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DERIVATION OF A CHRONIC SITE-SPECIFIC WATER QUALITY STANDARD FOR SELENIUM IN THE GREAT SALT LAKE, UTAH, USA

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Abstract—The purpose of this study was to develop a site-specific water quality standard for selenium in the Great Salt Lake, Utah, USA. The study examined the bioavailability and toxicity of selenium, as selenate, to biota resident to the Great Salt Lake and the potential for dietary selenium exposure to aquatic dependent birds that might consume resident biota. Because of its high salinity, the lake has limited biological diversity with bacteria, algae, diatoms, brine shrimp, and brine flies being the only organisms present in the main (hypersaline) portions of the lake. To evaluate their sensitivity to selenium, a series of acute and chronic toxicity studies were conducted on brine shrimp (*Artemia franciscana*), brine fly (*Ephydra cinerea*), and a hypersaline alga (*Dunaliella viridis*). The resulting acute and chronic toxicity data indicated that resident species are more selenium tolerant than many freshwater species. Because sulfate is known to reduce selenate bioavailability, this selenium tolerance is thought to result in part from the lake's high ambient sulfate concentrations (>5,800 mg/L). The acute and chronic test results were compared to selenium concentrations expected to occur in a mining effluent discharge located at the south end of the lake. Based on these comparisons, no appreciable risks to resident aquatic biota were projected. Field and laboratory data collected on selenium bioaccumulation in brine shrimp demonstrated a linear relationship between water and tissue selenium concentrations. Applying a dietary selenium threshold of 5 mg/kg dry weight for aquatic birds to this relationship resulted in an estimate of 27 μg/L Se in water as a safe concentration for this exposure pathway and an appropriate chronic site-specific water quality standard. Consequently, protection of aquatic birds represents the driving factor in determining a site-specific water quality standard for selenium.

Keywords—Selenium Site-specific water quality standard Great Salt Lake

INTRODUCTION

The Great Salt Lake (GSL) is the fourth largest terminal lake in the world [1] and the largest hypersaline lake in North America [2]. In 1957, the Southern Pacific Railroad Company constructed a rock-filled causeway across the lake, dividing it into two arms. Although culverts link the two arms, they are insufficient to maintain mixing between them. Consequently, the GSL essentially consists of two lakes, each with varying salinity and dominant organisms. Approximately 92% of freshwater inputs enter the southern arm [3], resulting in the northern arm (approximate salinity 330 g/L) being more saline than the southern arm (approximate salinity 100 g/L). For comparison, fully marine waters typically have salinity in the range of 32 to 37 g/L.

The food web of the southern arm of the GSL is relatively simple because few organisms can tolerate its high salinity and low oxygen solubility [4,5]. The aquatic food web consists of at least 4 species of bacteria (mainly *Halobacterium* and *Halococcus*), up to 20 species of algae (mainly *Dunaliella viridis* and *D. salina*), at least 17 diatom species, brine shrimp (*Artemia franciscana*), and 7 species of brine flies (*Ephydra* spp.). Additionally, in areas near significant freshwater inputs where the salinity is less than 75 g/L, corixids (*Trichocorixa verticalis*), rotifers (*Brachionus* sp.), and two species of copepods (*Cletocampus albuquerquensis* and *Diaptomus connexus*) have been observed [2,5–8]. The abundance of these taxa fluctuates with season and salinity [1].

Because of the high salinity, no fish occur in the lake except in freshwater estuaries near the Bear, Jordan, and Weber Rivers (Utah). This lack of aquatic predators, in turn, can lead to extraordinarily high densities of brine shrimp and brine flies, which are an important food source for resident and migratory birds. The lake and its surrounding wetlands is an important stopover point for migratory shorebirds and waterfowl. Greater than 75% of the West's population of tundra swans (*Cygnus columbianus*), 50% of the continent's Wilson's phalaropes (*Phalaropus tricolor*), 25% of the continent's northern pintails (*Anas acuta*), the world's largest nesting population of California gulls (*Larus californicus*), and millions of other waterfowl use the lake during their annual migration periods.

The eastern and southeastern shorelines of the lake's southern arm are bordered by the Salt Lake City metropolitan area. Among the industries bordering the lake are the smelting and refining facilities for a copper mine. A major constituent of this facility's wastewater discharge is selenium, with historic concentrations as high as 300 μg/L Se. Current selenium discharge levels are approximately 20 to 50 μg/L before dilution. The majority (>95%) of this Se is in the form of selenate, and unless otherwise noted, all discussion of Se in this paper is referring to selenate. The effluent is considerably less saline (5 g/L) than the lake, creating a small estuarine zone in the immediate area of the discharge.

