Evaluation of Rio Grande Salinity
San Marcial, New Mexico to
El Paso, Texas

Prepared for **New Mexico Interstate Stream Commission**
New Mexico Environment Department

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Executive Summary

The salinization of rivers, as indicated by salinity increases in the downstream direction, is characteristic of arid and semiarid regions throughout the world (Postel, 1993; Pillsbury, 1981) and the Rio Grande is no exception. Water quality in the Lower Rio Grande (LRG) of New Mexico has been extensively studied, and salinity increases in the downstream direction have historically been attributed to various mechanisms. While some previous investigations assume that salinization in the LRG is entirely due to agricultural activities, the bulk of evidence strongly suggests that salinization in the LRG is due to upwelling of geothermal waters and "vertical leakage from deep-seated regional groundwater flow systems" (Witcher et al., 2004; Moore and Anderholm, 2002; Anderholm, 2002; Mills, 2003; Phillips et al., 2003; Frenzel et al., 1992).

At the request of the New Mexico Interstate Stream Commission (ISC) and the New Mexico Environment Department (NMED), Daniel B. Stephens & Associates, Inc. (DBS&A) and Geochemical Technologies Corporation (GTC) have investigated the processes that affect salinity in the LRG, which extends from Elephant Butte Reservoir to El Paso, Texas. The following activities were completed as part of the ongoing study:

- Previous investigations were reviewed and evaluated.
- Historical streamflow and water quality data were evaluated using statistical methods and a mass balance approach (i.e., calculation of annual loads).
- Two synoptic water quality sampling events were conducted, one during the 2004 irrigation season and one during the 2005 winter season, to test for environmental tracers to help identify contributing sources.
- The various sources (or types) of water in the LRG were identified and characterized; water sources include Rio Grande water, deep saline groundwater, geothermal water, wastewater, and agricultural water.
- For each synoptic sampling event, daily chloride loads were calculated to evaluate contributions to the LRG from various sources.

- Geochemical modeling was employed to simulate mixing of the various water sources in the LRG in an attempt to explain the observed salinity increases.

Evaluation of early historical data indicates that salinization in the LRG occurred before the reservoirs, agricultural drains, and centralized wastewater treatment plants (WWTPs) were present. The current downstream pattern of salinization in the LRG, as indicated by observed increases in chloride concentrations and chloride loads, is similar to that observed prior to the construction of the reservoirs, agricultural drains, and WWTPs.

While evapotranspiration and agricultural processes do contribute to small increases in salinity, those contributions are small compared to the contribution from geothermal and deep saline groundwater. Results of this study indicate that it is not possible to reproduce the observed salinization by evapotranspiration and agricultural processes alone. The isotopic data collected as part of this study are essential in defining the mixing process because of the independent constraint they provide.

Results of isotopic analyses, geochemical modeling, and a chloride mass balance assessment indicate that natural sources of salinity are the principal contributors to the salinization of the Rio Grande. More specifically, a combination of geothermal and deep saline groundwater inflow to the Rio Grande, both directly and via the agricultural drains, is primarily responsible for the observed salinization of the LRG. As an example, large salinity inputs occur in the southernmost reaches of Mesilla Valley (just north of the El Paso Narrows).

1. Introduction

The salinization of rivers, as indicated by salinity increases in the downstream direction, is characteristic of arid and semiarid regions throughout the world (Postel, 1993; Pillsbury, 1981) and the Rio Grande is no exception. The Lower Rio Grande (LRG) extends from Elephant Butte Reservoir to El Paso, Texas (NM OSE, 2005). Water quality in the LRG has been extensively studied. Salinity increases have historically been attributed to various mechanisms, including (1) evaporation and concentration during reservoir storage, irrigation, and subsequent reuse, (2) displacement of shallow saline groundwater during irrigation, (3) erosion of natural deposits, and/or (4) inflow of deep saline groundwater.

In 2003, the State of New Mexico initiated a comprehensive water quality investigation in the LRG that includes an ongoing water quality monitoring program for both surface water and groundwater. Early results of this investigation were published in Moore et al. (2008). There has recently been increased interest in (1) processes affecting salinization in the LRG and (2) salinity management in the LRG. This increased interest is evidenced by several recent publications (Bastien, 2009; Hibbs et al., 2003; Hogan et al., 2007; Hutchinson and Hibbs, 2008) and the formation of the multistate Rio Grande Project Salinity Management Coalition. Due to this recent interest and activity, the New Mexico Interstate Stream Commission (ISC) and New Mexico Environment Department (NMED) decided to make available results of their early work from 2005 conducted as part of their ongoing water quality investigations. This report presents complete results of that early work, including those published in Moore et al. (2008).

As part of the State's comprehensive water quality investigation that was initiated in 2003, the ISC and the NMED requested that Daniel B. Stephens & Associates, Inc. (DBS&A) and Geochemical Technologies Corporation (GTC) investigate processes that affect water quality, especially salinity, in the LRG. The focus of this investigation was to improve the understanding of the processes effecting changes in water quality in the Rio Grande in New Mexico.

DBS&A investigated how salinity in the LRG has changed historically and identified mechanisms and contributing sources, or end members. In cooperation with the ISC and NMED, DBS&A conducted two synoptic water quality sampling events to test for environmental

tracers to identify end members: one during an irrigation season (August 2004) and one during a winter season (January 2005). The main objectives of this LRG water quality study were:

- To determine, based on the existing data, any trends in the quality of water delivered in the LRG
- To investigate seasonal variability of primary constituents in the LRG, including chloride and total dissolved solids (TDS)
- To identify principal sources of salinity to the Rio Grande
- To identify, to the extent possible, geographic locations and relative contributions of salinity

This section presents basic water quality concepts. Hydrogeology of the LRG is discussed in Section 2. Previous investigations and water quality data are reviewed in Section 3. Section 4 evaluates the variability of historical data and presents calculated annual salt loads. Section 5 provides a general overview of water quality conditions observed during the recent synoptic water quality sampling events. Potential end members are defined in Section 6. Results of end member mixing scenarios are presented in Section 7. Section 8 presents conclusions.

1.1 The Rio Grande

The Rio Grande flows from its headwaters at over 12,000 feet above mean sea level in southern Colorado, through New Mexico, to Texas and Mexico, where it forms the international border. Surface water is delivered to Mexico through operations of the Rio Grande Project, in accordance with the May 21, 1906 Convention between the United States and Mexico for the Equitable Distribution of the Waters of the Rio Grande. Within the United States, the waters of the Rio Grande are apportioned between the three states by the Rio Grande Compact (the Compact), an agreement entered into by New Mexico, Texas, and Colorado in 1938 and approved by the U.S. Congress and the State of New Mexico (NMSA 72-15-23).

The Compact applies to surface water of the Rio Grande, from its headwaters in Colorado to Fort Quitman, Texas, for use by each of the three states. Each upstream state is required to make a surface water delivery to its downstream neighbor; Colorado delivers water to the Rio Grande at Lobatos gage near the Colorado-New Mexico state line and New Mexico delivers to Elephant Butte Reservoir. The volumes of water required to be delivered to New Mexico and Texas are calculated based on upstream flows and are accounted for by credits and debits based on annual deliveries. The Compact primarily describes water deliveries; however, water quality is a component of the Compact and is addressed in Article XI.

Surface water stored in Elephant Butte Reservoir is distributed to water users in Texas and New Mexico, and delivered to Mexico, by the operations of the Rio Grande Project. Most of this water is used for irrigation; however, a significant portion is now diverted for municipal purposes by the City of El Paso.

1.2 Basic Water Quality Concepts

Water quality is a general term used to describe the chemical composition of a particular water sample. Water quality is affected by many natural and anthropogenic factors. The water quality of a particular sample represents "the net effect of a series of antecedent chemical reactions", as well as antecedent physical and biological processes (Hem, 1992). Different water sources generally have different chemical "signatures" or "fingerprints" that can be used to identify and differentiate the various sources. This concept is discussed in greater detail in Sections 5 through 7.

Salinity is defined as the concentration of dissolved salts in a particular water sample; it is a general indicator of water quality. Several methods are available to quantify salinity. The concentration of TDS is a measure of the dissolved ions in a water sample, and is reported in milligrams per liter (mg/L). TDS is generally considered a conservative constituent in surface water environments (although it is not conservative in a groundwater environment). The concentration of chloride is generally proportional to the concentration of TDS, and therefore may be used as an indicator of salinity. Chloride is also considered a conservative constituent in both surface water and groundwater environments. For purposes of this report, salinity will

be discussed primarily in terms of chloride concentrations. Chloride concentration was chosen as the main water quality parameter for this discussion for the following reasons:

- Chloride is a conservative tracer, and its movement within the hydrologic cycle is largely controlled by physical processes (Hem, 1992).
- Measurement of chloride concentration is one of the “simplest and most dependable procedures in water analysis” (Hem, 1992).
- A large amount of historical chloride concentration data is available for a variety of water types.
- Chloride concentration is one of the primary water quality concerns in the LRG.

1.3 Effects of Natural and Anthropogenic Factors on Salinization

Like water quality, salinity is affected by many natural and anthropogenic factors (Figure 1-1). Increases in salinity may occur directly, through the addition of dissolved salts, or indirectly, through the removal of water. Natural sources of dissolved salts are often referred to as "cyclic salts", which include wet or dry atmospheric deposition and the weathering of rocks. Other natural processes that result in the addition of salt include upwelling of deep saline groundwater, geothermal water, or magmatic water. Evaporation and riparian transpiration are naturally occurring processes that result in higher salinity concentrations by removing water; however, these processes do not increase the salt load because the increase in concentration is offset by the decrease in the volume of water, and the load, or total amount of salt, remains the same (Moore and Anderholm, 2002). These processes may be enhanced by anthropogenic activities such as irrigation and reservoir storage. Anthropogenic sources of dissolved salts include a variety of municipal and industrial sources, such as urban runoff, wastewater effluent, septic tank discharge, and fertilizers.

The effects of agriculture on salinization are well understood and well documented (Hem, 1992). These effects are briefly discussed here. When water is used for irrigation purposes, some of that water is lost to evapotranspiration. When water is removed from the system, the

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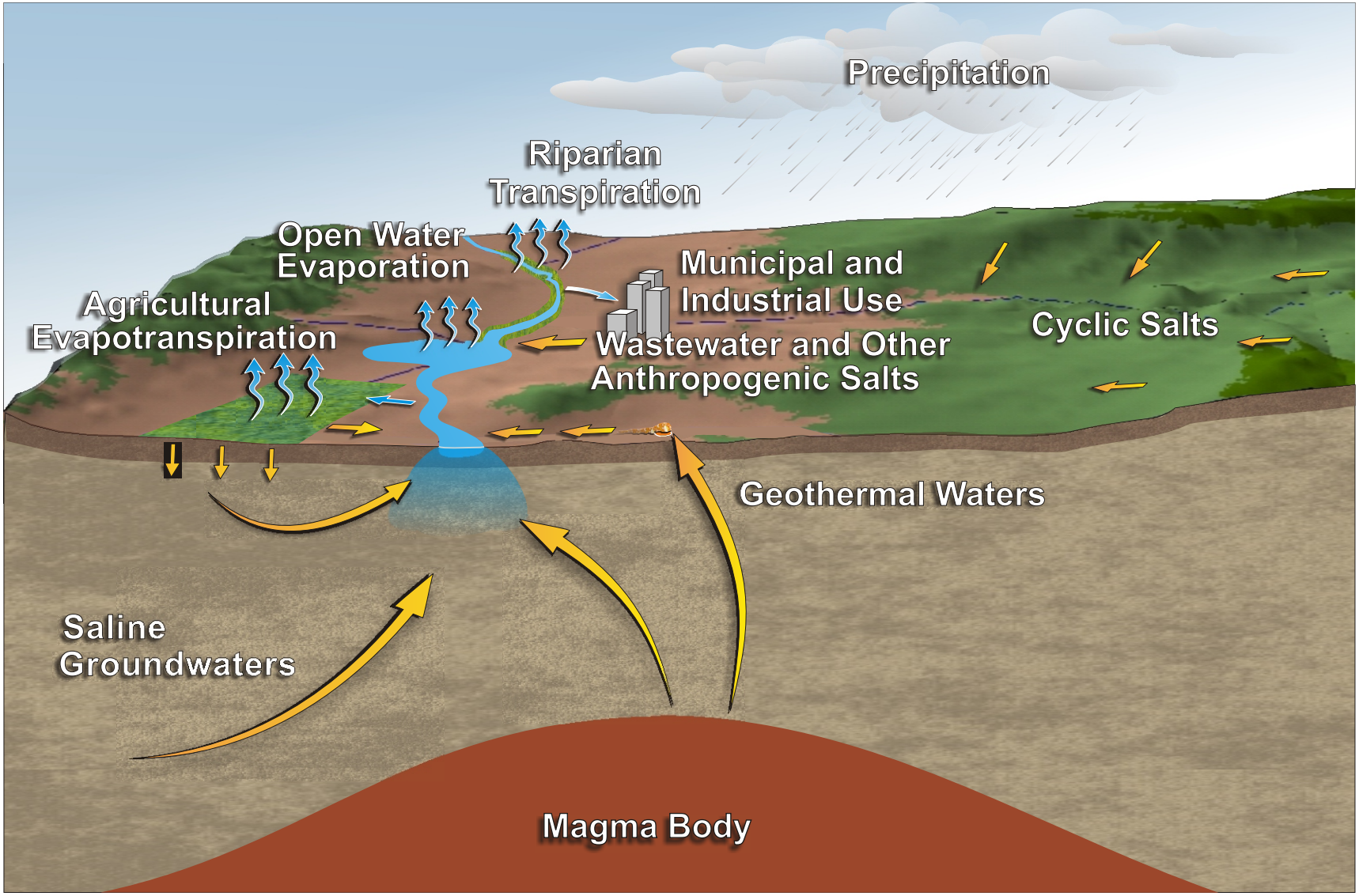

Figure 1-1

LRG SALINITY
Sources of Salinity

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concentration of TDS increases even if no other salts (dissolved solids) are added. In other words, TDS concentrations increase when subjected to increased evapotranspiration that inevitably occurs with irrigation. This does not mean, however, that irrigation or agricultural practices are the only sources of TDS. In fact, salts are not added to the system during evapotranspiration; rather, water is removed from the system during evapotranspiration.

Salts may be introduced to the system when irrigation water is applied to fields. Potential sources include fertilizers and soil amendments that may leach into the water during the irrigation process; however, the quantity of salts added to the system through this process is estimated to be rather small (Hem, 1992). The combination of (1) water removal during evapotranspiration and (2) the leaching of fertilizers and soil amendments results in increased TDS concentrations. However, increases in TDS concentrations that result from agricultural practices are not the sole source, or even a significant source, of salinization in the LRG (Frenzel et al., 1992; Anderholm, 2002; Moore and Anderholm, 2002; Mills, 2003; Phillips et al., 2003; Witcher et al., 2004; Hogan et al., 2007; Moore et al., 2008).

2. Description of Study Area

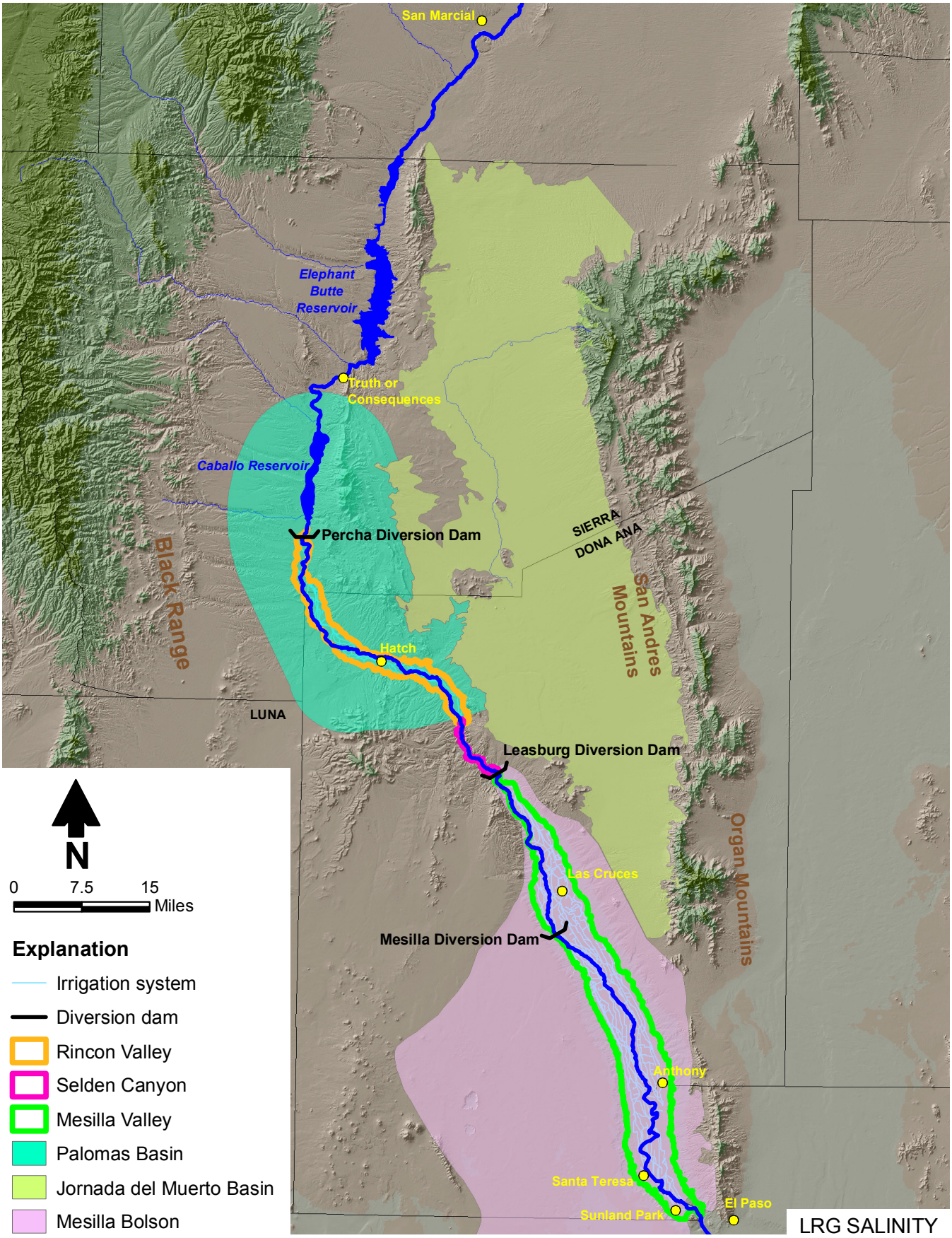
The study area extends from San Marcial above Elephant Butte Dam, New Mexico to the El Paso Narrows, Texas (Figure 2-1). A basic understanding of the study area and the processes at work within the study area are required to provide the necessary background and context with which to understand previous investigations, study design, and interpretations. The purpose of this section is to present a concise description of the study area. See the selected references cited throughout this section for additional details of the various aspects of the study area.

The study area is located within the Basin and Range Physiographic Province. The climate is arid to semiarid, with large fluctuations in daily temperature, low relative humidity, and potential evaporation far exceeding precipitation. Annual precipitation varies from 8 to 10 inches along the inner valley to as much as 16 inches in the highest elevations that border the study area (Ellis et al., 1993). Potential evapotranspiration generally exceeds 75 inches per year (Ellis et al., 1993). Most of the annual precipitation falls in thunderstorms during the monsoon season (July through September). Land use is predominantly agricultural and urban within the inner valley of the LRG (that is, the area within Rincon and Mesilla Valleys) (Figure 2-1). Outside of the inner valley, rangeland is the predominant land use.

2.1 River Administration

Streamflow in the LRG is highly regulated, primarily to meet the irrigation demands of the Rio Grande Project and to meet the international delivery requirements of the 1906 Convention between the United States and Mexico for the Equitable Distribution of the Waters of the Rio Grande. The Rio Grande Project was developed to serve 90,640 acres of farm land in the Elephant Butte Irrigation District (EBID) and 69,010 acres in El Paso County Water Improvement District 1. Not all of this acreage is currently irrigated, and at the present time considerable acreage in Texas has been retired in order to allow the Rio Grande Project to supply surface water for municipal purposes to the City of El Paso.

The U.S. irrigation districts and the U.S. Bureau of Reclamation (USBR) have developed an operating agreement that describes the allocation of water between the two irrigation districts



LRG SALINITY

Lower Rio Grande Study Area

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Figure 2-1

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and Mexico, as well as the day-to-day management of the river. In general, the USBR releases surface water from reservoir storage during the primary irrigation season, from March through October, in response to orders from the irrigation districts and in accordance with annual scheduling agreements with Mexico. During the winter months, and at other times during low-supply years, there are no releases of water from the reservoirs, and the flows of the Rio Grande in the LRG consist mostly of drain flows and wastewater.

2.2 Anthropogenic Structures

A complex system of anthropogenic structures controls streamflow and affects groundwater/surface water interactions throughout the study area. Any discussion of hydrology in the LRG would be incomplete without an understanding of the many anthropogenic structures that affect it.

Streamflow in the LRG is almost entirely regulated by releases from Elephant Butte and Caballo Reservoirs. The reservoirs are operated to meet interstate compact deliveries and international treaty obligations and to support agricultural activities within the Rio Grande Project, including the New Mexico portion of the LRG. Large-scale water diversion and storage in New Mexico began in 1916 with the completion of Elephant Butte Dam, which was part of the Rio Grande Project of the USBR. In 1938, Caballo Dam was completed farther downstream, primarily as a flood control structure and also to allow electricity generation to occur at Elephant Butte Dam in response to electrical demand (i.e., not only when there is agricultural demand for water).

There are three diversion dams in the study area: Percha, Leasburg, and Mesilla Dams (Figure 2-1). These dams control diversions from the Rio Grande for agricultural use. The Percha Diversion Dam was constructed in the late 1910s. It diverts water into the Rincon Valley Main Canal, and is used to irrigate up to 16,000 acres in the Rincon Valley. The Leasburg Diversion Dam was completed in 1908. It diverts water into the Leasburg Canal, and is used to irrigate up to 32,000 acres in the upper Mesilla Valley. The Mesilla Diversion Dam was built from 1914 to 1919. It diverts water into the East and West Side Canals, and is used to irrigate up to 54,000 acres in the lower Mesilla Valley (Mills, 2003). Water from the diversion dams is

delivered to agricultural fields by a system of canals. Water is delivered from the canals to the fields by gravity flow.

Once the Rio Grande Project had established a dependable water supply for irrigation purposes, water levels in the shallow alluvial aquifer began to rise (Conover, 1954). Rising water levels soon resulted in water-logged land that was unsuitable for agriculture. To remedy this situation, a complex network of agricultural drains was installed throughout the Rincon and Mesilla Valleys (Figure 2-1) during the 1930s and 1940s. These drains generally define the water table elevation and intercept (1) shallow alluvial groundwater, (2) any unused irrigation water, and in some cases, (3) wastewater effluent. Water intercepted by the agricultural drains is returned to the main stem of the Rio Grande and is referred to as return flow. During periods of drought, there is increased reliance on groundwater pumping for water supply, which can result in increased drawdown that disconnects the drains from the water table, and significantly reduces return flow to the river.

Wastewater effluent is discharged to the Rio Grande throughout the LRG (Table 2-1) and provides a relatively constant source of streamflow to the Rio Grande. In the LRG, discharge from wastewater treatment plants (WWTPs) is the primary source of wastewater effluent. In addition to the WWTPs, one industrial site (El Paso Electric) discharges wastewater effluent to the river (Table 2-1). Wastewater effluent affects both the quantity and the quality of streamflow in the Rio Grande. There are 11 discharge locations or outfalls permitted by the U.S. Environmental Protection Agency (EPA) within the LRG (Table 2-1) (NMED, 2005); however, only 10 of these outfalls are currently active. Note that the permitted design flow shown in Table 2-1 is the maximum allowable discharge, not necessarily the actual discharge. While not all the facilities discharge directly to the Rio Grande, most wastewater effluent discharged to drains eventually reaches the Rio Grande as return flow. Within the study area, wastewater effluent is not a very large contributor to flow on an annual basis; however, during times of low streamflow, wastewater effluent can be proportionally significant. The relative proportions of wastewater effluent to instream flow are discussed in greater detail in Section 5.

Table 2-1. NPDES Permits on the Lower Rio Grande in New Mexico

Record Number	Facility Name	Permitted Design Flow (mgd)	Receiving Waterbody	First Year Issued
1	City of Truth Or Consequences WWTP	1.06	Rio Grande	1980
2	Village of Salem WWTP	0.2	Rio Grande	2003
3	Village of Hatch WWTP	0.3	Hatch Drain	1980
4	City of Las Cruces WWTP	8.9	Rio Grande	1977
5	South Central Regional WWTP/ Dona Ana County (Vado)	1.05	Rio Grande	2003
6	Anthony Water And Sanitation District WWTP	0.9	East Drain	1987
7	Santa Teresa [a]	0.53	West Drain	1995
8	Gadsden Independent School District	0.09	Rio Grande	1978
9	City of Sunland Park WWTP	1.2	Rio Grande	1985
10	El Paso Electric Company 002	0.52	Montoya Drain	1978
11	El Paso Electric Company 001	0.33	Rio Grande	1978

[a] The Santa Teresa outfall is currently inactive (NMISC, 2005).

NPDES = National Pollution Discharge Elimination System
mgd = Million gallons per day
WWTP = Wastewater treatment plant

2.3 Streamflow

The surface water system of the LRG is comprised of several components, including:

- The Rio Grande
- The irrigation system, which includes canals (or acequias) and agricultural drains
- Tributaries to the Rio Grande, which includes wastewater effluent and ephemeral tributaries

The Rio Grande is the first major component of the surface water system in the LRG. Most of the water in the Rio Grande originates as precipitation in the San Juan or Sangre de Cristo Mountains, in the headwaters of the Rio Grande watershed (Moore and Anderholm, 2002). This water is stored in Elephant Butte and Caballo Reservoirs (Figure 2-1) and is released primarily for irrigation purposes and to meet the U.S.-Mexico treaty and the Interstate Compact delivery requirements. The nature of streamflow in the Rio Grande is such that two distinct periods or "seasons" can be defined:

- The irrigation season, which is characterized by high streamflow
- The winter season, which is characterized by low streamflow

The irrigation season generally coincides with the growing season and lasts from mid-March through mid-October; however, the exact dates may vary. During the irrigation season, discharges greater than 1,000 cubic feet per second (cfs) are released from Caballo Reservoir, and streamflow in the system is relatively high. At this time, irrigation diversions and return flows comprise the majority of the flow in the river (Anderholm, 2002). Because reservoir releases dominate streamflow during the irrigation season, water quality in the river is reflective of the water quality released from Caballo Reservoir. Streamflow is therefore an important control on salinity concentrations.

The winter season generally extends from mid-October through mid-March. During the winter season, little to no water is released from Caballo Dam, although some seepage does occur. Accordingly, any surface flow below Caballo Dam is derived primarily from (1) seepage from

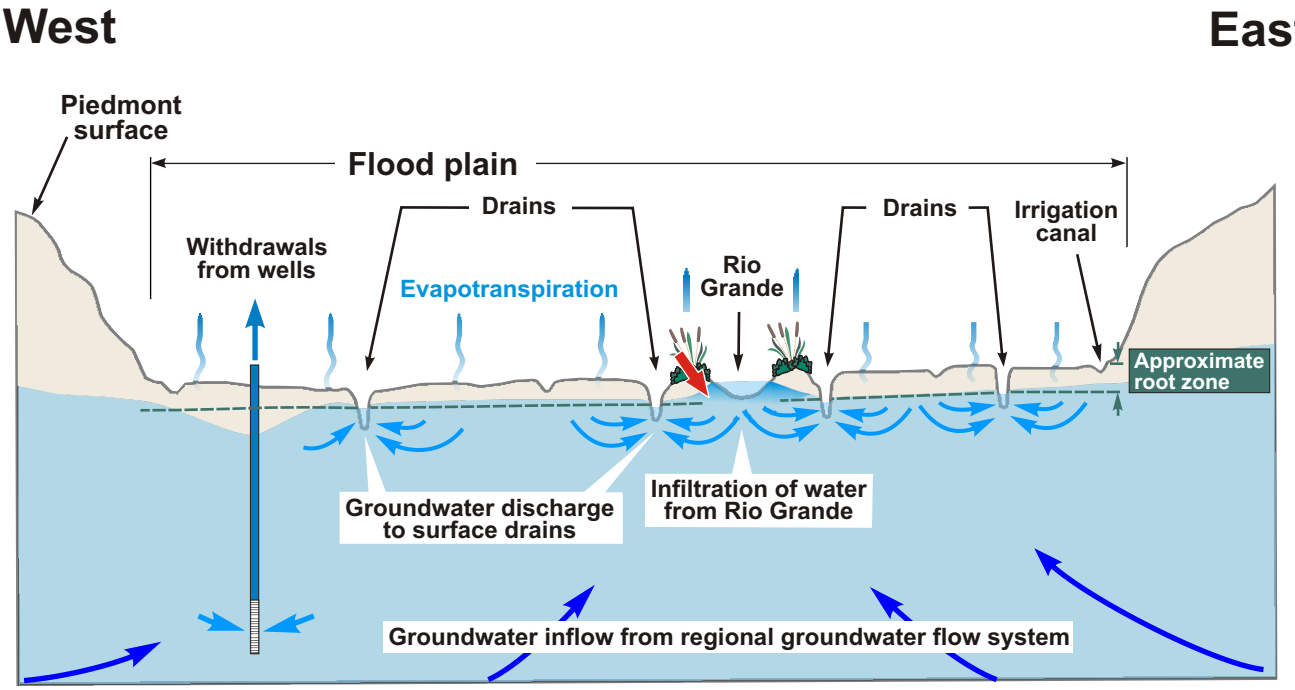
Caballo Reservoir, (2) drainage of the irrigated soils and the attendant return flows to the river from the agricultural drains, and (3) wastewater effluent. During the winter season, streamflow throughout the LRG system is relatively low. Although the majority of irrigation occurs in the spring and summer months, a small amount of irrigation occurs during the winter, especially of orchards and tree farms. Groundwater is the primary source for winter irrigation.

These streamflow patterns are typical of the LRG system and are well documented by previous investigators (e.g., Frenzel et al., 1992; Anderholm, 2002; Moore and Anderholm, 2002; Mills, 2003; Phillips et al., 2003; Witcher et al., 2004).

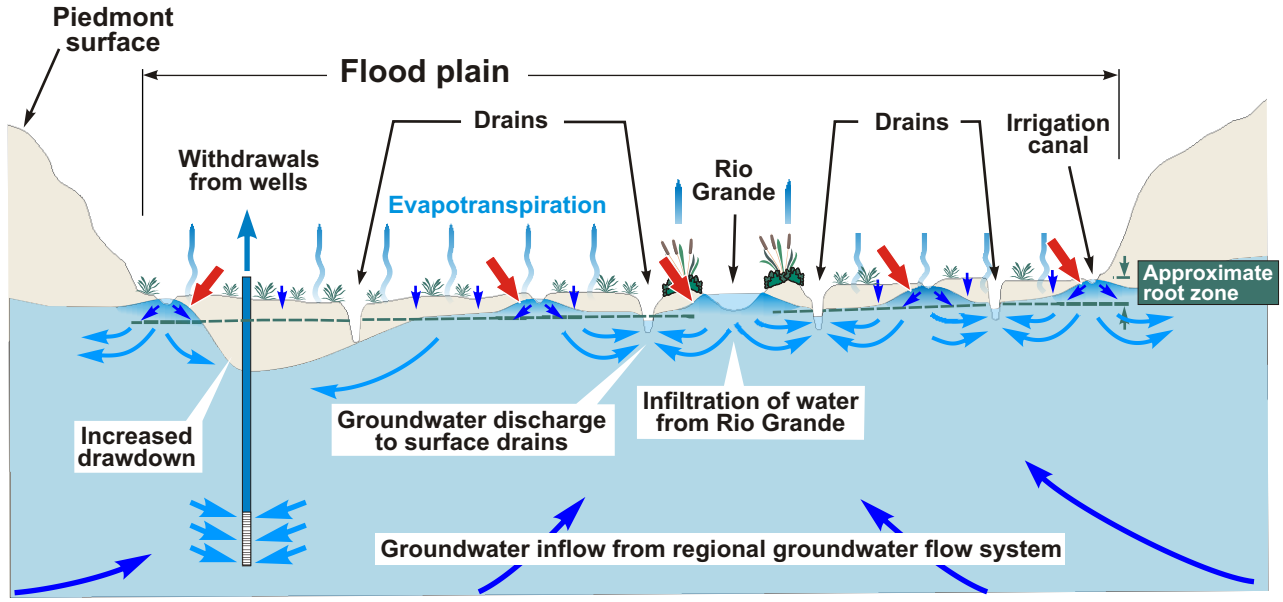
The second major component of the surface water system is the irrigation system. As with streamflow in the Rio Grande, surface water flows in the irrigation system are seasonal. During the irrigation season, water is diverted to agricultural fields via canals. The canals are generally empty (and dry) during the winter season. Flow in the agricultural drains varies from year to year. Flow in the drains is higher during the irrigation season and lower during the winter season (Anderholm, 2002; Frenzel et al., 1992).

Because water levels in the agricultural drains represent the water table, flow in the drains is generally perennial; however, flow in the drains may become intermittent when the water table in the shallow alluvial aquifer falls below the level of the drains (Figure 2-2). Declining groundwater levels result from increased groundwater withdrawals. During periods of drought, groundwater withdrawals increase to supplement surface water supplies. These increased groundwater withdrawals result in lower water table elevations.

There are no perennial tributaries to the Rio Grande within the study area except for the agricultural drains and wastewater effluent; however, even the agricultural drains may become intermittent during periods of drought. Surface water flow from wastewater effluent is relatively constant throughout the year. But due to the seasonal nature of streamflow in the Rio Grande, the relative contribution of wastewater effluent to Rio Grande streamflow varies throughout the year. More specifically, wastewater effluent is only a small portion of total streamflow in the Rio Grande during the irrigation season. During the winter season, when there is little to no water released from Caballo Dam, wastewater effluent is a significant portion of streamflow in the Rio



Winter Season



Irrigation Season

Explanation

Groundwater mounding

Not to scale

Source: Bexfield and Anderholm, 1997

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LRG SALINITY
Generalized Hydrologic Sections Showing Shallow Alluvial Aquifer System

Figure 2-2

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Grande. Several ephemeral tributaries flow primarily in response to late summer and early fall thunderstorms. These ephemeral tributaries can generate large but short-lived flood inflows, which provide only a small proportion of the flows in the Rio Grande.

2.4 Hydrogeologic Setting

The hydrogeologic setting of the LRG is distinguished "by high heat flow, recently active volcanoes, exceptionally deep [alluvial] basins and late Quaternary faulting" (Seager and Morgan, 1979). Regional extension along the Rio Grande Rift began approximately 32 to 27 million years before present and is still active today (Chapin, 1979).

The major components of the study area are the Rincon and Mesilla Valleys (Figure 2-1), which are located in the Palomas and Mesilla Basins, respectively, and include the active channel and floodplain of the modern Rio Grande. Groundwater flow and water quality of the Rincon and Mesilla Valleys are affected by groundwater flow and water quality of the Palomas and Mesilla Basins, and by the basins and stratigraphic units adjacent to the Palomas and Mesilla Basins. The following sections provide a brief discussion of the hydrogeologic setting of each of these major features.

2.4.1 Rincon Valley and Palomas Basin

The Rincon Valley includes the active channel and floodplain of the Rio Grande; the 2-mile-wide valley stretches from Caballo Dam downstream to Selden Canyon (Figure 2-1). Steep bluffs, from 50 to 100 feet high, separate the Rincon Valley from the surrounding uplands of the Palomas Basin (Anderholm, 2002).

The Palomas Basin extends from north of Elephant Butte Reservoir to the Sierra de las Uvas Mountains near the Selden Canyon restriction (Figure 2-1). The Caballo Mountains and Red Hills form the eastern boundary (Mack et al., 2000) and the foothills of the Mimbres Mountains form the western boundary (Wilson et al., 1981). In the Caballo Mountains and Red Hills, approximately 1.5 kilometers (km) of Paleozoic sedimentary rocks, primarily marine limestone and dolostone, overlie Precambrian metamorphic and granitic rocks (Mack et al., 2000). The

Precambrian and Paleozoic units generally have a low permeability, and are therefore considered barriers to groundwater flow (Wilson et al., 1981). The Black Range of the Mimbres Mountains is composed of Tertiary volcanic rocks (Mack et al., 2000). The basin-fill deposits of Palomas Basin are part of the Santa Fe Group, and were derived from the surrounding upland areas. The composition and hydrologic characteristics of the Santa Fe Group are described in more detail in Section 2.5.

2.4.2 Mesilla Valley and Mesilla Basin

The Mesilla Valley includes the active channel and floodplain of the Rio Grande. It is approximately 5 miles wide and extends more than 50 miles from the bedrock constriction at Selden Canyon to the El Paso Narrows, Texas (Frenzel et al., 1992). The Mesilla Valley is as much as 400 feet lower than the surrounding uplands of Mesilla Basin due to the incision of the Rio Grande (Frenzel et al., 1992).

The Mesilla Basin (also known as the Mesilla Bolson) is the southernmost basin of the Rio Grande Rift. Mesilla Basin extends from southern New Mexico to northern Mexico (Figure 2-1). It is bounded on the north by Robledo Mountain and the Doña Ana Mountains, and on the east by Goat Mountain, the Tortugas Mountains, Bishop Cap Mountain, the southern Organ Mountains, and the Franklin Mountains. The basin is bounded on the southeast by Sierra de Cristo Rey and Sierra de Juarez and on the west by the East and West Potrillo Mountains, the Aden Hills, and the Sleeping Lady Hills. There are many exposures of Tertiary and Quaternary igneous rocks in the Mesilla Basin, including intrusives and volcanics in the Robledo, Doña Ana Mountains, and Organ uplifts (Witcher et al., 2004; Wilson et al., 1981). Paleozoic and early Cretaceous marine carbonate and siliciclastic rocks are exposed in the Tortugas, Bishop Cap, Franklin, Juarez, East Potrillo, and Robledo uplifts (Witcher et al., 2004). Gypsite beds are commonly found in the upper Pennsylvanian rocks of the Franklin Mountains and Bishop Cap (Witcher et al., 2004). Cretaceous and early Tertiary sedimentary and intermediate-intrusive rocks are exposed at the southeastern terminus of the basin, near the El Paso Narrows (Witcher et al., 2004). An extensive Quaternary basalt field (more than 300 square miles) is centered around the West Potrillo Mountains, on the West Mesa of Mesilla Basin. Rhyolite was found in

several test holes in that area (Wilson et al., 1981). Like the Palomas Basin, the basin-fill deposits of the Mesilla Basin are of the Santa Fe Group (Section 2.4).

A bedrock high, which is also referred to as a buried horst and the Doña Ana-Tortugas uplift (Witcher et al., 2004), separates the Jornada del Muerto Basin from the Mesilla Basin. This fault-bounded horst is located between Goat Mountain and Tortuga Mountain and is composed of Tertiary volcanic and volcaniclastic rocks (Woodward and Myers, 1997). Previously, this bedrock high was thought to act as a groundwater barrier, preventing flow from the Jornada del Muerto into the Mesilla Basin; however, more recent studies have shown that some flow from the Jornada del Muerto does reach the Mesilla Basin (Frenzel et al., 1992; Witcher et al., 2004).

The Las Cruces East Mesa Geothermal System is associated with the buried horst that separates the Jornada del Muerto from the Mesilla Basin. This geothermal system is located in the Las Cruces area, generally east of and parallel to Interstate 25 (I-25); it extends from U.S. Highway 70, south to Vado and Anthony (Witcher and Cunniff, 2002). The largest area of heat and mass geothermal discharges is centered around Tortugas Mountain (Witcher et al., 2004). Data collected from deep boreholes in the Tortugas Mountain area indicate that the base reservoir temperature of this segment of the geothermal system ranges from 63.4 to 68.0°C and that the chloride concentration ranges from 482 to 578 mg/L (Witcher et al., 2004; Gross, 1988). New Mexico State University (NMSU) uses geothermal wells that are part of this system to provide heat to many of its facilities as part of the NMSU Campus Geothermal Project (Witcher and Cunniff, 2002).

2.4.3 Jornada del Muerto Basin

The Jornada del Muerto Basin lies east of the Mesilla Basin, but is relevant to this study because a small amount of groundwater is known to move from the southern Jornada del Muerto Basin westward into the Mesilla Basin (Frenzel et al., 1992). The Jornada del Muerto Basin is adjacent to the Mesilla Basin and extends north approximately 100 miles. It is separated from the Rio Grande Valley by the Caballo and Doña Ana Mountains (Wilson et al., 1981). The Jornada del Muerto Basin lies east of the Rio Grande and west of the San Andres and Organ Mountains (Figure 2-1). The Organ Mountains are composed of Precambrian and

Tertiary igneous rocks. The San Andres Mountains are composed of Lower Tertiary, Mesozoic, Paleozoic, and Precambrian igneous rocks (Wilson et al., 1981).

2.5 Aquifers in the Study Area

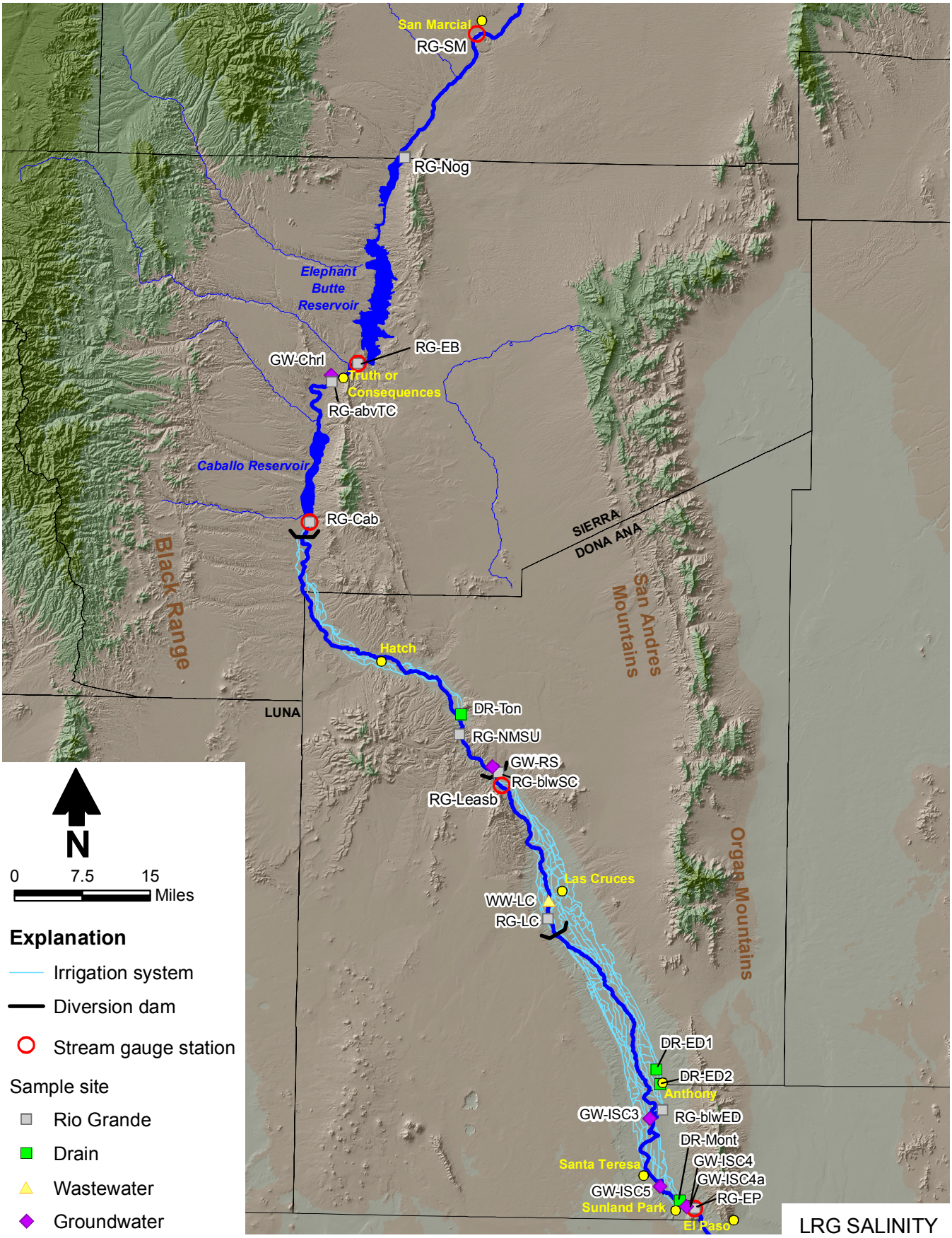
There are four major aquifer systems within the study area:

- Rio Grande floodplain alluvium (shallow alluvial aquifer) of Rincon and Mesilla Valleys
- Basin-fill aquifer (primarily Santa Fe Group) of the Palomas Basin
- Basin-fill aquifer (primarily Santa Fe Group) of the Mesilla Basin
- Basin-fill aquifer (primarily Santa Fe Group) of the Jornada del Muerto Basin

2.5.1 Rio Grande Floodplain Alluvium

The Quaternary-age Rio Grande floodplain alluvium forms the shallow, unconfined, alluvial aquifers of the Rincon and Mesilla Valleys. Thickness of the floodplain alluvium ranges from less than 50 feet to approximately 125 feet, but is generally less than 80 feet (Wilson et al., 1981). A 20- to 40-foot-thick layer of well-rounded siliceous gravel comprises the youngest layer of floodplain alluvium. The upper layer of floodplain alluvium is composed of sand and clay (Wilson et al., 1981). In the Rincon Valley, the shallow alluvial aquifer is the most productive water-bearing unit (King et al., 1971).

During the irrigation season in a year of ample surface water supply, the shallow alluvial aquifers of Rincon and Mesilla Valleys are typically “full”. In other words, the water table is higher (Figure 2-2) and a larger volume of water is stored in the shallow alluvial aquifer during the irrigation season than during the winter season. Water is diverted from the Rio Grande at Percha, Leasburg, and Mesilla Diversion Dams (Figure 2-3) and applied to agricultural fields. Some of this water is lost to the atmosphere through evapotranspiration, some water is “consumed” by crops, and some water infiltrates into the shallow alluvial aquifers. Infiltrating water provides recharge to the shallow alluvial aquifer and results in a rise in the water table. When the water table rises, groundwater flows toward the point of lowest potential (or head), which, in Rincon and Mesilla Valleys, is generally an agricultural drain. Thus, the agricultural



LRG SALINITY

August 2004 and January 2005 Sampling Locations

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Figure 2-3

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drains are a “sink” for groundwater in the shallow alluvial aquifers and define the water table elevation except during drought periods, when groundwater pumping has lowered the water table below the elevation of the drains (Figure 2-2).

During the winter season, the shallow alluvial aquifers of Rincon and Mesilla Valleys are not “full”. In other words, the water table is lower (Figure 2-2) and a lower volume of water is stored in the shallow alluvial aquifer during the winter season (relative to the irrigation season) because there is less recharge from applied irrigation water.

During the irrigation and winter seasons, the shallow alluvial aquifers of Rincon and Mesilla Valleys are generally in a steady state, where inflow to the system equals outflow from the system. However, during the transition between the irrigation and winter seasons, the aquifers are not in steady state. During the transition from the irrigation season to the winter season, water in the shallow alluvial aquifer slowly drains to the Rio Grande, water levels fall, and the volume of water in storage decreases. During the transition from the winter season to the irrigation season, water applied to the fields infiltrates into the shallow alluvial aquifer, water levels rise, and the volume of water in storage increases.

2.5.2 Basin-Fill Aquifers

The basin-fill deposits in the Palomas, Mesilla, and Jornada del Muerto Basins are part of the Quaternary- to Tertiary-age Santa Fe Group, which is primarily composed of basin-fill deposits with some basalt flows (Witcher et al., 2004). The basin-fill deposits, which pre-date the present through-flowing Rio Grande, can be further subdivided into the following broad categories: alluvial fan, clay, or fluvial facies (Wilson et al., 1981).

In the vicinity of the Rincon Valley, the Santa Fe Group unit is fine-grained and greater than 2,000 feet thick (King et al., 1971). The main Santa Fe Group formation in this area is the Rincon Valley Formation, which is composed of red clay of lacustrine origin with some gypsum beds and thin sand layers (Wilson et al., 1981).

In the Mesilla Basin, the thickness of the Santa Fe Group generally ranges from 1,500 to 2,500 feet (460 to 760 meters), but can be as much as 3,000 feet (TWDB and NMWRRI, 1997; Witcher et al., 2004). The Santa Fe Group deposits form the primary water source for the City of Las Cruces.

2.6 Groundwater/Surface Water Interaction

The Rio Grande is hydraulically connected to the shallow alluvial aquifers of Rincon and Mesilla Valleys, which are hydraulically connected to the basin-fill aquifers of Palomas and Mesilla Basins (Figure 2-4). Also, previous studies have confirmed minor groundwater flow from the Jornada del Muerto Basin into the Mesilla Basin (Section 2.4). Knowledge of the interactions between these components of the LRG groundwater/surface water system is essential to a complete understanding of the LRG hydrogeologic system. Bexfield and Anderholm (1997) state:

> An essential concept to a full understanding of ground-water quality in the study area is that the flood plain of the Rio Grande is a major point of discharge for both deeper regional and shallower local flow system through evaporation and transpiration.

This fundamental concept is supported by many previous investigators (Feth, 1964; Mifflin, 1968; Eakin et al., 1976; Wilson et al., 1981; Hibbs et al., 1998). In the floodplain of the Rio Grande, groundwater discharge may occur by discharge directly to the Rio Grande (groundwater inflow to the river), seeps and springs, evapotranspiration, and open-water evaporation. Outside of the Rio Grande floodplain, groundwater discharge may also occur through interbasin flow to adjacent aquifers, from seeps and springs, and through groundwater withdrawals.

Depending on the hydrologic conditions of the Rio Grande and the shallow alluvial aquifer, the river may be classified as a gaining or a losing reach. For a gaining reach, streamflow increases in the downstream direction; increases in streamflow could be due to inflow from an ephemeral stream, wastewater effluent, an agricultural drain, or groundwater seepage directly into the river. For a losing reach, streamflow decreases in the downstream direction; decreases

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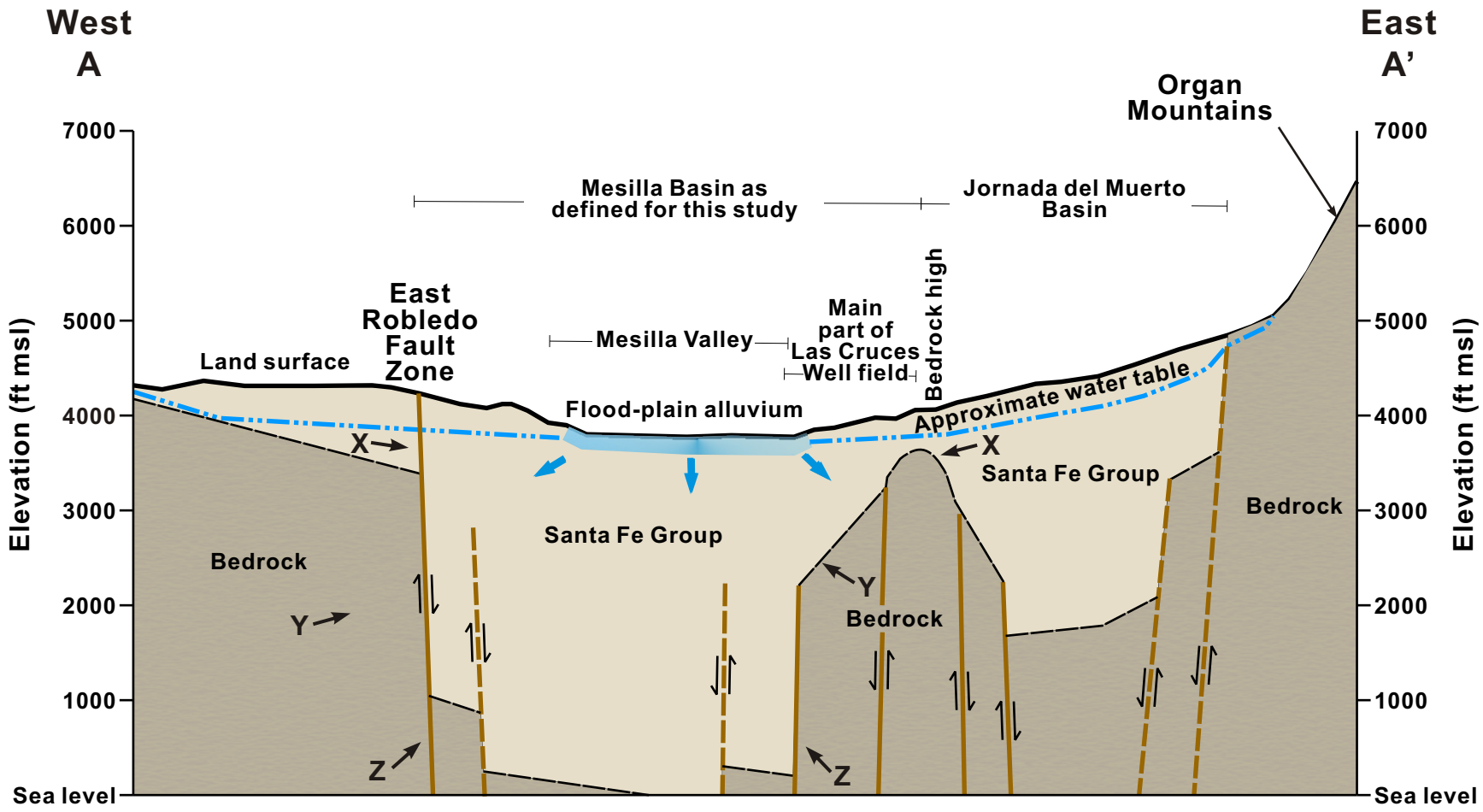

Source: Frenzel et al., 1992

0 — 4 mi

0 — 5 km

Vertical exaggeration x 10

Explanation

Fault (dashed where inferred)
Note: Arrows indicate direction of relative movement

Approximate contact between Santa Fe Group and underlying bedrock

Z — Possible path of underflow into the basin -
X indicates flow in the Santa Fe Group;
Y indicates flow partly through bedrock;
Z indicates very deep flow

LRG SALINITY

Generalized Geohydrologic Section of the Northern Mesilla Basin

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Figure 2-4

in streamflow could be due to direct diversions (for example, at Percha, Leasburg, or Mesilla Diversion Dams), open-water evaporation, riparian transpiration, or groundwater seepage.

The Rio Grande is generally a gaining stream (due to groundwater inflow) throughout the Rincon Valley; however, some parts of this reach may become losing reaches during certain hydrogeologic conditions (Anderholm, 2002; Wilson et al., 1981). Groundwater inflow to the Rio Grande along the 24-mile reach between Caballo Dam and Hatch, New Mexico, has been measured by previous investigators. Anderholm (2002) reported groundwater inflow at a relatively constant rate of 1.5 cfs per mile. This rate was based on streamflow measurements during January 1994, when no water was being released from Caballo Reservoir. Wilson et al. (1981) reported the following rates of groundwater inflow for the same reach: 0.58 cfs per mile in February 1974 and 1.2 cfs per mile in January 1975.

In the southern part of Rincon Valley, between Hatch and the Rincon Drain outfall, the Rio Grande may gain or lose small amounts of streamflow to the shallow alluvial aquifer. Anderholm (2002) reported groundwater inflow at a rate of 0.3 cfs per mile in January 1994. Wilson et al. (1981) reported a slight gain in 1974 and a slight loss in 1975.

In the northern part of the Mesilla Valley, roughly between Selden Canyon and Las Cruces, the Rio Grande is a gaining stream. Based on seepage tests during 1974 and 1975, Wilson et al. (1981) reported slight gains along this reach.

In the southern part of Mesilla Valley, generally between Las Cruces and the El Paso Narrows, the Rio Grande alternates between a gaining and a losing stream. Nickerson (1995) reported two gaining reaches in the southern Mesilla Valley during 1988 and 1992. Wilson et al. (1981) reported losses in streamflow (that is, seepage losses) along this reach during 1974 and 1975. The reported rate of loss varied from 1.98 to 4.8 cfs per mile; the largest seepage rates were measured between Las Cruces and Mesilla Diversion Dam.

In a recent seepage investigation, Nickerson (2005) identified five gaining reaches between Leasburg Dam and El Paso. Measured increases in streamflow were attributed to seepage (as opposed to drain, wastewater inflow, or tributary inflow) at three of those reaches where

streamflow increased by 0.06, 0.47, and 1.5 cfs per mile. Several losing reaches were identified during the same investigation.

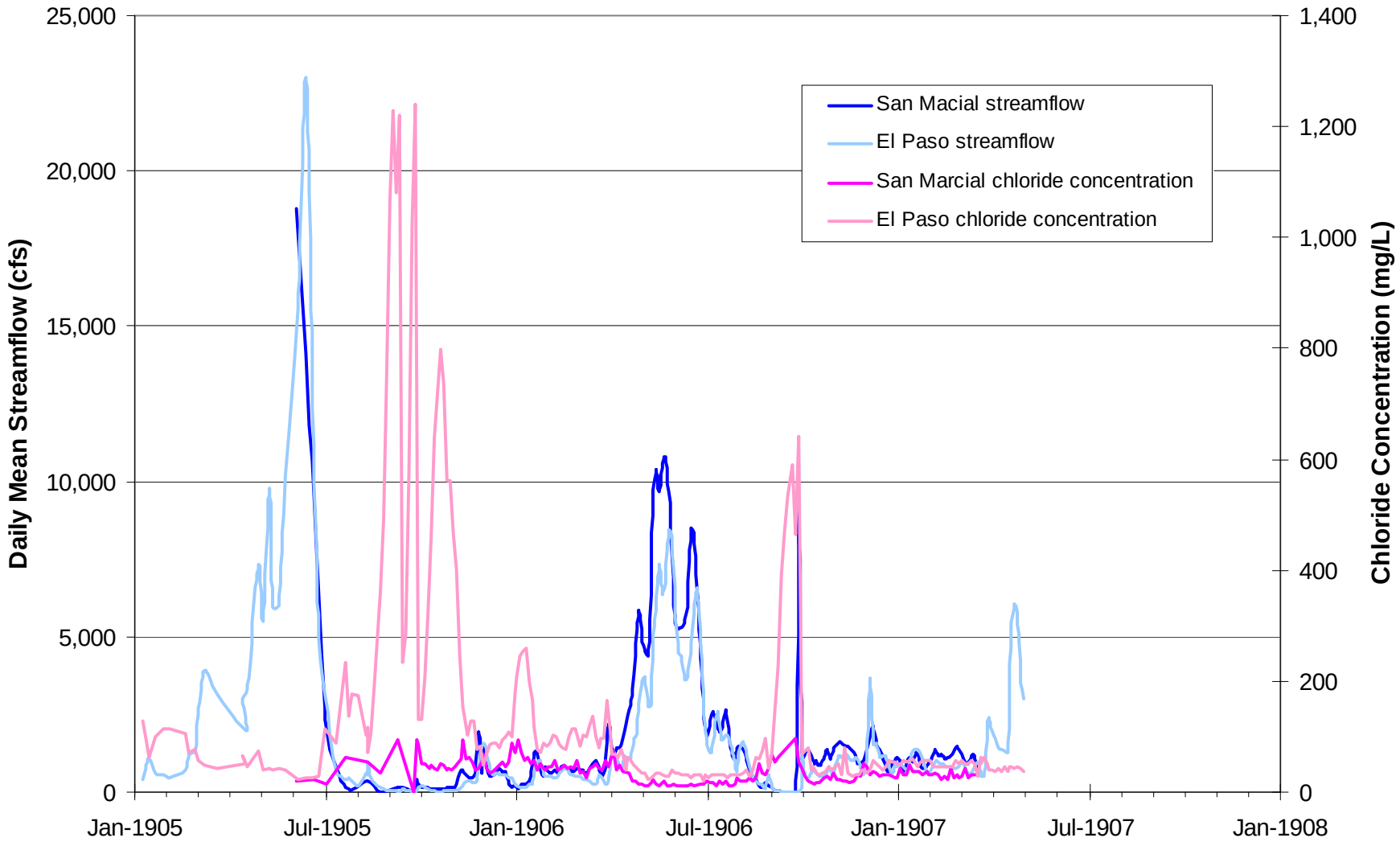
3. Previous Investigations

Water quality in the LRG has been extensively studied. Salinity increases have historically been attributed to various mechanisms, including (1) evaporation and concentration during reservoir storage, irrigation, and subsequent reuse, (2) displacement of shallow saline groundwater during irrigation, (3) wastewater effluent, (4) erosion of natural deposits, and/or (5) inflow of deep saline and geothermal groundwater.

