ESTIMATION OF DAILY SUSPENDED SEDIMENT AND MERCURY CONCENTRATIONS AND APPLICATION OF FLOW-NORMALIZED TREND ANALYSES TO ASSESS FLOODPLAIN RESTORATION, CARSON RIVER, NEVADA

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INTRODUCTION

The floodplain of the Carson River was severely destabilized and aggraded during the Comstock Lode mining boom of the late 19th century. The river flows about 180 miles from its headwaters on the eastern slopes of the Sierra Nevada in northeastern California to the Carson Sink in the high desert of western Nevada, draining nearly 4,000 square miles (Figure 1). The headwaters are in steep, volcanic and granitic terrain that is naturally susceptible to erosion. Hillslope erosion was exacerbated during the mining boom by extensive timber harvest from the upper watershed for mine-shaft structural supports and boomtown development. Moreover, sediment from an estimated ten million tons of waste rock and tailings from more than 200 stamp mills downstream of Carson City, Nevada is deposited along the floodplain and river channel (Figure 1). Carson River water quality is further compromised by the release of an estimated 7,500 tons of mercury used in the amalgamation process that was used to extract silver and gold from milled ores. In response to the mercury contamination, the U.S. Environmental Protection Agency (USEPA) listed more than 70 miles of the lower reach of the Carson River as a Superfund National Priorities Site in 1990 (USEPA, 2013).

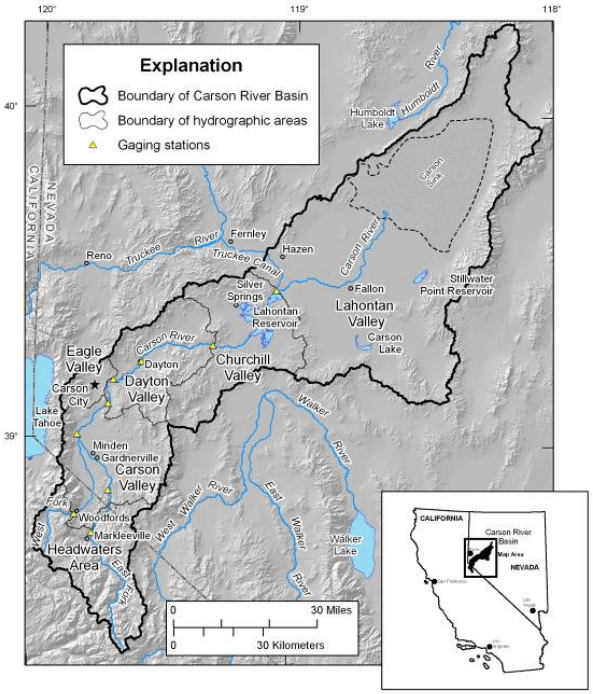

Figure 1 Location of Carson River Basin, California and Nevada

The Carson River has undergone significant geomorphological change that has destabilized its floodplain. As a result, agricultural and residential land has been lost to erosion and bank failure, and sedimentation has affected water quality, prompting efforts to stabilize the Carson River floodplain. Efforts in the mid-1960s to engineer flood control measures by channelizing the sinuous natural streambed, primarily along the East Fork Carson River are now acknowledged to have been a poor floodplain management practice. Renewed efforts beginning in the early 1990s by coalitions of private landowners, volunteers, non-profits, local school and conservation districts, and Tribal, County, State, and Federal agencies have included channel surveys, removal of sediment and constrictive debris, riparian vegetation plantings, flood protection, habitat enhancement, and bioengineered channel-stabilizing technologies (Azad, 2007). Conservation easements and public education about floodplains and recreational access are provided to promote awareness of floodplain value (http://water.epa.gov/type/oceb/upload/2006_11_02_showcase_showcasewatersheds.pdf).

