MEMORANDUM REPORT

AN OVERVIEW OF THE RESULTS OF AVAILABLE GROUND-WATER, SURFACE-WATER AND EVAPOTRANSPIRATION STUDIES ADDRESSING RIO GRANDE BASIN CHANNEL LOSS AND GAIN IN TEXAS, AND WITH SOME REGARD IN NEW MEXICO AND MEXICO

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FIGURES (SEPARATE)

1. Investigation of Channel Losses and Gains in the Rio Grande Basin

Channel losses and gains along the streams within the Rio Grande Basin have been researched and evaluated through the following activities:

- Review of the complex and very diverse geology and hydrogeology,
- Review and analysis of previous surface-water-delivery and low-flow investigation,
- Delineation of major stream reaches which had the potential for historical losses and gains, and
- Review of information concerning evapotranspiration losses from saltcedar infestations.

These are discussed in the following sections.

1.1 Geology and Hydrogeology

The important aquifers that occur in the Rio Grande Basin in Texas and are hydrologically connected to the Rio Grande and its major tributaries (Pecos River, Devils River etc.) are addressed in the following discussions. The aquifers are discussed as they occur from the upstream El Paso area to the downstream Brownsville area.

1.11 Hueco-Mesilla Bolson Aquifer Systems

These are major aquifer systems along the Rio Grande in New Mexico, Texas (El Paso and Hudspeth Counties) and Mexico. There are two aquifer systems. One is the Hueco Bolson Aquifer System consisting of a deep aquifer in bolson deposits overlain by a shallow aquifer in the Rio Grande alluvium (RGA) deposits. The Hueco Bolson Aquifer lies east of the Franklin Mountains in the "mesa" area of New Mexico and Texas and along the Rio Grande in the El Paso/Juarez Valley of Texas and Mexico. The Mesilla Bolson Aquifer System has three water-bearing units, two deep units in the bolson deposits overlain by a shallow water-bearing unit in the RGA deposits. The Mesilla Bolson Aquifer System lies west of the Franklin Mountains in the Lower Mesilla Valley of Texas and New Mexico. The deep bolson deposits consist of Tertiary and Quaternary age, unconsolidated to slightly consolidated deposits composed of fine to medium grained sand interbedded with lenses of clay, silt, gravel and caliche. The RGA deposits of Quaternary age are composed of sand, silty sand, silt, channel deposits of interbedded gravel sand, and silt, and conglomerate of pebbles, cobbles and boulders of various rock material (Taken and modified from Peckham, 1963; Ashworth and Hopkins, 1995; Ashworth, 1990b; and Barnes, 1968).

Natural recharge occurs primarily from precipitation runoff along the base of the mountains into the alluvial fan deposits adjacent to and above the "floor" of the bolsons in Texas, New Mexico and Mexico. Recharge by such means was estimated to be about 5,640 acre-feet per year for the Hueco Bolson (Meyer, 1976) (Scanlon, et al.. 2002). Muller and Price (1979) estimated the annual effective recharge to be 6,000 acre-feet to the Hueco Bolson. Recharge by such means was estimated to be about 3,547 acre-feet per year for the Mesilla Valley (Scanlon, et al., 2002). Recharge to the Mesilla Bolson in the Lower Mesilla Valley was estimated to be about 15,000 acre-feet per year (Leggat, et al., 1962). Muller and Price (1979) estimated and Scanlon, et al., (2002) reported that the effective annual recharge to the Mesilla Bolson in the Lower Mesilla Valley of Texas and New Mexico is about 18,000 acre-feet per year.

Prior to ground-water development in the area there was equilibrium of ground-water inflow-outflow where natural recharge along the mountain fronts was equal to ground-water seepage (discharge) to the Rio Grande and ground water discharged in the Rio Grande floodplain by evapotranspiration. Prior to development, the water levels of the deep bolson water-bearing units generally were higher than the water levels in the overlying shallow RGA water-bearing unit which had water-levels higher than the stream bed. These water-level conditions allowed upward leakage of ground water from the bolson deposits into the RGA deposits. Both aquifer high water level conditions caused ground water to be discharged to the Rio Grande making it a gaining stream. But heavy ground-water pumpage, the infestation of the Rio Grande floodplain by saltcedar and other phreatophytes, and the consumptive use of water by irrigated crops changed ground-water inflow and outflow conditions in the valleys.

Since ground-water development (pumpage), the natural recharge still occurs from the mountain-front alluvial fans, but also induced recharge has occurred as 1.) underflow from New Mexico and Mexico, 2.) seepage (channel losses) from the Rio Grande, canals and laterals, 3.) deep subsurface seepage into the deep bolson aquifer from ground water in the deep bedrock of the mountains, and 4.) return flows from irrigation, primarily in the floodplain of the Rio Grande. However, ground-water investigations of the Mesilla Valley in Texas indicate that urbanization of formerly irrigated lands has probably reduced the amount of recharge from irrigation return flows (White, 1987), (Ashworth, 1990b), (Ashworth and Hopkins, 1995), (Scanlon, et al., 2002).

Since the 1950s, large withdrawals of ground water from the bolson deposits for public supply and from the RGA for irrigation of the Lower Mesilla Valley has caused water-level declines which have caused induced recharge and channel losses from the Rio Grande, canals and drains. In turn the large withdrawals of ground water from the bolson deposits underlying the RGA in the El Paso and Juarez area of the El Paso Valley have caused Rio Grande channel losses to the RGA and downward leakage of ground water from the RGA into the deeper bolson aquifer.

Meyer (1976) using a digital model of the Hueco Bolson Aquifer System simulated the ground-water-surface-water conditions in the aquifer system and estimated by model applications the average annual seepage (channel gain and loss) to and from the Rio Grande and the average leakage between the RGA and bolson aquifers. As example, during a 1968-73 period such downward leakage to the deep bolson aquifer was estimated to be about 33,278 acre-feet per year. Approximately 12,765 acre-feet per year or about 38 percent of the leakage was channel loss from the Rio Grande.

The remaining 20,513 acre-feet was estimated to be leakage from ground-water storage in the RGA aquifer. Such leakage from storage in the RGA causes increasing water level declines which migrate southeastward down the El Paso/Juarez Valley causing the water table of the RGA to decline further and further down the Valley. This continuing condition reverses the hydraulic gradient of the RGA aquifer which was originally southeastward and toward the river. This reversal of gradient and its increase and continuation toward the northwest and away from the river will cause migration of dewatering southeastward, and poor water quality of the RGA to encroach and deteriorate the quality of the fresh water in the underlying bolson aquifer. Parts of the Rio Grande channel in the El Paso/Juarez Valley were lined in 1968 (Meyer, 1976) and in 1973 and 1998 (Sheng, et al., 2001) to reduce such channel losses from the river.

The estimated average annual seepage (induced recharge) from the Rio Grande and the RGA to the Hueco Bolson Aquifer System from 1903 to 1991 are given in Table 1, page 26 of Meyer (1976). Muller and Price (1979, page 28, Table 3) using information from Meyer (1976) provide a schedule for induced recharge as a percentage of annual historical and projected ground-water pumpage from the Mesilla Bolson and Hueco Bolson Aquifer Systems from 1974 through the year 2030.

Meyer and Gordon (1973) reported water budgets for the Lower Mesilla Valley and the El Paso Valley. Estimated annual ground-water recharges from two annual budgets for in the Mesilla Bolson Aquifer system in the Lower Mesilla Valley were calculated to be 26,170 acre-feet in 1970 and 33,500 acre-feet in 1971. These estimates are up to two times greater than the average 15,000 acre-feet per year estimated by Leggat, et al. (1962). The estimated average annual ground-water recharge determined in the annual budgets for the El Paso Valley in 1968 through 1971 was about 80,710 acre-feet. The range was about 74,100 acre-feet in 1968 and about 89,330 acre-feet in 1970.

Alvarez and Buckner (1980) and White (1987) describe the hydrologic relationships and changes of the ground-water and surface-water regimes of the Mesilla and Hueco Bolsons under historical recharge-discharge conditions that occurred in the El Paso area. Sheng, et al., (2001) discuss the hydrogeology and the up-to-date ground-water modeling and ground-water availability of the Hueco Bolson Aquifer System.

Texas Water Development Board and New Mexico Water Resources Research Institute (1997) (Executive Summary, pages 3 through 7) provide a brief but very informative description of the hydrogeology and the ground-water recharge-discharge conditions of the Mesilla Basin Ground-Water Aquifer System, the Hueco-Tularosa Aquifer, a "Southeastern Hueco Aquifer", the Rio Grande Aquifer (RGA of the El Paso Valley), and a "Diablo Plateau Aquifer." The report addresses to some extent, the conditions of the aquifers in Texas, New Mexico and Mexico. The following discussions as direct quotes, give the authors' concepts of ground-water conditions of the RGA aquifers and their hydrologic relationship to the surface water regime of the Rio Grande in the El Paso area.

- **RGA in the Mesilla Valley (page 3)**

"The water table is approximately 10 to 25 feet below the land surface."
"Recharge to the aquifer occurs primarily as vertical flow from the surface water system (river, canals, laterals and drains) and irrigated crop fields."
"The majority of discharge from the floodplain alluvium occurs through evapotranspiration of irrigated crops, flow to drain system, irrigation pumpage, municipal pumping, and industrial pumping."

- **RGA in the El Paso-Juarez Valley (pages 5 & 6)**

"Water level contour maps prepared with data collected in 1973 – 74 and 1994 – 1995 illustrate losing stream, underflow, and baseflow conditions on different segments of the alluvial floodplain. The condition of losing stream is apparent along the Chamizal zone where drawdown cones from municipal well fields *(at Juarez as well as El Paso)* have reversed the hydraulic gradient between the river and the Rio Grande *(RGA)* aquifer. Drawdowns have intensified along the Chamizal zone since 1973. Alluvial under flow predominates between Chamizal zone and the El Paso/Hudspeth county line. Along this stretch of floodplain, ground-water flows subparellel to the direction of surface discharge, and head in the aquifer is approximately equal to the head in the river. The head elevation along this reach did not change significantly since 1973. The condition of baseflow prevails between county line and Fort Quitman. Flow is oriented subperpendicular to the direction of surface discharge and ground water clearly discharges to the Rio Grande. Hydraulic head in this part of the floodplain has increased since 1973."
"Recharge to the Rio Grande *(RGA)* aquifer along irrigated reaches is due primarily to infiltration of surface water that has been applied to irrigable crops. Recharge also occurs to some extent by direct seepage from diversion canals and river channels, although lining of the

Rio Grande channel along the Chamizal zone limits recharge by the river locally. Other sources of recharge to the Rio Grande alluvium include direct precipitation on the floodplain surface, seepage from irrigation canals and drains, infiltration of runoff along arroyos, and recharge from cross-formational flow with the Hueco Bolson. Quantification of the amounts of recharge to the alluvial *(RGA)* aquifer is infeasible with available data."

"Ground water is discharged from the Rio Grande alluvium by irrigation pumping, by subsurface seepage to the Rio Grande, by leakage to drains, and cross-formational leakage to the Hueco Bolson. Along the heavily urbanized Chamizal zone, discharge occurs primarily by cross-formational leakage from the alluvium to the Hueco Bolson where storage in the Rio Grande *(RGA)* aquifer is depleted by heavy municipal pumping in the bolson aquifer *(by El Paso and Juarez)*. From Chamizal zone to the El Paso/Hudspeth County line, discharge occurs by irrigation pumping and by leakage to the many drains which help to maintain nearly constant water levels in the alluvial aquifer. From the county line to Fort Quitman, discharge occurs by irrigation pumping, by seepage to the Rio Grande, and by leakage to a few drains."

Hawley, et al., (2001) provide an up-to-date overview of the hydrogeologic framework, ground-water flow and chemistry, and ground-water modeling of the Mesilla Bolson Aquifer System in Texas, New Mexico and Mexico. These reports provide "References" sections that provide useful and meaningful historical information on the hydrology and hydrogeology of the Aquifer Systems in the El Paso area of Texas, New Mexico and Chihuahua.

Calculations of the difference between the available elevations of RGA water levels and the elevations of the streambed of the Rio Grande in the Lower Mesilla Valley and the El Paso Valley of Texas were made. Since the occurrence of large withdrawals of ground waters from the Hueco-Mesilla Bolson Aquifer Systems, the potential for large Rio Grande channel losses to the aquifer systems was confirmed; because the elevations of available RGA water levels were calculated to be significantly and consistently lower than the elevations of the streambed of the Rio Grande throughout both Valleys.

A pilot-project in the Hueco Bolson indicates that artificial recharge may be successful in the future as a means to augment the ground-water supply. Treated wastewater has been injected in a dry well at about 800 liters per minute, and is being recharged through a half acre recharge basin at about 13 feet per day (Scanlon, et al., 2002).

1.12 West Texas Bolsons of Red Light Draw, Green River Valley, Presidio-Redford

These three bolson aquifers consist of Cretaceous, Tertiary and Quaternary age deposits ranging from carbonate rocks of limestone and dolomite to fine- to coarse-grained sand and conglomerate to lake deposits of very fine-grained sand, silt and clay. The composition of the bolson fill rock materials differs according to the rocks that were eroded from the uplands adjacent to the bolson. Where these bolsons meet the Rio Grande, their deposits are overlain by Quaternary age, river floodplain alluvium, namely the Rio Grande alluvium (RGA) which is composed of silty sand, channel deposits of gravel and sand, and rounded pebbles, cobbles and boulders of various rock material (Barnes, 1979 and Barnes, 1979a). The RGA are the deposits which are beneath the floodplain area of the river, are water saturated under water-table conditions, and have the stream channel of the Rio Grande and the saltcedar infestations of the river floodplain.

The Red Light Draw Bolson is in remote southern Hudspeth County and is drained by Red Light Draw Arroyo (Quitman Arroyo on some maps) which enters the Rio Grande several miles downstream from Indian Hot Springs. Ground water occurs in rocks of Cretaceous age, Cenozoic basin fill, Tertiary igneous rocks and the RGA along the river (Darling and Hibbs, 2001).

