the point of the confluence into the Rio Grande (original data from IBWC).

The annual mean salinity of the Pecos as well as the Rio San Juan appears to be increasing (Figure 5A), while that of the Rio Conchos has been more stable. The flow of these tributaries has fluctuated rather widely over the years (Figure 5B). The increases in salinity of these tributaries directly contribute to the salinity increase of the main flow of the Rio Grande.

In order to examine salinity trends, the annual mean salinity readings were fitted to the linear regression equation.

$$EC = a(X-1969) + b \qquad (1)$$

where EC is the annual mean salinity in dS m^{-1}, X the years since 1969, and a and b are regression coefficients. The changes in the annual flow were also fitted to Equation 1. In addition, the flow data were analyzed by using the autocorrelation functions to determine its dependence on year. For details on autocorrelation, one should refer to Journal and Huijbreqts (1978). The correlation between annual mean salinity and annual flow was also determined.

The linear regression analysis indicated a significant correlation between the annual mean salinity and the years since 1969 at all locations examined, except at El Paso, Camargo and Brownsville (Table 8). The rate of increase was largest at the Pecos River, 0.061 dS m^{-1} per year (or 38 mg L^{-1} per year) followed by 0.029 dS m^{-1} per year at Presidio. Salinity increases at Amistad and the Foster Ranch station were similar, 0.023 dS m^{-1} per year (or 15 mg L^{-1} per year). If this trend continues, salinity of Amistad Reservoir is expected to increase to 1.52 dS m^{-1} (or 1,000 mg L^{-1}) by the year 2000, or salinity will double the level of 1969 by the year 2004. Salinity increases at Falcon as well as Laredo were somewhat modest, 0.015 dS m^{-1} per year (or 7.8 mg L^{-1} per year). If this trend continues, salinity at Falcon is projected to reach 1.34 dS m^{-1} (885 mg L^{-1}) by the year 2000. The rate of salinity increase is higher in low rainfall areas (such as Pecos and Presidio) as compared to higher rainfall areas (e.g., Laredo and Falcon). An exception was at Fort Quitman where salinity had significant negative correlation with the years since 1969, and this seems to be related to the increased flow in recent years (Figure 3).

The annual flow was not significantly related to the years since 1969 when evaluated by the linear regression or the autocorrelation. The flow appears to fluctuate randomly with the coefficient of variation ranging from 29 to 88 percent (Table 9). The annual mean salinity had significant correlation with the annual flow at El Paso, Fort Quitman, and to a lesser extent ($p = 0.05$) at Brownsville (Table 9). No significant correlation was observed at all other locations examined (Table 9).

Overall, two different patterns were observed: flow-dependent salinity at El Paso, Fort Quitman and Brownsville and flow-independent salinity at all other locations examined. The first pattern is probably related to the fact that the flow at El Paso and Fort Quitman consists of tail water, and that at Brownsville is a mixture of tail water and spills. Salinity of the flow-through portion of the Rio Grande appears to be independent of the annual flow, but all show increasing trends, especially in drier parts of the Rio Grande Basin. It is possible that the salts once accumulated in the El Paso and Fort Quitman section had moved downstream due to the increased flow in recent years. Lower rates of salinity increases observed in wetter parts of the Rio Grande Basin may be accounted for by dilution. A comprehensive water and salt balance analysis is needed to explain these observations.

c. Salt Load and Balance

For the analysis of salt load, it is more appropriate to use flow-weighted annual salinity than arithmetic mean salinity. We, therefore, computed the annual flow-weighted mean salinity using the monthly flow and monthly salinity data from the IBWC since 1969. It is also more appropriate to use salt concentrations than the electrical conductivity for the estimate of salt load. The conversion factor from dS m^{-1} to mg L^{-1} was determined using the IBWC data which contained both EC and the concentration of salt elements. Results (Table 10) show that the conversion factor is fairly constant, except for the Pecos River and the Rio Grande at El Paso. The low conversion factor obtained for the Pecos River is associated with high Na and Cl concentrations of the Pecos River at this location. (The Pecos River upstream actually has high Ca and SO_4 concentrations). The high conversion factor at El Paso is related to high SO_4 concentrations.

T able 8. The linear regression by Equation 1 of the annual mean salinity with years since 1969 at various locations along the Rio Grande (original data from IBWC).