River channel stabilization is apparent where rehabilitation projects, including riparian revegetation and placement of riprap, among others. have been completed (Azad, 2007), but reductions in sediment concentrations and loading have yet to be assessed. The U.S. Geological Survey (USGS) has monitored Carson River streamflow at the Fort Churchill gage (10312000) since 1911 (Figure 2). In October 1997, the USGS, in support of the USEPA Superfund Site Remedial Investigation program, began monitoring concentrations of suspended sediment, total mercury, and methyl mercury in water samples collected from the Carson River near Silver Springs (10312020) and below Lahontan Reservoir (10212150; Figure 2). Daily mean discharge recorded at USGS gaging stations ranged from 0 to 9,500 ft^3/s and averaged 330 ft^3/s as inflow and from 0 to 2,260 ft^3/s and averaged 400 ft^3/s as outflow. Instantaneous discharge measurements made above the reservoir during sampling events ranged from 0.2 to 4,200 ft^3/s and averaged 710 ft^3/s and below the reservoir ranged from 6 to 2,000 ft^3/s and averaged 620 ft^3/s. Sample summary statistics shown in table 1 indicate that Lahontan Reservoir is an effective sink for both suspended sediment and mercury. The statistical summary also indicates significant variability in concentrations. Results from a new statistical model to estimate trends and loading into Lahontan Reservoir are presented as metrics of the Carson River status and the possible effects of floodplain restoration efforts.

Table 1 Summary statistics for water sample concentrations, Carson River near Silver City, Nevada and below Lahontan Reservoir, 1997-2013; concentrations are nanograms per liter except suspended sediment concentrations are milligrams per liter

Constituent	Mean	Minimum	Median	Maximum	Count
10312020; Carson River near Silver Springs, Nevada					
Suspended sediment	220	1.0	61	3,600	309
Unfiltered mercury	2,500	34	1,000	36,000	281
Filtered mercury	29	9.0	25	100	281
Unfiltered methyl mercury	2.9	0.05	2.2	22	285
Filtered methyl mercury	1.2	0.02	1.0	6.8	285
10312150; Carson River below Lahontan Dam, near Fallon, Nevada					
Suspended sediment	28	6	32	100	134
Unfiltered mercury	250	0.04	250	740	134
Filtered mercury	11	2.4	8.4	52	135
Unfiltered methyl mercury	1.4	0.09	0.41	35	135
Filtered methyl mercury	0.6	0.04	0.2	13	133

Figure 2 Locations of selected USGS sampling sites, Carson River, Nevada

APPROACH

Statistical methods that attempt to estimate the mass of water-quality constituents conveyed with streamflow where concentrations are not continuously measured have been developed and evaluated for decades. These investigations aim to better understand temporal load behavior and reduce inherent biases and uncertainties associated with estimated loads (Hirsch, 2014, p. 2). While multiple regression models have demonstrated valid relations between continuous

streamflow and concentrations, analyses of long-term datasets (more than 20 years) have led to the development of models that can accommodate concentration-discharge relations that may change over time.

Exploration and Graphics for RivEr Trends (EGRET, Hirsch and De Cicco, 2014; http://pubs.usgs.gov/tm/04/a10/) is a USGS model written in R (R Core Team, 2014), an Open Source computer and statistical environment that adds flexible enhancements to earlier regression models. The EGRET package has exploratory graphics and statistical tools designed to identify long-term changes in streamflow by computing annual statistics for daily-mean streamflow. The period of analysis can be specified to explore monthly, seasonal, or annual trends in annual average, minimum, and maximum streamflow. Also included in the EGRET software package is the statistical modeling algorithm Weighted Regression on Time, Discharge, and Season (WRTDS; Hirsch et al., 2010) that estimates a continuous concentration time series where continuous streamflow data are available, but observations of constituent concentrations are intermittent. The WRTDS weighted regression equation (Equation 1) estimates daily concentrations by fitting the natural logarithmic function (*ln*) of concentration (*c*) to discharge (*Q*) and time (*t*); including seasonality as sine and cosine functions and ε is the unexplained variation. The regression coefficients (β_i) are estimated for every combination of *Q* and *t* in a weighting system defined by the proximity of each point in *Q* and *t* space (Hirsch and others, 2010).