The next bolson downstream is Green River Valley which is in remote parts of Hudspeth, Culberson, Jeff Davis and Presidio Counties (where these counties meet at the Rio Grande). Ground water occurs in Cretaceous age limestone, sandstone, conglomerate and siltstone, Tertiary volcanic rocks, Cenozoic basin fill and the RGA along the river (Darling and Hibbs, 2001)

Further down the Rio Grande is the larger Presidio-Redford Bolson which extends along the Rio Grande from near Candelaria in northern Presidio County to just downstream from Redford in southern Presidio County (Ashworth and Hopkins, 1995) (Barnes, 1979 and Barnes, 1979a). The basin fill of the bolson is composed of eroded volcanic and sedimentary rock material consisting of gravel, sand, silt and clay from the adjacent mountains which have bedrock of Cretaceous and Tertiary age. The RGA of Quaternary age overlies the bolson fill in the river floodplain (Gates, et al., 1980).

Because of their remote locations, there is very little ground-water development in the Red Light Draw and Green River Bolsons. Only a few shallow irrigation wells have been completed in the RGA along the river at Red Light Draw and Green River Valley. These wells were reported to produce 1,000 to 1,500 gallons per minute and indicate that the shallow RGA water-bearing unit of the bolsons is very permeable. Other less productive wells are used for livestock watering in the upland parts of the bolsons away from the river (Gates, et al., 1980). Bolson ground-water is artificially discharged by these wells, and naturally discharged by springs, seeps and evaporation in the bolson uplands, by seasonal seepage into the Rio Grande through the RGA, and by evapotranspiration, mainly by saltcedar infestations in the RGA in the river floodplain (Gates, et al., 1980)..

The Presidio-Redford Bolson is composed of basin fill deposits. These very thick deposits which contain mostly saline ground water are overlain in the river floodplain by RGA which are up to 100 feet thick and contain fresh to slightly saline ground-water. The entire reach of the Rio Grande channel within the bolson occurs on the RGA deposits in the floodplain of the river. Wells completed in the upland basin fill deposits of the Presidio-Redford Bolson away from the floodplain and RGA are small diameter wells used for livestock watering. Larger capacity wells are completed mainly in the RGA and are used for public supply at Presidio and for irrigation in the river floodplain around Presidio. The RGA wells are capable of discharging 300 to 800 gallons per minute in the Presidio area, and up to 1,500 gallons per minute near Redford (Gates, et al., 1980). Ground water is naturally discharged by evaporation and by numerous small springs and seeps in the drainage channels in the upland slopes of the bolson. Besides wells, ground water is discharged from the RGA aquifer by large infestations of saltcedar and other phreatophytes especially along the river in the floodplain reach from about Candelaria to just upstream from Presidio (Gates, et al., 1980)..

Scanlon, et al. (2001) determined that recharge to the saturated zones of West Texas Bolsons occurs primarily from runoff in the adjacent mountains and in the drainage channels of the bolsons deposits immediately adjacent to the mountains. Recharge was determined to be absent in the interdrainage areas and valley floor streambeds of the bolsons due to extreme evaporation and evapotranspiration (the infiltration of precipitation and runoff never reaches the saturated zone beneath these areas of the bolsons).

Gates, et al. (1980) estimated and Muller and Price (1979) reported that effective recharge in the Red Light Draw Bolson to be 2,000 acre-feet per year, and about 1,000 acre-feet per year in the Green River Valley Bolson. Recharge from runoff in the Rio Grande and its tributaries has a great potential to occur into the RGA when the elevations of the water level of the RGA aquifer are below the elevations of the streambeds. Such potential recharge was determined probable for the RGA in Rio Grande reaches above and below the bolson reaches of the Red Light Draw and the Green River. Other water level and streambed elevation data indicates that under early 1970s hydrogeologic conditions, ground water in the deep bolson deposits of the two bolsons is probably discharging into the RGA aquifer which in turn is apparently seeping ground water into the Rio Grande (Gates, et al., 1980). Darling and Hibbs (2001), Figure 16-3 confirms discharge to the RGA in both bolsons, and then apparently to the river.

Gates, et al. (1980) estimated and Muller and Price (1979) reported that recharge to the Presidio-Redford Bolson is about 7,000 acre-feet per year. This amount does not include recharge from the Rio Grande, recharge in the drainage areas of Cibolo and Alamito Creeks outside of the bolson, and recharge as underflow in the Alamito Valley. Available RGA water level and streambed elevation data for the reach of the Rio Grande within the Presidio-Redford Bolson indicates that from near Candelaria to near Redford there are four (4) potential loosing reaches and three (3) potential gaining reaches in the Rio Grande. The most prominent gaining reach is just upstream from the confluence of the Rio Conchos and Rio Grande while the most prominent loosing reach is at Presidio-Ojinaga due to the decline of RGA water levels by ground-water pumpage. There are other potential loosing reaches in the Rio Grande within the Presidio-Redford Bolson. One extends several miles downstream from Capote Creek in the northern part of the bolson, and another extends several miles downstream from Alamito Creek in the southern Redford end of the bolson.

1.13 Edwards-Trinity (Plateau) Aquifer (ETPA)

This extensive major aquifer underlies the Edwards Plateau east of the Pecos River and the Stockton Plateau west of the Pecos. The ETPA underlies all or parts of about 20 counties within the Rio Grande Basin, and extends up the Pecos River Valley from Val Verde County to Culberson County, up the Devils River Valley in Val Verde, Sutton, Schleicher and Crockett Counties, and up the Rio Grande Valley from Kinney County through Val Verde and Terrell Counties to eastern Brewster County. The ETPA has the most productive water-bearing units east of the Pecos River, and the least productive water-bearing units beneath the Stockton Plateau west of the Pecos and north of the Rio Grande. (Taken and modified from Peckham, 1963; Ashworth and Hopkins, 1995; Anaya, 2001; Barker, et al., 1994; and Barker and Ardis, 1996)

In the Rio Grande Basin, the ETPA is contained in Cretaceous age rocks of the Washita, Fredericksburg, and Trinity Groups. In the following discussions the Washita and Fredericksburg Group rocks of the ETPA will be lumped together and presented and discussed as the Edwards Group. Generally from east to west across the Rio Grande Basin, geologic units of the Edwards Group and Trinity Group are subdivided and named (identified) based on their lateral changes in composition, sedimentation, alteration, thickness and stratigraphic position. The Edwards Group geologic units consist predominantly of carbonate rocks with limestone and dolomite beds of varying thickness, composition, porosity and permeability. Ground water in these carbonate rocks commonly occurs under water-table conditions in faults, fractures, joints, collapsed zones, vuggy zones, and other solution openings and channels of various sizes and shapes. The underlying Trinity Group geologic units consists mostly of clastic rocks consisting of interbedded, unconsolidated and consolidated sands, silts and clays of varying thickness, mineralogy, porosity and permeability. In most of the Rio Grande Basin, the Glen Rose Formation is encountered as the upper geologic unit of the Trinity Group, and consists of shale, shaly limestone, limestone and sand. In the eastern Basin, the Glen Rose is underlain by a sand unit probably equivalent to the Hensel Sand in the river basins to the east. Further westward the clastic geologic units of the Trinity Group (sands) are separated by a westward thinning section of the Glen Rose with the Maxon Sand above the Glen Rose and the Basal Cretaceous Sand below the Glen Rose. Further westward in the Trans-Pecos, the Glen Rose Limestone pinches out and the Trinity Group sands have become two geologic units, namely the Cox Sandstone and the Yearwood Formation (shale, limestone and sand). Ground water in the Trinity Group rocks occur under artesian conditions where the Trinity Group rocks are overlain by the Edwards Group rocks which act as semi confining units throughout most of the extent of the ETPA. However, ground water is under water-table conditions in the Trinity Group rocks where they occur along part of the Pecos River floodplain just above and below Girvin in northeastern Pecos County and northwestern Crockett and eastern Terrell Counties. (Taken and modified from Anaya, 2001; Barker, et al., 1994; Barker and Ardis, 1996; Barnes, 1977; and Barnes, 1981)

In the Devils River Valley (Amistad Reservoir and northward) beneath the Edwards Plateau in the eastern part of the Basin, Edwards Group geologic units consists of the Salmon Peak, Devils River and Segovia Formations all of which are carbonate rock units and essentially stratigraphically equivalent. The Fort Terrett Formation underlies the Segovia Formation in the northern part of the Valley. According to Iglehart (1967), the Trinity Group units consist of an upper unit, the Paluxy Sand (or its western equivalent, the Maxon Sand), underlain by the Glen Rose Limestone which overlies a section of "Basal" Sand (maybe an equivalent of the Hensell Sand which occurs below the Glen Rose to the east and southeast). The "Basal" Sand is underlain by Triassic age rocks of the Dockum Group. (modified from Iglehart, 1967; Brown, et al., 1965; Barker, et al., 1994; Barnes, 1977; and Barnes, 1981). In this eastern part of the Basin, ground water is mainly produced from the Edwards Group limestones and dolomites and the Paluxy Sand. Some ground water is obtained from the Glen Rose (mainly by upward leakage due to pumpage from overlying Edwards Group units and the Paluxy Sand). Wells are not known to penetrate and produce water from the "Basal" Sands below the Glen Rose (Iglehart, 1967 and Reeves and Small, 1973). Thin Quaternary alluvium occurs as floodplain deposits in the streambeds of the Devils River and Dry Devils River in the upper part of the Devils River Subbasin in northern Val Verde, Sutton, Schleicher and Crockett Counties (Barnes, 1977 and Barnes, 1981).

In the Pecos River Valley from Amistad Reservoir to near Pecos in Reeves County, Edwards Group geologic units of the ETPA include in Val Verde and Crockett Counties laterally equivalent sections of the Salmon Peak, Devils River and Fort Lancaster Formations. The Segovia Formation to the east is an equivalent unit of the Fort Lancaster. The Fort Lancaster is underlain by the Fort Terrett Formation. Further to the northwest into the Trans-Pecos in Pecos and Reeves Counties, the Fort Lancaster laterally becomes the Boracho Formation and the Fort Terrett laterally becomes the Finlay Formation. The Trinity Group geologic units underlying the Fort Terrett Formation (before the western pinch out of the Glen Rose Limestone) include the Maxon Sand (upper unit), a westward thinning Glen Rose Limestone underlain by the "Basal" Sand which is underlain by Triassic age rocks of the Dockum Group. West of the Glen Rose pinch out west of the Pecos River, the Trinity Group is represented by the Cox Sandstone underlain by the limestone and basal conglomerate of the Yearwood Formation. The Triassic Dockum Group underlies the basal conglomerate. The upper unit of the Dockum, the Santa Rosa Sandstone, is hydrologically connected to the Trinity Group rocks and is known to yield small to moderate quantities of ground water to wells in Pecos, Reeves and Ward counties in the Pecos River Valley. Also in the Pecos River Valley, the ETPA is hydrologically connected to the overlying Cenozoic Pecos Alluvium Aquifer and other minor aquifers of the Trans-Pecos region. (Taken and modified from Barker, et al., 1994; Barker and Ardis, 1996; Armstrong and McMillion, 1961; Oglibee, et al., 1962; Brown, et al., 1965; Small and Ozuna, 1993; Barnes, 1976a; Barnes, 1977; and Barnes, 1981). The Edwards Group rocks and Trinity Group rocks that occur along the Pecos River in northern Val Verde County and Crockett and Terrell Counties are overlain by water-bearing Quaternary alluvium deposits in the floodplain of the river (Barnes, 1977 and Barnes, 1981).

Along the Rio Grande from Amistad Reservoir to the western extent of the ETPA in eastern Brewster County, Edwards Group geologic units of the ETPA include laterally equivalent sections of the Salmon Peak, Devils River and Fort Lancaster Formations in Val Verde County with the Fort Terrett Formation underlying the Fort Lancaster. To the west in Terrell and Brewster Counties along and beneath the river, the Edwards Group geologic units thicken with the Fort Lancaster Formation laterally becoming the Santa Elena and Sue Peaks Formations and the Fort Terrett Formation laterally becoming the Del Carmen and Telephone Canyon Formations. The Trinity Group geologic units underlying the Edwards Group in this area of the ETPA are not well known. The Maxon Sandstone (reported to thin and feather out eastward and thicken northward) and the Glen Rose Formation (reported to have a basal Cretaceous conglomerate) outcrop in the Santiago and Rine Mountain areas of eastern Brewster County, and probably exists beneath the Edwards Group rocks in the subsurface of parts of eastern Brewster County and Terrell County. Ground water is known only to occur in the limestone and dolomite rocks of the Edwards Group. There is insufficient well data to determine if the Trinity Group deposits below the Edwards Group in the subsurface of western and southwestern Val Verde, southern Terrell and southeastern Brewster Counties along and north of the Rio Grande are capable of yielding significant quantities of good quality ground water. The reach of the Rio Grande over the ETPA does not have any significant amounts of RGA deposits (Quaternary alluvium) that is water-bearing in the narrow river floodplain. (Taken and modified from Anaya, 2001; Barker, et al., 1994; Barker and Ardis, 1996; Barnes, 1977; Barnes, 1979b; and Barnes, 1981; and Barnes, 1982).