Location	River	Slope	r	Intercept	1990	2000
		dS m^{-1}/year		....	dS m^{-1}	....
El Paso	Rio Grande	-0.023	-0.57	1.78	1.30	—
Fort Quitman	Rio Grande	-0.216	-0.71*	8.03	3.28	—
Ojinaga	Rio Conchos	0.013	0.68*	1.14	1.40	1.54
Presidio	Rio Grande	0.029	0.80**	1.20	1.81	2.10
Foster Ranch	Rio Grande	0.022	0.89**	0.84	1.30	1.52
Langtry	Pecos river	0.061	0.64*	2.59	3.87	4.48
Amistad	Rio Grande	0.023	0.89**	0.81	1.29	1.52
Laredo	Rio Grande	0.014	0.78*	0.89	1.19	1.33
Falcon	Rio Grande	0.015	0.79**	0.88	1.20	1.34
Camargo	Rio San Juan	0.032	0.40	1.56	2.24	—
Brownsville	Rio Grande	-0.0035	0.16	1.39	1.46	—

*, ** significant at 0.05 and 0.01 levels of probability.

The annual salt load and balance estimates were made based on the annual flow and the annual flow-weighted salinity since 1969. Salinity readings of small tributaries, creeks, and bank seepage were not available, thus the following analyses are merely rough estimates.

In the El Paso to Fort Quitman section of the Rio Grande, the main salt carrying flow is the main flow of the Rio Grande from New Mexico and some inflow from El Paso municipal sewage. The combined salt inflow is estimated at 0.425 million tons (Table 11). The outflow from this section of the Rio Grande includes the diversion to the El Paso and the Juarez Valleys and the flow leaving the Fort Quitman station. The salt carried out through American Diversion returns back to the Rio Grande as irrigation return flow, thus was not considered as the outflow from the segment. The flow balance in this segment is only slightly positive, indicating that the recorded inflow slightly exceeds the recorded outflow in this segment of the Rio Grande. The salt balance in this segment (estimated as the salt inflow minus the salt outflow) is positive, indicating possible salt accumulation and/or subsurface salt flow. The magnitude of unaccounted salt load amounts to approximately 13 percent of the recorded salt inflow. This estimate is in line with the well-known fact that salinity of irrigated

Table 9. The linear regression and variation of the annual flow with years since 1969, the significance of autocorrelation for the annual flow and years, and the linear regression between the annual mean salinity and the annual flow at selected locations along the Rio Grande (original data from IBWC).

Location	River	Linear reg. (r)	Auto-Correln.	Mean	Standard dev.	Coeff. of variation
Annual flow vs years				mill m^3	mill m^3	percent
El Paso	Rio Grande	0.49	N/S	483	300	62
Fort Quitman	Rio Grande	0.54	N/S	165	223	34
Foster Ranch	Rio Grande	0.34	N/S	1516	693	46
Near Ojinaga	Rio Conchos	0.16	N/S	966	460	48
Presidio	Rio Grande	0.40	N/S	1144	604	53
Amistad	Rio Grande	0.49	N/S	2188	903	41
Falcon	Rio Grande	0.05	N/S	3179	935	29
Brownsville	Rio Grande	0.44	N/S	1200	1051	88
Annual mean salinity vs annual flow					Slope dSm^{-1}/mill m^3	Intercept dS m^{-1}
El Paso	Rio Grande	-0.86**	—	—	-1.00	2.04
Fort Quitman	Rio Grande	-0.81**	—	—	-0.093	0.70
Ojinaga	Rio Grande	0.03	—	—	—	—
Presidio	Rio Grande	0.09	—	—	—	—
Foster Ranch	Rio Grande	0.21	—	—	—	—
Langtry	Pecos	0.05	—	—	—	—
Amistad	Rio Grande	0.19	—	—	—	—
Laredo	Rio Grande	0.03	—	—	—	—
Falcon	Rio Grande	-0.03	—	—	—	—
Camargo	Rio San Juan	-0.46	—	—	0.50	1.34
Brownsville	Rio Grande	-0.64*	—	—	-6.44	10.30

*,** Significant at 0.05 and 0.01 levels of probability.

Table 10. The conversion coefficients from the electrical conductivity (dS m^{-1}) to mg L^{-1} (original data from IBWC).

River	Location	mg L^{-1}
Rio Grande	El Paso	692
Rio Grande	Fort Quitman	670
Rio Conchos	Ojinaga	659
Pecos river	Langtry	618
Rio Grande	Amistad	661
Rio Grande	Falcon	661
Rio Grande	Brownsville	658
Average		658