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Estimation of Selenium Loads Entering the South Arm of Great Salt Lake, Utah, from May 2006 through March 2008

Scientific Investigations Report 2008–5069

U.S. Department of the Interior
U.S. Geological Survey

Cover: Photograph taken by David L. Naftz, U.S. Geological Survey, June 2006

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Conversion Factors, Datums, and Abbreviated Water-Quality Units

Conversion Factors

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
kilometer (km)	0.6214	mile (mi)
meter (m)	1.094	yard (yd)
	Area	
square kilometer (km^2)	247.1	acre
square kilometer (km^2)	0.3861	square mile (mi^2)
square centimeter (cm^2)	0.1550	square inch (ft^2)
	Volume	
liter (L)	1.057	quart (qt)
cubic centimeter (cm^3)	0.06102	cubic inch (in^3)
	Mass	
gram (g)	0.03527	ounce, avoirdupois (oz)
kilogram (kg)	2.205	pound avoirdupois (lb)
	Density	
gram per cubic centimeter (g/cm^3)	62.4220	pound per cubic foot (lb/ft^3)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

°F=(1.8×°C)+32.

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

°C=(°F-32)/1.8.

Datums

Horizontal coordinate information is referenced to North American Datum of 1983 (NAD 83). Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88). Altitude, as used in this report, refers to distance above the vertical datum.

Abbreviated Water-Quality Units

Specific conductance is reported in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25°C).

Concentrations of chemical constituents in water are reported in micrograms per liter µg/L). Concentrations of chemical constituents in sediment are reported in micrograms per gram (µg/g).

Estimation of Selenium Loads Entering the South Arm of Great Salt Lake, Utah, from May 2006 through March 2008

By David L. Naftz[1], William P. Johnson[2], Michael L. Freeman[1], Kimberly Beisner[2], Ximena Diaz[2], and VeeAnn A. Cross[3]

Abstract

Discharge and water-quality data collected from six streamflow-gaging stations were used in combination with the LOADEST software to provide an estimate of total (dissolved + particulate) selenium (Se) load to the south arm of Great Salt Lake (GSL) from May 2006 through March 2008. Total estimated Se load to GSL during this time period was 2,370 kilograms (kg). The 12-month estimated Se load to GSL for May 1, 2006, to April 30, 2007, was 1,560 kg. During the 23-month monitoring period, inflows from the Kennecott Utah Copper Corporation (KUCC) Drain and Bear River outflow contributed equally to the largest proportion of total Se load to GSL, accounting for 49 percent of the total Se load. Five instantaneous discharge measurements at three sites along the railroad causeway indicate a consistent net loss of Se mass from the south arm to the north arm of GSL (mean = 2.4 kg/day, n = 5). Application of the average daily loss rate equates to annual Se loss rate to the north arm of 880 kg (56 percent of the annual Se input to the south arm). The majority of Se in water entering GSL is in the dissolved (less than 0.45 micron) state and ranges in concentration from 0.06 to 35.7 micrograms per liter (µg/L). Particulate Se concentration ranged from less than 0.05 to 2.5 µg/L. Except for the KUCC Drain streamflow-gaging station, dissolved (less than 0.45 um) inflow samples contain an average of 21 percent selenite (SeO_3^{2-}) during two sampling events (May 2006 and 2007).

Selenium concentration in water samples collected from four monitoring sites within GSL during May 2006 through August 2007 were used to understand how the cumulative Se load was being processed by various biogeochemical processes within the lake. On the basis of the Mann-Kendall test results, changes in dissolved Se concentration at the four monitoring sites indicate a statistically significant (90-percent confidence interval) upward trend in Se concentration over the 16-month monitoring period. Furthermore, the upward trend at three of the four GSL sites also was significant at the 95-percent confidence interval. Given the large amount of Se removal from GSL of greater than 1,900 kg/year by gaseous flux and permanent sedimentation, the observed increase in both dissolved (less than 0.45 micron) and total (dissolved + particulate) Se in the open-water monitoring sites indicates additional, unquantified source(s) of Se are contributing substantial masses of Se load to the south arm of GSL. Potential source(s) of this unmeasured Se load could include (1) Se loads entering GSL from unmeasured surface inflows; (2) ground-water discharge to GSL; (3) wind-blown dust that is deposited directly on the lake surface; (4) wet and dry atmospheric deposition falling directly on the lake surface; and (5) lake sediment pore-water diffusion into the overlying water column. Electrical resistivity surveys in the south part of GSL indicate areas of potential ground-water discharge to the open water of GSL and elevated (exceeding 10,000 µg/L) Se concentrations have been previously measured in ground water within 1.6 kilometers of the south shore of GSL.

Introduction

Great Salt Lake (GSL), in the Western United States, is a terminal lake with a surface area that can exceed 5,100-km^2 (fig. 1). The GSL ecosystem receives industrial, urban, mining, and agricultural discharge from a 37,500-km^2 watershed that includes more than 1.7 million people. The open water and adjacent wetlands of the GSL ecosystem support millions of migratory waterfowl and shorebirds from throughout the Western Hemisphere (Aldrich and Paul, 2002). In addition to supporting migratory water birds, the brine shrimp (*Artemia franciscana*) population residing in GSL supports a shrimp industry with annual revenues as high as 60 million dollars (Isaacson and others, 2002). Other industries supported by GSL include mineral production (sodium chloride, potassium salts, magnesium metal, chlorine gas, magnesium chloride,

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and nutritional supplements) and recreation that includes waterfowl hunting (Anderson and Anders, 2002; Butts, 2002; Isaacson and others, 2002; and Tripp, 2002). Natural oil seeps and potential oil reserves also exist within and adjacent to the shoreline of GSL (Bortz, 2002; Hunt and Chidsey, 2002). Full production of these reserves has been limited by high production and refining costs; however, increasing trends in the market value of crude oil could strengthen the economic viability of these reserves. Despite the ecological and economic importance of GSL, little is known about the input and biogeochemical cycling of trace elements, including selenium (Se) in the lake. Information on the input and biogeochemical cycling of trace elements is needed to understand potential geochemical and biological effects from increased loadings.

Domagalski and others (1990) evaluated the geochemical response of a suite of trace metals (cadmium [Cd], cobalt [Co], copper [Cu], iron [Fe], manganese [Mn], molybdenum [Mo], lead [Pb], vanadium [V], and zinc [Zn]) to diagenetic processes in the bottom sediments of GSL. Results from their research indicated that most trace metals were associated with sulfide mineral phases in conjunction with decomposition of organic matter and production of hydrogen sulfide that occurred in the near-surface sediments. Enrichment of Co, Cu, Pb, and Zn in near-surface bottom sediments was attributed to anthropogenic sources in the GSL watershed. Most of the organic matter at the sediment/anoxic water interface was mineralized to carbon dioxide as a result of excess sulfate in the system.

Work completed by Tayler and others (1980) postulated that GSL acts as a “natural disposal system” with respect to the immobilization of dissolved and suspended heavy metals and metalloids (silver [Ag], arsenic [As], Cd, Cu, mercury [Hg], Mn, Mo, Pb, Se, and Zn) in the water column. Concentration factors (concentration in lake/concentration in inflow) for selected heavy metals and metalloids in the water column of GSL indicated accumulation (greater than 1.0) or depletion (less than 1.0). The concentration factors calculated by Tayler and others (1980) ranged from 0.1 for Cd to 2.5 for Se to 11.5 for As; however, industrial inflows were not considered during their calculations. In general, the highest enrichments of heavy metals and metalloids in GSL sediments were observed in areas beneath an anoxic layer, likely as a result of the production of sulfide and subsequent precipitation of insoluble metal sulfides.

From 1998 to 2001, the U.S. Geological Survey (USGS) conducted a water quality and biological assessment within the GSL watershed (Waddell and others, 2004). Results from that study indicated that most streambed sediment, collected from areas affected by mine tailings and metal smelters, had elevated concentrations of selected trace elements that exceeded aquatic life guidelines for As, Cd, Cu, Pb, Hg, Ag, and Zn. Elevated phosphorus (P) concentrations were measured in 12 of the 27 streams in the GSL watershed that were sampled. Pesticides were present in 95 percent of the sampled streams, with the concentrations of carbaryl, diazinon, and malathion exceeding guidelines for the protection of aquatic life.

Sediment cores collected from the Farmington Bay area of GSL (Naftz and others, 2000) were used to reconstruct changes in the quality of water entering GSL from the early 1700s to 1998. The 28-cm core indicated that deposition of contaminated sediments (elevated concentrations of Cd, Cu, Pb, Zn, nitrogen [N], organic carbon [C], and P) began to occur sometime in the early to mid-1900s and concentrations became progressively greater in recently deposited sediments. Selenium was not included in this analytical schedule. The most contaminated sediments were deposited during 1979-98. Prior to the early 1900s, uncontaminated sediments were deposited in Farmington Bay. The historical trends observed in the GSL core were attributed to the increase in anthropogenic activities in the Salt Lake Valley.

In response to increasing public concern regarding Se input to the GSL ecosystem, the Utah Department of Environmental Quality/Division of Water Quality (UDEQ/DWQ) initiated coordinated studies with the USGS and University of Utah to quantify and evaluate the significance of current and future inputs of Se to GSL. Although a number of USGS stream gages existed on upstream reaches of inflow sources to GSL, additional gage sites were needed to allow the measurement of Se loads that are input directly to the lake after passing through the perimeter wetlands systems. The specific objectives of this project are to (1) accurately measure water discharge and Se concentration at all major inflow sites to GSL; (2) use the data collected in the first objective in combination with regression modeling techniques to simulate daily, monthly, and annual Se loads to Gilbert Bay of Great Salt Lake; (3) compare current and historic Se load data from selected inflow sites; and (4) simulate the Se concentration of lake water from monitored loading rates and compare to the observed water-column Se concentration and temporal trends.

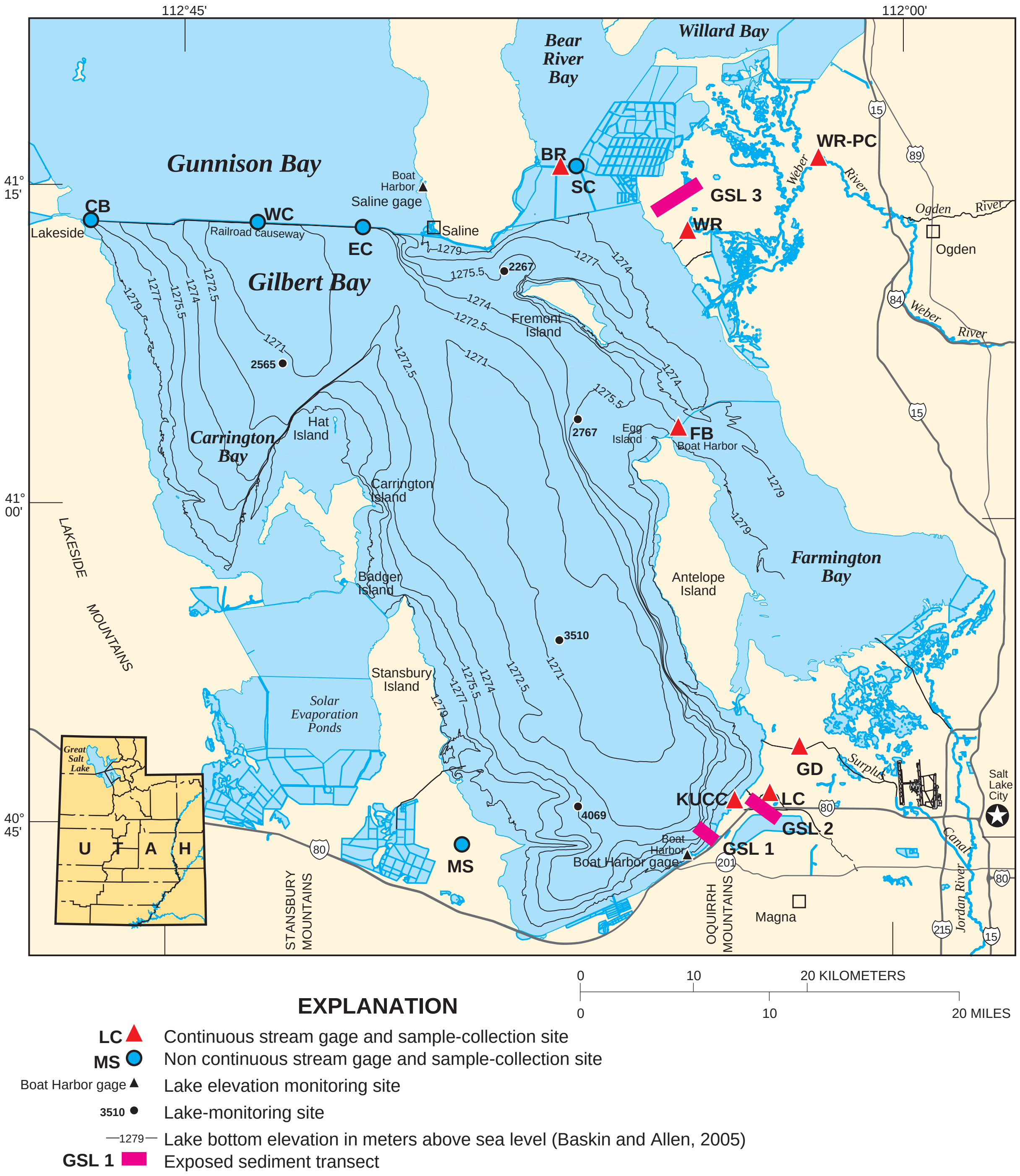

Figure 1. Location of continuous and noncontinuous stream gages, lake-monitoring sites, and exposed sediment transects adjacent to and within Great Salt Lake, Utah.

Methodology

Field Methods

The FB and BR gages (fig. 1; table 1) already were operating prior to the initiation of this study in May 2006. Four additional gages (GD, WR, LC, and KUCC) were installed or reactivated during May and June 2006 (fig. 1; table 1). Prior to the reactivation of the KUCC Drain streamflow-gaging station, discharge and Se data collected by Kennecott Utah Copper Corporation (KUCC) were used. Stream discharge at the GD, WR, and LC gages was measured using standard USGS methods (Buchanan and Somers, 1968, 1969; Carter and Davidian, 1968) by using a continuous record of water stage calibrated to periodic measurements of streamflow. Because of the low channel gradients and wind influence on inflow rates at the BR, FB, and KUCC gage sites, normal stage-to-discharge relations did not exist. Instead, hydroacoustic equipment in combination with velocity index methods (Simpson, 2001) was used to accurately gage discharge at those sites. The period of operation for each gage is summarized in table 1. Discharge data from each gage site can be accessed at http://waterdata.usgs.gov/ut/nwis/sw.

Water samples (filtered and unfiltered) were collected periodically from each gage site (May 2006 through February 2008) for the analysis of dissolved and total Se. Water samples from each inflow site were composited by using the equal discharge increment (EDI) or equal width increment (EWI) methods (Wilde and others, 1999). Water samples were composited into a churn splitter and processed on site using standard USGS procedures (U.S. Geological Survey, variously dated). Automated samplers were installed at the GD, FB, and BR gage sites (fig. 1) to collect daily water-quality samples during the peak runoff period (unfiltered samples only). The stream hydrograph was used to select which samples collected by the autosamplers were submitted for chemical analyses. Filtered water samples (dissolved Se and selenite [SeO_3^{2-}]) were passed through a 0.45-micron capsule filter and placed into acid- and field-rinsed polyethylene bottles and acidified to a pH of less than 2 with ultra-pure nitric acid. Unfiltered water samples (total Se) were placed directly into acid- and field-rinsed polyethylene bottles and acidified to a pH of less than 2 with ultra-pure nitric acid.

Daily water samples collected from the autosamplers were processed every two to three weeks in a similar manner as the composite water samples. Only unfiltered water samples were collected from the autosamplers. Sample bottles used in the autosamplers were cleaned with a 10 percent hydrochloric (HCl) solution and then triple rinsed with deionized water prior to redeployment. Specific conductance and pH also were measured on each water sample collected by the autosampler.

Laboratory Methods

Dissolved and total (dissolved + particulate) Se, as well as SeO_3^{2-}, concentration was measured by hydride generation atomic fluorescence (HG-AF) at Frontier GeoSciences, Inc. in Seattle, Washington. The concentration of dissolved selenate (SeO_4^{2-}) was determined by the difference (dissolved Se – SeO_3^{2-}).

Table 1. Streamflow-gaging stations adjacent to Great Salt Lake, Utah, with continuous record and where stream discharge and water-quality samples were collected to simulate selenium loads.

[Discharge measurements after September 30, 2007, are provisional. **Abbreviations:** USGS, U.S. Geological Survey]

Field ID	USGS station identification No.	USGS streamflow-gaging station name	Number of selenium samples collected for model calibration	Time period for which loads were simulated
BR	411403112200801	Bear River Bay Outflow at GSL Minerals Corp Bridge	45	[1]March 21, 2006–March 31, 2008
WR	411316112132201	North Fork Weber River near West Warren, Utah	18	May 11, 2006–March 31, 2008
GD	10172630	Goggin Drain near Magna, Utah	47	May 3, 2006–March 31, 2008
LC	10172640	Lee Creek near Magna, Utah	21	May 18, 2006–March 31, 2008
KUCC	10172650	Kennecott Drain near Magna, Utah	163	October 1, 2005–March 31, 2008
FB	410401112134801	GSL Farmington Bay Outflow at Causeway Bridge	52	[1]May 3, 2006–March 31, 2008

[1] Missing discharge record reconstructed with adjacent streamflow gages.

Quality Assurance

Thirty-six process blanks were collected during the inflow site sampling from May 2006 through February 2008, and analyzed for Se. The Se concentration in the process blanks did not exceed the lower reporting limit (0.05 µg/L) in 34 of the 36 samples. The only two process blanks to exceed the lower reporting limit, contained a Se concentration of 0.05 µg/L. On the basis of the process blank results, there was no Se contamination greater than the lower reporting limit introduced during sample processing at the inflow sites.

Twenty-one sample replicates were collected during the inflow site sampling from May 2006 through February 2008. The Se concentration for each sample replicate was compared to the Se concentration in the original sample collected from the churn splitter about 5 minutes prior to collection of the sample replicate. The absolute difference between the original and replicate samples ranged from 0.002 to 0.457 µg/L and the median difference was 0.023 µg/L (table 2).

Table 2. Results of field process blanks and sample replicates collected at inflow sites to Great Salt Lake, Utah, from May 2006 through July 2007.