Natural recharge to the ETPA in the Rio Grande Basin occurs from infiltration of precipitation on the Edwards Plateau and Stockton Plateaus mainly through faults, fractures/joints, sinkholes, caves and other openings in the Edwards Group carbonate rocks at and near the land surface. Some recharge also occurs from infiltration of storm runoff in some ephemeral streams crossing the outcrop of Edwards Group rocks. Edwards Group rocks of the ETPA are readily recharged by downward seepage where they are overlain by Quaternary alluvial water-bearing deposits in the floodplains of the Pecos River, Devils Rivers and some other tributaries in the Rio Grande Basin. Also recharge to the Edwards Group rocks of the ETPA occurs as subsurface lateral and upward leakage/seepage from underlying Trinity Group water-bearing rocks. The Edwards and Trinity Group rocks of the ETPA are recharged by lateral and upward leakage/seepage from shallow and deep adjacent Trans-Pecos water-bearing units of the Wild Horse Flats portion of the Salt Basin (Bolson) Aquifer, Capitan Reef Aquifer, Rustler Aquifer, Cenozoic Pecos Alluvium Aquifer, Dockum Aquifer, Igneous Aquifers and the Marathon Aquifer (west Texas aquifers covered by Mace, 2001 and Ashworth and Hopkins, 1995). Significant recharge to the ETPA occurs as return flows in irrigated areas. Induced recharge may occur to the ETPA from the Pecos River by leakage through the water-bearing deposits of the Quaternary river alluvium and Cenozoic Pecos Alluvium Aquifer due to heavy ground-water withdrawals in parts of Pecos and Reeves Counties. The Trinity Group rocks of the ETPA are recharged by infiltration of precipitation where they outcrop near and subcrop the Quaternary alluvium in the floodplain of the Pecos River in Pecos, Crockett and Terrell Counties. The Trinity Group rocks are recharged by downward leakage/seepage of water from the Quaternary alluvium and Edwards Group water-bearing units, and from deep underflow from adjacent water-bearing units. (Taken and modified from Hood and Knowles, 1952; Armstrong and McMillion, 1961; Ogilbee, et al., 1962; Brown, et al., 1965; Iglehart, 1967; Reeves and Small, 1973; Walker, 1979; Small and Ozuna, 1993; Barker, et al., 1994; Kuniansky and Holligan, 1994; Barker and Ardis, 1996; and Anaya, 2001)

Estimated recharge to the ETPA from precipitation is less than 0.5 inch per year on the Stockton Plateau of the Trans-Pecos (Barker, et al., 1994 and Barker and Ardis, 1996). Use of a baseflow technique in Crockett/Terrett Counties determined recharge to be about 0.3 inches per year (Iglehart, 1967 and Scanlon, et al., 2002).

Armstrong and McMillion (1961) estimated recharge to the ETPA and the Cenozoic Pecos Alluvium Aquifer (which combined were called the "Pecos Aquifer") in Pecos County was estimated to be 78,000 acre-feet per year based on spring flow and underflow. The large amounts of evapotranspiration along the Pecos River were not considered, and some underflow may have been recirculated spring flow which would make estimated amount somewhat less.

According to Reeves and Small (1973) the recharge catchment area for the ETPA that is equivalent to the average annual spring flow and baseflow of 502,000 acre-feet (estimated for the 1961-67 period) in Val Verde County (the major Rio Grande Basin ground-water discharge/rejected recharge area of the ETPA) is estimated to be about 4.16 million acres or 6,500 square miles. This 6,500 square-mile, catchment area of the ETPA natural recharge was estimated to be in the lower Pecos River basin and the Devils River basin in Val Verde County and parts of Terrell, Pecos, Crockett, Schleicher, Sutton, Edwards and Kinney Counties. Using these estimates, ground-water recharge to the ETPA in the area was about 1.5 inches per year or about nine (9) percent of the average annual precipitation of 16 inches over the 6,500 square mile area.

The above natural recharge is based on and equivalent to natural ground-water discharge from the same 6,500 acre catchment area. The 502,000 acre-feet per year of ground water discharge for the ETPA for the 1961-67 period is as follows (Reeves and Small, 1973):

- Pecos River -- 32,000 acre-feet/year
- Goodenough Springs (now under Amistad Reservoir) ---------- 89,000 acre-feet/year
- Devils River -- 240,000 acre-feet/year
- Minor springs on the Rio Grande ------------------------------ 2,000 acre-feet/year
- Estimated unmeasured springs on the Rio Grande -------------- 81,000 acre-feet/year
- San Filipe Springs at Del Rio ----------------------------------- 58,000 acre-feet/year

Total Natural Discharge -- 502,000 acre-feet/year

The above estimates probably do not include natural discharge by evaporation where ETPA and Quaternary alluvium aquifer water levels were 4 feet or less from the land surface. However, the above estimates probably were made using the assumption that evaporation and related evapotranspiration are negligible during the winter months.

Before conducting detailed water supply-demand analyses for the first detailed Texas water plan, the TWDB Planning Division estimated the effective recharge of the major and minor aquifers throughout the state. Muller and Price (1979) estimated using information in Reeves and Small (1973) and Brune (1975) the annual effective recharge of the ETPA within the Rio Grande Basin in Texas to be about 513,900 acre-feet.

Based on this author's current analysis of 1925 and 1926 low-flow measurements of the Rio Grande and its tributaries in Texas and Mexico (TBWE, 1960), and the geologic conditions within the extent of the ETPA (Barnes, 1977 and 1979b), the approximate annual recharge to the ETPA in the Rio Grande Basin of Texas and Mexico in the mid-1920s was estimated to be 1,093,200 acre-feet. The low-flow of the river and the inflow of the tributaries in Texas and

Mexico were measured during February 1925 and February and early March of 1926 when evaporation and evapotranspiration probably were negligible. Also, the measurements were made during the time of the years when ground-water pumpage was not significant to intercept low flows of the river and its tributaries. Therefore, the 1,093,200 acre-feet amount can be considered a reliable amount of annual effective, natural recharge of the ETPA in the Rio Grande Basin of Texas and Mexico.

Ground water is artificially discharged from the ETPA by numerous wells. Large capacity/diameter wells completed in the ETPA and other adjacent connected aquifers supply large amounts of ground water for municipal, industrial and irrigation uses in mainly Reeves, Pecos, Upton, Crockett, Schleicher and Sutton Counties. Numerous small capacity/diameter wells completed in the ETPA provide ground water for domestic/household and livestock watering purposes throughout the aquifer's extent beneath the Stockton and Edwards Plateaus of the Rio Grande Basin

1.14 Cenozoic Pecos Alluvium Aquifer (CPAA)

This primary and productive aquifer in the Pecos River Valley and adjacent areas provides ground-water to wells in parts of Andrews, Crane, Ector, Loving, Pecos, Upton, Ward, and Winkler Counties in Texas and in part of Lea County, New Mexico within the Rio Grande Basin. The aquifer is generally under water-table conditions, and is contained in Cenozoic (Tertiary, Quaternary and Recent age) alluvium deposits which were derived from various volcanic, igneous and sedimentary rocks, and are interbedded and discontinuous over relatively short distances at the surface and in the subsurface.

The Cenozoic alluvium deposits consists of unconsolidated to consolidated clastic deposits of sands, silt, gravel (pebble and cobbles), boulders, and clay. The deep deposits also contain some gypsum. The deep saturated alluvial fill deposits are found in two hydrologically separated basin/troughs. One is called the Pecos Trough and occurs along, west and southwest of the upper Pecos River in Loving, Ward and Pecos Counties. The other basin is called the Monument Draw Trough which essentially occurs northeast of the Pecos River in parts of Winkler, Ward, Ector, Crane and Upton Counties and probably extends beneath the Pecos River into a part of northern Pecos County. Another unnamed basin with saturated Cenozoic alluvial fill extends from the Pecos River southward along the Reeves-Pecos county line. Caliche deposits exist in some areas at and near the surface above the alluvial fill. The upland area of the Monument Draw Trough area is overlain by Recent windblown sands which are effective catchment deposits for natural recharge.

The Pecos River alluvium (PRA) occurs in the floodplain of the Pecos River as fluviatile terrace deposits which overlie the deeper basin fill deposits. The PRA consists of dry and saturated beds of quartz sand, silt and gravel of pebbles and cobbles of chert, igneous rocks, metamorphic rocks, caliche, and abraded Cretaceous fossils. The quartz sand beds of the PRA commonly are crossbedded, massive, and lenticular. The saturated PRA deposits are the uppermost water-bearing unit of the CPAA, and are hydrologically connected to some reaches of the Pecos River from Red Bluff Reservoir to near Girvin, Texas. Within the Rio Grande Basin, the CPAA is hydrologically connected to four adjacent underlying aquifers, namely the Edwards-Trinity Plateau, Dockum, Rustler, and Capitan Reef Aquifers.

(The geology and hydrogeology presented in the above paragraphs that address the CPAA were taken and modified from Hood and Knowles, 1952; Armstrong, et al., 1961; Ogilbee, et al., 1962;

Peckham, 1963; Brown, et al., 1965; White, 1971; Ashworth, 1990a; Kuniansky and Holligan, 1994; Barker, et al., 1994; Barker and Ardis, 1996; Ashworth and Hopkins, 1995; Boghici, 1999; and Mace, 2001.)

Natural recharge to the CPAA is by infiltration of precipitation. The extensive outcrops of windblown sands and silts which occur as cover sheets, dunes, and dune ridges in the Monument Draw area in Winkler, Ward and Crane Counties are very favorable catchment areas for recharge from precipitation. Natural recharge to the CPAA also occurs 1.) from seepage into the alluvium of storm runoff in ephemeral streams draining the mountains and high country bedrock to the west and south, 2.) from seepage of some of the spring flow from the ETPA into the alluvium, primarily in Reeves and Pecos Counties, 3.) from seepage of surface water in irrigation canals and drains, 4.) from irrigation return flows from irrigation with surface water and ground water, and 5.) from subsurface underflow from the ETPA and other adjacent aquifers. Since the 1950s, heavy ground-water withdrawals for irrigation, municipal and industrial purposes in Reeves, Pecos and Ward Counties have induced recharge to the CPAA as seepage from the Pecos River, and from other adjacent aquifers, mainly from the ETPA. The potential for the induced recharge from the river was confirmed by comparison of streambed elevations and the elevations of available CPAA water levels along the river. (Taken and modified from Armstrong and McMillion, 1961; Ogilbee, et al., 1962; White, 1971; Ashworth, 1990a; Barker, et al, 1994; Boghici, 1999; and Scanlon, et al., 2002.)

For Reeves County Ogilbee, et al., (1962) stated: "Before the development of irrigation wells, when the ground water in the alluvium was in a state of approximate equilibrium, the average annual amount of recharge probably equaled the average annual amount of discharge, or 50,000 – 100,000 acre-feet per year." According to Muller and Price (1979) using baseflow data and assumptions for infiltration of Pecos River diversions, the annual effective recharge to the CPAA in the Rio Grande Basin was estimated to be 70,800 acre-feet (a 34,000 acre-feet baseflow increase plus 36,800 acre-feet irrigation water seepage). According to Ashworth (1990a) such effective recharge is 67,800 acre-feet per year (31,000 acre-feet as baseflow and 36,800 acre-feet irrigation water seepage). Ashworth (1990a) eliminated 3,000 acre-feet of baseflow into the river from Crane County, because the investigation and subsequent report did not address the CPAA in Crane County.

According to White (1971), the total natural recharge from precipitation and underflow to the "Allurosa Aquifer" in Ward County was estimated to be about 12,000 acre-feet per year. The annual recharge of about 5,000 acre-feet from the average annual precipitation in Ward County was assumed to be about one-eighth (1/8) of an inch per year of the precipitation reaching the water table of the alluvium and PRA. The Allurosa Aquifer of White (1971) is composed of the CPAA and the underlying less permeable, water-bearing rocks of the Santa Rosa Sandstone of the Dockum Aquifer. A summary of the sources and estimated amounts of recharge to the Allurosa Aquifer in 1967 in Ward County are given in the following list.

- **Underflow from the Sand Dunes in NE part of County ———— 2,000 acre-feet**
- **Infiltration of Precipitation (Excludes Sand Dune Area) ——— 5,000 acre-feet**
- **Infiltration of Water Diverted from River for Irrigation ——— 45,000 acre-feet (1)**
- **Underflow from the CPAA in Winkler and Loving Counties ---- 5,000 acre-feet**

Total Estimated Recharge in 1967 ———————————— 57,000 acre-feet
(1) Of the 45,000 acre-feet, 7,700 acre-feet was estimated as irrigation return flow.

Very significant amounts of ground water are naturally discharged from the CPAA by evaporation where the water table is near the land surface. This condition has greatest potential in the saturated Recent windblown sands and the shallow PRA water-bearing unit of the CPAA in the floodplain of the Pecos River. Historically, especially before infestations by saltcedar and before heavy ground-water pumping, CPAA ground water was discharged readily from the PRA aquifer to the river. Very significant natural discharge occurs from the floodplain PRA aquifer by evapotranspiration through saltcedar and other phreatophyte infestations. According to White (1971) based on a 1964 study by the USBR of phreatic vegetation infestation and water use along a significant reach of the Pecos River, approximately 40,000 acre-feet per year of water is naturally discharged/transpired along the Pecos River in its reach opposite Ward County. (Taken and modified from White, 1971; Scanlon, et al., 2002.)

1.15 Carrizo-Wilcox Aquifer (CWA)

This major aquifer of Texas occurs in a relatively narrow portion of the Rio Grande Basin where the outcrops of Tertiary, Eocene rocks of the Indio Formation of the Wilcox Group and the Carrizo Sand of the Claiborne Group are the recharge zone of the CWA in southern Maverick and northwestern Webb Counties. Along the river in the floodplain, the upper Indio Formation is overlain by RGA consisting of relatively thick Quaternary alluvium and terrace deposits. A very thin small amount of Quaternary alluvium overlies the Carrizo Sand in the floodplain downstream (Barnes, 1976b).

The Indio Formation is composed of fine-grained, multicolored sandstone in thin discontinuous layers interbedded with multicolored, sandy, carbonaceous shale, and having in its upper part near the Carrizo abundant limy, sandy and iron-bearing concretions. The Carrizo Sand consists of coarse to fine-grained, slightly cemented, friable, massively bedded, crossbedded sandstone with well-sorted sand in limy and siliceous cement and with some sandy, iron-bearing concretions. Some thin shale layers occur in the Carrizo. The Carrizo Sand is the most pourous and permeable water-bearing unit of the CWA in the Rio Grande Basin. The RGA overlying the Indio and Carrizo in the Rio Grande floodplain consists of gravel, sand, silt, clay and organic matter. These clastic rocks of the RGA include a very wide variety of igneous and sedimentary rock material transported from Trans-Pecos Texas, Mexico and New Mexico. The water-bearing deposits of the RGA are under unconfined (water-table) conditions, very pourous and permeable, hydrologically connected to the underlying, water-bearing bedrock deposits of the CWA, and hydrologically connected to the river. The CWA dips southward beneath the confining to semi-confining rocks of the Bigford Formation and provides fresh to slightly saline water under artesian conditions considerable distance downdip into the subsurface to a point along the Rio Grande just north of Laredo. (Taken and modified from Barnes, 1976b; Klemt, et al., 1976; and Ashworth and Hopkins, 1995.)