While some previous investigations assume that salinization in the LRG is due to agricultural activities, the bulk of evidence strongly suggests that salinization in the LRG is due to upwelling of geothermal waters and "vertical leakage from deep-seated regional groundwater flow systems" (Witcher et al., 2004; Moore and Anderholm, 2002; Anderholm, 2002; Mills, 2003; Phillips et al., 2003; Frenzel et al., 1992; Hogan et al., 2007; Moore et al., 2008). An exhaustive review of previous investigations is beyond the scope of this report. Excellent discussions of previous investigations are available in Mills (2003) and Boyle Parsons (2000).

Most previous investigations focused on increases in salinity, as indicated by increases in chloride or TDS concentrations of surface water in the Rio Grande and agricultural drains, and/or the salt balance of the system. Many of these studies focused solely on surface water quality in the LRG hydrogeologic system and neglected to consider other, perhaps less obvious, factors that affect water quality in the LRG hydrogeologic system. As discussed in Section 2, water quality of the Rincon and Mesilla Valleys is affected by groundwater flow and water quality of the Palomas and Mesilla Basins, and by the basins and stratigraphic units adjacent to the Palomas and Mesilla Basins. In other words, all components of the LRG hydrogeologic system must be considered "to fully appreciate the saline sources and relative strength of salinity additions" (Witcher et al., 2004).

One method of evaluating the effects of natural sources on salinization in the LRG is to compare historical data with recent data. By comparing data collected prior to widespread agricultural use or the presence of WWTPs with recent data, the effects of "non-agricultural" or natural sources can be evaluated. The earliest available data for the LRG (Figure 3-1) were published by Stabler (1911) for the period January 1905 through May 1907. Data were collected at Rio



Source: Stabler, 1911

LRG SALINITY

Streamflow and Chloride Concentration 1905 to 1907

Figure 3-1

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Grande at San Marcial and at Rio Grande at El Paso (Figure 2-1) prior to the construction of Elephant Butte Reservoir, Caballo Reservoir, and the network of agricultural drains in the LRG. The seasonal nature of streamflow in the Rio Grande and the inverse relationship between chloride and streamflow are apparent in these data (Figure 3-1). Mills (2003) used these data to calculate monthly mean chloride loads to be 110,000 kilograms per day (kg/d) at San Marcial and 145,000 kg/d at El Paso. Therefore, salinization in the LRG occurred before the reservoirs, agricultural drains, or wastewater discharge were present, and are therefore likely attributable primarily to natural salinity sources discharging to the Rio Grande.

More recently, comprehensive water quality investigations have been applied to the study of hydrogeologic systems in the LRG. These investigations tend to consider the complete hydrogeologic system (as opposed to only a portion of that system, such as the Rio Grande floodplain), and many employ geochemical methods to identify the various sources of water for a particular hydrogeologic system. Most of these studies, described below, have found that salinization in the LRG is primarily caused by natural sources, including deep saline and geothermal groundwater.

Frenzel et al. (1992) identified several natural sources of salinity in the LRG, including groundwater upwelling along fault lines in the vicinity of East Potrillo Mountain and inflow of geothermal water along the entire eastern side of Mesilla Basin. By evaluating mixing ratios of various elements, Frenzel et al. (1992) determined that there are at least two distinct geothermal sources (or end members), each with a unique chemical composition.

Moore and Anderholm (2002) evaluated variations in streamflow, TDS concentrations, and TDS loads to gain understanding about the quality of unmeasured inflows along the Rio Grande Basin upstream from El Paso, Texas. They concluded that agricultural processes and wastewater effluent may contribute to increases in TDS concentrations in the LRG, but that regional groundwater discharge is responsible for salinization, as indicated by increases in TDS loads.

Mills (2003) and Phillips et al. (2003) used environmental tracers to identify various sources of salinity in the Rio Grande Basin upstream from Fort Quitman, Texas; they also evaluated mass

balance models to further investigate the processes of salt input to the Rio Grande. They concluded that "a significant percentage of Rio Grande salinization is due to inflow of deep sedimentary brines" (Mills, 2003) and that salt input from deep sedimentary brines is structurally controlled, occurring at the distal end of sedimentary basins.

Witcher et al. (2004) published the most recent study, which was a geologic and geochemical investigation of groundwater and a review of temporal changes in surface water loads from San Marcial, New Mexico to Fort Quitman, Texas. Witcher et al. (2004) evaluated isotopic signatures and major ion compositions, with special attention to the "fingerprinting processes, mixing, and flow paths". They conclude that salinization in the LRG is controlled by "structurally forced upwelling of brackish and saline water from deep hydrostratigraphic units and by upflow of geothermal water from shallow bedrock structures and bedrock boundaries" (Witcher et al., 2004; Hogan et al., 2007).

4. Evaluation of Historical Data

A major goal of this study was to compile and evaluate existing streamflow and water quality data. In order to develop a working database for analysis of LRG surface water quality, it was necessary to prioritize data sources, sampling locations as identified by site identification (ID), and water quality parameter codes. This prioritization allowed efforts to be focused on evaluating the most relevant data by:

- Eliminating data that overlap or are reported multiple times
- Acknowledging uncertainties inherent in comparing data with similar but not identical source codes, site IDs, and/or parameter codes

The ISC compiled the database from numerous sources, including the U.S. Geological Survey (USGS), U.S. EPA STORET, reports from Boyle Parsons (2000) for the Texas-New Mexico Water Commission, and a thesis by Williams (2001).

Discussions between the ISC and DBS&A focused on six key water quality parameters at nine surface water locations (Appendix A). DBS&A made several recommendations regarding data prioritization; conclusions and recommendations are provided in Appendix A. For analysis of historical data, streamflow, chloride concentration, and TDS concentration data were retrieved from the ISC Access database according to the priorities outlined in the prioritization report (DBS&A, 2004) (Appendix A).

This section examines historical streamflow and chloride concentration data at the following streamflow gaging stations: Rio Grande at San Marcial (RG-SM), Rio Grande below Elephant Butte Dam (RG-EB), Rio Grande below Caballo Dam (RG-Cab), Rio Grande below Leasburg Dam (RG-Leasb), and Rio Grande at El Paso (RG-EP) (Figure 2-3). Streamflow at Rio Grande at San Marcial is divided into two channels: the Low Flow Conveyance Channel and the Rio Grande Floodway. Streamflow measurements are made at each channel and, for the purposes of this discussion, are summed to represent total flow past San Marcial. These five stations were selected because of the large amount of historical data available at each station. In some cases, sampling locations were co-located with streamflow gaging stations; however, this was

not always the case. Streamflow gaging stations, corresponding site IDs, and station locations are shown in Table 4-1.

In some cases, the sample location and gage location are slightly different. It is important to keep the gage location in mind when interpreting streamflow data, particularly in areas of the LRG where water is moving downstream not only in the main stem of the Rio Grande but also in drains and canals (e.g., Moore et al., 2008).

One example of different sample and gage locations is RG-blwSC; while this sampling location is just upstream from the Leasburg Diversion Dam, the EBID-operated streamflow gage (RG-Leasb) is located downstream from the dam. Streamflow at the RG-blwSC sample location may be calculated by adding streamflow measured at RG-Leasb to streamflow diverted for irrigation purposes (i.e., first check on Leasburg Main Canal plus Arguelles Lateral).

As discussed in Section 1.2, chloride concentration was chosen as the main water quality parameter for this discussion. Historical TDS concentrations, though not discussed in this report, also provide useful information regarding the water quality of the LRG. TDS concentrations generally mimic chloride concentrations. Figures showing TDS concentrations and loads are provided in Appendix B.

4.1 Methods of Analysis

Many of the historical data discussed in this report are presented in the form of box plots (or box and whisker diagrams). Box plots visually summarize important information about the distribution of a dataset (Helsel and Hirsch, 1992). The median, or the center of the data, is represented by the horizontal line within the box. The lower and upper edges of the box represent the first and third quartiles, respectively (or the 25th and 75th percentiles); the box portion therefore represents the interquartile range, or middle 50 percent of the data. The skewness of the dataset is represented by the relative size of the box halves. The lines (or whiskers) extend outward to represent the lowest and highest values of the dataset, excluding outliers. Outliers are defined as values that are more than 1.5 times the interquartile range outside the quartile.

Table 4-1. Streamflow Gaging Station Locations

Location Description	Site ID	Corresponding Sampling Location ID
Rio Grande Floodway at San Marcial plus Rio Grande Conveyance Channel at San Marcial [a]	RG-SM	NA
Rio Grande below Elephant Butte Dam	RG-EB	RG-EB
Rio Grande below Caballo Dam	RG-Cab	RG-Cab
Rio Grande below Selden Canyon (just below Leasburg Diversion Dam)	RG-Leasb	RG-blwSC
Rio Grande at El Paso (at Corchesne Bridge)	RG-EP	RG-EP

[a] For discussion purposes, streamflow at RG-SM has been combined with Low Flow Conveyance Channel flow to represent total streamflow at San Marcial, New Mexico.

NA = Not applicable

Annual loads were calculated for four stations in the LRG, including RG-EB, RG-Cab, RG-Leasb, and RG-EP (Table 4-1). Annual loads were calculated as the sum of monthly loads, which were calculated as the product of mean monthly chloride (or TDS) concentration and mean monthly streamflow. Mean monthly chloride and TDS concentrations used to calculate loads were measured in composite samples collected between 1929 and 1963. Samples were collected on a daily basis, and the monthly composite samples were analyzed for chloride and TDS. Mean monthly streamflow was determined from daily mean streamflow data.

Chloride and TDS loads were only calculated for the period 1929 to 1963 due to data availability. After 1963, monthly composite samples were no longer collected in the LRG; the available data are not sufficient to calculate average monthly concentrations.

4.2 Streamflow

Streamflow in the LRG is highly regulated, primarily to meet the irrigation demands of the Rio Grande Project and to meet the international delivery requirements (Section 2.1). Daily mean streamflow data for two years (1942 and 1980) are presented to provide insight into streamflow variations of the LRG within a given year (Figures 4-1 and 4-2). These two years represent extreme high-flow conditions and a typical full-release year, respectively. Annual mean streamflow data for the available period of record were also examined (Figure 4-3).

Streamflow is highly variable at the upstream end of the study area, where daily mean streamflow at Rio Grande at San Marcial (RG-SM) can vary within a given year from less than 10 cfs to over 17,000 cfs (Figure 4-1). Prior to the completion of Cochiti Reservoir in 1975, streamflow on the Rio Grande above Elephant Butte Reservoir was almost entirely unregulated. Although some small reservoirs were in operation in the headwaters of the Rio Grande Basin, streamflow was unregulated throughout most of the basin. Streamflow generally peaked in late spring or early summer due to snowmelt runoff from the mountainous headwaters of the Rio Grande. Streamflow was lowest during the late fall and winter months (October through February), when baseflow was the dominant surface water supply.

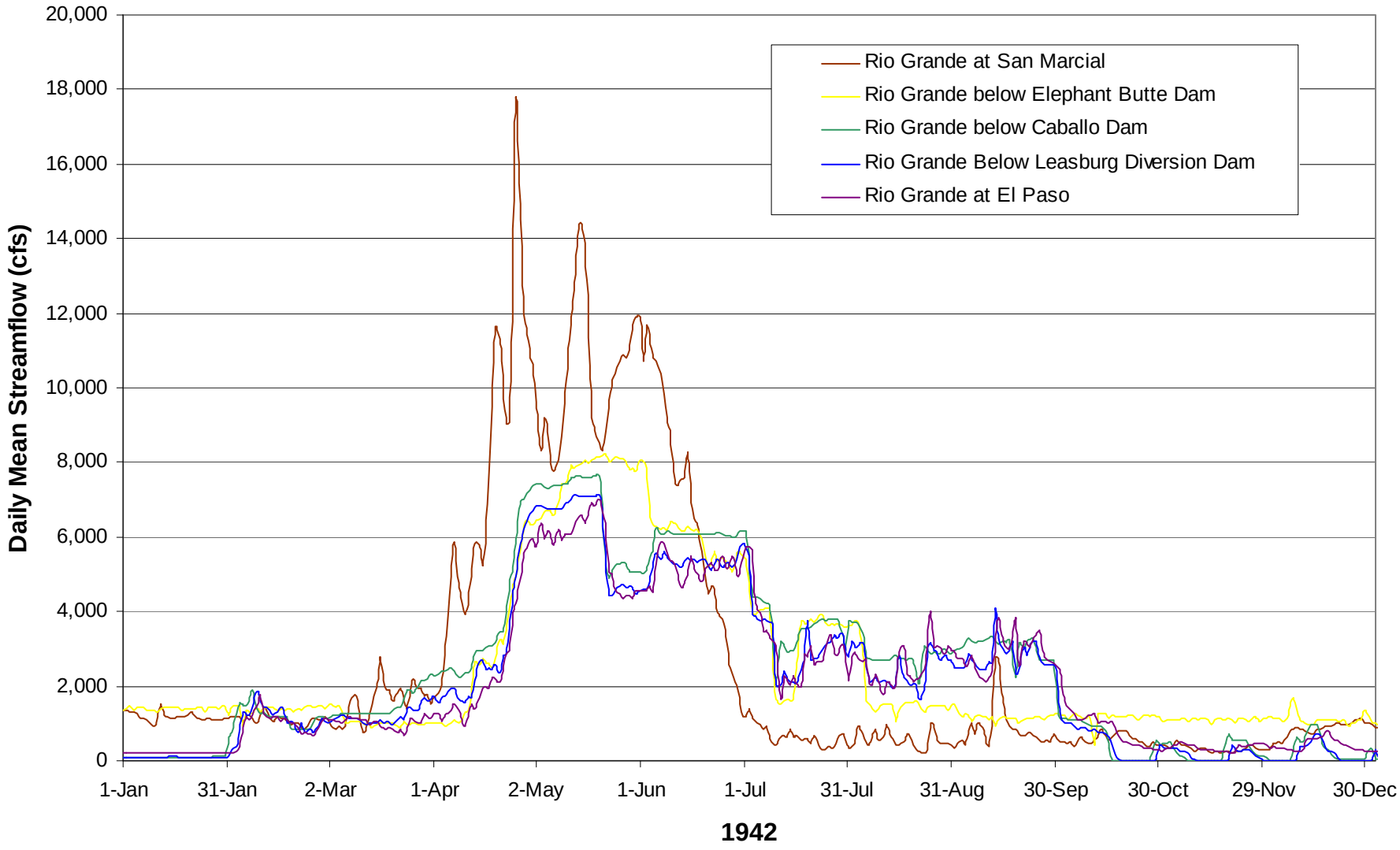

Figure 4-1

LRG SALINITY

Historical Streamflow, 1942

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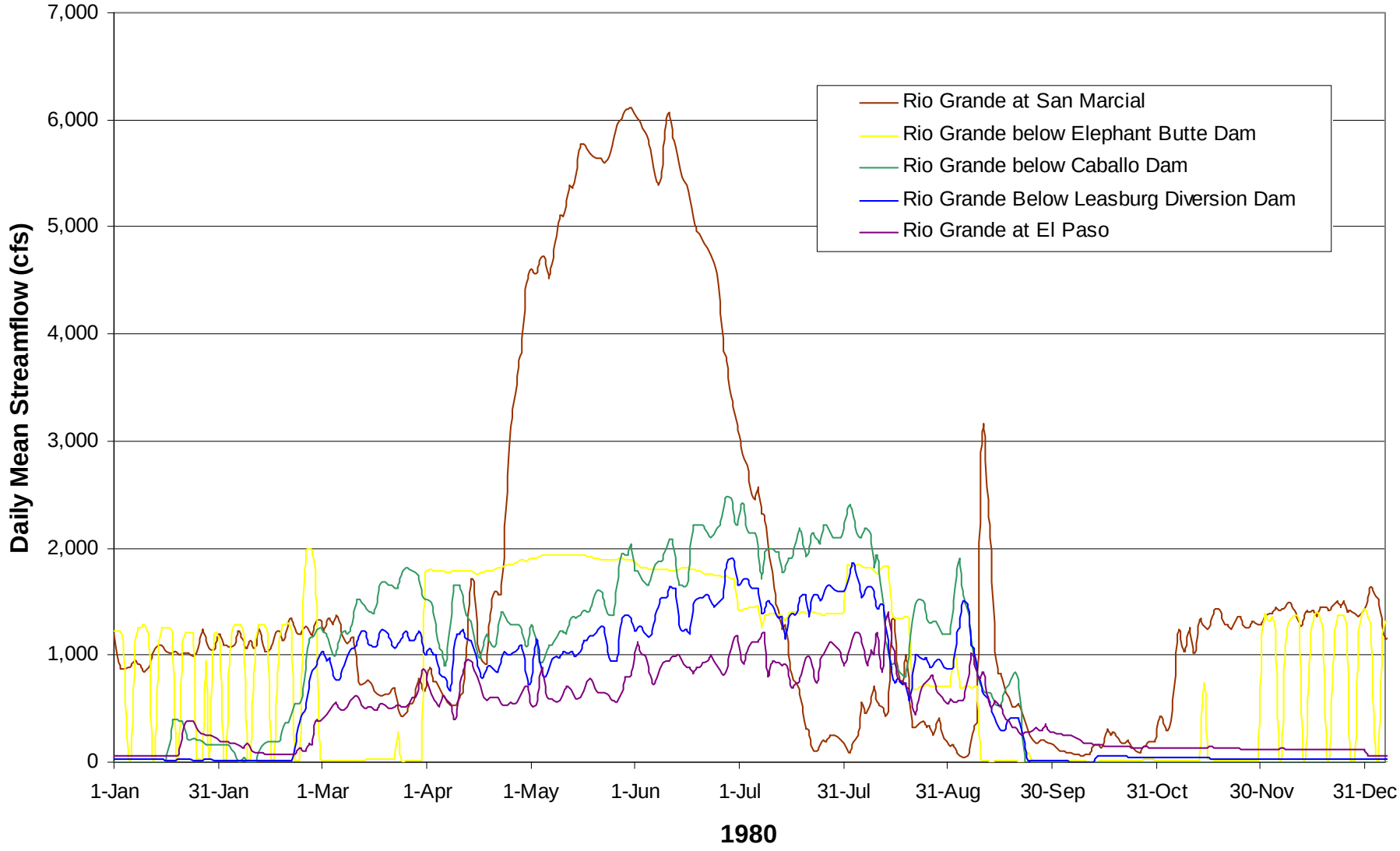

Figure 4-2

LRG SALINITY

Historical Streamflow, 1980

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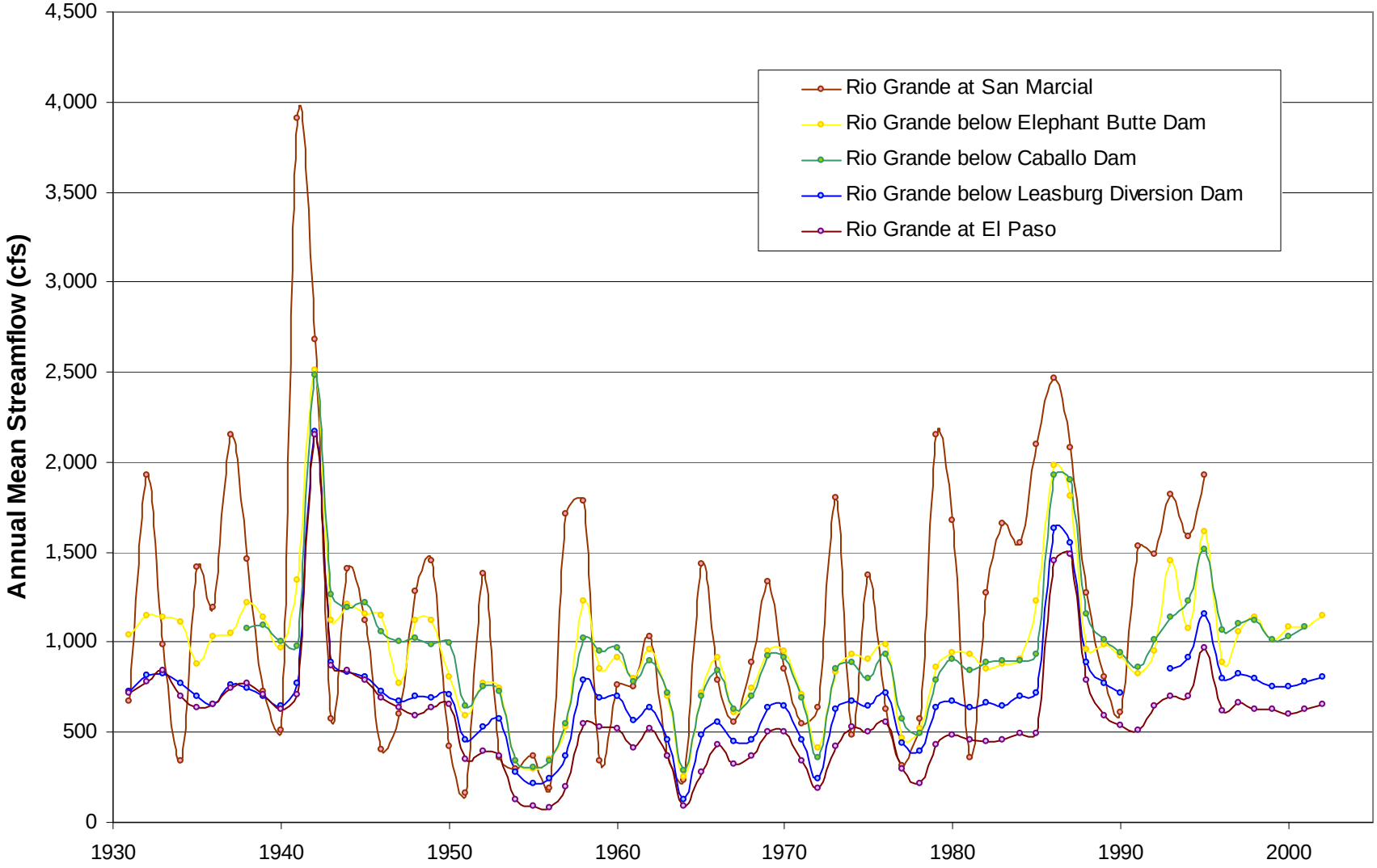

Figure 4-3

LRG SALINITY

Annual Mean Streamflow

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Another factor contributing to the large variability in streamflow at RG-SM (Figures 4-1 and 4-2) is inflow from ephemeral tributaries. The Rio Puerco and Rio Salado, two of the largest ephemeral streams in the Rio Grande Basin, enter the Rio Grande just upstream from RG-SM. During the late summer/early fall rainy season, these ephemeral streams can contribute large amounts water in relatively short amounts of time (i.e., hours to days).

Streamflow below Elephant Butte Reservoir is entirely regulated by releases from Elephant Butte Dam. Water is released from Elephant Butte Dam throughout the year for power generation and during the growing season for irrigation needs in New Mexico, Texas, and Mexico (Figures 4-1 and 4-2).

Streamflow below Caballo Reservoir is almost entirely regulated by releases from Caballo Dam. Water is released from Caballo Dam primarily to supply surface water for irrigation in the Rio Grande Project and to meet international delivery requirements prescribed by the 1906 Convention between the United States and Mexico for the Equitable Distribution of the Waters of the Rio Grande. Historically, the irrigation season begins when water is released from Caballo Dam (Figures 4-1 and 4-2) and typically extends from March through October; however, the actual period of release is affected by the available supply (i.e., in drought years with less than a full irrigation supply, the period of release is shortened and can also be subdivided into separate “block” releases). During the irrigation season, streamflow generally decreases in the downstream direction between RG-Cab and RG-EP (Figures 4-1 and 4-2) because outflows (irrigation diversions, evapotranspiration by riparian vegetation, evaporation from open-water surfaces, and losses to the groundwater system) are greater than inflows (tributary inflow, return flows from agricultural areas, inflow from the groundwater system, and wastewater effluent).

Historically, the non-irrigation (or winter) season extends from October through February; during this period, there are generally no releases from Caballo Reservoir (Figures 4-1 and 4-2). The Rio Grande below Caballo Reservoir is essentially shut off or disconnected from any upstream surface water supply during the winter months. Consequently, streamflow during this season in the Rio Grande below Caballo Reservoir is derived from groundwater inflow (including seepage from Caballo Reservoir and return flows from agricultural areas), wastewater effluent, or tributary inflow from ephemeral streams. During the winter months, streamflow generally

increases in the downstream direction between RG-Cab and RG-EP because inflows are greater than outflows.

Annual mean streamflow in the LRG can vary substantially from year to year (Figure 4-3). As with daily mean streamflow, the largest variations in annual mean streamflow are at the upstream end of the study area (RG-SM). Annual mean streamflow at RG-SM varies from almost 0 cfs to close to 4,000 cfs (Figure 4-3). Annual mean streamflow generally decreases in the downstream direction (Figure 4-3) because outflows are greater than inflows.

4.3 Chloride Concentrations

Chloride concentrations vary seasonally at a given location due to a variety of factors, including variations in the magnitude and sources of streamflow. In the LRG, streamflow is inversely related to chloride concentration (Moore and Anderholm, 2002); that is, chloride concentrations are high when streamflow is low, and chloride concentrations are low when streamflow is high. During the winter months (November through February), water is not usually released from Caballo Reservoir, and water in the Rio Grande is composed almost entirely of groundwater inflow, return flows from agricultural drains, and wastewater effluent. During the irrigation season (March through October), chloride concentrations are diluted by streamflow released from Caballo Reservoir. Most streamflow released from Caballo Reservoir is derived from snowmelt runoff, which originates in the headwaters of the Rio Grande watershed (Moore and Anderholm, 2002). Because snowmelt has a low chloride concentration (and generally low TDS concentration) relative to other sources (groundwater, geothermal water, return flows, or wastewater effluent), releases from Caballo Reservoir result in lower chloride concentrations.

At RG-Cab, RG-Leasb, and RG-EP, median chloride concentrations are larger and exhibit greater variation (that is, larger interquartile range) during the winter season, when no water is being released from Caballo Reservoir (Figure 4-4). During the irrigation season, groundwater inflow, return flows, and wastewater effluent are diluted by irrigation releases from Caballo Reservoir. High streamflow during the irrigation season results in lower median chloride concentrations and less variation (smaller interquartile range) in chloride concentration at RG-Cab, RG-Leasb, and RG-EP (Figure 4-4).

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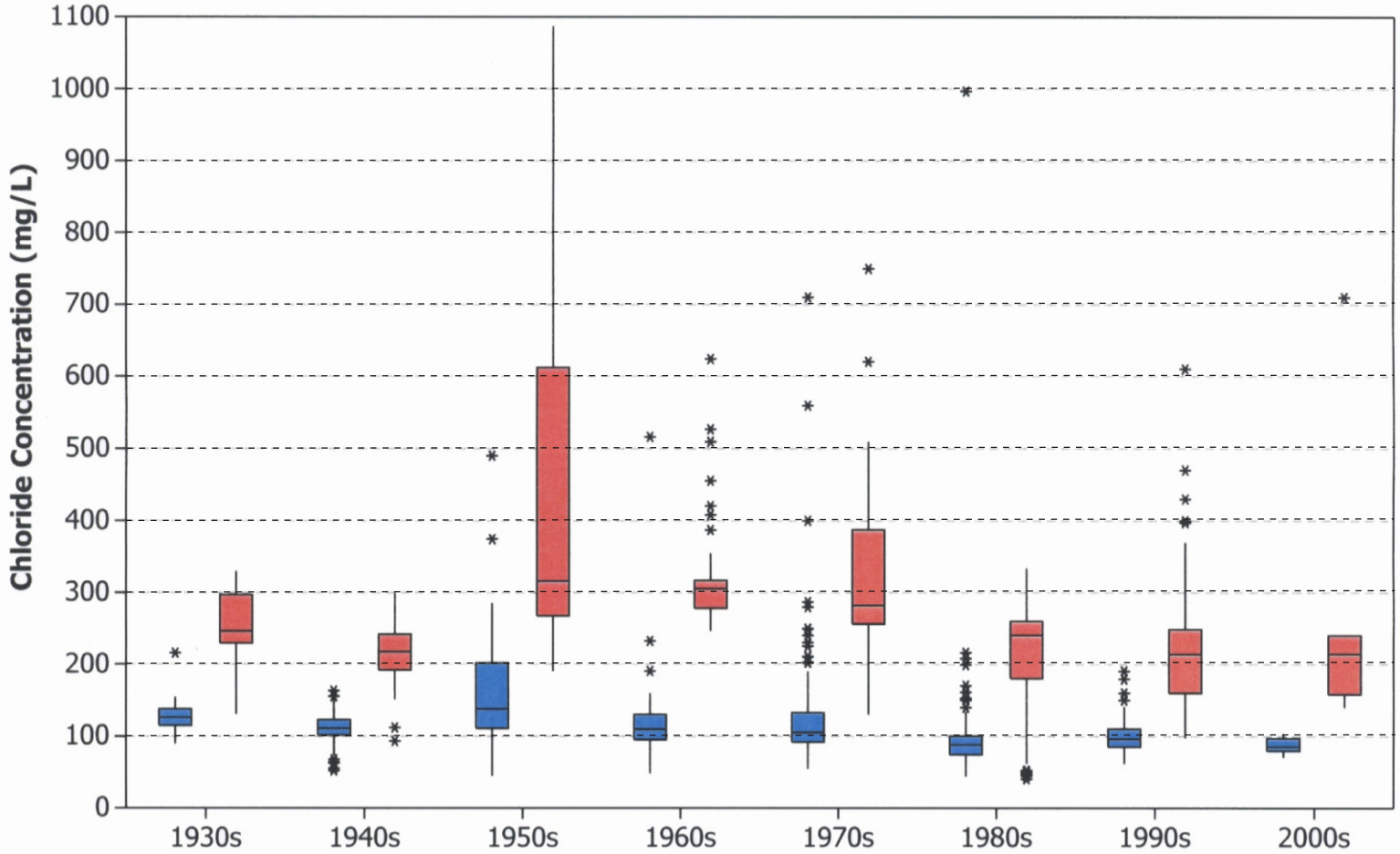

Explanation

Irrigation season (Mar-Sep)

Winter season (Oct-Feb)

LRG SALINITY

Seasonal Chloride Concentrations by Decade at Rio Grande at El Paso

Figure 4-8

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At RG-EB, the median chloride concentrations are similar for the irrigation and winter seasons (Figure 4-4). The lack of seasonal variation at this site can be attributed to reservoir effects, which tend to damp out seasonal variations in streamflow and chloride concentration.

Chloride concentrations vary spatially throughout the LRG. Median chloride concentrations increase in the downstream direction during both irrigation and winter seasons (Figure 4-4). Previous investigators have attributed this downstream salinization to various factors, including inflow from saline groundwater (e.g., sedimentary brine), inflow from wastewater effluent, return flows from agricultural drains, and evapotranspiration (e.g., Wilcox, 1957; Hendrickx, 1998; Moore and Anderholm, 2002; Mills, 2003). The various sources of salinization are discussed in more detail in Sections 6 and 7.

Regardless of the season, chloride concentrations in the main stem of the Rio Grande generally increase in the downstream direction (Figures 4-5 and 4-6). However, the largest increases in chloride concentration occur during the winter season, when no water is being released from Caballo Reservoir (Figure 4-6).

Chloride concentration at RG-EP has generally decreased with time (Figures 4-7 and 4-8), as indicated by lower median chloride concentrations in the 1980s, 1990s, and 2000s. The largest median chloride concentration (232 mg/L) occurred in the 1950s, during which time the entire Rio Grande Basin experienced an extended period of below-normal precipitation.

4.4 Chloride Mass Balance Assessment Using Historical Data

Chloride loads were calculated using historical chloride data in order to perform a simple mass balance assessment. A constituent load is defined as the mass of that particular constituent transported past a given point in a given period of time (i.e., a mass flux). Loads are calculated as the product of concentration and discharge; in this report, loads are reported in kilograms per year (kg/yr).

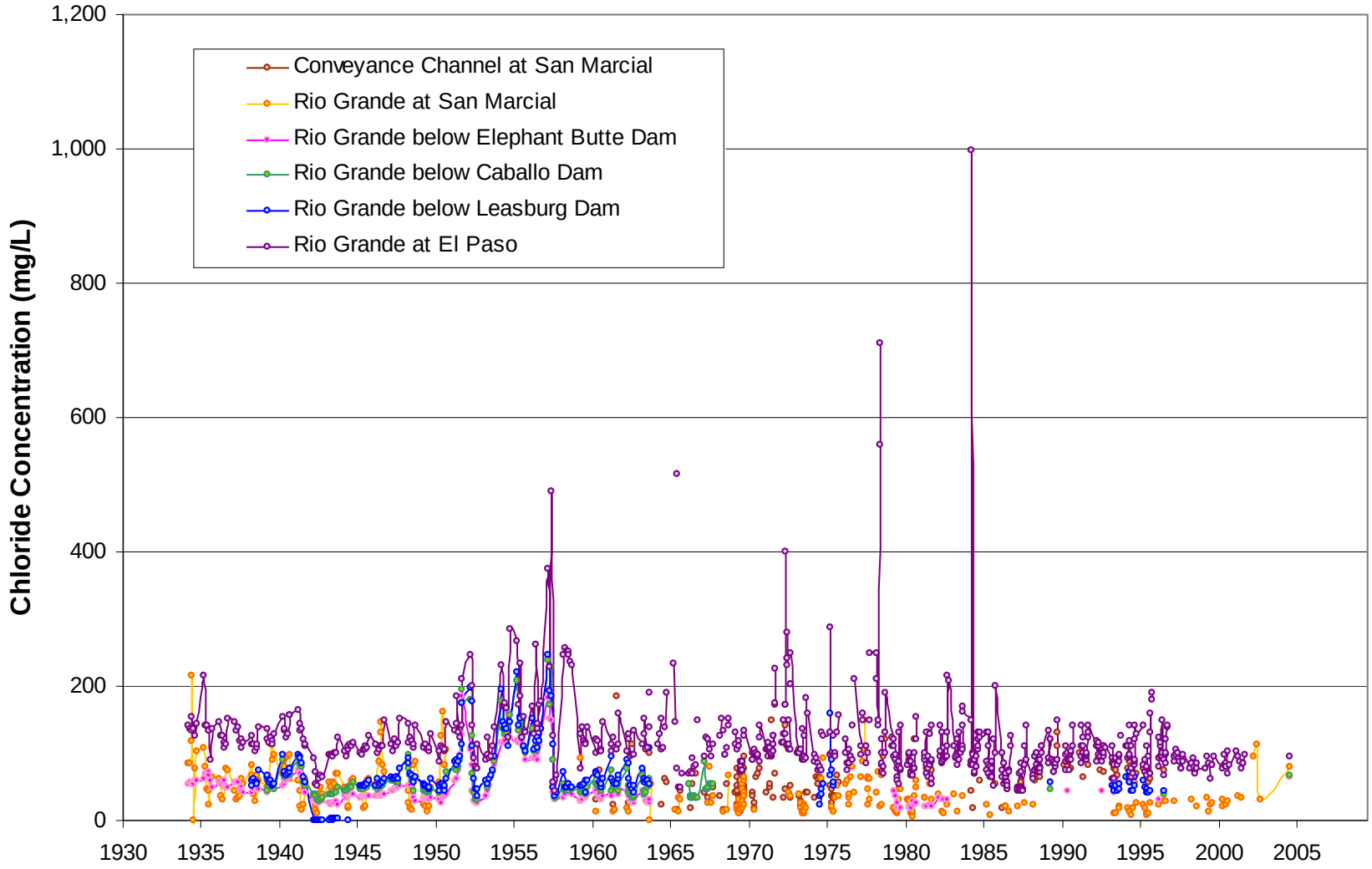

Figure 4-5

LRG SALINITY

Chloride Concentration vs. Time
Irrigation Season (March through October)

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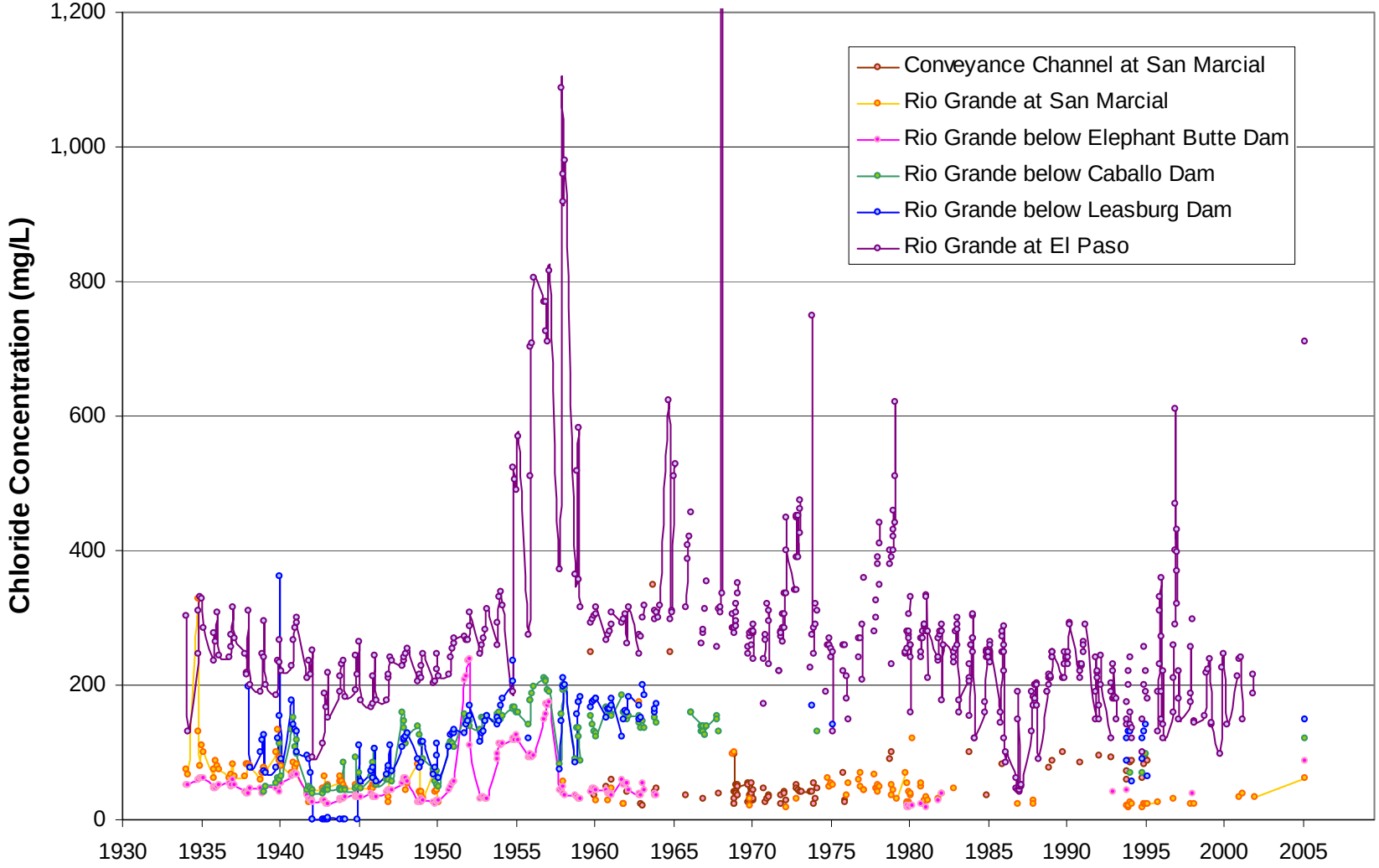

Figure 4-6

LRG SALINITY

Chloride Concentration vs. Time
Winter Season (November through February)

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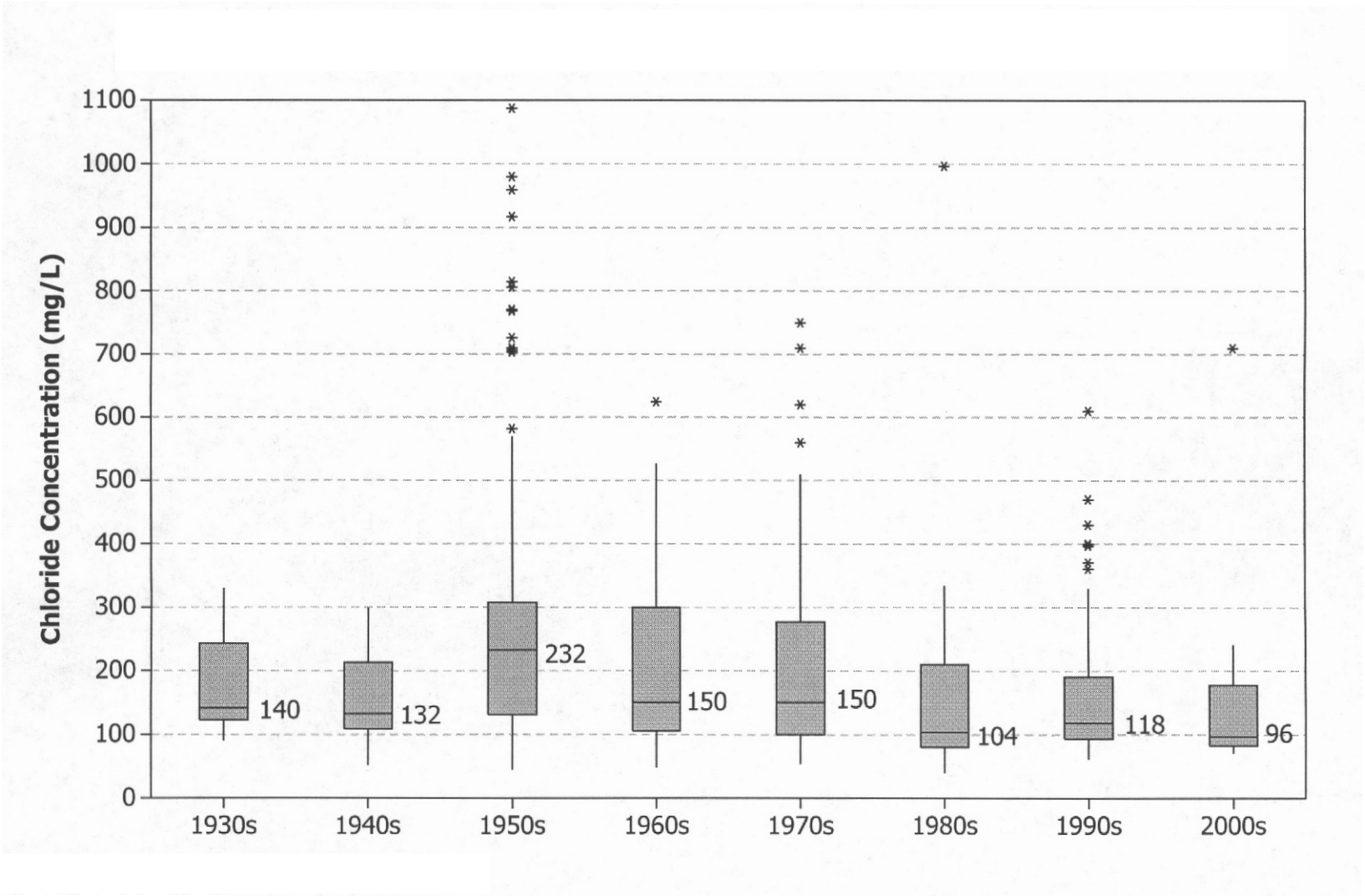

Median concentration shown on graph.

LRG SALINITY

Chloride Concentrations by Decade at Rio Grande at El Paso

Figure 4-7

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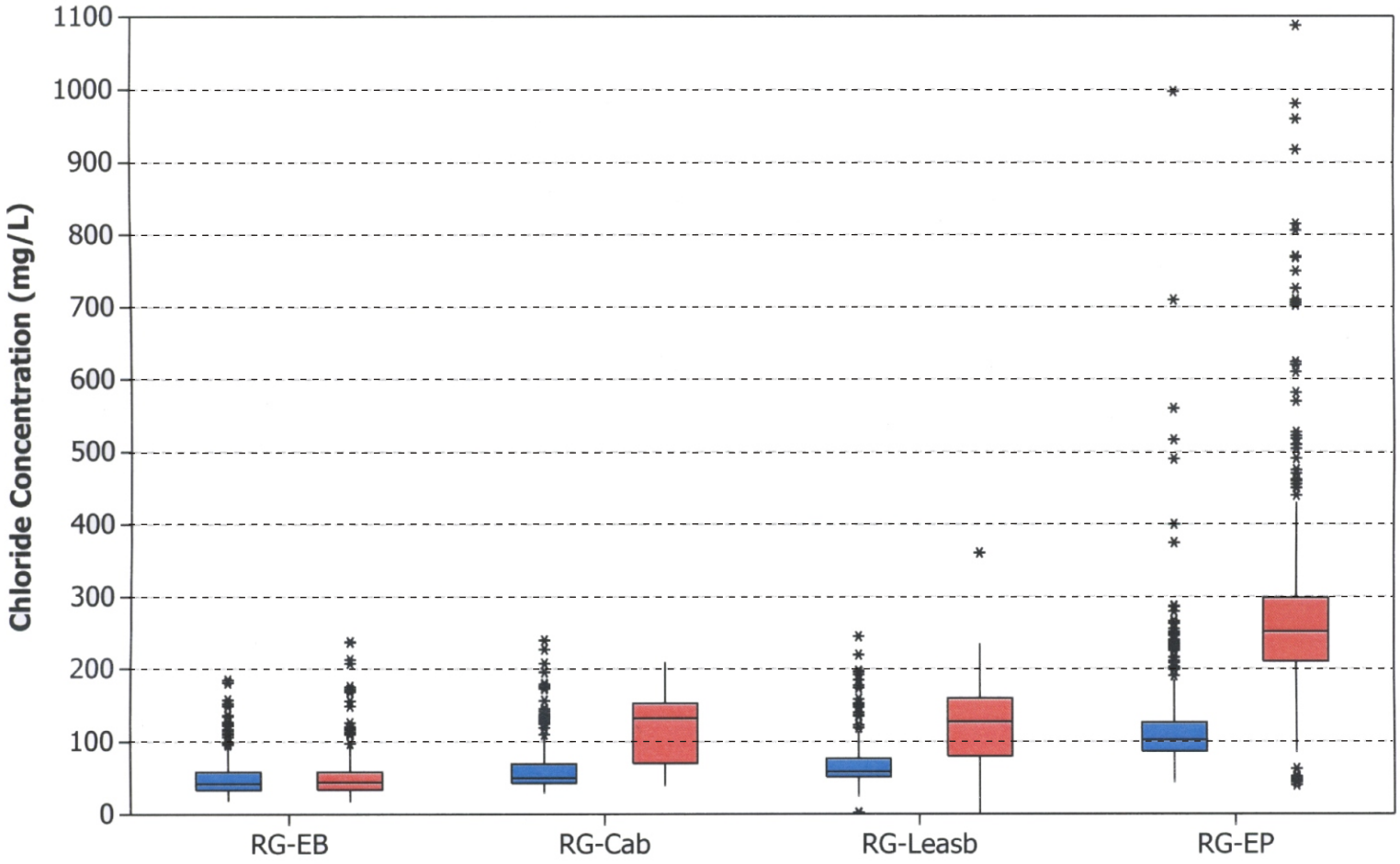

Explanation

Irrigation season (Mar-Sep)

Winter season (Oct-Feb)

LRG SALINITY

Seasonal Variations in Historical Chloride Concentrations in the Lower Rio Grande Valley 1929 to 1963

Figure 4-4

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Annual chloride loads were calculated as the sum of monthly chloride loads for a given year. Monthly chloride loads were calculated as the product of the average monthly chloride concentration and the average monthly streamflow.

4.4.1 Assumptions and Limitations

Annual chloride loads presented in this report are only estimates of the actual annual chloride (or TDS) load. The accuracy of these estimates depends on a variety of factors, including the accuracy of streamflow measurements and the variability of chloride (or TDS) concentrations throughout any particular month.

For a conservative constituent such as chloride (or TDS), the load is not affected by evapotranspiration. During the process of evapotranspiration, water is removed from the system, resulting in increased chloride concentrations. However, the increase in concentration is offset by the decrease in the volume of water, and the load, or total amount of salt, remains the same. Increases in the salt load are caused by addition of salt through inflow of saline water. Decreases in the salt load are caused by removal of salt, where salt is removed by diversion (removal) of saline water; in this case, salts can remain behind in soil or in an aquifer. If there is a reservoir in a particular reach, changes in salt load can be caused by changes in reservoir storage volume.

4.4.2 Implications of Annual Loads

Annual chloride loads in the LRG are shown on Figure 4-9. Annual chloride loads increase between RG-EB and RG-Cab, most likely due to inflow of saline groundwater rather than changes in reservoir storage (because there is little change in streamflow between these two stations). Annual chloride loads decrease between RG-Cab and RG-Leasb, primarily due to decreases in streamflow (Figure 4-3) that result from irrigation diversions at Leasburg Dam.

Chloride loads generally increase between RG-Leasb and RG-EP (Figure 4-9) despite decreases in streamflow (Figure 4-3). The increasing chloride load cannot be caused by evapotranspiration (as explained in Section 1.2); this increase in chloride load and coincident

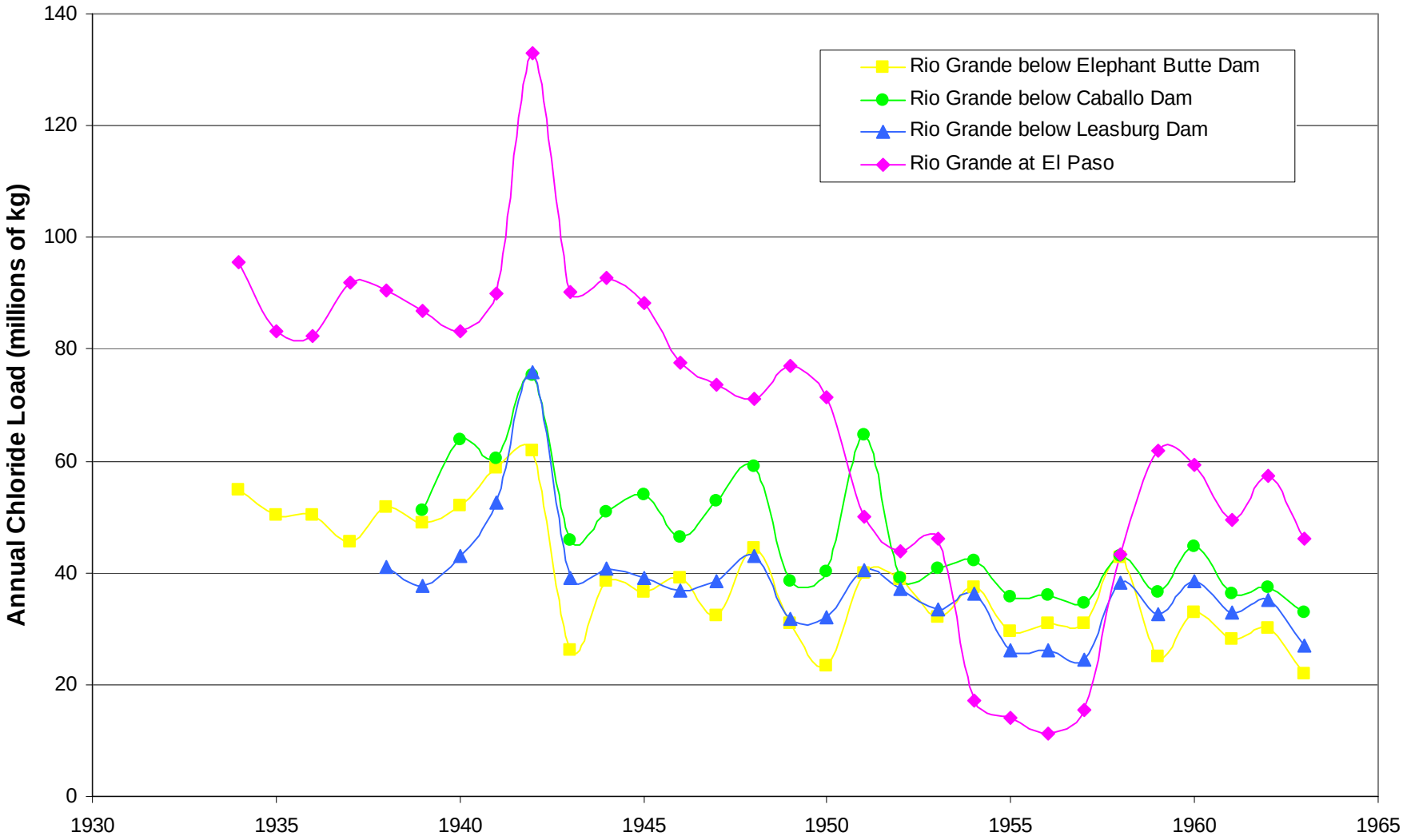

Figure 4-9

LRG SALINITY

Historical Chloride Loads

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decrease in streamflow therefore suggest the presence of an inflow with an elevated chloride concentration (relative to that at RG-Leasb).

From 1954 to 1957, the chloride load decreased between RG-EB and RG-EP (Figure 4-9). These data suggest that the chloride source, which generally contributes to the increase in chloride load, was cut off from the river during that period. USBR records indicate that drain flow in the Mesilla Valley portion of the LRG was close to zero from 1954 to 1956 due to regional drought conditions (Frenzel et al., 1992). These data suggest that (1) drains are a conduit of a saline source of inflow that formerly (prior to 1954 and after 1957) caused the increase in salt load, and (2) agricultural drains therefore cease to flush salts from the aquifer, at which time the aquifer begins accumulating salts, thus acting as a salt sink. The concept of drains acting as a source of saline inflow is supported by previous investigators (Mills, 2003), who proposed that agricultural drains contribute to the salinization of the Rio Grande primarily by intercepting deep sedimentary brines. If the drains were disconnected from the water table (for example, due to increased groundwater pumping), then they would cease to intercept and deliver the chloride source to the river, and chloride loads would decrease.

5. Synoptic Sampling Events

It is well documented that seasonal variation exists in the LRG (Section 2.3); however, the nature and magnitude of the seasonal variation is not well understood. For that reason, the ISC contracted with DBS&A to conduct two synoptic water quality sampling events in the LRG: one in August 2004 to characterize LRG water quality during the irrigation season, and one in January 2005 to characterize LRG water quality during the winter months.

Water quality samples were collected from a variety of locations and sources, including the main stem of the Rio Grande, groundwater wells, the Las Cruces WWTP, and agricultural drains (Table 5-1). Samples were analyzed for a suite of constituents, including major ions, trace metals, and stable and radioactive isotopes (Table 5-2). After evaluating the results from the August 2004 sampling event, several new sampling locations were selected (for the January 2005 sampling event) to ensure that the study objectives, as outlined in this section, were met. Table 5-1 describes sampling locations, provides site IDs for each location, and shows when each location was sampled. All sampling locations are shown on Figure 2-3. A general discussion of results is included in this section; more detailed discussion of results is presented in Sections 6 and 7.