[Location of each site shown in figure 1. GSL, Great Salt Lake. **Site ID:** BR, Bear River Bay Outflow at GSL Minerals Corp. Bridge; FB, GSL Farmington Bay Outflow at Causeway Bridge; GD, Goggin Drain near Magna, Utah; GSL99, process blank; LC, Lee Creek near Magna, Utah; WR, North Fork Weber River near West Warren, Utah. **Sample type:** FA, filtered and acidified; RA, unfiltered and acidified. **Validation flag:** U, analyte was not detected at reporting limit; J, analyte concentration is considered estimated because of a quality-control outlier. **Abbreviations:** µg/L, microgram per liter]

Site ID	Sample type	Sample date	Sample time	Selenium concentration (µg/L)	Validation flag	Reporting limit (µg/L)
Process blank results						
BR	FA	06-21-06	14:20	0.05	U	0.05
BR	FA	10-10-06	16:30	.05	U	.05
BR	RA	06-21-06	14:20	.05	U	.05
FB	FA	05-08-06	16:00	.05	U	.05
FB	FA	09-07-06	12:25	.05	U	.05
FB	FA	11-20-06	11:20	.05	U	.05
FB	RA	05-08-06	16:00	.05	U	.05
FB	RA	09-07-06	12:25	.05	U	.05
FB	RA	11-20-06	11:20	.05	U	.05
FB	FA	03-05-07	13:55	.05	U	.05
FB	RA	03-05-07	13:55	.05	U	.05
FB	FA	05-18-07	13:20	.05	U	.05
FB	RA	05-18-07	13:20	.05	U	.05
GD	FA	05-17-06	09:40	.05	U	.05
GD	FA	11-09-06	13:05	.05	U	.05
GD	RA	05-17-06	09:40	.05	U	.05
GD	RA	11-09-06	13:05	.05	U	.05
LC	FA	08-10-06	09:10	.05	U	.05
LC	FA	12-21-06	12:20	.05		.05
LC	RA	08-10-06	09:10	.05	U	.05
LC	RA	12-21-06	12:20	.05	U	.05
LC	FA	04-18-07	12:15	.05		.05
LC	RA	04-18-07	12:15	.05	U	.05
LC	RA	07-19-07	11:20	.05	U	.05
LC	FA	07-19-07	11:20	.05	U	.05
LC	RA	02-01-07	09:25	.05	U	.05
LC	FA	02-01-07	09:25	.05	U	.05
WR	FA	08-08-06	10:30	.05	U	.05
WR	FA	10-12-06	9:35	.05	U	.05
WR	RA	08-08-06	10:30	.05	U	.05
WR	RA	10-12-06	9:35	.05	U	.05
WR	FA	06-20-07	10:20	.05	U	.05
WR	RA	06-20-07	10:20	.05	U	.05
GSL99	FA	04-05-07	16:20	.05	U	.05
GSL99	RA	04-05-07	16:20	.05	U	.05

Table 2. Results of field process blanks and sample replicates collected at inflow sites to Great Salt Lake from May 2006 through July 2007.—Continued

[Location of each site shown in figure 1. **Site ID:** BR, Bear River Bay Outflow at GSL Minerals Corp. Bridge; FB, GSL Farmington Bay Outflow at Causeway Bridge; GD, Goggin Drain near Magna, Utah; GSL99, process blank; LC, Lee Creek near Magna, Utah; WR, North Fork Weber River near West Warren, Utah. **Sample type:** FA, filtered and acidified; RA, unfiltered and acidified. **Validation flag:** U, analyte was not detected at reporting limit; J, analyte concentration is considered estimated due to QC outlier. **Abbreviations:** µg/L, micrograms per liter]

Site ID	Sample type	Sample date	Sample time	Selenium concentration (µg/L)	Validation flag	Original minus replicate (µg/L)
			Sample replicates			
BR	FA	05-03-06	14:20	0.219		
BR	FA	05-03-06	14:25	.242		-0.023
BR	RA	05-03-06	14:20	.307		
BR	RA	05-03-06	14:25	.366		-.059
BR	FA	05-25-06	14:30	.301		
BR	FA	05-25-06	14:35	.460		-.159
WR	RA	08-08-06	09:45	.148	J	
WR	RA	08-08-06	09:50	.153	J	-.005
WR	FA	08-08-06	09:45	.062		
WR	FA	08-08-06	09:50	.101		-.039
LC	FA	08-10-06	09:00	1.53		
LC	FA	08-10-06	09:05	1.57		-.04
LC	RA	08-10-06	09:00	1.64		
LC	RA	08-10-06	09:05	1.62		.02
GD	FA	09-05-06	08:20	1.07	J	
GD	FA	09-05-06	08:25	1.13	J	-.06
GD	RA	09-05-06	08:20	1.17	J	
GD	RA	09-05-06	08:25	1.16	J	.01
WR	FA	12-20-06	12:45	.189		
WR	FA	12-20-06	12:50	.646		-.457
WR	RA	12-20-06	12:45	.192		
WR	RA	12-20-06	12:50	.195		-.003
WR	FA	07-16-07	14:00	.236		
WR	FA	07-16-07	14:05	.232		.004
WR	RA	07-16-07	14:00	.210		
WR	RA	07-16-07	14:05	.218		-.008
WR	FA	05-17-07	15:30	.207		
WR	FA	05-17-07	15:35	.214		-.007
WR	RA	05-17-07	15:30	.220		
WR	RA	05-17-07	15:35	.192		.028
GD	FA	01-31-07	14:35	1.67		
GD	FA	01-31-07	14:40	1.62		.05
GD	RA	01-31-07	14:35	1.68		
GD	RA	01-31-07	14:40	1.57		.11
GD	FA	06-18-07	11:25	1.22		
GD	FA	06-18-07	11:30	1.21		.01
GD	RA	06-18-07	11:25	1.19		
GD	RA	06-18-07	11:30	1.22		-.03
FB	FA	04-19-07	10:45	.372		
FB	FA	04-19-07	10:50	.392		-.020
FB	RA	04-19-07	10:45	.543		
FB	RA	04-19-07	10:50	.541		.002

Mass Loading Estimation Method

The USGS loading software, LOADEST (Runkel and others, 2004), was used to estimate the mass loading of total Se at each gage site. The automated model selection in LOADEST was used to select the best regression model from the set of nine predefined models (table 3). Under the automated selection option, adjusted maximum likelihood estimation (AMLE) (Cohn, 1988; Cohn and others, 1992) is used to determine model coefficients and estimates of log load. The predefined model with the lowest value of the Akaike Information Criterion (AIC) statistic was then used for final load estimation (Judge and others, 1988).

Exposed Sediment Collection and Processing

Sediment samples from mud flats surrounding the Great Salt Lake were collected at three transect sites (fig. 1). Five samples were collected at each site along a transect perpendicular to the shoreline. Samples at each transect were separated by variable distances: (transect 1) samples separated by 60-m intervals; (transect 2) samples separated by 120-m intervals; and (transect 3) samples separated by 180-m intervals. The samples closest to the shoreline were numbered GSL 1 sequentially up to GSL 5 (sample farthest from the shoreline).

Samples were processed according to methods in Hageman and Briggs (2000). Each sample was dried at 60°C for 7 days before processing. After drying, 50 g of sediment was added to 1 L of deionized water and mixed for 1 hour. After settling, the samples were processed as unfiltered acidified (RA) and filtered (less than 0.45 micron) acidified (FA). Samples were acidified with ultrapure nitric acid to a pH value of less than 2.0 standard units. Water samples were analyzed for Se at Frontier GeoSciences, Inc. A split of the sediment collected before extraction with deionized water was sent to LET, Inc. for analysis of total available Se using a strong acid digestion.

Table 3. Regression models considered during the automated selection option in LOADEST.

[From Runkel and others, 2004. **Abbreviations:** a_0 through a_6, model-determined regression coefficients; ln, natural log; *Q*, discharge; *dtime*, decimal time; π (pi), 3.141593]

Model number	Regression model
1	$a_0 + a_1 \ln Q$
2	$a_0 + a_1 \ln Q + a_2 \ln Q^2$
3	$a_0 + a_1 \ln Q + a_2 dtime$
4	$a_0 + a_1 \ln Q + a_2 \sin(2\pi dtime) + a_3 \cos(2\pi dtime)$
5	$a_0 + a_1 \ln Q + a_2 \ln Q^2 + a_3 dtime$
6	$a_0 + a_1 \ln Q + a_2 \ln Q^2 + a_3 \sin(2\pi dtime) + a_4 \cos(2\pi dtime)$
7	$a_0 + a_1 \ln Q + a_2 \sin(2\pi dtime) + a_3 \cos(2\pi dtime) + a_4 dtime$
8	$a_0 + a_1 \ln Q + a_2 \ln Q^2 + a_3 \sin(2\pi dtime) + a_4 \cos(2\pi dtime) + a_5 dtime$
9	$a_0 + a_1 \ln Q + a_2 \ln Q^2 + a_3 \sin(2\pi dtime) + a_4 \cos(2\pi dtime) + a_5 dtime + a_6 dtime^2$

Estimation of Selenium Loads

Simulation of Selenium Loadings from Inflow Sites

Lee Creek near Magna, Utah: The LOADEST model calibration file contained 21 observations for total (dissolved + particulate) Se load during the time period of May 2006 through March 2008 (fig. 2). The LOADEST estimation file contained 684 measurements of mean daily discharge. Both the calibration and estimation file used in the LOADEST model are contained in appendix A. Regression model 8 (table 3) was determined to best simulate daily total Se loads from Lee Creek to GSL with an R^2 value of 0.8244 (appendix A).

Comparisons between the measured and the simulated loads of total Se at the Lee Creek gage indicate reasonable agreement (fig. 3) and ranged from –27.8 percent to +17.8 percent. The average error between the measured and the simulated total Se load was +/-10.4 percent (n = 20). The complete output of LOADEST model results is contained in appendix A.

Goggin Drain near Magna, Utah: The LOADEST model calibration file contained 47 observations for total (dissolved + particulate) Se load during May 2006 through March 2008 (fig. 4). The LOADEST estimation file contained 699 measurements of mean daily discharge. Both the calibration and estimation file used in the LOADEST model are contained in appendix A. Regression model 9 (table 3) was determined to best simulate daily total Se loads from the Goggin Drain to GSL with an R^2 value of 0.9938 (appendix A).

Comparisons between the measured and the simulated loads of total Se at the Goggin Drain gage indicate good agreement (fig. 5) and ranged from –35.5 percent to +21.1 percent. The average error between the measured and the simulated total Se load was +/-10.4 percent (n = 47). The complete output of LOADEST model results is contained in appendix A.

Weber River near West Warren, Utah: The LOADEST model calibration file contained 18 observations for total (dissolved + particulate) Se load during May 2006 through March 2008 (fig. 6). The LOADEST estimation file contained 691 measurements of mean daily discharge. Both the calibration and estimation file used in the LOADEST model are contained in appendix A. Regression model 9 (table 3) was determined to best simulate daily total Se loads from the Weber River with an R^2 value of 0.9463 (appendix A)

Comparisons between the measured and the simulated loads of total Se at the Weber River gage indicate reasonable agreement (fig. 7) and ranged from –22.5 percent to +19.9 percent. Average error between the measured and the simulated total Se load was +/-10.2 percent (n = 18). The complete output of LOADEST model results is contained in appendix A.

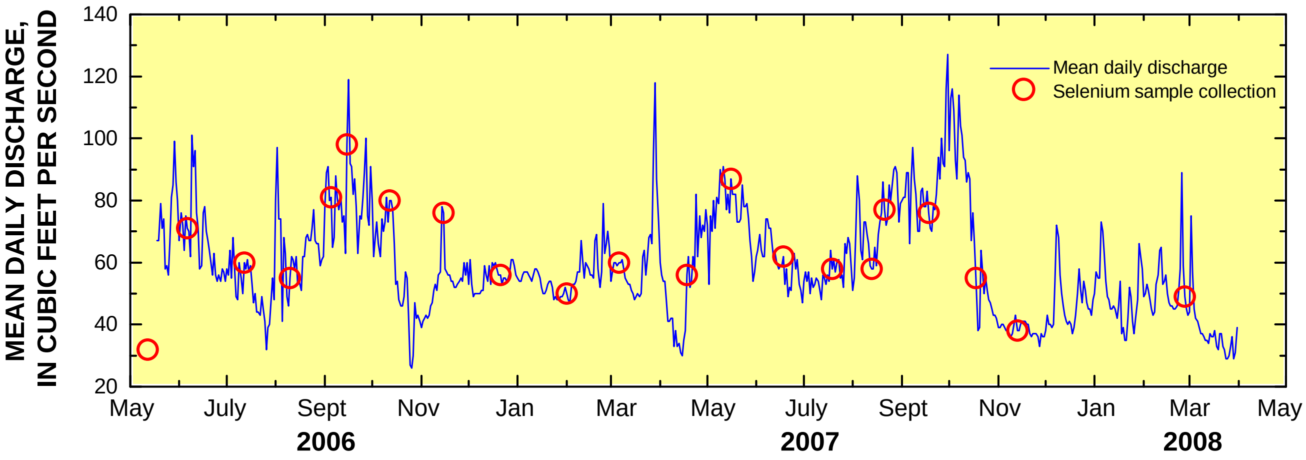

Figure 2. Stream discharge and dates when water samples were collected for selenium analysis at the Lee Creek streamflow-gaging station near Magna, Utah, May 2006 through March 2008.

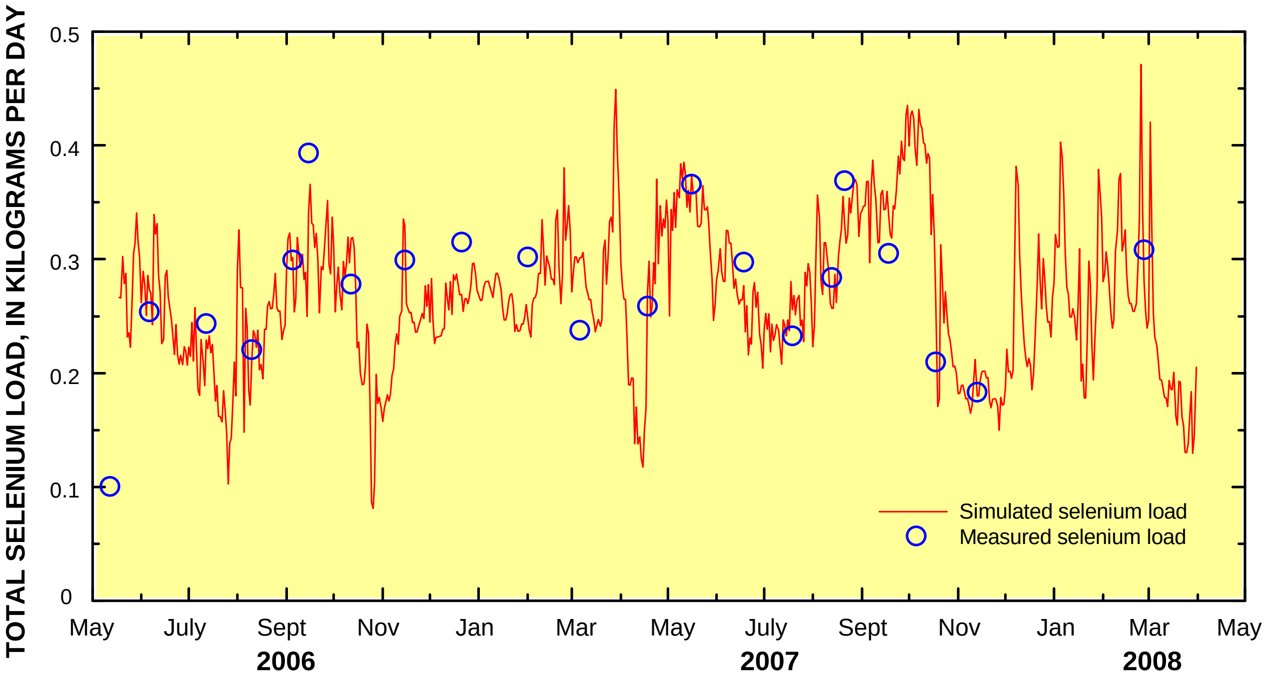

Figure 3. Measured and simulated loads of total selenium at the Lee Creek streamflow-gaging station near Magna, Utah, May 2006 through March 2008.

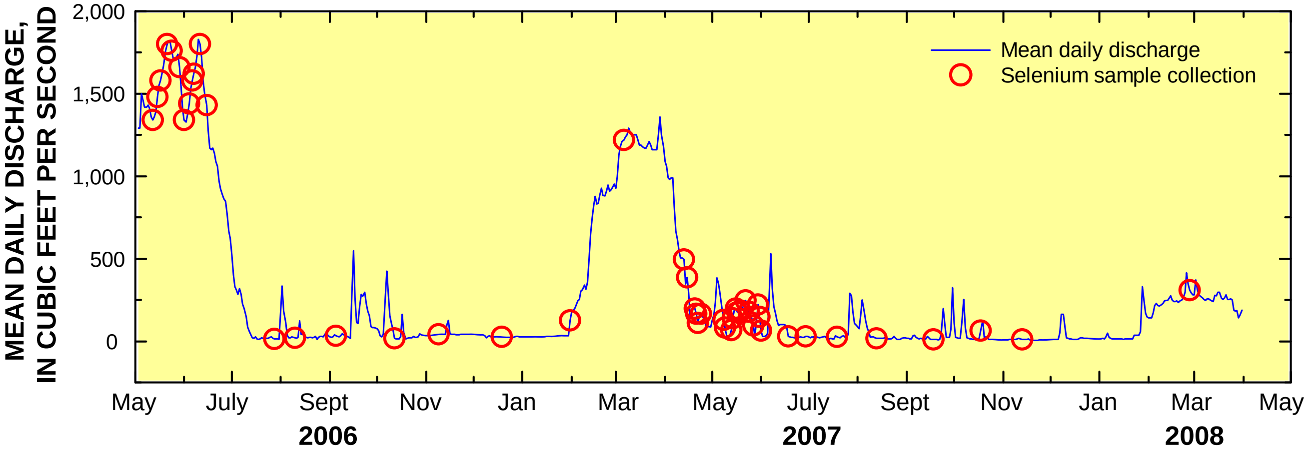

Figure 4. Stream discharge and dates when water samples were collected for selenium analysis at the Goggin Drain streamflow-gaging station near Magna, Utah, May 2006 through March 2008.

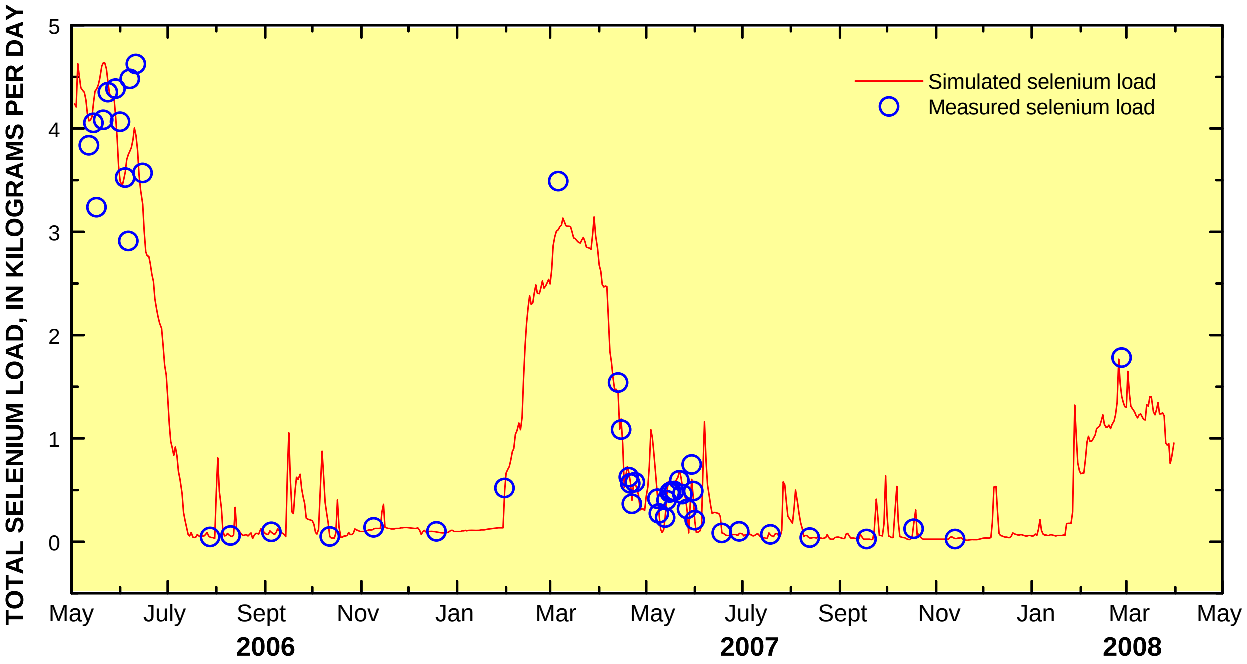

Figure 5. Measured and simulated loads of total selenium at the Goggin Drain streamflow-gaging station near Magna, Utah, May 2006 through March 2008.