Comparison of Rio Grande streambed elevations and elevations of available CWA water levels indicate that the head in the aquifer is significantly higher than the streambed. This confirms that the CWA and RGA water-bearing deposits discharge ground water to the Rio Grande. Ground water is discharged from the CWA by numerous small springs and seeps in the upland bedrock areas of the aquifer. Ground water is discharged by evaporation where the water table is near the surface, and probably by evapotranspiration by mainly mesquite in the uplands and mainly by saltcedar in the floodplain. Small diameter/capacity wells are used in the uplands for domestic and livestock watering purposes. (Taken and modified from Brown, et al., 1965; Klemt, et al., 1976; Muller and Price, 1979; USGS, 1985, San Ambrosia Creek map; and Scanlon, et al., 2002.)

The CWA is recharged by infiltration of precipitation in the interstream areas on the outcrops of the Carrizo Sand and Indio Formation. The amount of infiltration in these interstream areas is controlled by soil and vegetation types. Natural recharge to the aquifer occurs by seepage of storm runoff through the upland, ephemeral, tributary streambeds that cross the outcrops in the uppermost areas of the watersheds. San Ambrosia, Chupudera and Jardin Creeks are tributaries of the Rio Grande on the Texas side which are perennial streams fed by near-river, upland spring flow and related seepage. Part of these tributary flows enter the Rio Grande within the Carrizo Sand outcrop-reach of the river. Part of this spring flow and seepage into the tributaries reenters the aquifer as recharge before discharging to the river. The average annual effective recharge to the CWA in the Rio Grande Basin in parts of southern Maverick, southwest Dimmit and northwest Webb County is about 13,700 acre-feet. (Above taken and modified from Brown, et al., 1965; Klemt, et al., 1976; Muller and Price, 1979; and USGS, 1985, San Ambrosia Creek map.) Based on an analysis of gain-loss measurements and related geological conditions, the approximate average annual recharge to the Carrizo-Wilcox Aquifer in the Rio Grande Basin of Texas and Mexico in the 1920s was about 86,875 acre-feet (TBWE, 1960 and Barnes, 1976b).

1.16 Gulf Coast Aquifer System (GCAS)

This very extensive, Cenozoic, coastal plain aquifer system of Texas underlies the Rio Grande Basin in Starr, Hidalgo, and Cameron Counties, Texas, and extends southwest across the Basin in Mexico. The Gulf Coast Aquifer System (GCAS) contains ground water under unconfined, semi-confined and confined conditions, and is a very large (extensive and thick) and complex leaky artesian aquifer system. In the Rio Grande Basin of Texas, the GCAS has been subdivided into an upper, fresh to slightly saline water-bearing unit, the Chicot Aquifer, and a lower, fresh to slightly saline water-bearing unit, the Evangeline Aquifer. The Chicot and Evangeline Aquifers are subdivided because of they have different geologic, water quality and hydraulic characteristics. The deeper Jasper Aquifer, that is a prominent water-bearing unit of the GCAS to the east of the Rio Grande Basin, is not included in the GCAS in the Basin, mainly because it contains saline to very saline ground water.

The Chicot Aquifer is composed of saturated, Quaternary age, clastic deposits; namely from youngest to oldest, 1.) The Rio Grande alluvium and terrace deposits (RGA), 2.) The Beaumont Formation, and 3.) The Lissie Formation. The Recent alluvium and Pleistocene terrace deposits of the RGA consists of gravel, sand, silt, and clay, and contains ground water under unconfined (water-table) conditions. The Beaumont Formation consists of Pleistocene clay with some minor amounts of sand and silt, and contains ground water under both unconfined and confined conditions. Because of extensive clay content, the Beaumont generally acts as a semi-confining layer within the Chicot Aquifer. The Lissie Formation consists of Pleistocene clay, silt, sand, and gravel, and is the lower water-bearing unit of the Chicot Aquifer. Because of the overlying Beaumont clays, it has ground water mostly under confined conditions in the Rio Grande Basin. The Evangeline Aquifer underlies the Chicot Aquifer, and is composed of Tertiary, Pliocene age clay, sand, sandstone, marl, limestone and conglomerate of the Goliad Formation. In the Rio Grande Basin of Texas the Evangeline is the deepest aquifer of the GCAS that contains fresh to slightly saline ground water. Because of the Goliad Formation outcrops (occurs at the land surface) in a relatively large area within and north of the Basin, ground water occurs under unconfined conditions. In the subsurface beneath the Chicot Aquifer, the Evangeline Aquifer (Goliad Formation) contains ground water under confined conditions.

Within the extent of the GCAS in the Rio Grande Basin of Texas, the RGA water-bearing unit is the upper unit of the Chicot Aquifer that is hydrologically connected to the Rio Grande.

Therefore, it should be considered as the primarily and most important, GCAS hydrogeologic unit that is most related to the hydrology of the river in the Lower Rio Grande Valley of Texas.

(The geology and hydrogeology presented in the above paragraphs that address the GCAS were taken and modified from Baker, 1965; Barnes, 1976d; Muller and Price, 1979; McCoy, 1990; Ashworth and Hopkins, 1995; Scanlon, et al., 2002; and Chowdhury and Mace, 2002.)

Natural recharge to the GCAS is by infiltration of precipitation as diffuse recharge across interstream areas. The amount of subsurface infiltration of rainfall to the zone of saturation is dependent 1.) on the area potential for evaporation, 2.) on evapotranspiration by phreatic vegetation, 3.) on the mineralogy and permeability of the soil, and 4.) on pre-recharge event moisture content of the soil and the unsaturated zone above the water table. Natural recharge from infiltration of rainfall will be much greater on the sandy soils and unsaturated alluvium of the RGA than the inherently clayey soil and unsaturated zone of the Beaumont Formation clays. Recharge occurs into the RGA water-bearing deposits by seepage of surface water and pumped ground water conveyed in the river, irrigation canals and drains. This seepage condition occurs when the RGA water-table is lower than the streambeds. Additional significant recharge occurs as return flows from surface water and ground water applied to irrigate various crops. When surface water supplies are low or unavailable the irrigation water demand is met by ground water pumpage from the shallow RGA water-bearing deposits of the Chicot Aquifer. This condition induces recharge to the RGA from available water in the river, canals and drains (which may be of poorer quality and some of which is pumped ground water), and from upward seepage from the deeper water-bearing units of the Chicot Aquifer which have higher hydraulic head and poorer quality water. This induced recharge/seepage has changed the water quality of the RGA aquifer making it less and less desirable for irrigation and as a drinking water supply. Ground water in the unconfined RGA aquifer may be readily recharged in one reach of the river, and at the same time discharge water as baseflow to another reach of the river. Also because of the shallow water table of the RGA aquifer, significant water is discharged by evaporation from the shallow water table surface, and by evapotranspiration through phreatophytic vegetation such as saltcedar and mesquite. (Taken and modified from Baker, 1965; Muller and Price, 1979; McCoy, 1990; Scanlon, et al., 2002; and Chowdhury and Mace, 2002.)

Muller and Price (1979) estimated the effective recharge to the GCAS in the Rio Grande Basin to be 11,400 acre-feet per year. This amount was determined by the application of a digital model of the GCAS which in a specific application provided that an estimated 4 percent of the mean annual rainfall on the outcrops of the geologic units of the GCAS would be needed to support the estimated annual effective recharge. A TWDB ground water model of the GCAS in the Rio Grande Valley indicated that annual recharge is 2 to 3 percent of the annual rainfall (Chowdhury and Mace, 2002). Scanlon, et al., (2002), Table 1 reports various amounts of recharge rates to the GCAS as inches per year. For the southern portion of the GCAS including the Rio Grande Valley, such amounts were reported to range from zero (0) and 0.0004 inches per year to 0.7 inches per year (Groschen, 1985; Hay, 1999; Ryder, 1988; and Williamson, et al., 1990).

Baker (1965) states, "The potential for additional development from the alluvium is fairly large when compared to the other aquifers in the basin. Water from the alluvium is largely for irrigation, and the potential yield from the alluvium probably is adequate to irrigate all of the area of the basin underlain by alluvium that was not irrigated from the Rio Grande in 1961. The potential yield of the alluvium in the basin depends on the amount of water recharged by the infiltration of precipitation and by seepage from the Rio Grande and the amount of water withdrawn from the alluvium in the area north of the basin.

Muller and Price (1979) states, "In the Lower Rio Grande Valley, supplemental ground water is pumped from the Gulf Coast aquifer for irrigation as well as municipal use during times when the Rio Grande does not meet demands."

1.2 Previous Surface Water Investigations

There have been a number of historical surface-water/ground-water investigations in the Rio Grande Basin of the Rio Grande, Pecos River, and Devils River and their tributaries related to channel losses. These investigations were part of ground-water studies, delivery of surface water, and low-flow or base-flow investigations by the USGS and others water agencies. A short summary of the results, of what is believed to be the most important investigations as they occurred in time, are presented for the Rio Grande, the Pecos River and Devils River in the following discussions.

1.21 Rio Grande

1.211 February 7-20, 1925 Low-Flow Investigation of the Rio Grande from Lajitas to Del Rio (TBWE, 1960)

During this investigation a series of measurements were made when the river was at constant stage and the measurements represented natural conditions. The flow of the river at Lajitas was 1,060 cfs which consisted of inflow from the Rio Conchos and other tributaries and baseflow and spring flow upstream of Lajitas. Since the measurements were made in February, evaporation and evapotranspiration probably were negligible.

- From Lajitas to about one-half mile below mouth of Terlingua Creek (which had no inflow) at "Sublett, Texas", the river passed through Santa Elena Canyon over faulted and fractured Upper Cretaceous, carbonate rocks of the Boquillas Formation (limestone, marl and chalk) and the Santa Elena Limestone (Barnes, 1979b). Within this reach there was a loss of about 20 cfs (about 1.16 cfs/mile), most of which was probably channel loss as the river flowed over faults and related fractures in the carbonate rocks.
- The flow in the river remained the same at 1,040 cfs from "Sublett, Texas" to river mile 60.5 (from Lajitas) near "Mariscal damsite" which probably was on the river as it passed through the Mariscal Canyon. In this reach, the river flowed over a wide variety of Quaternary, Tertiary, and Cretaceous sedimentary clastic and carbonate rocks in the southern part of Big Bend National Park (Barnes, 1979b). However, there probably were reaches having gain and reaches having loss.
- From "Mariscal damsite" (Mariscal Canyon) (mile 60.5) to Boquillas (mile 79.5) the river gained 50 cfs as it passed over minor amounts of Quaternary alluvium, and the faulted and fractured, Cretaceous, clastic and carbonate rocks of mainly the Aguja and Boquillas Formations (Barnes, 1979b). Within this reach, the river received a significant amount of gaining flow from the Hot Springs upstream from Boquillas. The Hot Springs apparently issue water through faults and fractures from some unknown deep aquifer.
- From Boquillas to Reagan Canyon (39.4 river miles) the river net gains 130 cfs (3.3 cfs/mile) over very faulted and fractured Cretaceous carbonate rocks of the Edwards Group (Santa Elena, Sue Peaks, Del Carmen and Telephone Canyon Formations) and the Trinity Group (Glen Rose Formation) (Barnes, 1979b). This reach apparently occurs over the faulted and fractured carbonate Cretaceous rocks containing the ETPA. Therefore, the 130 cfs low-flow gain in the river is considered ground-water discharge from the ETPA.
- From Reagan Canyon to Langtry, the river crosses the Edwards Group (mainly the limestones and dolomites of the Santa Elena and Devils River Formations), and the Trinity

Group (Glen Rose Formation) (Barnes, 1979b and Barnes, 1977). In this reach, the river gained 220 cfs or about 2.18 cfs/mile of ground-water discharge from the ETPA.

- From Langtry to near Del Rio, the Rio Grande gained 980 cfs of which 403 cfs was from the reach of the Rio Grande, 199 cfs was from the Pecos River, and 378 cfs was from the Devils River. All of this gain was ground-water discharge as spring flow and base flow from the ETPA.

In conclusion, the total gain of the Rio Grande from ground-water discharge as spring flow and baseflow from the Cretaceous rocks from Boquillas to near Del Rio (including the Pecos and Devils Rivers inflow) is about 1,330 cfs. Subtracting the amounts for the Pecos and Devils River and leaving the 130 cfs for the Boquillas to Reagan Canyon reach, gives 753 cfs of flow which can be assumed to be the estimated amount of ground water discharged to the Rio Grande and its other tributaries from the Cretaceous rocks of the ETPA in Texas and Mexico. Therefore, the annual effective, natural recharge to the ETPA in the Rio Grande Basin in Texas and Mexico in the 1920s above Del Rio, Texas probably was approximately equivalent to the estimated natural discharge of 1,330 cfs or about 962,875 acre-feet per year. The results of this Rio Grande low-flow investigation are given and delineated as reaches I A – I F on the map on Figure 1.

1.212 February 9 – March 3, 1926 Low-Flow Investigation of the Rio Grande from Del Rio to Eagle Pass (TWDB, 1960)

During this investigation the Rio Grande was reported to be at a constant stage, therefore, the measurements are assumed to represent natural conditions. The measuring point on the Rio Grande at Del Rio was approximately just upstream from Salt Creek where the river is on RGA overlying the Lower Cretaceous, Georgetown Limestone (Brown, et al., 1965) or its equivalent Salmon Peak Limestone (Barnes, 1977). The measuring point at the Eagle Pass gage was on the Upper Cretaceous, Olmos Formation (Barnes, 1976b) which consists mostly of clay.

- From Del Rio to about 3 miles downstream from the mouth of the Rio San Rodrigo in Mexico near Normandy in Maverick County, the Rio Grande apparently is a gaining stream with about 136 cfs of net gain. This reach of the River passes over Lower and Upper Cretaceous formations containing no significant ground-water. Ground water is available in the RGA aquifer which is connected to the Rio Grande in the Quemado-Normandy area north of Eagle Pass.
- From the point near Normandy to the Eagle Pass gage in a 14-mile reach of the river the Rio Grande lost about 20 cfs probably to evapotranspiration by saltcedar and other phreatophytes in the floodplain. Losses to the bedrock geology is unlikely, because the river and RGA are underlain by relatively impermeable Upper Cretaceous clay-bearing rocks of the San Miquel and Olmos Formations (Barnes, 1976b).

