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The role of climate in increasing salt loads in dryland rivers

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Dryland river systems are becoming saltier, severely degrading the quality of water used for agriculture and limiting its domestic use. In this context, it is becoming important to understand how the sources and abundances of salts in these river systems will respond to increasingly arid climates. Using the Rio Grande in the Southwest U.S. as an example dryland river system, we show that changes in climate over the last century are closely linked to variations in salt chemistry and therefore salt sources. Starting ~25 years ago there has been a shift toward more Cl-rich surface waters in the Rio Grande. This shift may reflect a tipping point in the relative influence of anthropogenic activities on the overall surface water budget. Climate change is accelerating this transition through the loss of rain and snow in the headwaters region, resulting in a loss of connectivity of surface flow in the upper and lower sections of the river. The implication of this relationship for dryland rivers is that salt chemistry and sources are likely to become more heterogeneous in the future, reflecting more localized natural (inflow of groundwater) and anthropogenic (waste and industrial effluents, irrigation returns) influences.

1. Introduction

Arid and semi-arid landscapes are forecast to expand to become the single largest terrestrial biome on Earth and already host over 35% of the world's population (Reynolds and Stafford Smith, 2002; Reynolds et al., 2007). Population growth and a changing climate are placing enormous pressures on water resources in dry regions across the globe (Kingsford, 2006). In addition to dwindling water resources, the increasing salinity of dryland rivers and their associated shallow aquifer systems represents a major threat to water sustainability (e.g., Williams, 2001). As climate transitions occur, it is increasingly important to understand how natural and anthropogenic sources of salts for dryland river systems will respond.

The Rio Grande is the 5th longest river system in North America and the upper and middle reaches of the river serve as an excellent example of a dryland river impacted by desertification and increasing salinity (Phillips et al., 2011). This section includes the high desert region of central New Mexico and the Chihuahuan desert landscape of Southern New Mexico and far West Texas (Phillips et al., 2011, Fig. 1). In these areas, the Rio Grande provides water for municipalities like Albuquerque and Las Cruces, (887,000 and 209,000 people in the metro areas, respectively), New Mexico, and the bi-national metroplex of El Paso, Texas and Ciudad Juarez, Mexico (~2.2 million people). Despite these municipal demands, agricultural activities represent the largest fraction of withdrawals and the biggest consumptive use of surface water in the Rio Grande Valley (Ellis et al., 1993).

The magnitude and temporal variability of discharge in the upper and middle Rio Grande is driven largely by the annual melting of snowpack in the headwaters region (Ellis et al., 1993; Moore and Anderholm, 2002). Snowpack and drought in the Rocky Mountains and Southwest U.S. have been shown to correlate with the Pacific Decadal Oscillation (PDO) climate index, which measures inter-decadal North Pacific sea surface temperature anomalies (Brown and Comrie, 2002; Gray et al., 2003; Yuan and Miyamoto, 2004). Previous investigations have confirmed that changes in the PDO generally correlate with discharge and elemental fluxes in the middle Rio Grande (Yuan and Miyamoto, 2004). Discharge in the middle Rio Grande reaches its maximum around Albuquerque, New Mexico (e.g., Moore and Anderholm, 2002), and generally decreases downstream. Rio Grande water is stored in Elephant Butte Dam in Southern New Mexico (~640 km downstream; Fig. 1) and is released annually to support agriculture. Previous workers investigating atmospheric teleconnections on seasonal precipitation in mountainous recharge areas of the southwestern U.S. have also suggested that the El Niño–Southern Oscillation (ENSO) plays a secondary role of dampening low

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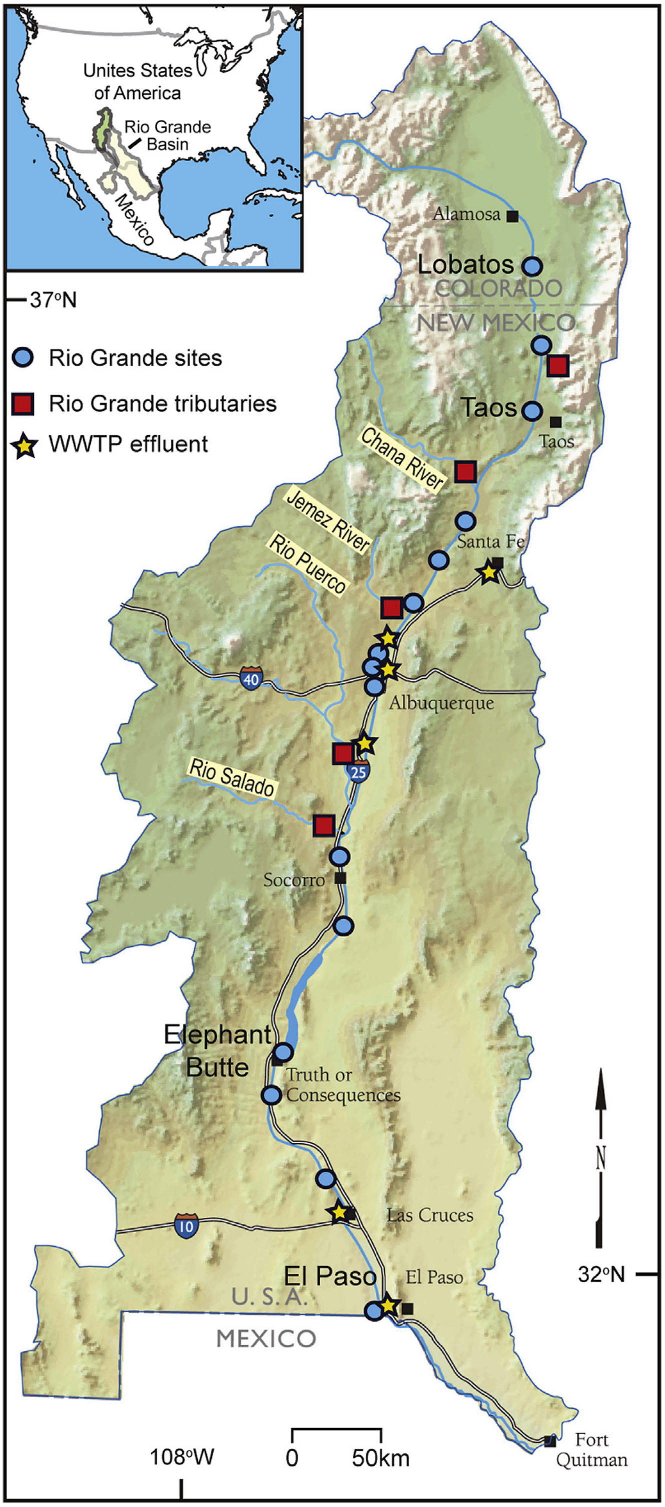