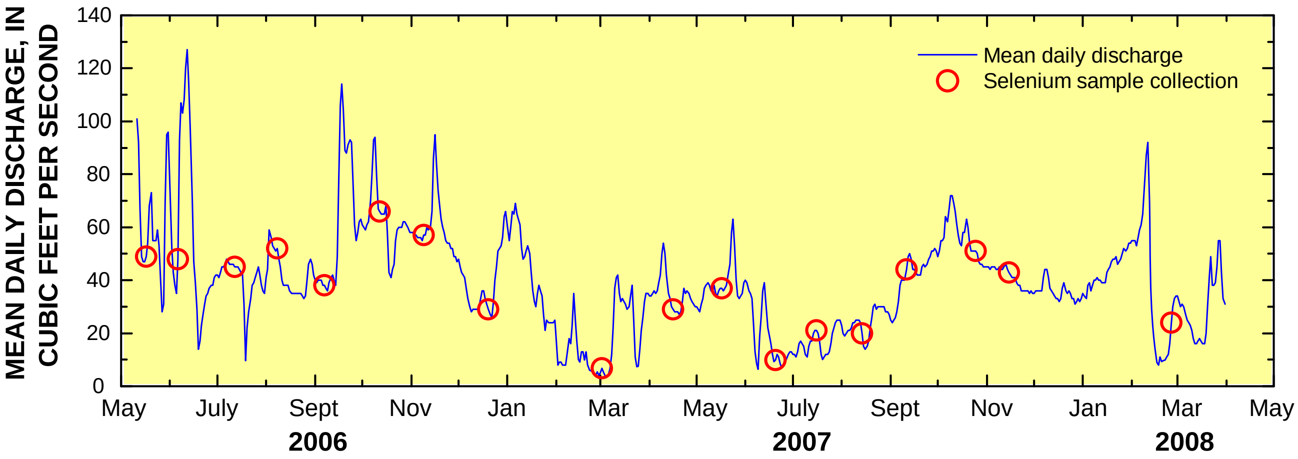

Figure 6. Stream discharge and dates when water samples were collected for selenium analysis at the Weber River streamflow-gaging station near West Warren, Utah, May 2006 through March 2008.

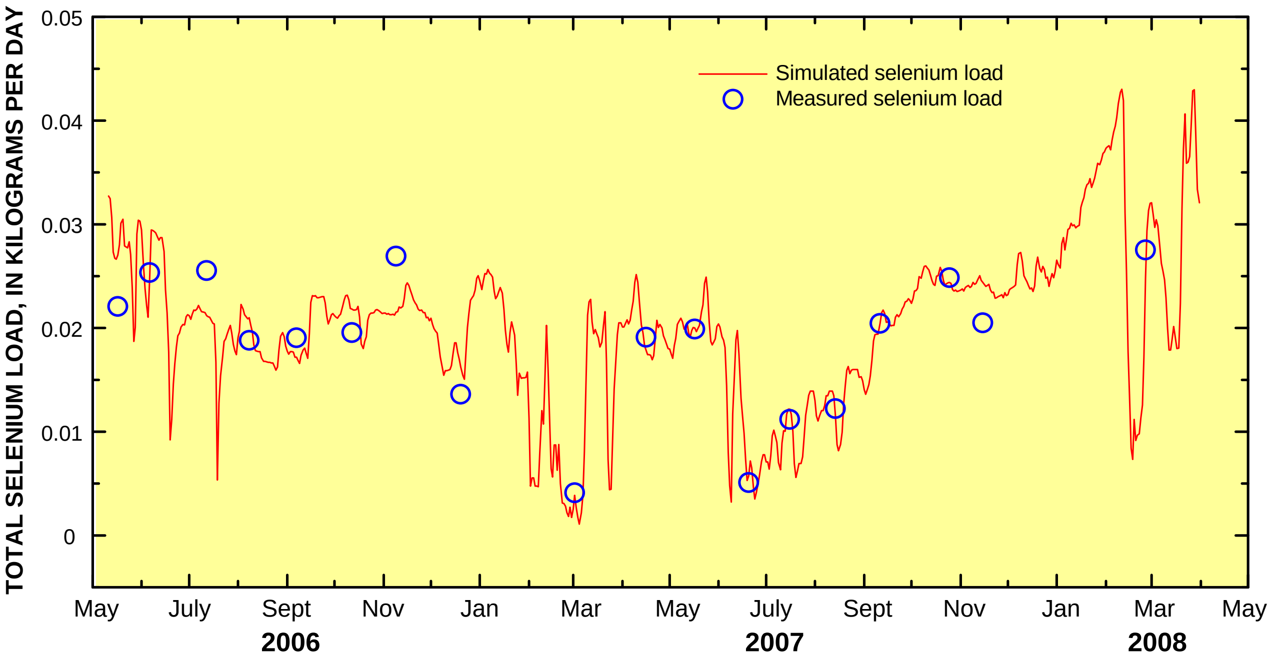

Figure 7. Measured and simulated loads of total selenium at the Weber River streamflow-gaging station near West Warren, Utah, May 2006 through March 2008.

Kennecott Drain near Magna, Utah: Because of the large number of samples collected by KUCC at the Kennecott Drain gaging station from October 2005 through September 2006 (fig. 8), the LOADEST software was used to estimate total Se loads only during June 20, 2006 through March 31, 2008. The LOADEST model calibration file contained 163 observations for total (dissolved + particulate) Se load during July 2006 through March 2008. The LOADEST estimation file contained 641 measurements of mean daily discharge measured by the USGS from June 2006 through March 2008. Both the calibration and estimation file used in the LOADEST model are contained in appendix A. Regression model 4 (table 3) was determined to best simulate daily total Se loads from the Kennecott Drain to GSL with an R^2 value of 0.9956 (appendix A).

Comparisons between the measured and the simulated loads of total Se at the Kennecott Drain gage indicate good agreement (fig. 9) and ranged from –38.1 percent to +28.6 percent. Average error between the measured and the simulated total Se load was +7.8 percent (n = 163). The complete output of LOADEST model results are contained in appendix A.

Bear River Bay Outflow at GSL Minerals Corp. Bridge: The LOADEST model calibration file contained 45 observations for total (dissolved + particulate) Se load during May 2006 through March 2008 (fig. 10). The LOADEST estimation file contained 742 measurements of mean daily discharge collected from March 2006 through March 2008. Because of equipment failure and gage removal in November 2006 as a result of ice conditions, daily discharge measurements from October 1, 2006, through April 16, 2007, and July 6, 2007, through March 31, 2008, were estimated from an upstream gage (Bear River near Corinne, Utah). Mean daily discharge for the missing time period was estimated from the linear relation between measured discharge at both sites from March 21, 2006, through September 30, 2006 (fig. 11). The regression equation developed from this comparison explained 80 percent of the variance (p less than 0.0001, N = 194).

Both the calibration and the estimation files used in the LOADEST model are contained in appendix A. Regression model 7 (table 3) was determined to best simulate daily total Se loads from the Bear River to GSL with an R^2 value of 0.9988 (appendix A).

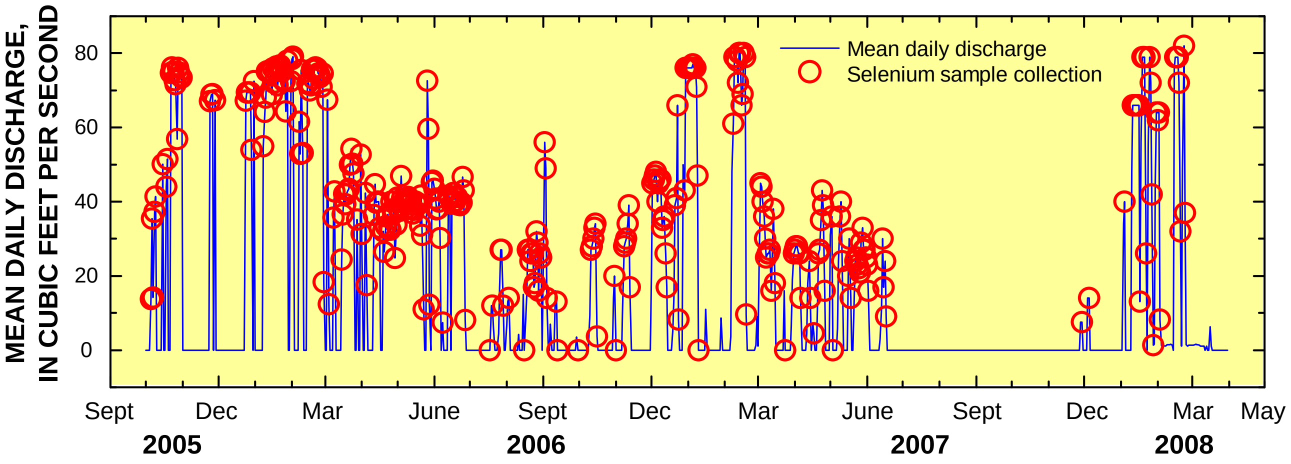

Figure 8. Stream discharge and dates when water samples were collected for selenium analysis at the Kennecott Drain streamflow-gaging station near Magna, Utah, October 2005 through March 2008. Discharge and selenium data prior to June 30, 2006, provided by Kennecott Utah Copper Corporation (K. Payne, written commun., 2006). Selenium and discharge data after June 30, 2006, provided by Kennecott Utah Copper Corporation (K. Payne, written commun., 2006, 2007, and 2008) and U.S. Geological Survey.

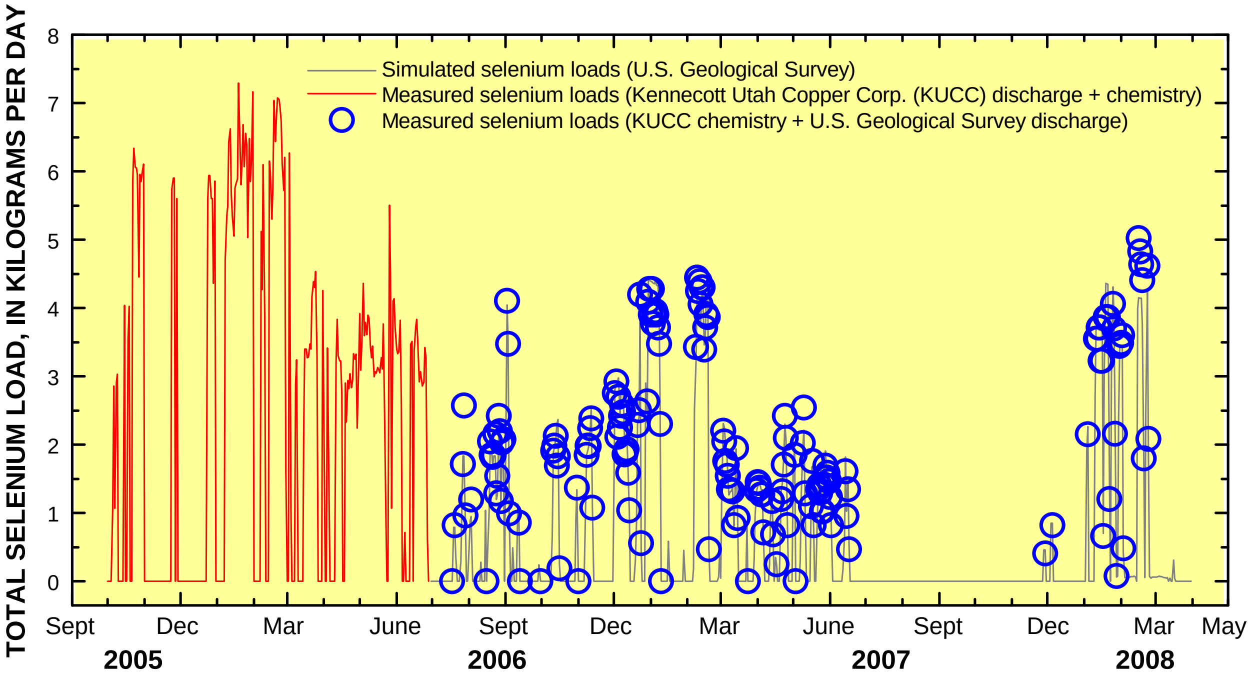

Figure 9. Measured and simulated loads of total selenium at the Kennecott Drain streamflow-gaging station near Magna, Utah, October 2005 through March 2008.

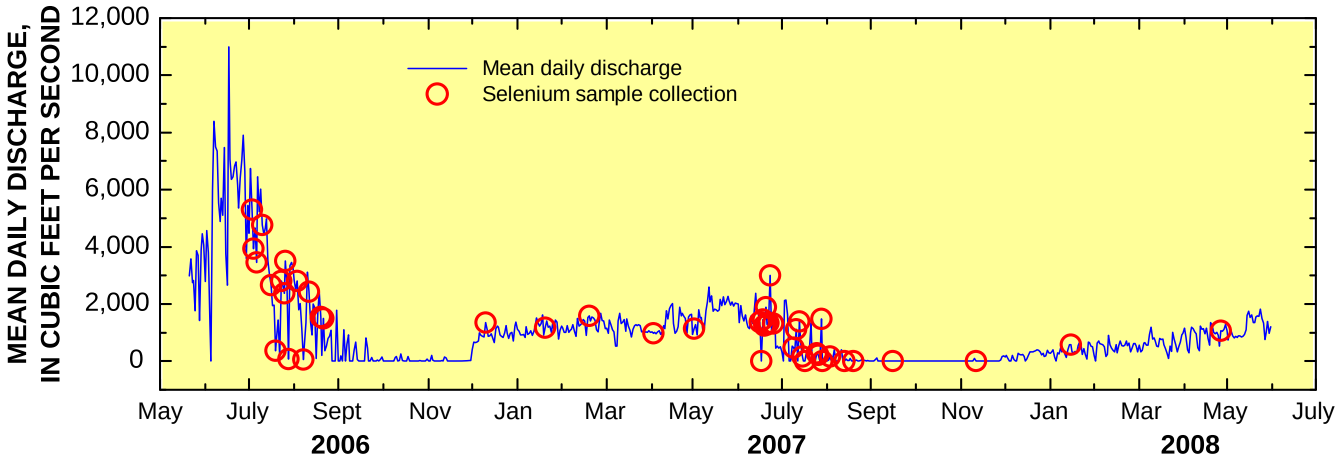

Figure 10. Stream discharge and dates when water samples were collected for selenium analysis at the Bear River Bay outflow gaging station. Negative mean daily discharge values (wind-driven flow into Bear River Bay) were assigned a discharge value of 0.0001 cubic foot per second. Discharge data from October 1, 2006, to April 16, 2007, and July 6, 2007, through March 31, 2008, were calculated by using a simulated mean daily discharge value obtained from an upstream U.S. Geological Survey gage (10126000 Bear River near Corinne, Utah).

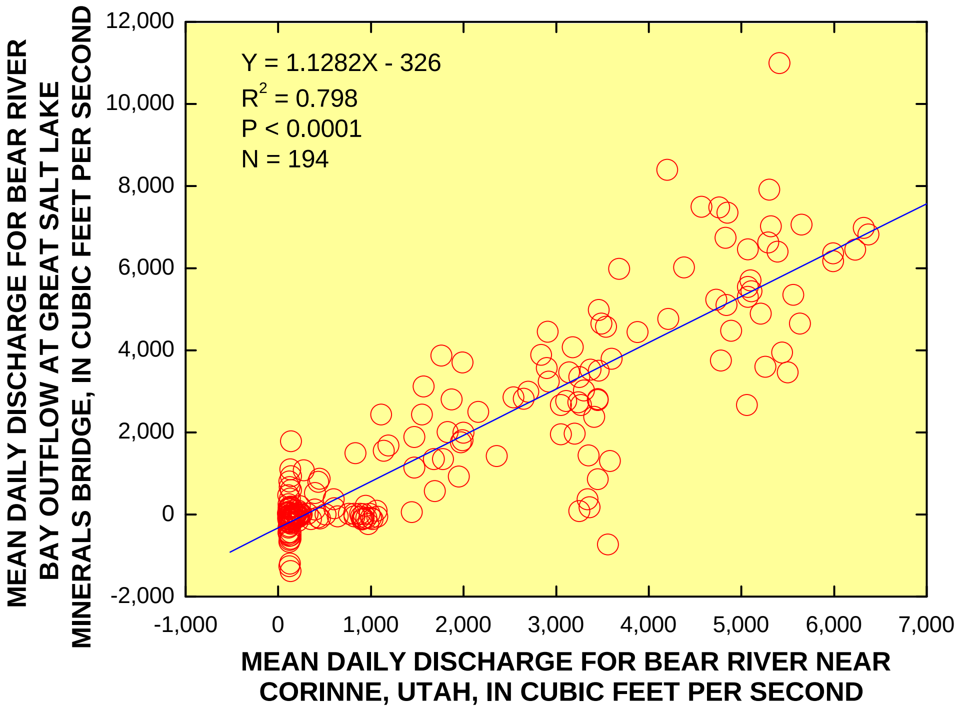

Figure 11. Comparison of mean daily stream discharge determined at two USGS stream-gage sites on the Bear River for the time period of March through September 2006. The linear regression equation developed from this comparison was used to estimate mean daily discharge for Bear River Bay outflow when the discharge was not measured.

Comparisons between the measured and the simulated loads of total Se at the Bear River Bay outflow gage indicate good agreement (fig. 12) and ranged from –55.9 percent to +36.0 percent. Average error between measured and simulated total Se load was +4.9 percent (n = 45). Differences between the measured and simulated loads of total Se from October 1, 2006, through April 15, 2007, and July 6, 2007, through March 31, 2008, are likely due to the estimated discharge measurements during these time periods. The complete output of LOADEST model results are contained in appendix A.

Farmington Bay Outflow at Causeway Bridge: The LOADEST model calibration file contained 52 observations for total (dissolved + particulate) Se load during May 2006 through March 2008 (fig. 13). The LOADEST estimation file contained 699 measurements of mean daily discharge measured from May 2006 through March 2008. Because of intermittent equipment failures, selected mean daily discharge records were reconstructed from three existing USGS gages (fig. 14), using the formula:

$$Q_{FB} = (Q_{SC} + Q_{JR}) - Q_{GD} \qquad (1)$$

where Q_{FB} is the calculated discharge at Farmington Bay outflow, in cubic feet per second; Q_{SC} is the mean daily discharge measured at the Surplus Canal gage, in cubic feet per second; Q_{JR} is the mean daily discharge measured at the Jordan River gage, in cubic feet per second; and Q_{GD} is the mean daily discharge measured at the Goggin Drain gage, in cubic feet per second. This formula estimates the amount of water from the Jordan River system that is discharged into Farmington Bay and was used to estimate discharge when mean daily discharge records for FB were missing prior to October 9, 2006. After October 9, 2006, discharge data were missing only for short time periods, and the mean daily discharge was estimated by interpolating between last and next mean daily discharge value that was measured.

Both the calibration and the estimation files used in the LOADEST model are contained in appendix A. Regression model 9 (table 3) was determined to best simulate daily total Se loads from the Farmington Bay to GSL with an R^2 value of 0.9991 (appendix A).

Comparisons between the measured and the simulated loads of total Se at the Farmington Bay Outflow gage during water year 2006 indicate reasonable agreement (fig. 15) and ranged from –94.3 percent to +33.6 percent. Average error between measured and simulated total Se load was +13.5 percent (n = 52). The complete output of LOADEST model results is contained in appendix A.