$$ln(c) = \beta_0 + \beta_1 (ln(Q)) + \beta_2 (t) + \beta_3 sin(2\pi t) + \beta_4 cos(2\pi t) + \varepsilon \qquad (1)$$

EGRET and WRTDS have been used to analyze data collected from the Carson River near Silver Springs (USGS site number: 10312020; Table 1 and Figure 2), along with daily streamflow data from the nearby USGS gaging station (USGS site number: 10312000; Figure 2; http://waterdata.usgs.gov/nv/nwis/dv/?site_no=10312000&agency_cd=USGS&referred_module=sw). Standard USGS protocols for measurement of streamflow discharge (Rantz and others, 1982) and isokinetic, depth-integrated water sampling using the equal-discharge-increment method (U.S. Geological Survey, variously dated) were followed for the data collection. Quality assurance and control (QA/QC), documentation, and data validation considerations are described in sampling and analysis plan documentation for mercury monitoring in the Carson River system (Praskins and Thomas, written commun., 2011).

RESULTS

Time series graphs of annual streamflow statistics for Carson River near Fort Churchill during the period of operation (water years 1911-2013) and during the sample collection period (water years 1998-2013) are shown in Figure 3. Both time periods indicate year-to-year variability with decreasing trends in average mean-daily streamflow. The short-term record also indicates decreasing trends in maximum and minimum streamflows. Potential causes of decreasing trends in streamflow cannot be determined with the available data, but changes in land- or water-use, drought, and climate change each may be contributing factors.