The results of this low-flow investigation of the Rio Grande are given and delineated as reaches II A – II B on the map of Figure 1.

The gain of 330 cfs in the 43 mile reach below Del Rio includes 194 cfs of inflow from tributaries, the major part of which includes inflows from San Felipe Creek/Springs in Texas (76 cfs), the Rio San Diego in Mexico (77 cfs) and the Rio Rodrigo in Mexico (27 cfs). These large tributary inflows totaling 180 cfs probably represent ground-water discharge from the ETPA in the Rio Grande Basin in Texas and Mexico below Del Rio, Texas. When combined with the 1,330 cfs above Del Rio, Texas, the total ground-water discharge from the ETPA in the Rio Grande Basin of Texas and Mexico in the mid-1920s was 1,510 cfs. This amount is equivalent to about 1,093,200 acre-feet of annual effective, natural recharge for the ETPA in the Basin in Texas and Mexico. All or part of the inflow to the Rio Grande of 71 cfs on February 13, 1926 from the Rio Chico (see Eagle Pass to San Ygnacio low-flow measurements of TBWE, 1960) may be ground-water discharge from the ETPA in Mexico. This inflow would add about 51,400 acre-feet per year to the 1,093,200 acre-feet per year; making the total Basin annual effective recharge for the ETPA in Texas and Mexico about 1.145 million acre-feet.

1.213 February 12 – 22, 1926 Low-Flow Investigation of the Rio Grande, Eagle Pass to San Ygnacio, Texas (TBWE, 1960).

These low-flow measurements were made with the Rio Grande at constant stage, and the measurements represent natural conditions. This investigation is a continuation of the previous investigation from Del Rio to the Eagle Pass gage. The 167-mile reach of this investigation of the Rio Grande is underlain by discontinuous outcrops of Quaternary RGA which is saturated and connected to the river. The 8 bedrock units underlying the RGA and the river include from oldest to youngest the Upper Cretaceous, Olmos and Escondido Formations, and the Tertiary, Eocene, Kincaid Formation (Midway Group), Indio Formation (Wilcox Group), and the Carrizo Sand, Bigford Formation, El Pico Clay, and Laredo Formation of the Claiborne Group. The principal aquifer that crosses and is hydrologically connected to the Rio Grande in this reach is the Carrizo-Wilcox Aquifer. Only reaches of the river with significant losses, and the apparent recharge of the Carrizo Sand will be discussed in the following analyses.

- From below mouth of Rio Escondido (Mexico) at about mile 3 to 1 mile above the Rio Santo Domingo(Mexico) at mile 11, the Rio Grande had a significant loss of about 161 cfs. This loss of about 20 cfs/mile was in the reach having significant RGA underlain by the mostly clay-bearing Escondido Formation. A major part of the loss was probably due to evapotranspiration loss by saltcedar in the floodplain of the river in Texas and Mexico.
- From about 29 miles downstream of Eagle Pass gage above shoals (streambed with steeper gradient) to one-half mile downstream from San Ambrosia Creek at mile 55, the river had a significant loss of 130 cfs over the Kincaid and Indio Formations. This condition was probably due mostly to evapotranspiration by saltcedar. However, a portion of the loss across the RGA over the Indio Formation may have occurred as lateral seepage to the downstream reach crossing the Carrizo Sand outcrop, and may be part of the significant gain in that reach representing ground-water discharge from the Carrizo Sand of the Carrizo-Wilcox Aquifer.
- From just downstream from San Ambrosia Creek at mile 55 to 2 miles below San Lorenzo Creek (Mexico?) at mile 67, there was a gain of 120 cfs. This reach crosses the Carrizo Sand outcrop. The 120 cfs is assumed to be ground-water discharge from the Carrizo Sand aquifer, and is considered as the estimated equivalent to the Carrizo natural recharge. Using this assumption, about 86,875 acre-feet per year of effective natural recharge occurs to the Carrizo-Wilcox Aquifer within the Rio Grande Basin in Texas and Mexico.
- From 2 miles below San Lorenzo Creek (Mexico?) at mile 67 to 1 mile below Apache Ranch at mile 77, there was a loss of 110 cfs probably by evapotranspiration by saltcedar in the river floodplain. Here RGA is underlain by the Bigford Formation.

From Apache Ranch at mile 77 to San Ygnacio at mile 167, the river was measured 9 times with a net loss of about 120 cfs. The river measurements should be considered as being accurate, but the accuracy of the diversions for irrigation above and below Laredo in Texas and Mexico may not be accurate because of unknown amounts of diversions and possible ground-water pumpage. The results of this low-flow investigation of the Rio Grande is given and delineated as reaches III A – III H on the map of Figure 1.

1.214 Low-Flow Investigation of the Rio Grande from an Old Zapata Gage (Mile 0) to an Old Anzalduas Gage (Mile 127.3), June 1948. Taken from Lowry, et al. (1948).

Lowry, et al., (1948) conducted a gain-loss investigation of the 67.8 mile reach of the Rio Grande from a Zapata gage to a Rio Grande City gage to a gage at Anzalduas. The field test was made over a period of several weeks of relatively low-flow of the river during June 1948. During the field tests of the investigation all visible side inflows from ground water and surface water diversions were measured. However, losses due to evaporation and consumptive use by native vegetation were near maximum rates. The channel losses and gains for this tests are presented as follows:

- Zapata to Chapeno --- 95.0 cfs loss at 3.49 cfs/mile,
- Chapeno to Roma – 22.9 cfs gain at 1.32 cfs/mile,
- Roma to Rio Grande City – 51.7 cfs loss at 2.22 cfs/mile, and
- Rio Grande City to Anzalduas – 32.7 cfs loss at 0.55 cfs/mile.
- Zapata to Anzalduas – 156.5 cfs loss at 1.23 cfs/mile.

The results of this low-flow investigation of the Rio Grande are given and delineated as reaches IV A – IVD on the map of Figure 1.

1.215 Average Annual Channel Loss of the USA Share of Rio Grande Flow from Falcon Dam to the Gulf of Mexico, 1954 - 1963. Taken and modified from Hendricks (1965).
Hendricks (1965) determined the average annual channel losses from IB&WC accounting of U. S. share of releases from Falcon Reservoir for 1954 through 1957 and 1960 through 1963 (losses not determine for 1958 and 1959 because of unusually high flows). The average annual channel losses of the U. S. share of water in the Rio Grande from Falcon Dam to the Gulf of Mexico, 1954-1963 are given below by river reach, acre-feet, and percentage of the total average annual loss of 73,800 acre-feet.

- Falcon Dam to Fort Ringgold Gage – 12,100 acre-feet – 16 Percent
- Fort Ringgold Gage to Anzalduas Dam – 23,600 acre-feet – 32 Percent
- Anzalduas Dam to Progreso Bridge Gage – 25,000 acre-feet – 34 Percent
- Progreso Bridge Gage to San Benito Gage – 5,900 acre-feet – 8 Percent
- San Benito Gage to Lower Brownsville Gage – 4,900 acre-feet – 7 Percent
- Lower Brownsville Gage to the Gulf of Mexico – 2,300 acre-feet – 3 Percent
- **Total Average Annual Channel Loss and Total Percent –73,800 acre-feet– 100 Percent**

The results of this channel loss investigation of the Rio Grande are given and delineated as reaches V A – V F on the map of Figure 1. Hendricks (1965), Table 2, page 52 provides channel-loss coefficients by the same river reaches based on 6.25 percent of the average annual releases from Falcon of 1,180,000 acre-feet for 1954 – 1963. Also Hendricks (1965), Table 3, page 52 provides corresponding water loss per mile of river channel as a function of releases. All data is presented as applicable and from the United States share of water in the Rio Grande from Falcon Dam to the Gulf of Mexico.

1.216 Estimated Historical Average Annual Rio Grande Gain or Loss in the Hueco Bolson of the El Paso/Juarez Area of Texas, New Mexico and Mexico, 1903 – 1991. Taken from Meyer (1976).
Meyer (1976), Table 1, page 26 includes the average annual Rio Grande seepage from or to the Rio Grande Alluvium for 9 periods of years from 1903 to 1991. The seepage was determined by the use of a digital ground-water model of the Hueco Bolson Aquifer System in the El Paso/Juarez area of Texas, New Mexico, and Mexico. The following amounts of seepage (+ to the river and – from the river) by 9 periods (years) in acre-feet per year (af/yr) were estimated by applications of the model.

- **1903-20 Period ------- +6,864 af/yr**
- **1920-36 Period ------- +355 af/yr**
- **1936-48 Period ------- -4,588 af/yr**
- **1948-53 Period ------- -7,625 af/yr**
- **1953-58 Period ------- -13,466 af/yr**
- **1958-63 Period ------- -18,767 af/yr**

- **1963-68 Period -------- -19,183 af/yr**
- **1968-73 Period -------- -12,765 af/yr**
- **1973-91 Period -------- -21,075 af/yr – Projected results from model application.**

The results of this Rio Grande gain and loss investigation are given and located on the map of Figure 1.

1.127 Miscellaneous Low-Flow Investigations of the Rio Grande from Eagle Pass to Indio Ranch, and Eagle Pass to Laredo, January 12 – April 25, 1928. Taken and modified from TBWE (1960).

This investigation was conducted using 8 temporary gaging stations from Eagle Pass, Texas to Laredo Texas. All stations were well rated by current-water measurements from a boat for range of stage. The gains due to visible inflows and losses due to small diversions observed in the reach under investigation were considered negligible and were considered to balance each other.

- **Eagle Pass to Indio Ranch, January 13 to March 18, 1928 – 60 cfs gain – 18 miles – 3.33 cfs per mile.**
- **Eagle Pass to Indio Ranch, February 2 to March 14, 1928 – 55 cfs gain – 18 miles – 3.06 cfs/mile.**
- **Eagle Pass to Indio Ranch, January 12 to April 12, 1928 – 55 cfs gain – 18 miles – 3.06 cfs/mile.**
- **Eagle Pass (Mile 0) to Laredo (Mile 128), February 22 to April 12, 1928.**
    1. **Eagle Pass to Indio Ranch – 35 cfs gain – 18 miles – 1.94 cfs/mile.**
    2. **Indio Ranch to Palafox (upper) – 10 cfs loss – 69 miles – 0.14 cfs/mile.**
    3. **Palafox (upper) to Palafox (lower) – 60 cfs gain – less than 0.1 mile.**
    4. **Palafox (lower) to Islitas – 120 cfs loss – 21 miles – 5.71 cfs/mile.**
    5. **Islitas to Laredo – 25 cfs gain – 20 miles – 1.25 cfs/mile.**
- **Eagle Pass (Mile 0) to Laredo (Mile 128), April 3 to April 22, 1928.**
    1. **Eagle Pass to Palafox (upper) – 25 cfs loss – 87 miles – 0.29 cfs/mile.**
    2. **Palafox (upper) to Palafox (lower) – 60 cfs gain – less than 0.1 mile.**
    3. **Palafox (lower) to Islitas – 130 cfs loss – 21 miles – 6.19 cfs/mile.**
    4. **Islitas to Laredo – 20 cfs gain – 20 – 1.00 cfs/mile.**
- **Eagle Pass (Mile 0) to Laredo (Mile 128), February 22 to April 22, 1928 – 25 cfs loss – 128 miles – 0.19 cfs/mile.**

1.22 Pecos River

1.221 May 28 –30, 1918 Low-Flow Investigation from Angeles Gaging Station to Girvin, Texas (Grover, et al., 1922; NRPB, 1942; and TBWE, 1960)

This study of losses and gains of seepage was made on the Pecos River between the New Mexico – Texas State line and Girvin, Texas. Gages were operated at Angeles (near state line), above Barstow, Texas, and near Grandfalls, Texas. The river was at constant stage previous to and during the investigation so that few corrections for time interval were necessary. Muller and Price (1979) and Ashworth (1990a) used this study to equate the river gain (ground-water discharge) to predevelopment of ground water, average annual effective recharge of about 34,000 acre-feet to the Cenozoic Pecos Alluvium Aquifer System. The following gains and loss were determined from the investigation.

- **Angeles Gage to Arno – Porterville Highway Bridge ———————— 25 cfs Gain**
- **Arno – Porterville Highway Bridge to Barstow Gage ——————— 30 cfs Loss**
- **Barstow Gage to Girvin ————————————————————— 48 cfs Gain**

The results of this 1918 (oldest available) low-flow investigation of the Pecos River from Tx-NM State line to near Girvin, Texas are given and delineated as reaches IA – IC on the map of Figure 2.

1.222 Water-Delivery Investigation of the Pecos River from Red Bluff Dam to Girvin, Texas, March 1964 (Grozier, et al., 1966).

A water-delivery investigation was conducted from Red Bluff Dam to Girvin Gage (188.4 river miles) during March 3 – 5, 1964. About 129 cfs was measured in the Pecos River below the dam on March 3rd, and about 66 cfs was measured at Girvin on March 5th which is a net loss of about 63 cfs or about 0.33 cfs per mile. In the 174.1 river miles between the Orla gage and the Girvin gage, 57 percent of the released water was lost to the Cenozoic Pecos Alluvium Aquifer System, evaporation, or transpiration. The banks and floodplain, and in some cases the channel of the river, were heavily infested with saltcedar. The March 1964 water-delivery study had the following approximate losses and gain of flow in the 188.4-mile reach of the Pecos River.

- From below Red Bluff Dam to Pecos – 51 cfs Loss – about 0.7 cfs per mile.
- From Pecos to 0.5 mile below Grandfalls-Big Valley Diversion Dam – 2.6 cfs Gain – about 0.12 cfs per mile.
- From 0.5 mile below G-BV Diversion Dam to Girvin Gage – 16 cfs Loss – about 0.17 cfs per mile.

The results of this March 1964 water-delivery investigation of the Pecos River are given and delineated as reaches IA – IC on the map of Figure 4. The results of this study indicates that during a given year under hydrological conditions at the time, about 46,000 acre-feet per year of Pecos River seepage loss was possible to recharge the Cenozoic Pecos Alluvium Aquifer System.