5.1 Objectives of Synoptic Sampling Events and Study Design

DBS&A conducted surface water and groundwater quality sampling in the LRG during two synoptic sampling events:

- August 3 through 5, 2004
- January 24 through 27, 2005

The objectives of these synoptic sampling events were as follows:

- To test a wide range of geochemical constituents for suitability to fingerprint the end member sources and processes that contribute to LRG salinization

Table 5-1. Sampling Locations and Dates Sampled

Location Description	Site ID	Streamgage ID	Sample Type	Date(s) Sampled	
				August 2004	January 2005
Rio Grande at Nogal Canyon	RG-Nog	NA	Surface water	•	•
Rio Grande below Elephant Butte Dam	RG-EB	RG-EB	Surface water	•	•
Charles Geothermal well (total well depth is ~210 feet bgs)	GW-Chrl	NA	Geothermal		•
Rio Grande above Truth or Consequences WWTP	RG-abvTC	NA	Surface water		•
Rio Grande below Caballo Dam	RG-Cab	RG-Cab	Surface water	•	•
Tonuco Drain above discharge to Rio Grande	DR-Ton	NA	Drain	•	•
Rio Grande at the NMSU station	RG-NMSU	NA	Surface water		•
Rio Grande below Selden Canyon (just above Leasburg Diversion Dam)	RG-blwSC	RG-Leasb	Surface water		•
Radium Springs geothermal well (total well depth is ~150 feet bgs)	GW-RS	NA	Geothermal	•	
Las Cruces WWTP	WW-LC	NA	Wastewater	•	•
Rio Grande below Las Cruces WWTP	RG-LC	NA	Surface water		•
East Drain above Anthony WWTP	DR-ED1	NA	Drain		•
East Drain above discharge point to Rio Grande	DR-ED2	NA	Drain	•	•
LRG-ISC-3 well (sampled at ~1,250 feet bgs)	GW-ISC3	NA	Groundwater	•	
Rio Grande below East Drain	RG-blwED	NA	Surface water		•
LRG-ISC-5 well (sampled at ~280 feet bgs)	GW-ISC5	NA	Groundwater		•
LRG-ISC-4a well (sampled at ~60 feet bgs)	GW-ISC4a	NA	Groundwater		•
LRG-ISC-4 well (sampled at ~145 feet bgs)	GW-ISC4	NA	Groundwater		•
Montoya Drain above discharge to Rio Grande	DR-Mont	NA	Drain		•
Rio Grande at El Paso (at Corchesne Bridge)	RG-EP	RG-EP	Surface water	•	•

NA = Not applicable
bgs = Below ground surface
WWTP = Wastewater treatment plant
NMSU = New Mexico State University

Table 5-2. Geochemical Tracers

Constituent	Fingerprinting Application	Existing Data
Major cations and anions; trace elements	General geochemical characterization.	Significant amount of existing data
Hydrogen (δD) and Oxygen ($\delta^{18}O$)	Solvent specific, water source, evaporation.	Significant amount of existing data, including Mills (2003) and Witcher (1995)
Boron ($\delta^{11}B$)	Large isotopic range; expect different values for sources such as wastewater, agricultural, dairy, and deep groundwater.	No available local data
Sulfur ($\delta^{34}S$)	Natural sulfate sources differ depending on redox state and geologic age if included in minerals.	Some data for groundwater available in Witcher (1995)
Nitrogen ($\delta^{15}N$)	Distinguishes animal/human waste sources from agricultural and background.	Some data available in McQuillan et al. (2004)
Strontium ($^{87}Sr/^{86}Sr$) and Uranium ($^{234}U/^{238}U$)	Derived from weathering of local geologic sources; should distinguish deep and shallow groundwater.	Some data for groundwater available from Witcher (1995)
Radium (^{226}Ra, ^{228}Ra)	Derived from fertilizer and represents significant label for anthropogenic sources.	No available local data

- To sample at locations representing significant end members
- To sample the upstream and downstream ends of the study area to assess cumulative effects of sources within the study area in terms of the geochemical tracers selected
- To improve understanding of the range of end member chemistry by sampling more locations potentially representative of significant end members
- To better define the deep basin groundwater and geothermal end members in particular
- To capture the effects on the river of end member inputs that are not directly measurable, as well as to obtain more location-specific information about end member inputs by sampling more locations on the main stem Rio Grande
- To compare river chemistry between the winter season and the irrigation season
- To use geochemical tracers cost-efficiently while defining end members

Sites were selected in order to characterize the various water types in the LRG: surface water, groundwater, geothermal groundwater, agricultural (or drain) water, and wastewater. Identification of sample types was based on the current understanding of the LRG system; the sample types include water from each component of the hydrologic system (Section 2). Table 5-1 provides the sampling locations that were chosen to characterize each of the sample types. The geochemical constituents that were chosen for analysis with these goals in mind include (1) major cations, anions, and trace elements and (2) isotopes of hydrogen, oxygen, boron, sulfur, nitrogen, strontium, uranium, and radium (Table 5-2). Also included in Table 5-2 is the anticipated fingerprinting application of each constituent.

It is important to note that not all sample types represent a unique source of salinity; in fact, many of the samples represent a mixture of the various end members, or sources of salinity. Analysis of geochemical data for all sample types, in the context of the conceptual model of the system, allowed for individual end members to be identified (Sections 5, 6, and 7).

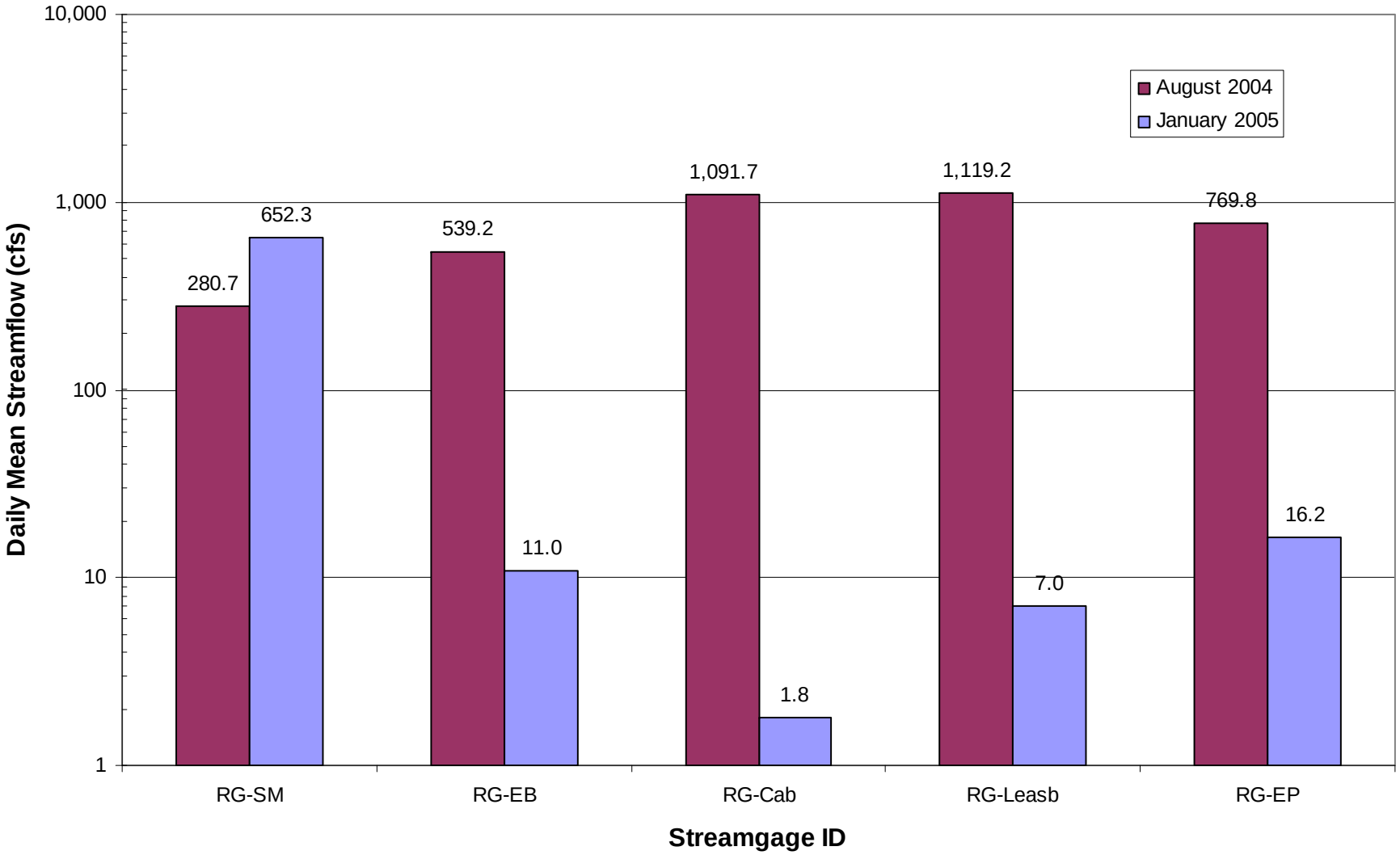
5.2 Rio Grande Streamflow Conditions

Variations in streamflow affect variations in water quality. A general understanding of streamflow in the LRG is therefore necessary to provide the context with which to understand variations in water quality. Although streamflow data were not collected during either sampling event, streamflow data for both sampling periods were available from various government agencies.

Streamflow conditions during the August 2004 sampling event were typical of irrigation season conditions of the LRG (Section 2.3). Daily mean streamflow was lowest (281 cfs) at the upper end of the study area, above Elephant Butte Reservoir (RG-SM) (Figure 5-1). Daily mean streamflow increased to 540 cfs at RG-EB and to 1,092 cfs at RG-Cab (Figure 5-1) due to releases for the irrigation season. Between Caballo Reservoir and RG-EP, daily mean streamflow decreased from 1,092 to 770 cfs (Figure 5-1) because outflows were greater than inflows.

Streamflow conditions during the January 2005 sampling event were typical of winter conditions in the LRG (Section 2.3). Daily mean streamflow decreased from approximately 650 cfs above Elephant Butte Reservoir (RG-SM) to almost 0 cfs below Caballo Reservoir (RG-Cab) (Figure 5-1). Below Caballo Reservoir, the Rio Grande gains streamflow due to groundwater inflow, agricultural return flows, and wastewater effluent (Figure 5-1). However, despite inflows from various sources, streamflow was not continuous between RG-Cab and RG-EP. During the January 2005 sampling event, the river was dry in several locations, and therefore could not be sampled. The river was observed to be dry at the following locations:

- Above the Las Cruces WWTP
- At Mesilla Diversion Dam
- Downstream from RG-blwED
- At Borderland
- At Frontera Road



LRG SALINITY

Daily Mean Streamflow
August 2004 and January 2005

Figure 5-1

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The river is essentially "reset" at each location where the river goes dry and streamflow is not continuous. Streamflow was observed in the Canutillo area; this streamflow was due to groundwater discharge from two nearby City of El Paso municipal wells that were being pumped for well development. The discontinuous nature of streamflow during January 2005 (and throughout much of the winter season) has important consequences for water quality interpretation and mixing calculations.

5.3 Results of Synoptic Sampling Events

5.3.1 August 2004 Sampling Event

Water quality results of the August 2004 sampling event are provided in Appendix C. River water in the LRG was generally low in chloride and TDS (Figures 5-2 through 5-7), and exhibited little variation in major ion concentrations (Figures 5-3 through 5-7) between Rio Grande at Nogal Canyon (RG-Nog) and RG-EP and almost no variation between Rio Grande below Caballo Dam (RG-Cab) and RG-EP. The small amount of variation in major ion concentrations indicates that the Rio Grande is largely unaffected by inflow from various sources due to the relatively high streamflow present in the Rio Grande (Figure 5-1), which easily dilutes small contributions of concentrated inflow. The largest variation in major ion concentrations along the Rio Grande was upstream of RG-Cab, between RG-Nog and RG-EB, where sulfate concentration decreased from 190 to 140 mg/L (Figure 5-6). Possible causes of this decrease in sulfate concentration include reservoir effects from Elephant Butte Reservoir and inflow of geothermal groundwater.

During the August 2004 sampling event, the drains (DR-Ton and DR-ED2), wastewater (WW-LC), geothermal water (GW-RS), and groundwater (GW-ISC3) were more saline than Rio Grande water (Figures 5-2 through 5-7). The highest major ion concentrations were measured in the geothermal water (GW-RS) (Figures 5-2 through 5-7).

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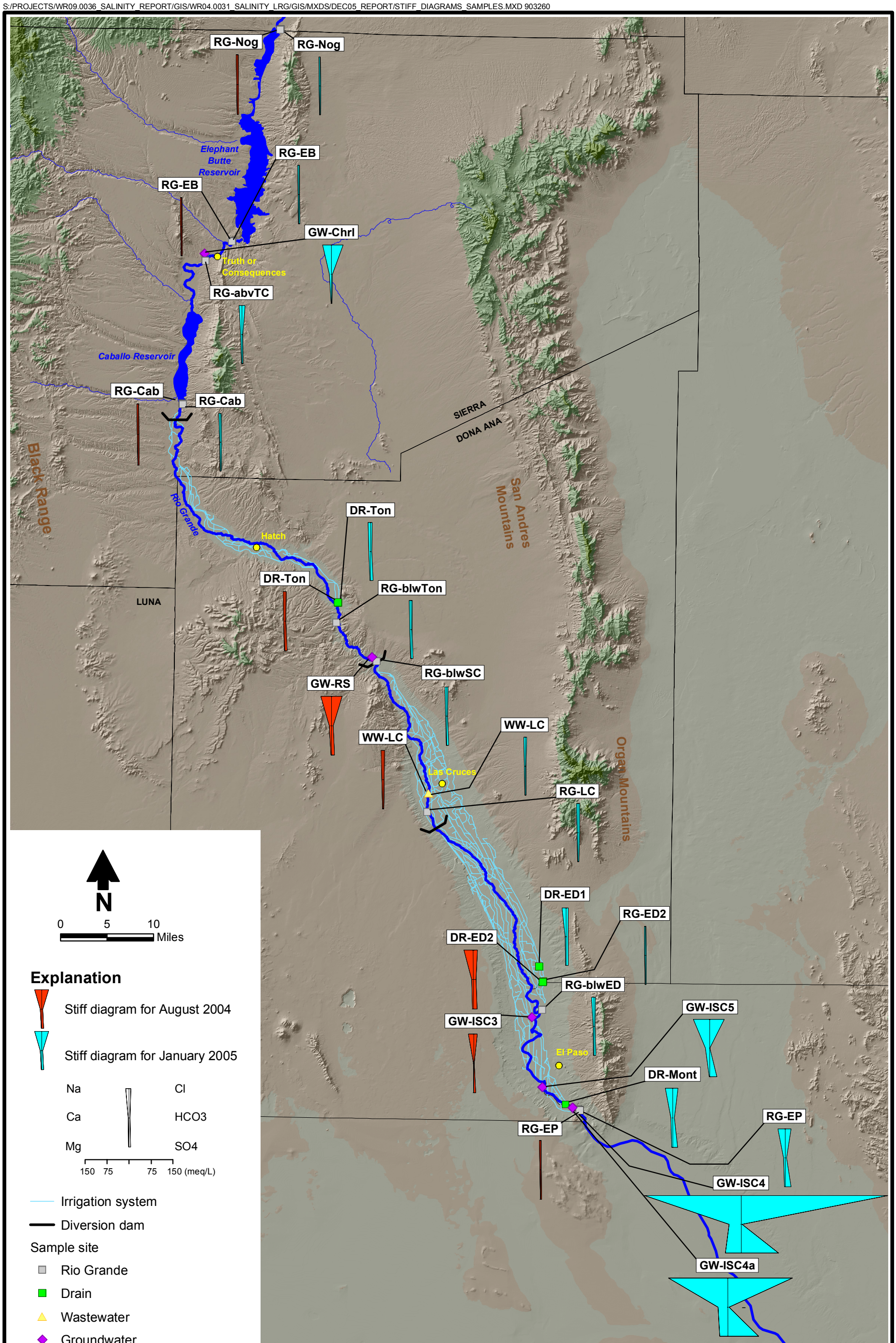

LRG SALINITY

Stiff Diagrams for August 2004 and January 2005 Sampling Locations

Figure 5-2

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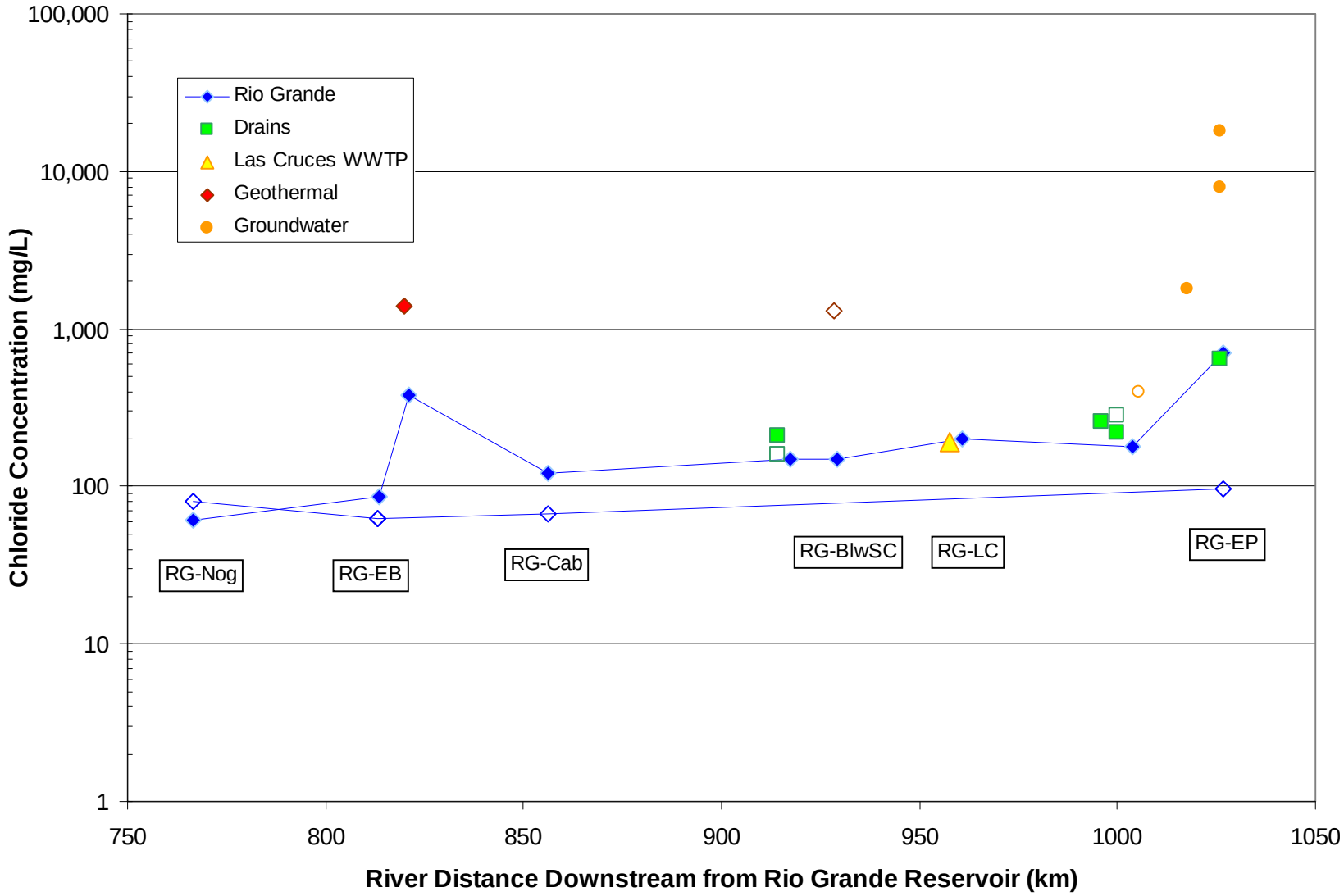

Note: Hollow symbols indicate August 2004 data, while solid symbols indicate January 2005 data.

Figure 5-3

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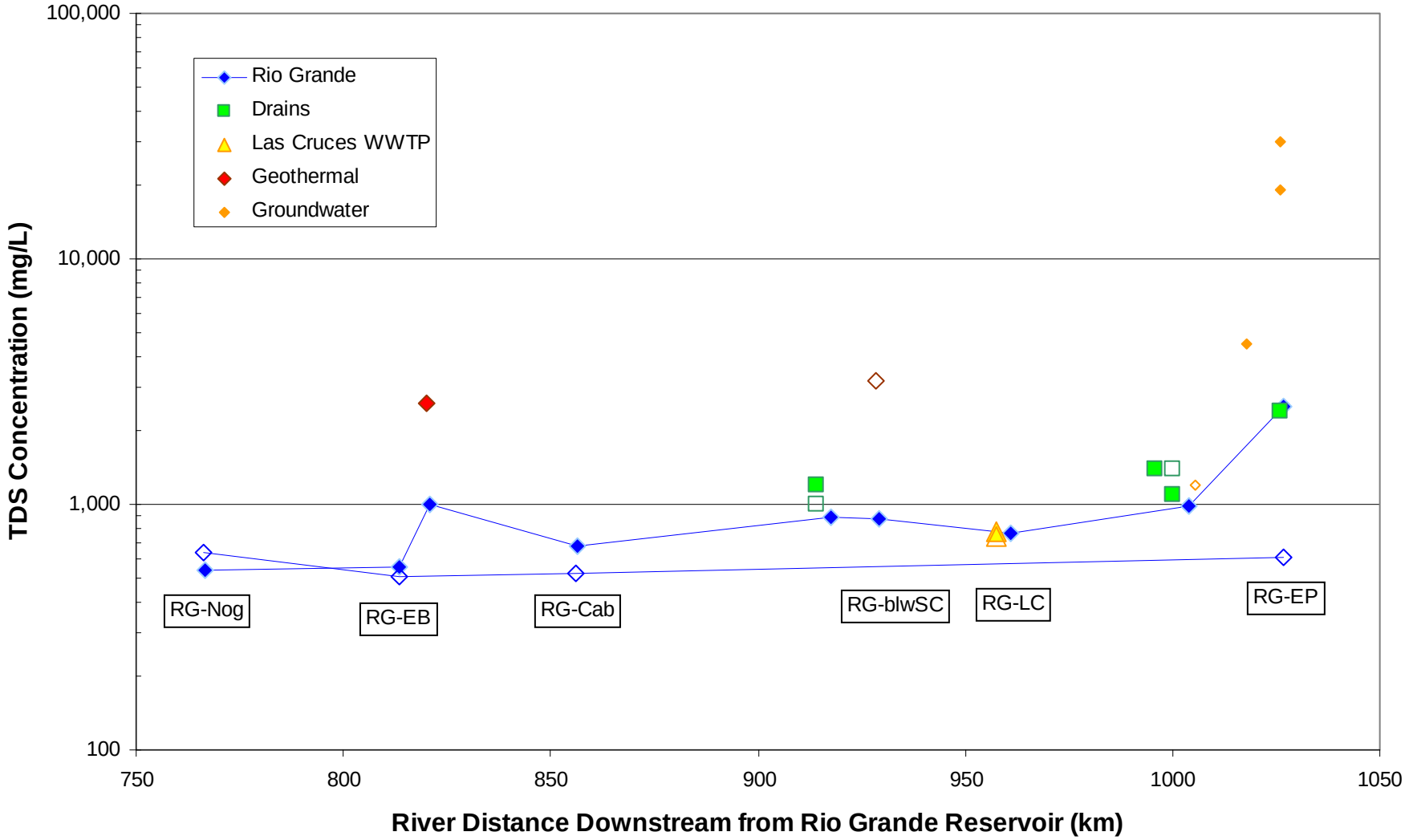
LRG SALINITY

Spatial Variation in Chloride Concentration



Note: Hollow symbols indicate August 2004 data, while solid symbols indicate January 2005 data.

Figure 5-4

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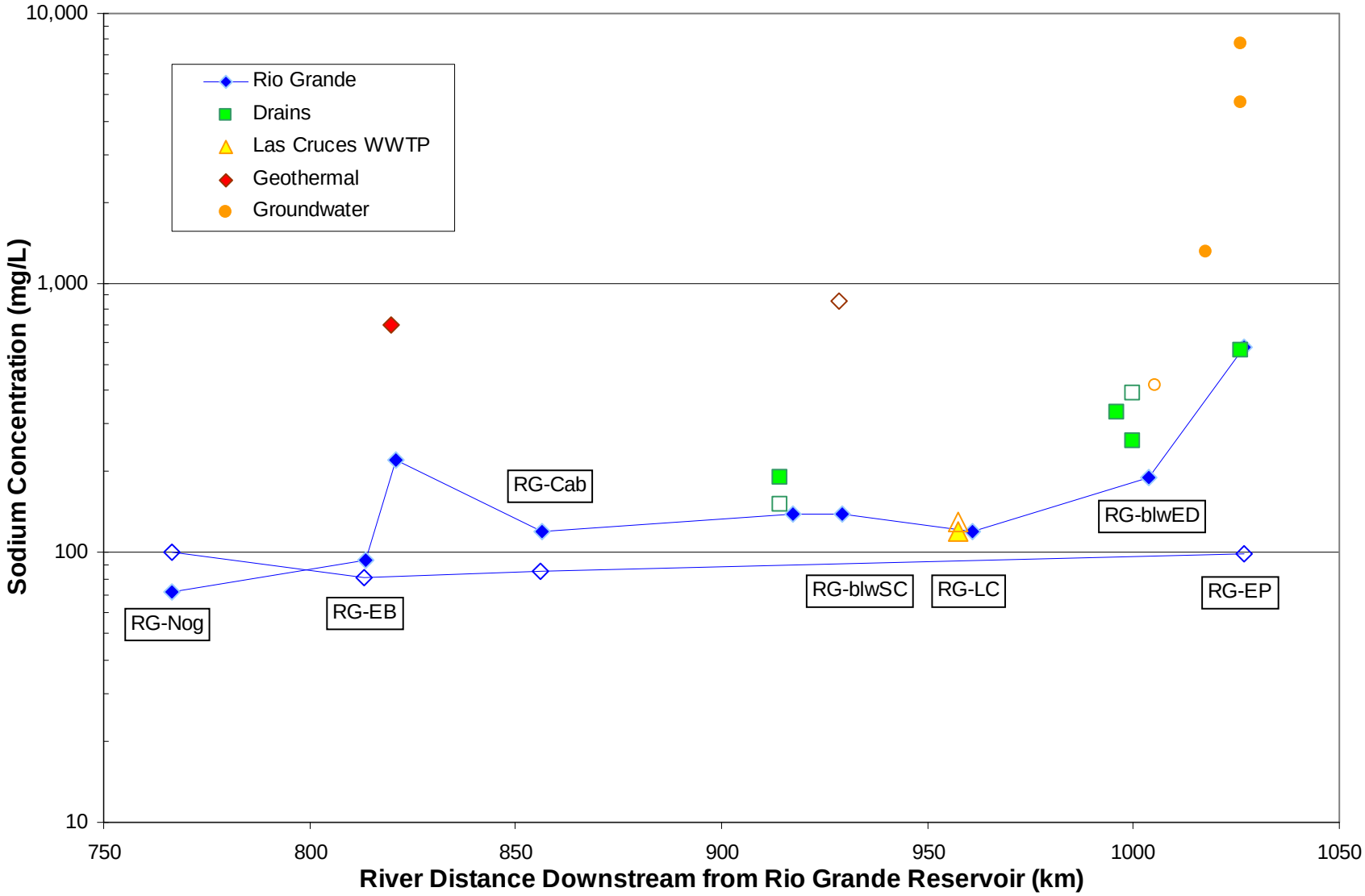
LRG SALINITY

Spatial Variation in TDS Concentration



Note: Hollow symbols indicate August 2004 data, while solid symbols indicate January 2005 data.

Figure 5-5

LRG SALINITY

Spatial Variation in Sodium Concentration

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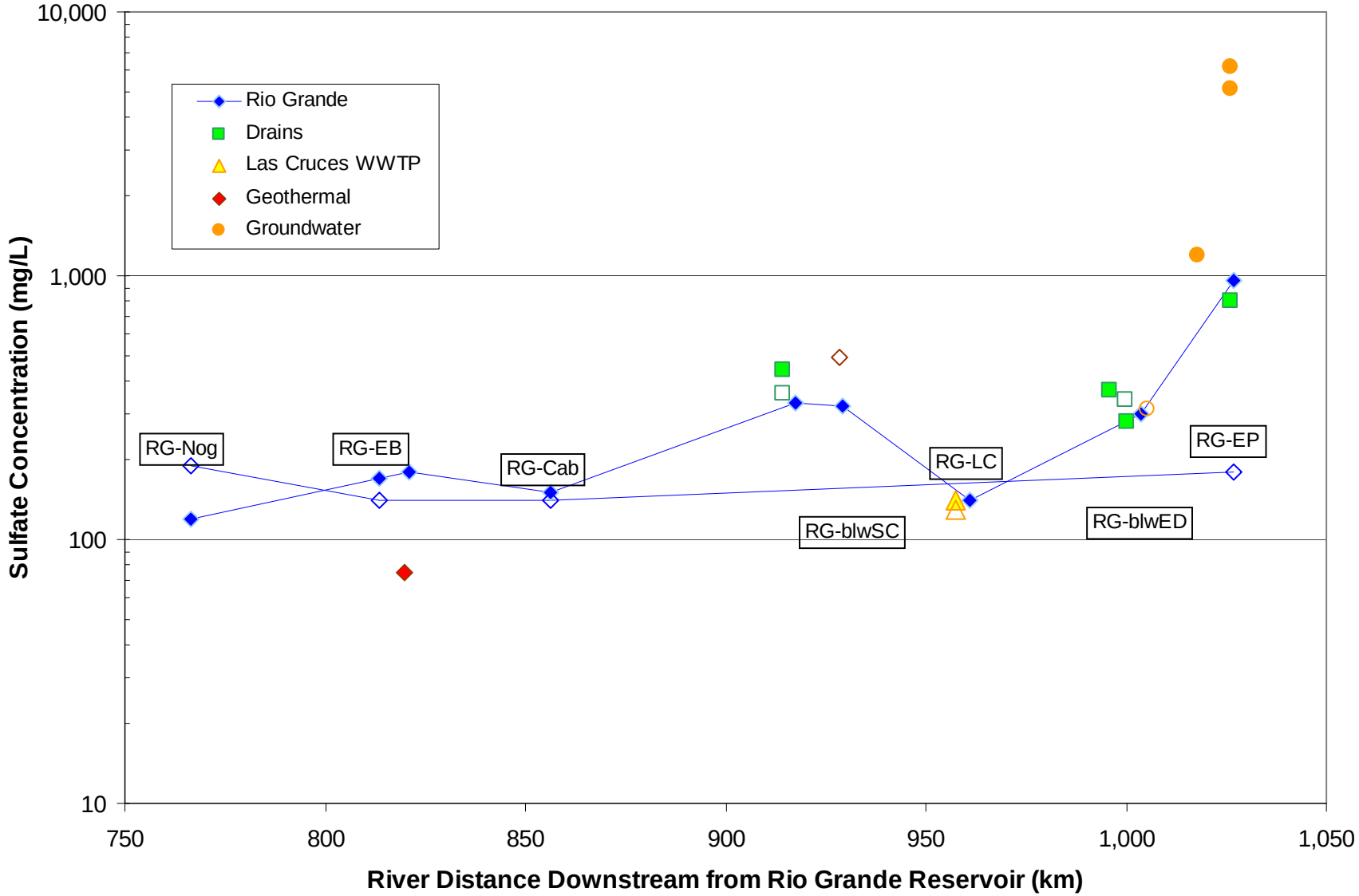

Note: Hollow symbols indicate August 2004 data, while solid symbols indicate January 2005 data.

Figure 5-6

LRG SALINITY

Spatial Variation in Sulfate Concentration

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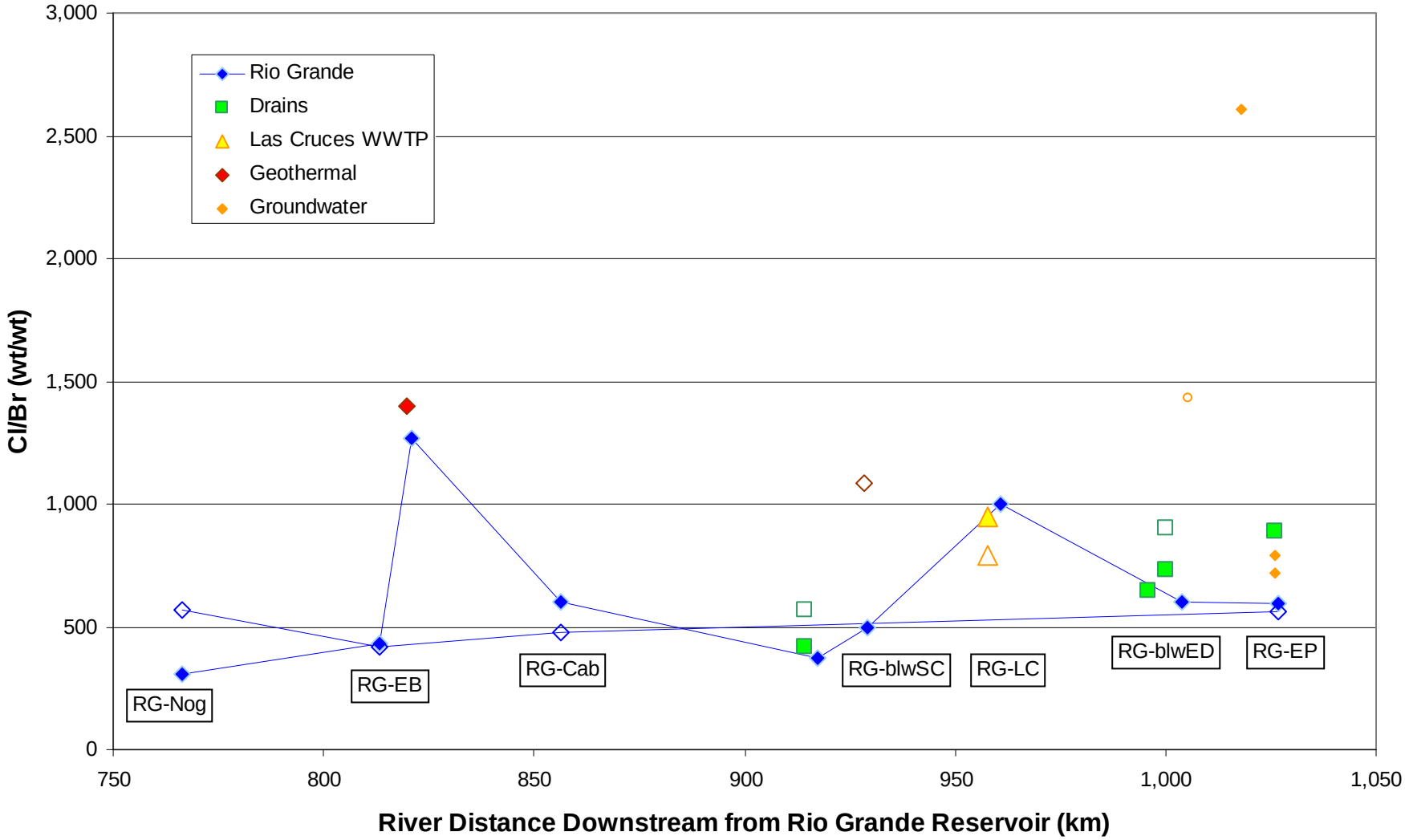

Note: Hollow symbols indicate August 2004 data, while solid symbols indicate January 2005 data.

Figure 5-7

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LRG SALINITY

Spatial Variation in Cl/Br

5.3.2 January 2005 Sampling Event

Water quality results from the January 2005 sampling event are provided in Appendix C. Rio Grande water was generally dilute relative to other water types, and major ion concentrations increased in the downstream direction (Figures 5-2 through 5-7). It is important to note that the apparent changes in major ion concentrations (Figures 5-3 through 5-7) between RG-blwSC and Rio Grande below Las Cruces WWTP (RG-LC) are the direct result of the intermittent streamflow conditions in the Rio Grande during January 2005. Because the Rio Grande is completely dry above the Las Cruces WWTP, water at RG-LC is entirely derived from wastewater effluent. In other words, the river is essentially "reset" at this point below the Las Cruces WWTP.

The slight increases in chloride concentration (61 to 86 mg/L) between RG-Nog and RG-EB (Figure 5-3) can be attributed to reservoir effects, primarily evaporation. Increases in TDS, sodium, and sulfate concentrations between RG-Nog and RG-EB are also due to reservoir effects. The most substantial increases in major ion concentrations between RG-EB and RG-EP can be attributed to inflow from various end members throughout the LRG, as discussed in the following examples.

The large increase in chloride concentration between RG-EB and Rio Grande above Truth or Consequences WWTP (RG-abvTC) (86 to 380 mg/L) is most likely the result of inflow from geothermal groundwater with elevated chloride concentration (1,400 mg/L at GW-Chrl) relative to that measured at RG-EB (Figure 5-3). Field observations support this assertion; water from hot springs in the Truth or Consequences area discharges directly into the Rio Grande. Variations in the chloride-bromide ratio throughout the Rio Grande support the conclusion that inflow from geothermal groundwater occurs between RG-EB and RG-Cab (Figure 5-7). The chloride-bromide ratio increases from 430 to 1,270 between RG-EB and RG-abvTC. The extremely high chloride-bromide ratio of geothermal groundwater in the vicinity of Truth or Consequences (1,400 at GW-Chrl) is strong evidence that inflow of geothermal groundwater is the primary cause of increased chloride-bromide ratio in the Rio Grande.

Chloride concentration increases by a factor of four over a distance of roughly 23 miles between RG-blwED and RG-EP (180 to 710 mg/L). This increase is likely due to inflow from deep saline groundwater with elevated chloride concentrations (e.g., 1,800 to 18,000 mg/L in GW-ISC4, GW-ISC4a, and GW-ISC5). TDS and sodium concentrations (Figures 5-4 and 5-5) are consistent with chloride concentrations, and load data confirm these conclusions.

Sulfate concentration increases between RG-Cab and RG-blwSC (150 to 320 mg/L). This increase can be attributed to inflow from the Tonuco Drain (DR-Ton) and from local geothermal water (GW-RS), both of which have elevated sulfate concentrations relative to the river (Figure 5-6). Geochemical modeling and analysis of loads (Section 7) indicate that elevated sulfate concentrations in Tonuco Drain are a result of inflow from local geothermal water and/or deep saline groundwater.

Below RG-LC, sulfate concentrations increase dramatically (140 to 960 mg/L) due to inflow from East Drain (DR-ED2), Montoya Drain (DR-Mont), wastewater effluent, and deep saline groundwater (e.g., as represented by GW-ISC4, GW-ISC4a, GW-ISC5) with elevated sulfate concentrations (800 to 6,200 mg/L). Geochemical modeling and mass balance assessments indicate that elevated sulfate concentrations in the drains are the result of inflow from deep saline groundwater (Sections 7.1.2 and 7.1.3).

5.3.3 Seasonal Variations

The most striking seasonal variation in the water quality of the LRG is that observed in the Rio Grande between irrigation season and the winter season (Figures 5-2 through 5-7). During August 2004, downstream changes in the water quality of the Rio Grande between RG-EB and RG-EP were minimal. During January 2005, however, downstream changes were substantial (Figures 5-2 through 5-7). These observations confirm the conceptual model of the system and are supported by the available literature (Sections 2 and 3). As previously discussed, these observations can be explained by the dominant sources of water during the irrigation and winter seasons. During the irrigation season, water quality of the Rio Grande is dominated by that of water released from Caballo Reservoir; therefore, minimal downstream changes in water quality of the Rio Grande were observed during August 2004. During the winter season, water quality

of the Rio Grande is dominated by that of the various sources of water to the river, including groundwater inflow, drain flow, and inflow from wastewater effluent; therefore, substantial downstream changes in water quality of the Rio Grande were observed during January 2005.

Several locations in the LRG were sampled during both the August 2004 and January 2005 sampling events (Table 5-1). Data from these locations allow for direct comparison of water quality during the irrigation and winter seasons.

Four surface water locations (RG-Nog, RG-EB, RG-Cab, and RG-EP) were sampled during both seasons (Table 5-1). Above Elephant Butte Dam (at RG-Nog), major ion concentrations were lower during August 2004 than during January 2005 (Figures 5-3 through 5-6).

Below Elephant Butte Dam (at RG-EB, RG-Cab, and RG-EP), higher major ion concentrations in winter indicate that, as expected, water was more saline during January 2005 than during August 2004 (Figures 5-2 through 5-6). Higher major ion concentrations during the winter season can be attributed to the lower streamflow during that season (Figure 5-1). Without a large and relatively dilute source of water being released from Caballo Reservoir, other end members—including inflow from wastewater effluent, deep saline groundwater, and geothermal groundwater—dominate streamflow in the LRG. While these other end members contribute streamflow to the LRG throughout the year, the quantity contributed is small relative to that released from Caballo Reservoir during the irrigation season.

During the irrigation season, large volumes of dilute water released from Caballo Reservoir mix with small volumes of concentrated water contributed by the various end members. The result is lower major ion concentrations throughout the LRG during the irrigation season, as indicated by observed concentrations during August 2004 (Figures 5-2 through 5-6).

Two drains (DR-Ton and DR-ED2) were sampled during both seasons (Table 5-1). Major ion concentrations in the East Drain (DR-ED2, downstream distance of 1,000 km) (Figures 5-2 through 5-6) were lower during January 2005 than August 2004. Lower major ion concentrations during January 2005 may be due to dilution by effluent from Anthony WWTP. The water quality of Tonuco Drain is less saline during August 2004 than January 2005, as

indicated by the lower major ion concentrations at DR-Ton (downstream distance of 914 km) (Figures 5-2 through 5-6). This difference may be due to higher streamflow in Tonuco Drain during the irrigation season, when agricultural fields are being irrigated with diverted river water.

One WWTP (WW-LC) was sampled during both seasons. Water quality at WW-LC is relatively constant throughout the year (Figures 5-2 through 5-6). The City of Las Cruces relies on groundwater for municipal use. Because the quality of municipal water is relatively constant throughout the year, there is little seasonal variation in salinity of wastewater inflow.

6. Source Water Characterization

The major sources of streamflow and salinity in the LRG were sampled in August 2004 and January 2005. Water quality data collected during these two sampling events allowed for a detailed characterization of the various streamflow and salinity sources. However, the source characterization provided in this report is necessarily limited (1) by the number of samples collected for each source or end member, (2) by the locations sampled, and (3) to the time frame during which the samples were collected (i.e., August 2004 and January 2005).

The various sample types include surface water, groundwater, geothermal groundwater, and wastewater. Based on the conceptual model (Section 2), particular sample locations were selected to represent the end member of each sample type. The various end member signatures of the LRG, as well as the sample locations used to characterize each end member, are described in detail in this section (Table 6-1). Geochemical data are provided in Appendix D.

6.1 Rio Grande Water

The water quality of streamflow at the upper end of the study area is the baseline for the LRG, while the water quality at the lower end of the study area represents various mixes of Rio Grande water and inputs from the various end member sources. Two sampling locations were used to characterize Rio Grande water as it enters the LRG: RG-EB and RG-Cab (Figure 2-3). RG-EB is located immediately below the outlet to Elephant Butte Reservoir; RG-Cab is located immediately below the outlet to Caballo Reservoir.

Rio Grande water entering the LRG system is relatively dilute compared to other downstream locations on the Rio Grande. Despite large seasonal variations in water quality of Rio Grande water, which is due to inflow from other sources, a distinct end member signature is apparent. Based on the August 2004 and January 2005 synoptic sampling events, Rio Grande water is characterized by (Table 6-1):

- Low boron concentrations (less than 0.15 mg/L)

Table 6-1. Lower Rio Grande End Member Signatures

End Member	Sample Location	Site ID	Constituent										
			B (mg/L)	$\delta^{11}B$ (‰)	Cl (mg/L)	Cl/Br	SO_4 (mg/L)	$\delta^{34}S$ (‰)	$\delta^{18}O$ (‰)	$\delta^{15}N$ (‰)	Total N (mg/L)	Sr (µg/L)	$^{87}Sr/^{86}Sr$
River	Elephant Butte and Caballo outlets	RG-EB and RG-Cab	<0.15	4.7 to 11.2	<150	400 to 600	140 to 170	<2.8	–8.9 to 7.2	–4 to 24	<0.4	635 to 775	0.7100 to 0.7120
Geothermal	Charles well	GW-Chrl	0.27	5.6	1,400	1,400	75	9.7	–9.1	5	<0.5	3,450	>0.7140
	Radium Springs well	GW-RS	0.68	5.9	1,300	1,083	490	4.7	–8.4	21	<0.3	2,420	>0.7140
Groundwater	Groundwater	GW-ISC3	0.82	–6.9	400	1,428	310	4.2	–11.7	–12	<0.2	316	0.7103
	Deep saline groundwater	GW-ISC4 and GW-ISC4a	>2.2	30.9 to 31.7	7,900 to 18,000	720 to 790	5,100 to 6,200	12.2 to 12.4	–8.0 to –8.2	–5 to 2	<1.0	16,500 to 19,600	0.7095 to 0.7105
		GW-ISC5	0.84	5.3	1,800	2,608	1,200	7.9	–7.7	–2	<0.2	2,190	<0.7090
Wastewater	Las Cruces WWTP	WW-LC	0.20 to 0.25	3.9	190	900 to 1,100	130 to 140	5.5 to 6.1	–11.1 to –10.6	13 to 21	7 to 9	925 to 1,090	<0.7100

mg/L = Milligrams per liter
‰ = Per mille
µg/L = Micrograms per liter
WWTP = Wastewater treatment plant

- Medium $\delta^{11}B$ values (4.7 to 11.2‰)
- Low chloride concentrations (less than 150 mg/L)
- Low chloride-bromide ratio (400 to 600)
- Low sulfate concentrations (140 to 170 mg/L)
- Low $\delta^{34}S$ values (less than 2.8 per mille [‰])
- Low total nitrogen concentrations (less than 0.4 mg/L)
- Low strontium concentrations (635 to 775 micrograms per liter [µg/L])
- Medium $^{87}Sr/^{86}Sr$ (0.7100 to 0.7120)

6.2 Deep Saline Groundwater

The quality of groundwater varies substantially throughout the LRG; however, the goal of water quality sampling for this study was to sample deep saline groundwater because historical data (Section 4) suggest and previous investigators (Section 3) have concluded that deep saline groundwater is a major salinity source in the LRG. Four groundwater wells were sampled: GW-ISC3, GW-ISC4, GW-ISC4a, and GW-ISC5; however, water quality data (particularly the low chloride concentration [Table 6-1]) indicate that GW-ISC3 is not representative of deep saline groundwater. Therefore, only three groundwater wells were used to characterize deep saline groundwater: GW-ISC4, GW-ISC4a, and GW-ISC5.

Based on the August 2004 and January 2005 synoptic sampling events, deep saline groundwater of the LRG is characterized by (Table 6-1):

- High boron concentrations (0.84 to greater than 2.2 mg/L)
- Medium to high $\delta^{11}B$ values (5.3 to 31.7‰)
- High chloride concentrations (1,800 to 18,000 mg/L)
- Medium to high chloride-bromide ratio (720 to 2,608)
- High sulfate concentrations (1,200 to 6,200 mg/L)
- Medium to high $\delta^{34}S$ values (7.9 to 12.4‰)
- Medium to low total nitrogen concentrations (less than 1.0 mg/L)
- High strontium concentrations (2,190 to 19,600 µg/L)

- Low to medium $^{87}Sr/^{86}Sr$ (less than 0.709 to 0.710)

This characterization of deep saline groundwater, which is based on data collected as part of this study, is supported by previous investigators. Witcher et al. (2004) report chloride-bromide ratios greater than 600 to 800 and $^{87}Sr/^{86}Sr$ greater than 0.710.

6.3 Geothermal Water

Geothermal water, a type of groundwater with elevated water temperature, is another salinity source in the LRG. Two geothermal wells were sampled and used to characterize geothermal water: GW-Chrl and GW-RS. GW-Chrl is located between Elephant Butte and Caballo Reservoirs (Figure 2-3), and was chosen to represent geothermal inflow in the vicinity of Truth or Consequences, an area of known geothermal activity. GW-RS is a geothermal well located in Selden Canyon, between Rincon and Mesilla Valleys.

Based on the August 2004 and January 2005 synoptic sampling events, geothermal water in the LRG is characterized by (Table 6-1):

- Medium boron concentrations (0.27 to 0.68 mg/L)
- Medium $\delta^{11}B$ values (5.6 to 5.9‰)
- High chloride concentrations (1,300 to 1,400 mg/L)
- Medium to high chloride-bromide ratio (1,083 to 1,400)
- Low to medium sulfate concentrations (75 to 490 mg/L)
- Medium to high $\delta^{34}S$ values (4.7 to 9.7‰)
- Low total nitrogen concentrations (less than 0.5 mg/L)
- Medium to high strontium concentrations (2,400 to 3,400 µg/L)
- Very high $^{87}Sr/^{86}Sr$ (greater than 0.7140)

This characterization of geothermal groundwater, which is based on data collected as part of this study, is supported by previous investigators. Witcher et al. (2004) report chloride-bromide ratios greater than 600 to 800 and $^{87}Sr/^{86}Sr$ greater than 0.710.

6.4 Wastewater

Wastewater effluent is a major source of water to the Rio Grande during the winter season, when no water is released from Caballo Dam. The largest WWTP in the LRG is the Las Cruces WWTP. Data from the Las Cruces WWTP were used to characterize wastewater in the LRG.

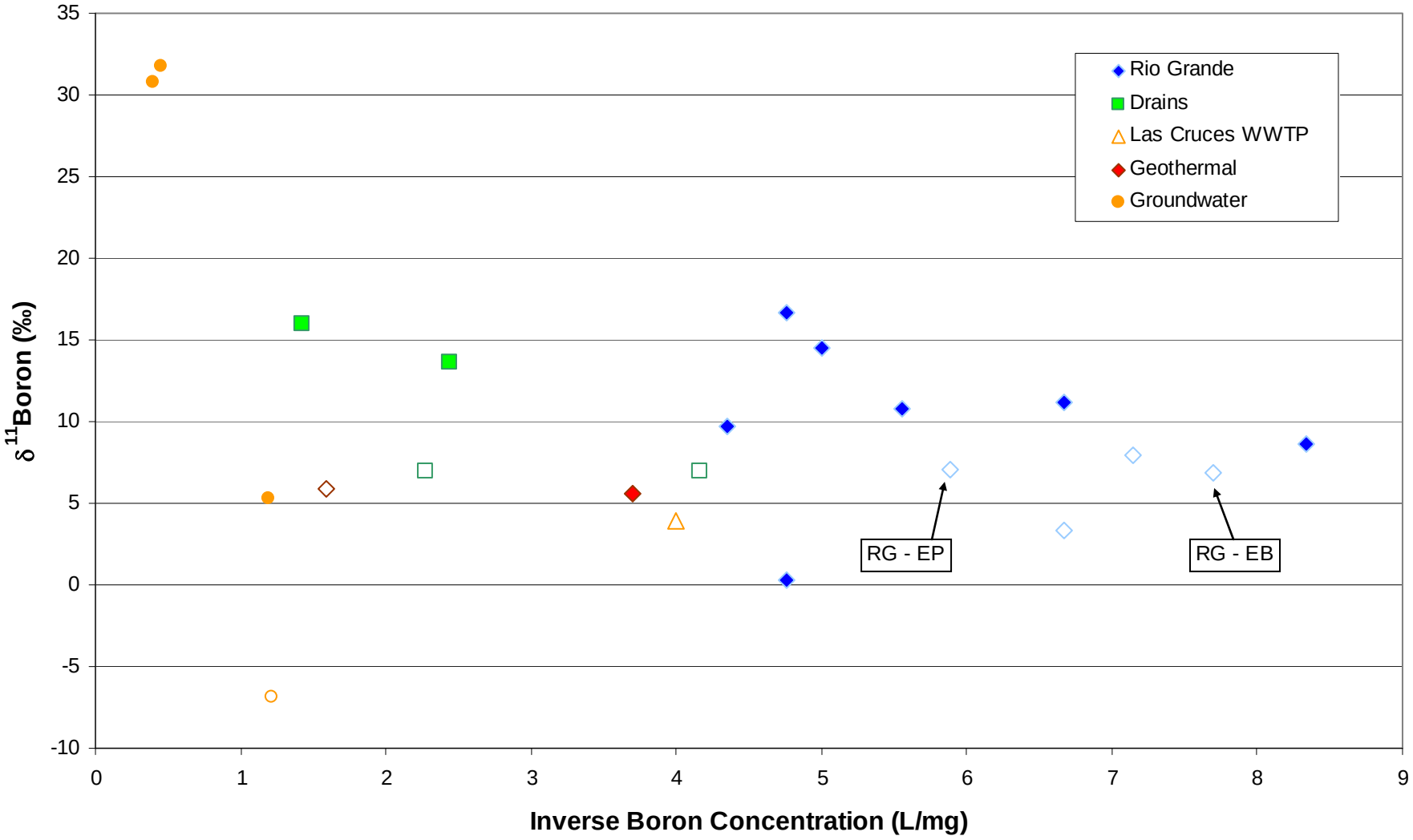
Compared to other end member sources in the LRG, the quality of wastewater entering the Rio Grande is relatively constant throughout the year. Based on the August 2004 and January 2005 synoptic sampling events, wastewater in the LRG is characterized by (Table 6-1):

- Low boron concentrations (0.20 to 0.25 mg/L)
- Medium δ^{11}B values (3.9‰)
- Low chloride concentrations (190 mg/L)
- Medium chloride-bromide ratio (900 to 1,100)
- Low sulfate concentrations (130 to 140 mg/L)
- Medium to high δ^{34}S values (5.5 to 6.1‰)
- High total nitrogen concentrations (7 to 9 mg/L)
- Medium strontium concentrations (925 to 1,090 µg/L)
- Low to medium ^{87}Sr/^{86}Sr (0.710)

6.5 Agricultural Water

Previous investigators have suggested that agricultural practices are a source of salinization in the LRG. In an attempt to test this hypothesis and characterize agricultural sources, several agricultural drains in the LRG were sampled: DR-Ton, DR-ED1, DR-ED2, and DR-Mont. The Tonuco Drain (DR-Ton) represents the cumulative agricultural affects of the Rincon Valley (Figure 2-3). The East Drain, which is located in the southern Mesilla Valley (Figure 2-3), was sampled at two locations, above and below the Anthony WWTP at the state line (DR-ED1 and DR-ED2). The Montoya Drain is at the terminus of the Mesilla Basin, and was sampled just upstream from where it discharges to the Rio Grande (DR-Mont).

Inspection of water quality data from DR-Ton, DR-ED1, DR-ED2, and DR-Mont (Figures 6-1 through 6-5) indicates that the agricultural drains represent a mixture of Rio Grande water and deep saline groundwater, rather than a unique end member or source. This conclusion is also supported by geochemical modeling, which is discussed in further detail in Section 7.



Note: Hollow symbols indicate August 2004 data, while solid symbols indicate January 2005 data.

Figure 6-1

LRG SALINITY

δ^{11}B vs. Inverse of Boron Concentration

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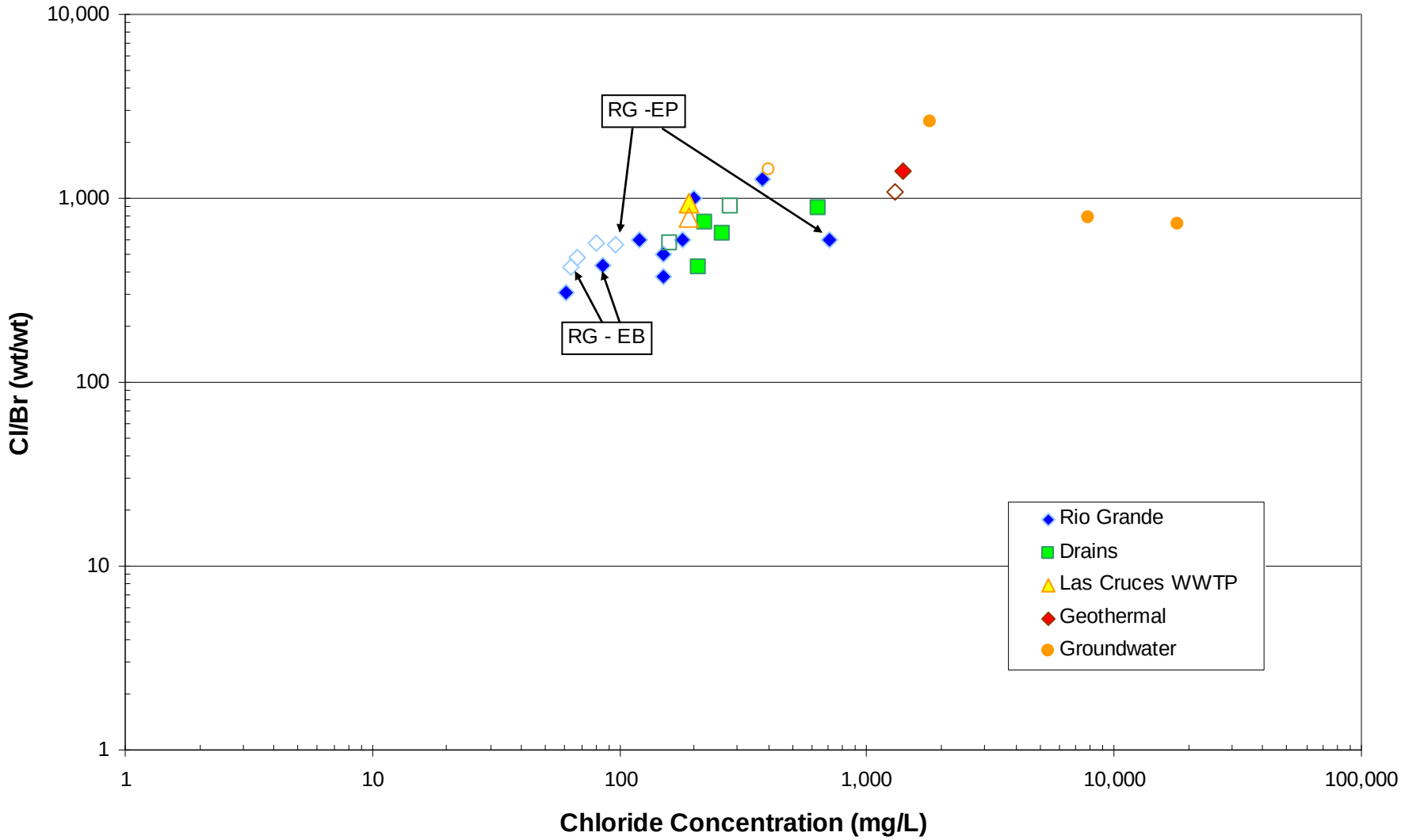

Note: Hollow symbols indicate August 2004 data, while solid symbols indicate January 2005 data.