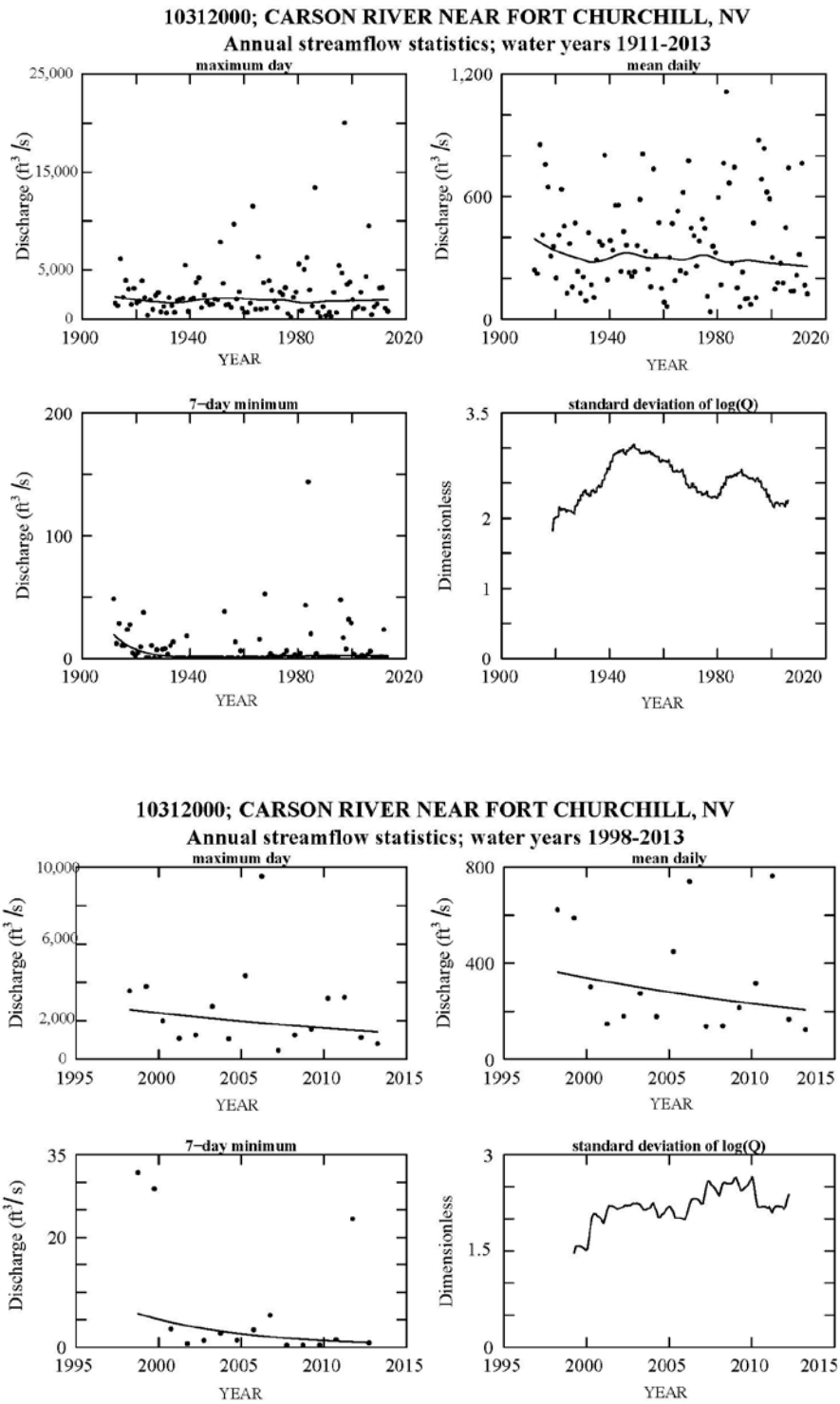

Figure 3 Selected time series of annual streamflow statistics computed for 1911-2013 and 1998-2013, Carson River near Fort Churchill, Nevada

Figure 4 compares mean daily discharge for the 7,457 days that span the suspended sediment sampling period (right box-and-whisker) to the mean daily discharge recorded on the 309 days on which sample collection took place (left box-and-whisker) and shows that sampling may have been biased toward higher streamflows, but is a fair representation of the streamflow distribution during the sampling period.

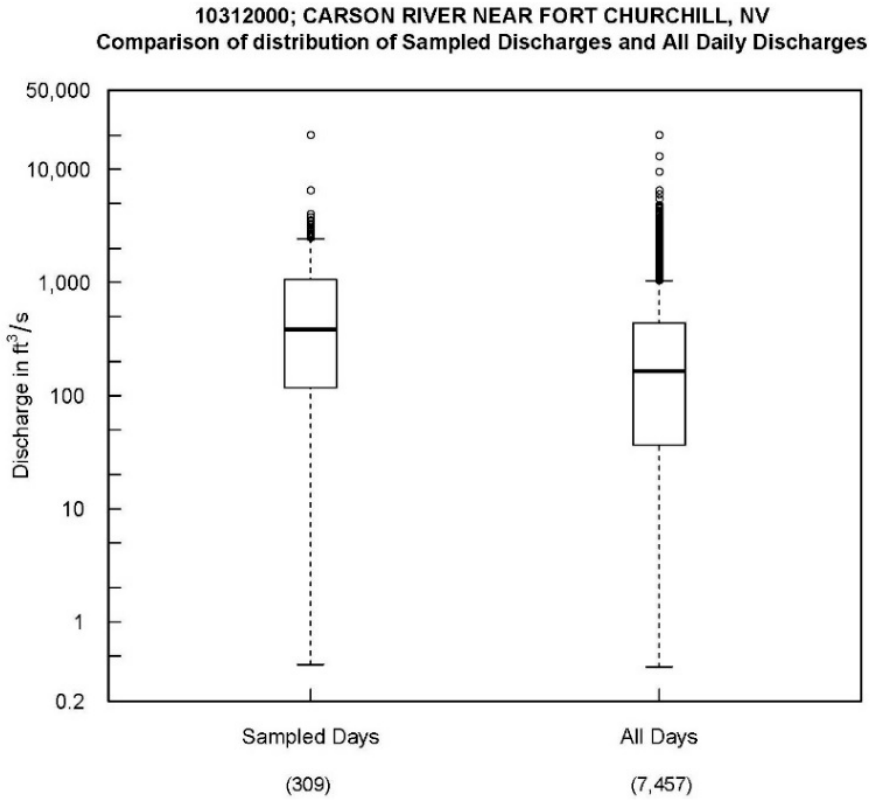

Figure 4 Box and whisker diagrams of mean daily streamflow during sample-collection days and all days during 1998-2013, Carson River near Fort Churchill, Nevada

