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PAGES 289–296

Monitoring Change in Great Salt Lake

PAGES 289–290

Great Salt Lake is the largest hypersaline lake in the Western Hemisphere and the fourth largest terminal lake in the world (Figure 1). The open water and adjacent wetlands of the Great Salt Lake ecosystem support millions of migratory waterfowl and shorebirds from throughout the Western Hemisphere [*Aldrich and Paul,* 2002]. In addition, the area is of important economic value: Brine shrimp (*Artemia franciscana*) residing in Great Salt Lake support an aquaculture shrimp cyst industry with annual revenues as high as $60 million.

This globally significant ecosystem is facing increasing anthropogenic pollutants from industrial, urban, mining, and agricultural sources from a watershed that includes the highly urbanized Wasatch Front in northern Utah. In fact, about 90% of all treated sewage effluent in Utah is discharged into this water body. Because Great Salt Lake is a terminal lake, chemical inputs have no opportunity to be removed via water outflow from the system.

Furthermore, the completion of a rock-filled railroad causeway in 1959 divided the lake into northern (Gunnison Bay) and southern (Gilbert Bay) arms and significantly changed the water and salt balance while also changing biogeochemical conditions in the deeper sections of Gilbert Bay, which range in depth from 6.5 to 9 meters at current lake levels. About 90% of the fresh surface water inflows enter the lake south of the railroad causeway, resulting in consistently higher salinities in lake water north of the causeway that can approach and exceed halite saturation, meaning that the water is so salty that salt crystals readily precipitate out of solution. A persistent higher-density and oxygen-depleted layer in Gilbert Bay is supported by density-driven flow of highly saline water from Gunnison Bay from flow through the permeable fill material as well as constructed openings in the causeway. This oxygen-depleted layer contains elevated levels of mercury [*Naftz et al.,* 2008] and nutrients [*Belovsky et al.,* 2011].

Despite the ecological and economic importance of Great Salt Lake, only limited limnological and water quality monitoring has occurred historically. In response to recent and increasing public concern about contaminant input to this ecosystem, the U.S. Geological Survey (USGS), in cooperation with multiple state agencies, began to install and operate additional monitoring stations and networks. These involve gauges of lake level height and rate of inflow, an on-lake station providing real-time monitoring data, and multiple lake-bottom sensors tracking the movement of dense, ultrasaline water through the lake.

Lake Elevation and Inflow Gauges

USGS has operated a lake elevation gauge in Gilbert Bay (near the Saltair Marina) since 1938 and in Gunnison Bay (on the east shore; the gauge is named Saline) since 1966 (Figure 1). Short-term changes in lake elevations from sustained wind events and the associated seiches (low-frequency oscillations of lake surface elevation) can affect flow direction and velocity in the highly saline oxygen-depleted water layer on the bottom of Gilbert Bay. Because of the shallow nature of Great Salt Lake, updated lake elevations also provide recreational boaters with important information. Lake elevations are currently measured every 15 minutes using noncontact radar at the Saltair site and a calibrated shaft encoder at the Saline site.

Inflow sites to Great Salt Lake are monitored every 15 minutes with USGS gauges (Figure 1). Three other USGS gauges continuously monitor water exchange between Gilbert and Gunnison bays (Railroad Causeway Breach gauge), between Bear River and Gilbert bays (Bear River Bay gauge), and between Farmington and Gilbert bays (Farmington Bay Causeway Breach gauge). Because of low channel gradients, density-stratified flow, and wind influence on inflow rates and directions at the Bear River Bay, Farmington Bay, and Railroad Causeway Breach gauge sites, normal relations do not exist between water height and discharge rate. Instead, hydroacoustic equipment (acoustic Doppler profilers) is used in combination with velocity index methods to accurately gauge inflow.

Data from both elevation and inflow gauges are transmitted hourly via satellite and displayed in near real time on the USGS National Water Information System (NWIS) Web site. Nutrient loads into this terminal lake have been monitored at monthly to bimonthly intervals by collecting and analyzing water samples at each inflow site since 2009.

Lake Environmental Sensing Platform

During May 2010, a Lake Environmental Sensing Platform (LakeESP) was installed in Gilbert Bay (Figure 1a) to better understand hydrodynamic forcings in Great Salt Lake and short-term mixing of the mercury- and nutrient-enriched lower brine layer with the upper water column.

The LakeESP provides seasonal real-time monitoring of water column temperature at 15 depths; specific conductance and photosynthetically active radiation at 3 depths; and meteorological parameters that include net long- and short-wave radiation, humidity, air temperature, wind speed and direction, barometric pressure, and precipitation. A Sontek Argonaut-XR, which is an acoustic Doppler velocity meter (ADVM), is also integrated with LakeESP to provide data on current directions and velocities. ADVM data are collected every 20 minutes, and all other data are collected once per minute. Data are transmitted hourly via cell phone to a shore station, and selected data are displayed in near real time via NWIS.

Hydroacoustic and Salinity Monitoring Network

Bathymetric mapping of Gilbert Bay by USGS revealed a natural "spillway-like" structure on a bottom ridge trending from southwest to northeast. This structure acts as a conduit to transport oxygen-depleted, high-density, and mercury-, nutrient-, and salinity-enriched bottom water into the southern part of Gilbert Bay (Figure 1).