1.223Low-Flow Investigation of the Pecos River from Red Bluff Dam to Girvin, Texas, May 1965 (Grozier, et al.,1966).

A low-flow investigation was conducted May 10 – 12, 1965 from Red Bluff Dam to Girvin Gage (188.4 river miles). There were no significant inflows from tributaries, and no diversions from the river. The following losses and gains occurred during the low-flow investigation.

- From Red Bluff Dam to downstream of Reeves Co. WID Channel Dam – 2.58 cfs Loss – about 0.06 cfs per mile.
- From RCWID Channel Dam to mouth of Toyah Creek (river miles 43.4 to 86.3) – 5 measurement points had no flow.
- 0.1 mile below mouth of Toyah Creek the river had flow of 3.18 cfs (river mile 86.4).
- From just below mouth of Toyah Creek to FM Hwy 1776 Bridge (river mile 114.3) – 2.19 cfs Loss – about 0.08 cfs per mile.
- From FMH 1776 Bridge to old gage site near Highway 11 (at river mile 141.4) – 3.91cfs Gain – about 0.14 cfs per mile.
- From old gage site near Highway 11 to Girvin Gage (river mile 188.4) – 6.60 cfs Gain – about 0.14 cfs per mile.

The results of this May 1965 low-flow investigation of the Pecos River from Red Bluff Dam to Girvin are given and delineated as reaches IA – ID on the map of Figure 3. The consistent gain per mile of 0.14 cfs from FM Hwy 1776 Bridge to Girvin Gage probably represents mostly the ground-water seepage to the river from the natural recharge in the "Sand Hills" north of the river in Ward and Crane Counties (Barnes, 1976a). Since it is May, some of the losses and low flow of the river may be due to ground-water pumpage in Reeves, Pecos, and Ward counties. However, most of the losses and low flow probably are due to evapotranspiration by the abundant concentrations of saltcedar on the river floodplain.

1.224 Water-Delivery Study from Red Bluff Dam to Girvin, Texas,1967 (Grozier, et al., 1968)

This water-delivery study was made during April 17 – 18, 1967 using 25 discharge measurements and 29 water sample sites for chemical analyses. The study reach had the same discharge measurement sites used in the March 1964 study (Grozier, et al., 1966). The following discussions summarize the results of the study and its comparison with the results of the previous 1964 and 1965 studies..

- Water was released from Red Bluff, and along with seepage, amounted to 547 cfs at mile 2.9 downstream from the dam. In the total reach studied, 346 cfs was diverted or leaked into canals. Surface inflows included 0.74 cfs at mile 2.9 from Salt Draw, and 0.11 cfs at mile 93.0 from "Sulphur Well."
- Water lost in the reaches between Red Bluff (river mile 0) and the Ward Co. ID #1 canal (river mile 61.0) varied from 2.44 cfs per mile to 4.17 cfs per mile. During the previous studies in 1964 and 1965, the highest loss in any of the same reaches was 1.27 cfs per mile.
- The loss between Pecos (river mile 71.8) to the bridge on Highway 18 (river mile 127.4) varied from 0.31 to 2.12 cfs per mile. In the 1964 and 1965 studies, the reach between Pecos (river mile 71.8) to the mouth of the Toyah Creek (river mile 86.4) was an insignificant gaining reach.
- After large upstream diversions, the very significant loss of about 15.8 cfs (1.0 cfs per mile) between the site downstream from the Ward Co. WID #2 diversion dam (mile 111.7) and the Highway 18 Bridge site (mile 127.4) probably was a seepage loss that was 1.) partly due to possible pre-irrigation ground-water pumpage in the Caynosa irrigation area of northern Pecos County, and 2.) partly due to significant consumptive water use by the dense growth of saltcedar reported to be on the river channel, banks and floodplain within the relatively short 15.7-mile reach. The probable seepage loss due to ground-water pumpage is considered to be induced recharge to the Cenozoic Pecos Alluvium Aquifer System.
- Between the Highway 18 site and the Girvin gage, there was a net gain of 8.2 cfs. A gain of 12.2 cfs in one reach and a loss of 3.6 cfs in another were the only significant changes, otherwise the flow was stable, or water losses were equal to inflow. Each of the flows that were measured at the last three sites in the last 30 river miles (includes Girvin gage and 2 sites upstream), were stabilized at 13 cfs.
- The quality of the water released was satisfactory for irrigation of soils with good drainage. The water quality was unsatisfactory for drinking or for industrial purposes.

The results of this water-delivery investigation of the Pecos River are given and delineated as reaches IIA – IIF on the map of Figure 4.

1.225 Low Flow in the Pecos River below Girvin, Texas, February 6 – 9, 1968 (Spiers and Hejl, 1970)

Spiers and Hejl (1970), pages 2 and 3, explain the purpose and scope, description of the basin, conditions of flow, chemical quality of the water, and gains and losses of flow related to this detailed study. Spiers and Hejl (1970), pages 2 and 3 state, "During this investigation there was an overall gain in flow throughout the total reach of 193.6 miles (Table 1). Between individual sites, however, the measurements show four gains, three major losses, and numerous smaller gains and losses. These gains and losses are summarized in Table 3."

The review of the data has the following major losses and gains as low-flow seepage of the river to and ground-water discharge from the Cenozoic Pecos Alluvium Aquifer (CPAA) and the Edwards-Trinity Plateau Aquifer (ETPA).

- The river had a loss of 6.3 cfs (0.17 cfs/mile) from the Girvin Gage (25.9 cfs measured flow) to Highway 349 Crossing northwest of Iraan. Some of this loss of flow was seepage to the Pecos River alluvium water-bearing deposits of the CPAA. Some of this seepage could have reentered the river and/or the ETPA further downstream in the downstream gaining. There was medium to heavy saltcedar infestation reported to be present in the floodplain within this reach.

- The reach of the Pecos River from the Highway 349 Crossing to the Low Water Crossing below Richland Canyon (56.5 river miles further downstream) had a very significant gain of 79.1 cfs (1.4 cfs/mile). This significant gain represented ground-water discharge to the river from springs and baseflow from the ETPA. There was light saltcedar and some mesquite growth reported to be along the river in this reach.
- The reach from below Richland Canyon to above a County Road Crossing below Pandale (30.2 river miles further downstream) had a loss of 14.0 cfs (0.34 cfs/mile). Medium to light saltcedar and some mesquite reported to be along the river. Part of this loss is natural seepage of river flow to the ETPA, and is not induced recharge caused by ground-water pumpage.
- The reach from above a County Road Crossing below Pandale to just above Everett Canyon (17.7 river miles further downstream) had a large gain of 52.3 cfs (2.95 cfs/mile). This very significant gain represented ground-water discharge to the river from springs and baseflow from the ETPA. This reach of the river channel consisted of rocky and smooth limestone with some mesquite reported in its uppermost part.
- The reach from Everett Canyon to the IB&WC Gage hear Comstock (42.8 river miles further downstream and one mile above the Rio Grande) had a small loss of 3 cfs (0.07 cfs/mile). The channel was rocky and smooth limestone. The discharge measured at the gage was about 134 cfs. From the Girvin Gage to the IB&WC Gage the river had a net gain of 108 cfs or about 0.56 cfs/mile.

The results of this low-flow investigation of the Pecos River from the Girvin, Texas gage to the IB&WC gage near Comstock, Texas are given and delineated as reaches IIA – IIG on the maps of Figures 2 and 3.

1.226 Relation Between the Edwards-Trinity (Plateau) Aquifer and Streamflow of the Pecos River.

Reeves and Small (1973) using USGS streamflow records for the Pecos River collected for the period from 1961 through 1967, constructed and used streamflow hydrographs to identify by a graphical method the baseflow. The average annual baseflow/springflow discharge of the Pecos River from the Edwards-Trinity Plateau Aquifer at the Rio Grande was estimated to be 32,000 acre-feet.

1.23 Devils River

1.231 Low-Flow Investigation of the Devils River, January 26 – 27, 1921 (TBWE, 1960)

During this low-flow investigation, only a partial discharging reach of the river was considered. From Rubboard Ford at zero (0) river mile with 283 cfs discharge to below the Southern Pacific Railroad Bridge at downstream river mile 27.2, there was a net gain of about 165 cfs or 6.07 cfs/mile. The gain probably was mostly ground-water discharge. The investigation was conducted when evaporation and evapotranspiration was negligible. The results of this low-flow investigation is given and delineated as reaches IIIA – IIIB on the map of Figure 4.

1.232 Low-Flow Investigation of the Devils River, October 6 – 7, 1921 (TBWE, 1960)

During this low-flow investigation of the river, only a partial discharging reach was considered. From a site called Rough Canyon Damsite (zero upstream river mile with 292 cfs discharge) to an abandoned gage site on river (7.8 downstream river miles), the river had a net gain of 52 cfs or

6.67 cfs per mile. The gain probably was mostly ground-water discharge. The investigation was conducted when evaporation and evapotranspiration may have been occurring. The results of this low-flow investigation is given and delineated as reach IVA on the map of Figure 4.

1.233 Low-Flow Investigation of the Devils River, August 8 – 13, 1925 (TBWE, 1960)
During this most comprehensive, 1925 low-flow investigation, the Devils River was at a constant stage and the measurements represented natural conditions. Within a 52.3 mile reach from just upstream of Pecan Springs Creek (mile 13.7 from upstream starting point) and the Devils River Gage 52.3 river miles further downstream, there was a very significant gain of 512 cfs. This amount represents about 9.8 cfs/mile ground-water discharge as spring flow and base flow from the Edwards-Trinity Plateau Aquifer during August 1925. The results of this low-flow investigation of the Devils River from above Juno to an old Devils River gage site at the Highway 90 crossing are given and delineated as reaches IIIA – IIIB on the map of Figure 2.

1.234 Low-Flow Investigation of the Devils River, February 7 – 11, 1928 (TBWE, 1960)
During this low-flow investigation, only a partial discharging reach of the river was considered. From above a point called "Smith Ranch house" at zero (0) upstream river mile with 242 cfs flow to 3,000 feet below the Southern Pacific Railroad Bridge, there was a net gain of 124 cfs or 7.5 cfs/mile. During the investigation, the river was at constant stage, and the measurements represent the natural conditions of ground-water discharge. Evaporation and evapotranspiration was probably negligible. The results of this low-flow investigation of February 7 – 11, 1928 are given and delineated as reach IIIF on the map of Figure 3. This investigation occurred before the February 14 – 20, 1928 low-flow investigation (see documentation 1.235 below), and is presented on Figure 3 as reach IIIF downstream of reaches IIIA – IIIE of the February 14 – 20, 1928 investigation.

1.235 Low-Flow Investigations of the Devils River, February 14 – 20, 1928 and February 7 – 11, 1928 (TBWE, 1960)
During this low-flow investigation, only a partial discharging reach of the Devils River was considered. From the river just above Dolans Creek at river mile zero (0) with 118 cfs flow to about 0.75 mile above a site called "Smith Ranch house" at down river mile 22.3, there was a net gain of 114 cfs or about 5.1 cfs/mile. During the investigation, the river was at constant stage, and the measurements represent the natural conditions of ground-water discharge. The investigation was conducted in February when evaporation and evapotranspiration is negligible. The results of this low-flow investigation of February 14 – 20, 1928 are given and delineated as reaches IIIA – IIIE on the map of Figure 3. The results of another connecting, downstream, low-flow investigation conducted in February 2 – 7, 1928 (see documentation 1.234 above) are given and delineated as reach IIIF on the map of Figure 3.

1.236 Relation Between the Edwards-Trinity (Plateau) Aquifer and Streamflow of the Devils River.
Reeves and Small (1973) estimated the average annual baseflow/springflow discharge of the Devils River to be 240,000 acre-feet. Streamflow hydrographs were plotted using USGS streamflow records and the baseflow component was identified by a graphical method and estimated for each year. An average annual amount as given above was calculated by averaging the annual baseflow/springflow discharge amounts estimated for 1961 through 1967.

1.3 Evapotranspiration By Saltcedar and Some Other Phreatophytes

To find and review the publications that address the various aspects of the results of phreatophyte research, this author recommends the bibliographies by Horton (1973) and Moore, et al., (2000). Both of these bibliographies are annotated and emphasize evapotranspiration by riparian vegetation such as saltcedar, mesquite and other water using plants found in and adjacent to the floodplains of the Rio Grande and Pecos River and their tributaries. A U. S. Bureau of Reclamation environmental report (USBR, 1979) has a very comprehensive bibliography which addresses evapotranspiration and other environmental aspects of the Pecos River Basin in New Mexico and part of Texas.

The first identification of saltcedar (*Tamarix*) in Texas was in the San Jacinto River Basin in Harris County in 1884. Saltcedar may have been observed in the Rio Grande Basin in New Mexico in 1859. Eight species were introduced in the U. S. by 1915. It's estimated that there are currently about 40 species that occur in the U.S. Three species are phreatophytes, namely *Tamarix gallicia*, *Tamarix pendantra*, and *Tamarix ramosissima*. Saltcedar is the common name of these species.

Since its introduction into the U. S., saltcedar has spread rapidly and infested large arid and semiarid areas of alluvial plains in 15 of the 17 western states. The increase in salt cedar growth in the western states was estimated to increase from about 10,000 acres in 1920 to about 900,000 acres in 1961. By 1970, it was predicted that saltcedar growth was about 1.33 million acres in the western states. By about 1961, saltcedar was estimated to have infested about 450,000 acres in Texas. Before about 1912, there were no saltcedar in the Pecos Valley of New Mexico. The first were reported in the Pecos River basin in 1912, and by 1915 had spread and covered about 600 acres. The plant continued to spread up and down the Pecos Valley so that by 1925 they covered 12,300 acres, and by 1939, 13,300 acres. The total acreage by 1953 in the Pecos Valley of New Mexico was about 41,000 acres. The rate of spreading was estimated at about 1,000 to 1,500 acres per year.