Suspended sediment data and WRTDS-estimated daily concentrations as a continuous trace are shown in Figure 5a. Because the streambed of the Carson River near Silver Springs is deeply scalloped and has a mobile bedload, suspended sediment concentrations of particles less than 63 microns are computed using silt-sand percentage break determinations and are shown in Figure 5b. The WRTDS model fit is improved for the fine-grained particle size data because the sampling equipment is designed to sample suspended sediment that is at least 0.3 ft above the streambed. The mobile and uneven streambed of the Carson River results in coarser particles being intercepted by the sampler nozzle when it is downstream of submerged sand and gravel dunes.

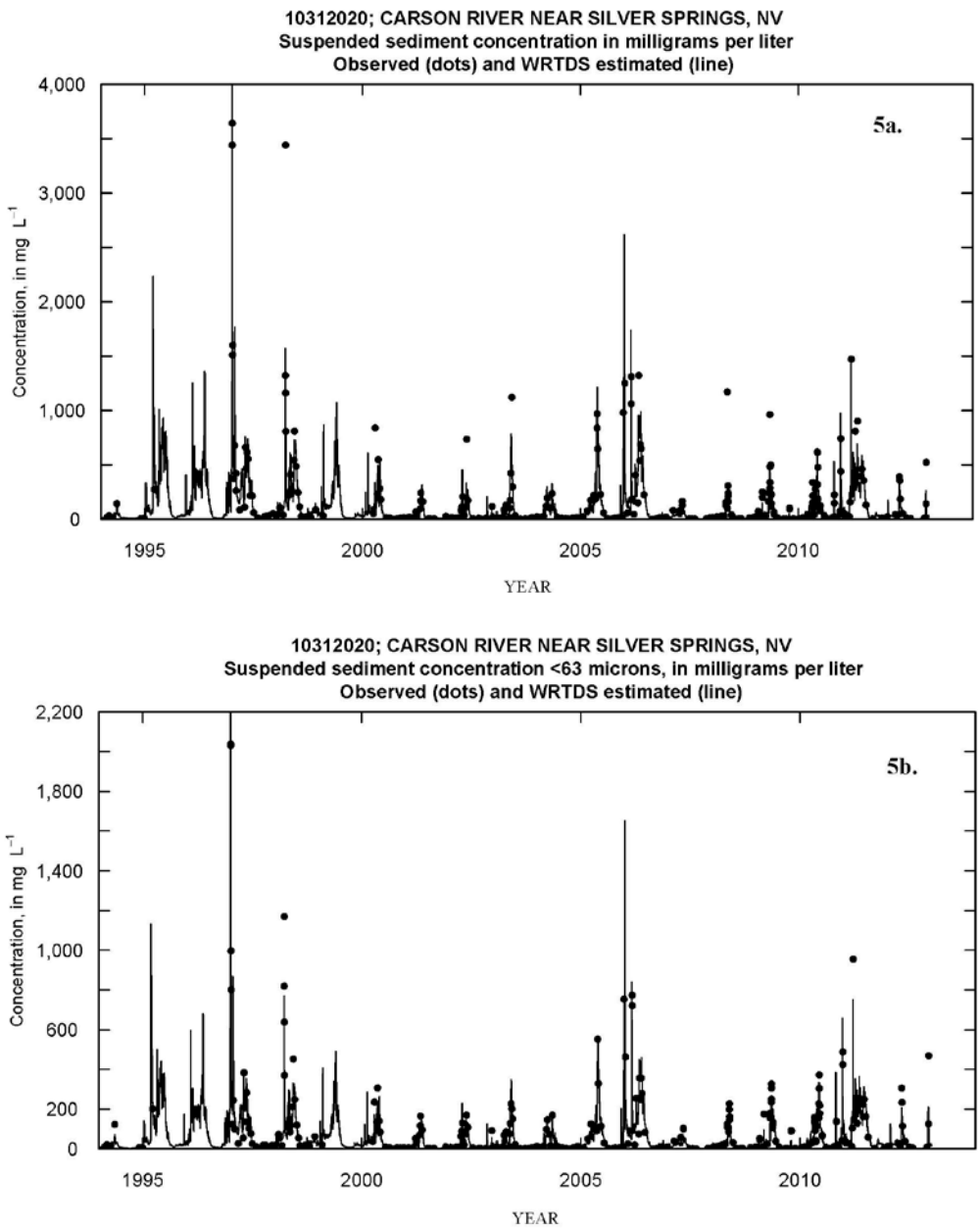

Figure 5 Observed (black dots) and estimated (black line) (5a) concentrations of suspended sediment and (5b) concentrations of suspended sediment less than 63 microns grain size, Carson River near Silver Springs, Nevada

Modeled changes in flow-normalized concentrations and fluxes (loads) for time periods that include all samples and for time periods that arbitrarily bracket the first and last halves of the sampling period are listed in Table 2. Estimated concentrations and fluxes of suspended sediment for the period 1994 through 2012 increased but at a lesser rate of annual change compared to estimates for the period 1994 through 2002. For the period 2002 through 2012 the trend had begun to decrease. Similarly, unfiltered concentrations of mercury and methyl mercury show a decreasing trends in concentrations of -9.5 and -6.9 percent, respectively, while the mass flux estimates decreased by 23 and 35 percent for the period 1998 through 2013. These trends may be