Figure 6-2

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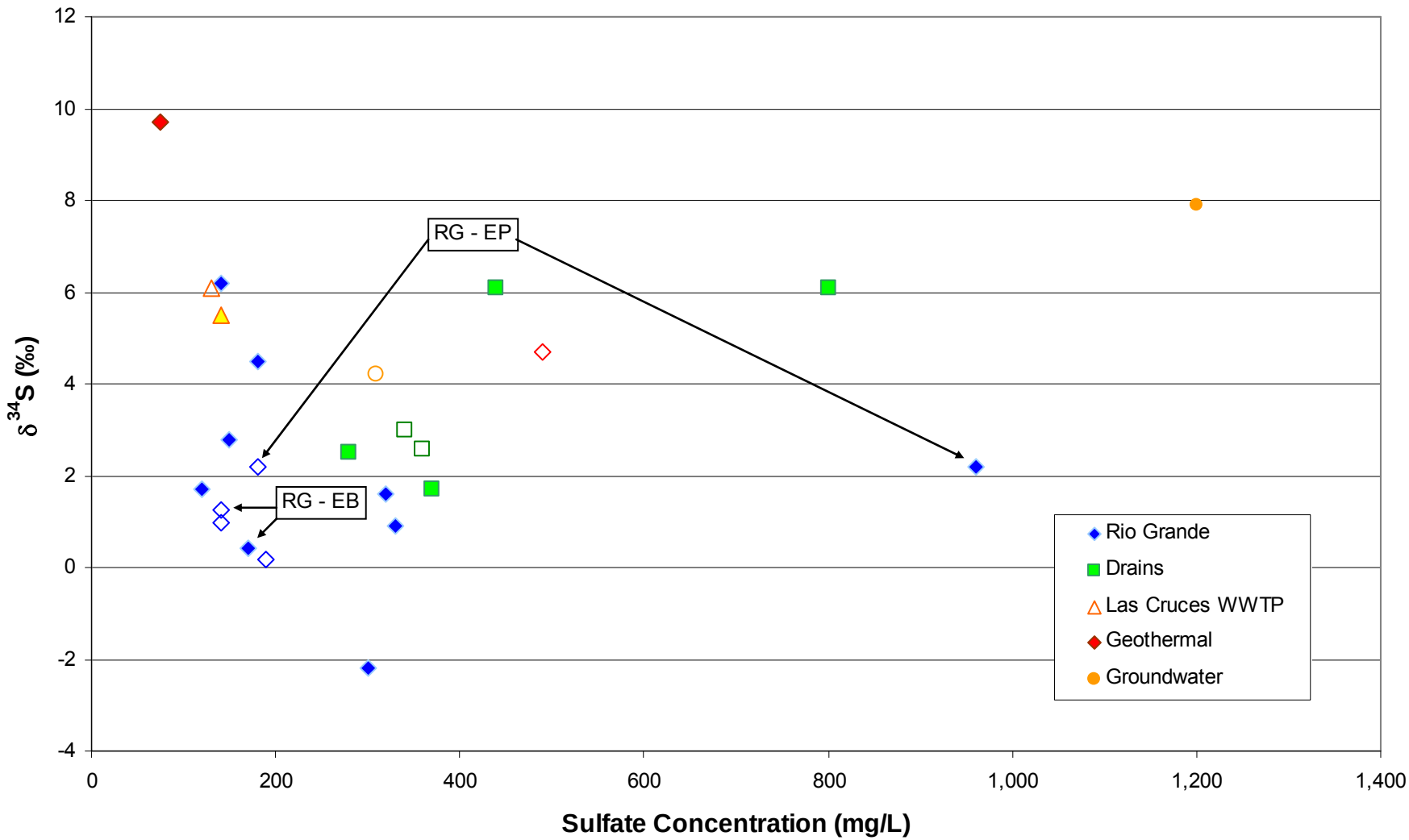
LRG SALINITY

Chloride/Bromide Ratio vs. Chloride Concentration



Notes: 1. Hollow symbols indicate August 2004 data, while solid symbols indicate January 2005 data.
2. The chart does not show the following data due to scale:
ISC4 (GW): SO_4 = 6,200 mg/L, □^{34}S = 12.4‰
ISC4a (GW): SO_4 = 5,100 mg/L, □^{34}S = 12.2‰

Figure 6-3

LRG SALINITY

δ^{34}S vs. Sulfate Concentration

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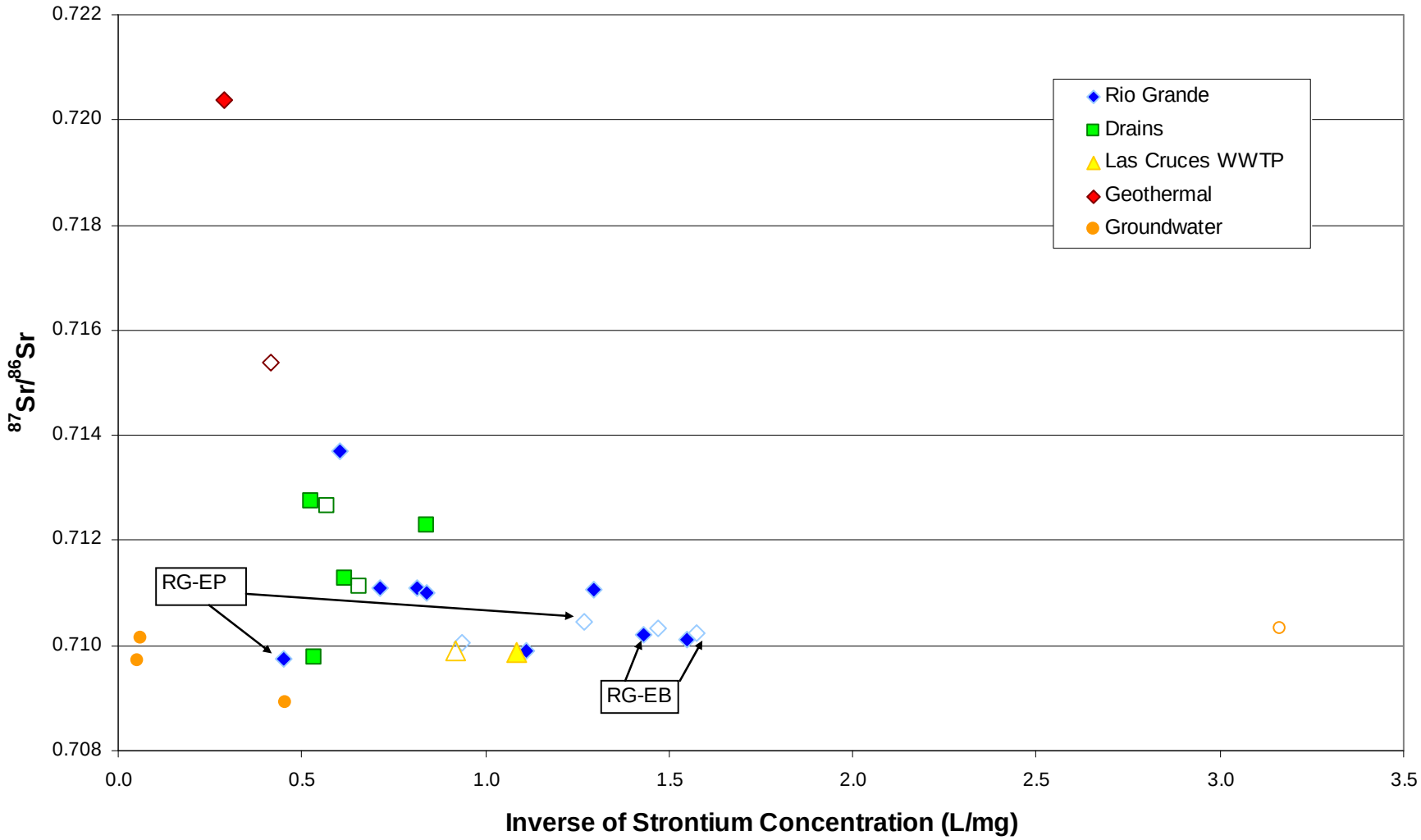

Note: Hollow symbols indicate August 2004 data, while solid symbols indicate January 2005 data.

Figure 6-4

LRG SALINITY

$^{87}Sr/^{86}Sr$ vs. Inverse of Strontium Concentration

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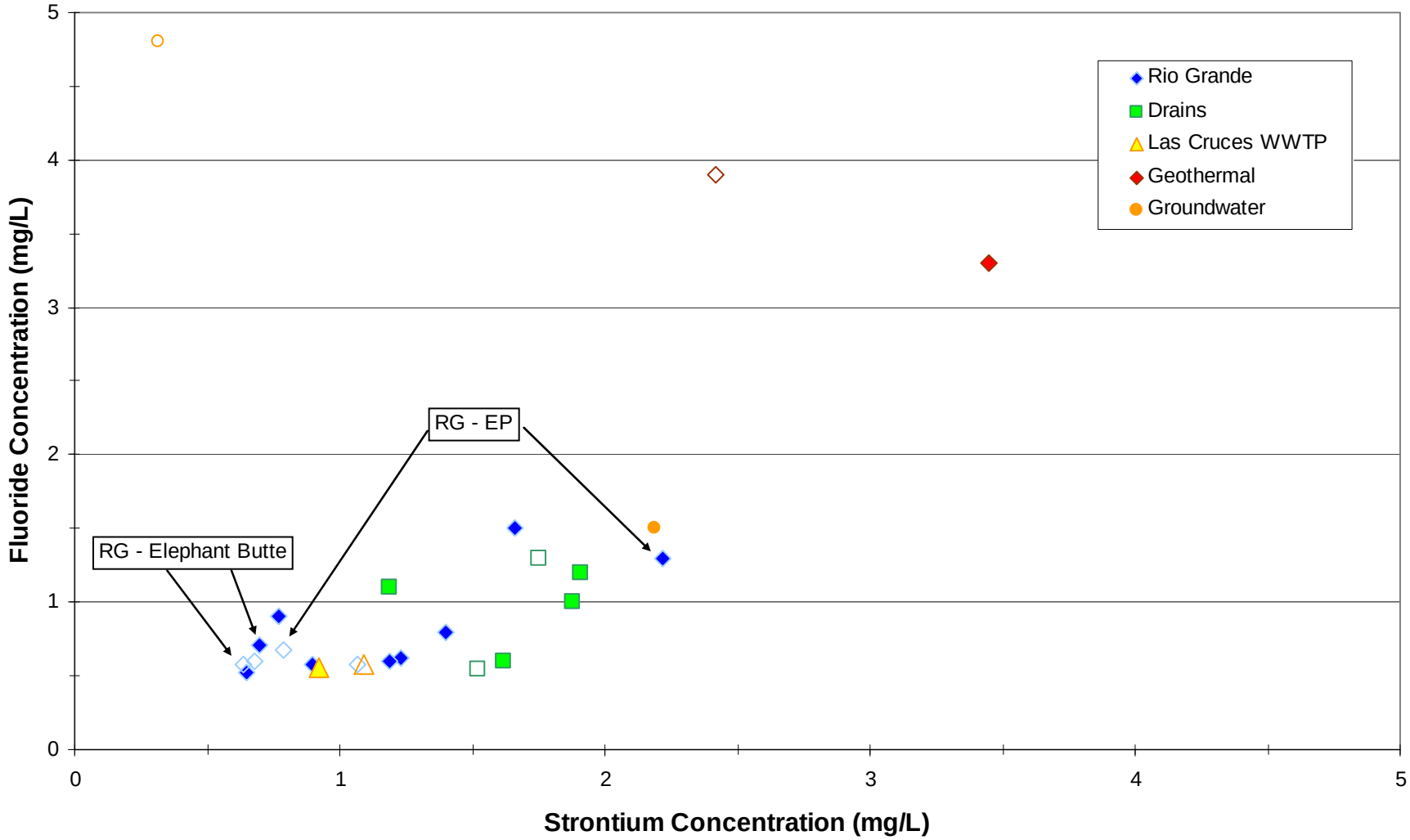

Notes: 1. Hollow symbols indicate August 2004 data, while solid symbols indicate January 2005 data.
2. The chart does not show the following data due to scale:
ISC4a (GW): Sr = 16.5 mg/L, F = 1 mg/L
ISC4 (GW): Sr = 19.6 mg/L, F = 1 mg/L

Figure 6-5

LRG SALINITY

Fluoride vs. Strontium Concentration

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7. Modeling and Interpretation of Chemical and Isotopic Data

In order to better quantify contributions from the various sources to (or end members of) the LRG, geochemical modeling and a simple chloride mass balance assessment were performed using data collected during August 2004 and January 2005. These analyses were constrained by available data, which were limited to selected locations. Because it was not possible to sample every potential source of streamflow and salinity to the Rio Grande, attempts were made to select a representative set of the various sources, as described in detail in Section 6.

7.1 Geochemical Modeling

The primary purpose of geochemical modeling was to evaluate the feasibility of simulating the observed geochemical changes in the LRG by mixing the various sources to (or end members of) the Rio Grande. Results of the geochemical modeling were interpreted to gain insight into the processes that affect and control geochemistry of the LRG.

The current understanding of the LRG (Section 2) was used to develop several probable "mixing scenarios" for various reaches of the LRG. Each mixing scenario has a minimum of four components:

1. The starting composition (source A) is the geochemical composition at the starting point for a particular reach, and is generally a point along the Rio Grande.

2. A potential source (source B) represents the composition of another source that may cause the observed geochemical changes. The potential source water is often a deep groundwater or geothermal water. Based on the conceptual model, the potential source is believed to be a probable source of salinity for a particular reach.

3. The target sample is the "end point" composition of a particular reach. The goal of performing the mixing scenario is to match the composition of the target sample.

4. The mixed composition is the result of mixing the starting composition with the potential source water. The composition of the resulting mix is compared to that of the target sample to evaluate the feasibility of that particular mixing scenario.

Generally, more than one potential source is considered for a particular reach; therefore, there is more than one mixing scenario for each reach (Table 7-1). The modeling discussed in this section is obviously limited by the available data.

Due to the spatial and temporal constraints on source water quality data, it was sometimes necessary to use water quality data from a source that was not in the immediate vicinity of the surface water component. For example, the only deep saline groundwater sampling locations were in the southern portion of the study area (Figure 2-3). To demonstrate the result of mixing surface water at RG-EB or RG-Cab with a deep saline groundwater, a deep saline groundwater sampling location from the southern portion of the study area was used, with the assumption that those samples are representative of deep saline groundwater throughout the study area. Additionally, all of the groundwater sampling locations were only sampled during one sampling event (i.e., August 2004 or January 2005) (Table 5-1). In some cases, a groundwater sample from January 2005 was mixed with a surface water or drain sample from August 2004 because groundwater samples from a particular season are assumed to be representative of the average water quality for that particular source over the entire year. In other words, the water quality of geothermal and deep saline groundwater is assumed to have little seasonal variation (relative to that of surface water samples).

Another limitation of the mixing calculations is the lack of continuous streamflow along the Rio Grande during the January 2005 sampling event (Section 5.4.2). When streamflow is not continually present along a particular reach, mixing calculations are not possible because the composition for the starting point of the mix is unknown.

The geochemical modeling presented in this section includes simple mixing calculations, reaction modeling, and inverse mass balance computations. All models are a simplification of a complex hydrogeologic system; nevertheless, even simple, two-component mixing models can provide useful information about the plausibility or likelihood of various mixing scenarios.

Table 7-1. Mixing Scenarios

Reach [a]	Mixing Scenario	Starting Composition (A)	% A	Potential Source [b] (B)	% B	Target Sample	Type of Mixing	Other Processes Considered	Major Ion Figure	Sulfur Isotope Figure	Strontium Isotope Figure	Boron Isotope Figure	Table
1	Mix 1	RG-EB (Jan)	77.6	GW-Chrl	22.4	RG-abvTC (Jan)	Simple mixing with reaction	Dissolution of gypsum and the addition of strontium due to leaching from Tertiary volcanics	7-1	7-3	7-4	7-5	7-2
	Mix 2		96.2	GW-ISC4a	3.8	RG-abvTC (Jan)	Simple mixing	None	7-2				7-3
2	Mix 3	RG-Cab (Aug) concentrated by 1.7	92.5	GW-Chrl	7.5	DR-Ton (Jan)	Simple mixing with reaction	Dissolution of gypsum and the addition of strontium due to leaching from Tertiary volcanics	7-6	7-8	7-9	7-10	7-4
	Mix 4		98.8	GW-ISC4a	1.2	DR-Ton (Jan)	Simple mixing	None	7-7				7-5
3	Mix 5	RG-Cab (Aug) concentrated by 1.83	69.1	GW-ISC5	30.9	DR-Mont (Jan)	Simple mixing	None	7-11	7-13	7-14	7-15	7-6
	Mix 6		93.3	GW-ISC4a	6.7	DR-Mont (Jan)	Simple mixing with reaction	Dissolution of gypsum and the addition of strontium due to leaching from Tertiary volcanics	7-12				7-7
4	Mix 7	RG-blwED (Jan)	NA	GW-ISC5	NA	RG-EP (Jan)	Simple mixing and inverse modeling [c]	None	NA	7-16	7-17	7-18	NA
	Mix 8		NA	DR-Mont	NA	RG-EP (Jan)			NA				NA
	Mix 9		NA	GW-ISC4a	NA	RG-EP (Jan)			NA				NA

[a] Reach 1 = Rio Grande below Elephant Butte Dam to Rio Grande above Truth or Consequences wastewater treatment plant
Reach 2 = Rio Grande below Caballo Dam to Tonuco Drain
Reach 3 = Rio Grande below Caballo Dam to Montoya Drain
Reach 4 = Montoya Drain to the Rio Grande at El Paso

[b] End member sample dates not reported because there is only one sample available for each site, and it is assumed that the geochemical signature of deep groundwater and geothermal water does not change significantly with time.

[c] See Table 7-8 for details of the inverse modeling.

Simple mixing calculations are performed in a spreadsheet model. Two sources (the starting composition and a potential source) are proportionally combined so that the chloride concentration of the mix matches that of the target. The major ions and isotopic compositions of the resulting mix are then compared to that of the target.

Mixing with reaction extends the simple mixing approach to include physical processes, such as evaporation, transpiration, or chemical reactions with the soil minerals. As with the simple mixing calculations, these calculations are performed in a spreadsheet. The details of such reactions require a significant amount of data from a specific location to model this process precisely; consequently, the computations done here are designed to approximate the mixing with reactions that "bound" the target composition. If a bounding set of water compositions cannot be simulated using real analyses, then the correct end members have probably not been identified.

Inverse modeling is a more rigorous approach in which initial water compositions (the starting point and potential sources) are mixed and reacted mathematically in virtually every possible combination that could yield a hypothetical water composition that matches a final actual water composition. The degree to which the match is considered acceptable can be defined. For example, the composition of one or more source waters could be mixed mathematically with Rio Grande water such that the major ions and isotopic compositions of the defined proportions match a final target composition within a certain defined error limit, or there is no solution. The purpose is to objectively determine if the identified sources could plausibly be mixed in such a way to yield the observed final composition of a downgradient water sample.

Sections 7.1.1 through 7.1.4 discuss the investigation of four reaches of the LRG (Table 7-1). For each reach and each modeling scenario, the essential assumptions are presented and justified. Major ions are compared graphically, mixing proportions are identified, and the plausibility of the various mixing scenarios is evaluated based on the goodness of fit. The isotopic values of hydrogen (δD), oxygen ($\delta^{18}O$), sulfur ($\delta^{34}S$), strontium ($^{87}Sr/^{86}Sr$) and boron ($\delta^{11}B$) are examined. Other isotopic data (e.g., nitrogen [$\delta^{15}N$], uranium [$^{234/238}U$], and radium [^{226}Ra, ^{228}Ra]) are available, but are not useful in the mixing evaluations for several reasons: (1) the analytical error is too large, (2) the concentrations are near the detection limit, or

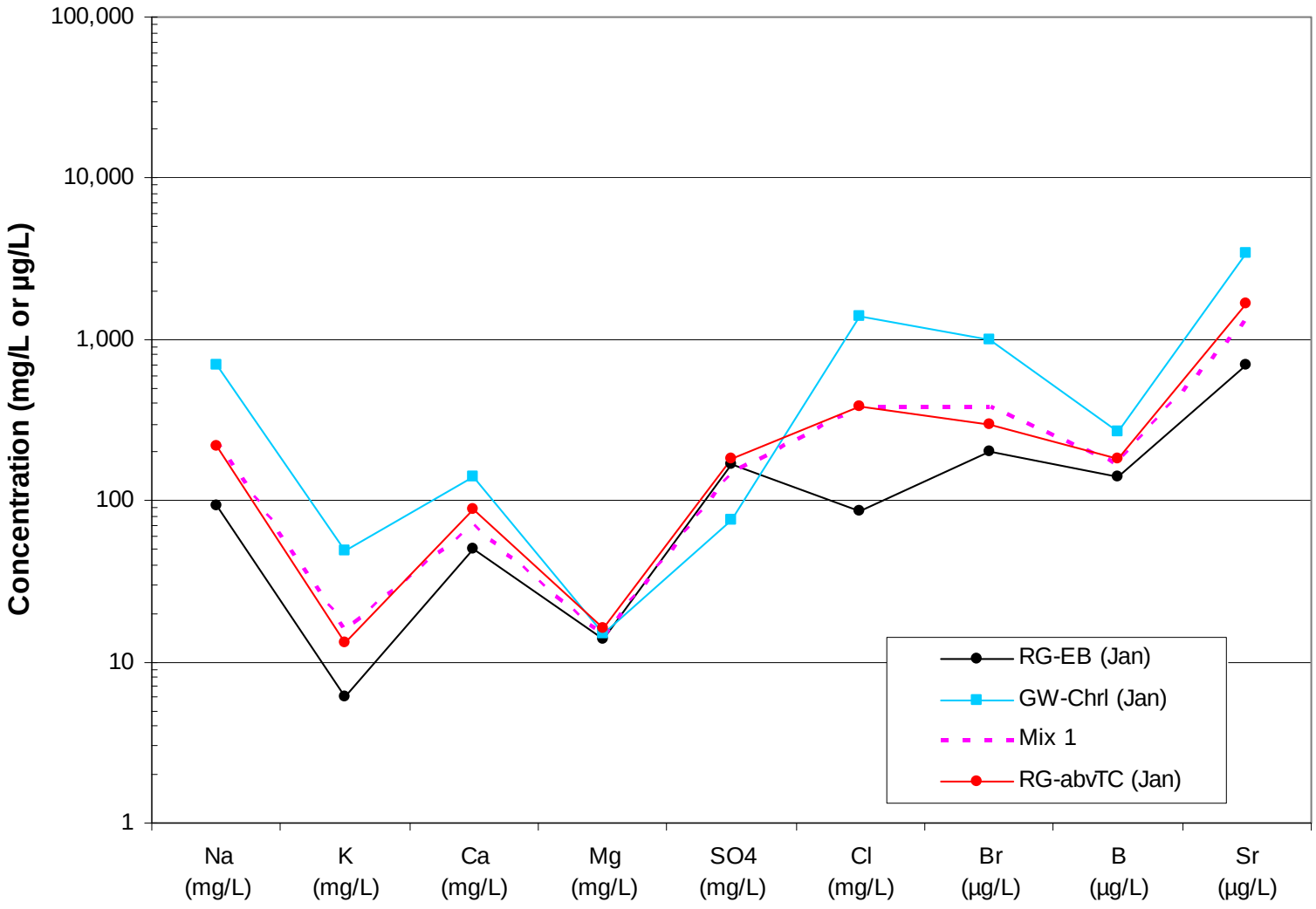
(3) there is evidence of reaction and mass loss that cannot be quantified. Isotopic ratios plotted against the elemental composition of the isotope being examined yield non-linear mixing curves because the mixes are volume-based and the isotopes are mixed by mass. Isotopic mixing calculations are useful because they provide an independent check of mixing plausibility and yield more accuracy when defining small mixing proportions (Bassett, 1990; Davidson and Bassett, 1993; Bassett et al., 1995).

7.1.1 Reach 1: Rio Grande below Elephant Butte Dam to Rio Grande above Truth or Consequences WWTP

The mixing scenarios discussed in this section were designed to gain insight into the causes of the observed geochemical changes that occur over the relatively short distance between RG-EB and RG-abvTC (Reach 1) (Figure 2-3). The starting point for this reach is RG-EB (Jan). The January data from RG-EB were used as the starting point because it allows for consistency with the January end point at RG-abvTC and because using the January data point is more conservative (because it is already more concentrated than the August data point). The Truth or Consequences area is known for geothermal springs; therefore, GW-Chrl was selected as a potential source for one of the mixing scenarios (Mix 1) (Table 7-1). Because there were no deep saline groundwater samples available for this area, GW-ISC4a was selected as a potential source to evaluate the possibility of input from deep saline groundwater (Mix 2) (Table 7-1). Simple mixing calculations were performed on Mix 1 and Mix 2. The proportions of each source required to reproduce the chloride composition of the target sample are shown in Table 7-1.

A mixture of 78 percent RG-EB (Jan) and 22 percent GW-Chrl results in an identical chloride concentration to that of the target sample, RG-abvTC (Jan). Error for other major ion concentrations is less than or equal to 26 percent (Figure 7-1; Table 7-2). This mixture is reasonable during the winter season, when little water is released from Elephant Butte Reservoir and contributions from groundwater seepage are relatively large; however, during the irrigation season, 22 percent of groundwater would be an unreasonable assumption.

A mixture of 96 percent RG-EB (Jan) and 4 percent GW-ISC4a results in an identical chloride concentration to that of the target sample, RG-abvTC (Jan); however, error for other major ion



Note: (Jan) indicates data from January 2005 sampling event, while (Aug) denotes data from August 2004.

LRG SALINITY

Major Ion Concentrations
Mix 1

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Figure 7-1

Table 7-2. Mixing Results, Mix 1

Analyte	Units	Starting Composition [RG-EB (Jan)]	Potential Source [GW-Chrl (Jan)]	Mix 1 [a]	Target Sample [RG-abvTC (Jan)]	% Error [b]
Na	mg/L	94	700	230	220	4
K	mg/L	6.1	49	15.7	13	21
Ca	mg/L	50	140	70	88	20
Mg	mg/L	14	15	14	16	11
SO_4	mg/L	170	75	149	180	17
Cl	mg/L	86	1,400	380	380	0
Br	µg/L	200	1,000	379	300	26
B	µg/L	140	270	169	180	6
Sr	µg/L	698	3,450	1,314	1,660	21
N	mg/L as N	0.2	0.43	0.3	0.25	1
Cl/Br	Ratio	430	1,400	1,003	1,267	21
δD	‰	–69	–67	–68.6	–69	1
$\delta^{18}O$	‰	–8.1	–9.1	–8.3	–8.4	1
$\delta^{11}B$	‰	9.1	5.6	7.85	10.8	NA
$^{87}Sr/^{86}Sr$	Ratio	0.710193	0.720366	0.716170	0.713708	NA
$\delta^{34}S$	‰	0.4	9.7	1.4	4.5	NA

[a] Mix 1 = 77.6% RG-EB (Jan) + 22.4% GW-Chrl
[b] Absolute value of error

mg/L = Milligrams per liter
µg/L = Micrograms per liter
‰ = Per mille
NA = Not applicable

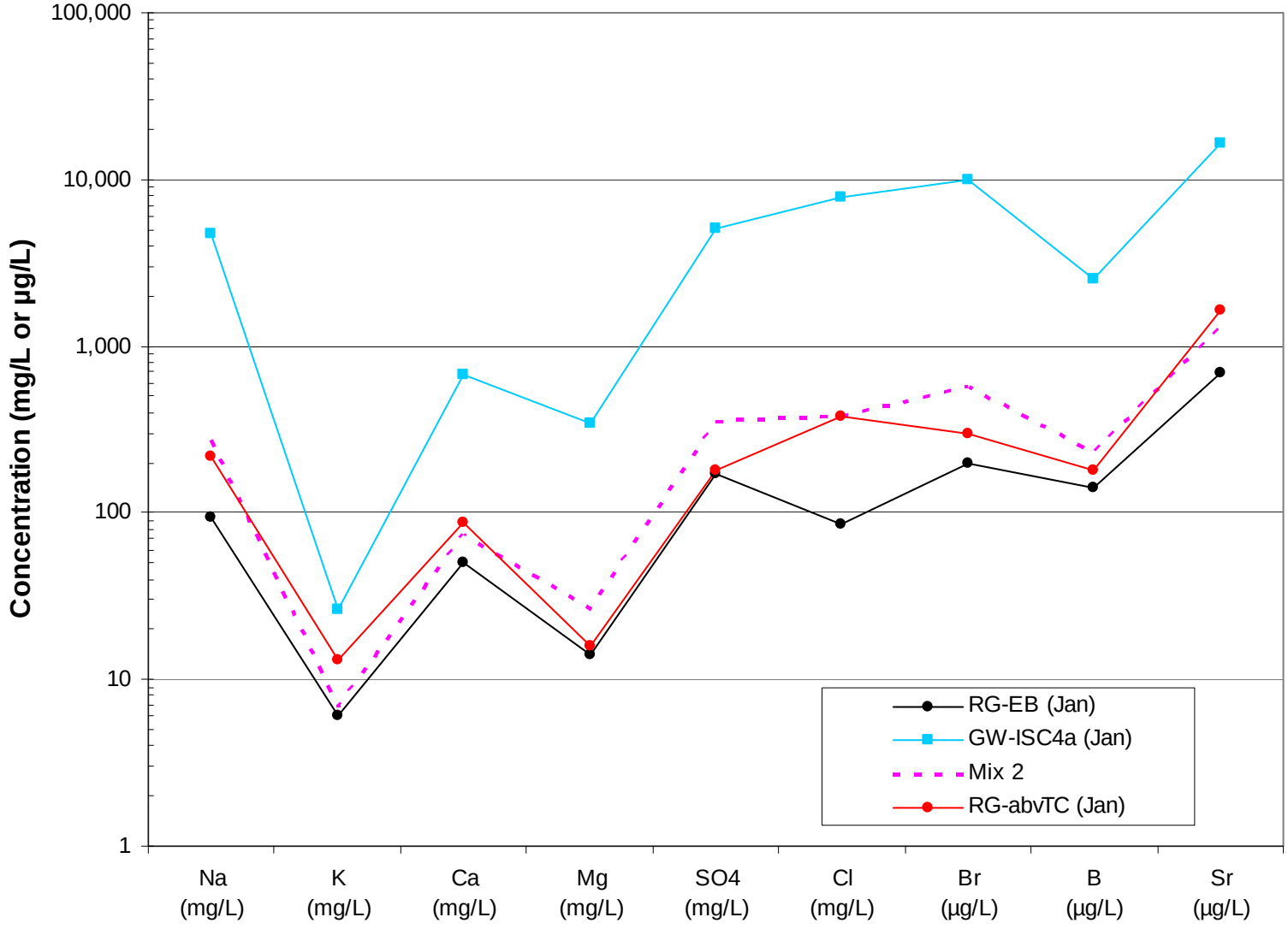
concentrations is as high as 97 percent (Figure 7-2; Table 7-3). The large error associated with the major ion concentrations for Mix 2 indicates that a simple mix of RG-EB (Jan) and GW-ISC4a cannot explain the observed geochemical changes along Reach 1.

Examination of isotopic compositions that result from Mix 1 and Mix 2 indicate that simple two-component mixing cannot adequately explain the observed isotopic compositions (Figures 7-3 through 7-5). However, the target point, RG-abvTC (Jan), is bounded by the two mixing lines that represent Mix 1 and Mix 2, indicating that a three-component mix between RG-EB (Jan), GW-Chrl, and GW-ISC4a could yield an appropriate isotopic composition. The isotopic change and significant increase in chloride concentration along Reach 1 is such that groundwater must be one of the components because evapotranspiration alone cannot cause the observed changes.

Another plausible scenario for Reach 1 is mixing a geothermal groundwater (such as GW-Chrl) with some dissolution of minerals. Examination of the geochemical composition of the components in Mix 1 (Table 7-2) indicates that the composition of the resulting mix matches the chloride, boron, and bromide composition of the target, RG-abvTC (Jan), rather well; however, the resulting mix is deficient in sulfate and strontium. Examination of the isotopic compositions of Mix 1 indicates that the additional mass of sulfate and strontium is required to match the composition of the target sample (Figures 7-3 and 7-4; Table 7-2). Furthermore, the isotopic data indicate that the new mass must have a more enriched $\delta^{34}S$ value and a lower $^{87}Sr/^{86}Sr$ ratio.

The dissolution of a mineral such as gypsum is a reasonable consideration for the sulfate source. Gypsum as a source makes sense for several reasons:

- It is ubiquitous in the region as aeolian dust.
- It provides additional sulfate and calcium.
- The water is undersaturated with respect to gypsum so it has the potential to dissolve.



Note: (Jan) indicates data from January 2005 sampling event, while (Aug) denotes data from August 2004.

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Major Ion Concentrations
Mix 2

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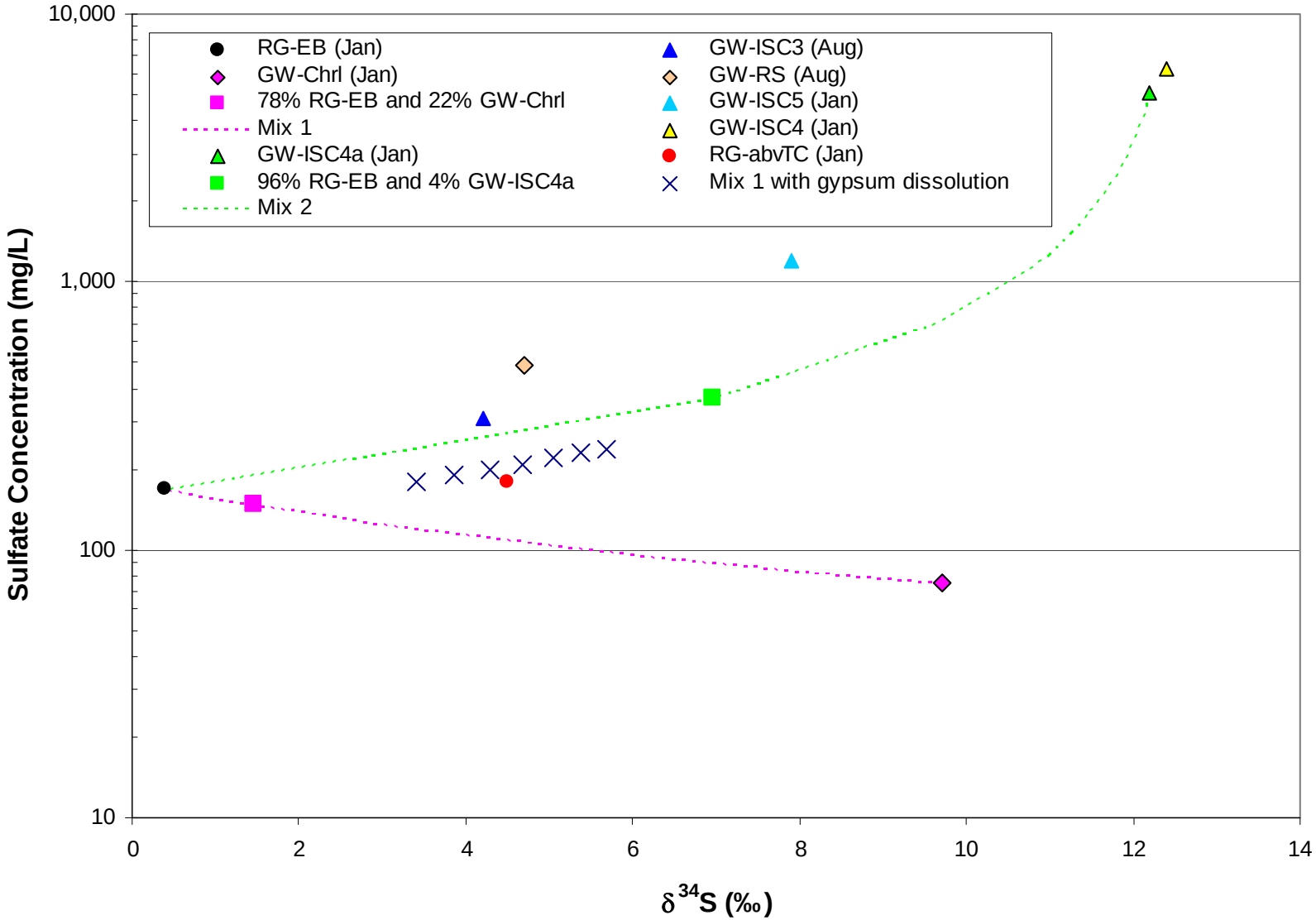
Figure 7-2

Table 7-3. Mixing Results, Mix 2

Analyte	Units	Starting Composition [RG-EB (Jan)]	Potential Source [GW-ISC4a (Jan)]	Mix 2 [a]	Target Sample [RG-abvTC (Jan)]	% Error [b]
Na	mg/L	94	4,700	267	220	22
K	mg/L	6.1	26	6.8	13	47
Ca	mg/L	50	670	73	88	17
Mg	mg/L	14	340	26	16	64
SO_4	mg/L	170	5,100	355	180	97
Cl	mg/L	86	7,900	380	380	0
Br	µg/L	200	10,000	568.73	300	90
B	µg/L	140	2,500	229	180	27
Sr	µg/L	698	16,500	1,292.55	1,660	22
N	mg/L as N	0.2	0.96	0.2	0.25	9
Cl/Br	Ratio	430	790	668	1,267	47
δD	‰	–69	–66	–68.9	–69	0.2
$\delta^{18}O$	‰	–8.1	–8.0	–8.1	–8.4	3.6
$\delta^{11}B$	‰	9.1	30.8	18.06	10.8	NA
$^{87}Sr/^{86}Sr$	Ratio	0.710193	0.710149	0.710172	0.713708	NA
$\delta^{34}S$	‰	0.4	12.2	6.8	4.5	NA

[a] Mix 2 = 96.2% RG-EB (Jan) + 3.8% GW-ISC4a
[b] Absolute value of error

mg/L = Milligrams per liter
µg/L = Micrograms per liter
‰ = Per mille
NA = Not applicable



Note: (Jan) indicates data from January 2005 sampling event, while (Aug) denotes data from August 2004.

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Sulfur Isotopic Values
Mix 1 and Mix 2

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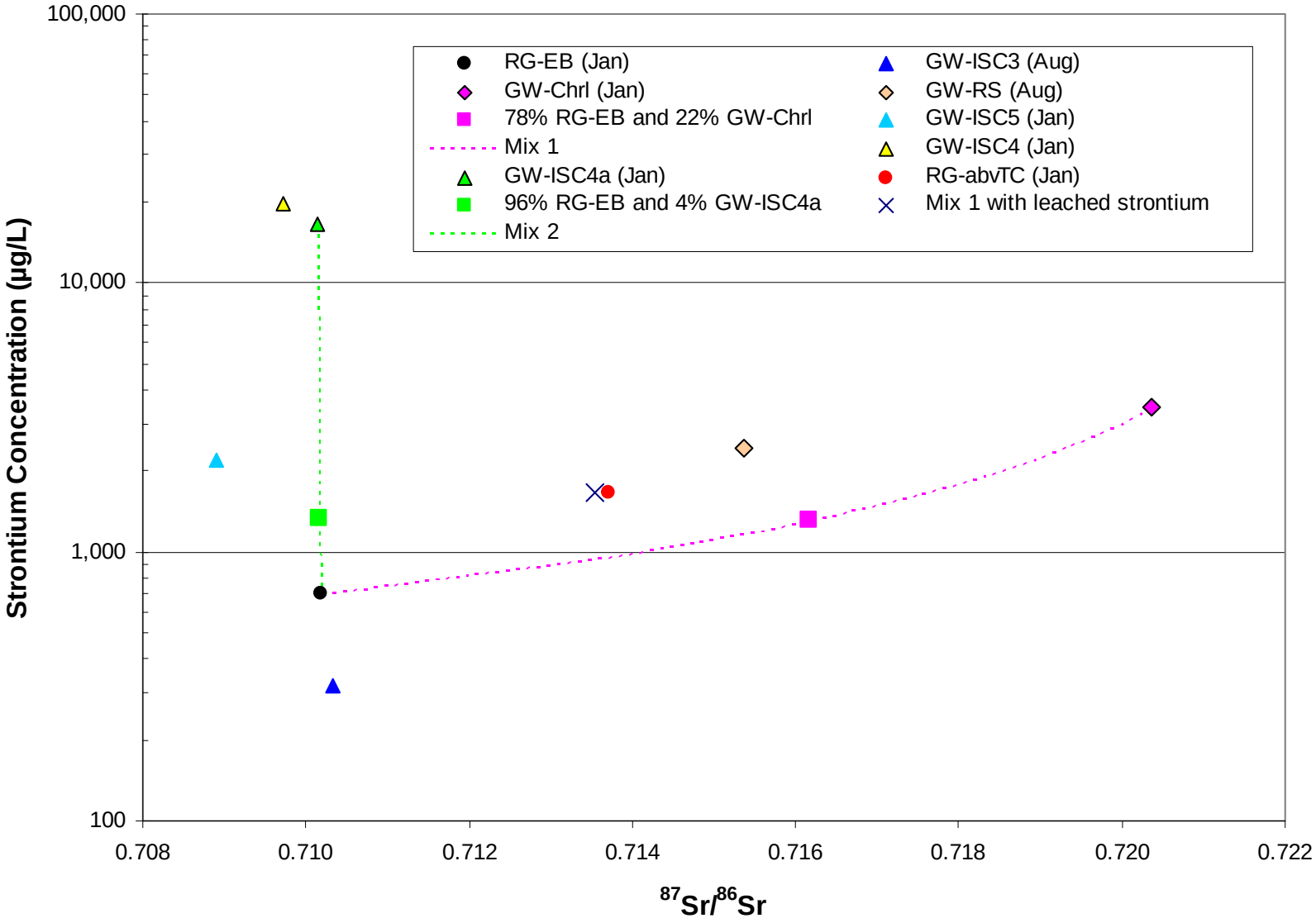
Figure 7-3



Note: (Jan) indicates data from January 2005 sampling event, while (Aug) denotes data from August 2004.

LRG SALINITY

Strontium Isotopic Values
Mix 1 and Mix 2

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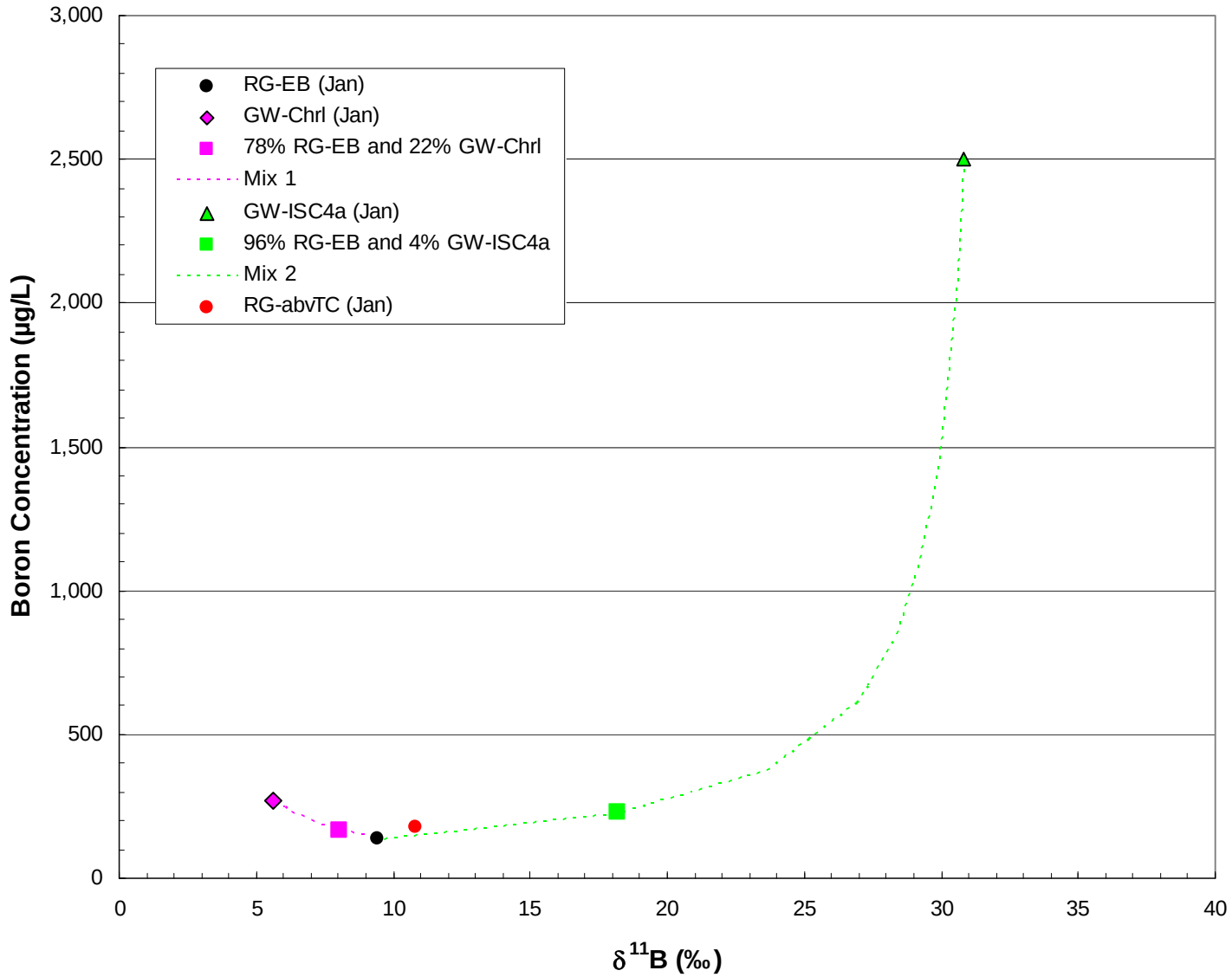
Figure 7-4



Note: (Jan) indicates data from January 2005 sampling event, while (Aug) denotes data from August 2004.

LRG SALINITY

Boron Isotopic Values
Mix 1 and Mix 2

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Figure 7-5

The $\delta^{34}S$ value for gypsum from Permian rocks in the Middle Rio Grande region is reported as 12.6 ± 1.3‰ (Plummer et al., 2004). The gypsum source is most likely aeolian gypsum-rich dust from the abundant Permian evaporites in the region. The $\delta^{34}S$ value of near 12‰ is typical of Permian sulfate minerals. By assuming that the difference in sulfate concentration between Mix 1 and the RG-abvTC sample is attributable to dissolution of gypsum with a $\delta^{34}S$ of 12.6‰, the elemental and isotopic composition of the resulting mix (Mix 1 with gypsum dissolution) approaches that of the target sample, RG-abvTC (Figure 7-3). Two additional observations can be made about Figure 7-3. First, considering only Mix 1, the progressive addition of gypsum yields a large isotopic shift with a trajectory that essentially intersects the composition of RG-abvTC, even if allowance is made for variability in sample composition. This is because the major change in trajectory is in the isotopic value, not the sulfate concentration. Secondly, if a small amount of mixing from another saline groundwater source is also occurring, it will only improve the prediction because the $\delta^{34}S$ of the saline groundwater is more enriched than RG-abvTC and a mix will shift the prediction closer to the target.

In a similar fashion, strontium is readily leached from volcanic rocks, and the region has significant coverage of Tertiary volcanics with $^{87}Sr/^{86}Sr$ ratio between 0.703 and 0.704 (Witcher et al., 2004). Again, if the strontium deficiency between Mix 1 and RG-abvTC is attributed to leaching of strontium with this isotopic ratio, the elemental and isotopic composition of the resulting mix approaches that of the target sample, RG-abvTC (Figure 7-4). As in the case of the $\delta^{34}S$, a small contribution from a saline groundwater may even improve the prediction.

The boron isotopic data (Figure 7-5) further support the concept of predominant mixing defined by Mix 1 with a small contribution from a saline groundwater. The boron isotopic composition for the target sample, RG-abvTC (Jan), is more enriched in ^{11}B than either the starting point, RG-EB (Jan), or the geothermal groundwater, GW-Chrl. In order to reproduce the boron isotopic composition of the target sample, there must be a contribution from a source that is enriched in ^{11}B, such as GW-ISC4a, which has $\delta^{11}B$ values in the +30‰ range. Boron isotopic compositions in this range are commonly observed in waters of marine origin (Bassett, 1990). Such a source could be a marine limestone or shale; however, it is more probable that at least a small part of the mixing observed in this part of the LRG is in fact also being derived from a

deep saline groundwater (perhaps one that has not yet been sampled), in addition to the geothermal groundwater source.

This analysis is useful because it confirms that actual groundwater and mineral compositions have been identified that have the appropriate isotopic values to bound or approximate the target Rio Grande sample, and to explain (1) the increase in boron, chloride, sulfate, and strontium concentrations, and (2) the change in the isotopic composition of the river. It is sufficient at this stage to acknowledge that a deep groundwater mixing component is necessary, and that this groundwater must have a composition that contributes elevated chloride, enriched $\delta^{34}S$ and $\delta^{11}B$ values, and reduced $^{87}Sr/^{86}Sr$ ratio. Further sampling of local groundwater could help to constrain mixing in the lower Rio Grande.

7.1.2 Reach 2: Rio Grande below Caballo Dam to Tonuco Drain

The mixing scenarios discussed in this section were designed to gain insight into the causes of the observed geochemical changes that occur between RG-Cab and DR-Ton (Reach 2) (Figure 2-3). The water from the Rio Grande is diverted into the Rincon Valley at Percha Diversion Dam (Figure 2-3), which is immediately below Caballo Dam. The RG-Cab (Aug) sample is therefore used as the starting point for this reach (Table 7-1). The winter sample for DR-Ton was chosen as the target sample for this reach.

Water in Tonuco Drain represents shallow alluvial groundwater that has discharged from the adjacent agricultural fields. It is assumed that the following sequence of events is representative of the process:

1. During the irrigation season, water from the Rio Grande (represented by the RG-Cab [Aug] sample), is diverted into the irrigation canals at Percha Diversion Dam (Figure 2-3).

2. During transit from Percha Diversion Dam to the agricultural fields, some water is lost from the canals due to leakage and evaporation; however, the chemical composition of the water does not change significantly.

3. The diverted water is applied to the fields for irrigation. Water in the Rincon Valley is concentrated by a factor of 1.7 due to losses to evapotranspiration and seepage from canals (NMISC, 2005).

4. Excess irrigation water (the water that is not lost to evapotranspiration) infiltrates into the shallow alluvial aquifer and mixes with a deep saline groundwater, which is more saline and has a different isotopic composition that Rio Grande water.

5. Water that has infiltrated into the shallow alluvial aquifer discharges to the agricultural drains throughout the year.

Simple mixing with reaction was the modeling approach used for this reach (Table 7-1). Two potential sources were chosen for the mixing scenarios: GW-Chrl and GW-ISC4a. For both mixing scenarios, the RG-Cab (Aug) sample, which represents the starting point for Reach 2, was concentrated by a factor of 1.7 (NMISC, 2005; Appendix E). The concentration factor is an important consideration. The assertion might be made that saline groundwater sources are not needed to explain the increase in chloride because similar increases could be attributed to evaporation and transpiration. This assertion is addressed first by relying on evaporation and transpiration data from independent hydrologic studies that limit the concentration factor to 1.7 (NMISC, 2005); thus, the resultant increase in chloride concentration is well below that observed for the Tonuco Drain composition (Table 7-4).

It is important to note that the isotopic data also support the need for an additional water source. The δD and $\delta^{18}O$ values are enriched (Table 7-4), but the observed enrichment indicates evaporation is limited to approximately 11 percent. The concentration factor of 1.7 therefore frames the context of the change in composition to one of mixing with other water sources or reaction with minerals or other additives. Additionally, concentration alone will not alter the stable isotopic ratios of the solute, and mixing with other water sources is the most plausible alternative.

The 1.7 concentration factor is an average value for typical full supply water year; major assumptions are provided in Appendix E (NMISC, 2005). This concentration factor varies, and

Table 7-4. Mixing Results, Mix 3

Analyte	Units	Starting Composition [RG-Cab (Aug), concentrated [a]]	Potential Source [GW-Chrl (Jan)]	Mix 3 [b]	Target Sample [DR-Ton (Jan)]	% Error [c]
Na	mg/L	144.5	700	186	190	2
K	mg/L	10.2	49	13.1	7.5	75
Ca	mg/L	91.8	140	95.4	120	20
Mg	mg/L	22.1	15	21.6	26	17
SO_4	mg/L	238	75	225.8	440	49
Cl	mg/L	113.9	1,400	210.0	210	0
Br	µg/L	238	1,000	294.9	500	41
B	µg/L	238	270	240.4	230	5
Sr	µg/L	1,157.7	3,450	1,328.9	1,620	18
N	mg/L as N	0.187	0.43	0.2	0.32	36
Cl/Br	Ratio	479	1,400	712	420	70
$\delta^{11}B$	‰	4.7	5.6	4.78	17.3	NA
$^{87}Sr/^{86}Sr$	Ratio	0.710331	0.720366	0.712277	0.711091	NA
$\delta^{34}S$	‰	1.0	9.7	1.2	6.1	NA

[a] Concentrated by 1.7
[b] Mix 3 = 92.5% RG-Cab (Aug), concentrated + 7.5% GW-Chrl
[c] Absolute value of error

mg/L = Milligrams per liter
µg/L = Micrograms per liter
‰ = Per mille
NA = Not applicable

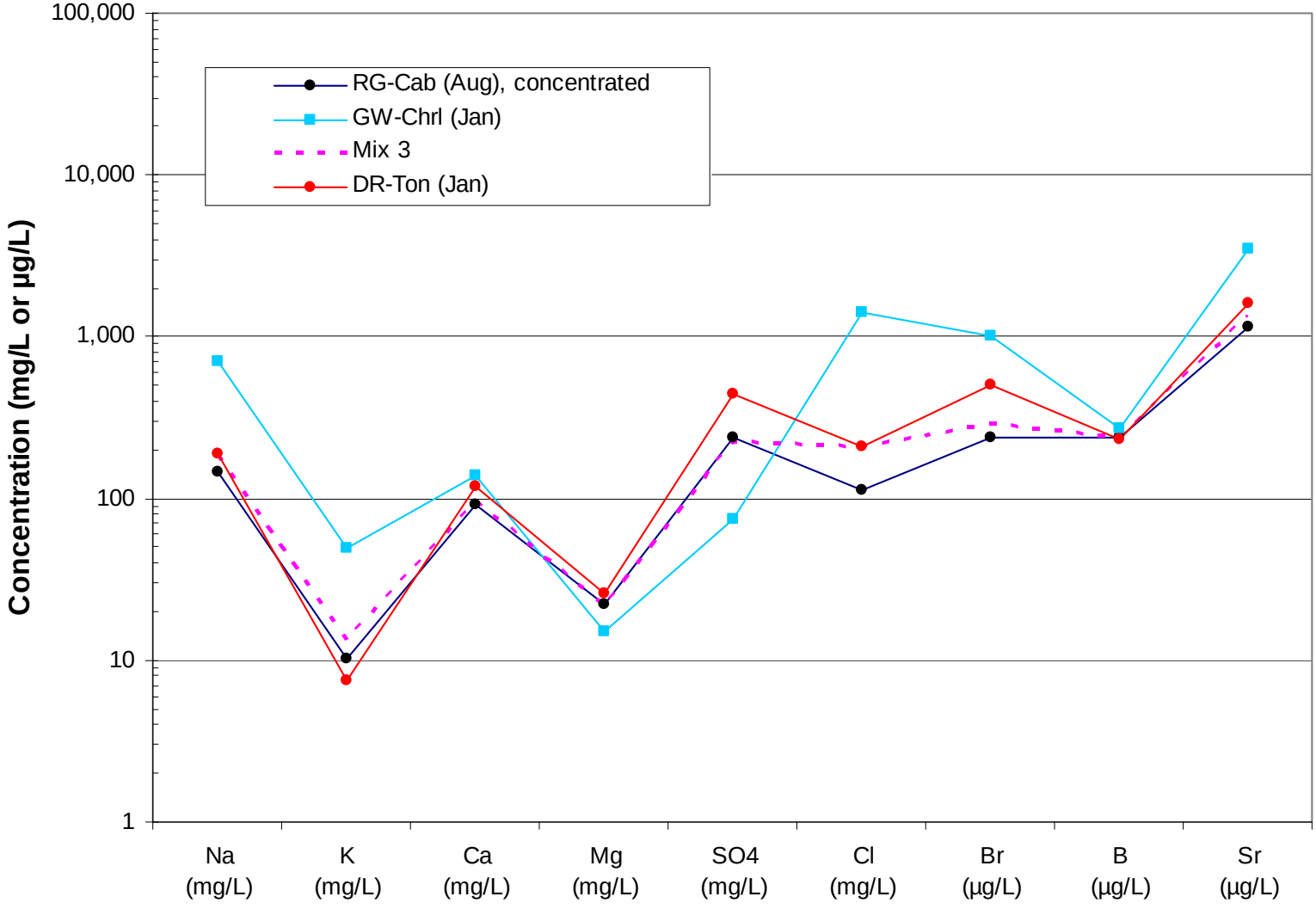
would likely increase in a low-supply year. Even with a concentration factor as high as 3.1 (which is needed to match the 210 mg/L chloride concentration of the target sample), the isotopic values of the concentrated water would still not match that of the target sample, which indicates the need for an additional water source.

Major ion compositions indicate that a simple two-component mixing scenario is insufficient to reproduce the observed geochemical changes along Reach 2 (Table 7-1). A mixture of 92.5 percent concentrated RG-Cab (Aug) and 7.5 percent GW-Chrl (Mix 3) results in an identical chloride concentration to that of the target sample, DR-Ton (Jan). Error for other major ion concentrations is less than or equal to 75 percent (Figure 7-6; Table 7-4). A mixture of 98.8 percent concentrated RG-Cab (Aug) and 1.2 percent GW-ISC4a (Mix 4) results in an identical chloride concentration to that of the target sample, DR-Ton (Jan). Error for other major ion concentrations is less than or equal to 39 percent (Figure 7-7; Table 7-5). It is important to remember that not only is the error large; there is also a deficit in mass for several key elements such as sulfate, calcium, strontium, and bromide, and the stable isotope values do not match. As discussed in Section 7.1.1, additional sulfate and calcium can be obtained from gypsum dissolution and strontium from leaching, and the isotopic data will shift with mixing of additional groundwater.

The elemental concentration and isotopic composition of sulfur at DR-Ton (Jan) can be reproduced by either one of the following mixing scenarios (Table 7-1; Figure 7-8); however, only Mix 3 satisfies the constraints imposed by the other stable isotopes:

1. Mix 3 (RG-Cab with GW-Chrl) with additional reaction (i.e., gypsum dissolution)
2. Mix 4 (RG-Cab with GW-ISc4a) with additional reaction (i.e., gypsum dissolution)

The strontium data indicate that of the two scenarios, only a source with a lower $^{87}Sr/^{86}Sr$ ratio (such as leached Tertiary volcanics) combined with Mix 3 will match the target, because this same source will move the Mix 4 value away from the target isotopic value (Figure 7-9).



Note: (Jan) indicates data from January 2005 sampling event, while (Aug) denotes data from August 2004.