Robinson (1965) provides a map of the western states including Texas delineating the extents of saltcedar growth. Robinson stated as quoted in USBR (1979):
"The largest area of saltcedar, 275,000 acres, occurs in the Pecos River basin of New Mexico and Texas. It was estimated by the Geological Survey ground-water office in Albuquerque that in 1960 some 57,000 acres in the New Mexico portion of the basin was infested. In the Texas portion, on the basis of a general reconnaissance of the basin by the Soil Conservation Service in 1959, there was about 218,000 acres (C. A. Rechenthin, written communication, 1963). In this portion of the basin according to Mr. Rechenthin, 'saltcedar covers most of the bottom lands from the New Mexico line to a point below Sheffield, *** is found on many tributary streams such as Salt Draw, Toyah Creek, Tornillo Draw and others *** and is found extensively on 'gyp' soils in the Pecos, Imperial, Fort Stockton, and Girvin areas.'"

Saltcedar produces very abundant, light seeds that are easily spread by the wind. The very large amounts of seed produced germinate rapidly at the expense of other vegetation. Saltcedar has roots capable in arid regions of penetrating to a depth of about 100 feet. The depth and lateral penetration of saltcedar roots is basically controlled by the water-table depth. The plant 1.) is high in tannins, 2.) has wood that makes good fence post, and 3.) bears flowers that are a source of honey. But in actuality, saltcedar has no beneficial use, and its consumptive use of water is considered a great waste of the earth's most valuable natural resource.

Chemical analyses of saltcedar (*Tamarix pentandra* Pallas) leaves in Arizona determined that they may contain up to 15 percent by dry weight of inorganic ions of calcium, magnesium, sulfate and chloride. Up to 3 percent by dry weight of the inorganic ions could be washed off the leaf surface by rainfall. The amounts and content of the inorganic ions was found to be controlled by several factors including the quality of the ground-water used by the plant and the amount and frequency of rainfall. The presents of saltcedar in the arid and semiarid environments of the southwest U. S. appears to recycle mineral salts and build up the salinity of the soil.

(The above six paragraphs were taken and modified from Robinson, 1958; Mower, et al., 1964; Robinson, 1965; Hem, 1967; Horton, 1973; USBR, 1979; King and Bawazir, 2000; and Moore, et al., 2000.)

A final environmental statement by the U. S. Bureau of Reclamation (USBR, 1979, pages B-28 to B-34) provides very comprehensive discussions and findings of various authors addressing the latest information concerning saltcedar and related water salvage in the Pecos River basin from Lake Sumner in New Mexico to Pecos, Texas. In specific regard to saltcedar, the statement addresses the various characteristics of saltcedar and saltcedar growth, related consumptive water use, the water salvage after saltcedar removal, and revegetation in previously cleared areas.

Engel-Wilson and Ohmart (1977) mapped on 33 sheet/maps with scale 1:7,700 the vegetation, including saltcedar types, along the Rio Grande in Texas and Mexico from Fort Quitman in Hudspeth County to just upstream from Presidio in Presidio County. These maps were used to help conduct an assessment of vegetation and terrestrial vertebrates along the Rio Grande for the IB&WC. The study concludes that the quality of the Rio Grande floodplain as wildlife habitat is declining because of saltcedar growth replacing habitats of other vegetation, wetlands have disappeared because of the spread of saltcedar in the floodplain, and saltcedar has caused decreased flow in the river (due to consumptive use of river water and ground-water in the Rio Grande alluvium by evapotranspiration) (Engel-Wilson and Ohmart, 1978).

The consumptive use of ground water by saltcedar at their optimum volume-density is probably the highest of any of the phreatophytes. The consumptive use/waste of ground water by saltcedar in the western states was estimated to be about 45,000 acre-feet in 1920, 3.5 million acre-feet in 1961, and was predicted to increase to about 5.0 million acre-feet in 1970. The average water use in tank experiments in 1940 amounted to 5.48 feet/year with a 2-feet tank water level, and 4.68 feet/year with a 4-feet water level. Saltcedar was reported to use on an average annual basis 6.0 feet in the Carlsbad area of New Mexico including 1.0-foot precipitation. In the Gila River Valley of Arizona tank experiments at 100 percent volume-density not including precipitation had water use of 9.17 to 7.33 feet/year with average depths to water level in feet ranging from 4.0 to 7.0 respectively. Another experiment in thickets of saltcedar indicated 6.05 feet/year at 100 percent volume-density, not including percipitation. (Taken and modified from Robinson, 1958 and Robinson, 1965.)

In a 1940 study, the amounts of water used by vegetation along and adjacent to the Pecos River from Red Bluff Dam to Girvin, assumed 5.9 and 6.0 acre-feet per acre per year as consumptive use by saltcedar. The 1940 unit consumptive uses by saltcedar was reported to be 5.9 feet per acre for the Imperial – Zimmerman area, and 5.5 feet per acre for the Fort Stockton area. During 1940 evapotranspiration studies at Carlsbad, New Mexico, tank measurements of average monthly consumptive water use by saltcedar ranged from highs of 9.53 inches and 8.28 inches in July and August to lows of 0.40 inches and 0.58 inches in December and January. The annual 1940 amount was 57.25 inches or 4.77 feet. The measurements for August 1940 at Carlsbad were 8.38 inches for a 2-feet water table and 8.19 inches for a 4-feet water table. For December 1940 the amounts were 0.49 inches for a 2-feet water table and 0.32 inches for a 4-feet water table. (Taken and modified from NRPB, 1942.)

An evapotranspiration study of saltcedar, baccharis, cottonwood and mesquite in an infested alluvial lowland plain along the Gila River in the Lower Safford Valley, Graham County, Arizona, estimated that the total consumptive water use by the phreatophytes in a 12 month period was about 28,000 acre-feet in a total of 9,303 acres. Since precipitation and runoff were below normal it would be possible that the annual amount could be greater than 28,000 acre-feet. Approximately 23,000 acre-feet was from the valley shallow aquifer while the remaining 5,000 acre-feet was from precipitation. Of the 23,000 acre-feet, more than 75 percent was estimated to be used by saltcedar. Range in use by saltcedar was 2 to 20 acre-feet per acre per year. Six methods of estimating water use were applied during the investigation. (Taken and modified from Gatewood, et al., 1950 and Jones, 2001.)

A 1956-1958 study of the Acme-Artesia, New Mexico reach of the Pecos River, mapped about 41,000 acres of phreatophytes. During that period, saltcedar increased in areal and vertical density and encroached on about 5,000 acres of grassland. The consumptive use of the phreatophytes was determined by the use of 4 methods that provided an estimated average annual consumptive use of about 73,600 acre-feet. The study estimated that if saltcedar was eradicated with only phreatophyte grass remaining, and ground-water conditions were controlled, evapotranspiration would still be on the order of 45,000 acre-feet per year. If the saltcedar growth continued and ground- water conditions stayed about the same as in 1958, the consumptive use by evapotranspiration could increase to 170,000 acre-feet in just a few years. Phreatophyte growth may be controlled by mechanical clearing, burning and spraying with chemicals. (Taken from Mower, et al., 1964.)

Van Hylckama (1974) conducted detailed tank evapotranspiration studies of saltcedar from 1961 to 1967 in the floodplain of the Gila River bear Buckeye, Arizona. The study provided the following results.

- The water use was about 7 feet per year with the tank water table at about 5 feet.
- Water use was about 5 feet per year with the tank water table at about 6.75 feet.
- Water use was less than 3.3 feet per year with the tank water table at about 8.9 feet.
- Water use varied significantly with the salinity of the moisture of the soil in the tank.
- When 10-feet saltcedar were cut to about 1.5 feet twice a year, the water use decreased about 50 percent.
- When the saltcedar was thinned to 50 percent of the original density, the water use decreased by only 10 percent.
- The greatest water use was about 10 feet in 1965 in a tank with a high water table, dense saltcedar growth, and a relatively low soil moisture salinity.
- The daily evaporation from bare soil diminished during mid-day summer days due to the formation of a vapor barrier. Significant evaporation continued, however, from the soil beneath a dense growth of vegetation.
- Atmospheric pressure changes which effect the water table in the plastic-lined tanks was not considered when tank water levels were used to quantify consumptive water use by the saltcedar.

Jones (1977) used 38 color-infrared, aerial photographic missions over the Gila River Phreatophyte Project in southeastern Arizona to determine the possibility of identifying and measuring parameters of the project vegetation and the associated hydrologic variables of the vegetation. The study determined that a color-infrared, aerial photographic mission and a computer analysis of the photographic data cost about a tenth of the cost of conventional vegetation species classification and canopy measurement techniques.

Culler, et al., (1982) found that on the Gila River floodplain of Graham County, Arizona, evapotranspiration by phreatophytes occurred as follows:

- An annual 43 inches before clearing with range of 56 inches with dense growth and 25 inches with no phreatophytes.
- After clearing of the phreatophytes, annual average of 19 inches with range of 14 inches on one reach to 26 inches on another.

Welder (1988) states,
"The U. S. Bureau of Reclamation began a phreatophyte clearing and control program in the bottom land of the Acme-Artesia reach of the Pecos River in March 1967. The initial cutting of the 19,000 acres of saltcedar trees, the dominant phreatophyte in the area, was completed in May 1969. Saltcedar regrowth continued each year until July 1975, when root plowing eradicated most of the regrowth. The major objective of the clearing and control program was to salvage water that could be put to beneficial use."
"Measurements of changes in the water table in the bottom land and changes in the base flow of the Pecos River were made in order to determine the hydrologic effects of the program. Some salvage of water was indicated, but it is not readily recognized as an increase in base flow. The quantity of salvage probably is less than the average annual base-flow gain of 19,110 acre-feet in the reach during 1967-82."

King and Bawazir (2000) conducted evapotranspiration studies of riparian vegetation in the Middle Rio Grande Basin, and stated (in part),
"....Riparian evapotranspiration (ET) is one of the largest loss components in the Middle Rio Grande hydrologic budget and one of the least understood. Much uncertainty exists as to the consumptive use of riparian vegetation such as saltcedar (*Tamarix ramosissima*) and cottonwood (*Populus fremontii*). The primary objective of this study is to create models that would predict consumptive use of water by saltcedar and cottonwood and identify methods of long-term ET quantification. Evapotranspiration by saltcedar and cottonwood was measured in 1999 using eddy covariance methods on the floodplain of the Middle Rio Grande at Bosque del Apache National Wildlife Refuge, New Mexico. * * * the water budget of deciduous saltcedar and cottonwood clearly showed a transpiration pulse during the summer , and defined effects of spring budbreak and autumn senescence; 4) a dense stand of saltcedar used 1325 mm/yr (4.35 ft/yr) and 1193 mm (3.91 ft) during growing season DOY 95-325 (April 5-November 21); 5) a sparse stand of cottonwood used 904 mm (2.97 ft/yr) and 799 mm (2.62 ft) during the growing season from DOY 95-325 (April 5-November 21); and 6) daily ET from saltcedar and cottonwood during the growing period was predicted adequately with a fourth degree polynomial function to estimate crop coefficients applied with the Penman equation."
The study report can be downloaded from the internet at
http://cagesun.nmsu.edu/~tamarisk/information/publication.html.

Jones (2001), page 127 states:
"Water uptake by vegetation can be substantial. For example, estimated transpiration rates for saltcedar, juniper, mesquite, cattail, and shrubs are 2 to 20, about 2, 1 to 2, 4 to 10, and 1 to 2 acre-ft/acre/yr, respectively *(various references given)*."

A Pecos River, Texas study by Clayton (2002) addresses aerial herbicide treatment to control saltcedar, the impact of treatment on river quality, and quantity changes by analyses of river losses. The study results are:

- Several aerial herbicide treatments were made on the saltcedar. All treatments except one caused saltcedar mortality. One treatment was determined to be the best for control of the saltcedar.
- Herbicide treatments had no significant adverse effect on vegetation cover. Drought did cause some changes in vegetation cover.
- No effect on soil salinity was found following treatment of saltcedar.
- A trend toward decreasing water quality in the Pecos River from red Bluff Dam to Girvin appears to be occurring. The decrease could not be attributed to the treatment control of saltcedar.
- Concerning river water quantity the following is stated:
  "Water quantity was characterized by historical release and delivery data from the Red Bluff Power Control District. Losses occurring during release and delivery from Red Bluff to irrigation districts are influenced by evaporation by riparian vegetation and from the river and accuracy of release and delivery. Water levels and delivery appear to be influenced by seasonal release from Red Bluff and by the level of a shallow water table underneath the river. The highest average percent loss (67%) occurs during the first month of release for the average delivery year. This indicates that during the irrigation off-season the water table drops and during the first month of release, recharge occurs. Average percent loss decreases to 39% during the growing season, indicating that the water table is recharged. Late season average percent loss increases to 43% following low releases that allow the water table to retreat.

The study report can be downloaded from the internet at http://farwest.tamu.edu/rangemgt/prep.html.

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FIGURE EXPLANATIONS

FIGURE 1 – MAP SHOWING THE RESULTS OF LOW-FLOW AND OTHER GAIN-LOSS INVESTIGATIONS OF THE RIO GRANDE, TEXAS AND MEXICO.

EXPLANATION

(On the map, reaches with GAINS are indicated in BLUE, reaches with LOSS are indicated in RED, and reaches with constant flow or zero/no flow are indicated in GREEN.)

I. Low-Flow of Rio Grande from Lajitas, Texas to Del Rio, Texas, February 7-20, 1925. Taken from TBWE (1960).

Reach Map I. D.	Date(s)	Reach Miles	Net Gain (+) or Loss (-) CFS	CFS/Mile	Aquifer
I A	2/7-8/25	17.3	-20	-1.16	Not Delineated
I B	2/8-9/25	43.2	Constant Flow = 1,040 cfs		RGA
I C	2/9-11/25	19.0	+50	+2.63	Includes Hot Springs
I D	2/13-14/25	39.4	+130	+3.30	Edwards-Trinity
I E	2/15-19/25	100.9	+220	+2.18	do.
I F	2/19-20/25	73.3	+980	+13.37	do.
1) I F	2/19-20/25	73.3	+403	+5.50	do.
2) I F	2/19/25	Inflow	+199	—	do.
3) I F	2/20/25	Inflow	+378	—	do.
4) I C – I F	2/7-20/25	293.1	+1783	+6.08	I. H. S. & E-T
5) I D – I F	2/13-20/25	213.6	+1330	+6.22	Edwards-Trinity

Footnotes: 1) Gain in Rio Grande channel over Edwards-Trinity Plateau Aquifer (ETPA). 2) Inflow from Pecos River which apparently is ground-water discharge from the ETPA. 3) Inflow from the Devils River which apparently is ground-water discharge from the ETPA. 4) Total gain from "Mariscal damsite" (Mariscal Canyon) to Del Rio (includes flow of Hot Springs above Boquillas). 5) Total gain from ground-water discharge as spring flow and baseflow from the ETPA in the Rio Grande Basin of Texas and Mexico.