A single monitoring station was installed on the bottom of the spillway structure (see CENT, Figure 1) in March 2012 to monitor the flow direction and velocity (with a Sontek Argonaut-XR), temperature, and specific

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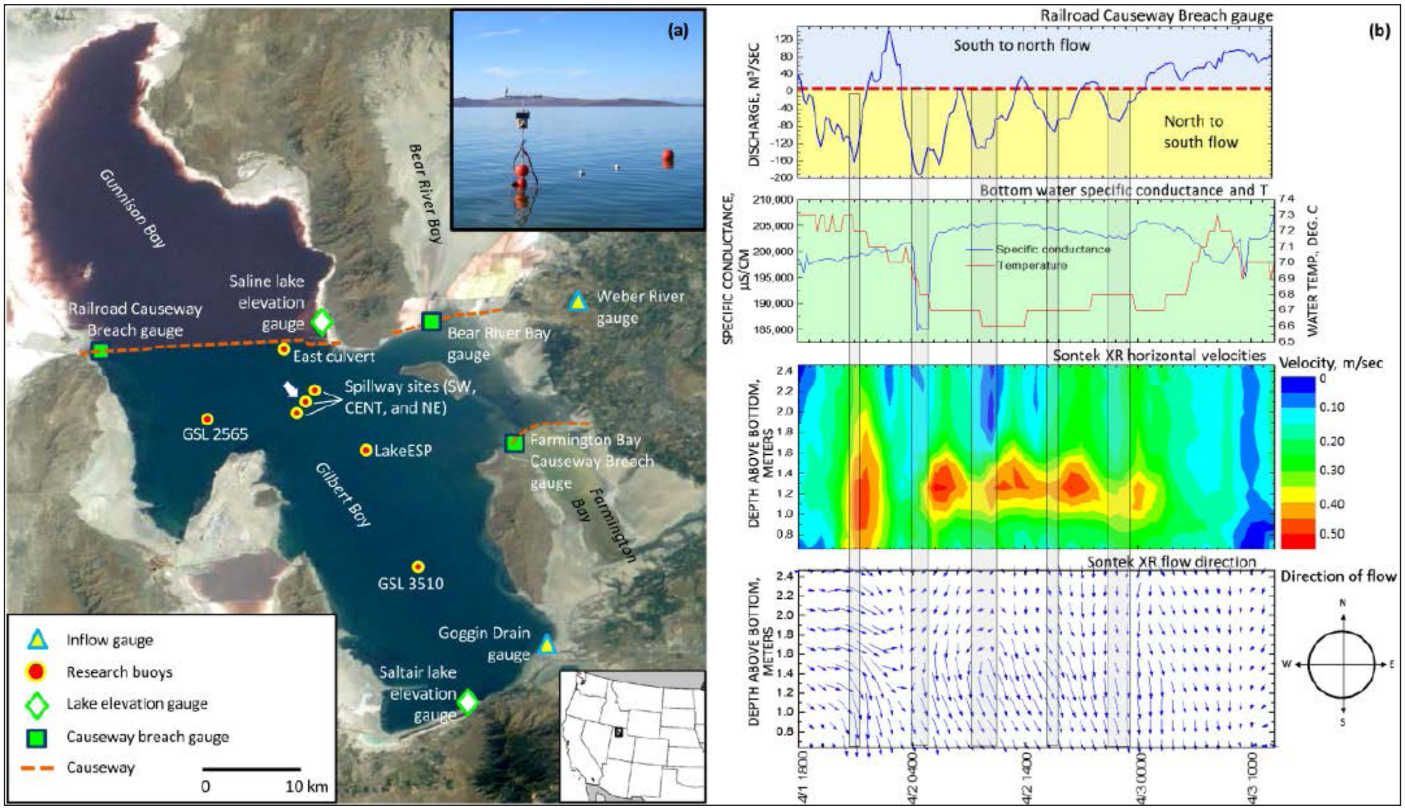

Fig. 1. Map of Great Salt Lake monitoring sites and networks. White arrow shows the approximate location of the naturally occurring spillway structure on the lake bottom. Background map is from the Image Science and Analysis Laboratory, NASA Johnson Space Center: "The Gateway to Astronaut Photography of Earth" (see http://eol.jsc.nasa.gov/scripts/sseop/photo.pl?mission=ISS002&roll=707&frame=87). (a) Photograph of the Lake Environmental Sensing Platform (LakeESP) research buoy after installation. (b) An example of the high-resolution monitoring data collected at the Railroad Causeway Breach and CENT spillway sites during 1–3 April 2012. Gray vertical bars on Figure 1b outline discharge peak during reverse flow events at Railroad Causeway Breach gauge.

conductance of water moving through this area of Gilbert Bay. Direction and velocity data are collected at 60-minute intervals, and temperature-specific conductance data are collected at 15-minute intervals. The data are stored internally and retrieved every 2 to 3 months. In response to potential construction modifications to the existing railroad causeway (e.g., the proposed addition of a second causeway breach, still under review by the U.S. Army Corp of Engineers), five additional stations with similar monitoring equipment were added during September 2012 (Figure 1).

Monitoring Data Applications

Figure 1b provides an example of how the high-frequency monitoring data from the spillway and railroad causeway breach sites can be combined to provide insights into the hydrodynamic processes controlling water movement across this geographic restriction (D. Naftz et al., Density stratified flow events in Great Salt Lake, Utah, USA: Implications for mercury and salinity cycling, submitted to *Chemical Geology,* 2013). Wind-driven, flow reversal events "push" water from Gunnison Bay into Gilbert Bay via the railroad causeway breach, which results in the accelerated movement of water across the natural spillway structure.

Future applications of monitoring data collected from Great Salt Lake include calibration and verification of a three-dimensional hydrodynamic model of water exchange between Gilbert and Gunnison bays, insights into loading and biogeochemical cycling of nutrients in Gilbert Bay, and assessment of limnological and salinity impacts from modifications to the existing railroad causeway. Together, these efforts will provide important tools and data for state and federal regulators that can be used to make informed decisions regarding future management of the Great Salt Lake ecosystem.

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