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Major Ion Concentrations
Mix 3

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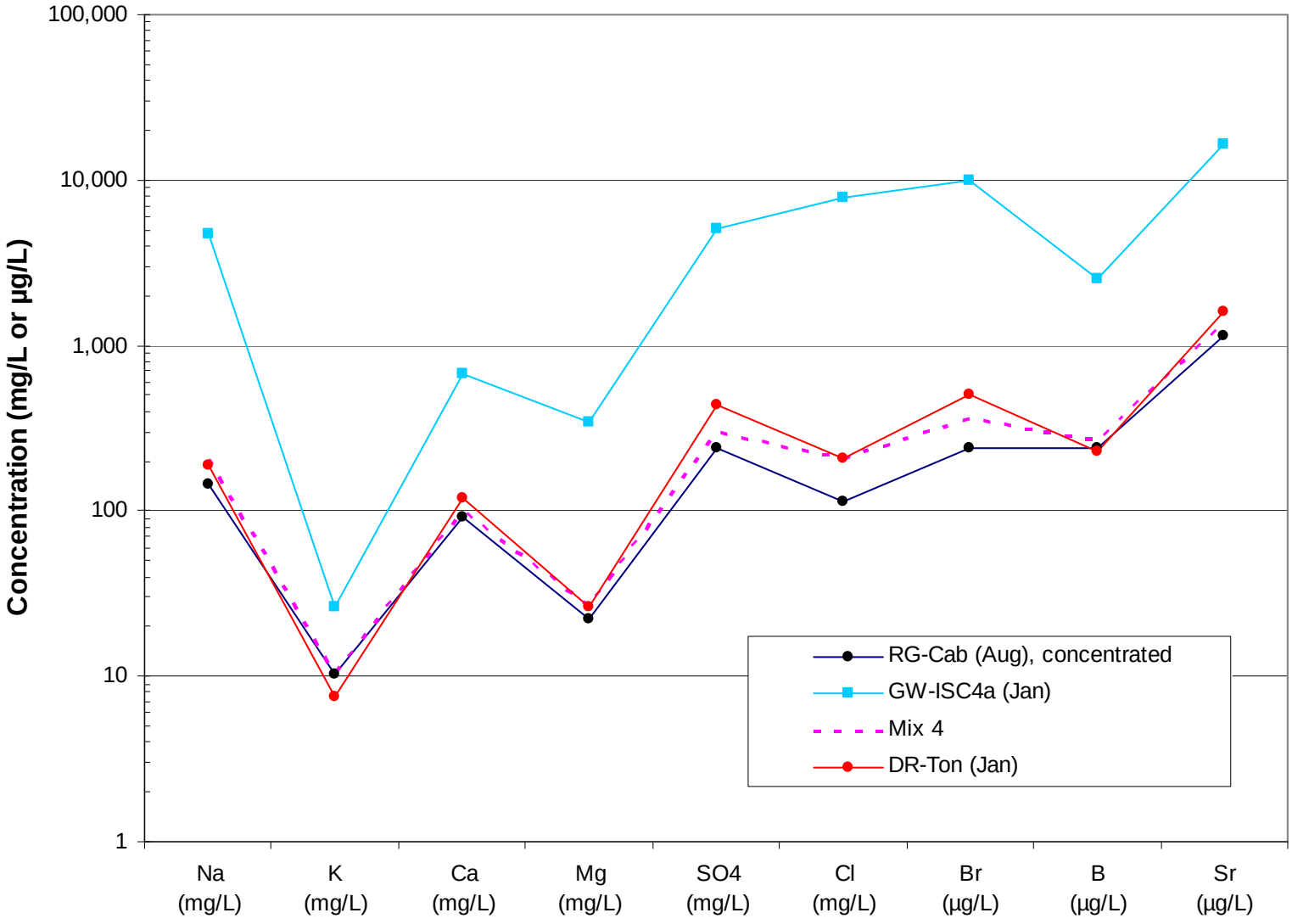
Figure 7-6



Note: (Jan) indicates data from January 2005 sampling event, while (Aug) denotes data from August 2004.

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Major Ion Concentrations
Mix 4

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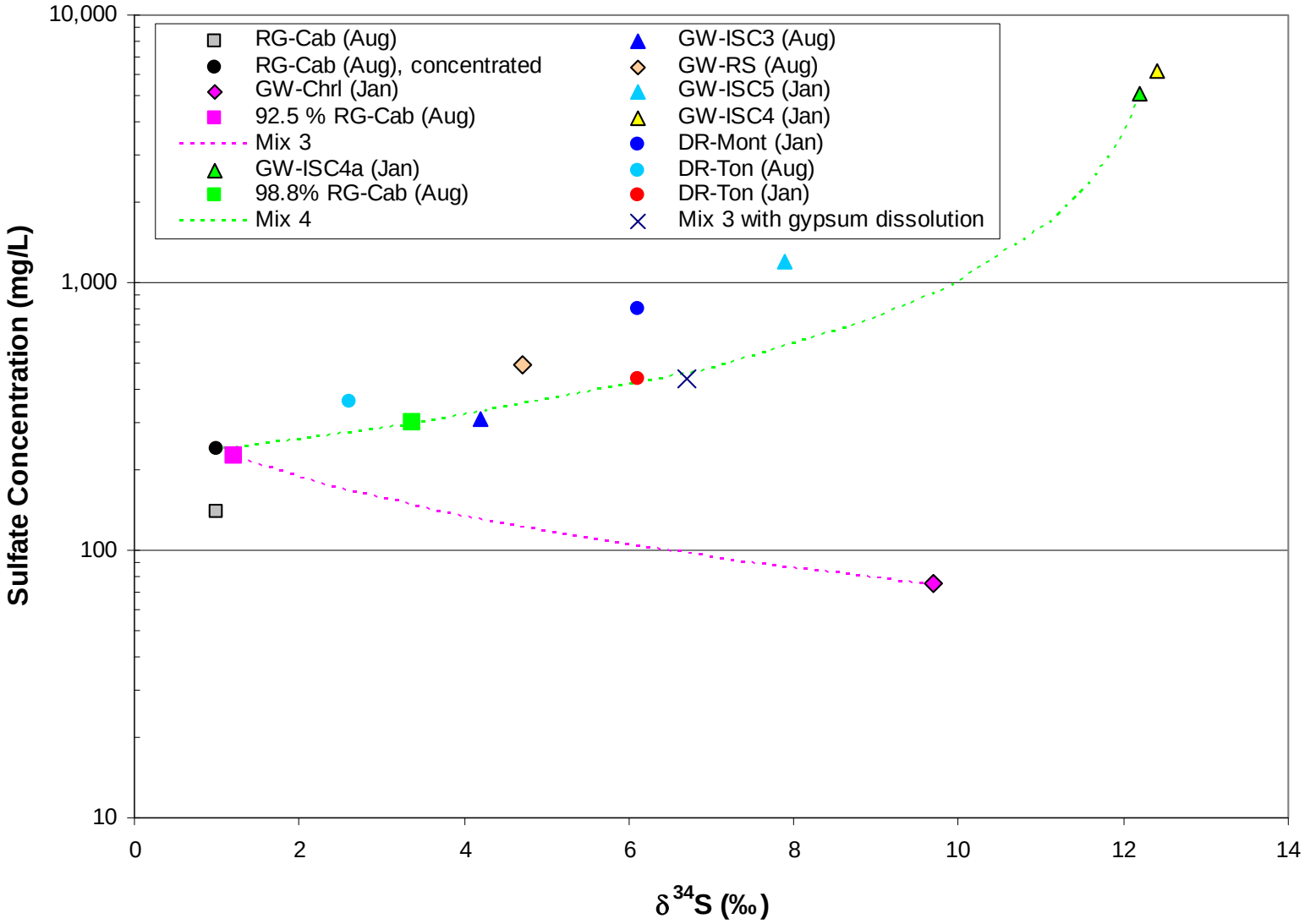
Figure 7-7

Table 7-5. Mixing Results, Mix 4

Analyte	Units	Starting Composition [RG-Cab (Aug), concentrated [a]]	Potential Source [GW-ISC4a (Jan)]	Mix 4 [b]	Target Sample [DR-Ton (Jan)]	% Error [c]
Na	mg/L	144.5	4,700	201	190	6
K	mg/L	10.2	26	10.4	7.5	39
Ca	mg/L	91.8	670	98.9	120	18
Mg	mg/L	22.1	340	26.0	26	0
SO_4	mg/L	238	5,100	298.0	440	32
Cl	mg/L	113.9	7,900	210.0	210	0
Br	µg/L	238	10,000	358.5	500	28
B	µg/L	238	2,500	265.9	230	16
Sr	µg/L	1,157.7	16,500	1347.0	1620	17
N	mg/L as N	0.187	0.96	0.2	0.32	39
Cl/Br	Ratio	479	790	586	420	39
$\delta^{11}B$	‰	4.7	30.8	7.73	17.3	NA
$^{87}Sr/^{86}Sr$	Ratio	0.710331	0.710149	0.710303	0.711091	NA
$\delta^{34}S$	‰	1.0	12.2	3.4	6.1	NA

[a] Concentrated by 1.7
[b] Mix 4 = 98.8% RG-Cab (Aug), concentrated + 1.2% GW-ISC4a
[c] Absolute value of error

mg/L = Milligrams per liter
µg/L = Micrograms per liter
‰ = Per mille
NA = Not applicable



Note: (Jan) indicates data from January 2005 sampling event, while (Aug) denotes data from August 2004.

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Sulfur Isotopic Values
Mix 3 and Mix 4

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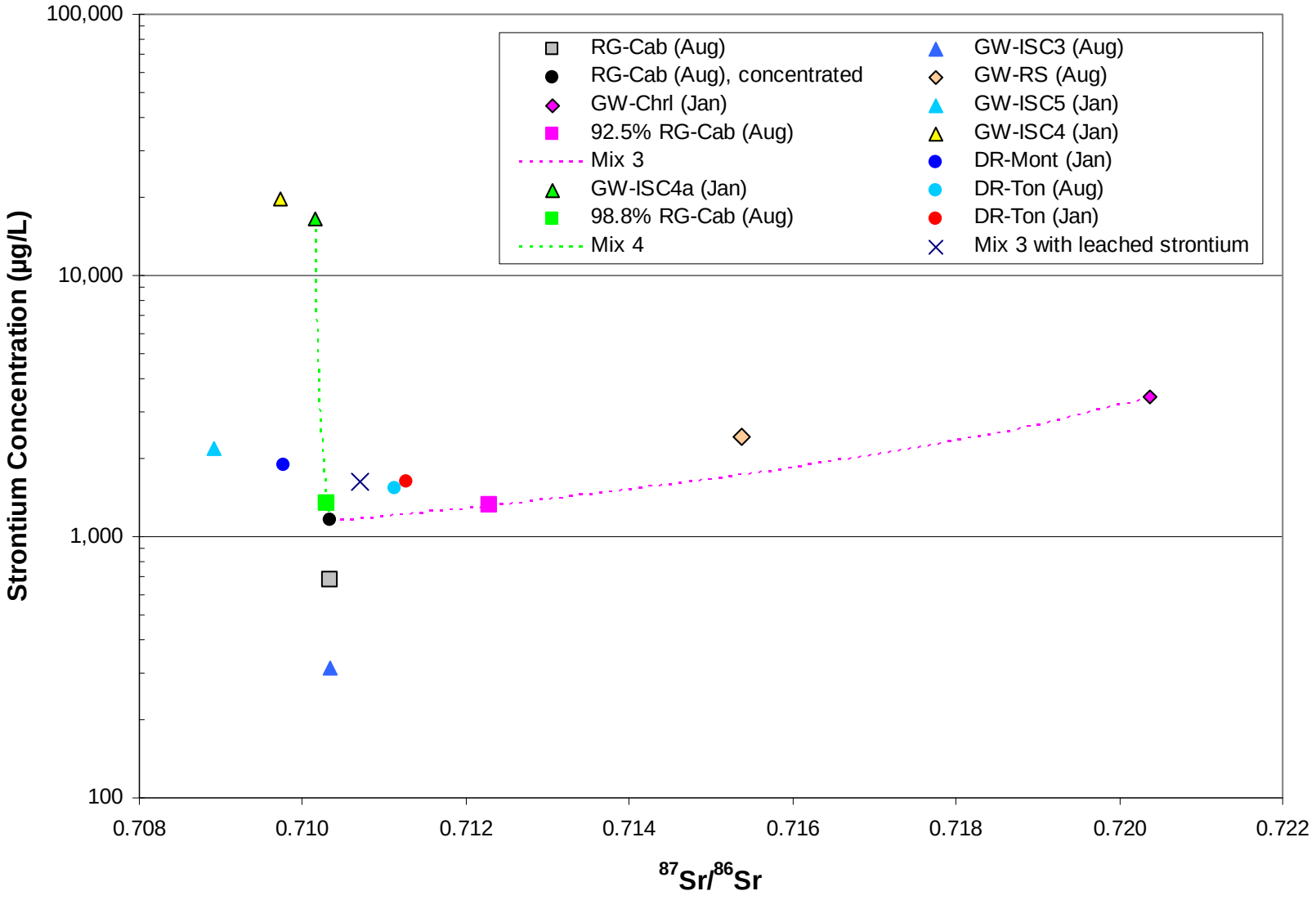
Figure 7-8



Note: (Jan) indicates data from January 2005 sampling event, while (Aug) denotes data from August 2004.

LRG SALINITY

Strontium Isotopic Values
Mix 3 and Mix 4

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Figure 7-9

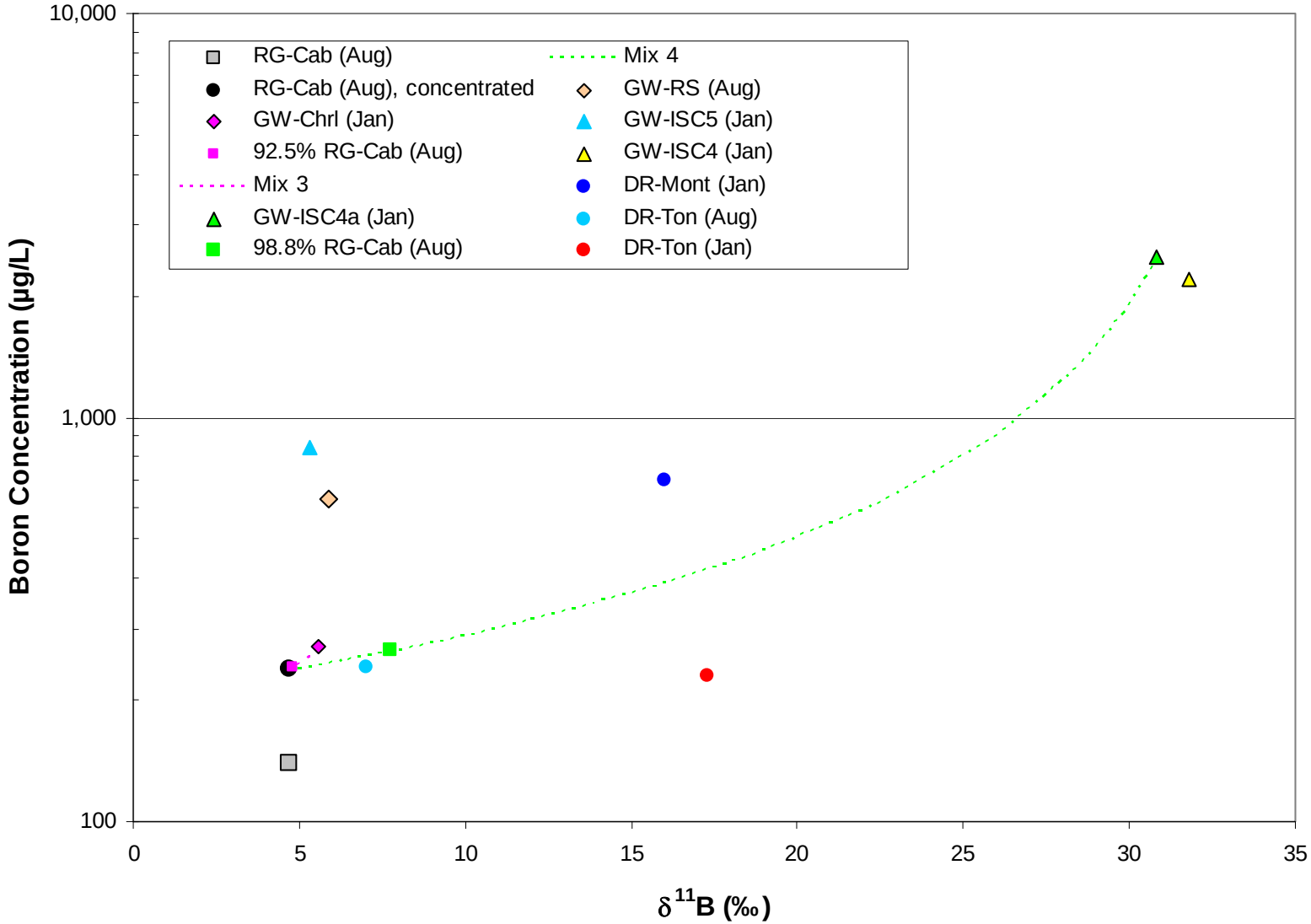
The figures do, however, indicate that a three-component mix between the concentrated RG-Cab (Aug), GW-Chrl, and GW-ISC4a could yield an appropriate isotopic composition because the addition of GW-ISC4a will lower the predicted value more in line with the target point, DR-Ton (Jan) (Figure 7-9). Again, if the strontium deficiency is attributed to leaching of strontium with an isotopic ratio between 0.703 and 0.704 (Witcher et al., 2004), the elemental and isotopic composition of the resulting mix approaches that of the target sample, DR-Ton (Jan) (Figure 7-9).

The elemental and isotopic boron data (Figure 7-10) indicate that another source is required to reproduce the observed changes along Reach 2. That is, the isotopic composition of boron at DR-Ton (Jan) cannot be derived by two-component mixing (Mix 3 or Mix 4) or by a three-component mix between RG-Cab (Aug), GW-Chrl, and GW-ISC4a. It is important to note that a saline groundwater must be part of the mixing scenario because saline groundwater sources have significantly enriched δ^{11}B values, which are required to yield the enriched δ^{11}B value observed for Tonuco Drain. A saline groundwater with a lower boron concentration would match the target (it may be that this will be observed in future sampling of nearby wells), or the same effect could be obtained by dilution of the saline source prior to mixing.

In summary, the elemental and isotopic composition of Tonuco Drain can be approximated by allowing RG-Cab (Aug) water to be concentrated by evapotranspiration, mixed with deep saline groundwater sources, and to react with a few key mineral sources. Identification of an additional source could improve the modeling.

7.1.3 Reach 3: Rio Grande below Caballo Dam to Montoya Drain

The mixing scenarios discussed in this section were designed to gain insight into the causes of the observed geochemical changes that occur between RG-Cab and DR-Mont (Reach 3) (Figure 2-3). During the irrigation season, water from the Rio Grande is diverted into the Mesilla Valley at Leasburg and Mesilla Diversion Dams (Figure 2-3). The Rio Grande was not sampled above either of these diversion dams during August 2004 (Table 5-1); therefore, the RG-Cab (Aug) sample is used as the starting point for this reach (Table 7-1). As discussed in Section 5.4.1, there is little spatial variation in geochemistry along the Rio Grande during August



Note: (Jan) indicates data from January 2005 sampling event, while (Aug) denotes data from August 2004.

LRG SALINITY

Boron Isotopic Values
Mix 3 and Mix 4

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Figure 7-10

2004, especially as compared to that during January 2005. In other words, during the irrigation season, the chemical composition of the river at RG-Cab is very similar to that at RG-EP. It is therefore reasonable to assume that the chemical composition of RG-Cab (Aug) is similar to that of water diverted into Mesilla Valley.

The winter sample for DR-Mont was chosen as the target sample for Reach 3. Water in Montoya Drain represents shallow alluvial groundwater that has discharged from the adjacent agricultural fields. A sequence of events similar to that described in Section 7.1.2 is assumed to occur here, except that the concentration factor for irrigation water in the Mesilla Valley is 1.83 (NMISC, 2005).

Two potential saline groundwater sources were chosen for the mixing scenarios: GW-ISC5 and GW-ISC4a, both of which are located near DR-Mont (Figure 2-3). In both cases, additional sulfate is needed in the mix to simulate the target composition (Tables 7-6 and 7-7; Figures 7-11 and 7-12), but only Mix 5 (GW-ISC5) has a $\delta^{34}S$ value that is initially more depleted than the target (Figure 7-13). Thus, addition of sulfate from gypsum, sufficient to match the target sulfate concentrations, will result in significantly over-enriched values: $\delta^{34}S$ of 7.9‰ and 8.9‰ for Mix 5 and Mix 6, respectively. Although there may be some sulfate contribution from gypsum, there clearly must be additional mixing with a source water that has depleted $\delta^{34}S$ but elevated sulfate concentration, such as DR-ED2. One plausible scenario is to assume (1) that water in the shallow alluvial aquifer has a composition similar to that of DR-ED2, and (2) that this water is one of the sources of water in Montoya Drain. East Drain discharges into the Rio Grande downgradient from Mesilla Diversion Dam. It may be possible that water in the shallow aquifer near the East Drain migrates into the area drained by Montoya. In such case, that composition could be the source of the needed depleted $\delta^{34}S$ signature. Alternatively, there may be a nearby saline groundwater source with this composition that has not yet been sampled. Nevertheless, as was the case before, mixing with saline groundwater is required. These results support the assertion that the observed increase in drain chloride concentration is derived from the elevated chloride in groundwater and not from any alternative source, including evaporation.

Table 7-6. Mixing Results, Mix 5

Analyte	Units	Starting Composition [RG-Cab (Aug), concentrated [a]]	Potential Source [GW-ISC5 (Jan)]	Mix 5 [b]	Target Sample [DR-Mont (Jan)]	% Error [c]
Na	mg/L	155.55	1,300	509	560	9
K	mg/L	10.98	6.8	9.7	7.2	35
Ca	mg/L	98.82	300	160.9	120	34
Mg	mg/L	23.79	19	22.3	37	40
SO_4	mg/L	256.2	1,200	547.3	800	32
Cl	mg/L	122.61	1,800	640.0	640	0
Br	µg/L	256.2	690	390.0	720	46
B	µg/L	256.2	840	436.3	700	38
Sr	µg/L	1,246.23	2,190	1,537.3	1,880	18
N	mg/L as N	0.2013	0.16	0.2	0.16	18
Cl/Br	Ratio	479	2,609	1641	889	85
$\delta^{11}B$	‰	4.7	5.3	5.06	16	NA
$^{87}Sr/^{86}Sr$	Ratio	0.710331	0.7089110	0.709707	0.709766	NA
$\delta^{34}S$	‰	1.0	7.9	5.7	6.1	NA

[a] Concentrated by 1.83
[b] Mix 5 = 69.1% RG-Cab (Aug), concentrated + 30.9% GW-ISC5
[c] Absolute value of error

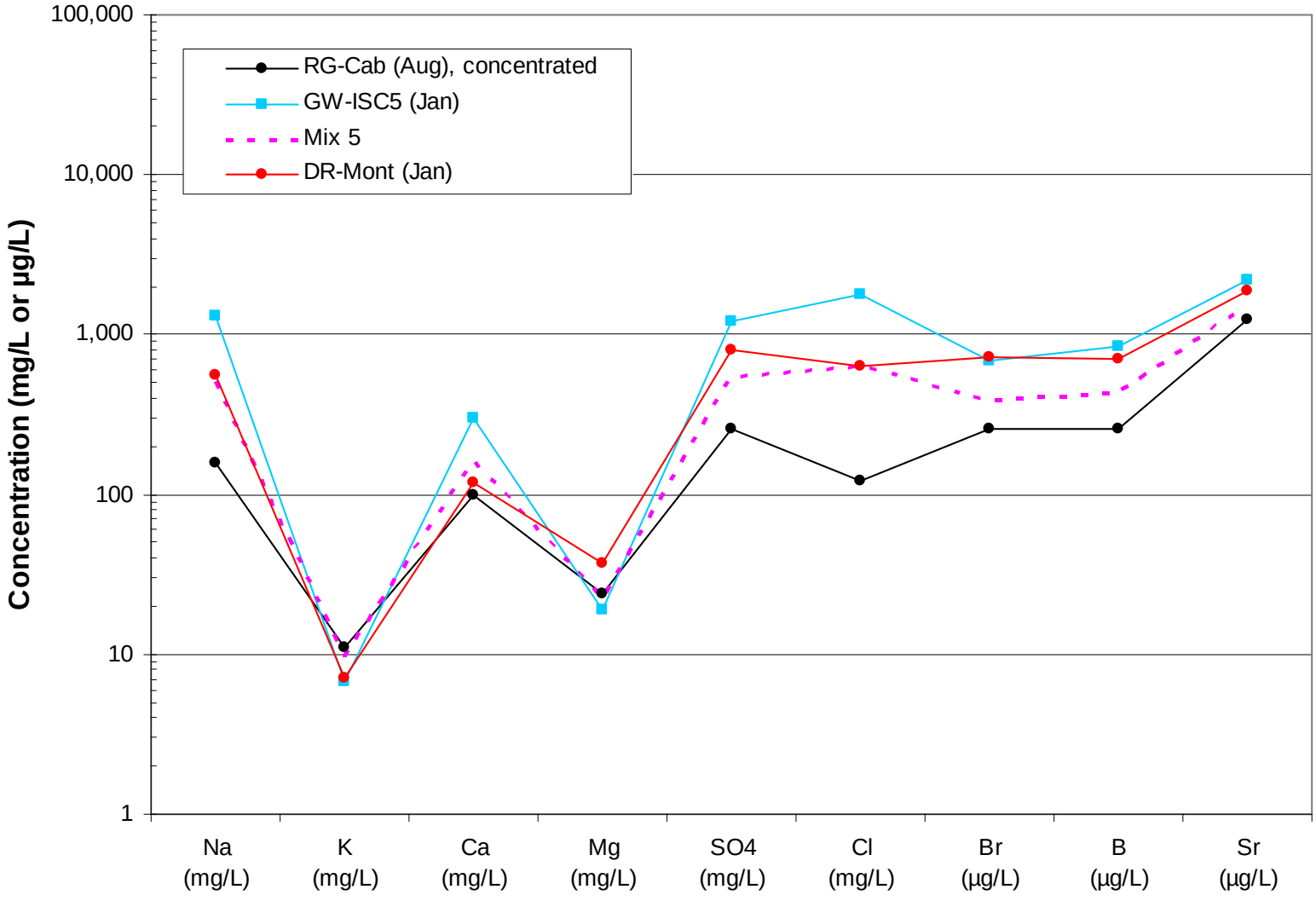
mg/L = Milligrams per liter
µg/L = Micrograms per liter
‰ = Per mille
NA = Not applicable

Table 7-7. Mixing Results, Mix 6

Analyte	Units	Starting Composition [RG-Cab (Aug), concentrated [a]]	Potential Source [GW-ISC4a (Jan)]	Mix 6 [b]	Target Sample [DR-Mont (Jan)]	% Error [c]
Na	mg/L	155.55	4,700	458	560	18
K	mg/L	10.98	26	12.0	7.2	66
Ca	mg/L	98.82	670	136.8	120	14
Mg	mg/L	23.79	340	44.8	37	21
SO_4	mg/L	256.2	5,100	578.5	800	28
Cl	mg/L	122.61	7,900	640.0	640	0
Br	µg/L	256.2	10,000	904.5	720	26
B	µg/L	256.2	2,500	405.5	700	42
Sr	µg/L	1,246.23	16,500	2,261.1	1,880	20
N	mg/L as N	0.2013	0.96	0.3	0.16	57
Cl/Br	Ratio	479	790	708	889	20
$\delta^{11}B$	‰	4.7	30.8	15.41	16	NA
$^{87}Sr/^{86}Sr$	Ratio	0.710331	0.710149	0.710243	0.709766	NA
$\delta^{34}S$	‰	1.0	12.2	7.6	6.1	NA

[a] Concentrated by 1.83
[b] Mix 6 = 93.3% RG-Cab (Aug), concentrated + 6.7% GW-ISC4a
[c] Absolute value of error

mg/L = Milligrams per liter
µg/L = Micrograms per liter
‰ = Per mille
NA = Not applicable



Note: (Jan) indicates data from January 2005 sampling event, while (Aug) denotes data from August 2004.

LRG SALINITY

Major Ion Concentrations
Mix 5

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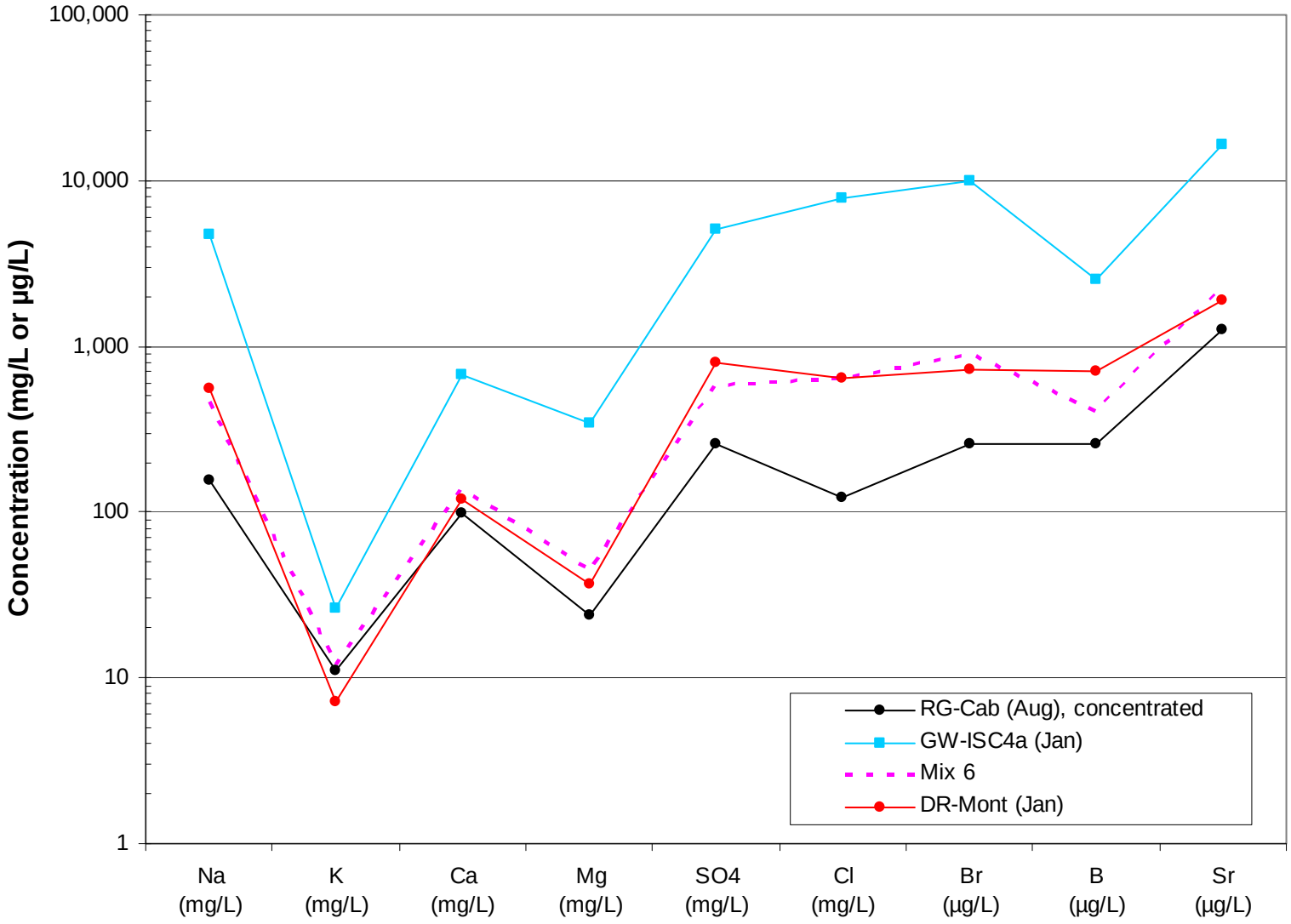
Figure 7-11



Note: (Jan) indicates data from January 2005 sampling event, while (Aug) denotes data from August 2004.

LRG SALINITY

Major Ion Concentrations
Mix 6

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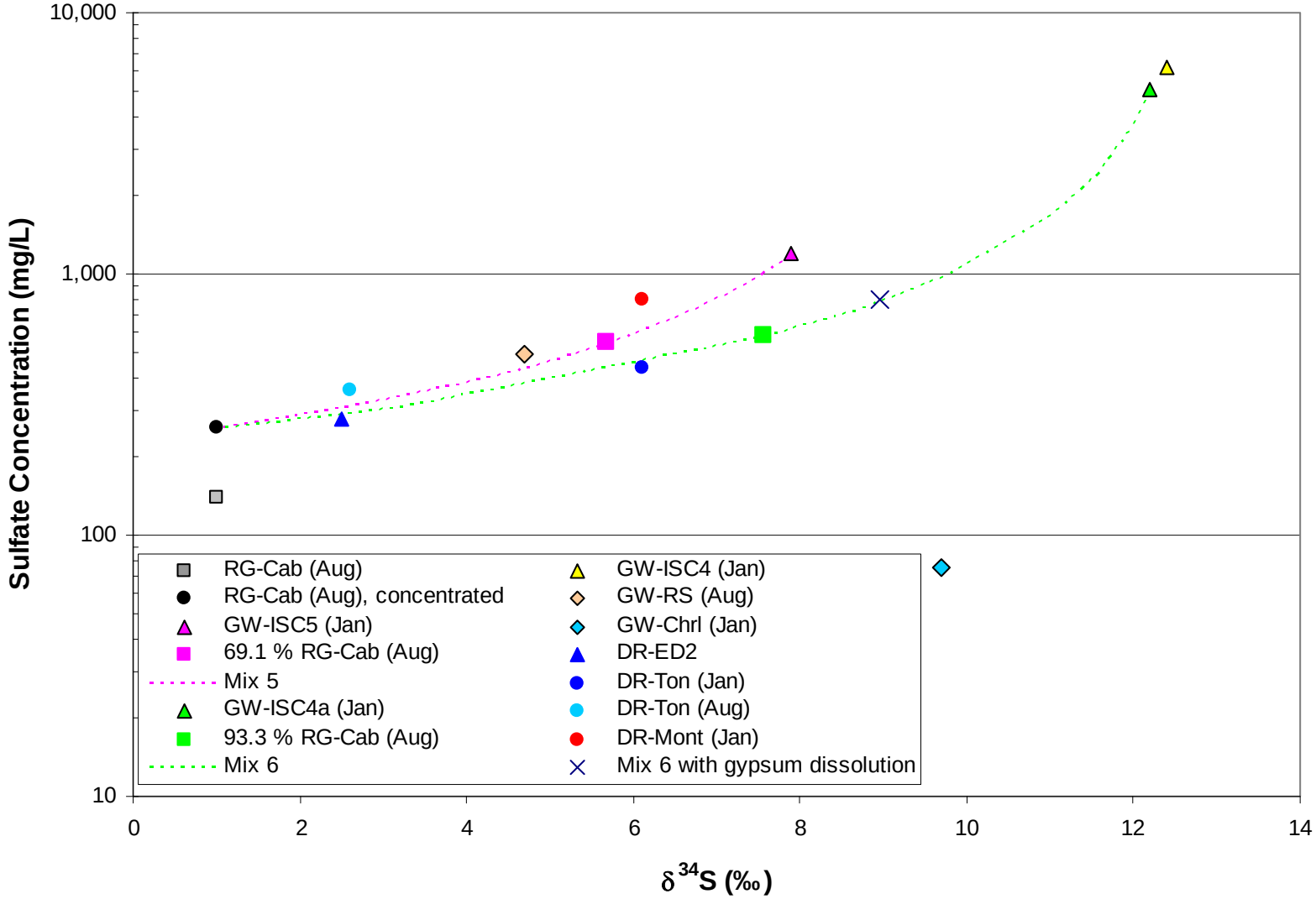
Figure 7-12



Note: (Jan) indicates data from January 2005 sampling event, while (Aug) denotes data from August 2004.

LRG SALINITY

Sulfur Isotopic Values
Mix 5 and Mix 6

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Figure 7-13

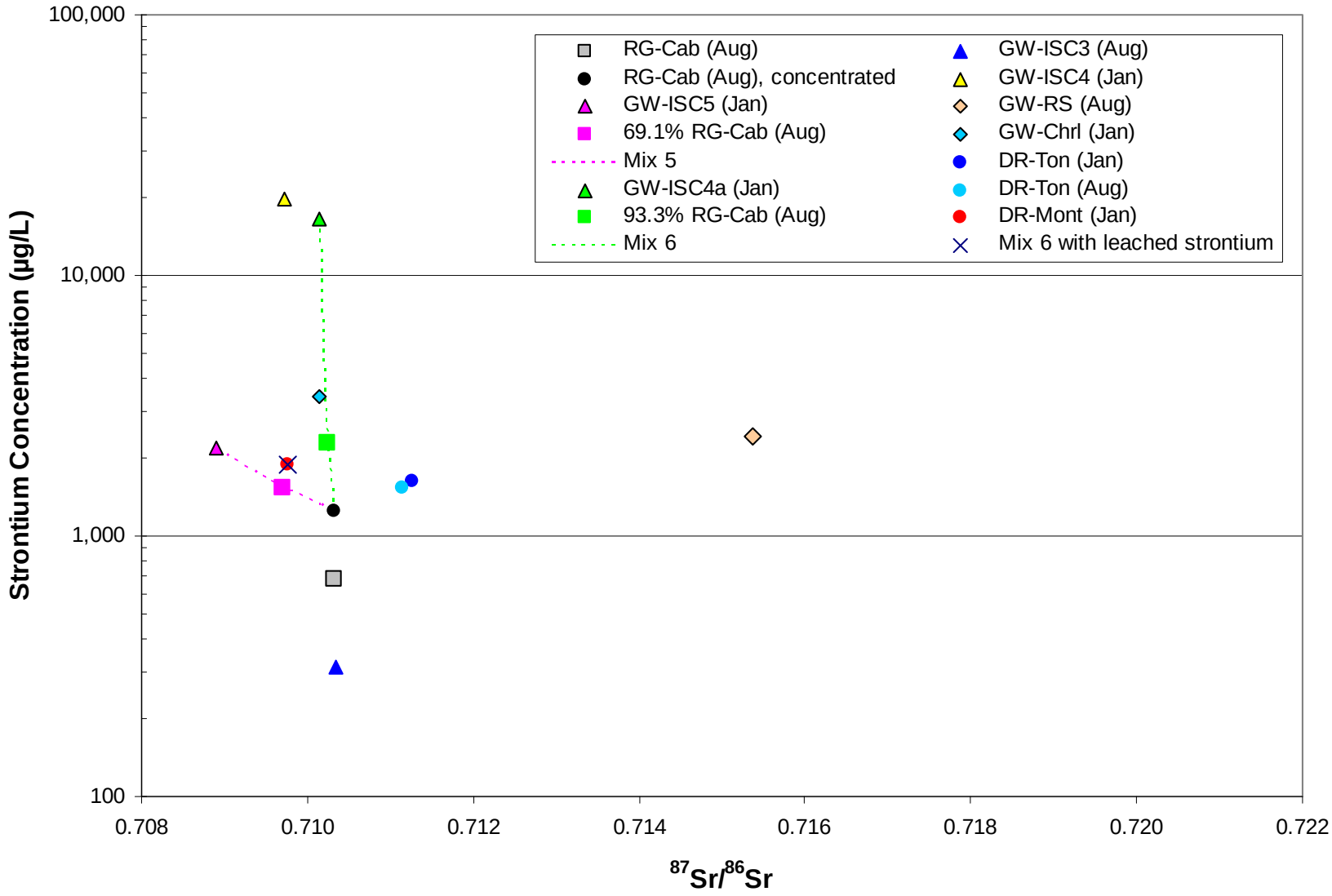
The elemental and isotopic sulfur compositions (Figure 7-13) indicate that a simple two-component mix (Mix 5 or Mix 6) is unable to reproduce the observed geochemical changes that occur between RG-Cab (Aug) and DR-Mont (Jan). The compositions of Mix 5 and Mix 6 have low sulfate concentrations compared to that of the target sample, DR-Mont (Jan). If additional gypsum dissolution (with a $\delta^{34}S$ of 12.6‰) is considered as part of the process for Mix 6, the composition of the resulting mix approaches that of the target sample, DR-Mont (Jan) (Figure 7-13; Table 7-7).

Strontium and boron data (Figures 7-14 and 7-15) indicate that a three-component mix of RG-Cab (Aug), GW-ISC5, and GW-ISC4a may yield the appropriate target composition of DR-Mont (Jan) because the mix lines for Mix 5 and Mix 6 bound the target sample. Alternatively, if strontium leaching is assumed to occur as part of Mix 6, the composition of the resulting mix (Figure 7-14) approaches that of the target sample, DR-Mont (Jan).

7.1.4 Reach 4: Rio Grande below East Drain to Rio Grande at El Paso

The mixing scenarios discussed in this section were designed to gain insight into the causes of the observed geochemical changes that occur between RG-blwED and RG-EP (Reach 4) (Figure 2-3). In the winter, the river is dry above the point where East Drain enters the channel except for a small amount of water from the Las Cruces WWTP; therefore, the starting point for this reach is RG-blwED (Jan). The river is also dry during the winter between East and Montoya Drains. Although water from the RG-blwED may reach the El Paso area by flowing through the shallow alluvium, the volume of such a contribution is not known. For this mixing scenario, the composition of RG-blwED (Jan) is used as the starting point because such a composition is required for some of the mixing solutions. In other words, the target composition, RG-EP (Jan), cannot be reproduced without using RG-blwED as one of the sources. It is recognized, however, that the actual source of this water may be other discharge points along the LRG that have not yet been sampled but that have a composition similar to that of RG-blwED (Jan).

The target sample for Reach 4 is RG-EP (Jan). Three potential sources were chosen for mixing scenarios (Mixes 7 through 9) along this reach:



Note: (Jan) indicates data from January 2005 sampling event, while (Aug) denotes data from August 2004.

LRG SALINITY

Strontium Isotopic Values
Mix 5 and Mix 6

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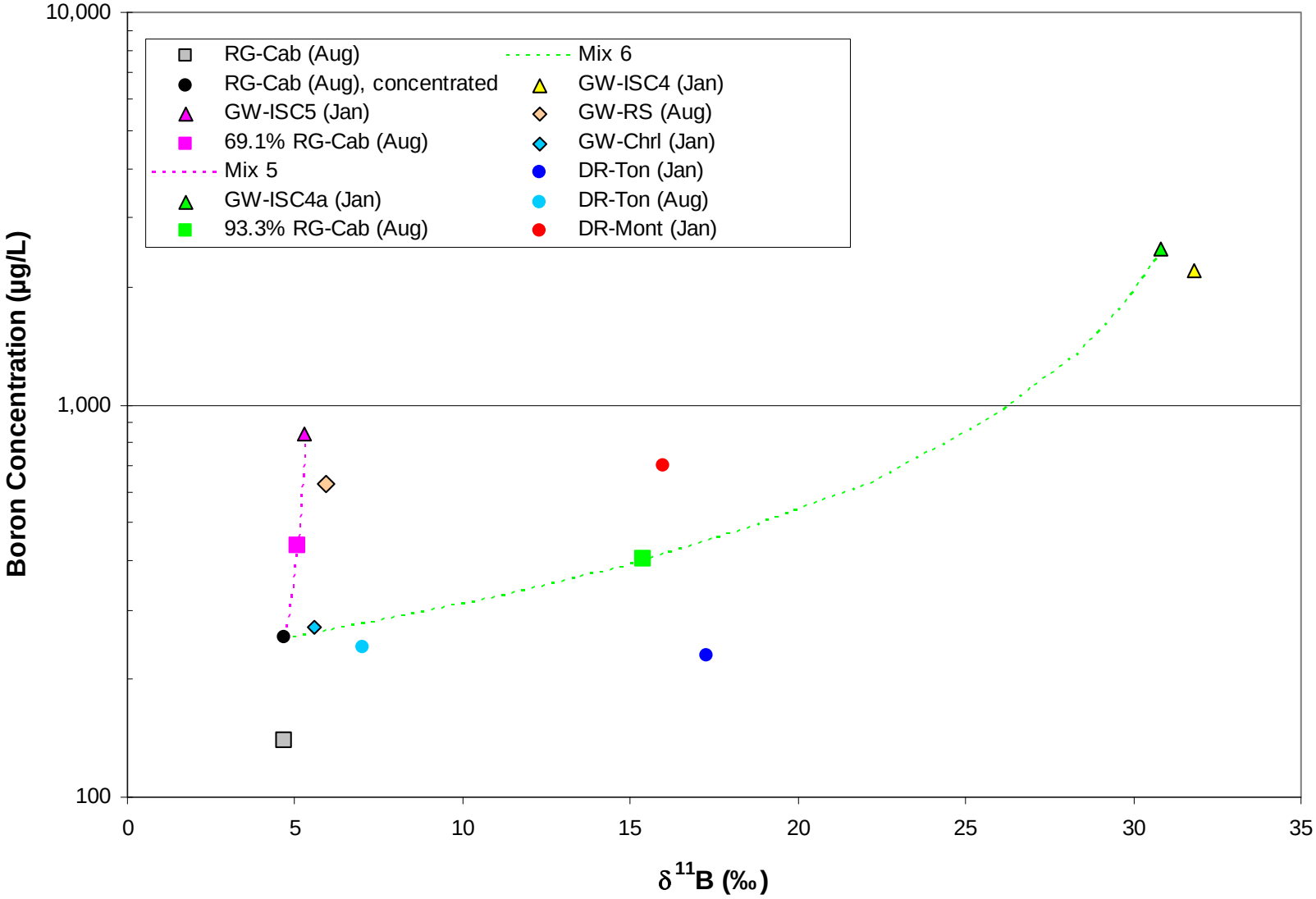
Figure 7-14



Note: (Jan) indicates data from January 2005 sampling event, while (Aug) denotes data from August 2004.

LRG SALINITY

Boron Isotopic Values
Mix 5 and Mix 6

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Figure 7-15

- DR-Mont (Jan), because the Montoya Drain enters the Rio Grande a short distance above RG-EP (Figure 2-3)
- GW-ISC5 and GW-ISC4a, which represent deep saline groundwater in the El Paso Narrows area

The groundwater with a composition represented by the GW-ISC3 well is not considered because its isotopic composition is so unusual that it would cause a modification to the model that is not consistent with observations. The GW-ISC4 well is not considered because it is so similar to GW-ISC4a that it would be redundant. Undoubtedly, water enters the channel from other sources, but these other sources are either minor in flow, too low in concentration to effect a change in the river composition, or are not needed because this assemblage of sources is sufficient. Also, no data are available to characterize these sources.

Inverse modeling was performed using the geochemical computer code PHREEQC (Parkhurst, 1995). The model is a speciation/reaction path/transport/inverse code that is widely used in geochemical interpretation of hydrologic systems. Bassett (1997) discussed modeling approaches including the one followed here. PHREEQC was selected because it includes several of the required features in one code, and because it is a non-proprietary public domain program. To objectively determine the various combinations of sources that could be mixed so as to reproduce the composition of RG-EP (Jan), the analyses were charge balanced, pH adjusted, and brought to equilibrium with a key phase. Selected mass balance equations were then solved simultaneously with a defined uncertainty limit to identify all possible combinations and their required proportions. The approach followed is defined below:

1. The chemical composition of each sample is entered into the data file.

2. The samples have varying degrees of charge imbalance due to analytical error. Any ion can be used to eliminate the charge imbalance. Sodium was used here because it does not impact any of the isotopic evaluations.

3. The observed pH of the samples may not be the actual pH of either the well samples or the surface water at the point of mixing. The indication of this is the fact that most

samples are supersaturated with respect to calcite, a mineral that reacts rapidly and is most likely close to equilibrium, especially in the groundwater samples. This assumption is not critical to the inverse modeling process, but does allow for consistency among the samples. The model was allowed to compute the pH at which each water would be in equilibrium with calcite, and this pH was used in subsequent computations.

4. One important consideration introduced earlier is the potential for reaction of the water from the drains or groundwater with minerals in the soil, aquifer, or streambed that could add or remove mass from the water. Because most of the mixing probably occurs in the river or in the aquifer close to the river channel, one might assume that mineral dissolution would be minor. However, GW-ISC4a is very close to equilibrium with respect to gypsum, GW-ISC5 is only slightly undersaturated, and all other samples were somewhat more undersaturated. Furthermore, all samples are at equilibrium with calcite. This implies that the water could potentially react with gypsum or calcite. The most important consequence of these reactions could be a change in the sulfate concentration during mixing. Gypsum is widespread throughout the area and a modification of the sulfate concentration could potentially alter the $\delta^{34}S$ isotope ratio as discussed in Section 7.1.2. It is possible that sulfate could have entered the water from dissolution of mineral sources or could have been lost as a result of gypsum precipitation.

5. The other four components for this reach (i.e., the starting point and three potential sources) are mixed in any proportion, first considering only a single source and then progressively adding sources in any proportion to find arrangements (or models) that will result in the target composition.

The inverse modeling process yielded 12 models in which various proportions of these sources could be mixed to match the calcium, sulfate, sodium, chloride, bromide, boron, and strontium concentrations in the target sample. The isotopic values are not calculated as part of the mathematical solution of the inverse modeling process; rather, the isotopic content is used to independently evaluate the models for plausibility. Of the 12 models, 2 use all four sources for the mixture, 5 use only three components, and 5 use only two components. All 12 models

match the $\delta^{11}B$ and $^{87}Sr/^{86}Sr$ isotopic data reasonably well, but the computed $\delta^{34}S$ values are from 2 to 4‰ more enriched than the observed value for El Paso.

Of the 12 models, 7 include RG-blwED as a component in the solution. Because the reach of the river between East and Montoya Drains was dry during the sampling period, RG-blwED may not be considered a reasonable part of the solution, but the East Drain composition is important in the evaluation, as indicated by the fact that it was included in more than half of the models. An example of a solution that includes RG-blwED (Jan) is included in Table 7-8 as Inverse Model 6. Although it does not match the boron and strontium isotopic content for RG-EP (Jan) any better than the other 5 models, RG-blwED (Jan) is important because it has a depleted $\delta^{34}S$ value of –2.2‰ and a composition with such a depleted value is necessary to match the $\delta^{34}S$ value at RG-EP of 2.2‰ (Figure 7-16). The model that includes RG-blwED (Jan) has a $\delta^{34}S$ match that is closer to that of the target sample than the other models.

Because all other sources have $\delta^{34}S$ values greater than 2.2‰ (GW-ISC4a, DR-Mont, and GW-ISC5 are 12.2, 6.1, and 7.9‰, respectively), RG-blwED (Jan) is the only source that can draw the mixed water calculation closer to the actual value. It is speculated that another water source similar to RG-blwED, not yet sampled but with a depleted $\delta^{34}S$, is probably entering the river above El Paso.

Of the 12 models, 6 are shown in Table 7-8 to illustrate the various combinations of sources that are required to reproduce the isotopic and chemical composition of RG-EP (Jan). The resulting chemical compositions of each model are not shown because, by definition of the inverse modeling process, the chemical composition of each model is identical to that of the target sample. The isotopic compositions of each model are calculated according to the proportions identified during the modeling process. Except for the sulfur isotopes, the resulting isotopic compositions are reasonably close to that of the target sample, RG-EP (Jan), and are similar for each model (Table 7-8). Each model is dominated by the Montoya Drain composition.

Comparison of the modeled isotopic compositions to that of the target sample indicate that Inverse Model 6 is the best fit (Table 7-8). Inverse Model 4 is the best fit of the remaining 5 models. The sulfur, strontium, and boron isotopic compositions of the two best fit models are

Table 7-8. Inverse Modeling Results

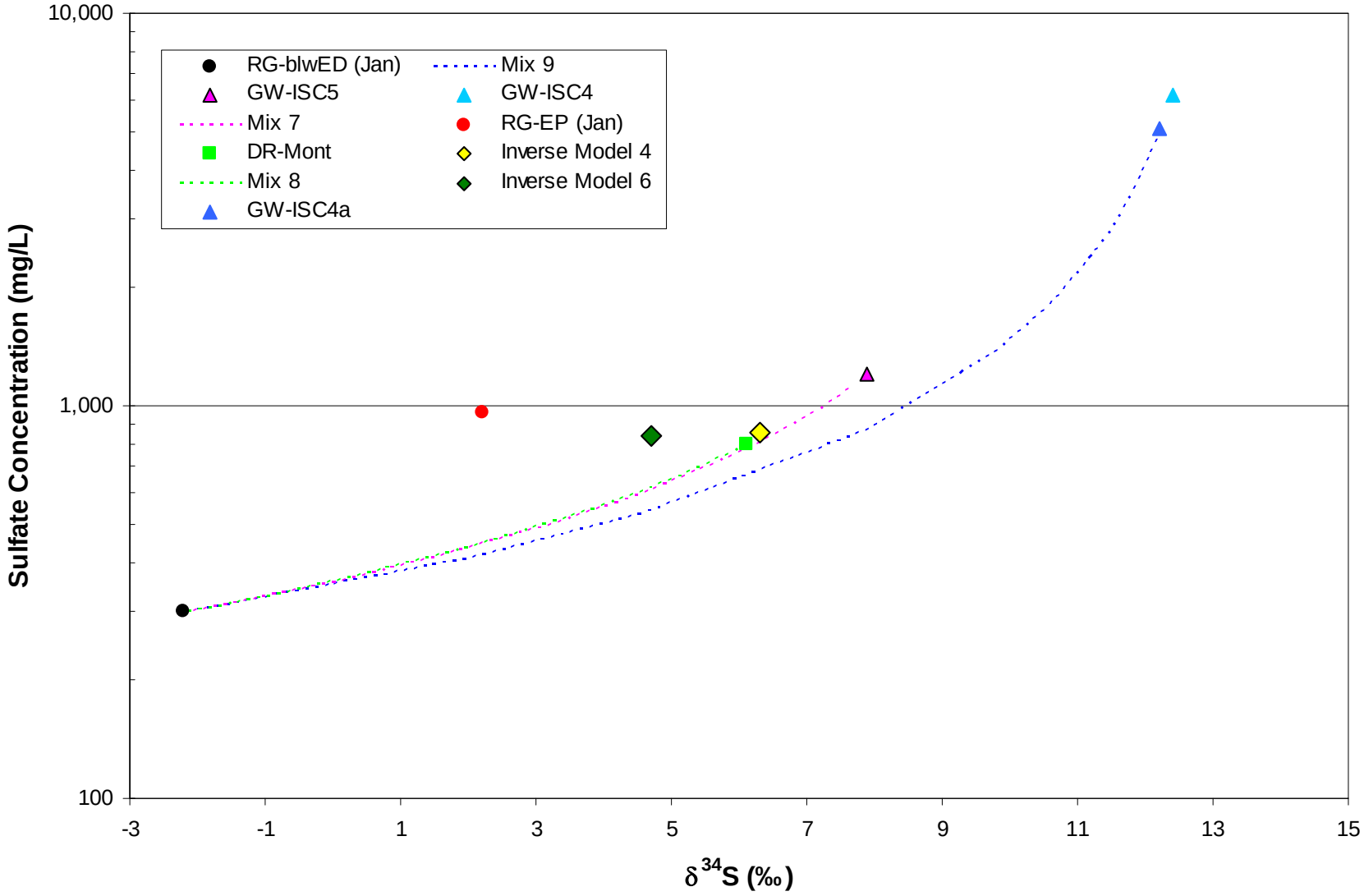
Inverse Model Number	RG-blwED (%)	GW-ISC4a (%)	DR-Mont (%)	GW-ISC5 (%)	$\delta^{11}B$ (‰)	$\delta^{34}S$ (‰)	$^{87}Sr/^{86}Sr$
1 [a]	0	0	87.3	12.7	14.6	6.3	0.709657
2	0	0.5	89.9	9.6	15.1	6.3	0.709661
3	0	0.6	90.6	8.7	15.2	6.3	0.709656
4 [a]	0	0	87.3	12.7	14.6	6.3	0.709657
5	0	2	98	0	16.3	6.2	0.709752
6	19.3	3.2	77.5	0	15.3	4.7	0.710077
RG-EP (Jan) [b]	NA	NA	NA	NA	13.5	2.2	0.709734

[a] Although the proportional components of each source are identical in Models 1 and 4, the mass transfer from minerals (due to mineral dissolution) varies. More calcite was added in Model 4.

[b] Target sample

% = Percent

‰ = Per mille



Note: (Jan) indicates data from January 2005 sampling event, while (Aug) denotes data from August 2004.

LRG SALINITY

Sulfur Isotopic Values
Mixes 7, 8, and 9

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Figure 7-16

shown in Figures 7-16 through 7-18, along with the simple, two-component mix lines for the three potential sources. Examination of these plots indicates that the composition of the target sample, RG-EP (Jan), cannot be reproduced by simple two-component mixing.

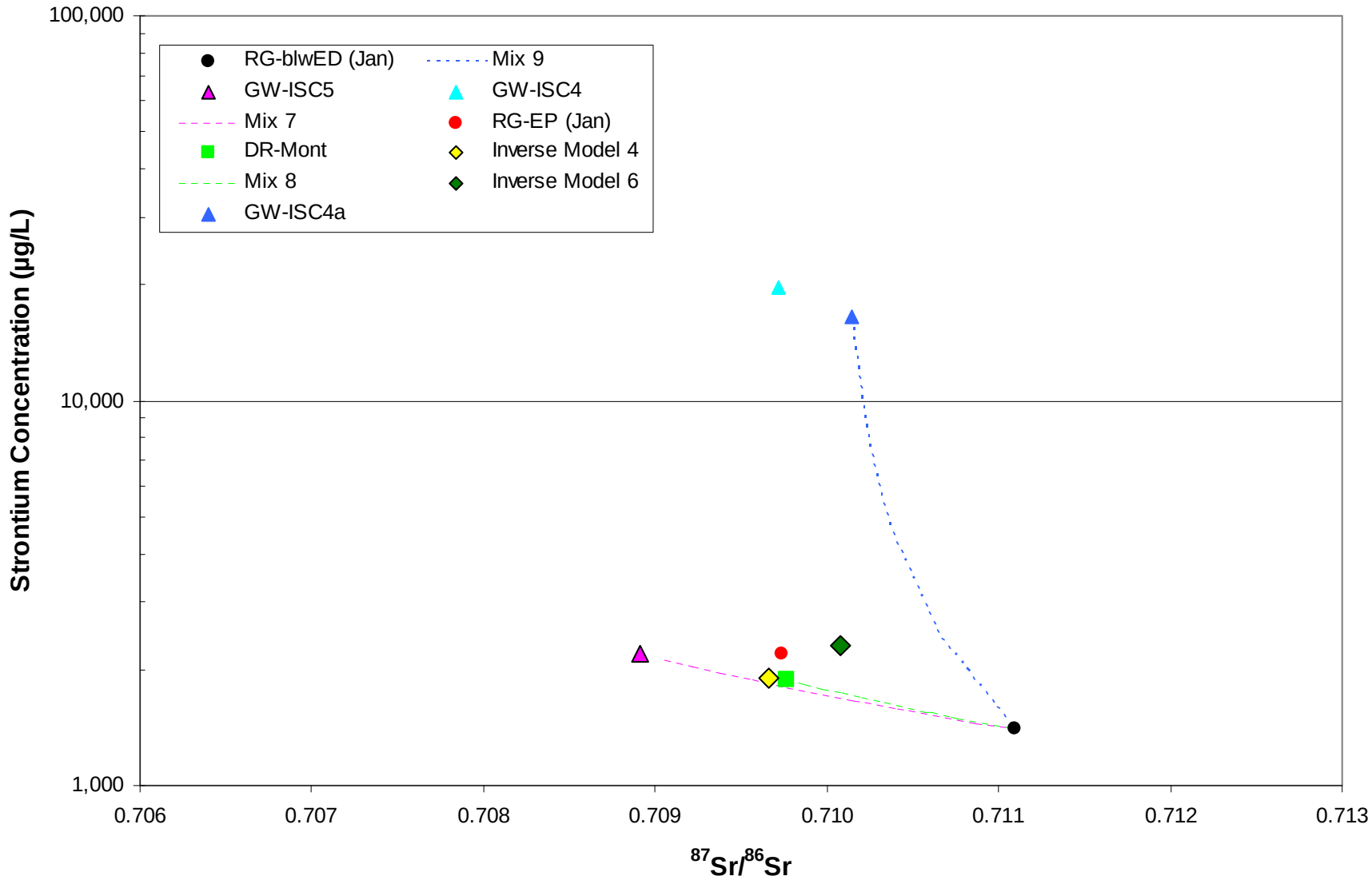
The boron isotopic composition of Inverse Model 4 (Figure 7-18; Table 7-8) is close enough to that of the target sample to be considered a match within the experimental error of the analysis. This result is significant because, of the three isotopes examined, boron is the most chemically conservative and is not modified by reaction with any mineral phase in this system. Most of the 12 mixing scenarios are within 2‰ of the boron isotopic value for the target sample (Table 7-8) and are therefore plausible scenarios because the range of end member boron isotopic values is greater than 30‰.

