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Calculating salt loads to Great Salt Lake and the associated uncertainties for water year 2013; updating a 48 year old standard

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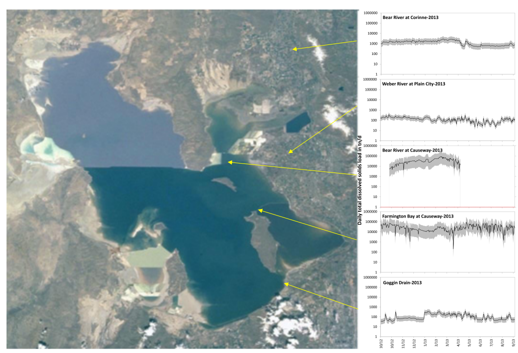
HIGHLIGHTS

- Calculate TDS loads/uncertainties for period of record at inflows to Great Salt Lake
- Comparison of results with previous years to improve estimates of GSL TDS loading
- Seiches limit interpretation of TDS loads under periodic measurement frequencies
- Uncertainty in load estimates is a function of sampling frequency.

GRAPHICAL ABSTRACT



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ABSTRACT

Effective management of surface waters requires a robust understanding of spatiotemporal constituent loadings from upstream sources and the uncertainty associated with these estimates. We compared the total dissolved solids loading into the Great Salt Lake (GSL) for water year 2013 with estimates of previously sampled periods in the early 1960s. We also provide updated results on GSL loading, quantitatively bounded by sampling uncertainties, which are useful for current and future management efforts. Our statistical loading results were more accurate than those from simple regression models. Our results indicate that TDS loading to the GSL in water year 2013 was 14.6 million metric tons with uncertainty ranging from 2.8 to 46.3 million metric tons, which varies greatly from previous regression estimates for water year 1964 of 2.7 million metric tons. Results also indicate that locations with increased sampling frequency are correlated with decreasing confidence intervals. Because time is incorporated into the LOADEST models, discrepancies are largely expected to be a function of temporally lagged salt storage delivery to the GSL associated with terrestrial and in-stream processes. By incorporating temporally variable estimates and statistically derived uncertainty of these estimates, we have provided quantifiable variability in the annual estimates of dissolved solids loading into the GSL. Further, our results support the need for increased monitoring of dissolved solids loading into saline lakes like the GSL by demonstrating the uncertainty associated with different levels of sampling frequency.

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1. Introduction

Effective management of surface water resources for human use and ecological health requires unbiased information on the flux of water-quality constituents transported by streams and rivers from upstream

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landscapes to downstream receiving waters. To better understand the nature of upstream sources of constituent mass and the relative contributions from different source areas, the constituent flux or load must be known or estimated. As climate change continues to impact hydrological and ecological systems, forecasting physical and water quality responses throughout the watershed can greatly improve management decisions (Aherne et al., 2006; Elsdon et al., 2009; Tweed et al., 2011). The effective design and evaluation of water-quality management programs requires both a robust estimate of constituent concentration or load and the uncertainty associated with the estimation of the flux estimates.

Typically the constituent flux is estimated as an average rate of the total mass passing a location over time. Ideally, the flux is quantified by integrating the product of concentration and discharge over regular and frequent time steps throughout a period of interest. Commonly, discharge is estimated by frequent stage measurements calibrated to discharge through the use of a site- and time-specific rating curve (Shope et al., 2013). However, concentration measurements are usually sparsely collected due to the expense of sample analysis and the logistical difficulties. To estimate the temporal flux, available concentration measurements are used to interpolate estimates for periods when no measurements were collected.

Many techniques have been developed to estimate the water-quality flux of specific constituents. Of these, multiple regression analysis of flux based on observed discharge, time, and season are commonly utilized (Cohn et al., 1989, 1992; Crawford, 1991; Dolan et al., 1981; Ferguson, 1986, 1987; Preston et al., 1989; Robertson and Roerish, 1999; Robertson and Saad, 2011; Runkel et al., 2004; Runkel, 2013; Stenback et al., 2011). While simple linear regression of the constituent concentration versus discharge can provide a reasonable estimate to predict concentrations at times that were not sampled, statistical estimation methods typically provide more robust predictive capabilities. An example is the USGS LOADEST (Runkel, 2013; Runkel et al., 2004) software package that analyzes up to 9 specified regression models with the option to create additional user-specified models. LOADEST estimates constituent flux as a function of discharge, time, and season. The model also uses a number of bias diagnostics including summary statistics, the Partial Load Ratio (Stenback et al., 2011), Load Bias, Nash-Sutcliffe Efficiency Index (Nash and Sutcliffe, 1970), and residual outputs. The benefits of more robust statistical flux estimation techniques include assessment of the systematic error associated with bias and the random error associated with variance. Random error is expected and defines the standard error surrounding the flux estimate, although systematic error is more problematic and is introduced by unexpected watershed and in-stream processes. Bias diagnostics with statistical models can be applied to salt load estimates to discern sample collection differences or dynamic processes such as precipitation and wind-driven transport.