considered improvements, but there may be several contributing factors, including the decreasing trend in discharge, natural recovery of the historically destabilized channel, and floodplain rehabilitation efforts. However, in contrast to decreasing trends in unfiltered mercury and methyl mercury, increasing trends in concentration and flux of filtered mercury was estimated with the highest rate of increase (Table 2) and the flow-normalized concentrations and annual mean concentrations increase at nearly identical rates (Figure 6). The annual changes in average concentrations are relatively small: average suspended sediment concentrations decrease less than 2 milligrams per liter per year, while average filtered mercury concentrations increase by about 1 nanogram per liter (one part per trillion) per year.

Table 2 Estimated trends in concentrations and fluxes of suspended sediment, and mercury for selected time spans, Carson River near Silver Springs, Nevada

Constituent	Time period	Mean-annual percent change in:	
		Concentration	Flux
Suspended Sediment	1994 to 2012	0.1	0.24
	1994 to 2002	1.8	2
	2002 to 2012	-1.1	-0.98
Suspended Sediment, less than 63 microns	1994 to 2012	1.5	1.5
	1994 to 2002	2	2
	2002 to 2012	1	0.85
Unfiltered total mercury	1998 to 2013	-0.64	-1.5
	1998 to 2005	-0.65	-1.6
	2005 to 2013	-0.65	-1.6
Unfiltered methyl mercury	1998 to 2013	-0.46	-2.3
	1998 to 2005	-0.46	-1.9
	2005 to 2013	-0.57	-3.1
Filtered total mercury	1998 to 2013	3.6	4.2
	1998 to 2005	2.5	2.8
	2005 to 2013	3.8	4.6
Filtered methyl mercury	1998 to 2013	-0.35	0.52
	1998 to 2005	-0.18	1.2
	2005 to 2013	-0.51	-0.07