Even in this preliminary evaluation for the RG-blwED to RG-EP reach, it was possible to identify plausible scenarios in which the composition of RG-EP (Jan) could be explained in terms of mixing between only a few sources of water. In summary:

1. The increase in salinity cannot be explained simply by evaporation of Rio Grande water sources because the isotopic composition changes from upgradient sources and isotopic ratios are not altered simply by evaporation.

2. The two principal drains upgradient are saline, but they also have compositions that are isotopically different from Rio Grande water and are conclusively altered by the presence of more saline groundwater.

3. Wells near El Paso have been sampled. These wells may represent a source for salinity, but more importantly, they provide the isotopic composition required to create the composition observed in the Rio Grande at El Paso. No other source for salinity has been identified that can also produce the observed isotopic changes.



Note: (Jan) indicates data from January 2005 sampling event, while (Aug) denotes data from August 2004.

LRG SALINITY

Strontium Isotopic Values
Mixes 7, 8, and 9

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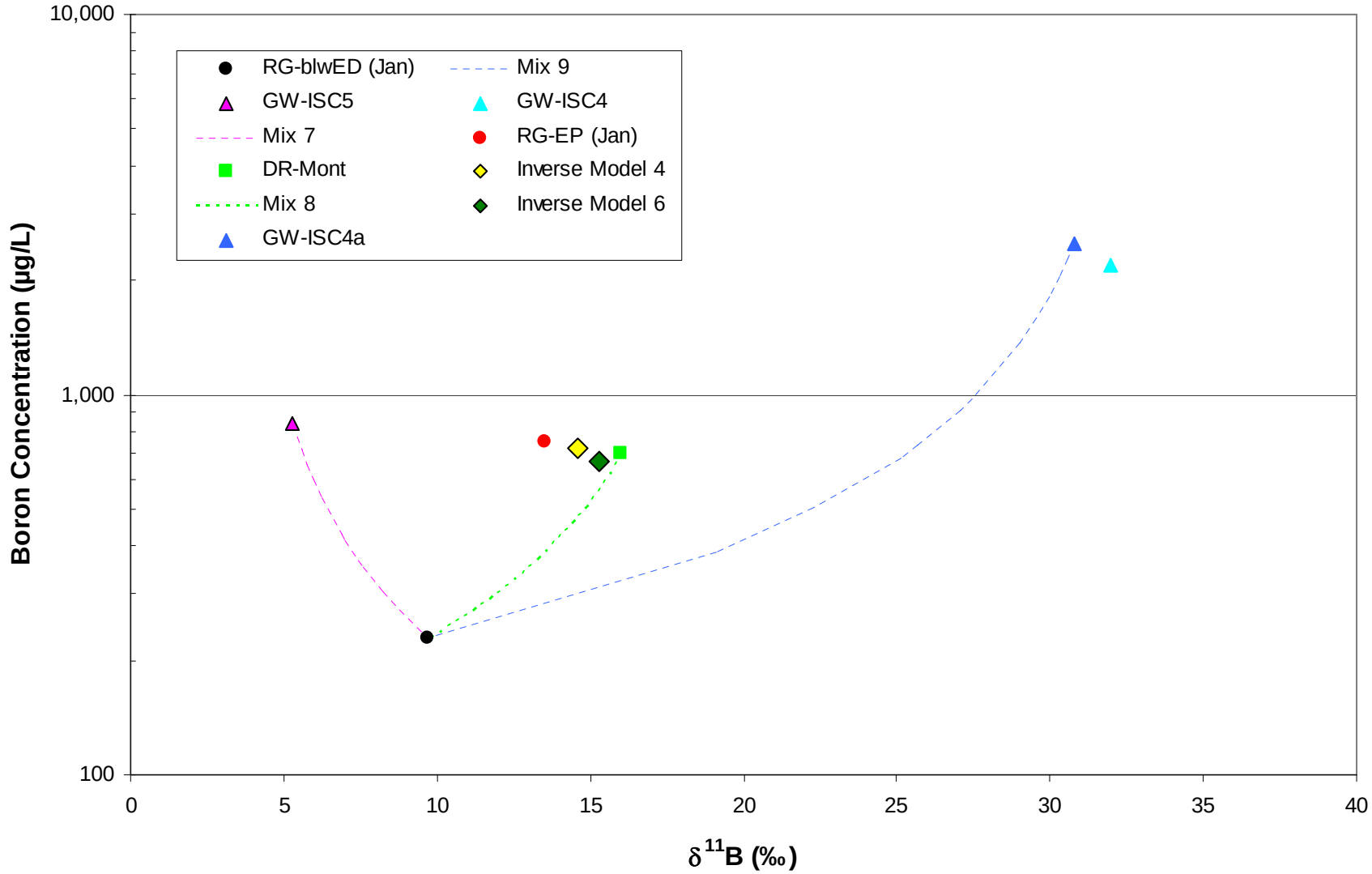
Figure 7-17



Note: (Jan) indicates data from January 2005 sampling event, while (Aug) denotes data from August 2004.

Figure 7-18

LRG SALINITY

Boron Isotopic Values
Mixes 7, 8, and 9

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4. Although there may be many other minor contributors of water to the Rio Grande that have not yet been sampled, this geochemical analysis indicates that the mixing of the four major sources of water to the Rio Grande (RG-blwED, GW-ISC4a, DR-Mont, and GW-ISC5) will yield a plausible explanation for the observed composition.

5. These results were obtained using only one sample from each location. Future replicate sampling events will allow for the assessment of the range of compositional changes and provide a more defined database for modeling the possible combinations of sources that can yield the observed chemical composition in the Rio Grande at El Paso.

7.2 Chloride Mass Balance Assessment using Recent Data

Daily chloride loads were calculated in order to evaluate contributions to the LRG from various sources. Daily chloride loads were calculated for both August 2004 and January 2005 sampling events. Loads were only calculated at sampling locations that coincided with streamflow gaging stations (Table 4-1): RG-EB, RG-Cab, RG-blwSC (January 2005 only), and RG-EP. At each of these stations, the chloride concentration measured during a given sampling event was assumed to represent the mean chloride concentration for the three- to four-day sampling event. The mean streamflow for a given sampling event was calculated as the mean of the daily mean streamflow for each day in that sampling event. The daily chloride load was calculated as the product of the mean chloride concentration and mean streamflow, and is reported in kg/d.

In August 2004, the daily chloride load increased in the downstream direction (Figure 7-19). Between RG-EB and RG-Cab, the daily chloride load increased (from 83,100 to 178,915 kg/d) with increasing streamflow (539 to 1,092 cfs). These parameters are both controlled by reservoir operations. Between RG-Cab and RG-EP, there was a slight increase in daily chloride load (from 178,915 to 180,762 kg/d) despite a substantial decrease in streamflow (from 1,092 to 770 cfs). Simple mixing calculations indicate that the decrease in streamflow is proportional to the increase in chloride concentration (67 to 96 mg/L); therefore, the slight increase in chloride concentration between RG-Cab and RG-EP could be the result of evapotranspiration.

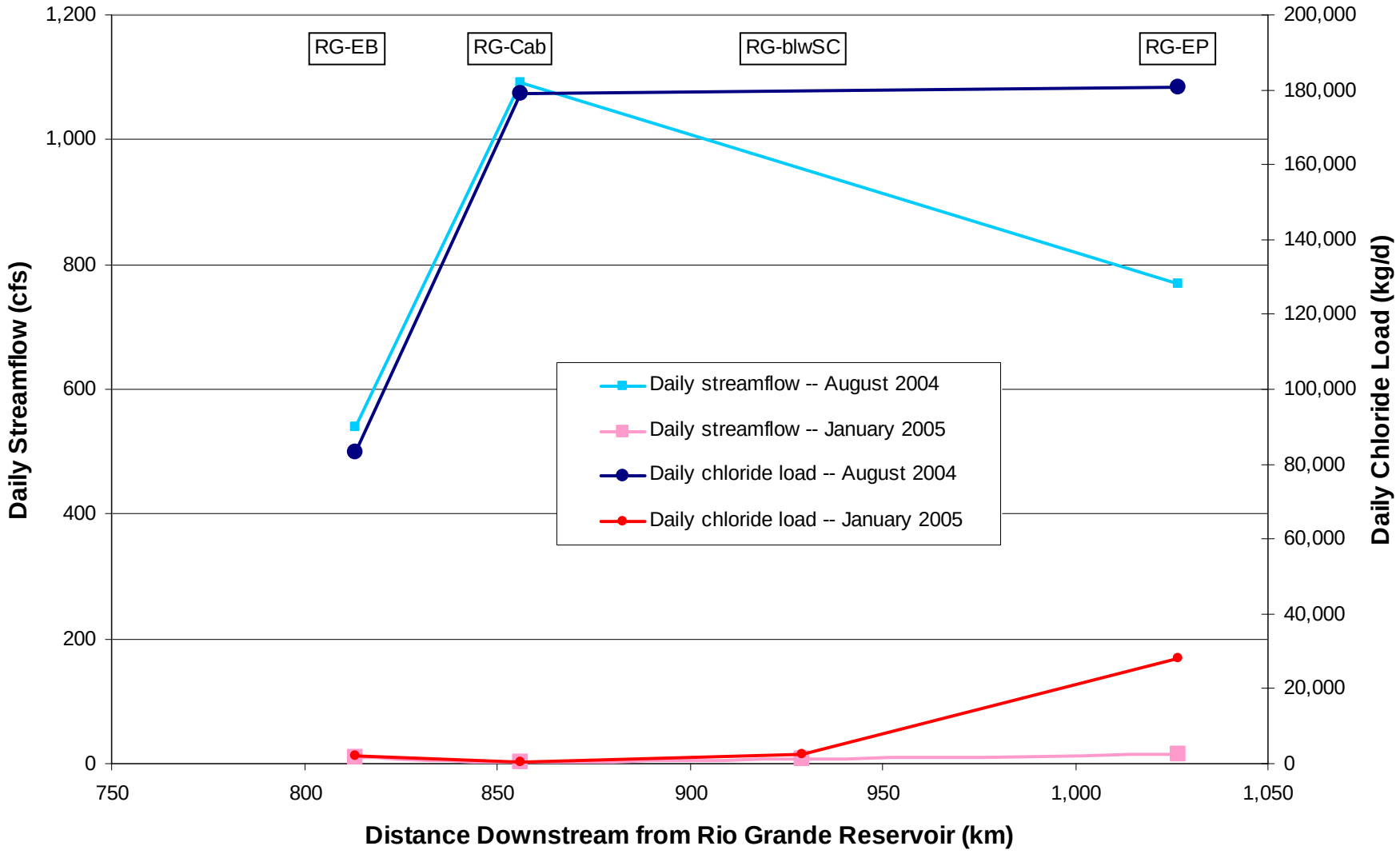

Figure 7-19

LRG SALINITY

Streamflow and Chloride Loads
August 2004 and January 2005

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In January 2005, the daily chloride load increased in the downstream direction (Figure 7-19). Between RG-EB and RG-Cab, the daily chloride load decreased with decreasing streamflow due to reservoir operations. Between RG-Cab and RG-blwSC, there was a small increase in daily chloride load and streamflow. The largest increase in daily chloride loads was between RG-blwSC and RG-EP (Figure 7-19). Between these two sites, the daily chloride load increased by a factor of 11 (from 2,570 to 28,100 kg/d), while streamflow increased by a factor of 2.3 (from 7 to 16.2 cfs). The large increase in chloride load and relatively small increase in streamflow indicates the presence of an inflow (or inflows) with an elevated chloride concentration. Sources of elevated chloride concentrations (relative to the Rio Grande) between RG-Cab and RG-EP include Tonuco Drain (DR-Ton), geothermal groundwater in the Selden Canyon area (GW-SC), wastewater effluent (WW-LC), Montoya and East Drains (DR-Mont and DR-ED2), groundwater (GW-ISC3) and deep saline groundwater (GW-ISC4, GW-ISC4a, and GW-ISC5).

Note that Witcher et al. (2004) report a chloride flux of 834 tons per year from the Las Cruces East Mesa Geothermal System alone. If we assume that the average daily chloride load increases by 25,500 kg/d (Figure 7-19) between RG-Cab and RG-EP, then the increase in chloride load would be equivalent to 1,000 tons per year. Evidence reported in Witcher et al. (2004) indicates that most of this chloride load is from the East Mesa Geothermal System.

7.3 Contributions to the Rio Grande from Various Sources

Geochemical modeling and the chloride mass balance assessment indicate that:

- A combination of geothermal and deep saline groundwater inflow to the Rio Grande is the major source of observed salinization of the LRG.

- Agricultural drains represent shallow groundwater that is a mixture of various sources (Rio Grande water and a combination of geothermal and deep saline groundwater).

- It is not possible to reproduce the observed salinization by evapotranspiration and agricultural processes alone; contributions from geothermal and deep saline groundwater are required.

- The primary sources of water in the LRG have been identified, as evidenced by the fact that the observed changes in salinization can be reproduced.

The observations and interpretations presented in this section are supported by and consistent with many recent previous investigations (Frenzel et al., 1992; Anderholm, 2002; Moore and Anderholm, 2002; Mills, 2003; Phillips et al., 2003; Witcher et al., 2004) and the historical data (Stabler, 1911) (Section 3).

8. Conclusions and Recommendations

Evaluation of historical data indicates that salinization in the LRG occurred before the reservoirs, agricultural drains, and wastewater dischargers were present. The downstream pattern of salinization in the LRG, as indicated by observed increases in chloride concentrations and chloride loads, is similar to that observed prior to the construction of the reservoirs, agricultural drains, and wastewater dischargers.

Geochemical modeling and the chloride mass balance assessment indicate that a combination of geothermal and deep saline groundwater inflow to the Rio Grande, both directly and via the agricultural drains, is primarily responsible for the observed salinization within the LRG. These analyses demonstrate that it is not possible to reproduce the observed salinization by evapotranspiration and agricultural processes alone.

Salinity in the LRG was studied by selecting specific reaches of the river for more detailed examination of potential salinity sources. The river composition is affected by numerous surface and groundwater additions that cannot all be identified. However, as has been demonstrated by this study, it is possible to identify principal water types and specific water/rock reactions that can be mixed in physically realistic proportions to yield the observed chemical composition of the river and of several key drains such as Tonuco Drain (at the base of the Rincon Valley) and Montoya Drain (near the El Paso Narrows). Compositional changes in the river can be explained by mixing upstream river water with groundwater inflow, drain inflow, and some mineral reaction. In summary:

- RG-EB (Jan) mixed with geothermal groundwater such as GW-Chrl, a small percentage of saline groundwater such as GW-ISC4, dissolved gypsum, and strontium leached from Tertiary volcanic rocks will yield a water composition very similar to that observed at RG-abvTC (Jan).

- RG-Cab (Aug) concentrated by a factor of 1.7 and mixed with geothermal groundwater (such as GW-Chrl), a small percentage of saline groundwater (such as GW-ISC4a),

dissolved gypsum, and leached strontium will yield a composition similar to that observed at DR-Ton (Jan).

- RG-Cab (Aug) concentrated by a factor of 1.83 and mixed with saline groundwater (such as GW-ISC4a or GW-ISC5), dissolved gypsum, and leached strontium will yield a water composition similar to that observed at DR-Mont (Jan).

- RG-EP (Jan) can be simulated by mixing DR-Mont (Jan) with saline groundwater (such as GW-ISC4a or GW-ISC5) and a small contribution from a water source with a composition similar to that of RG-blwED, assuming that RG-blwED represents the composition of water in the shallow alluvial aquifer.

In all scenarios, one source must be saline groundwater in order to match the observed target composition. There are no identified scenarios for obtaining the required salinity via evapotranspiration or mineral reaction without also including a geothermal or deep saline groundwater.

The isotopic data are essential in defining the mixing process because of the independent constraint they provide. Chemical concentration data alone will not yield a unique solution to the mixing scenarios or uniquely identify the end members; however, the boron, hydrogen, oxygen, strontium and sulfur isotopic values are sufficiently distinct to yield specific potential mixing scenarios.

Additional data are always beneficial and will allow investigators to confirm established conclusions and gain better understanding of the investigated system. Glynn and Plummer (2005) assert that the best approach to understand groundwater systems is "an optimized iterative process between field data collection and analysis, interpretation, and the application of forward, inverse, and statistical modeling tools".

Although there is a high degree of confidence in the source water characterization provided in this report, that characterization is necessarily limited (1) by the number of samples collected for each source or end member, (2) by the locations sampled, and (3) to the time frame during

which the samples were collected (i.e., August 2004 and January 2005). Continued sampling of the various sources of water in the LRG is recommended, at least on a seasonal basis. Continued sample collection would provide increased confidence in the source water characterization. An increased frequency of sample collection would provide insight into the temporal and seasonal variations in the water quality of the various sources. Additionally, the characterization of the deep saline groundwater and geothermal groundwater end members is limited by the small number of locations that have been sampled. More samples may help develop a more representative characterization of these sources and may result in the identification of distinct classes of each end member. Future water quality analyses should include, at a minimum, major ions, nutrients, stable isotopes (δD, $\delta^{18}O$, $\delta^{11}B$, and $\delta^{34}S$), and strontium isotopes ($^{87}Sr/^{86}Sr$).

Finally, improved understanding of the structural controls on groundwater flow in the LRG will assist in interpreting water quality variations in that system. Additional nested piezometers could provide valuable information on the spatial variations in water quality and hydraulic gradients within the LRG. Similarly, construction of additional hydrogeologic cross sections (using data from various time intervals) at selected locations throughout the LRG would provide valuable information and help to improve understanding of the groundwater flow paths, groundwater gradients, and structural controls in the LRG.

Many of the recommendations made herein have been accomplished as part of the NMED and ISC's ongoing water quality investigation:

- The number of surface water and groundwater sampling sites has been increased.
- Sampling frequency was increased from biannually to quarterly.
- Quarterly water quality sampling events have been conducted almost continuously since late 2005.
- Continuous water quality monitoring stations were installed at Caballo, Leasburg, and El Paso in January 2009. Water quality data from these stations are available at the USGS website (http://waterdata.usgs.gov/nm/nwis/current/?type=gw).

- Old and poorly completed wells in the Rio Grande alluvium have been replaced with new properly completed wells.

Data provided by the NMED and ISC's ongoing water quality investigation, both those presented in this report and those collected since 2005, are a valuable resource to all parties interested in water quality in the LRG.

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Appendix A

Prioritization Report
September 7, 2004

Prioritization of Data Sources, Site IDs, and Parameter Codes in the ISC Lower Rio Grande Water Quality Database

In order to develop a working database from the Interstate Stream Commission (ISC) Access database for analysis of Lower Rio Grande surface water quality, it is necessary to prioritize data sources, sampling locations as identified by site ID in the ISC database, and water quality parameter codes utilized in the ISC database. This prioritization will allow efforts to be focused efficiently on evaluating the most relevant data by:

- Eliminating overlapping or multiply reported data
- Acknowledging uncertainties inherent in comparing data with similar but not identical source codes, site IDs, and/or parameter codes

Conversations between the ISC and Daniel B. Stephens & Associates, Inc. (DBS&A) have focused the Lower Rio Grande salinity study thus far on six key water quality parameters at nine surface water locations. DBS&A makes the following recommendations for prioritization of the sources of data for these parameters and locations and for prioritization of parameter codes when compiling data overlapping in time and space into a single time series for use in further analysis (Sections 1 and 2). DBS&A also has evaluated the relevance of site IDs associated with locations of interest (Section 3).

1. Data Sources Recommended Priority Order

Four main sources of surface water quality data are associated with the six key water quality parameters and the nine surface water locations of interest. They are outlined in Sections 1.1 through 1.4, in the recommended order of prioritization.

1.1 U.S. Geological Survey (USGS)

- USGS data are described by four different source codes in the ISC database (2, 22, 27, 28) that correspond to the method of data acquisition (State office or Internet) from the USGS and the time of acquisition.

- Given that the USGS is considered to provide the industry standard for field sampling and laboratory analysis methods, it is assumed that original USGS data are of high quality.

- In a comparison of all USGS chloride concentration data in the study area available online (at the outlet of Elephant Butte Reservoir and the outlet of Caballo Reservoir) to data in the ISC database marked with a USGS source code (source code 27), 100% of data in the ISC database were identical to data reported online by the USGS (60 values).

Conclusion:

USGS data are assumed to be of the highest quality. The ISC database accurately reflects original USGS data for source code 27, and it is assumed that the other three USGS source codes are equally accurately represented.

Recommendation:

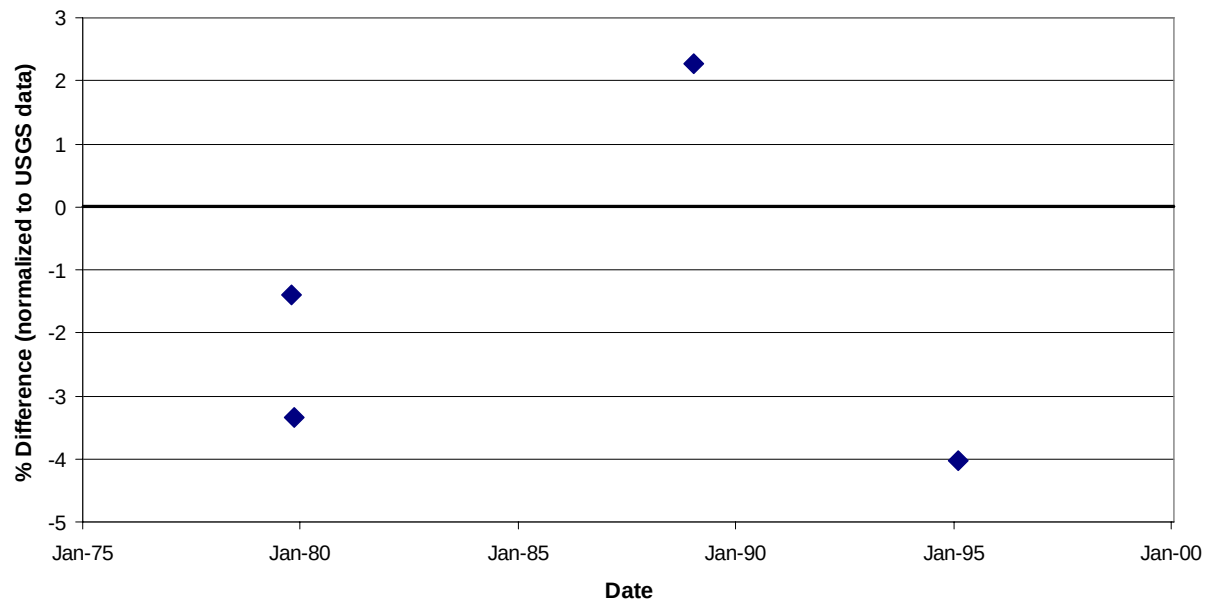
All USGS source codes should have priority over all other data sources and should be used whenever possible.

1.2 EPA STORET

- The EPA is also considered to provide industry-standard field sampling and laboratory analysis methods, some of which are the same as USGS methods. It is therefore assumed that data collected by the EPA are of high quality.

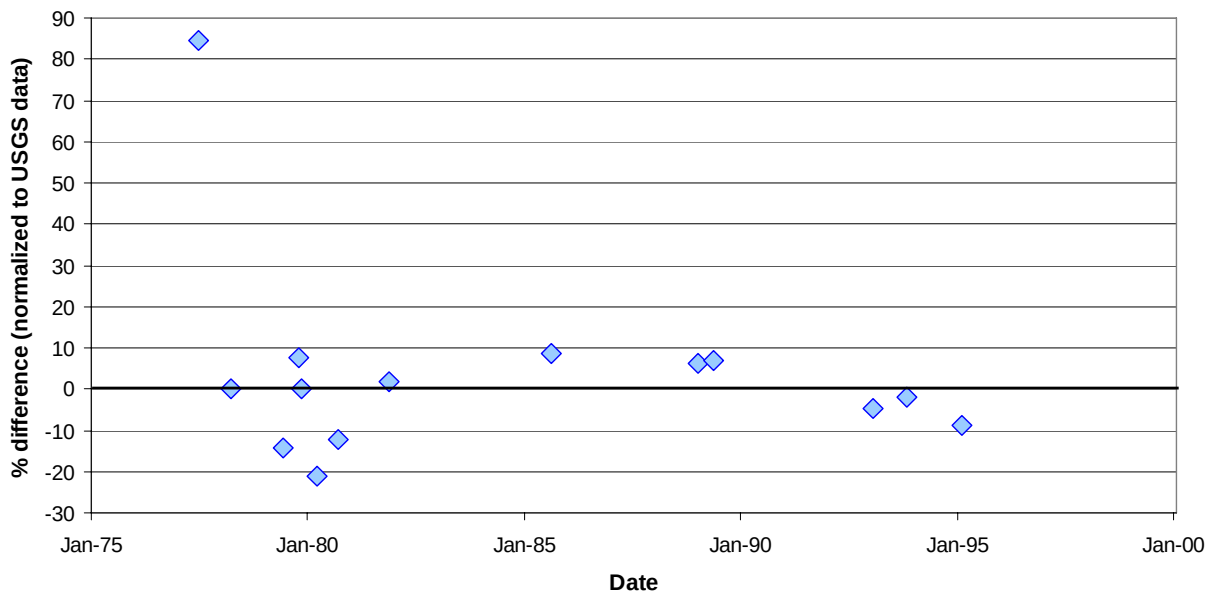
- The STORET database is comprised of data collected by the EPA as well as by several other smaller agencies. Thus, some data downloaded from STORET may originate at agencies with unknown field and laboratory techniques and quality assurance control.

- The only direct comparisons of EPA data with USGS data that can be made within the ISC database is for 4 TDS analyses (parameter code 70300) and 14 sulfate analyses (parameter code 945) performed by both the USGS and the EPA on the same dates at the same site ID. The TDS comparison shows a maximum of ±4% difference between EPA and USGS data (Figure 1), and the sulfate comparison shows a ±10% difference (Figure 2), suggesting that USGS and EPA data may differ by only a small amount. However, 4 of the 14 sulfate analyses compared between agencies had greater than ±10% difference, ranging up to an 85% difference for one data point. This indicates that caution should be exercised when using data from both sources in the same data set, even when all other sample characteristics (parameter code, date, and location) are considered identical.



Percent difference between dissolved solids data (code 70300) for EPA STORET and the USGS, El Paso

Figure 1



Percent difference between sulfate concentration data (parameter code 00945) from EPA STORET and the USGS (New Mexico office), El Paso

Figure 2

Conclusion:

Data from the EPA are of high quality, with some uncertainty in sampling methodology (compared to the USGS) that may be minor.

Recommendation:

Where USGS data and EPA STORET data are available on the same date, priority should be given to USGS data. Where USGS data are not available, EPA STORET data should be given priority over available data from all other sources.

1.3 Williams (2001) thesis

- Data in the Williams (2001) thesis originate from a USDA Salinity Laboratory report (Wilcox, 1957).

- The random number generator in Excel was used to select 3% of the values marked with the Williams (2001) source code for samples collected at the outlet of Elephant Butte Reservoir that are present in the original USDA report (of which a paper copy was obtained). In this random comparison, all Williams values in the ISC database were the exact values originally reported in the hard copy of the USDA report (55 values checked after converting Williams data to units used by the USDA).

Conclusion:

Reporting of Williams data in the ISC database is assumed to accurately represent original USDA data.

Recommendation:

Williams data should be chosen above other data sources where and when USGS and EPA STORET data are not available.

1.4 Boyle-Parsons (1996) report

- The Boyle-Parsons report (1996) is a compilation of data from other original sources, including the USDA Salinity Laboratory report (Wilcox, 1957) and the USGS.

- The random number generator in Excel was used to select 3% of the values marked with the Boyle-Parsons source code that are present in the original USDA report. Of the 67 randomly chosen values from the ISC database that have the Boyle-Parsons source code (for all key parameters at the key surface water locations), 66 were within 0.5% of the original value from the USDA report by Wilcox, after converting to the units used by Wilcox. The slight difference is most likely due to small calculation errors related to the choice of the atomic weight used by Boyle-Parsons to convert meq/L to mg/L. The 67th checked value (chloride concentration value for Leasburg on 6/15/1943) was off by almost 100%, suggesting that it is a transcription error. Further comparison of the Boyle-Parsons data with USDA and USGS data shows that:

- Data from the Boyle-Parsons report exhibit other discrepancies with the USDA report, including nearly two years (out of a total of 25 years) of possible transcription errors for chloride concentration at Leasburg (1942 to 1944).

- Boyle-Parsons reports some data that are identical to original USGS data that are also in the ISC database.

- The “day” component of the date of Boyle-Parsons data is often assigned to the 15th of the month in the ISC database in order to correspond with the sampling method (time-integrated samples) or due to lack of information about the actual sampling date.

Conclusion:

Boyle-Parsons data contain minor inaccuracies resulting from unit conversions and infrequent major inaccuracies probably resulting from transcription errors. Additionally, the date of Boyle-Parsons data in the ISC database is often an artifact of sample collection methodology and database construction rather than an actual sampling date.

Recommendation:

Boyle-Parsons data should be considered of lower priority than USGS, EPA STORET, and Williams data. However, Boyle-Parsons data are of suitable accuracy to be used where and when no other data source is available.

2. Data Parameter Code Recommended Priority Order, for each key parameter

Parameter codes related to each of the six key parameters are prioritized in Sections 2.1 through 2.6.

2.1 Total Dissolved Solids (TDS)

- Parameter codes and definitions:
  - 70300: RESIDUE,TOTAL FILTRABLE (DRIED AT 180C),MG/L
  - 70301: SOLIDS, DISSOLVED-SUM OF CONSTITUENTS (MG/L)

- Parameter codes 70300 and 70301 represent distinct measurement methodologies. Code 70300 represents an actual measurement of TDS as the residue remaining after evaporation of a water sample, while code 70301 represents the sum of all cation and anion analyses that were performed for a particular sample.

- EPA, Williams, Boyle-Parsons, and most USGS data are represented by code 70300. Some USGS data fall under code 70301.

- Comparison of 204 pairs of analyses for codes 70300 and 70301 from the USGS (source code 27) for the same date and same assumed location (different site IDs at El Paso, but assumed to be within 2250 feet of each other, as discussed in Section 3) indicates that values for the two parameter codes for otherwise equivalent samples may differ by ±10% or more (Figure 3). Samples with code 70301 tend to have lower values relative to 70300 samples, probably due to incomplete ion analyses.

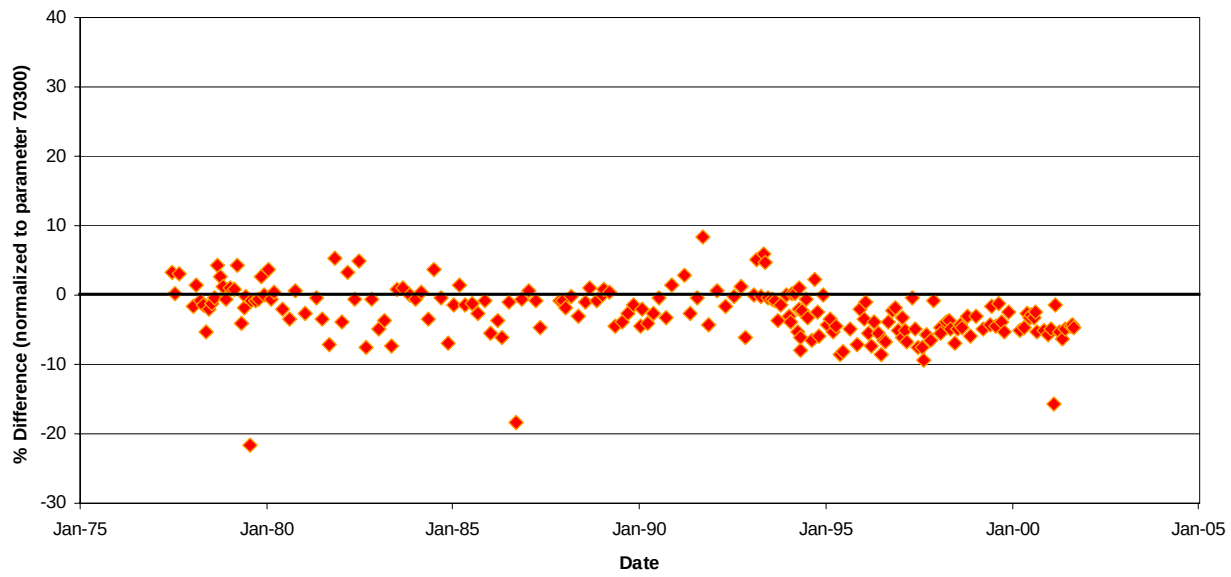
Conclusion:

A systematic difference is observed between parameter codes 70300 and 70301, even when all other data parameters are considered equivalent (data location, source code, and date). Analyses represented by 70301 are dependent upon the completeness of ion analyses performed.

Recommendation:

It is recommended that the 70300 parameter code be prioritized first, because it is the more common analysis and because it represents an actual TDS measurement rather than the sum of other analyses. Because of the observed systematic difference between 70300 and 70301

analyses, using the two parameter codes in the same data set should be done with this caveat in mind and only where and when 70300 data are not available.



Percent difference over time between dissolved solids parameter codes 70300 and 70301 for USGS data (source code 27), El Paso

Figure 3

2.2 Specific Conductivity (SC)

- Parameter codes and definitions:
  - 00094: SPECIFIC CONDUCTANCE,FIELD (UMHOS/CM @ 25C)
  - 00095: SPECIFIC CONDUCTANCE (UMHOS/CM @ 25C)
  - 90095: SPECIFIC CONDUCT
  - 999991: ELECTRICAL CONDUCTIVITY AS EC, TYPE/METHOD UNKNOWN
  - 999978: SPECIFIC CONDUCTANCE, METHOD UNKNOWN, US/CM @25C OR NONE

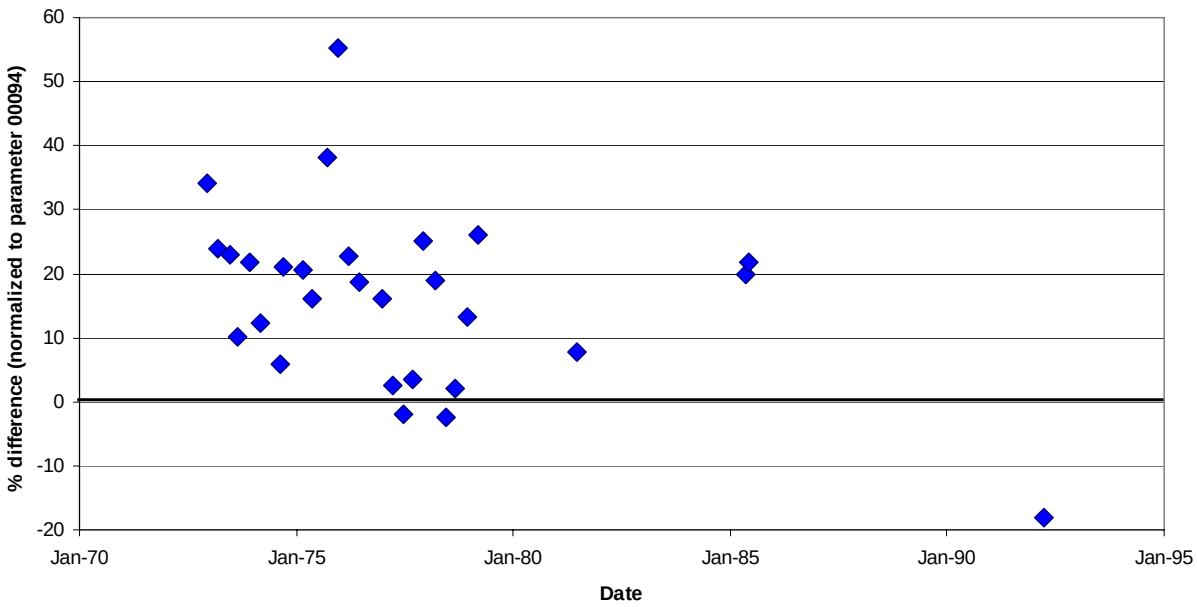
- The main difference among the SC parameter codes is probably whether the measurement was made in the field or in the laboratory. The parameter code definitions in the ISC database specify only that code 00094 is a field measurement. Based on the USGS definitions of code 90095 and possibly code 00095 (http://water.usgs.gov) and

the fact that many ISC parameter codes are based on those of the USGS, it is assumed that these two codes represent laboratory measurements. It is unknown whether codes 999991 and 999978 represent field or laboratory measurements.

- USGS data are represented by codes 00094, 00095, and 90095, EPA data are represented by codes 00094 and 00095, Williams data are represented by code 999991, and Boyle-Parsons data are represented by code 999978.

- Parameter code 00095 is the most common analysis performed for USGS and EPA data, followed by codes 90095 and 00094.

- Comparison of 29 pairs of 00094 and 00095 analyses performed by the EPA for the same date and location indicate a –2 to 55% difference between the two parameter codes, with most analyses differing by 10 to 30% (Figure 4).



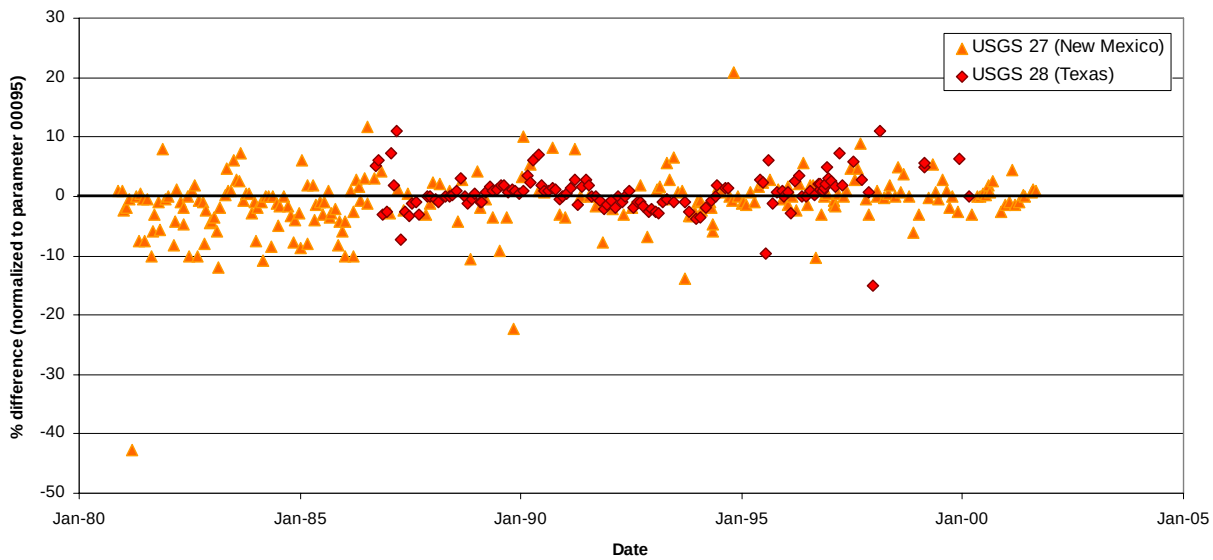
Percent difference over time between specific conductance parameters 00094 and 00095 for EPA STORET data, El Paso

Figure 4

- Comparison of 366 pairs of 00095 and 90095 analyses performed by the USGS (compared with source code 27 and within source code 28) for the same date and

location show a ±10% difference between the two parameter codes, with several outliers (Figure 5).

- Other comparisons between data codes are not possible due to inherent data availability constraints.



Percent difference over time between specific conductance parameters 00095 and 90095 for USGS data (source codes 27 and 28), El Paso

Figure 5

Conclusion:

Parameter codes that could be compared (00094, 00095, 90095) show consistent differences even when all other sample characteristics are considered identical. Comparisons between codes 00095 and 90095 indicate relatively small (±10%) differences, which is not unexpected given that both codes probably represent laboratory measurements. Comparisons between codes 00094 and 00095 show larger differences (>10%), which is likely due to the fact that code 00094 represents a field measurement and code 00095 probably represents a laboratory measurement. Parameters 999991 and 999978 could not be compared to any other parameters, but they appear to be assigned based on differences in source rather than on differences in measurement technique. However, it remains unclear whether these two codes

represent laboratory or field measurements, even when the source documents (Wilcox, 1957; Williams, 2001; Boyle-Parsons, 1996) were examined.

Recommendation:

Parameter code 00095 should be given first priority because it is most common and because it is used by both the USGS and the EPA. Parameter code 90095 should be given second priority because it generally shows a fairly small difference from code 00095. Parameter code 00094 shows overall considerable difference from code 00095, and should be used only when and where data of codes 00095 and 90095 are not available. Because of the correlation between parameter code and source code in the remaining two parameter codes (999991 and 999978) and the lack of available data to compare them directly with other codes or with each other, these two parameter codes should be prioritized based on prioritization of the associated source code. For this reason, the two codes should remain at a lower priority than all USGS and EPA codes (00095, 90095, and 00094). Additionally, parameter code 999991 (Williams data) should be prioritized above code 999978 (Boyle-Parsons data). When using these two parameter codes in a data set with other parameter codes, it should be kept in mind that the amount of uncertainty between the codes is unknown. Data therefore should be compared with caution.

2.3 pH

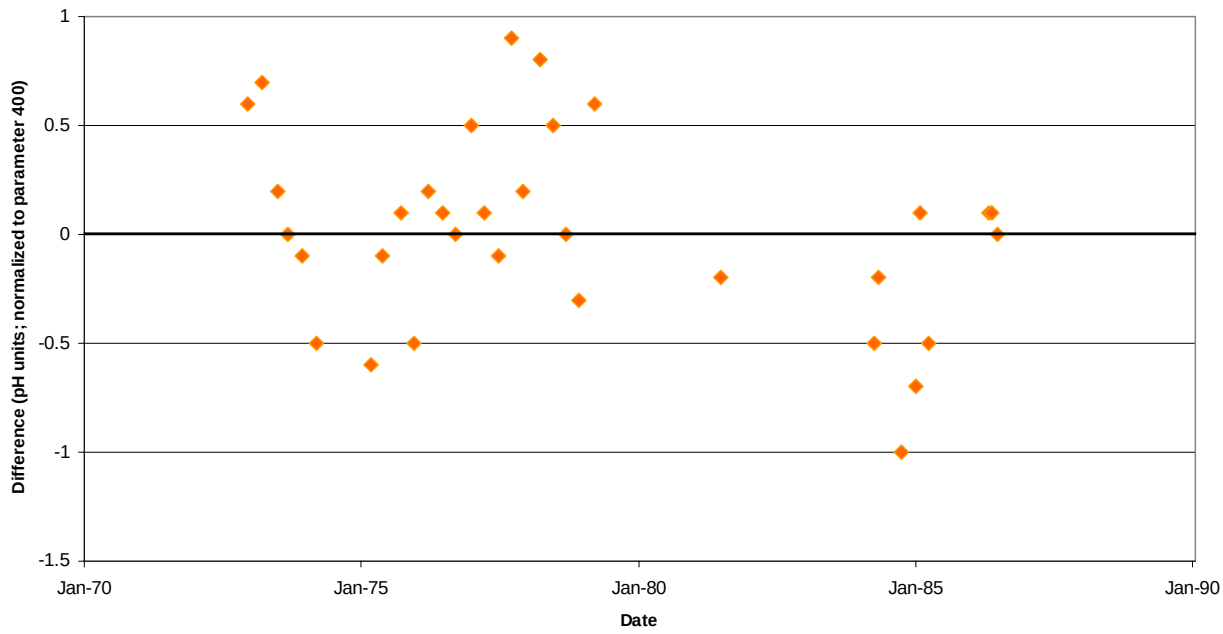
- Parameter codes and definitions:
  - 400: PH (STANDARD UNITS)
  - 403: PH, LAB, STANDARD UNITS, SU

- The most probable difference between parameter codes 400 and 403 is that one is a field measurement and the other is a laboratory measurement. The ISC parameter code definitions only specify that code 403 represents a laboratory measurement; however, USGS definitions (http://water.usgs.gov) define code 400 specifically as a field measurement and code 403 as a laboratory measurement. Because many of the ISC database parameter codes are based on USGS codes, it is assumed that code 400 represents a field measurement as in the original USGS data.

- Codes 400 and 403 are represented about equally in the database for both USGS and EPA data.

- Comparison of pairs of 400 and 403 analyses performed by the EPA for a single location and date indicate that the two measurements differ by as much as ±1 pH unit, which is equivalent to ±one order of magnitude (Figure 6).

- Other comparisons (not graphed here) of 400 and 403 analyses performed by the USGS for a single location and date show similar differences.



Absolute difference over time between pH parameters 400 and 403 for EPA STORET data, El Paso

Figure 6

Conclusion:

Differences between parameter codes 400 and 403 may be considerable and are probably due to the sensitivity of the pH measurement to holding time of the sample.

Recommendation:

Field pH measurements as represented by parameter code 400 are generally considered more accurate, and they should be prioritized first. Because of the potential for order-of-magnitude differences between codes 400 and 403, it is advised that data with parameter code 403 not be used in the same database with data of parameter code 400.

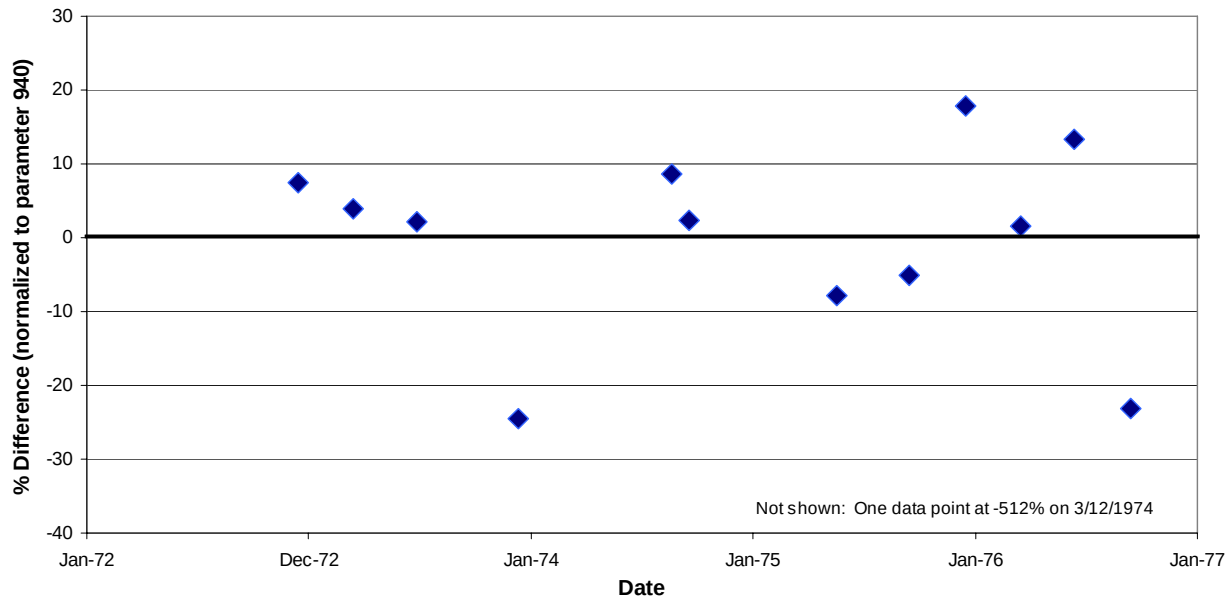
2.4 Chloride

- Parameter codes and definitions:
  - 940: CHLORIDE,TOTAL IN WATER, MG/L
  - 941: CHLORIDE, DISSOLVED IN WATER, MG/L
  - 999994: CHLORIDE, MG/L AS CL, TYPE/METHOD UNKNOWN

- Parameter codes 940 and 941 represent distinct laboratory measurements, as indicated by their definitions above. Code 940 is assumed to indicate an analysis of chloride present in suspended and dissolved material, while code 941 is a measurement of dissolved chloride only. It is unclear whether parameter code 999994 represents a total or dissolved chloride measurement, even after examination of the source documents (Wilcox, 1957; Boyle-Parsons, 1996; Williams, 2001).

- All USGS and most EPA data are classified by parameter code 940. Williams and Boyle-Parsons data are classified by parameter code 999994. A small amount of EPA data is classified by parameter code 941.

- In a comparison of 13 pairs of 940 and 941 analyses performed by the EPA on the same dates at the same location, most (8) pairs of measurements differ within ±10% (Figure 7). Four pairs of measurements differ by ±30%, and one measurement differs by more than 500%.



Percent difference over time between chloride concentration parameter codes 940 and 941 for EPA data, El Paso

Figure 7

Conclusion:

Parameter codes 940 and 999994 are the most common chloride codes. Comparison of parameter codes 940 and 941 indicate that the two measurements generally differ by ±10% though larger differences are not uncommon. It is not possible to compare code 999994 with other parameter codes due to data availability constraints.

Recommendation:

Parameter codes 940 and 999994 should be prioritized equally because they are equally common in the ISC database and do not overlap in time. They should be assumed to represent the same laboratory measurement, though it should be kept in mind that possible differences and uncertainty between the codes are unquantified and caution should be exercised. Data with the code 941 should not be used unless necessary because that code represents a different laboratory measurement, exhibits about a 10% difference from the more common parameter codes, and generally overlaps in time and space with the more common parameter codes as well. It is recognized that it is more desirable to use data pertaining to the dissolved

rather than the total constituent concentration, since the dissolved constituent concentration is more indicative of reaction state. However, very little data with parameter code 941, which is the only code known to pertain to dissolved chloride alone, exist in the ISC database. In order to make the most of use of the available data, parameter code 940 is thus prioritized over code 941.

2.5 Sodium

- Parameter codes and definitions:
  - 930: SODIUM, DISSOLVED (MG/L AS NA)
  - 999984: SODIUM, MG/L AS NA, TYPE/METHOD UNKNOWN

- Parameter code 930 represents a laboratory measurement of dissolved sodium, as indicated by the definitions above. It is unclear whether parameter code 999984 represents a total or dissolved chloride measurement, even when the source documents are examined (Wilcox, 1957; Williams, 2001).

- All USGS and EPA data are classified by parameter code 930. Williams data are classified by parameter code 999984.

- There is no overlap in time between the two parameter codes at any location, so it is not possible to directly compare data with different sodium parameter codes on the exact same date at the same location.

- Code comparisons for other parameters (Sections 2.1 through 2.4) indicate that pervasive differences often exist between different parameter codes.

Conclusion:

Though direct comparison of sodium parameter codes is not possible, other analyses suggest that the number of parameter codes analyzed together should be minimized where and when possible.

Recommendation:

Parameter codes 930 and 999984 will be prioritized equally because they are equally common in the ISC database and because they do not overlap in time. They will be assumed to represent the same laboratory measurement, though it will be kept in mind that possible differences and uncertainty between the codes are unquantified and caution should be exercised.

2.6 Sulfate

- Parameter codes and definitions:
  - 945: SULFATE, TOTAL (MG/L AS SO4)
  - 946: SULFATE, DISSOLVED (MG/L AS SO4)
  - 999974: SULFATE, MG/L, TYPE/METHOD UNKNOWN
  - 999979: SO4, MG/L, TYPE/METHOD UNKNOWN

- Parameter codes 945 and 946 represent distinct laboratory measurements, as indicated by their definitions above. Code 945 is assumed to indicate an analysis of sulfate present in suspended and dissolved material, while code 946 is a measurement of dissolved sulfate only. It is unclear whether parameter codes 999974 and 999979 represent a total or dissolved sulfate measurement, even after examining the source documents (Wilcox, 1957; Boyle-Parsons, 1996; Williams, 2001).

- All USGS and nearly all EPA data are classified by parameter code 945. A small amount of EPA data is classified by parameter code 946. Williams data are classified by parameter code 999979 and Boyle-Parsons data are classified by parameter code 999974.

- Although there are general periods of overlap in time and space among the four parameter codes, it is not possible to directly compare data with different sulfate parameter codes on the same date at the same location.

- Code comparisons for other parameters (Sections 2.1 through 2.4) indicate that pervasive differences often exist between different parameter codes.

Conclusion:

Parameter codes 945, 999974 and 999979 are the most common sulfate codes. Though direct comparison of sulfate parameter codes is not possible, other analyses suggest that the number of parameter codes analyzed together should be minimized where and when possible. Furthermore, parameters 999974 and 999979 appear to be assigned based on differences in source rather than on differences in measurement technique. However, it remains unclear whether these two codes represent dissolved or total constituent analyses, even when the source documents (Wilcox, 1957; Williams, 2001; Boyle-Parsons, 1996) were examined.

Recommendation:

Parameter code 945 should be given first priority because it is most common and because it is used by both the USGS and the EPA. Because of the correlation between parameter code and source code for parameter codes 999974 and 999979 and the lack of available data to compare them directly with other codes or with each other, these two parameter codes should be prioritized based on prioritization of the associated source code. For example, parameter code 999979 (Williams data) should be prioritized above code 999974 (Boyle-Parsons data). When using these two parameter codes in a data set with other parameter codes, it should be kept in mind that the amount of uncertainty between the codes is unknown and that data should therefore be compared with caution.

Data with the code 946 should not be used unless necessary because it is known to represent a different laboratory measurement than the preferred code (945). It is more desirable to use data pertaining to the dissolved rather than the total constituent concentration, since the dissolved constituent concentration is more indicative of reaction state. However, very few data with parameter code 946, which is the only code known to pertain to dissolved sulfate alone, exist in the ISC database. In order to make the most use of the available data, parameter code 945 is thus prioritized over code 946. Especially for a highly soluble species like sulfate, it is assumed that the percent difference between total and dissolved measurements is minimal, particularly at the high concentrations that are present in the Lower Rio Grande.

3. Data Location Code Recommended Priority Order

In previous discussions with the ISC, nine key surface water locations have been identified for parameter analysis. They are listed in Table 1 from the upstream to the downstream end of the study area, along with the site IDs that have been determined to be relevant and are recommended for use in the Lower Rio Grande salinity study.

A particular site ID was determined to be relevant if its location was in the vicinity of a key surface water location, if it was pertinent to the body of water of concern (i.e., river vs. reservoir) and if it was associated with data pertaining to the six key parameters. However, it is not recommended that site IDs be prioritized in the same way that source and parameter codes are because of the following unquantifiable uncertainties:

- Location information, including site ID, is referenced by data source code in the ISC database. However, a site ID is often used to characterize data from a source different than the source of the location data. For example, location information for site ID 1R1.1 is referenced to data source code 2, a USGS code. Yet Williams data are assigned to the same code. It is possible that the same site ID is used for both because the data reported by Williams were originally USGS data (Wilcox, 1957). However, it is not entirely clear that data collected by the USGS from 1934 to 1963 (and reported by Williams) were for the same locations as USGS data collected several decades later, after a time gap in sampling.

- Similarly, individual sampling events at the same sampling location over time may not have actually been collected at the exact same point indicated by the latitude and longitude information associated with the site ID.

- Some latitude and longitude coordinates seem to have transcription errors that make it difficult to determine the actual location of a site ID and its distance from other site IDs at the sampling location.

- Some sample locations appear to have significant positional inaccuracies with unknown causes. While most locations appear in their correct positions, some map hundreds of meters away from their described location. Several data sets (i.e., USGS Digital

Orthophotos, Digital Raster Graphics, and National Hydrography Dataset) were used to verify the accuracy of the base map data used on the surface water quality data location figures, and some source data for locations in the water quality database were checked to confirm coordinate information or to find descriptions of how coordinates were derived (e.g., EPA STORET online database).

- Many sample locations in the database do not have datum information for the decimal degree coordinates (either null or "R:NN"). Confusing the NAD83 and NAD27 datums where no datum information is available would result in an approximate 55-meter shift. The errors described above are much larger than this, so cannot be attributed to a datum problem.

Conclusion:

Site ID is not necessarily a fixed characteristic that can be consistently quantitatively evaluated or prioritized through time and space. To the extent possible, uncertainties in sampling location were quantified by determining the distance between adjacent site IDs with available latitude and longitude data, as indicated in Table 1 and Figures 8 through 15. Local inflows and outflows that may fall between particular site IDs at a single sampling location were noted for consideration when comparing water quality data in the vicinity of the sampling location.

Recommendation:

Relevance of site IDs was determined based on fulfillment of three criteria: (1) location in the vicinity of a key surface water location, (2) pertinence to the waterbody of concern, and (3) association with data pertaining to the six key parameters. Since site ID prioritization is precluded by database uncertainties, data associated with all relevant site IDs should be used. To work around the uncertainty inherent in the lack of location data recorded for individual sampling events, it should be assumed that most actual points of sample collection occurred within several hundred feet of the site IDs reported in the ISC database. This distance is generally thought to have a negligible effect on comparisons of water quality data, though possible exceptions of locations where local inflows and/or outflows may be significant are listed in Table 1.

Table 1. Relevance of Site IDs to Key Surface Water Sampling Locations
Page 1 of 2

Key Surface Water Location	Site ID in Vicinity	Relevant? (Y/N)	Reason for Irrelevance	Maximum Distance Between Relevant Site IDs (feet)	Possibly Significant Inflows	Possibly Significant Outflows
Rio Grande at San Marcial [a]	8358400	Y	NA	NA	None	None
Conveyance Channel at San Marcial [a]	8358300	Y	NA	NA	None	None
Rio Grande below Elephant Butte Dam	004	N	ND	150	None	None
	063	N	ND			
	1R1.1	Y	NA			
	057ERL	N	ND			
	350501	N	In reservoir			
	8360500	N	In reservoir			
	LRG103.002030	Y	NA			
Rio Grande below Caballo Dam	008	N	In reservoir	4,500	None	None
	009	N	ND			
	1R28.3	Y	NA			
	LRG102.001010	Y	NA			
	LRG102.001505	N	In reservoir			
Rio Grande below Leasburg Dam	016	N	ND	8,000	None	Leasburg Main Canal
	LRG044	Y	NA			
	3R75.1	Y	NA			
	8363500	Y	NA			
	322948106551910	Y	NA			
	322908106553400	Y	NA			

[a] Water quality data for the Rio Grande at San Marcial and the Conveyance Channel at San Marcial were compiled by DBS&A under a single site ID that includes USGS and Williams data.