Continuous salt flux estimates of inputs to the Great Salt Lake (GSL) have generally been nonexistent and to our knowledge, calculation of the estimate uncertainty has not been completed. GSL is a remnant of the prehistoric Lake Bonneville and is the largest hypersaline lake in the Western Hemisphere. It is the fourth-largest terminal lake in the world with salinity ranging from 1.4 to 8.0 times greater than the ocean. Saline lakes account for nearly 45% of the total global inland lake volume (Shiklomanov, 1990) and are therefore an important part of the landscape. The GSL ecosystem annually supports between 2 and 5 million migratory waterfowl and shorebirds from throughout the Western Hemisphere (Aldrich and Paul, 2002) and was designated a part of the Western Hemisphere Shorebird Reserve Network in 1992. The lake supports brine shrimp (*Artemia franciscana*), which are a valuable food supply for migratory birds and the brine shrimp cyst harvest industry with annual revenues as high as $60 million. The maximum adult brine shrimp salinity tolerance is approximately 30%, near the saturation level of 28%. Artemia require salinity less than 10% to initiate hatching but optimal cyst production ranges from 14–17% (Lenz and Browne, 1990; Van Stappen, 2002). The $1.1 billion GSL mineral extraction industry includes at least 4 corporations annually producing 3.2 million metric tons of salts, including NaCl, $MgCl_2$, and K_2SO_4. These industries can have conflicting objectives in terms of managing GSL salinity. For example Gunnison Bay is too saline to provide brine shrimp habitat; however, it provides an adequate pre-concentration step for mineral extraction activities. Because of the importance of the lake to wildlife and industry, an accurate understanding of the spatiotemporal dissolved solid balance within the lake is needed. Previous studies have primarily focused on salt concentration as a function of lake elevation and GSL processing (Mohammed and Tarboton, 2011, 2012). However, to our knowledge only two studies have attempted to quantify salt loading from inflows to the lake (Hahl, 1968; Loving et al., 2000). In fact, the results from Hahl (1968) have been the accepted steady-state input rate of dissolved salts into the GSL.

The objective of this study is to assess the spatiotemporal salt load into GSL for water year 2013 and describe the associated estimate uncertainty. We compare these results to previous estimates for water years 1960, 1961, and 1964, which have formed the basis for mineral extraction volumes since 1968. Even with the long history of scientific investigations, quantification of the spatial distribution and the temporal salt load into GSL remain elusive. For this study, we collected major ion chemistry and surface water discharge measurements at the dominant surface water inflow locations to the GSL to quantify the dissolved salt loading into the GSL for water year 2013. This approach has the benefit of evaluating changes in dissolved salt loading to GSL over time, which is necessary for operational management activities. In addition, the utility of incorporating a multi-variate statistical approach provides uncertainty bounds on observational quality and frequency that is useful to a broad range of surface water investigations.

2. Study location and physiography

The Great Salt Lake (40.7°N–41.7°N, 111.9°W–113.1°W) is in the northeast Great Basin province (Fig. 1). The mean lake elevation, based on 169 years of record, is 1279.8 ± 0.9 AMSL. The GSL drainage areas is about 55,000 km^2 and the lake is the fourth largest, perennial, closed-basin lake in the world (Mohammed and Tarboton, 2011). The Wasatch Mountains are east of the lake and the Oquirrh and Stansbury Mountains lie to the south, while the relatively uninhabited Bonneville Salt Flats lie to the west. GSL development was in response to tectonic extension of the eastern Basin and Range Province in the middle Tertiary (Miller, 1991). Numerous faults trending N–S and NE–SW are situated in the GSL and bioherm structures suggest that the faults served as conduits for sub-lacustrine discharge of groundwater (Colman et al., 2002). Marine sediments from Glacial Lake Bonneville dominate the area, which due to lake recession and evaporative processes, has left large concentrations of dissolved minerals such as potash and halite in the surrounding soils. The GSL watershed was investigated from 1998 to 2001 (Waddell et al., 2004) and results indicated that the majority of streambed sediment concentrations of selected trace elements exceeded aquatic standards in streams draining mine tailings and metal smelters. Jones et al. (2008) provide a thorough description of the complex impacts on solute inputs to the closed basin from the weathering of the Precambrian and Paleozoic mountains to the east and the Tertiary and Quaternary sediments to the west.

The Great Salt Lake is fed by direct precipitation, the Bear, the Weber, and the Provo-Jordan Rivers, several other minor streams, and groundwater seepage. The only outflow for the GSL is evapotranspiration, which depends on meteorological conditions, salinity, and lake surface area/altitude (Mohammed and Tarboton, 2011). The GSL is located on a shallow playa, in which small changes in the water-surface elevation results in large changes in the surface area of the lake. The average lake depth ranges from 4–6 m resulting in a surface area that ranges from 3000–6000 km^2 (Mohammed and Tarboton, 2011). The GSL is predominately fed by surface water inflows into the south arm. Therefore,

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