Fig. 1. Location map of the Rio Grande and its tributaries from its headwaters to El Paso, Texas. Sites from which data were compiled are highlighted.

precipitation wintertime and springtime anomalies during years of low PDO (Guan et al., 2005).

Like its counterparts across the globe (e.g., the Nile (Kotb et al., 2000), Jordan (Farber et al., 2004), and Murray-Darling Rivers (Pannell, 2001)), parts of the Rio Grande are quite saline, limiting the value of its water (Hogan et al., 2007; Moore and Anderholm, 2002; Szynkiewicz et al., 2011). Salt sources in the Rio Grande include agricultural activities, waste water effluent, upwelling of salt-rich groundwater, and chemical weathering (e.g., Hogan et al., 2007; Lippincott et al., 1939; Moore et al., 2008; Phillips et al., 2003; Witcher et al., 2004). Salt concentrations in the Rio Grande increase downstream (Ellis et al., 1993; Moore and Anderholm, 2002), evolving from a Ca–HCO_3–SO_4-rich composition in the headwaters to a saltier, more Na–Cl-rich composition (Ellis et al., 1993; Szynkiewicz et al., 2011). Given this downstream shift in composition, the molar ratio of SO_4/Cl serves as a useful proxy for tracking geochemical changes in the Rio Grande. The SO_4/Cl ratio is not subject to changes from evaporation or flow and to a first approximation these anions exhibit conservative behavior in surface water systems (Hanor and Chan, 1977; Pawellek et al., 2002; Schemel et al., 2006). Moreover, a previous investigation of the Rio Grande confirms, through the use of sulfur isotopes, that sulfate reduction does not appreciably impact the SO_4 mass balance in this surface water system (Szynkiewicz et al., 2011). Between Elephant Butte Dam and El Paso, Texas, the Rio Grande remains undersaturated with respect to gypsum ($CaSO_4$) but supersaturated with respect to calcite ($CaCO_3$; Bastien, 2009). This is thought to influence the concentrations of Ca and HCO_3 over this stretch of the Rio Grande. Thus, these ions do not serve as useful tracers.

In this study, we attempt to link climate change to salt chemistry and sources by comparing the >80-year historical record of the SO_4/Cl ratio of the Rio Grande at El Paso, Texas, with historical records of discharge in the upper and middle reaches of the Rio Grande, and with the PDO climate and multivariate ENSO indices (MEI). Both qualitative and quantitative (statistical) comparisons among these datasets, as well as comparisons with chemical data from other locations in the Rio Grande, are used to develop a conceptual model of the linkages of climate and salinity. Based on this model we attempt to forecast future salinity changes in the Rio Grande and discuss the implications of similar changes for other dryland river systems.

2. Methods

Historical chemical data for the Rio Grande at El Paso, Texas, were compiled using publically available Water Bulletins published by the International Boundary and Water Commission (IBWC; 1935–2005; http://www.ibwc.state.gov/) and online surface water data from the U.S. Geological Survey (2006–2011; http://waterdata.usgs.gov/nwis/sw). Chemical data were available at least monthly for more than 95% of the entire period. Selected chemical data from the USGS, IBWC, and Sevilleta Long Term Ecological Research (LTER) station were compiled for additional locations in the Rio Grande study area (Fig. 1; Table 1). For consistency, we did not use datasets older than the completion of Elephant Butte Dam in 1916 nor those that were averaged or only contained information on total dissolved salts. For comparison purposes, we also present SO_4/Cl ratios of our own chemical measurements of effluents collected from waste water treatment plants (WWTPs) from Santa Fe and Las Cruces, New Mexico, and El Paso, Texas. The collection and analytical methods for these analyses are identical to those of Szynkiewicz et al. (2011) and are not discussed further here. Data for average monthly volumetric flow were also compiled from the USGS database. For discharge data, we selected three of the most complete and longest-duration hydrograph records available for the Rio Grande between its headwaters and El Paso, Texas. These include from north to south, the Rio Grande at Lobatos, Colorado, the Rio Grande at Taos Junction Bridge, and the Rio Grande below Elephant Butte Dam (Fig. 1). The last is a consistent proxy for flow at El Paso, Texas. All records of flow covered the entire period for which chemical data were available for the El Paso site. Monthly data for the PDO from 1900 to 2012 were gathered from the