NA = Not applicable
ND = No data relevant to project

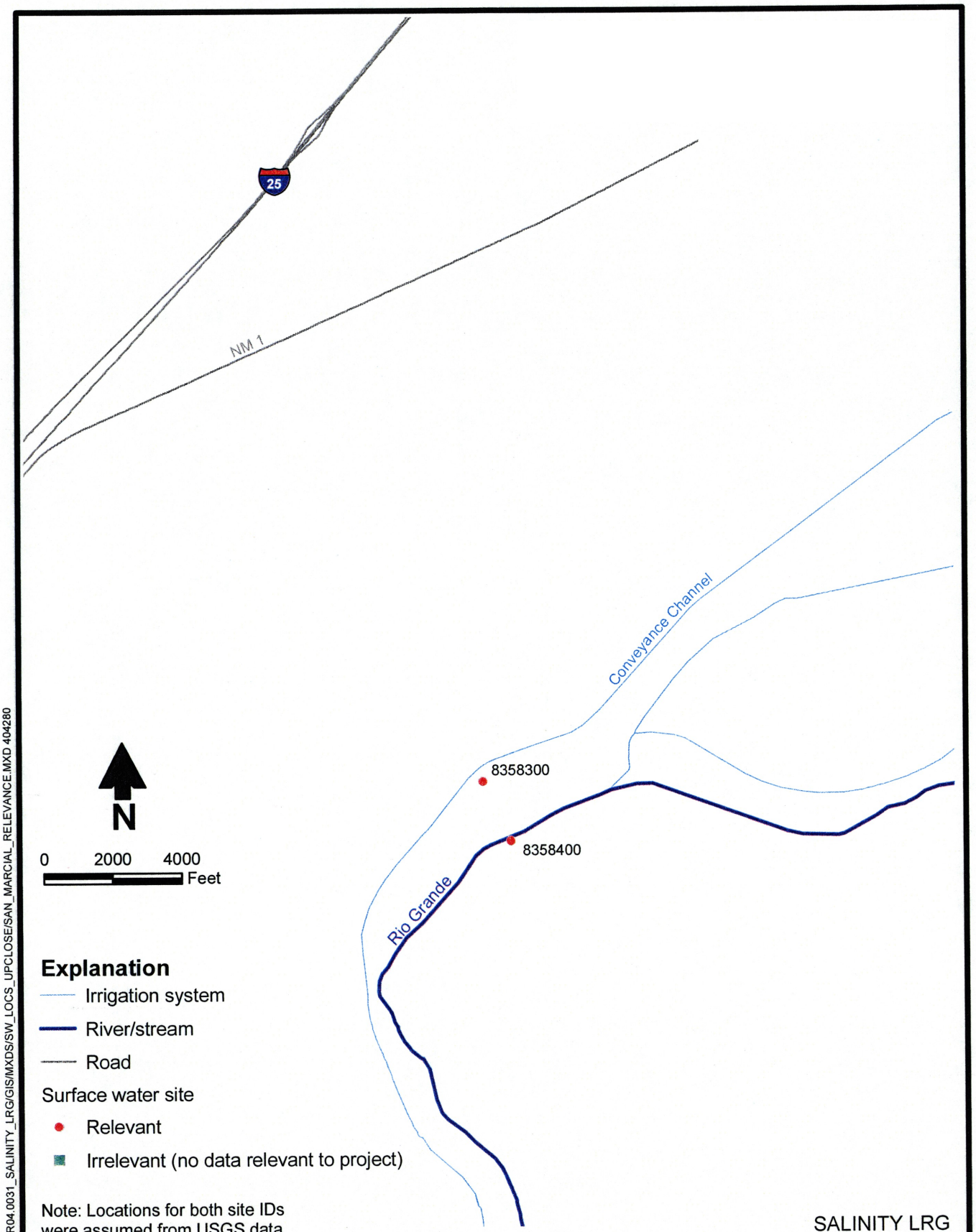
P:_Wr04-031\DatabasePriorities.8-04\T01_SiteID-Relevance_907.doc

Table 1. Relevance of Site IDs to Key Surface Water Sampling Locations
Page 2 of 2

Key Surface Water Location	Site ID in Vicinity	Relevant? (Y/N)	Reason for Irrelevance	Maximum Distance Between Relevant Site IDs (feet)	Possibly Significant Inflows	Possibly Significant Outflows
Rio Grande at Las Cruces	018	N	ND	7,500	Las Cruces WWTP Mesilla Lateral WW 11	None
	LRG046	Y	NA			
	LRG10100139	Y	NA			
	321837106493810	Y	NA			
	32173910639510	Y	NA			
Rio Grande below Mesilla Dam	022	N	ND	7,500	None	Eastside and Westside Canals
	LRG047	Y	NA			
	4R96.6	Y	NA			
	321317106471510	Y	NA			
Rio Grande at Anthony	027	N	ND	9,000	Anthony WWTP Rowley Lateral? (off La Union Canal)	None
	LRG056	Y	NA			
	13276	Y	NA			
	315957106380610	Y	NA			
	LRG101.000110	Y	NA			
Rio Grande at El Paso	032	N	ND	2,250	Montoya Drain El Paso Electric Co outfall Northwest WWTP? (waiting for NPDES location data)	None
	4R133.4	Y	NA			
	LRG101.000102	Y	NA			
	LRG101.000103	Y	NA			
	314812106324210	Y	NA			

[a] Water quality data for the Rio Grande at San Marcial and the Conveyance Channel at San Marcial were compiled by DBS&A under a single site ID that includes USGS and Williams data.

NA = Not applicable
ND = No data relevant to project



Note: Locations for both site IDs were assumed from USGS data.

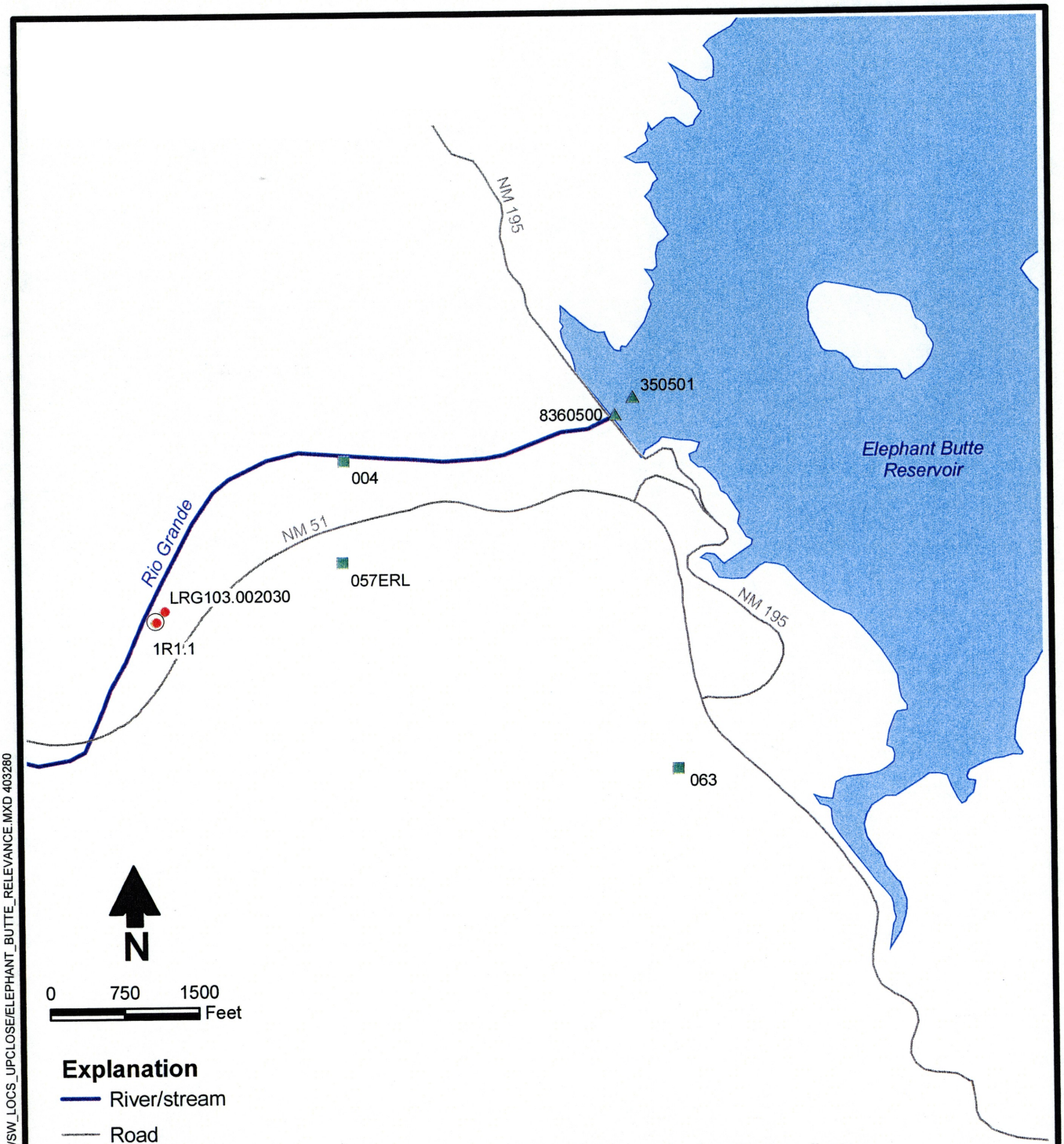
SALINITY LRG

Surface Water Quality Data Location Relevance
San Marcial

Daniel B. Stephens & Associates, Inc.
8-24-04
JN WR04.0031

Figure 8

M:/PROJECTS/WR04.0031_SALINITY_LRG/GIS/MXDS/SW_LOCS_UPCLOSE/SAN_MARCIAL_RELEVANCE.MXD 404280



Explanation

- River/stream
- Road
- USGS gaging station 8361000

Surface water site

- Relevant
- Irrelevant (no data relevant to project)
- Irrelevant (in reservoir)

Note: Gaging station location coordinates downloaded from USGS NWISWeb Data by DBS&A.

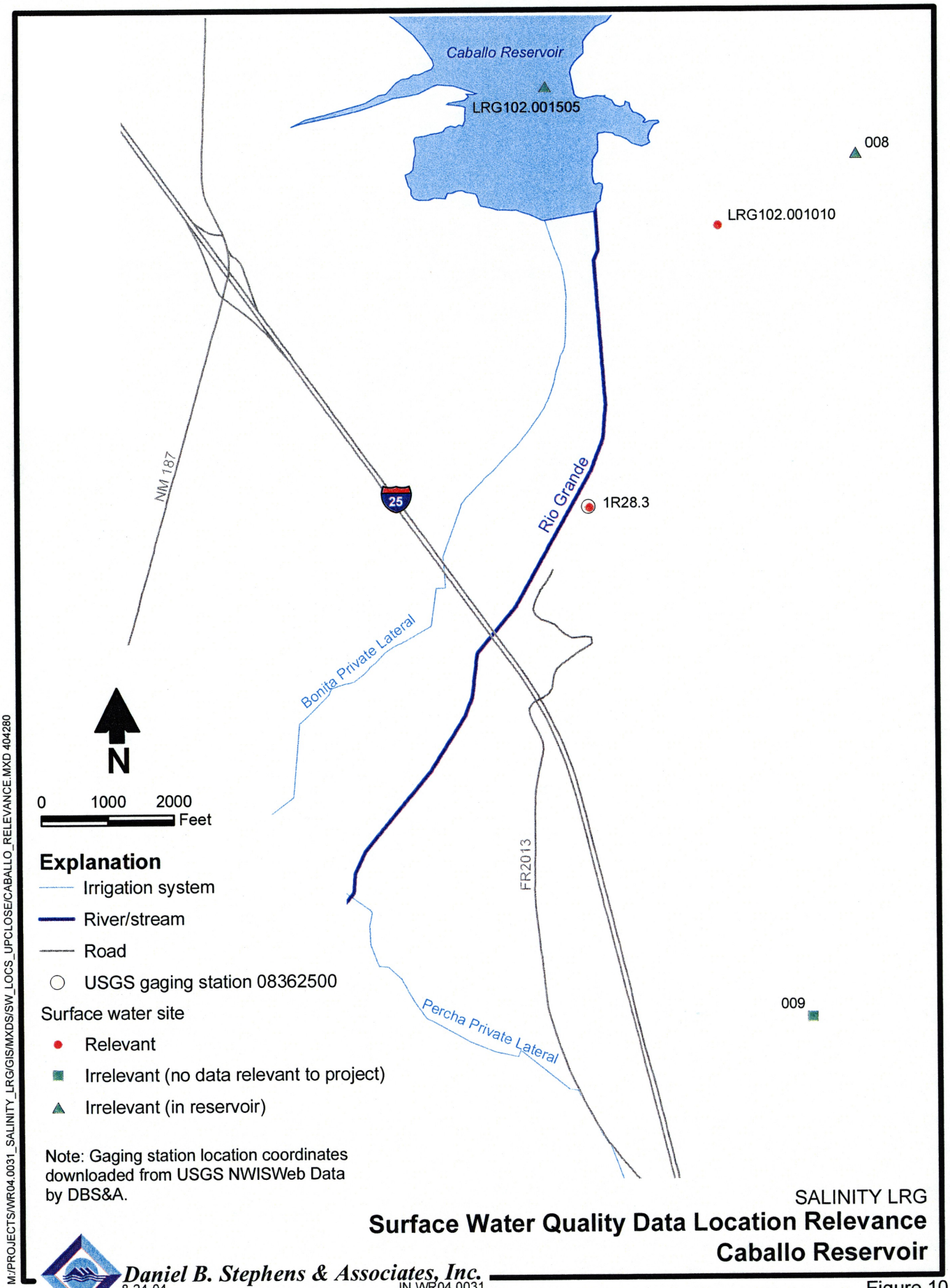
SALINITY LRG

Surface Water Quality Data Location Relevance
Elephant Butte

Daniel B. Stephens & Associates, Inc.
8-23-04
JN WR04.0031

Figure 9

M:/PROJECTS/WR04.0031_SALINITY_LRG/GIS/MXDS/SW_LOCS_UPCLOSE/ELEPHANT_BUTTE_RELEVANCE.MXD 403280



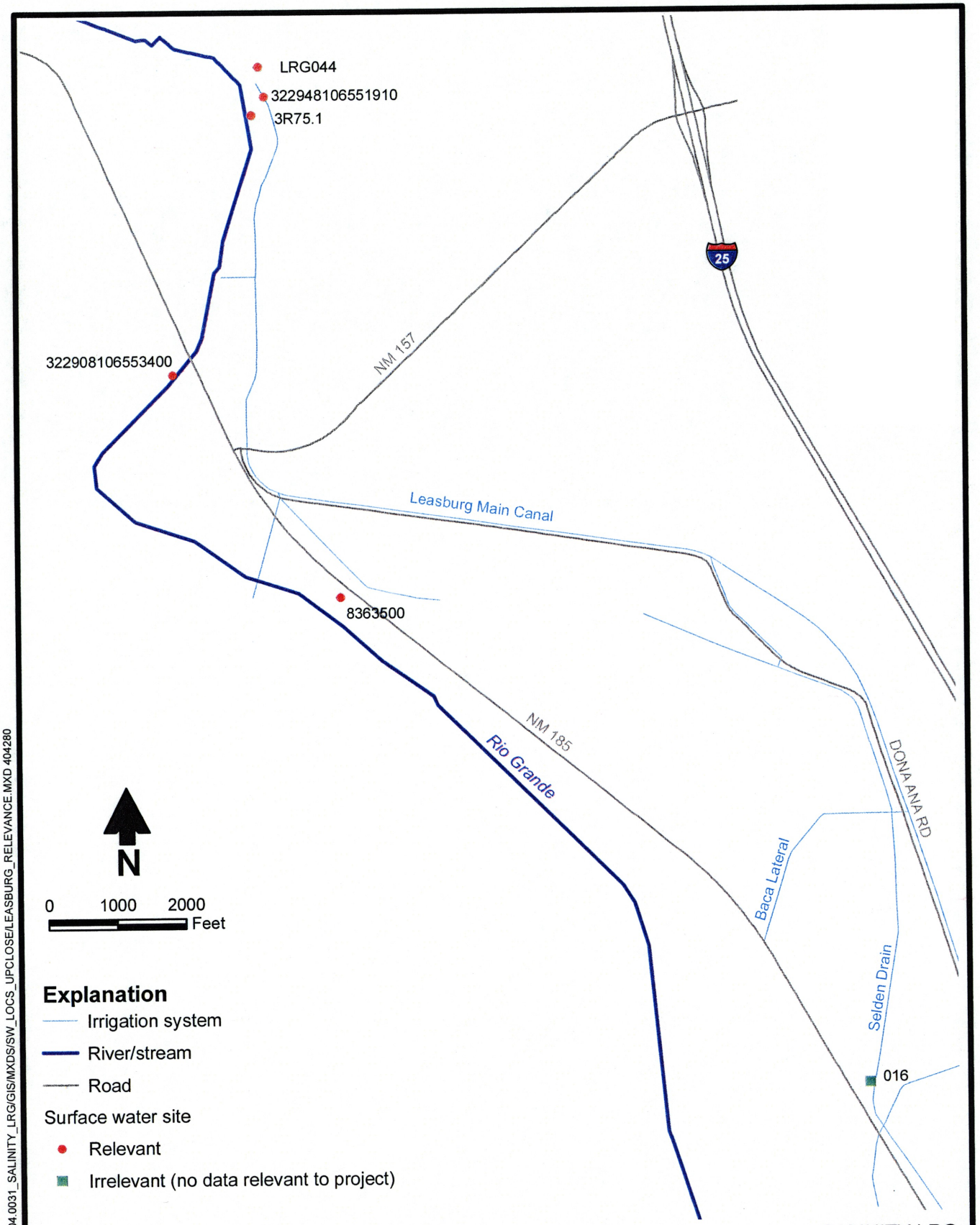
M:/PROJECTS/WR04.0031_SALINITY_LRG/GIS/MXDS/SW_LOCS_UPCLOSE/CABALLO_RELEVANCE.MXD 404280

SALINITY LRG

Surface Water Quality Data Location Relevance
Caballo Reservoir

Daniel B. Stephens & Associates, Inc.
8-24-04
JN WR04.0031

Figure 10



M:/PROJECTS/WR04.0031_SALINITY_LRG/GIS/MXDS/SW_LOCS_UPCLOSE/LEASBURG_RELEVANCE.MXD 404280

SALINITY LRG

Surface Water Quality Data Location Relevance

Leasburg Dam

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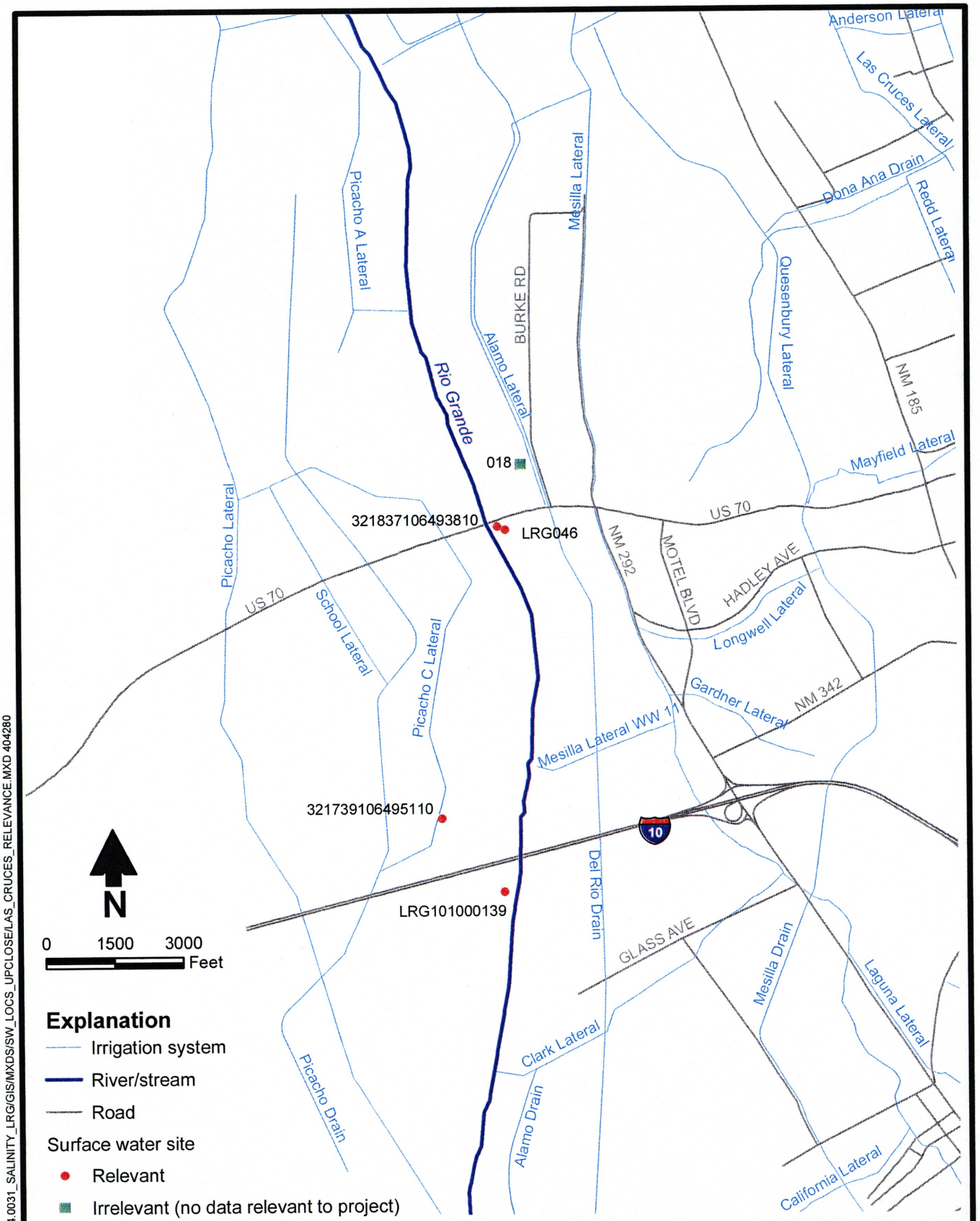
8-24-04

JN WR04.0031

Figure 11



SALINITY LRG

Surface Water Quality Data Location Relevance

Las Cruces

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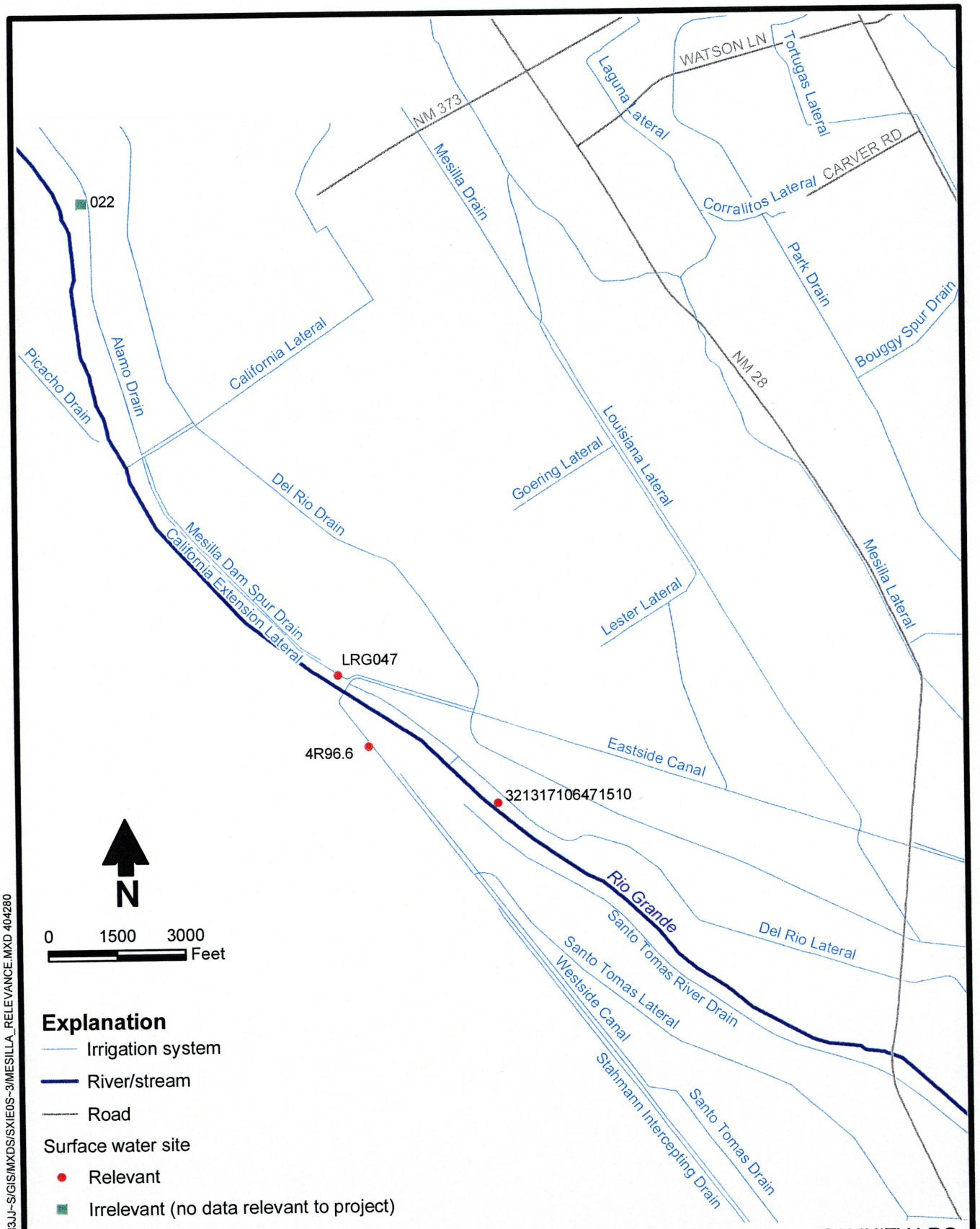
8-24-04

JN WR04.0031

Figure 12

M:/PROJECTS/WR04.0031_SALINITY_LRG/GIS/MXDS/SW_LOCS_UPCLOSE/LAS_CRUCES_RELEVANCE.MXD 404280



SALINITY LRG

Surface Water Quality Data Location Relevance

Mesilla Dam

M:/PROJECTS/W3M3JJ~S/GIS/MXDS/SXIE0S~3/MESILLA_RELEVANCE.MXD 404280

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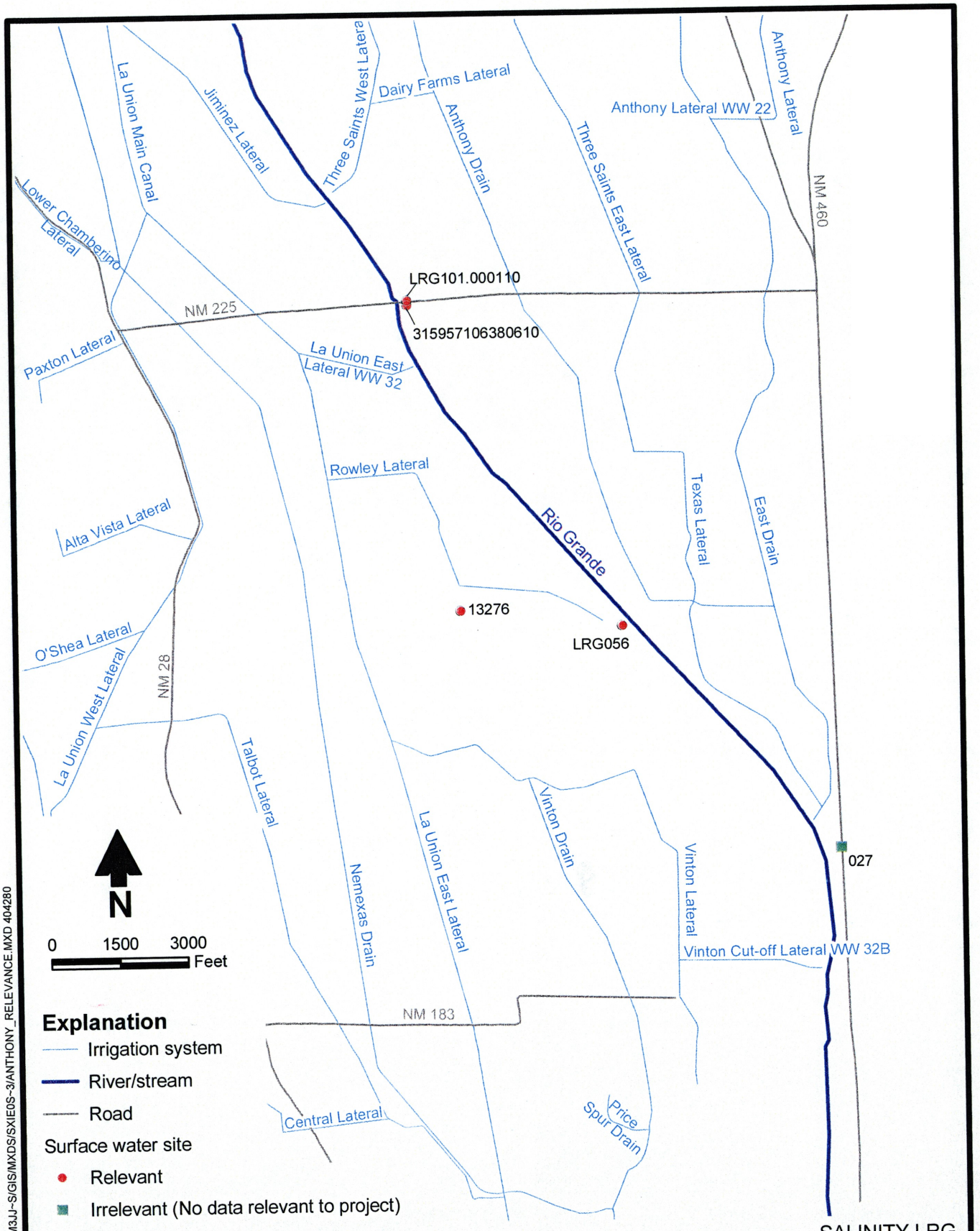
8-24-04

JN WR04.0031

Figure 13



SALINITY LRG

Surface Water Quality Data Location Relevance

Anthony

M:/PROJECTS/W3M3JJ~S/GIS/MXDS/SXIE0S~3/ANTHONY_RELEVANCE.MXD 404280

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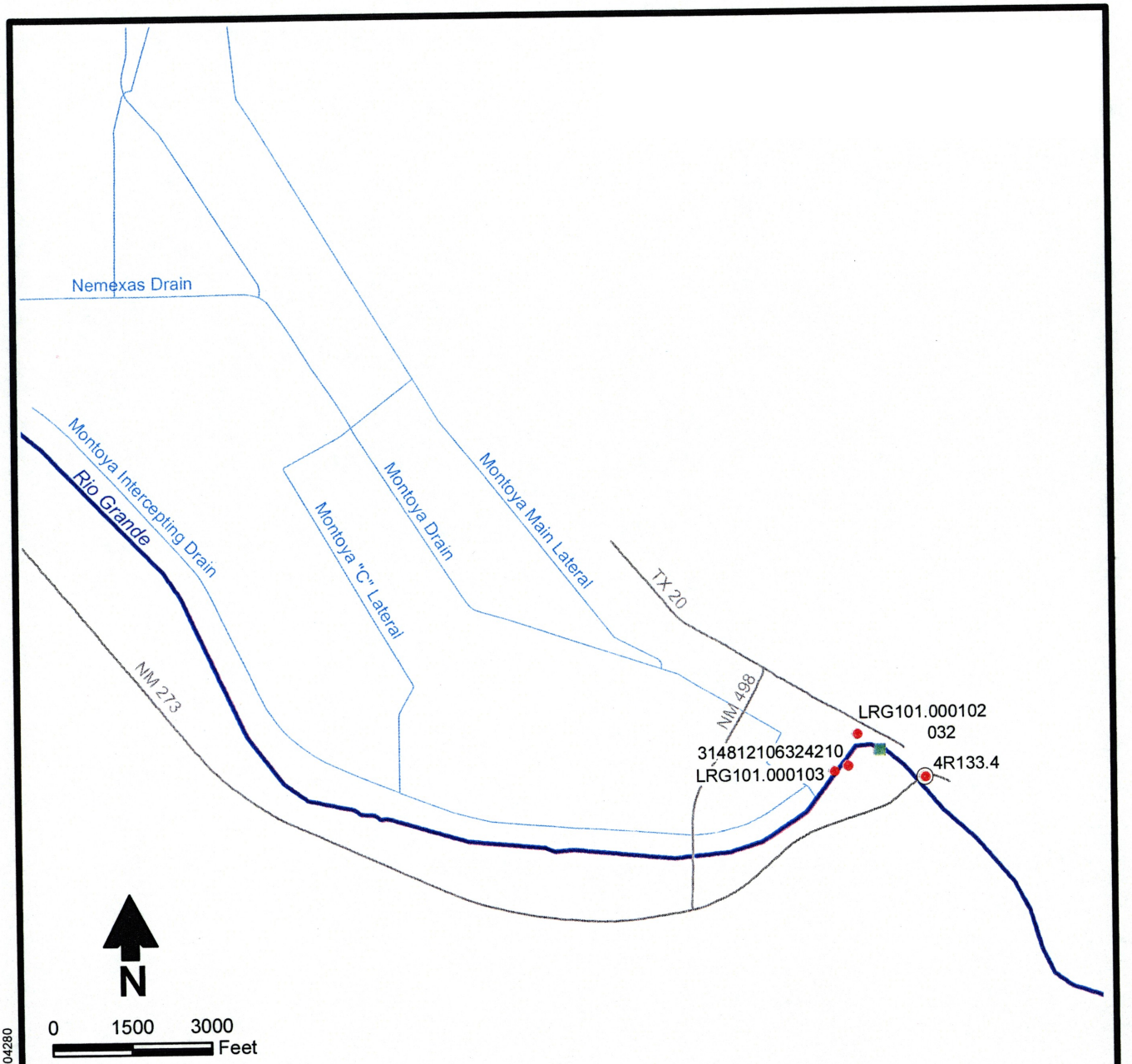
8-24-04

JN WR04.0031

Figure 14



Explanation

- Irrigation system
- River/stream
- Road
- USGS gaging station 8364000

Surface water site

- Relevant
- Irrelevant (no data relevant to project)

SALINITY LRG

Surface Water Quality Data Location Relevance

El Paso

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8-24-04

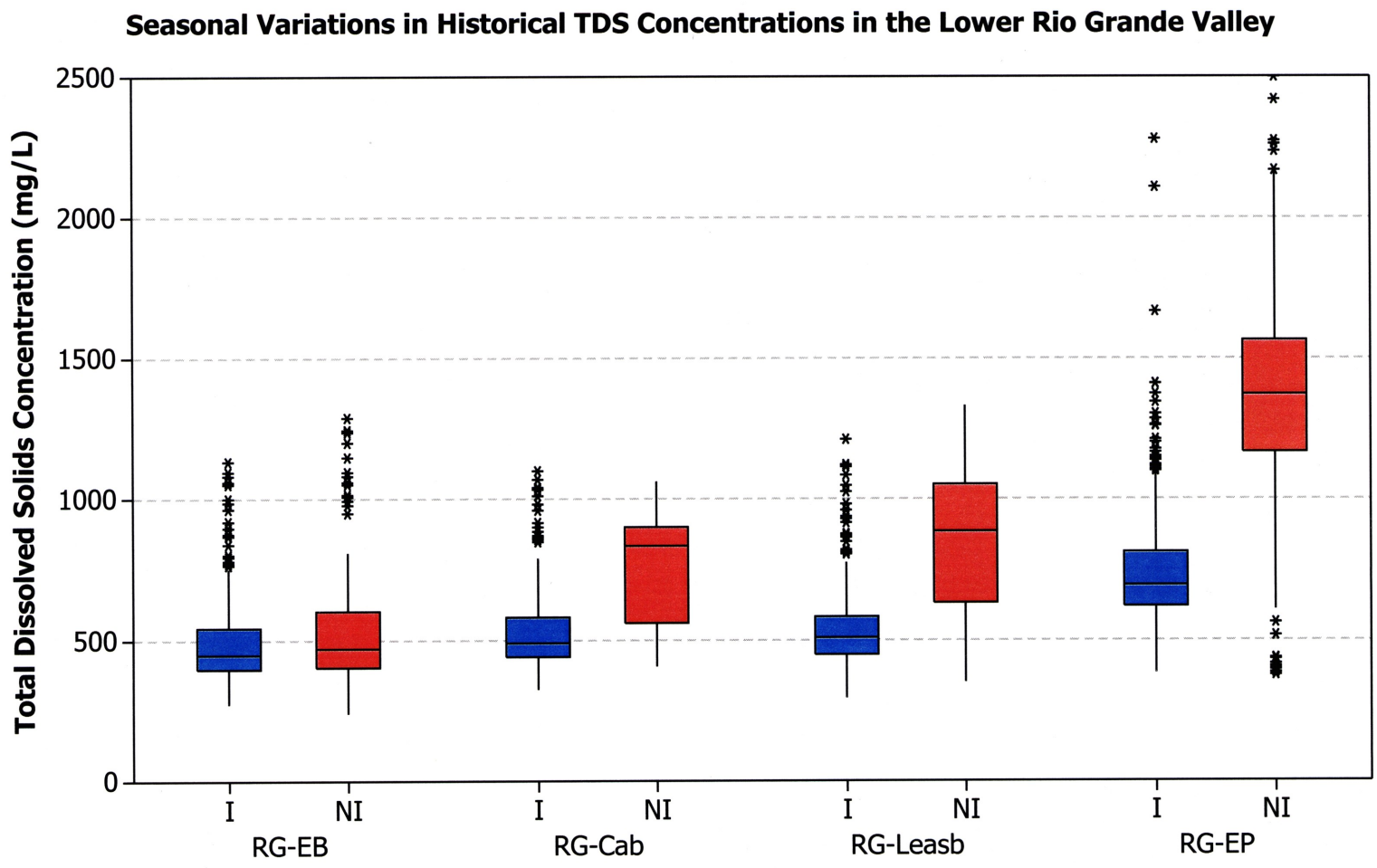
JN WR04.0031

Figure 15

M:/PROJECTS/W3M3JJ~S/GIS/MXDS/SXIE0S~3/EL_PASO_RELEVANCE.MXD 404280

Appendix B

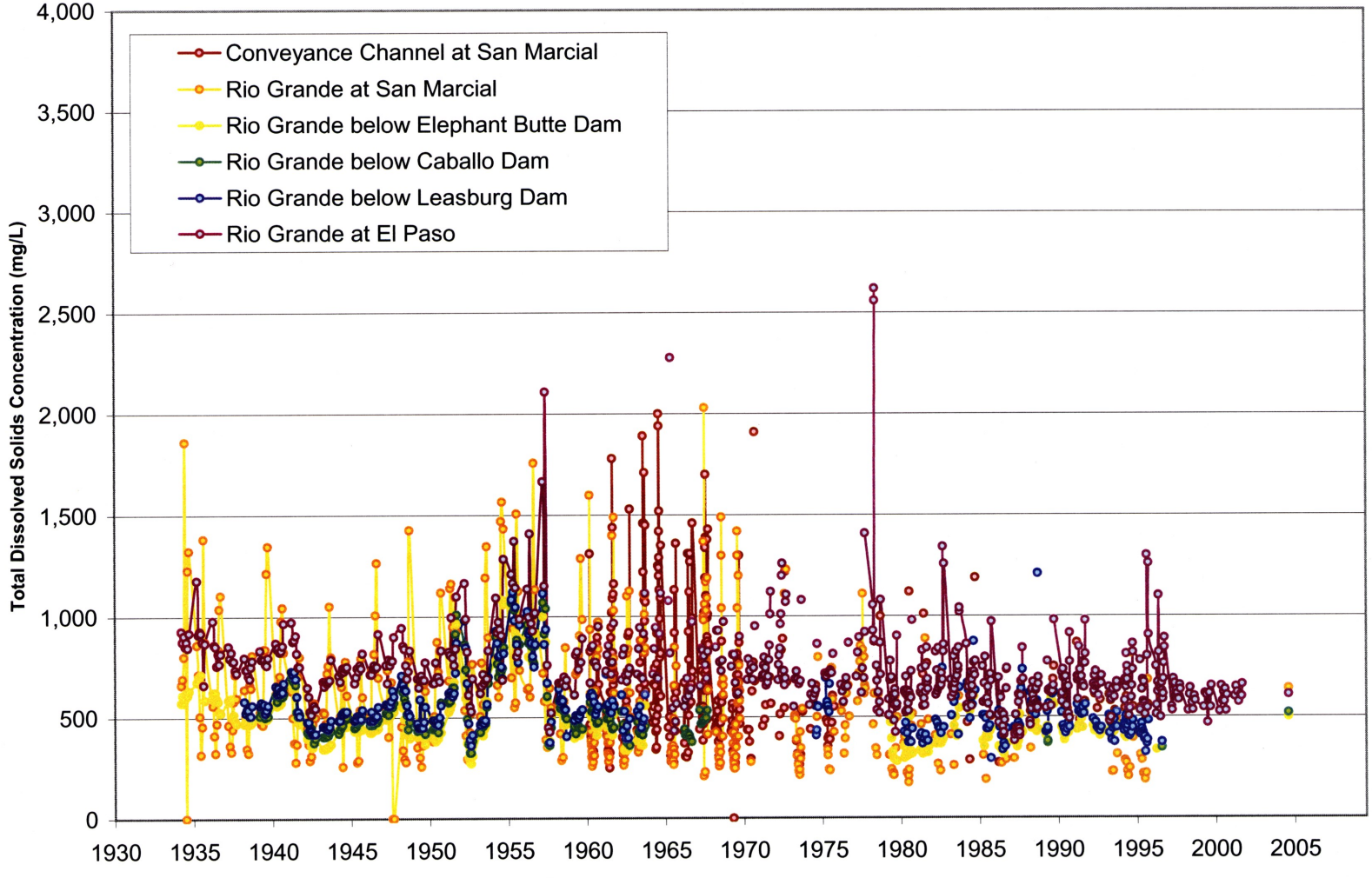
TDS Concentrations and Loads



Irrigation season (I) = Mar - Sept; non-irrigation season (NI) = Oct - Feb

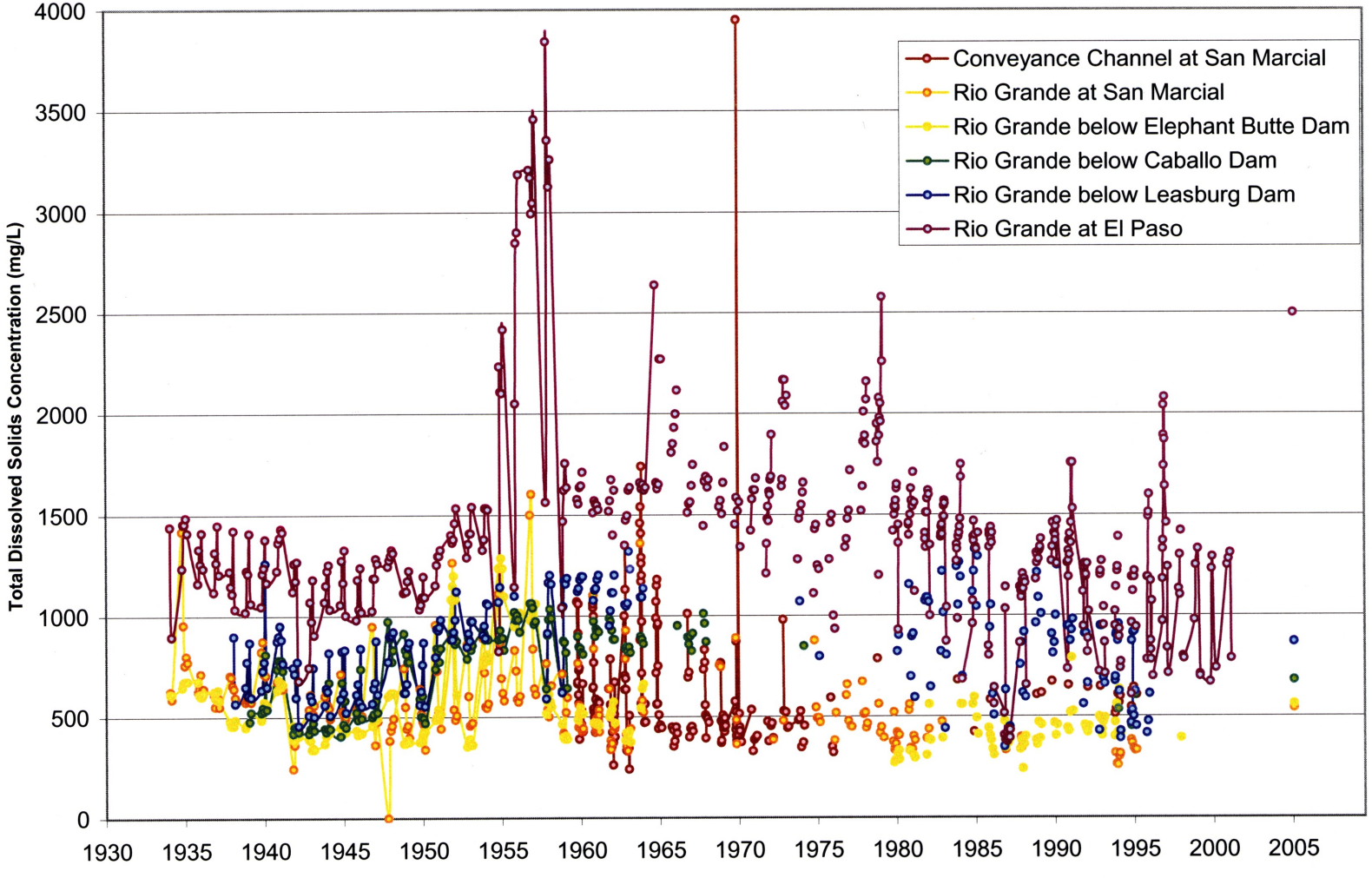
Historical Total Dissolved Solids Concentrations on the Lower Rio Grande

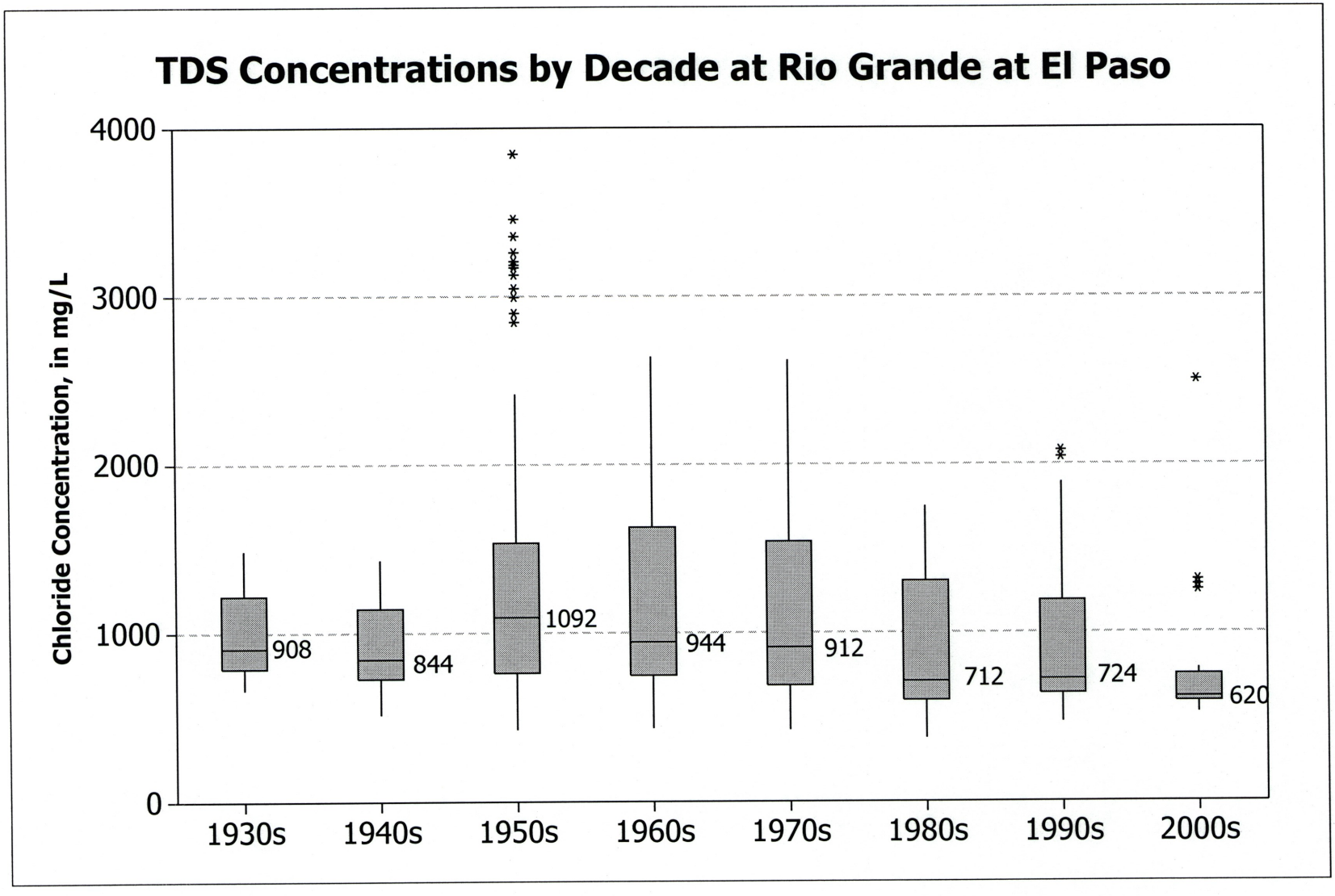
Irrigation season (Mar-Sept)



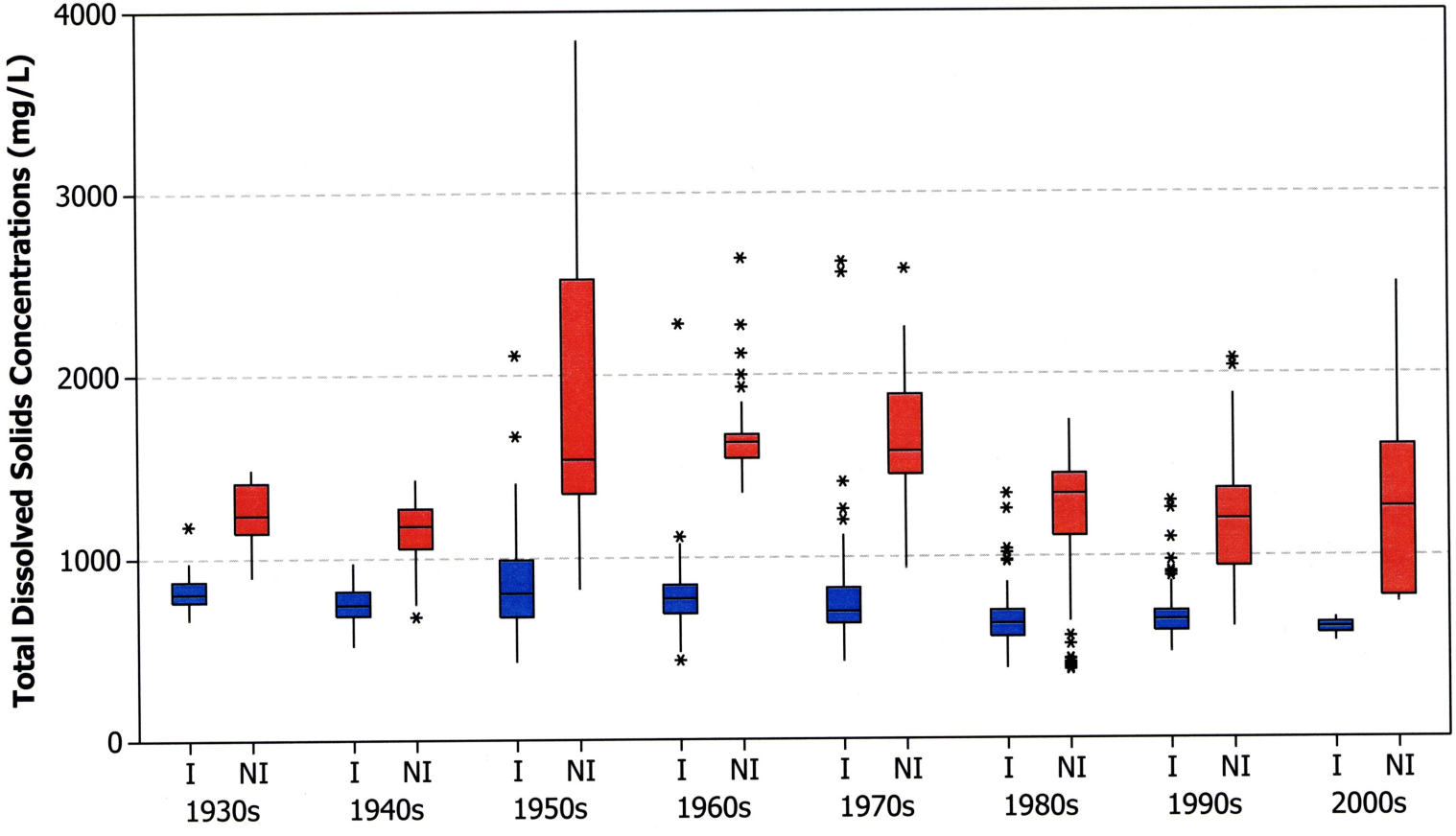
Historical Total Dissolved Solids Concentrations on the Lower Rio Grande

Non-irrigation season (Oct-Feb)

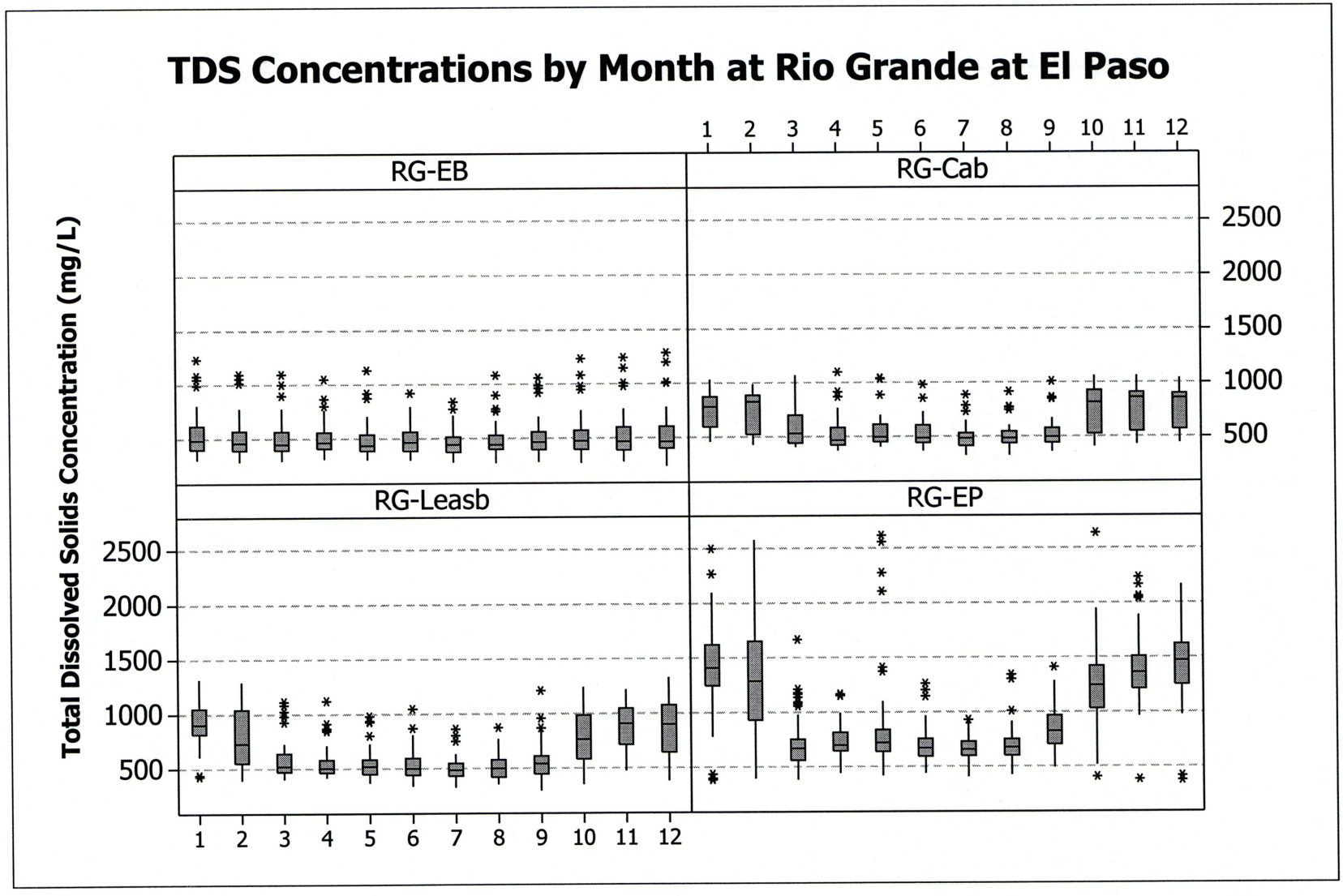


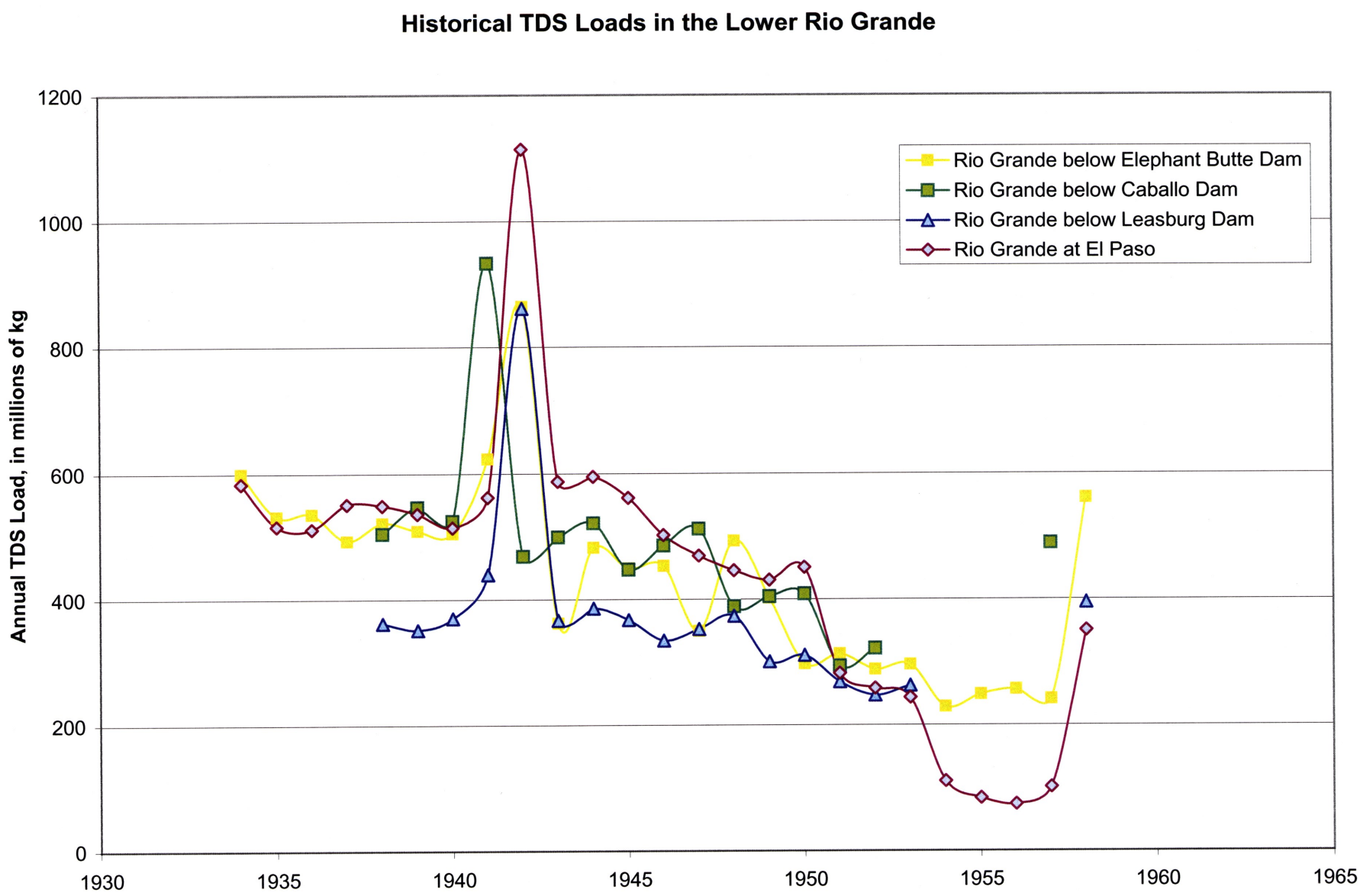

TDS Concentrations by Decade at Rio Grande at El Paso
Chloride Concentration, in mg/L
4000
3000
2000
1000
0
908
844
1092
944
912
712
724
620
1930s
1940s
1950s
1960s
1970s
1980s
1990s
2000s

Seasonal TDS Concentrations by Decade at Rio Grande at El Paso



Irrigation season (I) = Mar - Sept; non-irrigation season (NI) = Oct - Feb.