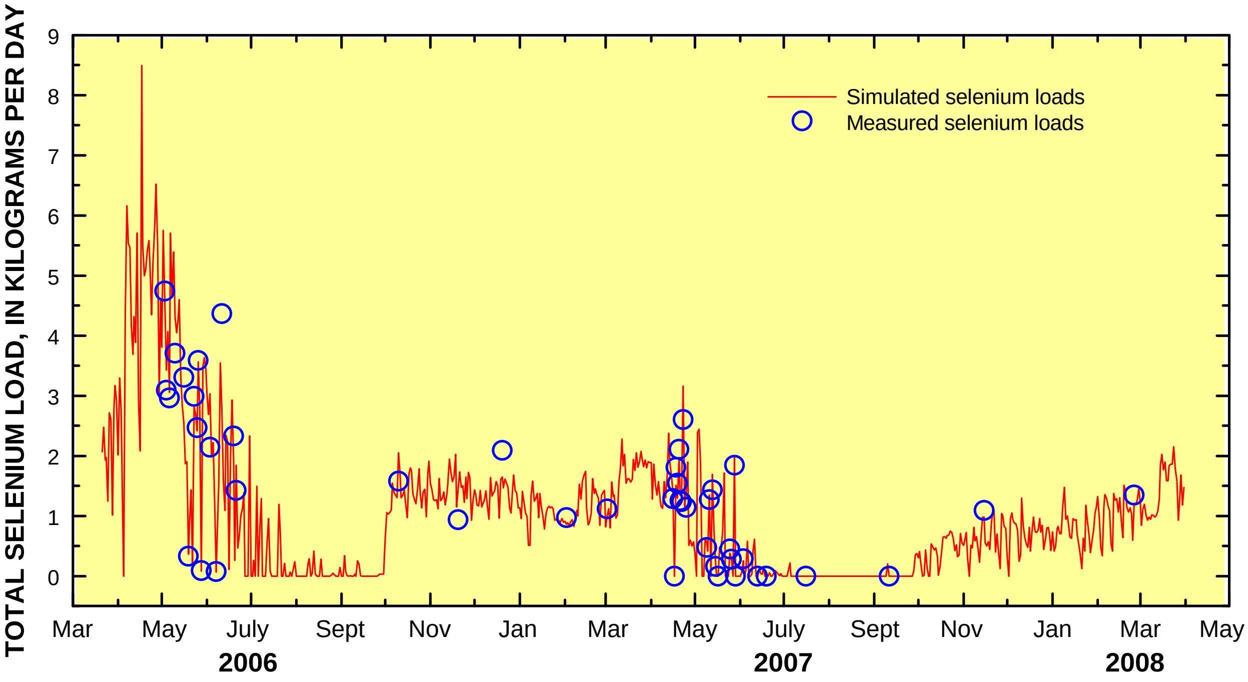

Figure 12. Measured and simulated loads of total selenium at the Bear River Bay Outflow streamflow-gaging station. Load estimates for October 1, 2006, through April 16, 2007, and July 6, 2007, through March 31, 2008, were calculated by using a simulated mean daily discharge value obtained from an upstream U.S. Geological Survey gage (10126000 Bear River near Corinne, Utah).

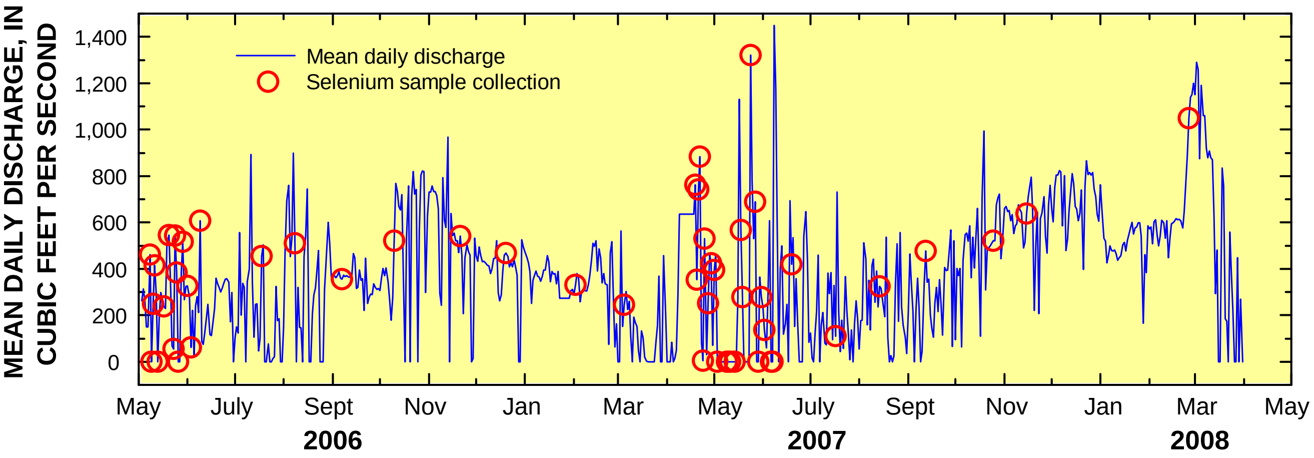

Figure 13. Stream discharge and dates when selenium samples were collected at the Farmington Bay Outflow streamflow-gaging station, May 2006 through March 2008. Negative mean daily discharge values (wind-driven flow into Farmington Bay) were assigned a discharge value of 0.0001 cubic foot per second. Because of intermittent periods of missing discharge record, discharge was estimated using the following formula: $Q_{FB} = (Q_{SC} + Q_{JR}) - Q_{GD}$, where Q is the mean daily discharge in cubic feet per second, FB is Farmington Bay Outflow, SC is the Surplus Canal, JR is the Jordan River at 1700 South, and GD is the Goggin Drain. The locations of these sites are shown in figure 14.

Wetting of Shoreline Sediments: Solubilization of Se into the water column in response to increasing lake level likely occurs on an annual cycle during the seasonal rise of lake level during spring runoff. Lake level increased from 1279.1 m in November 2006 to 1279.4 m in April 2007. The observed increase in lake level during this time period corresponds to a lake area increase of 60.6 km^2 and a lake volume increase of 5.72 X 10^8 m^3 (Baskin 2005).

Average total Se concentration from sediment samples was 0.37 ± 0.31 µg/g. Total Se concentrations in exposed sediment samples were identical from two transect sites (GSL 1 and GSL 3) 0.20 ± 0 µg/g and was significantly higher at the other transect site (GSL 2) 0.70 ± 0.37 µg/g. Average water soluble Se concentration in the raw acidified (RA) samples was 0.52 ± 0.42 µg/L, whereas the average water soluble Se concentration in the filtered acidified (FA) samples was slightly lower at 0.45 ± 0.32 µg/L.

The following equations were used to estimate the Se mass input contributed to GSL during the resaturation of near-shore sediments during the 0.3-m lake level increase recorded from November 2006 to April 2007. Assuming a sediment bulk density (ρ_b) of 1.6 g/ cm^3 and an effective leaching depth of 1 cm:

$$\mathrm{kg}_{\mathrm{Se}} = \frac{\mu\mathrm{g}_{\mathrm{solubilized}}}{\text{unit surface area (cm}^2)}(\text{area}_{\text{mud flat}})\left(\frac{\mathrm{kg}}{10^9\mu\mathrm{g}}\right)$$

where the unit surface area refers to the interaction (top) surface of a rectangular prism made up of the leached sediment mass (50 g).

$$\text{unit surface area (cm}^2) = \frac{\text{leached sediment mass (g)}}{\rho_b\left(\mathrm{g/cm}^3\right)}\left(\frac{1}{\text{leaching depth (cm)}}\right)$$

$$\text{unit surface area (cm}^2) = \frac{50\ \mathrm{g}}{1.6\ \mathrm{g/cm}^3}\left(\frac{1}{1\ \mathrm{cm}}\right)$$

$$\text{unit surface area (cm}^2) = 31.25\ \mathrm{cm}^2$$

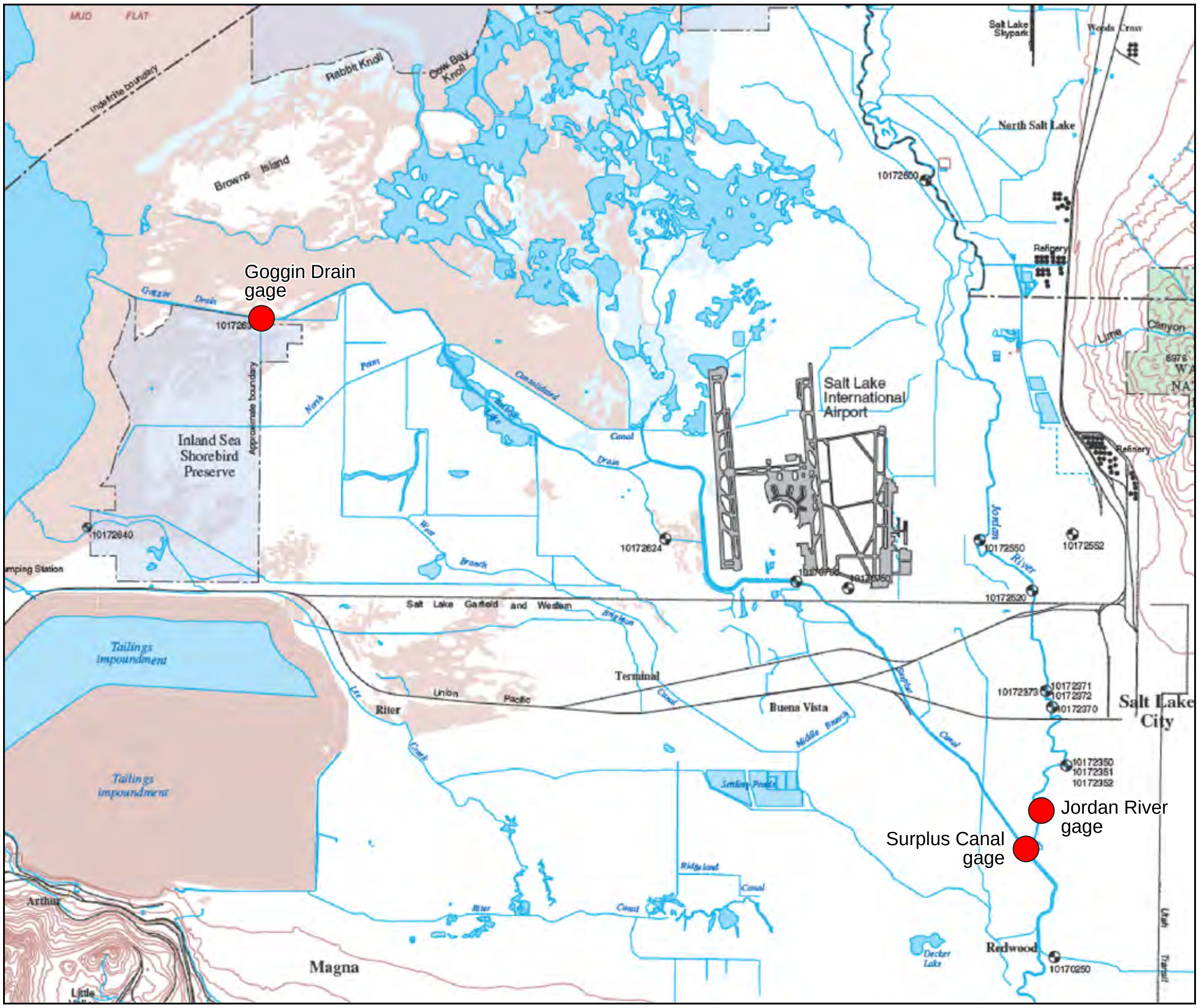

Figure 14. Locations of gages used to estimate mean daily discharge values at the Farmington Bay Outflow streamflow-gaging station during periods of missing record.

Using the average value obtained from the unfiltered water soluble Se tests (0.52 µg) over a mudflat area of 14,976 acres results in a calculated total Se mass contributed by the observed water-level increase.

$$\mathrm{kg_{Se}} = \frac{0.52\ \mu\mathrm{g_{solubilized}}}{31.25\ \mathrm{cm}^2}\, 60.6\,\mathrm{km}^2 \left(\frac{1\ \mathrm{X}\ 10^{10}\ \mathrm{cm}^2}{1\ \mathrm{km}^2}\right)\left(\frac{\mathrm{kg}}{10^9 \mu\mathrm{g}}\right)$$

$$\mathrm{kg_{Se}} = 10$$

The addition of 10 kg of Se from the flooding of near-shore sediments is not significant relative to the annual Se loads contributed by riverine inflow to GSL. Higher Se loads from near-shore sediments to GSL could be contributed by larger lake-level increases that could occur in future years.

The amount of extractable Se present in each sample was small relative to the total available Se (strong acid leachable) in each lake-shore sample. The average percentage of water-soluble Se relative to the total Se in each lake-shore sample was 3.12 ± 1.63 percent (unfiltered sediment extracts) and 2.72 ± 1.62 percent (filtered sediment extracts). The small amount of water-soluble Se relative to total Se (acid soluble) in lake-shore samples indicates that additional water-soluble Se likely will be made available during future wet/dry cycles.

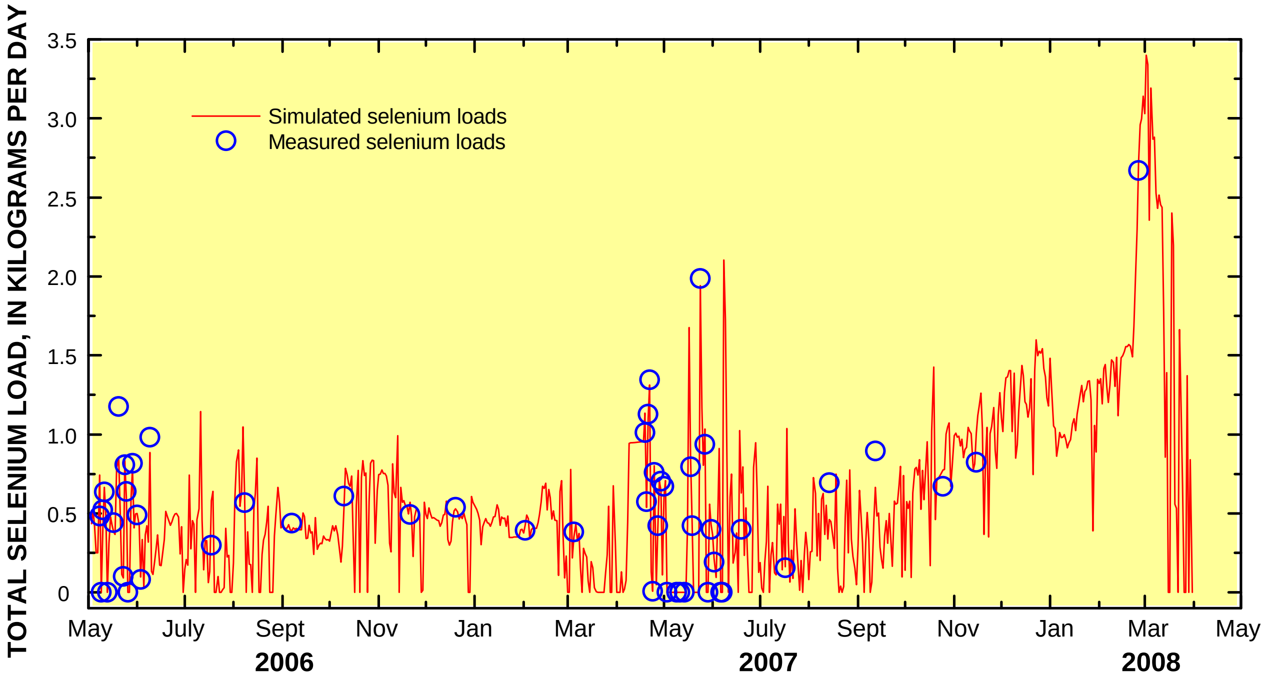

Figure 15. Measured and simulated loads of total selenium at the Farmington Bay Outflow streamflow-gaging station. Because of intermittent periods of missing discharge record during 2006, selected selenium load estimates were determined from calculated discharge estimates by using the following formula: ($Q_{FB} = Q_{SC} + Q_{JR}) - Q_{GD}$, where Q is the mean daily discharge in cubic feet per second, FB is Farmington Bay Outflow, SC is the Surplus Canal, JR is the Jordan River at 1700 South, and GD is the Goggin Drain. Location of these additional gages is shown in figure 14.

Cumulative Selenium Loadings

The Se input models developed for each gage site were used to estimate the cumulative daily total (dissolved + particulate) Se load to GSL from May 1, 2006 through March 31, 2008 (fig. 16). Total estimated Se load to GSL during this 23-month time period was 2,370 kg and included the projected loads from May 1 through May 17, 2006. The estimated 12-month Se load to GSL for the time period from May 1, 2006 through April 30, 2007 was 1,560 kg.

The largest estimated cumulative monthly Se load occurred in May 2006 (353 kg), and the smallest estimated cumulative monthly load occurred in July 2007 (20 kg). The large Se loads during May 2006 can be attributed to the large river inflows resulting from snowmelt runoff combined with active discharge from the KUCC Drain. In contrast, the low runoff conditions experienced during 2007 resulted in a May 2007 cumulative Se load of only 86 kg. As shown in figure 16, the largest single-day Se load to GSL occurred on May 26, 2006 (13.7 kg).

The low runoff conditions during Spring 2007 relative to Spring 2006 are further exemplified by comparing the date when Bear River discharge dropped to zero during both years (fig. 10). During water year 2006, there was measurable discharge from Bear River to GSL until late July. In contrast, during water year 2007 no measurable discharge to GSL was recorded after late May.

During the monitoring period from May 2006 through March 2008, the KUCC Drain and Bear River contributed almost equally to the largest proportion of total Se load to GSL (fig. 17). The combined input to GSL from both the KUCC Drain and Bear River accounted for 49 percent of the total Se load during the 23-month monitoring period. The Se load from Goggin Drain during this same time period contributed 22 percent of the total Se load to GSL, while Farmington Bay contributed 20 percent of the total Se load. This overall trend in loading was not consistent on a month-by-month basis. For example, the Se load from the Goggin Drain was the major loading source during May, June, and July 2006, and the KUCC Drain was the major loading source during August 2006 (fig. 16). The high proportion of Se loadings contributed by the Bear River from October 1, 2006, through April 15, 2007, is partly the result of the estimated streamflow from the upstream gage; however, equipment removal during winter “ice over” prevented site-specific measurements during this time period.