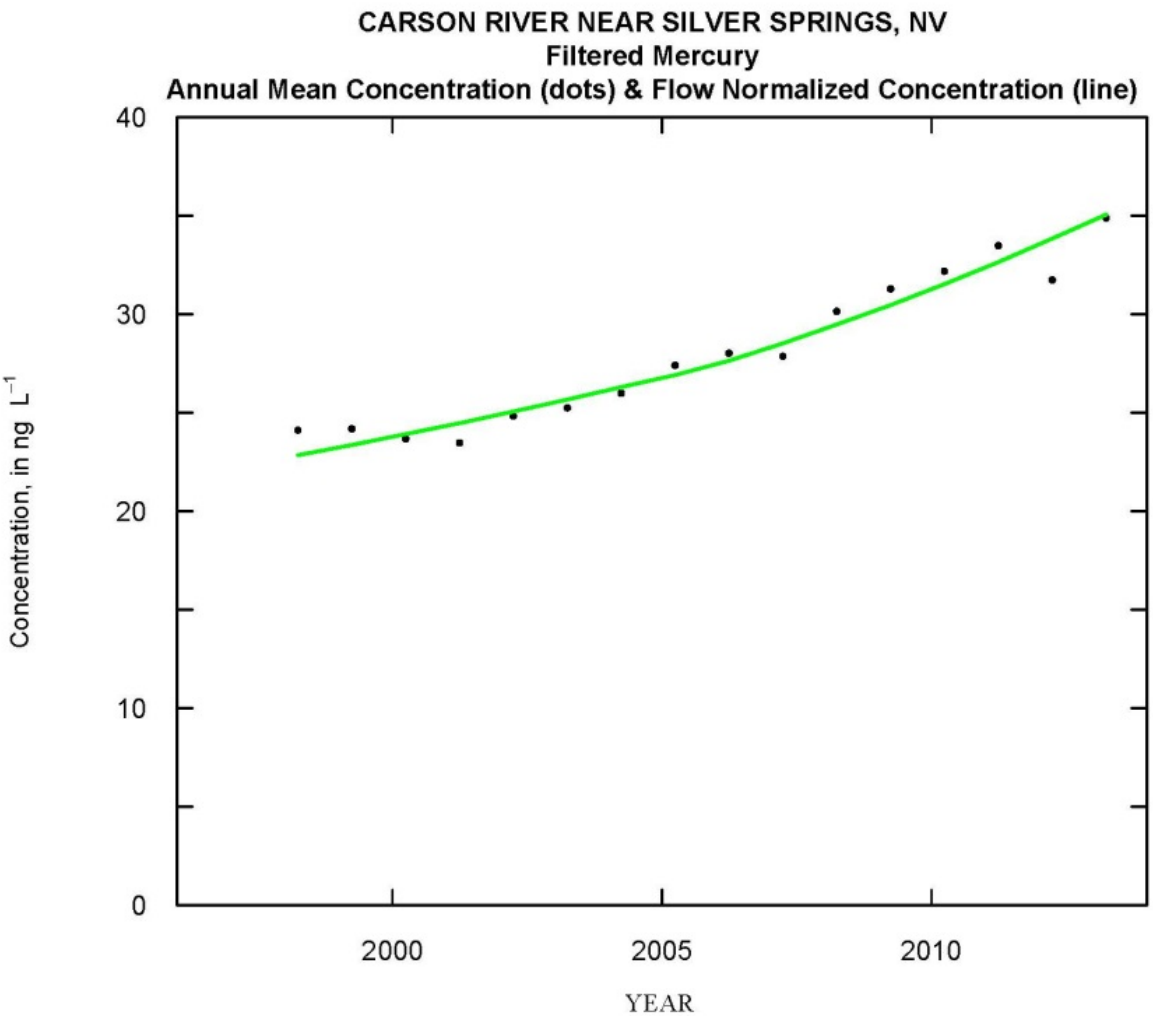

Figure 6 Annual mean filtered mercury concentrations (dots) and flow normalized concentration (line), Carson River near Silver Springs, Nevada

CONCLUSIONS

Statistical analyses, including trend estimation of the data collected in support of the USEPA Carson River Superfund Site Remedial Investigation, show decreasing concentrations and trends in suspended sediment and unfiltered total and methyl mercury. However, these subtle trends may be related to any of several factors, including decreasing streamflow, natural and engineered recovery of a destabilized watershed, or the gradual flushing and volatilization of mercury contamination from impacted sediment upstream of Lahontan Reservoir. The unanticipated increasing trend in filtered mercury concentrations may be related to a similar increasing trend in sample pH, or other unmeasured factors of which dissolved organic carbon and oxidation-reduction potential have been shown to be potential causative factors by other investigators (Aiken et al., 2011).

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