II. Low-Flow of the Rio Grande from Del Rio, Texas to Eagle Pass, Texas, February 9 – March 3, 1926. Taken from TBWE (1960).

Reach Map I. D.	Date(s)	Reach Miles	Net Gain (+) or Loss (-) CFS	CFS/Mile	Aquifer
II A	2/9 – 3/3/26	43	+330 1)	+7.67	Rio Grande Alluvium
II B	2/12/26	14	-20	-1.42	None

Footnote: 1) The net gain of 330 cfs includes 194 cfs of tributary inflow from San Felipe Creek (San Felipe Spring), Sycamore Creek, Pinto Creek and Las Moras Creek on the Texas side, and the Rio San Diego and Rio Rodrigo on the Mexico side. The remaining 136 cfs is estimated gain in the Rio Grande channel. The inflow from San Felipe Spring (76 cfs) in Texas, and the inflow from the Rio San Diego (77 cfs) and the Rio Rodrigo (27 cfs) in Mexico are considered ground-water discharge from Edwards-Trinity Plateau Aquifer in the Rio Grande Basin of Texas and Mexico.

FIGURE 1 – CONTINUED

III. Low-Flow of the Rio Grande from Eagle Pass, Texas to San Ygnacio, Texas, February 12 – 22, 1926. Taken from TBWE (1960).

Reach Map I. D.	Date(s)	Reach Miles	Net Gain (+) or Loss (-) CFS	CFS/Mile	Aquifer
III A	2/12-13/26	11	-90 1)	-8.18	None
III B	2/13-14/26	18	+50 2)	+2.78	do.
III C	2/14-16/26	26	-130	-5.00	RGA & Wilcox Gp.
III D	2/16/26	12	+120 3)	+10.00	Carrizo-Wilcox
III E	2/16-21/26	72.5	-214 4)	-2.97	None
III F	2/21/26	6.5	+40	+6.15	do.
III G	2/21-22/26	11	-30	-2.73	do.
III H	2/22/26	10	Constant Flow = 2,760 cfs		do.

Footnote: 1) Loss includes 71 cfs of inflow from Rio Chico in Mexico, and 19 cfs from the Rio Grande channel. 2) Gain includes 10 cfs of inflow from Rio Domingo in Mexico, and 40 cfs from Rio Grande channel. 3) This 120 cgs gain may be considered ground-water discharge from the Carrizo-Wilcox Aquifer which is equivalent to about 86,875 acre-feet of annual recharge to the aquifer in the mid-1920s in the Ro Grande Basin of Texas and Mexico. 4) Los of 215 cfs to Rio Grande channel with 25 cfs of diversions by irrigation pumps.

IV. Low-Flow of the Rio Grande from Old Zapata Gage (Mile 0) to Old Gage at Anzalduas Dam (Mile 127.3), June 1948. Taken from Lowery, et al. (1948).

Reach Map I. D.	Date(s)	Reach Miles	Net Gain (+) or Loss (-) CFS	CFS/Mile	Aquifer
IV A	June 1948	27.2	-95	-3.49	Rio Grande Alluvium
IV B	do.	17.3	+22.9	+1.32	do.
IV C	do.	23.3	-51.7	-2.22	do.
IV D	do.	59.5	-32.7	-0.55	do.
IV A – IV D	do.	127.3	-156.5	-1.23	do.

V. Average Annual Channel Loss of USA Share of Rio Grande from Falcon Dam to the Gulf of Mexico, 1954 – 1963. Taken and modified from Hendricks (1965).

Reach Map I. D.	Reach Miles	Annual Channel Loss Acre-Feet	CFS	CFS/Mile	Aquifer
V A	40	12,100	16.7	0.42	Rio Grande Alluvium
V B	63	23,600	32.6	0.52	do.
V C	47	25,000	34.5	0.73	do.
V D	27	5,900	8.15	0.30	do.
V E	48	4,900	6.77	0.14	do.
V F	49	2,300	3.18	0.06	do.
V A – V F	274	73,800	101.9	0.37	do.

FIGURE 1 – CONTINUED

VI. Estimated Average Annual Rio Grande Gain or Loss in the Hueco Bolson of the El Paso/Juarez Area of Texas, New Mexico and Mexico, 1903 – 1991. Taken form Meyer (1976).

	Gain (+) or Loss (-)		
Period	**Acre-Feet/Year**	**CFS**	**Aquifer**
1903 – 1920	+6,864	+9.49	Rio Grande Alluvium
1920 – 1936	+355	+0.49	do.
1936 – 1948	-4,588	-6.34	do.
1948 – 1953	-7,625	-10.39	do.
1953 – 1958	-13,466	-18.60	do.
1958 – 1963	-18,767	-25.92	do.
1963 – 1968	-19,183	-26.50	do.
1968 – 1973	-12,765	-17.63	do.
1973 – 1991 1)	-21,075	-29.11	do.

Footnote: 1) Projected by model application.

FIGURE 2 – MAP SHOWING RESULTS OF SELECTED EARLIEST LOW-FLOW INVESTIGATIONS OF THE PECOS RIVER AND DEVILS RIVER.

EXPLANATION

(On the map, reaches with low-flow GAINS are indicated in BLUE, reaches with low-flow LOSSES are indicated in RED, and reaches with constant flow or zero/no flow are indicated in GREEN.)

I. PECOS RIVER – From Texas-New Mexico State Line to Near Girvin, Texas, May 28-30, 1918. Taken from Grover, et al. (1922) and TBWE (1960).

Reach Map I. D.	Date(s)	Reach Miles	Net Gain (+) or Loss (-) CFS	Net Gain (+) or Loss (-) CFS/Mile	Aquifer
IA	5/28-29/18	56	+25	+0.45	Cenozoic Alluvium
IB	5/29/18	30.5	-30	-0.98	do.
IC	5/29-30/18	116.5	+48	+0.41	do.
IA – IC	5/28-30/18	203	+43	+0.21	do.

II. PECOS RIVER – From Girvin Gage to IB&WC Gage Near Comstock, Texas, February 6 – 9, 1968. Taken from Spiers, et al. (1970).

Reach Map I. D.	Date(s)	Reach Miles	Net Gain (+) or Loss (-) CFS	Net Gain (+) or Loss (-) CFS/Mile	Aquifer
IIA	2/6/68	36.7	-6.3	-0.17	Cenozoic Alluvium
IIB	2/6/68	9.7	Constant Flow = 19.6 cfs		Edwards-Trinity
IIC	2/6-7/68	56.5	+79.1	+1.40	do.
IID	2/6-8/68	30.2	-14	-0.46	do.
IIE	2/6-8/68	17.7	+52.3	+2.95	do.
IIF	2/7-8/68	17.3	-10	-0.58	do.
IIG	2/7-9/68	25.5	+7	+0.27	do.
IIA – IIG	2/6-9/68	193.6	+108.1	+0.56	CA & E-T
IIB – IIG	2/6-9/68	156.9	+114.4	+0.73	Edwards-Trinity

III. DEVILS RIVER – Above Juno and Below "Beaver Lake" (?) to Under Amistad Reservoir at old Devils River Gage at Highway 90 Crossing, August 8 – 13, 1925. Taken from TBWE (1960)

Reach Map I. D.	Date(s)	Reach Miles	Net Gain (+) or Loss (-) CFS	Net Gain (+) or Loss (-) CFS/Mile	Aquifer
IIIA	8/8/25	13.7	-7.4	-0.54	Edwards-Trinity
IIIB	8/8-13/25	62.3	+512	+8.22	do.
IIIA – IIIB	8/8-13-25	76.0	+505	+6.64	do.

FIGURE 3 –MAP SHOWING RESULTS OF LOW-FLOW INVESTIGATIONS OF THE PECOS RIVER IN MAY 1965 AND FEBRUARY 1968, AND THE DEVILS RIVER IN FEBRUARY 1928.

EXPLANATION

(On the map, reaches with low-flow GAINS are indicated in BLUE, reaches with low-flow LOSSES are indicated in RED, and reaches with constant flow or zero/no flow are indicated in GREEN.)

I. PECOS RIVER – From Below Red Bluff Dam to the Girvin Gage, May 10 – 12, 1965. Taken from Grozier, et al. (1966).

Reach Map I. D.	Date(s)	Reach Miles	Net Gain (+) or Loss (-) CFS	CFS/Mile	Aquifer
IA	5/10/65	43	-2.58	-0.06	Cenozoic Alluvium
IB	5/10-11/65	42.9	Four Zero Flow Mm'ts		do.
IC	5/11/65	27.9	-2.19	-0.08	do.
ID	5/11-12/65	74.1	+10.51	+0.14	do.
IA – ID	5/10-12/65	187.9	+5.74	+0.03	do.

II. PECOS RIVER – From Girvin Gage to IB&WC Gage Near Comstock, Texas, February 6 – 9, 1968. Taken from Spiers, et al. (1970).

Reach Map I. D.	Date(s)	Reach Miles	Net Gain (+) or Loss (-) CFS	CFS/Mile	Aquifer
IIA	2/6/68	36.7	-6.3	-0.17	Cenozoic Alluvium
IIB	2/6/68	9.7	Constant Flow = 19.6 cfs		Edwards-Trinity
IIC	2/6-7/68	56.5	+79.1	+1.40	do.
IID	2/6-8/68	30.2	-14	-0.46	do.
IIE	2/6-8/68	17.7	+52.3	+2.95	do.
IIF	2/7-8/68	17.3	-10	-0.58	do.
IIG	2/7-9/68	25.5	+7	+0.27	do.
IIA – IIG	2/6-9/68	193.6	+108.1	+0.56	CA & E-T
IIB – IIG	2/6-9/68	156.9	+114.4	+0.73	Edwards-Trinity

III. DEVILS RIVER – From Just above Dolans Creek to 0.75 Mile above Smith Ranch during February 14 – 20, 1928. Then During February 7 – 11, 1928 From 0.75 Mile above Smith Ranch to 3,000 Feet below the Southern Pacific Railroad Bridge. Taken from TBWE (1960).

Reach Map I. D.	Date(s)	Reach Miles	Net Gain (+) or Loss (-) CFS	CFS/Mile	Aquifer
IIIA	2/14-16/28	6.55	+85	+12.98	Edwards-Trinity
IIIB	2/16-18/28	4.25	-23	-5.41	do.
IIIC	2/18-20/28	6.0	+25	+4.17	do.
IIID	2/19-20/28	3.9	-12	-3.08	do.
IIIE	2/20/28	1.6	+39	+24.38	do.
IIIF	2/7-11/28	16.5	+124	+7.52	do.
IIIA – IIIF	2/7-20/28	38.8	+238	+6.13	do.

FIGURE 4 –MAP SHOWING RESULTS OF WATER-DELIVERY INVESTIGATIONS OF THE PECOS RIVER IN MARCH 1964 AND APRIL 1967, AND 1921 LOW-FLOW INVESTIGATIONS OF THE DEVILS RIVER.

EXPLANATION

(On the map, reaches with flow GAINS are indicated in BLUE, reaches with flow LOSSES are indicated in RED, and reaches with constant flow or zero/no flow are indicated in GREEN.)

I. PECOS RIVER – Water Delivery From Below Red Bluff Dam (129 cfs released flow) to the Girvin Gage (66.2 cfs flow), March 3-5, 1964. Taken from Grozier, et al. (1966).

			Net Gain (+) or Loss (-)		
Reach Map I. D.	Date(s)	Reach Miles	CFS	CFS/Mile	Aquifer
IA	3/3/64	71.4	-51	-0.71	Cenozoic Alluvium
IB	3/3-5/64	21.8	+2.6	+0.12	do.
IC	3/5/64	94.8	-16	-0.17	do.
IA – IC	3/3-5/64	188.0	-64	-0.34	do.

II. PECOS RIVER – Water Delivery from Below Red Bluff Dam (547 cfs release and seepage flow) to the Girvin Gage (13.0 cfs flow), April 17 – 18, 1967. Taken from Grozier. et al. (1968).

			Net Gain (+) or Loss (-)		
Reach Map I. D.	Date(s)	Reach Miles	CFS	CFS/Mile	Aquifer
IIA	4/17-18/67	40.5	-100	-2.47	Cenozoic Alluvium
IIB	4/17-18/67	43.0	-74	-1.72	do.
IIC	4/18-19/67	41.0	-36	-0.88	do.
IIA - IIC	4/17-19/67	124.5	-210	-1.69	do.
IID	4/18/67	14.0	+12	+0.86	do.
IIE	4/18/67	16.8	-4	-0.24	do.
IIA - IIE	4/17-18-67	155.3	-202	+1.30	do.
IIF	4/18/67	30.2	Constant Flow = 13.0 cfs		do.

III. DEVILS RIVER – Low-Flow From Rubbord Ford to 0.5 Mile Below Southern Pacific Railroad Bridge, January 26 – 28, 1921. Taken from TBWE (1960).

			Net Gain (+) or Loss (-)		
Reach Map I. D.	Date(s)	Reach Miles	CFS	CFS/Mile	Aquifer
IIIA	1/26-28/21	20	+110	+5.50	Edwards-Trinity
IIIB	1/27-28/21	7.2	+55	+7.64	do.
IIIA - IIIB	1/26-28/21	27.2	+165	+6.07	do.

IV. DEVILS RIVER – Low-Flow From Rough Canyon Damsite to Abandoned Gage About 1.1 Miles Below the Southern Pacific Railroad Bridge, October 6-7, 1921. Taken from TBWE (1960)

			Net Gain (+) or Loss (-)		
Reach Map I. D.	Date(s)	Reach Miles	CFS	CFS/Mile	Aquifer
IVA	10/6-7/21	7.8	+52	+6.67	Edwards-Trinity