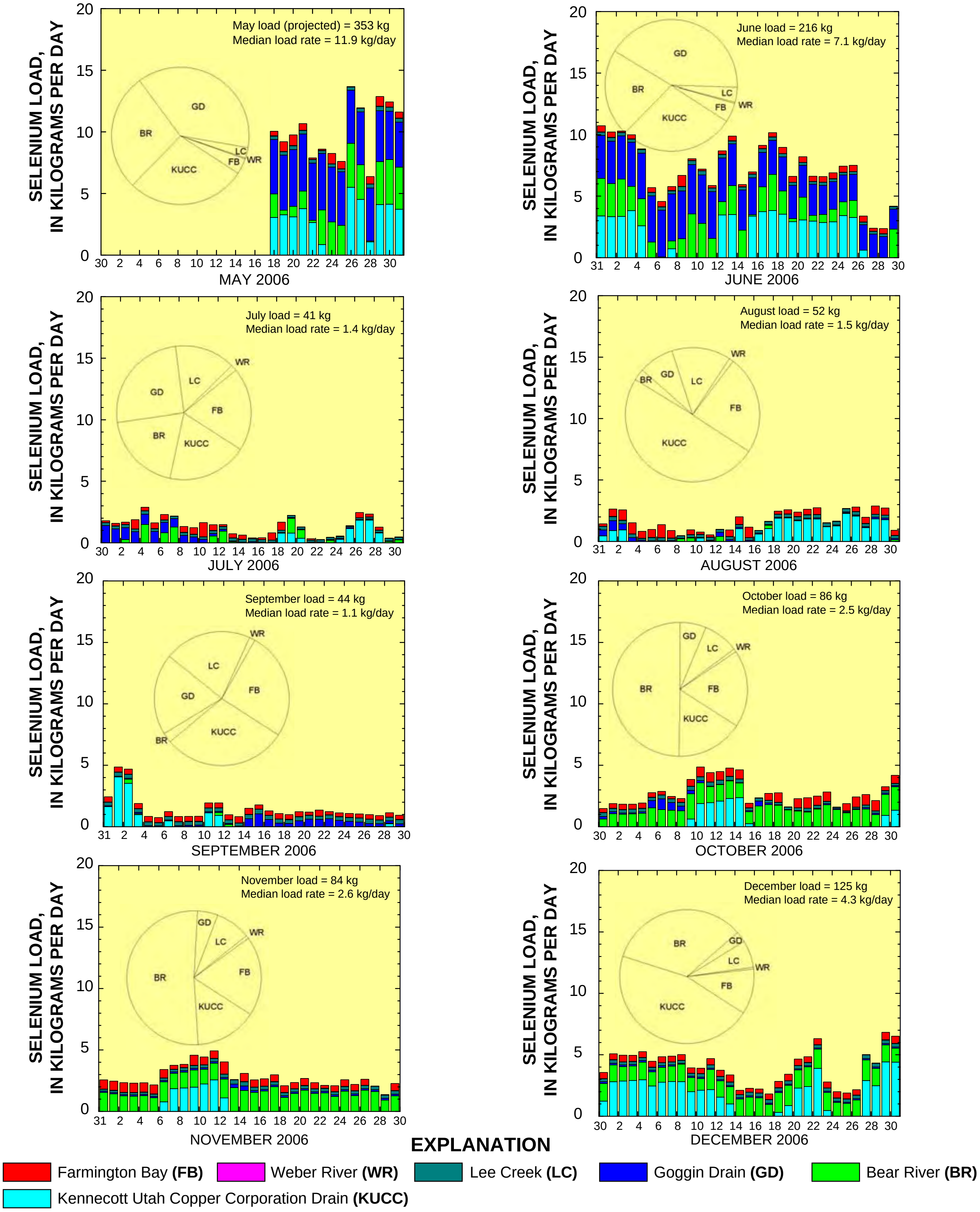

Figure 16. Simulated total (dissolved + particulate) daily selenium loads from May 2006 through March 2008, at the six major inflow sites to Great Salt Lake, Utah. Pie charts indicate relative load contributed by each inflow site.

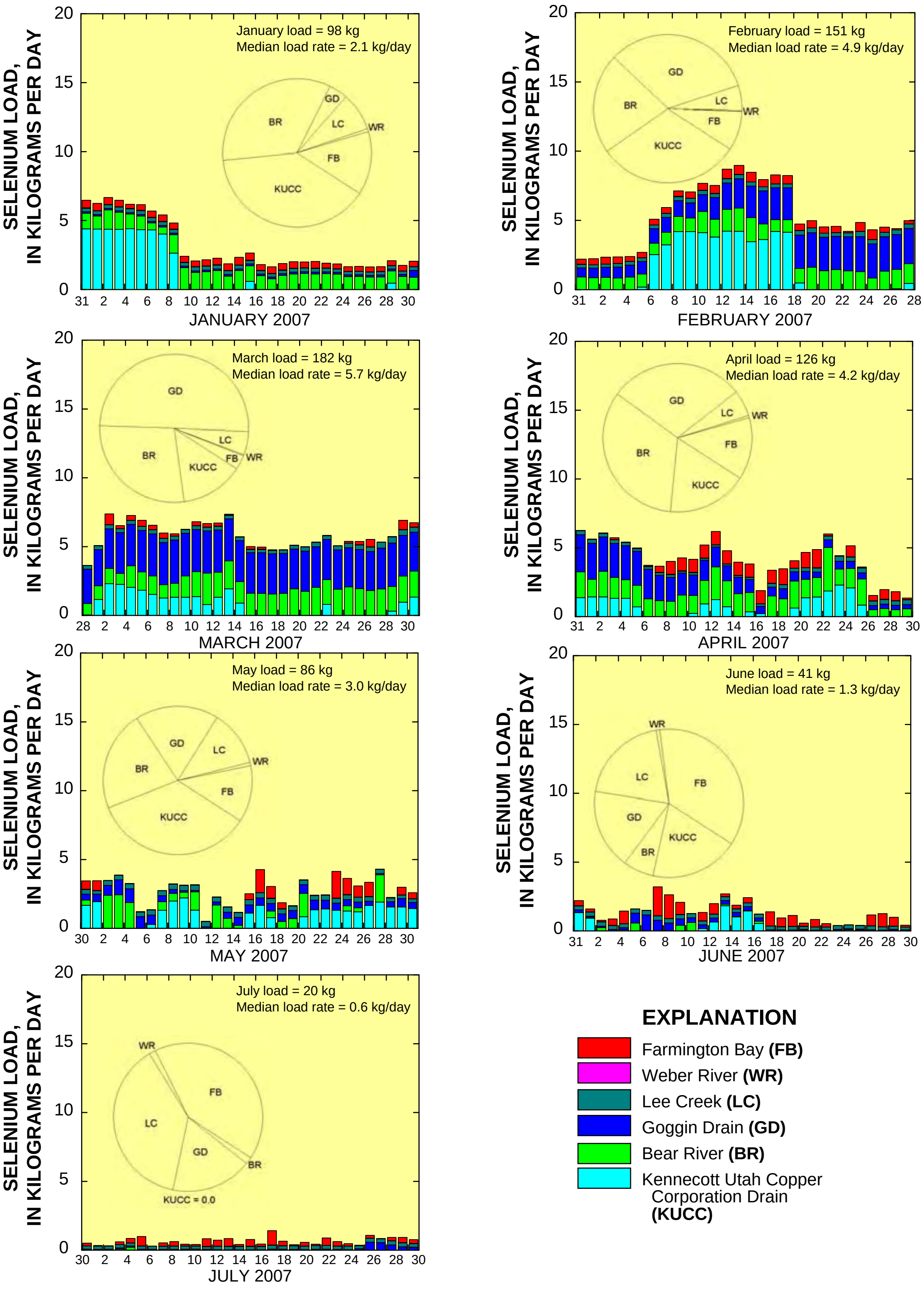

Figure 16. Continued.

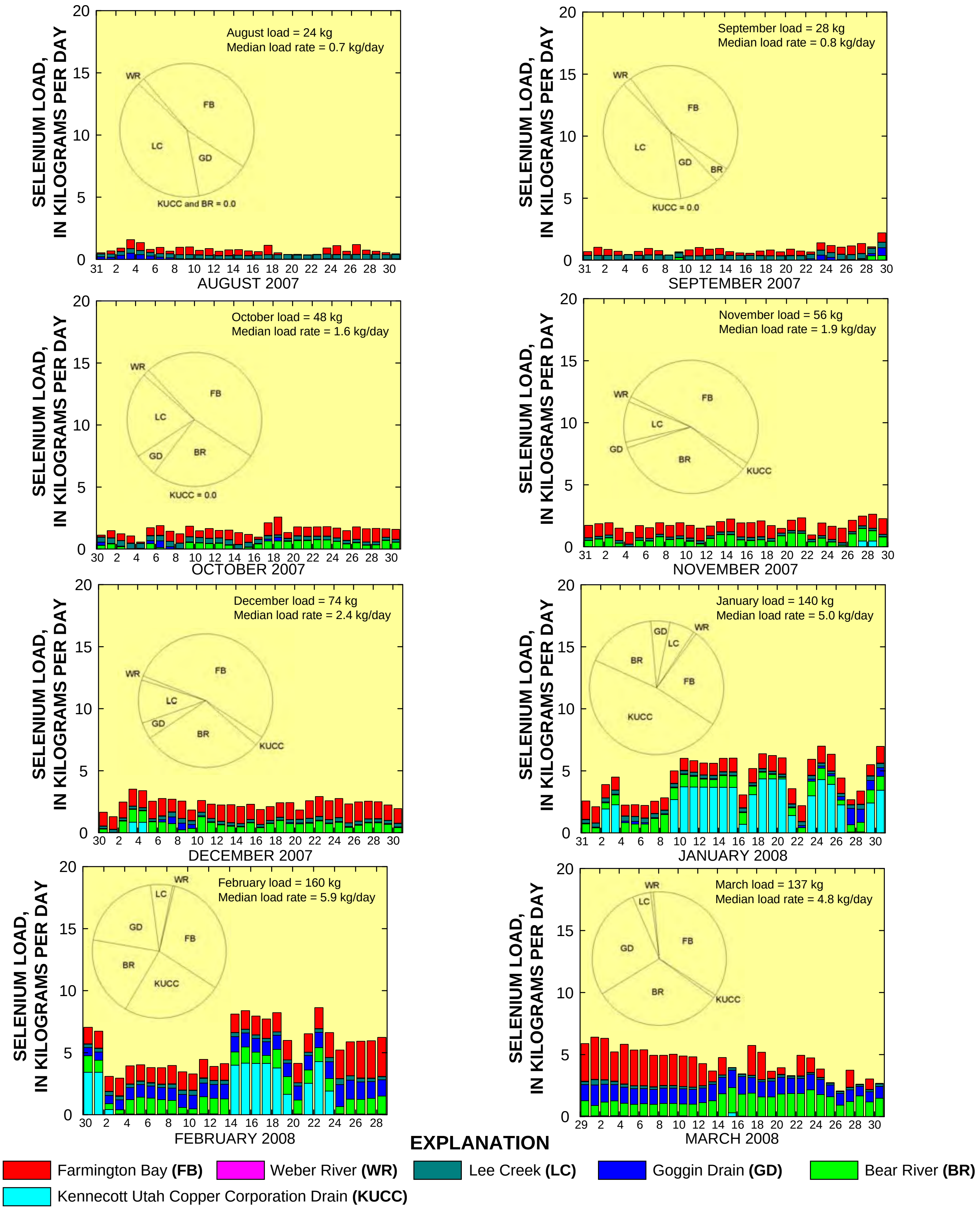

Figure 16. Continued.

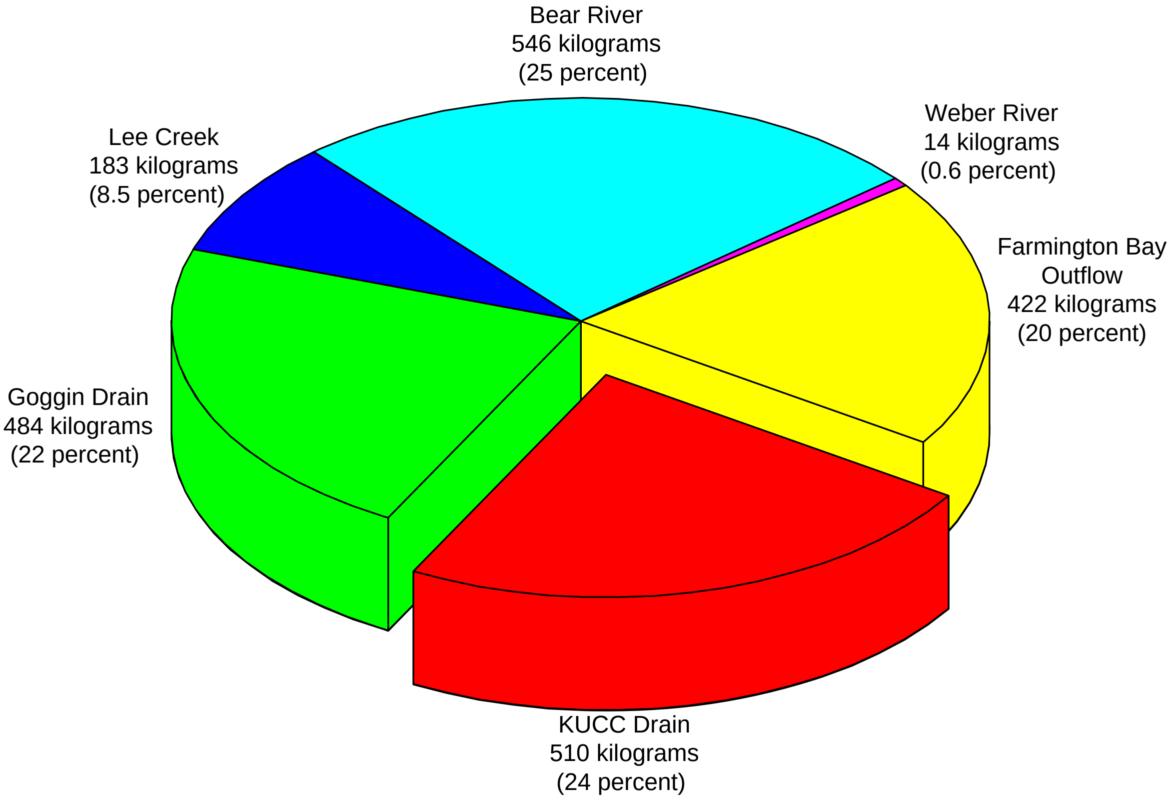

Figure 17. Distribution of total selenium loads contributed to Great Salt Lake, Utah, from each inflow site from May 18, 2006, through March 31, 2008.

Trends in Selenium Loads over Time

Prior to the start of the current study, the USGS operated gages at Lee Creek, Goggin Drain, and KUCC Drain sites. Dissolved (less than 0.45 micron) Se concentration was determined from water samples collected on an intermittent basis from these gage sites from 1972 through 1984. Because of improvements in analytical sensitivity and sample collection procedures, historic trace-element data must be interpreted with caution; however, it is likely that the historic USGS data from these sites are representative of actual Se concentrations and associated loadings. Current (2006–07) loadings from Lee Creek have increased by more than an order of magnitude relative to historic Se loads (fig. 18). Most historic Se loads were less than 0.025 kg/day relative to the median Se load from May 2006 through March 2008 of 0.26 kg/day. Although the historic Se loading data did not measure particulate Se, this would not account for the order-of-magnitude increase that is observed in the 2006–07 Se-load data.

The process(es) causing the increased Se loadings in Lee Creek are unknown. In the 1990s, KUCC stopped diverting water from their mine tailings impoundments into Lee Creek (Hillwalker, 2004). These diversions should have decreased the Se loading to Lee Creek instead of causing the observed increase in 2006 Se loads. It is likely that other processes may be causing the increased Se loadings to Lee Creek. These processes could include canal tailwater input from KUCC Drain to Lee Creek, increases in wastewater-treatment plant effluent, and increased discharge of ground water with elevated Se concentrations to selected stream reaches.

The historic Se load data from the Goggin Drain gage site during low-flow periods compares favorably with current (2006–07) daily Se loads (fig. 19). In contrast, historic Se loads during peak flow periods appear to be about 50 percent lower than current (2006–07) daily Se loads. This trend may be related to an increase in available Se within the contributing watershed to Goggin Drain resulting from increased development over the past 35 years.

The median Se load from the KUCC Drain from 1972 through 1984 was 3.8 kg/day (fig. 20). Comparison of this median Se load value with measured and modeled Se loading data collected from 2005 to 2007 suggest an overall decrease in recent Se loads from the KUCC Drain (fig. 20).

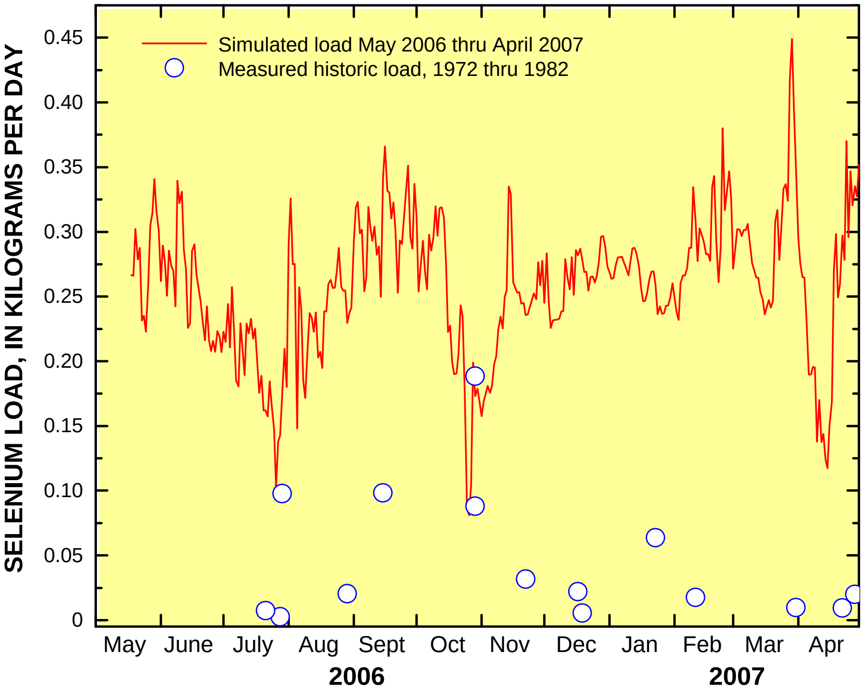

Figure 18. Relation of simulated daily total (dissolved + particulate) selenium loads (May 2006 through April 2007) to measured historic dissolved (less than 0.45 micron) selenium loads (1972 through 1982) at the Lee Creek streamflow-gaging station near Magna, Utah.

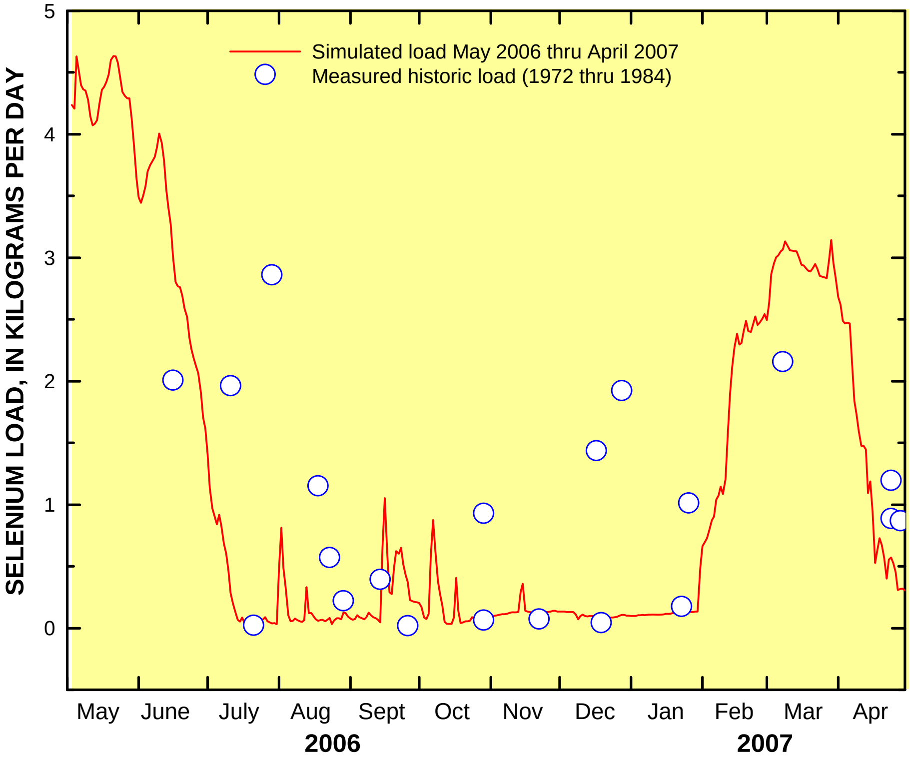

Figure 19. Relation of simulated daily total (dissolved + particulate) selenium loads (May 2006 through April 2007) to measured historic dissolved (less than 0.45 micron) selenium loads (1972 through 1984) at the Goggin Drain streamflow-gaging station near Magna, Utah.