TDS Concentrations by Month at Rio Grande at El Paso
Total Dissolved Solids Concentration (mg/L)
RG-EB
RG-Cab
RG-Leasb
RG-EP
2500
2000
1500
1000
500
1 2 3 4 5 6 7 8 9 10 11 12


Historical TDS Loads in the Lower Rio Grande
Annual TDS Load, in millions of kg
1200
1000
800
600
400
200
0
1930
1935
1940
1945
1950
1955
1960
1965
Rio Grande below Elephant Butte Dam
Rio Grande below Caballo Dam
Rio Grande below Leasburg Dam
Rio Grande at El Paso

Appendix C

Water Quality Data
August 2004 and
January 2005

Table C-1. Sampling Locations and Dates Sampled
Lower Rio Grande Water Quality

Sampling Location	Site ID	Sample Type	Date(s) Sampled	
			August 2004	January 2005
Rio Grande at Nogal Canyon	RG-Nog	Surface water	•	•
Rio Grande below Elephant Butte Dam	RG-EB	Surface water	•	•
Charles Geothermal well (total well depth is ~210 feet bgs)	GW-Chrl	Geothermal		•
Rio Grande above Truth or Consequences WWTP	RG-abvTC	Surface water		•
Rio Grande below Caballo Dam	RG-Cab	Surface water	•	•
Tonuco Drain above discharge to Rio Grande (below Rincon Drain)	DR-Ton	Drain	•	•
Rio Grande below Tonuco Drain (at the NMSU station)	RG-blwTon	Surface water		•
Rio Grande below Selden Canyon (just above Leasburg Diversion Dam)	RG-blwSC	Surface water		•
Radium Springs geothermal well (total well depth is ~150 feet bgs)	GW-RS	Geothermal	•	
Las Cruces WWTP	WW-LC	Wastewater	•	•
Rio Grande below Las Cruces WWTP	RG-LC	Surface water		•
East Drain above Anthony WWTP	DR-ED1	Drain		•
East Drain above discharge point to Rio Grande	DR-ED2	Drain	•	•
LRG-ISC-3 well (sampled at ~1,245 feet bgs)	GW-ISC3	Groundwater	•	
Rio Grande below East Drain	RG-blwED	Surface water		•
LRG-ISC-5 well (sampled at ~280 feet bgs)	GW-ISC5	Groundwater		•
LRG-ISC-4a well (sampled at ~60 feet bgs)	GW-ISC4a	Groundwater		•
LRG-ISC-4 well (sampled at ~145 feet bgs)	GW-ISC4	Groundwater		•
Montoya Drain above discharge to Rio Grande	DR-Mont	Drain		•
Rio Grande at El Paso (at Corchesne Bridge)	RG-EP	Surface water	•	•

bgs = Below ground surface WWTP = Wastewater treatment plant NMSU = New Mexico State University

Table C-2. Site Information and Field Parameters
Lower Rio Grande Water Quality
Page 1 of 2

Sample Type	Site ID [a]	Sample ID [b]	Distance Downstream [c] (km)	Sampling Date and Time	pH	Temperature (°C)	Specific Conductance [d] (µS/cm)
August 2004							
Surface water	RG-Nog	RG-Nogal	766.43	8/03/2004 1720	8.30	27.6	501
	RG-EB	RG-Butte-1	813.34	8/04/2004 0845	8.47	22.8	709
	RG-EB (Dup)	RG-Butte-2	813.34	8/04/2004 0845	8.47	22.8	709
	RG-Cab	RG-Cab	856.18	8/04/2004 0958	8.97	24.9	783
	RG-EP	RG-ElPaso	1,026.81	8/04/2004 1600	8.87	31.4	1049
Agricultural drain	DR-Ton[e]	Drain-Rincon[e]	914.17	8/05/2004 1950	7.79	29.8	1634
	DR-ED2	Drain-East	999.94	8/05/2004 1430	8.69	31.2	2411
Wastewater	WW-LC	LC-WWTP	957.60	8/05/2004 1400	8.46	25.0	624
Geothermal	GW-RS	GW-RadSpr	928.54	8/04/2004 1200	7.05	42.7	7030
	GW-ISC3	LRG-ISC3	1,005.44	8/05/2004 1630	8.24	25.1	2046
January 2005							
Surface water	RG-Nog	RG-Nogal-0105	766.45	1/24/2005 1550	8.62	11.6	554
	RG-EB	RG-Butte-1-0105	813.44	1/24/2005 1740	9.09	11.3	624
	RG-EB (Dup)	RG-Butte-2-0105	813.44	1/24/2005 1745	9.09	11.3	624
	RG-abvTC	RG-above T or C WWTP-0105	820.87	1/25/2005 1140	8.04	15.1	1711

[a] See Table C-1 for a more detailed description of the sampling locations for each Site ID.
[b] The Sample ID is the assigned name for field and laboratory purposes. It is shown here to provide a cross reference only; within the text, sampling locations are referred to by their assigned Site IDs.
[c] Measured from the outlet of the Rio Grande Reservoir in Colorado
[d] Also measured in the laboratory (Table 4)
[e] Originally planned to sample Rincon Drain; however, Rincon Drain was dry. Therefore, sample was collected from Tonuco Drain instead.
[f] Sample ID refers to ongoing NMSU research station; see Table 1 for description of sampling location.
km = Kilometer
µS/cm = Microsiemens per centimeter
Dup = Duplicate sample collected for quality assurance purposes

Table C-2. Site Information and Field Parameters
Lower Rio Grande Water Quality
Page 2 of 2

Sample Type	Site ID [a]	Sample ID [b]	Distance Downstream [c] (km)	Sampling Date and Time	pH	Temperature (°C)	Specific Conductance [d] (µS/cm)
January 2005 (cont.)							
Surface water	RG-Cab	RG-Caballo-0105	856.33	1/25/2005 1300	7.97	12.8	842
	RG-blwTon[f]	RG-NMSU station-0105[f]	917.47	1/25/2005 1735	8.57	14.2	1352
	RG-blwSC	RG-below Selden Canyon-0105	929.14	1/25/2005 1625	8.52	16.0	1333
	RG-LC	RG-Las Cruces-0105	960.91	1/26/2005 1120	8.17	12.0	1291
	RG-blwED	RG-below East Drain-0105	1,003.80	1/26/2005 1730	8.83	13.8	1498
	RG-EP	RG-El Paso-0105	1,026.78	1/26/2005 1640	8.55	14.4	3849
Agricultural drain	DR-Ton	Drain-Tonuco-0105	914.13	1/25/2005 1500	8.28	15.2	1770
	DR-ED1	Drain-East Drain above Anthony-0105	995.83	1/27/2005 1140	8.44	12.1	2163
	DR-ED2	Drain-East-0105	1,000.05	1/27/2005 1215	9.17	15.3	1696
	DR-Mont	Drain-Montoya above El Paso-0105	1,026.08	1/26/2005 1530	8.18	12.9	3651
Wastewater	WW-LC	LC-WWTP-0105	957.60	1/26/2005 1005	7.44	12.5	1260
Groundwater	GW-ISC5	LRG-ISC5-0105	1,017.79	1/27/2005 1315	7.80	28.7	7180
	GW-ISC4a	LRG-ISC4a-0105	1,026.06	1/26/2005 1200	7.20	20.2	2710
	GW-ISC4	LRG-ISC4-0105	1,026.06	1/26/2005 1450	7.10	20.1	4300
Geothermal	GW-Chrl	GW-Charles-0105	819.93	1/25/2005 0950	7.14	44.3	6460

[a] See Table C-1 for a more detailed description of the sampling locations for each Site ID.
[b] The Sample ID is the assigned name for field and laboratory purposes. It is shown here to provide a cross reference only; within the text, sampling locations are referred to by their assigned Site IDs.
[c] Measured from the outlet of the Rio Grande Reservoir in Colorado
[d] Also measured in the laboratory (Table 4)
[e] Originally planned to sample Rincon Drain; however, Rincon Drain was dry. Therefore, sample was collected from Tonuco Drain instead.
[f] Sample ID refers to ongoing NMSU research station; see Table 1 for description of sampling location.
km = Kilometer
µS/cm = Microsiemens per centimeter
Dup = Duplicate sample collected for quality assurance purposes

Table C-3. Analytical Results, Major Ions
Lower Rio Grande Water Quality

Sample Type	Site ID	Charge Balance (%)	Specific Conductance (µS/cm)	Concentration (mg/L [a])												
				Calcium	Magnesium	Fluoride	Potassium	Sodium	Sulfate	TDS	Chloride	Bromide	Chloride/ Bromide [b]	Carbonate (as $CaCO_3$)	Bicarbonate (as $CaCO_3$)	Total Alkalinity (as $CaCO_3$)
August 2004																
Surface water	RG-Nog	–1.1	910	71	15	0.58	6.2	100	190	640	80	0.14	571	<4.0	200	200
	RG-EB	0.0	730	52	13	0.58	5.6	81	140	510	63	0.15	420	<4.0	160	160
	RG-EB (Dup)	0.0	740	52	13	0.62	5.7	81	140	500	63	0.13	485	<4.0	160	160
	RG-Cab	–0.6	770	54	13	0.6	6	85	140	520	67	0.14	479	8	160	170
	RG-EP	–7.1	900	55	13	0.68	6.7	99	180	610	96	0.17	565	24	140	170
Agricultural drain	DR-Ton	–2.7	1,500	110	24	0.54	7.1	150	360	1,000	160	0.28	571	<4.0	180	180
	DR-ED2	1.8	2,100	57	19	1.3	26	390	340	1,400	280	0.31	903	40	300	340
Wastewater	WW-LC	3.8	1,200	79	21	0.58	28	130	130	740	190	0.24	792	<4.0	220	220
Geothermal	GW-RS	–2.5	5,000	160	22	3.9	110	860	490	3,200	1,300	1.20	1,083	<4.0	340	340
Groundwater	GW-ISC3	0.2	1,900	14	<1.0	4.8	2.3	420	310	1,200	400	0.28	1,429	<4.0	60	60
January 2005																
Surface water	RG-Nog	–2.7	720	56	11	0.52	4.9	72	120	540	61	0.2 [c]	305	<4.0	190	190
	RG-EB	–4.6	810	50	14	0.71	6.1	94	170	560	86	0.2 [c]	430	16	130	140
	RG-EB (Dup)	–8.6	830	49	13	0.73	5.9	92	180	560	89	0.2 [c]	445	16	140	160
	RG-abvTC	–5.1	1,700	88	16	1.5	13	220	180	1,000	380	0.3 [c]	1,267	<4.0	170	170
	RG-Cab	–6.8	960	59	17	0.9	5.6	120	150	680	120	0.2 [c]	600	<4.0	280	280
	RG-blwTon	–8.8	1,200	91	20	0.62	5.9	140	330	880	150	0.4 [c]	375	8	210	210
	RG-blwSC	–7.8	1,300	84	20	0.6	5.8	140	320	870	150	0.3 [c]	500	8	180	190
	RG-LC	–16.2	1,200	69	15	0.58	24	120	140	760	200	0.2 [c]	1,000	<4.0	350	350
	RG-blwED	–5.6	1,400	72	22	0.79	12	190	300	990	180	0.3 [c]	600	20	220	240
	RG-EP	–12.9	4,600	120	36	1.3	9.6	580	960	2,500	710	1.2	592	4.0	280	280
Agricultural drain	DR-Ton	–8.1	1,700	120	26	0.6	7.5	190	440	1,200	210	0.5 [c]	420	<4.0	270	270
	DR-ED1	–2.5	2,000	69	26	1.2	30	330	370	1,400	260	0.4 [c]	650	<4.0	410	410
	DR-ED2	–4.9	1,600	48	16	1.1	22	260	280	1,100	220	0.3 [c]	733	40	230	270
	DR-Mont	–9.1	4,500	120	37	1	7.2	560	800	2,400	640	0.72	889	<4.0	340	340
Wastewater	WW-LC	–1.8	1,200	69	15	0.56	24	120	140	770	190	0.2 [c]	950	<4.0	140	140
Groundwater	GW-ISC5	–2.0	8,300	300	19	1.5	6.8	1,300	1,200	4,500	1,800	0.69	2,609	<4.0	30	30
	GW-ISC4a	–11.1	40,000	670	340	<2	26	4,700	5,100	19,000	7,900	10	790	<4.0	270	270
	GW-ISC4	–19.3	63,000	840	670	<2	33	7,700	6,200	30,000	18,000	25	720	<4.0	200	200
Geothermal	GW-Chrl	–5.0	5,300	140	15	3.3	49	700	75	2,600	1,400	1.0	1,400	<4.0	180	180

[a] Unless otherwise noted
[b] Unitless
[c] Analyte detected at concentration below quantitation limit (Appendix B)

µS/cm = Microsiemens per centimeter
mg/L = Milligrams per liter

TDS = Total dissolved solids
$CaCO_3$ = Calcium carbonate
Dup = Duplicate sample collected for quality assurance purposes

Table C-4. Analytical Results, Nutrients
Lower Rio Grande Water Quality

Sample Type	Site ID	Concentration (mg/L)						
		Nitrate + Nitrite[a] (as N)	Nitrate[a] (as N)	Nitrite[a] (as N)	Total Inorganic N	Ammonia	Total Kjeldahl N	Phosphorus
August 2004								
Surface water	RG-Nog	<0.5	---	---	0.25	<0.5	1.1	<0.5
	RG-EB	<0.5	---	---	0.14	<0.5	<1.0	<0.5
	RG-EB (Dup)	<0.5	---	---	0.14	<0.5	<1.0	<0.5
	RG-Cab	<0.5	---	---	0.11	<0.5	<1.0	<0.5
	RG-EP	<0.5	---	---	0.18	<0.5	<1.0	<0.5
Agricultural drain	DR-Ton	---	<0.10	<0.10	0.22	<0.5	<1.0	<0.5
	DR-ED2	---	0.53	<0.10	0.46	<0.5	<1.0	0.88
Wastewater	WW-LC	---	0.98	3.2	7.2	12	13	0.83
Geothermal	GW-RS	<0.5	---	---	0.31	<0.5	<1.0	<0.5
Groundwater	GW-ISC3	---	<0.10	<0.10	0.14	<0.5	<1.0	<0.5
January 2005								
Surface water	RG-Nog	0.3	---	---	0.38	---	---	<0.5
	RG-EB	<0.5	---	---	0.20	---	---	<0.5
	RG-EB (Dup)	<0.5	---	---	0.16	---	---	<0.5
	RG-abvTC	---	0.14	<0.10	0.25	---	---	<0.5
	RG-Cab	---	<0.10	<0.10	0.16	---	---	<0.5
	RG-blwTon	---	0.36	<0.10	0.11	---	---	<0.5
	RG-blwSC	---	<0.10	<0.10	0.08	---	---	<0.5
	RG-LC	---	16	1.1	7.0	---	---	1.4

[a] Analytical methods for nitrate + nitrite, nitrate, and nitrite vary (see Appendix B). In cases where the holding time for nitrate and nitrite methods were exceeded, the method for nitrate + nitrite was used.

mg/L = Milligrams per liter
N = Nitrogen
--- = Not analyzed
Dup = Duplicate sample collected for quality assurance purposes

Table C-4. Analytical Results, Nutrients
Lower Rio Grande Water Quality
Page 2 of 2

Sample Type	Site ID	Concentration (mg/L)						
		Nitrate + Nitrite[a] (as N)	Nitrate[a] (as N)	Nitrite[a] (as N)	Total Inorganic N	Ammonia	Total Kjeldahl N	Phosphorus
January 2005 (cont.)								
Surface water	RG-blwED	---	0.68	<0.10	0.27	---	---	0.4
	RG-EP	---	0.9	<0.10	0.31	---	---	0.59
Agricultural drain	DR-Ton	---	<0.10	<0.10	0.32	---	---	<0.5
	DR-ED1	---	0.17	<0.10	0.16	---	---	<0.5
	DR-ED2	---	0.18	<0.10	0.23	---	---	0.66
	DR-Mont	---	<0.10	<0.10	0.16	---	---	<0.5
Wastewater	WW-LC	---	18	0.77	8.42	---	---	1.5
Groundwater	GW-ISC5	---	<0.10	<0.50	0.16	---	---	<0.5
	GW-ISC4a	---	<0.10	<2.0	0.96	---	---	<0.5
	GW-ISC4	---	<0.10	<50	0.49	---	---	<0.5
Geothermal	GW-Chrl	---	0.54	<0.5	0.43	---	---	<0.5

[a] Analytical methods for nitrate + nitrite, nitrate, and nitrite vary (see Appendix B). In cases where the holding time for nitrate and nitrite methods were exceeded, the method for nitrate + nitrite was used.

mg/L = Milligrams per liter
N = Nitrogen
--- = Not analyzed
Dup = Duplicate sample collected for quality assurance purposes

Table C-5. Analytical Results, Trace Elements
Lower Rio Grande Water Quality
Page 1 of 2

Sample Type	Site ID	Concentration (mg/L)				
		Arsenic	Boron	Molybdenum	Strontium	Uranium
August 2004						
Surface water	RG-Nog	<0.020	0.15	<0.0080	10.69	0.0039
	RG-EB	<0.020	0.13	<0.0080	0.635	0.0033
	RG-EB (Dup)	<0.020	0.13	<0.0080	0.651	0.0034
	RG-Cab	<0.020	0.14	<0.0080	0.681	0.0033
	RG-EP	<0.020	0.17	0.0081	0.789	0.0039
Agricultural drain	DR-Ton	<0.020	0.24	0.0085	1.521	0.002
	DR-ED2	<0.020	0.44	0.016	1.753	0.0127
Wastewater	WW-LC	<0.020	0.25	0.024	1.089	0.0071
Geothermal	GW-RS	<0.020	0.63	<0.0080	2.417	0.0027
Groundwater	GW-ISC3	0.065	0.82	0.028	0.316	<0.0003
January 2005						
Surface water	RG-Nog	<0.020	0.12	0.006	0.646	0.00268
	RG-EB	<0.020	0.14	0.006	0.698	0.00402
	RG-EB (Dup)	<0.020	0.14	0.008	0.694	0.00403
	RG-abvTC	<0.020	0.18	0.006	1.656	0.00386
	RG-Cab	<0.020	0.15	0.0093	0.772	0.00672
	RG-blwTon	<0.020	0.21	0.008	1.23	0.00402
	RG-blwSC	<0.020	0.20	0.007	1.19	0.00345
	RG-LC	<0.020	0.21	0.008	0.899	0.00570
	RG-blwED	<0.020	0.23	0.0096	1.4	0.00370
	RG-EP	<0.020	0.75	0.023	2.22	0.01300

mg/L = Milligrams per liter
Dup = Duplicate sample collected for quality assurance purposes

Table C-5. Analytical Results, Trace Elements
Lower Rio Grande Water Quality
Page 2 of 2

Sample Type	Site ID	Concentration (mg/L)				
		Arsenic	Boron	Molybdenum	Strontium	Uranium
January 2005 (cont.)						
Agricultural drain	DR-Ton	<0.020	0.23	0.005	1.62	0.00230
	DR-ED1	<0.020	0.41	0.018	1.91	0.01670
	DR-ED2	<0.020	0.35	0.013	1.19	0.00992
	DR-Mont	<0.020	0.70	0.016	1.88	0.00700
Wastewater	WW-LC	<0.020	0.23	0.0088	0.923	0.00456
Groundwater	GW-ISC5	0.02	0.84	0.052	2.19	<0.0003
	GW-ISC4a	0.02	2.50	0.012	16.5	0.01190
	GW-ISC4	<0.10	2.20	<0.040	19.6	0.16900
Geothermal	GW-Chrl	<0.020	0.27	0.005	3.45	0.00347

mg/L = Milligrams per liter
Dup = Duplicate sample collected for quality assurance purposes

Table C-6. Analytical Results, Stable Isotopes
Lower Rio Grande Water Quality
Page 1 of 2

Sample Type	Site ID	$\delta^{11}B$ (‰)	δD (‰)	$\delta^{15}N$ (‰)	$\delta^{18}O$ (‰)	$\delta^{34}S$ (‰)
August 2004						
Surface water	RG-Nog	3.3	–80	19.48	–10.0	0.2
	RG-EB	4.7	–75	23.89	–8.9	1.3
	RG-EB (Dup)	5.2	–75	22.88	–9.0	1.1
	RG-Cab	4.7	–72	10.53	–8.6	1.0
	RG-EP	7.1	–70	14.09	–8.0	2.2
Agricultural drain	DR-Ton	7.0	–62	24.00	–6.5	2.6
	DR-ED2	7.0	–68	19.00	–8.0	3.0
Wastewater	WW-LC	3.9	–82	21.60	–10.6	6.1
Geothermal	GW-RS	5.9	–70	20.93	–8.4	4.7
Groundwater	GW-ISC3	–7.0	–91	–12.00	–11.7	4.2
January 2005						
Surface water	RG-Nog	8.6	–87	8.31	–11.5	1.7
	RG-EB	9.1 [a]	–69	–3.99	–8.1	0.4
	RG-EB (Dup)	---	–70	–2.88	–8.0	0.0
	RG-abvTC	10.8	–69	4.58	–8.4	4.5
	RG-Cab	11.2	–65	–0.60	–7.2	2.8
	RG-blwTon	16.7	–64	21.14	–6.8	0.9
	RG-blwSC	14.5	–63	–16.10	–6.7	1.6
	RG-LC	0.3	–86	11.67	–10.9	6.2
	RG-blwED	9.7	–68	–5.40	–7.8	–2.2
	RG-EP	13.5	–67	0.11	–7.8	2.2

[a] Sample analyzed at a later date
‰ = Per mille
--- = Not analyzed
Dup = Duplicate sample collected for quality assurance purposes

Table C-6. Analytical Results, Stable Isotopes
Lower Rio Grande Water Quality
Page 2 of 2

Sample Type	Site ID	$\delta^{11}B$ (‰)	δD (‰)	$\delta^{15}N$ (‰)	$\delta^{18}O$ (‰)	$\delta^{34}S$ (‰)
January 2005 (cont.)						
Agricultural drain	DR-Ton	17.3 [a]	–62	–4.11	–6.4	6.1
	DR-ED1	13.6	–74	–9.38	–8.9	1.7
	DR-ED2	9.9	–81	11.53	–10.1	2.5
	DR-Mont	16.0	–70	–1.78	–8.2	6.1
Wastewater	WW-LC	3.4	–87	13.41	–11.1	5.5
Groundwater	GW-ISC5	5.3	–64	–2.29	–7.7	7.9
	GW-ISC4a	30.8	–66	2.24	–8.0	12.2
	GW-ISC4	31.8	–70	–4.85	–8.2	12.4
Geothermal	GW-Chrl	5.6	–67	4.93	–9.1	9.7

[a] Sample analyzed at a later date
‰ = Per mille
--- = Not analyzed
Dup = Duplicate sample collected for quality assurance purposes

Table C-7. Analytical Results, Radioactive Isotopes
Lower Rio Grande Water Quality

Sample Type	Site ID	$^{87}Sr/^{86}Sr$ [a]		Activity (pCi/L)										$^{234}U/^{238}U$ [a]
				^{226}Ra		^{228}Ra		^{234}U		^{235}U		^{238}U		
		Result	2σ error (mean) [b]	Result	Precision (+/–)	Result	Precision (+/–)	Result	Precision (+/–)	Result	Precision (+/–)	Result	Precision (+/–)	
August 2004														
Surface water	RG-Nog	0.710055	0.000013	1.1	0.8	<1.0	NA	2.3	1.1	---	---	1.9	1	1.21
	RG-EB	0.710222	0.000017	<0.2	NA	<1.0	NA	1.0	1.0	---	---	0.5	0.7	2.00
	RG-EB (Dup)	0.710212	0.000016	<0.2	NA	<1.0	NA	1.7	1.3	---	---	1.4	1.2	1.21
	RG-Cab	0.710331	0.000016	<0.2	NA	<1.0	NA	2.2	1.2	---	---	1.4	1	1.57
	RG-EP	0.710448	0.000009	<0.2	NA	<1.0	NA	2.4	1.0	---	---	1.4	0.7	1.71
Agricultural drain	DR-Ton	0.711138	0.000008	<0.2	NA	<1.0	NA	0.9	0.6	---	---	1.1	0.7	0.82
	DR-ED2	0.712652	0.000007	<0.2	NA	<1.0	NA	9.0	1.9	---	---	4.7	1.4	1.91
Wastewater	WW-LC	0.709899	0.000010	<0.2	NA	<1.0	NA	2.6	1.1	---	---	1.8	0.9	1.44
Geothermal	GW-RS	0.715375	0.000011	2.1	0.6	3.2	1.1	1.4	0.6	---	---	0.8	0.5	1.75
Groundwater	GW-ISC3	0.710339	0.000014	0.7	0.7	<1.0	NA	0.9	1.0	---	---	0.3	0.6	3.00
January 2005														
Surface water	RG-Nog	0.710126	0.000015	---	---	---	---	3.68	1.2	0.48	0.87	2.02	1.3	1.82
	RG-EB	0.710193	0.000013	---	---	---	---	2.9	1.1	0.46	0.87	1.62	1.3	1.8
	RG-EB (Dup)	0.710187	0.000009	---	---	---	---	4.22	1.4	0.22	0.81	3.25	1.5	1.30
	RG-abvTC	0.713708	0.000008	---	---	---	---	4.64	1.4	0.22	0.81	2.32	1.4	2.00
	RG-Cab	0.711055	0.000009	---	---	---	---	4.41	1.4	0.0 [c]	0.76	1.47	1.3	3.00
	RG-blwTon	0.711091	0.000013	---	---	---	---	3.43	1.3	0.54	0.89	2.57	1.4	1.33
	RG-blwSC	0.710995	0.000014	---	---	---	---	3.59	1.4	0.28	0.84	2.67	1.5	1.34
	RG-LC	0.709912	0.000014	---	---	---	---	3.84	1.4	0.1	0.79	2.83	1.5	1.36
	RG-blwED	0.711094	0.000012	---	---	---	---	2.47	1.1	0.45	0.87	2.13	1.4	1.16
	RG-EP	0.709734	0.000010	---	---	---	---	10.7	1.9	1.1	0.96	8.77	2	1.22
Agricultural drain	DR-Ton	0.711271	0.000029	---	---	---	---	3.42	1.2	0.44	0.87	4.08	1.6	0.838
	DR-ED1	0.712734	0.000015	---	---	---	---	11.6	2.2	0.43	0.87	6.38	1.9	1.82
	DR-ED2	0.712283	0.000010	---	---	---	---	7.4	1.7	0.23	0.81	4.39	1.6	1.7
	DR-Mont	0.709766	0.000010	---	---	---	---	4.98	1.5	0.0 [c]	0.76	1.97	1.4	2.53
Wastewater	WW-LC	0.709871	0.000015	---	---	---	---	3.75	1.4	0.1	0.79	3.35	1.6	1.12
Groundwater	GW-ISC5	0.708911	0.000010	<0.2	NA	<1.0	NA	2.17	1	0.97	0.96	1.57	1.3	1.38
	GW-ISC4a	0.710149	0.000008	0.7	0.4	<1.0	NA	7.7	1.6	0.95	0.94	4.19	1.5	1.8
	GW-ISC4	0.709718	0.000010	2.2	0.5	<1.0	NA	35.1	1.9	1.74	0.87	25.2	1.9	1.39
Geothermal	GW-Chrl	0.720366	0.000018	<0.2	NA	<1.0	NA	3.4	1.2	0.24	0.81	1.94	1.3	1.8

[a] Unitless

[b] 2σ error (mean) = 2 x (standard deviation)$_{mean}$, where (standard deviation)$_{mean}$ = $\frac{(\text{standard deviation})_{\text{sample}}}{\sqrt{\#\text{of analyses}}}$

[c] As reported by laboratory

Dup = Duplicate sample collected for quality assurance purposes

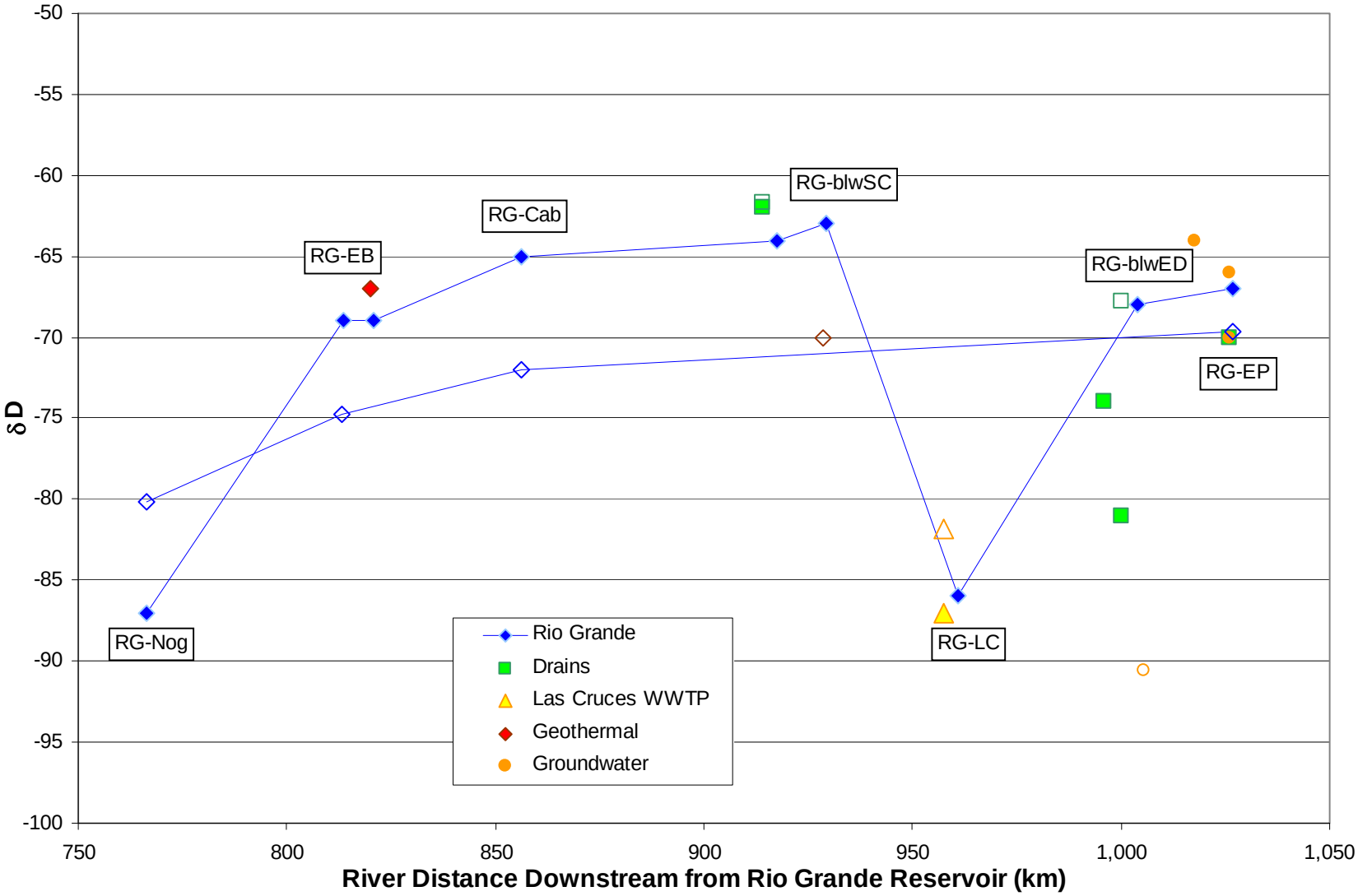
pCi/L = Picocuries per liter

--- = Not analyzed

NA = Not applicable

Appendix D

Additional Water Quality Plots



Note: Hollow symbols indicate August 2004 data, while solid symbols indicate January 2005 data.

Figure D-1

LRG SALINITY

Spatial Variation in δD

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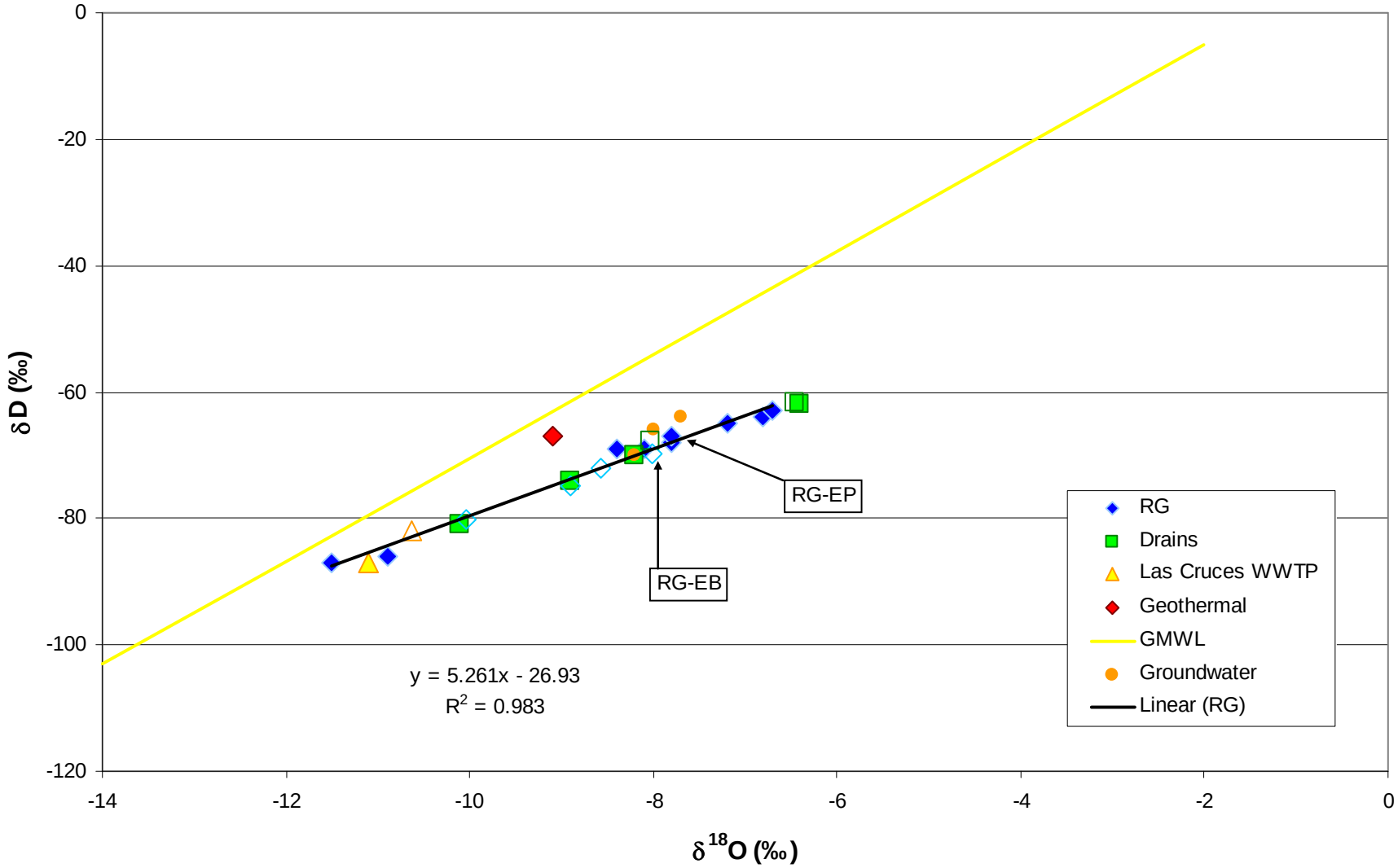

Note: Hollow symbols indicate August 2004 data, while solid symbols indicate January 2005 data.

Figure D-2

LRG SALINITY

δD vs. δ^{18}O, January 2005

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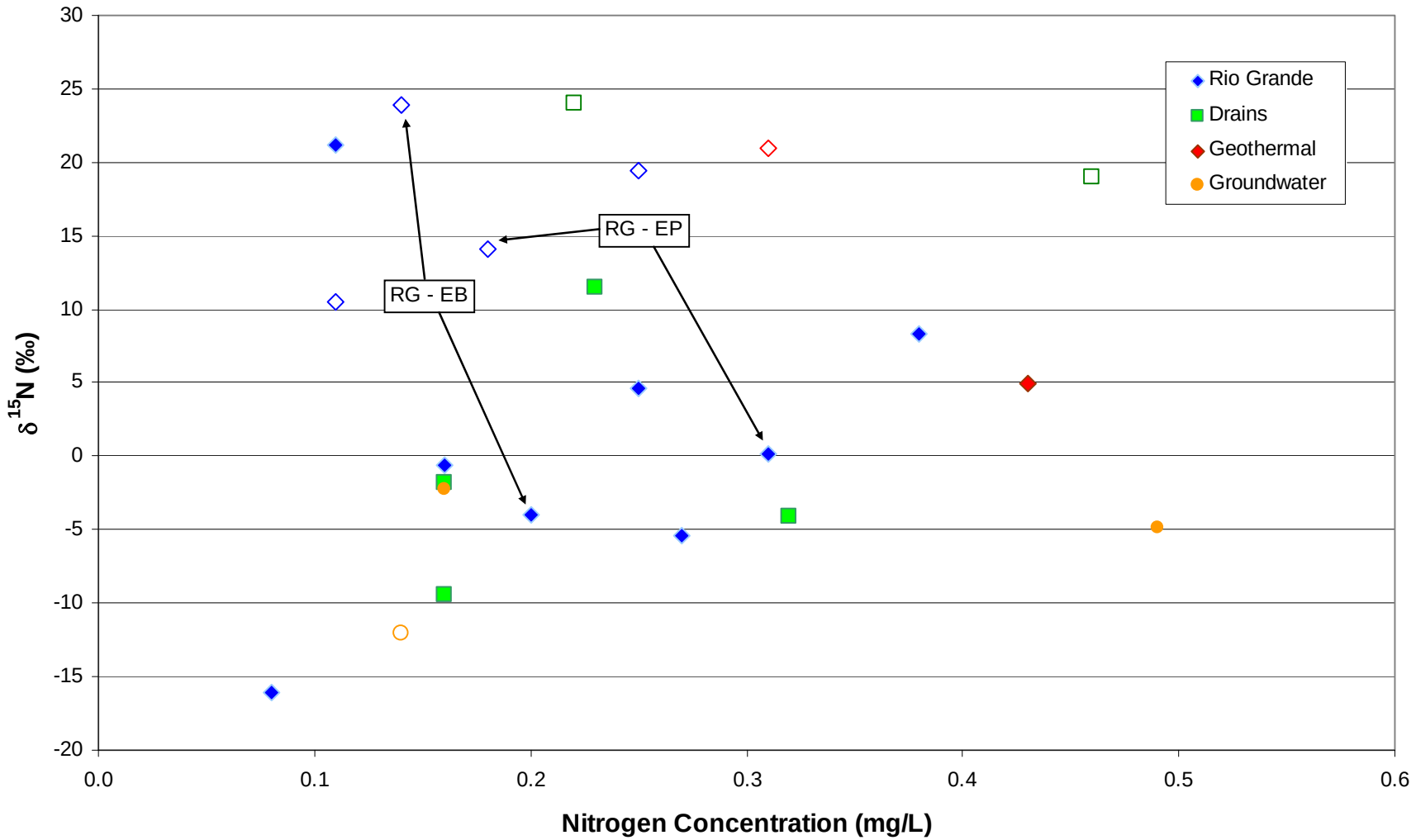

Notes: 1. Hollow symbols indicate August 2004 data, while solid symbols indicate January 2005 data.
2. The chart does not show the following data:
Las Cruces (SW): N = 7.00 mg/L, $\delta^{15}N$ = 11.67‰
ISC4a (GW): N = 0.96 mg/L, $\delta^{15}N$ = 2.24‰
WWTP (January 2005): N = 8.42 mg/L, $\delta^{15}N$ = 13.41‰
WWTP (August 2004): N= 7.20 mg/L, $\delta^{15}N$ = 21.60‰

Figure D-3

LRG SALINITY

$\delta^{15}N$ vs. Nitrogen Concentration

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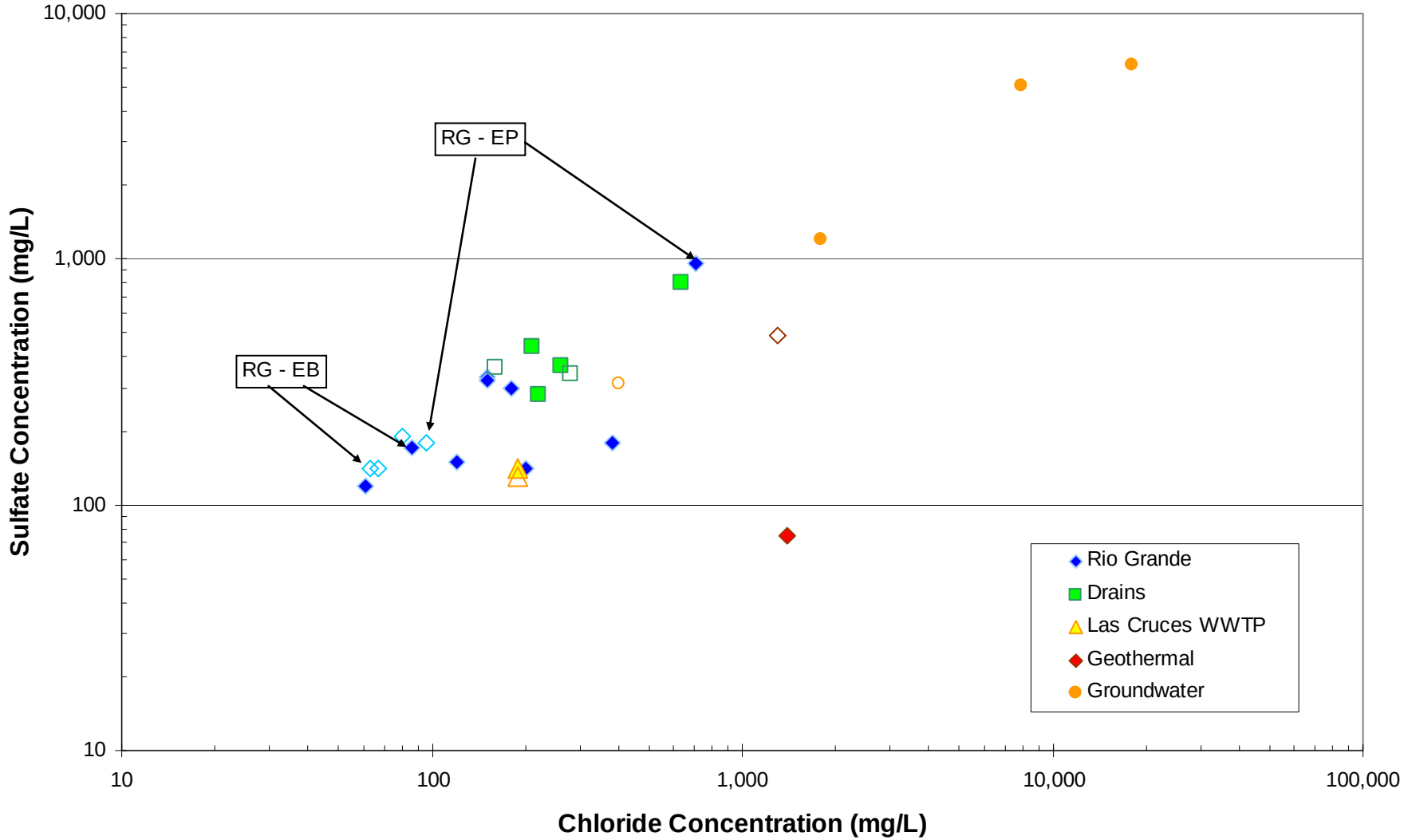

Note: Hollow symbols indicate August 2004 data, while solid symbols indicate January 2005 data.

Figure D-4

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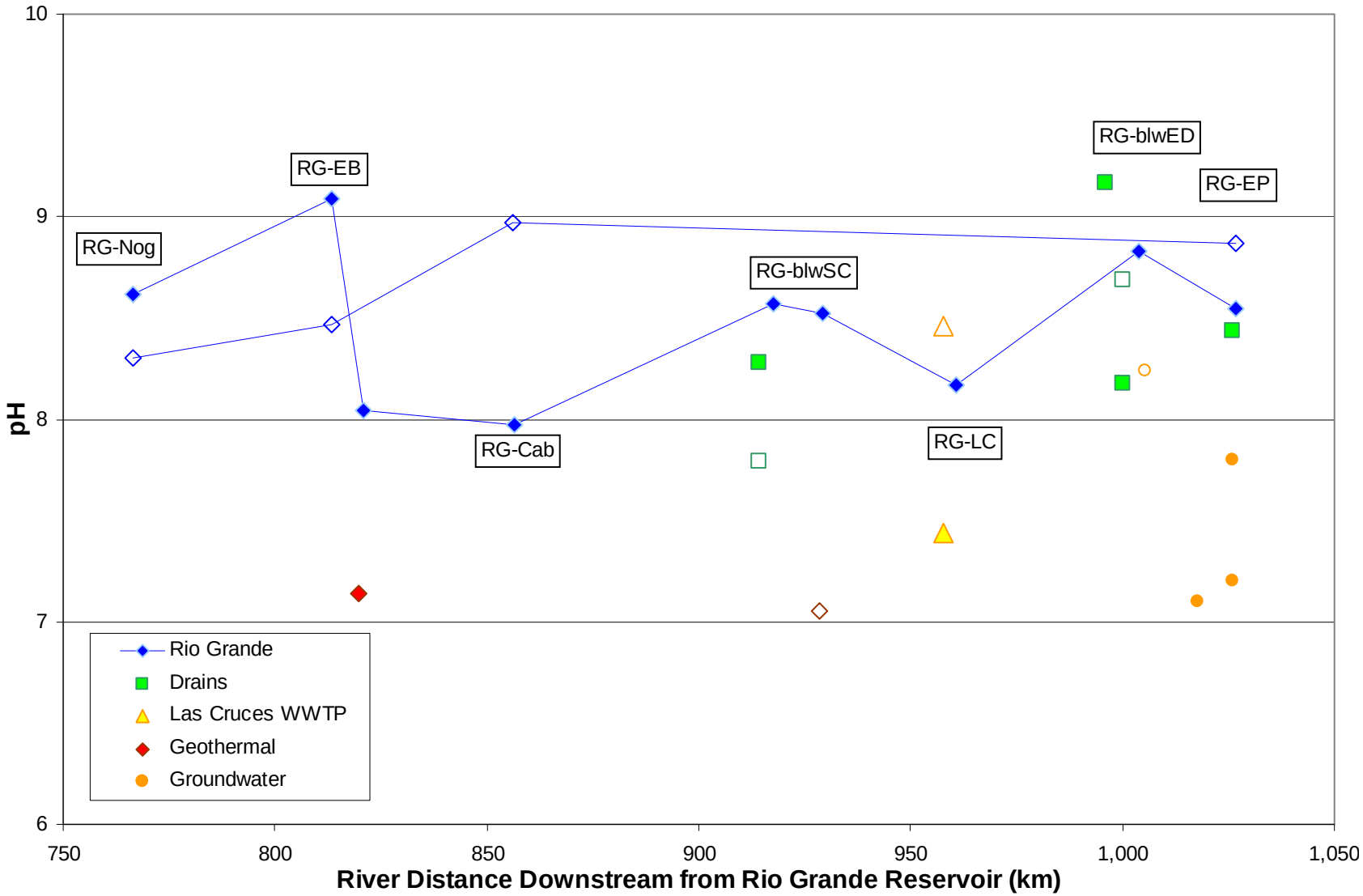
LRG SALINITY

Sulfate Concentration vs. Chloride Concentration



Note: Hollow symbols indicate August 2004 data, while solid symbols indicate January 2005 data.

Figure D-5

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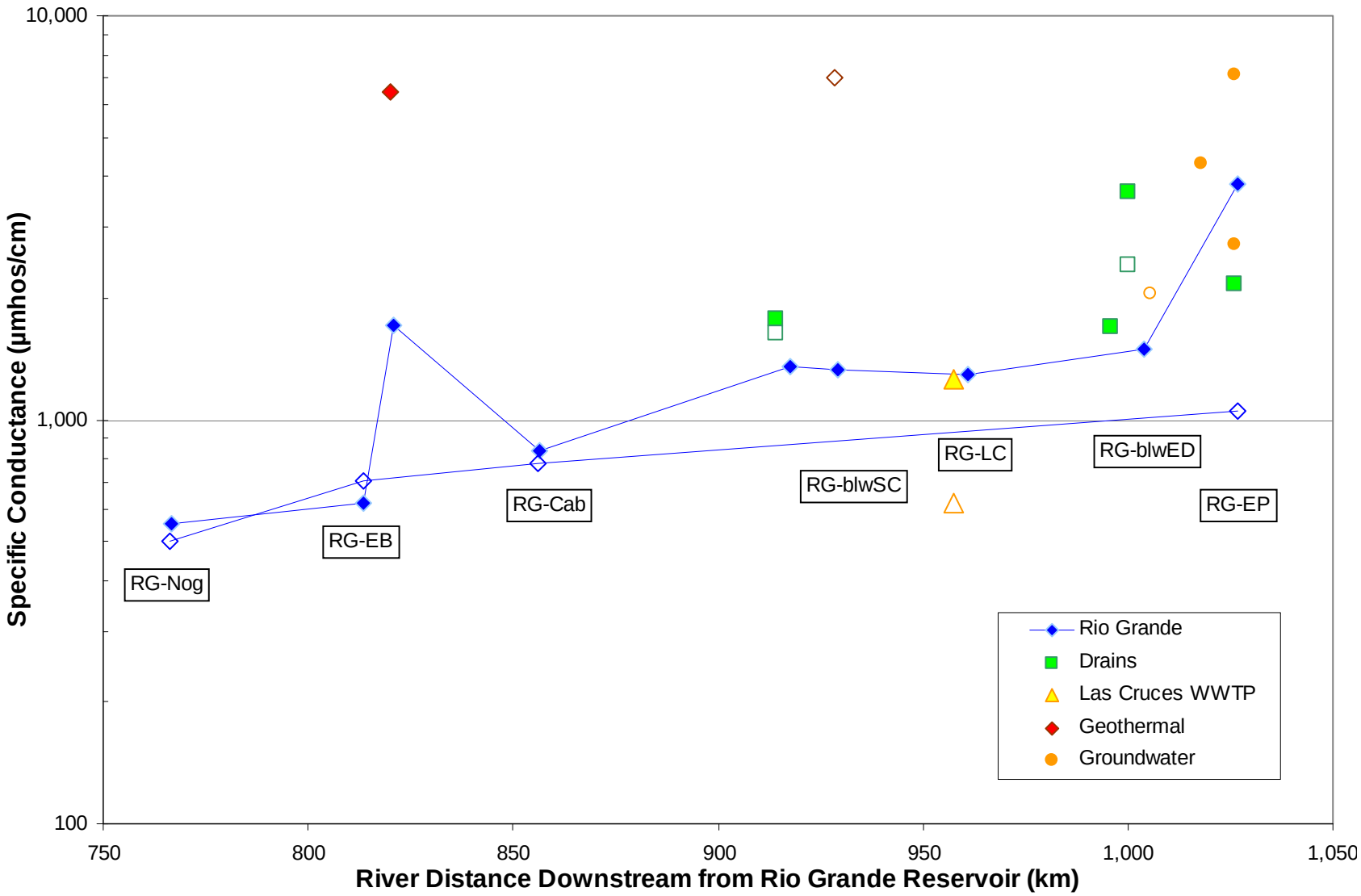
6/28/10

LRG SALINITY

Spatial Variation in pH



Note: Hollow symbols indicate August 2004 data, while solid symbols indicate January 2005 data.

LRG SALINITY

Spatial Variation in Specific Conductance August 2004 and January 2005

Daniel B. Stephens & Associates, Inc.

6/28/10

Figure D-6

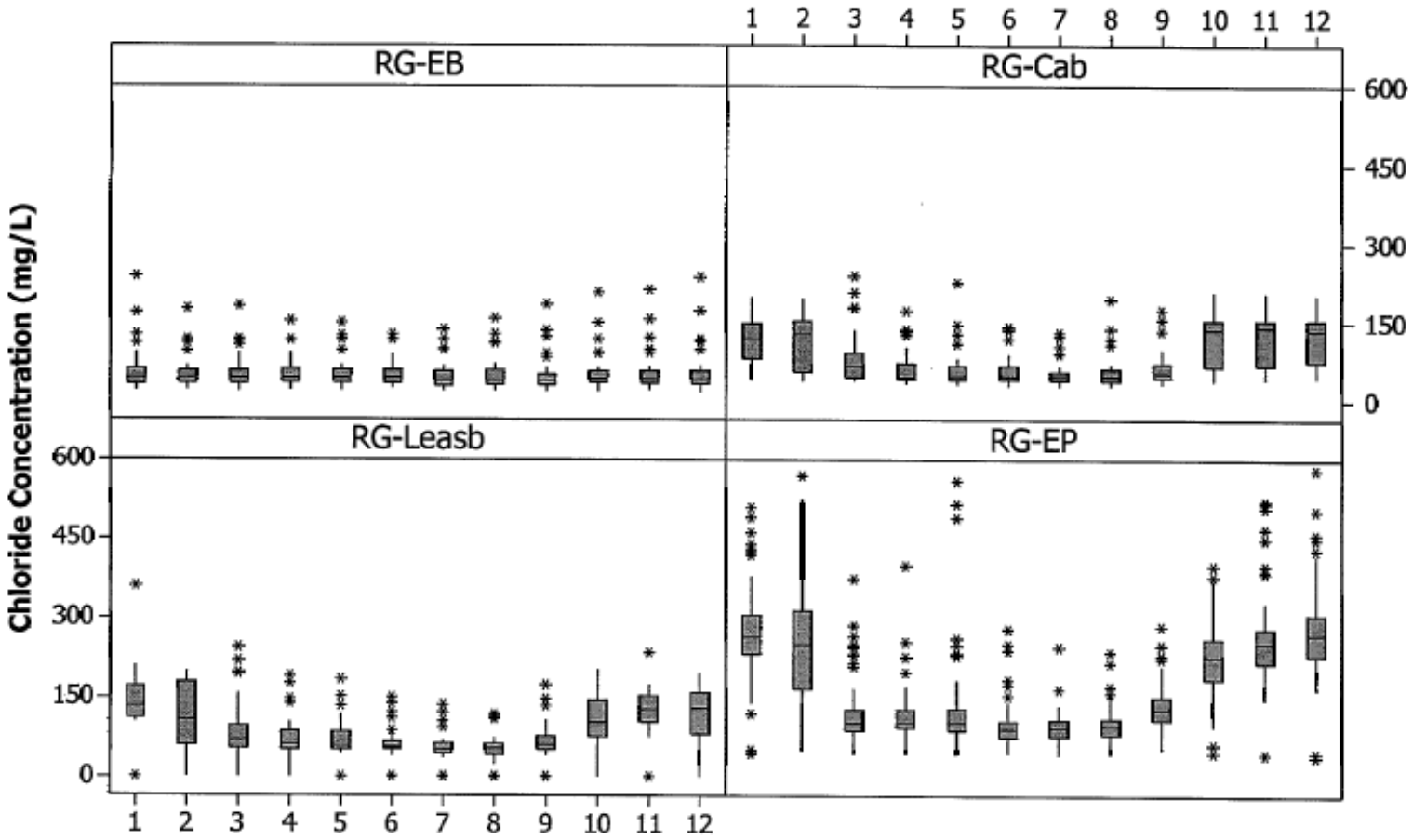


Figure D-7

LRG SALINITY

Monthly Chloride Concentrations

Daniel B. Stephens & Associates, Inc.

6/28/10

Appendix E

Estimated Concentration Factors for LRG Drain Water

This table is compiled by Beiling Liu, NMISC

Estimated Concentration Factors for LRG Drain Water

Area	Canal Loss	Maximum Achievable Farm Efficiency	Concentration Factor of Drain Water
Rincon	0.41	0.70	1.70
Northern Mesilla	0.35	0.70	1.83
Southern Mesilla	0.37	0.70	1.79
Data Source	SSP&A, 2007		Calculated

Assumptions for the calculation:
1. Water lost from canal would all seep into the shallow aquifer and mix with the field return flow to form the drain water.
2. Mountain front/slope recharge was neglected.

Appendix F

GIS Shapefiles

GIS shapefiles are provided in a separate folder on this report CD.