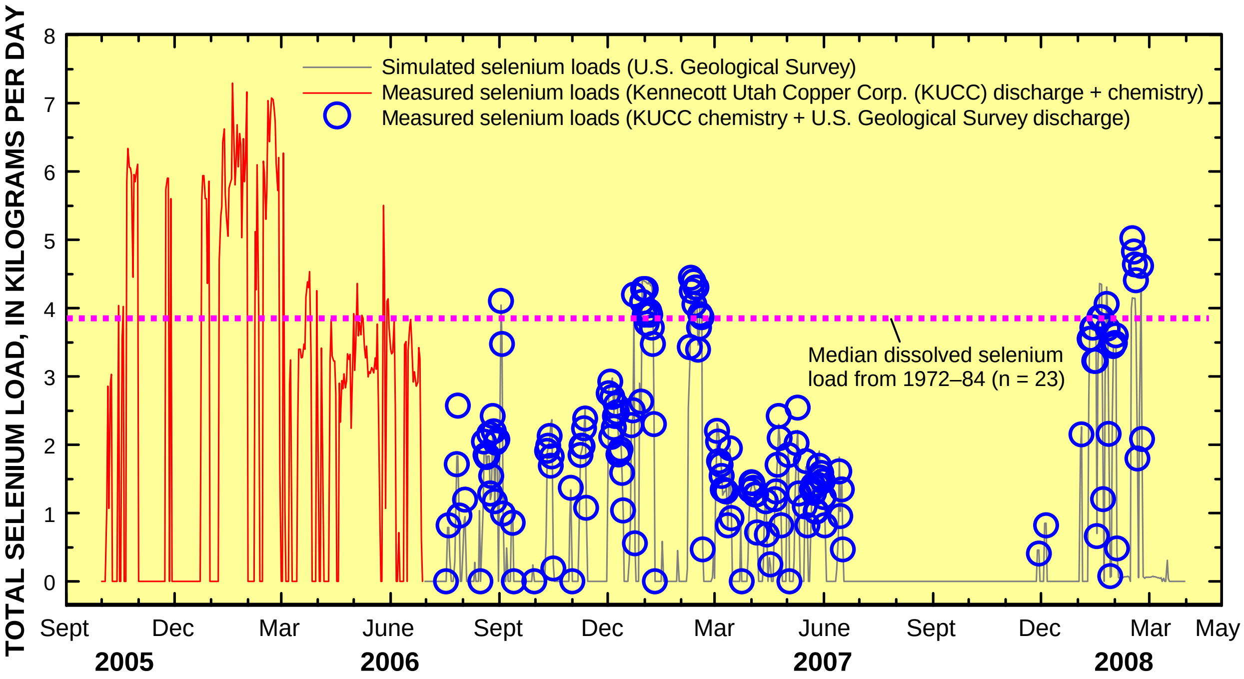

Figure 20. Relation of present day measured and simulated loads of total selenium at the Kennecott Drain streamflow-gaging station near Magna, Utah, to the median dissolved selenium loads measured from 1972 to 1984.

Selenium Concentration and Loads from Miscellaneous Sites

The railroad causeway that separates GSL into a north and a south arm has two culverts (WC and EC) and a breach (CB) that allow water to flow between the two arms (fig. 1). Although permanent streamflow gages are not installed on these openings, instantaneous discharge was measured five times from May 2006 through May 2007 (table 4). Because of the higher salinities present in the north arm of GSL, bidirectional flow in the causeway openings can occur. Unfiltered water samples collected during the discharge measurements were analyzed for total Se (dissolved + particulate) concentration. The instantaneous discharge data were combined with the concentration of Se in the water to calculate the Se load (kg/day) moving into the north arm of GSL (south-to-north flow) and south arm of GSL (north-to-south flow).

During the five measurement periods, a net loss of total Se to the north arm was observed (table 4). The net Se losses were greater than 4.1 kg/day on May 25, 2006; 1.9 kg/day on September 28, 2006; 2.2 kg/day on January 9, 2007; 2.4 kg/day on March 19, 2007; and 1.5 kg/day on May 30, 2007. These data provide a “snapshot” of Se exchange between the north and south arms; however, without a continuous discharge record at each site, an annual estimate of Se exchange cannot be determined. With this qualification, the average annual Se loss from the south to the north arm during the monitoring period would be about 2.4 kg/day. Applying the average daily Se loss to an annual cycle would equate to 880 kg of Se loss to the north arm. This would account for more than 56 percent of the total Se input to the south arm of GSL during an annual loading cycle.

Samples for total Se were collected and analyzed at two additional miscellaneous sites, Morton Salt (MS) and the salt canal at Great Salt Lake Minerals (SC) (fig. 1). The sample collected at the MS site on November 3, 2006, contained a total Se concentration of 0.99 µg/L. Three samples were collected and analyzed for total Se concentration from the SC site. The total Se concentrations in these samples were 0.35 µg/L (May 25, 2006), 1.08 µg/L (September 7, 2006), and less than 0.25 µg/L (December 16, 2006).

The amount of Se load contributed from ground-water inflow as well as dry and wet deposition falling directly on the open waters of GSL was not measured during this study; hence, no selenium loads associated with these potential sources were determined.

Table 4. Instantaneous discharge and associated total (dissolved + particulate) selenium loads measured along the railroad causeway across Great Salt Lake, Utah, from May 2006 through May 2007.

[Location of measurement sites shown in figure 1. **Abbreviations:** kg/d, kilogram per day; <, less than; >, greater than]

Site	Date	Discharge (cubic foot per second)		Selenium load (kg/d)		Net selenium load to Gilbert Bay[2] (kg/d)
		North-to-south	South-to-north	North-to-south	South-to-north[1]	
Causeway breach (CB)	05-25-06	0	3,120	0.00	3.79	3.79
East culvert (EC)		98	294	<.06	.36	> -.30
West culvert (WC)		131	100	.12	.12	.00
Causeway breach (CB)	09-28-06	0	1,380	.00	2.06	-2.06
East culvert (EC)	09-26-06	151	173	.11	.12	.01
West culvert (WC)		234	39	.22	.06	.16
Causeway breach (CB)	01-09-07	0	1,720	.00	2.14	-2.14
East culvert (EC)		92	139	.07	.17	-.10
West culvert (WC)		147	56	<.09	.07	<.02
Causeway breach (CB)	03-19-07	0	1,880	.00	3.00	-3.00
East culvert (EC)		218	158	.46	.25	.21
West culvert (WC)		285	59	.54	.10	.44
Causeway breach (CB)	05-30-07	0	1,560	.00	2.44	-2.44
East culvert (EC)		264	186	.51	.29	.22
West culvert (WC)		464	86	.86	.14	.72

[1] Calculated using unfiltered selenium concentration at 0.2-meter sample depth at site 2565.

[2] Negative value indicates a loss of selenium from Gilbert Bay to the north arm of Great Salt Lake.

Distribution of Selenium Species and Particulate Fractions

Dissolved (less than 0.45 micron) and total Se concentrations were determined from samples collected from inflow sites to GSL during the monitoring period from May 2006 through February 2008. Particulate Se concentration was calculated by subtracting the dissolved Se concentration from the total Se concentration (fig. 21). If the dissolved Se concentration was greater than the total Se concentration, it was assumed that this was caused by analytical variability and the particulate Se concentration was set to 0.0. Most Se in water entering GSL was in the dissolved (less than 0.45 micron) state and the concentration ranged from 0.06 to 35.7 µg/L. Particulate Se concentration entering GSL ranged from ~ 0 to 2.5 µg/L.

Filtered water samples collected during May 2006 and May 2007 were analyzed for selenite (SeO_3^{2-}). The concentration of selenate (SeO_4^{2-}) was then calculated by subtracting the concentration of SeO_3^{2-} from the total dissolved (less than 0.45 micron) Se concentration. With the exception of the KUCC Drain, each inflow site contained a substantial proportion of SeO_3^{2-}, which averaged 21 percent of the total dissolved Se concentration during the two monitoring periods. (fig. 22). Although the KUCC Drain discharge contained greater than 35 µg/L total dissolved Se in May 2006 and greater than 20 µg/L in May 2007, less than 5.1 percent was present as SeO_3^{2-}.

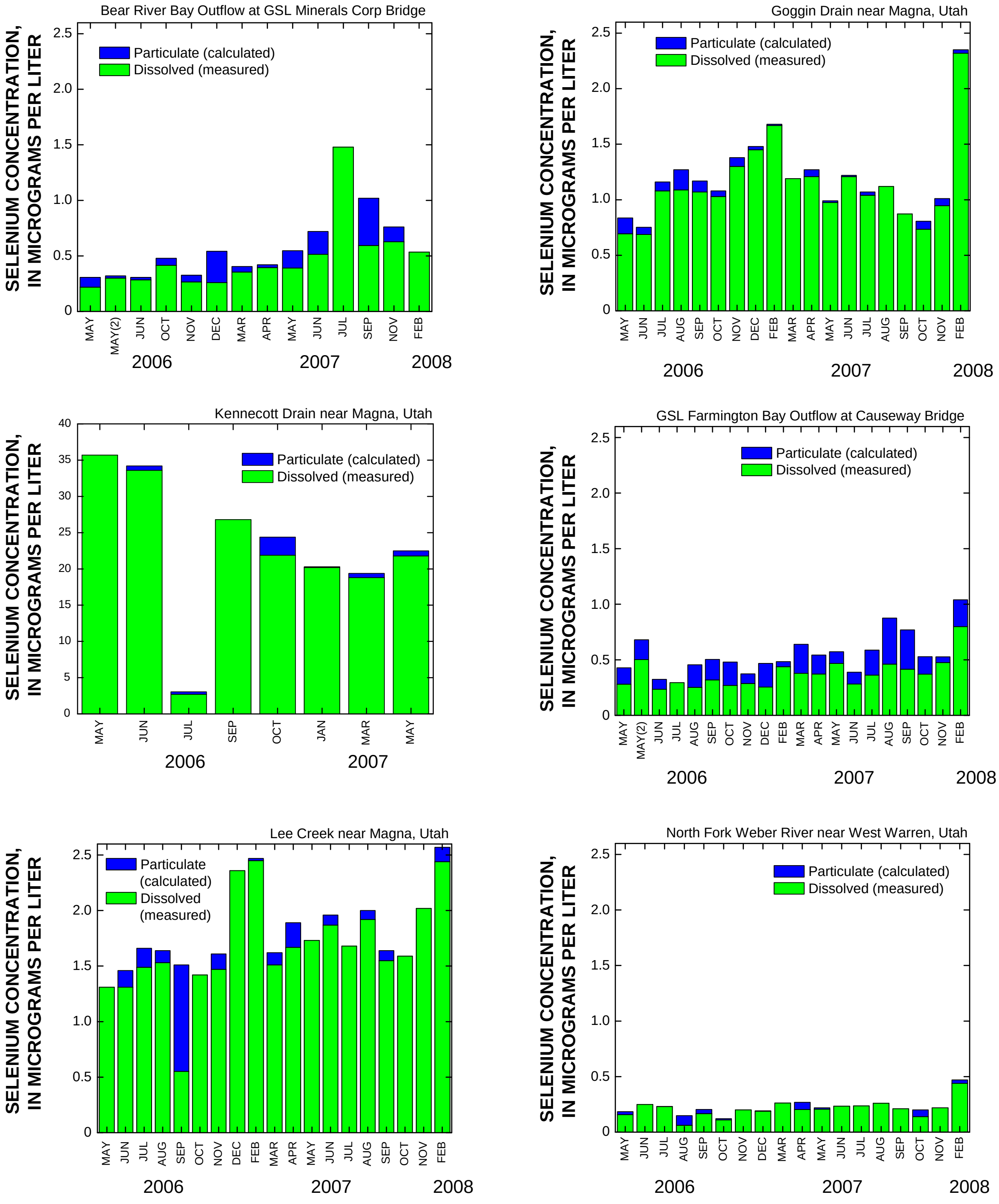

Figure 21. Distribution of dissolved and particulate selenium in water samples collected from inflow sites to Great Salt Lake during May 2006 through February 2008. Note the difference in scale for the KUCC Drain in comparison to other sites. Abbreviation: GSL, Great Salt Lake.

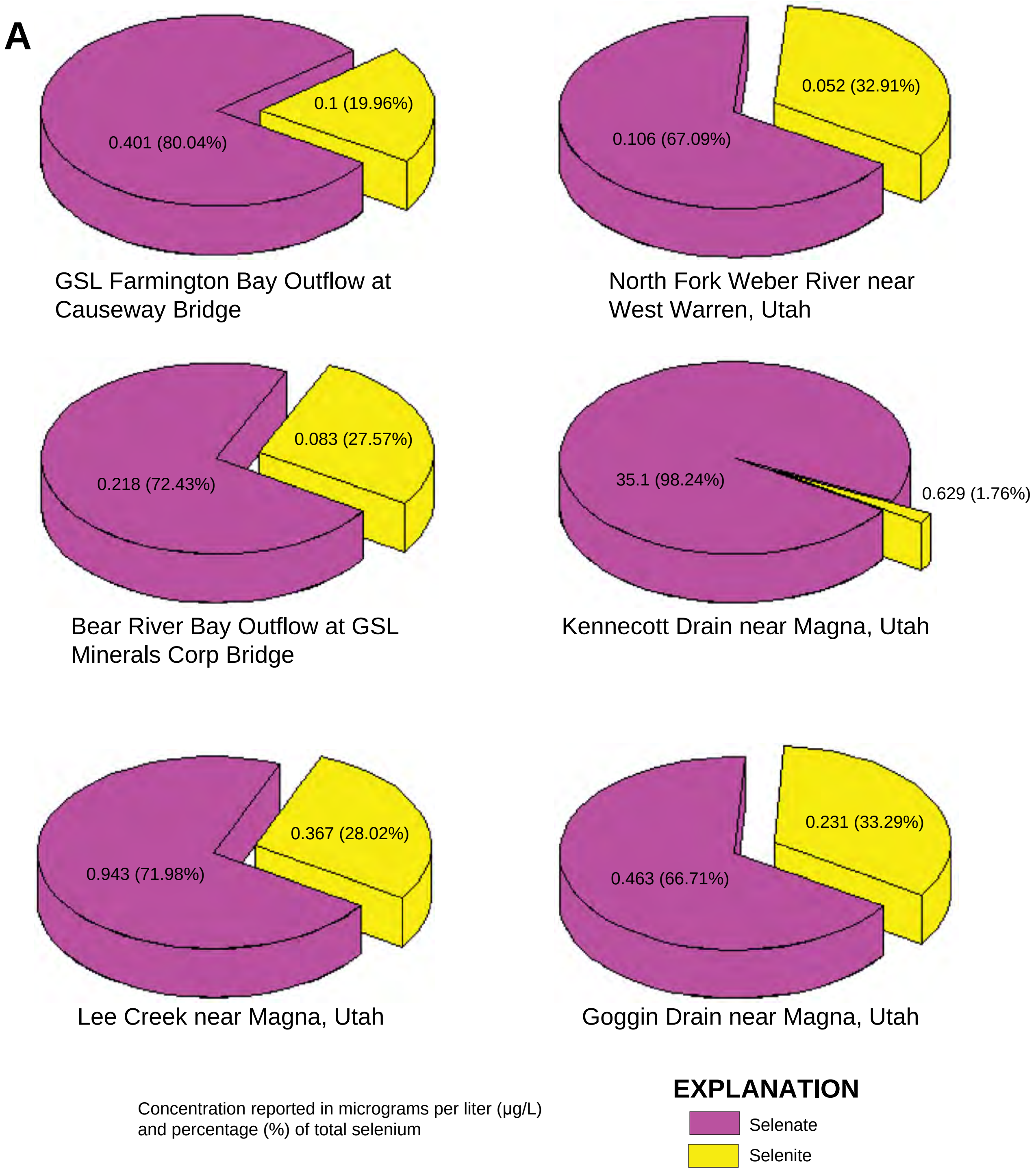

Figure 22. Distribution of selenate and selenite in filtered (less than 0.45 micron) water samples collected from inflow sites to Great Salt Lake, Utah, during May 2006 (*A*) and May 2007 (*B*).

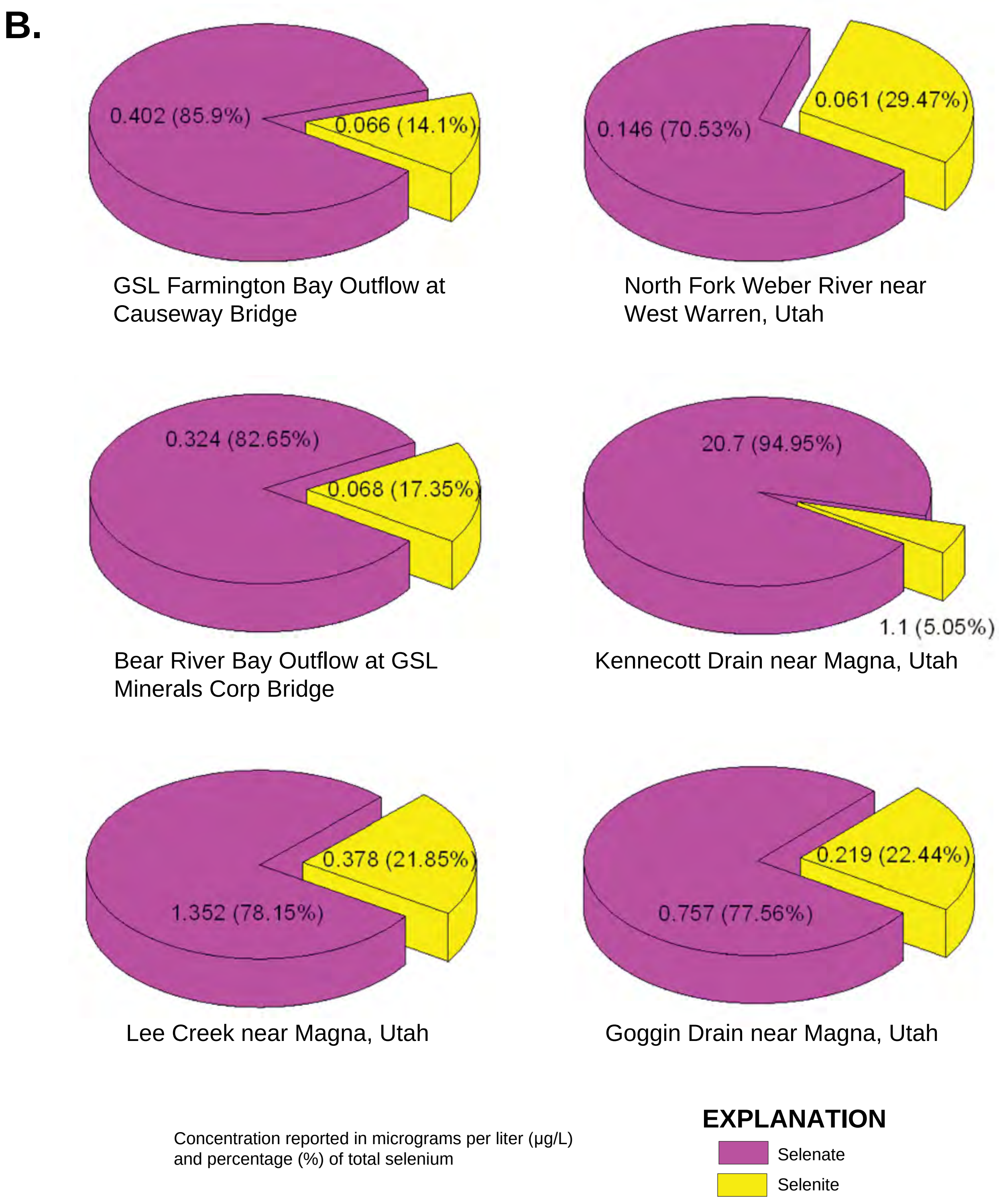

Figure 22. Continued.

Effects of Selenium Loads to Observed Selenium Concentrations in Great Salt Lake

The loading data collected throughout a 23-month period indicate that about 2,370 kg of total (dissolved + particulate) Se entered the south arm of GSL. Concurrent lake monitoring during part of the 23-month time period, was used to collect water samples from 4 sampling sites in the south arm of GSL (fig. 1). The Se concentration in water samples collected from GSL during a 16-month monitoring period from May 2006 through August 2007 were used to understand how the cumulative Se load was being processed by various biogeochemical processes within the lake. Changes in dissolved (less than 0.45 micron) and total Se concentration at the four monitoring sites (2267, 2565, 2767, and 3510) from May 2006 through August 2007 indicate an increasing concentration with time (fig. 23). The correlation coefficient (R) for the linear regression line through the filtered (less than 0.45 micron) water samples ranged from 0.49 ($p = 0.08333$, $n = 12$) at site 3510 to 0.85 ($p = 0.0002$, $n = 13$) at site 2767. The two shallow monitoring sites of 2267 and 2767 (total water depth less than 5 m) have the highest correlation coefficients indicating a statistically significant trend of increasing dissolved Se concentration concurrent with the measured riverine loads of Se.

The dissolved + particulate Se data exhibited similar trends to those of the filtered Se data (fig. 23). The correlation coefficient (R) for the linear regression line through the unfiltered (dissolved + particulate) water samples ranged from 0.39 ($p = 0.17166$, $n = 14$) at site 2767 to 0.50 ($p = 0.0085$, $n = 27$) at site 2267.

The Mann-Kendall statistical test (Helsel and Hirsch, 1992) was applied to the Se data from filtered (less than 0.45 micron) water samples collected from the monitoring sites in GSL to determine if the occurrence of increasing concentrations over time was statistically significant. The Mann-Kendall test is a non-parametric test that is suitable for censored data sets. The test was done at both the 95- and 90-percent confidence levels. The Z score calculated for each data set was compared to the expected Z score at both the 95- and 90-percent confidence levels. If the calculated Z score exceeded the expected Z score, the occurrence of an upward trend in Se concentration with time was indicated.

Results of the Mann-Kendall statistical analysis for the Se data collected from sites 2267, 2565, 2767, and 3510 are summarized in table 5. Statistically significant upward trend in dissolved (less than 0.45 micron) Se concentration was indicated at all four sites at the 90-percent confidence level (table 5). In addition, the upward trend in dissolved (less than 0.45 micron) Se concentration over the 16-month monitoring period was statistically significant at the 95-percent confidence level for 3 of the 4 sites 2267, 2767, and 2565.

A potential contributing source of variance in the observed increases in Se concentration over time could be associated with analytical error. To address the analytical error, a series of laboratory replicates of water samples collected from GSL were analyzed throughout the 16-month monitoring period. The Se concentration measured in 15 laboratory replicates was compared to the dissolved (less than 0.45 micron) Se concentration in the corresponding routine water sample (fig. 24). Results of these comparisons indicated that the mean difference between the routine and replicate samples was +15 percent. Elimination of the clear outlier from this data set resulted in a mean difference of +12 percent. On the basis of similar Se concentration between the routine and replicate samples, it is clear that laboratory error could not explain the observed dissolved (less than 0.45 micron) Se concentration increases that ranged from 0.21 to 0.33 µg/L during the 16-month monitoring period.

The observed net increase in dissolved + particulate Se observed from May 2006 through August 2007 at each lake monitoring site was compared to the Se concentration increase expected from the cumulative Se mass added during the same time period for both dissolved (less than 0.45 micron) and total (dissolved + particulate) Se in water. For the purpose of the following calculations, the biogeochemical behavior of Se in GSL is assumed to be conservative, which is certainly not the case, but provides a useful “worst case” end point to evaluate the impacts of annual Se loads to the open-water of GSL. The non-conservative behavior of Se in GSL is evidenced from the sediment core records and the gaseous Se flux measured from the lake surface (Diaz and others, 2009; Oliver and others, in press).

Based on the regression models for each lake monitoring site, the net change in dissolved (less than 0.45 micron) Se concentration ranged from 0.21 to 0.33 µg/L and the net change in total (dissolved + particulate) Se concentration ranged from 0.15 to 0.25 µg/L (table 6). Mixing the cumulative riverine Se input (dissolved + particulate) over the same 16-month monitoring period with the lake volume of the south arm of GSL measured on August 31, 2007 (Baskin 2005), the expected net increase in Se concentration would be 0.20 µg/L. This expected net increase in open-water Se concentration is approximately equal to the average net change of 0.19 µg/L in total (dissolved + particulate) Se observed at the four GSL monitoring sites during the 16-month monitoring period (table 6). A larger net change in dissolved (less than 0.45 micron) Se, averaging 0.26 µg/L, is observed at the four GSL monitoring sites during the 16-month monitoring period, suggesting resolution of particulate (>0.45 micron) Se in GSL.

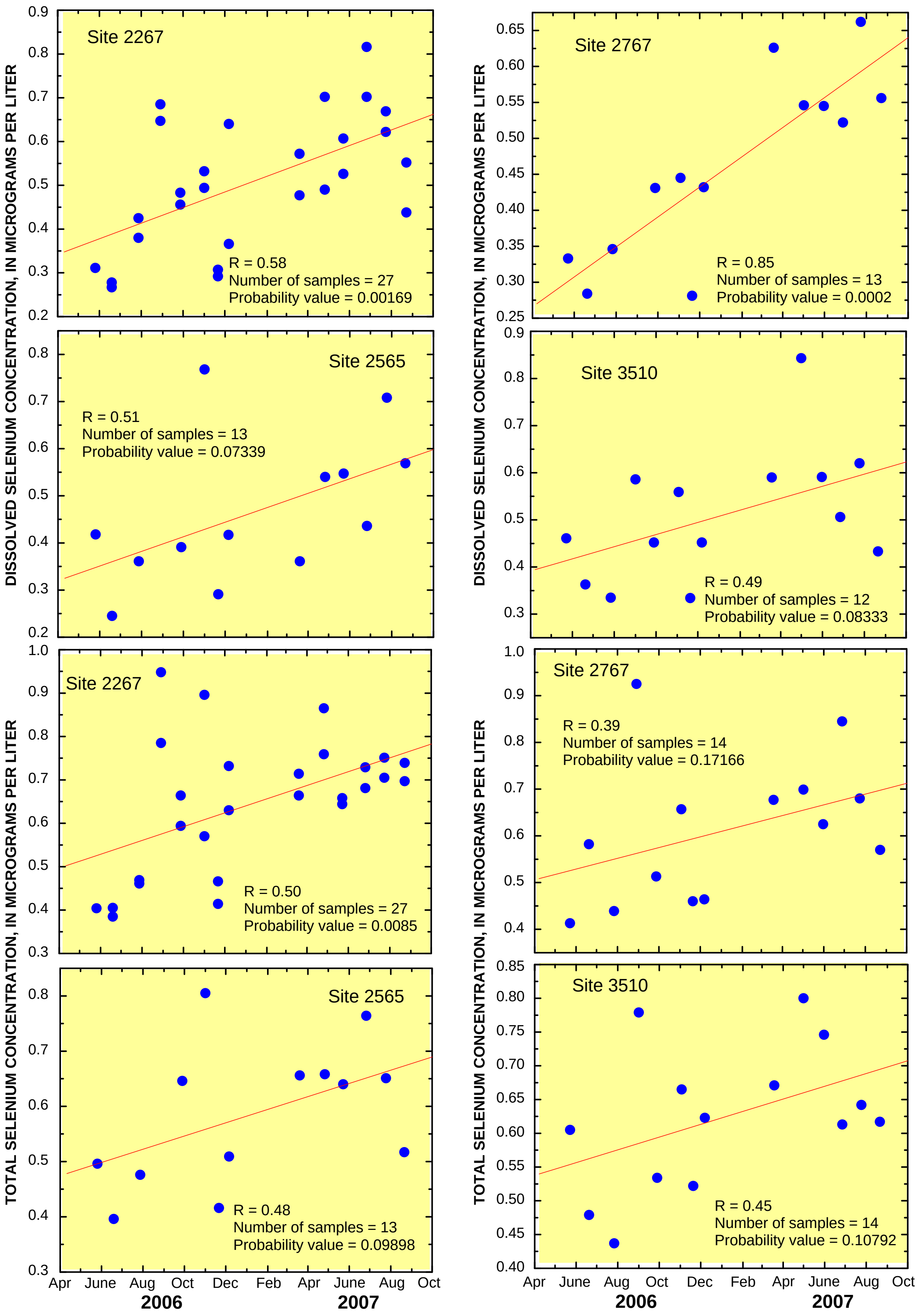

Figure 23. Trends in dissolved (less than 0.45 micron) selenium concentration and total selenium concentration at open water sites, Great Salt Lake, Utah, May 2006 through August 2007.

Table 5. Summary of Mann-Kendall statistical trend analysis conducted on water samples analyzed for dissolved selenium, Great Salt Lake, Utah.

Site identification No.	Sample		Number of samples	Z score		Occurrence of upward trend in concentration	
	Depth (meters)	Date range		Calculated	Expected at 95-percent confidence level	95-percent confidence level	90-percent confidence level
2267	0.2	May 2006–August 2007	14	2.2993	1.6546	Yes	Yes
2767	.2	May 2006–August 2007	13	2.8674	1.6546	Yes	Yes
3510	.2	May 2006–August 2007	14	1.3707	1.6546	No	Yes
2565	.2	May 2006–August 2007	13	2.0782	1.6546	Yes	Yes

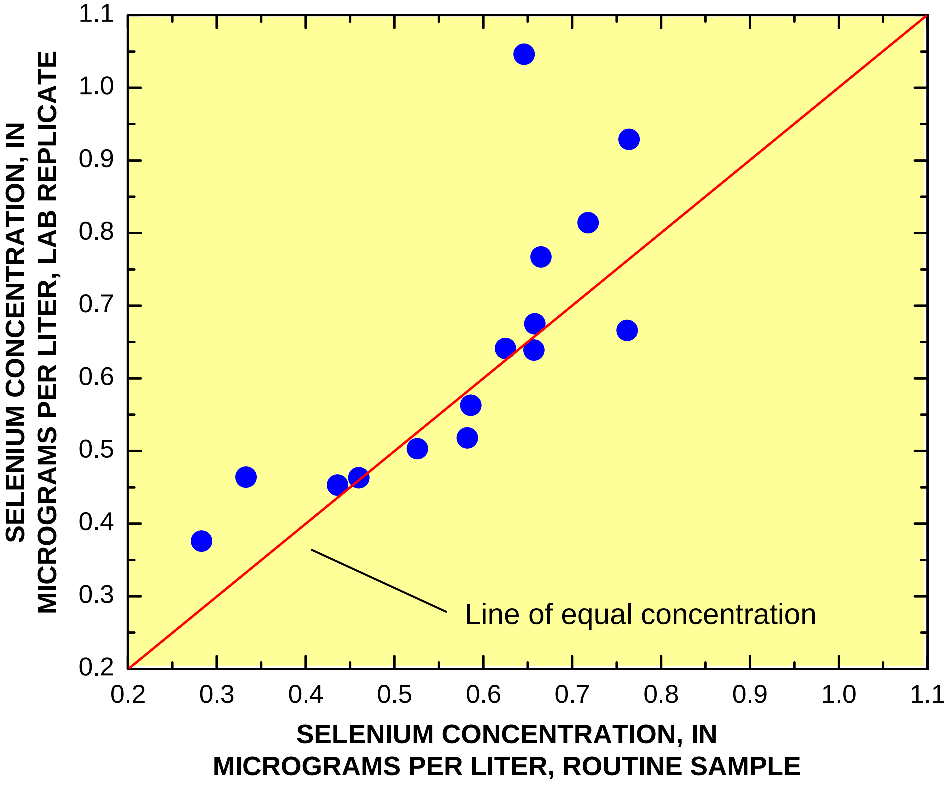

Figure 24. Relation of dissolved (less than 0.45 micron) selenium concentration in laboratory replicates to routine samples collected from near-surface depths at sites 2267, 2767, 2565, and 3510 in Great Salt Lake, Utah, from May 2006 through August 2007. The mean difference between routine and replicate samples is +/-15 percent (n = 15). Elimination of the outlier results in a mean difference of +/-12 percent (n = 14). Abbreviation: n, number.

Table 6. Simulated and measured increase in selenium concentration from riverine inputs at four lake sites in Great Salt Lake, Utah, from May 1, 2006, through August 31, 2007.

[**Selenium concentration** determined from regression model developed from site-specific monitoring data collected from May 2006 through July 2007. **Abbreviations:** μg/L, microgram per liter]

Site	Selenium concentration (μg/L)				Net change in selenium concentration during monitoring period[1] (μg/L)		Net change in open water selenium concentration, based on selenium input from May 15, 2006 to July 31, 2007[2]
	May 1, 2006		August 31, 2007				
	Dissolved	Total	Dissolved	Total	Dissolved	Total	
2767	0.29	0.52	0.62	0.70	+0.33	+0.18	+0.20
2267	0.37	0.51	0.64	0.76	+0.27	+0.25	+0.20
3510	0.40	0.55	0.61	0.70	+0.21	+0.15	+0.20
2565	0.33	0.49	0.58	0.67	+0.25	+0.18	+0.20

[1] Net change in selenium concentration during monitoring period May 15, 2006 through August 31, 2007.

[2] Net change in open water selenium concentration calculated by dividing total mass of riverine selenium (dissolved + filtered) input to Great Salt Lake from May 1, 2006 to August 31, 2007 (1,729 kilograms) by measured lake volume on August 31, 2007 of 8.84×10^{12} liters (Baskin, 2005).

Given the large amount of Se removal from GSL of greater than 1,900 kg/year by gaseous flux and permanent sedimentation (Diaz and others, 2009; Oliver and others, in press), the observed increase in both dissolved (less than 0.45 micron) and total (dissolved + particulate) Se indicates an additional, unquantified source(s) of Se are contributing substantial (>1,900 kg/year) masses of Se load to the south arm of GSL over the 16-month monitoring period. If Se export to the north arm is considered, the unquantified source contribution could be substantially higher. Potential source(s) of this additional Se load could include (1) Se loads entering GSL from unmeasured surface inflows, (2) ground-water discharge to GSL, (3) wind-blown dust that is deposited directly on the lake surface, (4) wet and dry atmospheric deposition falling directly on the lake surface, and (5) lake sediment pore water diffusion into the overlying water column. Additional supporting information regarding additional Se loads and concentration from a few of the unmeasured sources and processes listed previously is presented in the subsequent material. This supporting information was limited to the unmeasured sources and processes where site-specific supporting data were available (1) unmeasured surface inflows and (2) ground-water discharge to GSL.

The cumulative Se load to GSL contributed by the Weber River inflow may not have been measured during this study. Because of multiple diversion structures, flow in the Weber River is extensively diverted downstream of USGS gage site 10141000 (Weber River near Plain City, Utah) (fig. 1). The total discharge from May 11, 2006, through August 31, 2007, measured at Weber River near Plain City (upstream) was about 6.8 times larger than the total discharge measured at Weber River near West Warren, Utah (downstream gage monitored for Se load to GSL) during the same time period. Assuming that all the water flow measured at the upstream gage discharged to the open water of GSL (worst case scenario) and that this additional surface-water discharge had a similar Se concentration to what was measured at the downstream gage, an additional Se load of 49 kg was calculated for the 16-month monitoring period. This additional Se load of 49 kg is inconsequential relative to the potentially unmeasured Se load of greater than 1,900 kg/year.

The potential for ground-water discharge to GSL was assessed with a preliminary electrical resistivity survey conducted by the USGS in September 2007 along the southerly shoreline of GSL similar to work described by Cross (2006 and 2008). The electrical resistivity survey was designed to utilize a 50-m string of electrodes that was towed behind a boat to view areas of higher-resistivity (less-saline) water in the near-surface sediments underlying the lower-resistivity (highly saline) water in the south and east sides of GSL (fig. 25). Although additional follow-up work is needed for verification, higher-resistivity zones were detected that could indicate areas of less-saline, ground-water discharge to GSL and corresponding unmeasured Se loads to the open water of GSL. For example, regions of higher- and lower-resistivity were observed in the near-surface sediments on the south end of GSL (figs. 26 and 27). The higher-resistivity zones indicate potential areas of ground-water discharge that may justify the installation of nested piezometers to measure the shallow ground-water gradient and associated Se flux from these regions to the open water of GSL.

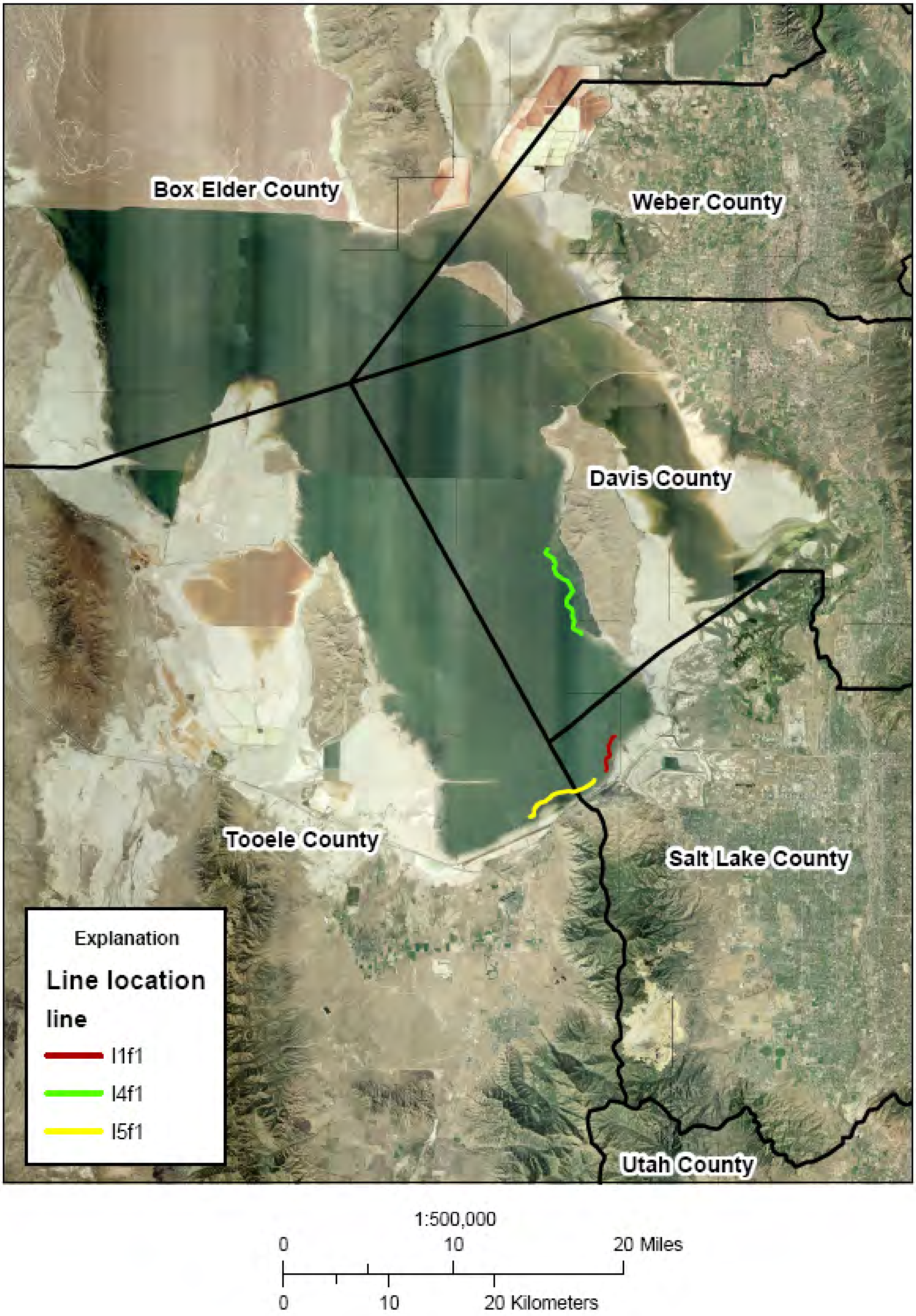

Figure 25. Location of continuous electrical resistivity survey profiles of Great Salt Lake, Utah, obtained during September 2007.

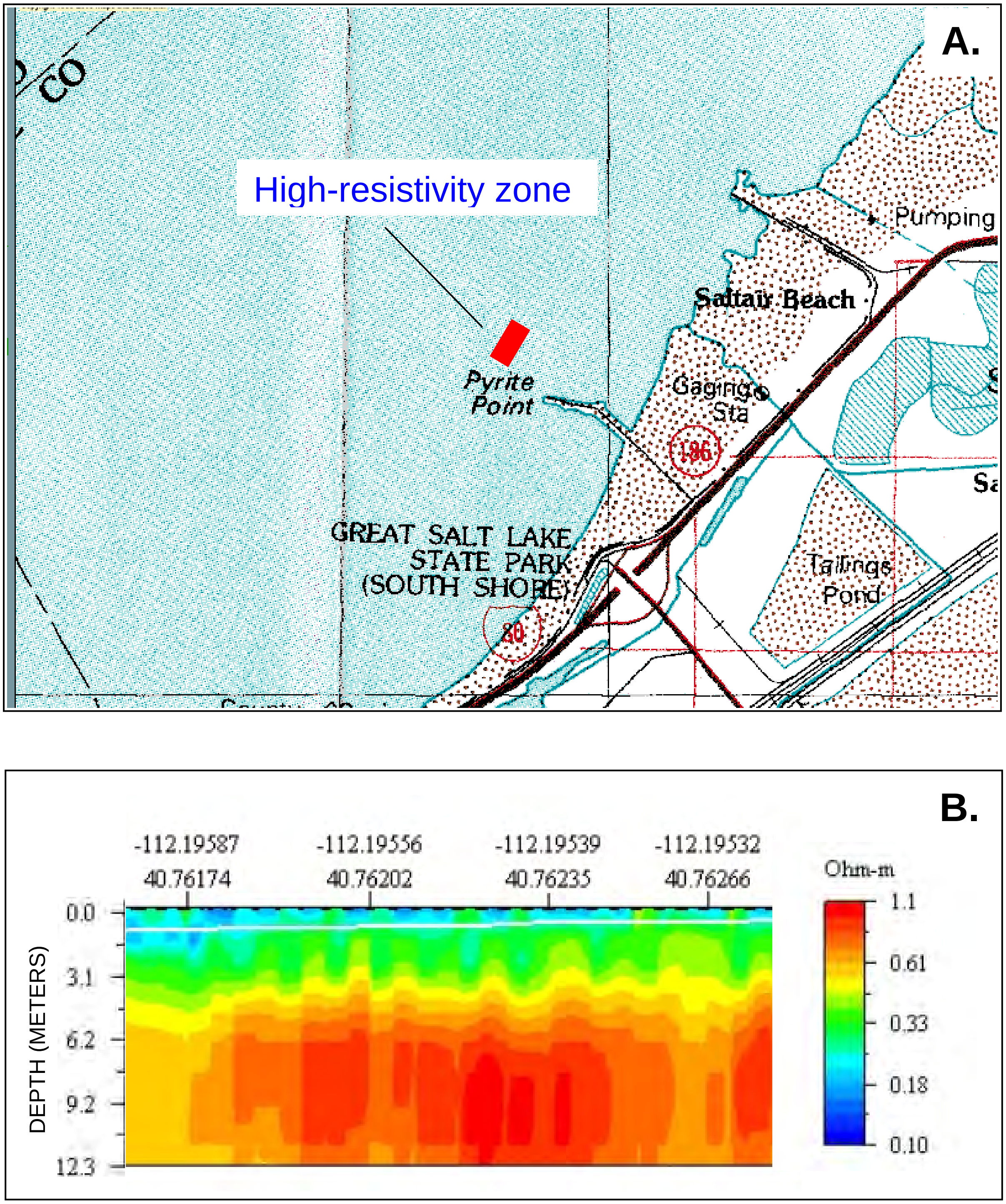

Figure 26. Location of a higher-resistivity zone along (*A*) transect I1f1, Great Salt Lake, Utah, and (*B*) cross section of electrical resistivity values. White horizontal line on electrical resistivity cross section denotes approximate position of surface water/sediment interface.

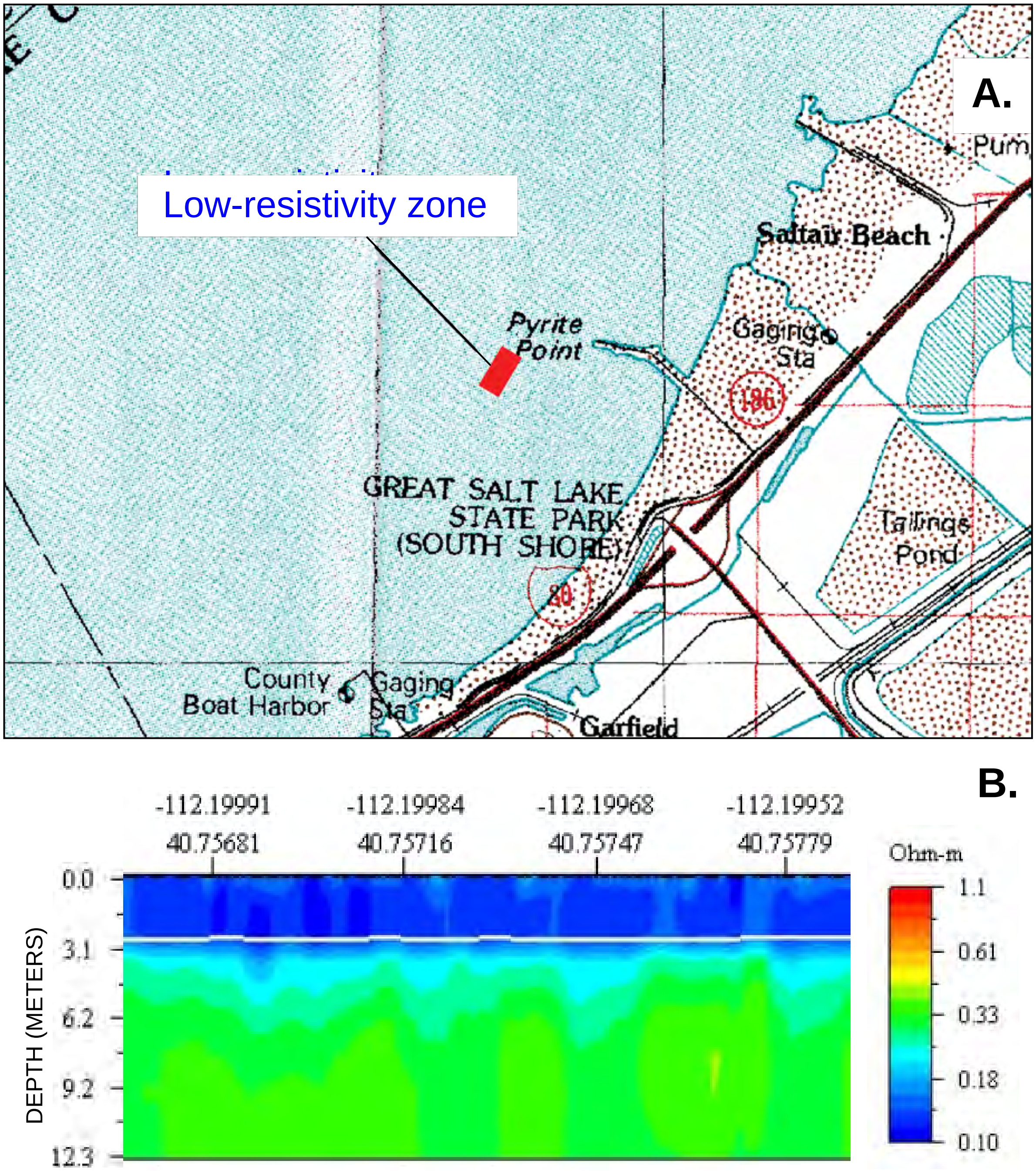

Figure 27. Location of low-resistivity zone along transect (*A*) I1f1, Great Salt Lake, Utah, and (*B*) cross section of electrical resistivity values. White horizontal line on electrical resistivity cross section denotes approximate position of surface water/sediment interface.

Previous work (Kennecott Utah Copper Corporation, unpub. data, 1999) documented elevated (exceeding 10,000 µg/L) Se concentration in ground water beneath KUCC smelter and refinery facilities within 1.5 km of the south shore of GSL (fig. 28). Ground-water modeling of this contaminant plume has indicated minimal discharge to GSL (Kennecott Utah Copper Corporation, unpub. data, 1999); however, no ground-water monitoring data have been collected beneath GSL to verify the ground-water modeling results. Based on KUCC estimates, total water volume in the contaminant plume may exceed 7.9 X 10^7 cubic meters (m^3) and contain a Se concentration ranging between 50 and 17,000 µg/L. Assuming that 30 percent of the contaminant plume eventually discharged to GSL and the plume contained an average Se concentration of 8,500 µg/L, this would represent a Se mass of 208,000 kg. This Se mass would represent more than 130 years of cumulative annual Se loads measured during the current study. Without monitoring data beneath GSL, the Se load to the open water associated with potential ground-water source(s) cannot be assessed.

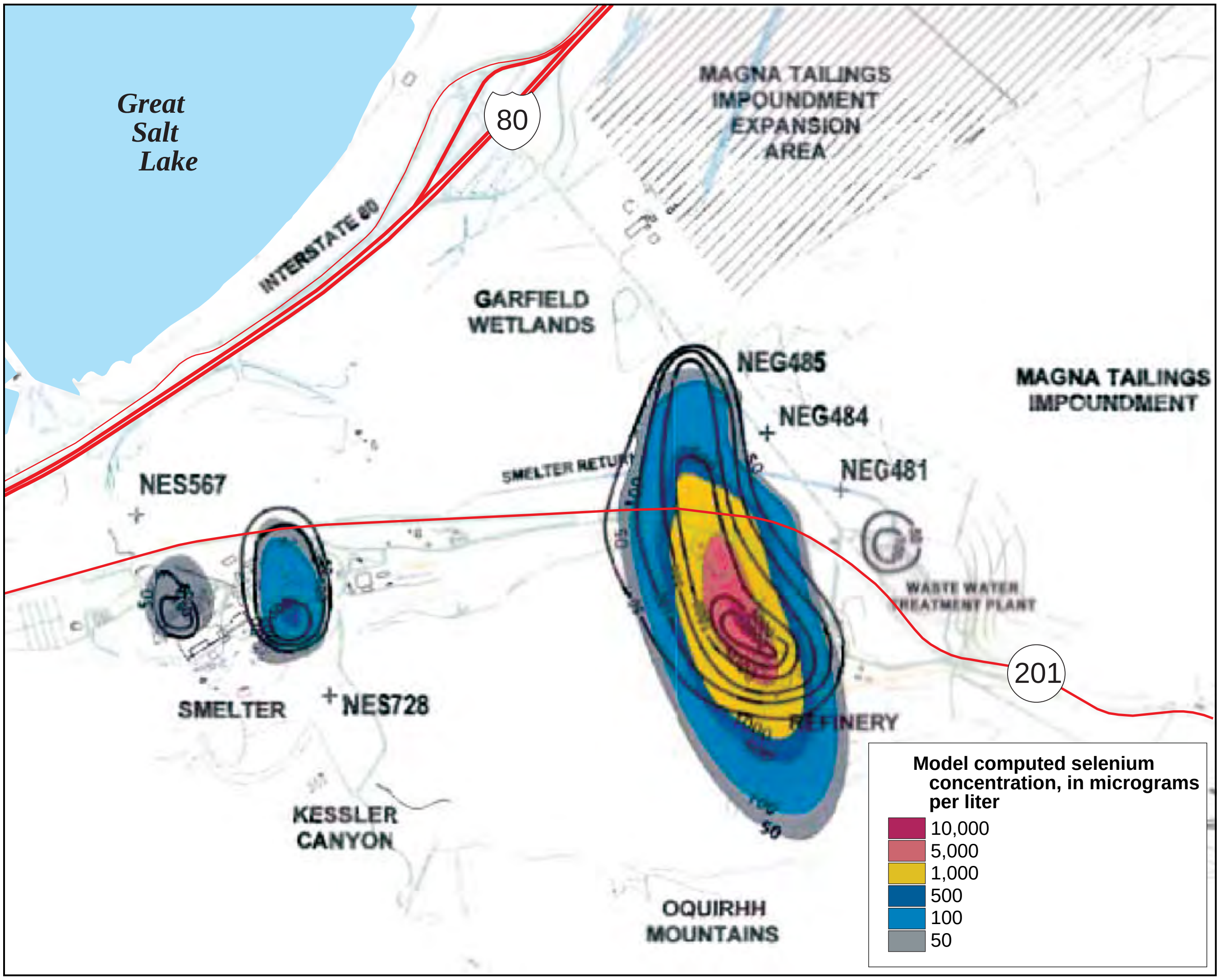

Figure 28. Predicted and observed extent of ground-water contaminant plume containing elevated concentrations of selenium located on the south margin of Great Salt Lake, Utah (Kennecott Utah Copper Corporation, unpub. data, 1999).

Summary

In response to increasing public concern regarding Se input to the GSL ecosystem, UDEQ/DWQ initiated coordinated studies with the USGS and University of Utah to quantify and evaluate the significance of current and future inputs of Se to GSL. Discharge and water-quality data collected from six streamflow-gaging stations were used in combination with the LOADEST software to provide an estimate of total (dissolved + particulate) Se load to the south arm of GSL from May 2006 through March 2008. The six USGS gages used for the Se loading calculations include (1) Bear River Bay Outflow at GSL Minerals Corp Bridge (site BR); (2) North Fork Weber River near West Warren, Utah (site WR); (3) Goggin Drain near Magna, Utah (site GD); (4) Lee Creek near Magna, Utah (site LC); (5) Kennecott Drain near Magna, Utah (site KUCC); and (6) GSL Farmington Bay Outflow at Causeway Bridge (FB). Because of the low channel gradients and wind influence on inflow rates, hydroacoustic equipment in combination with velocity index methods were used to accurately gage discharge at the KUCC, FB, and BR gage sites. Discharge data can be accessed at: http://waterdata.usgs.gov/ut/nwis/sw. Measured Se loads from the flooding of near-shore sediments during annual water-level increases were small (about 10 kg) and not considered significant relative to the measured surface-water loadings.

Total estimated Se load to GSL during the 23-month monitoring period was 2,370 kg. The 12-month estimated Se load to GSL for the time period from May 1, 2006, to April 30, 2007, was 1,560 kg. The largest cumulative monthly Se load occurred during May 2006 (353 kg) and the smallest cumulative monthly load occurred during July 2007 (20 kg). During the 23-month monitoring period, inflows from the KUCC Outfall and Bear River contributed equally to the largest proportion of total Se load to GSL, accounting for 49 percent of the total Se load. Current (May 2006 through March 2008) median Se loadings from Lee Creek (0.26 kg/day) have increased by more than an order of magnitude relative to historic Se loads (less than 0.025 kg/day) calculated from data collected during 1972–84. Historic Se loads during peak flow periods (1972–84) for the Goggin Drain outflow site were about 50 percent lower than current (2006–07) daily Se loads during peak runoff periods.

Five instantaneous discharge measurements at three sites along the railroad causeway indicate a consistent net loss of Se mass from the south arm to the north arm of GSL (mean = 2.4 kg/day, n = 5). Application of the average daily loss rate equates to annual Se loss rate to the north arm of 880 kg (56 percent of the annual Se input to the south arm); however, without continuous measurement of discharge, the error associated with this annual loss estimate is high. The majority of Se in water entering GSL is in the dissolved (less than 0.45 micron) state and ranges in concentration from 0.06 to 35.7 µg/L. Particulate Se concentration ranged from less than 0.05 to 2.5 µg/L. Except for the KUCC Drain gage site, dissolved (less than 0.45 micron) inflow samples averaged 21 percent selenite (SeO_3^{2-}) during two sampling events (May 2006 and 2007).

Selenium concentration in water samples collected from four monitoring sites within GSL during from May 2006 through August 2007 were used to understand how the cumulative Se load was being processed by various biogeochemical processes within the lake. On the basis of Mann-Kendall test results, changes in dissolved Se concentration at the four monitoring sites indicate a statistically significant (90-percent confidence interval) upward trend in Se concentration with time. Furthermore, the upward trend at three of the four GSL sites also was significant at the 95-percent confidence interval. Regression models for each lake monitoring site indicated a net change in total and dissolved (less than 0.45 micron) Se concentration that ranged from 0.15 to 0.33 µg/L during the 16-month monitoring period. The net increase expected from measured riverine Se influx (without accounting for sedimentation and gas losses) over the same monitoring period was +0.20 µg/L. Given the large amount of Se removal from GSL of greater than 1,900 kg/year by gaseous flux and permanent sedimentation, the observed increase in both dissolved (less than 0.45 micron) and total (dissolved + particulate) Se in the open-water monitoring sites indicates additional, unquantified source(s) of Se are contributing substantial masses of Se load to the south arm of GSL over the 16-month monitoring period. Potential source(s) of this unmeasured Se load could include (1) Se loads entering GSL from unmeasured surface inflows, (2) ground-water discharge to GSL, (3) wind-blown dust that is deposited directly on the lake surface, (4) wet and dry atmospheric deposition falling directly on the lake surface, and (5) lake sediment pore water diffusion into the overlying water column.

Processes and sources of additional Se loads and Se concentration from the unmeasured sources and processes identified during the study were further assessed with existing data. The findings are listed below:

- Additional Se loads from the Weber River system are small and would only contribute an additional 49 kg of Se during the 16-month monitoring period.

- Electrical resistivity surveys in the south part of GSL indicate higher-resistivity areas of potential ground-water discharge to the open water of GSL. Previous work has documented elevated (exceeding 10,000 µg/L) Se concentrations in ground water beneath KUCC smelter and refinery facilities within 1.6 km of the south shore of GSL. Total water volume in this contaminant plume may exceed 7.9 X 10^7 m^3 and contain a Se concentration ranging between 50 and 17,000 µg/L.

Acknowledgments

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Appendix A. LOADEST Input and Output Files

Appendix data can be accessed by downloading files at http://pubs.usgs.gov/sir/2008/5069.

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