The outfall discharge has cut a channel 0.5 to 1.5 m deep in the lake sediments immediately offshore. Water depth sur-

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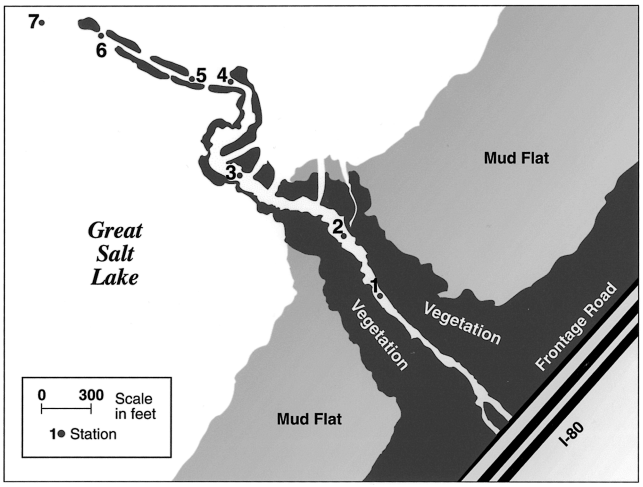

Fig. 1. Map of study area and sampling locations.

rounding the channeled area averages approximately 20 to 50 cm. Lake sediments consist of well-compacted silty, sandy clays. Sediments in the channeled area are less compacted and composed of finer material. Dense stands of *Phragmites* sp. have established along the banks of the channel, stabilizing it. Over time, deposition of fine sediments and organic material and continued colonization by *Phragmites* has extended the channel approximately 500 m out into the lake (Fig. 1). The water depth and velocity, along with the dense *Phragmites*, effectively limits shorebird use in the channel proper, but they are routinely observed to feed along the shorelines on either side of the channel.

Because of its unique water quality characteristics and biota, generic water quality criteria do not apply to the GSL [9], and historically very little toxicity data have been generated for the lake's resident species. Hence, the appropriate water quality standard for Se in the GSL is unclear. Additionally, unlike most other metals and metalloids, the diet typically represents the most important exposure pathway for Se. Top trophic level consumers (e.g., fish and aquatic-dependent birds) are the most sensitive environmental receptors of Se in an aquatic system [10,11]. Consequently, any site-specific water quality standard for selenium must consider exposure via both water and dietary pathways. This study was designed to evaluate potential exposure and effects from Se discharges to the lake via both exposure pathways through a series of laboratory and field studies on resident species. Study results were then used to develop an appropriate site-specific water quality discharge limit. The study was intended to derive a water quality standard specific to the discharge being studied rather than for the entire GSL.

METHODS AND MATERIALS

To evaluate the potential for direct effects on resident aquatic biota, we conducted toxicity tests on brine shrimp, larvae of the brine fly (*Ephydra cinerea*), and the most common alga in the southern arm of the lake (*Dunaliella viridis*). This alga species is a principal food source for brine shrimp. Acute testing was conducted using brine shrimp and brine fly larvae; chronic testing was conducted using *Dunaliella viridis* and brine shrimp. The chronic sensitivity of brine flies was not investigated because of their extreme insensitivity when larvae were in an acute exposure regime (see Table 2). Overall, these species were selected based on the ecological and economic importance rather than any predisposition regarding their relative sensitivity.

Table 1. Dilution water quality during all acute and chronic toxicity tests

Parameter	Range
Temperature (°C)	25 ± 1
pH	7.9–8.4
Dissolved oxygen (mg/L)	1.8–6.0
Salinity (g/L)	80–102
Total organic carbon (mg/L)	35–49
Dissolved organic carbon (mg/L)	34.8–40
Total suspended solids (mg/L)	5–18
Total selenium (μg/L)	<2
Sulfate (mg/L)	5,800

To evaluate the potential for avian toxicity arising from the dietary pathway, Se concentrations in brine shrimp were measured in specimens collected within and adjacent to the mine discharge, as well as at background (i.e., removed from anthropogenic influences) Se concentrations in the lake. These data were then compared to appropriate dietary thresholds for aquatic-dependent birds.

Toxicity testing

Acute testing. The methods used for conducting the acute tests were consistent with those described by the U.S. Environmental Protection Agency [12], although parameters such as dilution water and test volume were modified to meet species-specific requirements. All acute tests were 96 h in duration and evaluated mortality as the biological endpoint. Tests were static, nonrenewal studies conducted at 25 ± 1°C with five test concentrations and a control. Dilution water for the acute tests was GSL water collected from the shoreline on the north side of Antelope Island, a location well removed from anthropogenic inputs to the lake. Conventional water quality parameters were measured in the dilution water prior to testing (Table 1).

Reagent grade sodium selenate (CAS 13410-01-0) obtained from Sigma Chemical (St. Louis, MO, USA) was used to create stock solutions. For the brine shrimp study, a 10 g/L stock solution was prepared by adding 23.9 g of sodium selenate to 1 L of deionized water. For the brine fly larvae testing, sodium selenate was added directly to 5-L batches of dilution water in order to achieve the desired nominal test concentrations.

The brine shrimp test was initiated with nauplii <24 h old that were hatched overnight at 25°C in 25 g/L artificial seawater. Nauplii were not acclimated to the dilution water salinity (82 g/L) prior to testing. This treatment reflects natural conditions where cysts hatch in the relatively low salinity lens of water on the lake surface and then drop down in the more saline water column. Nauplii were randomly introduced to exposure chambers (600 ml beakers with 400 ml of test solution) for each of the five treatments (42, 56, 75, 100, 133 mg/L Se nominal) and control. Four replicates were conducted with each treatment. Preliminary testing indicated brine shrimp required daily feeding to achieve acceptable control survival and so were fed daily 2 ml of a 500,000 cells/ml stock of the marine algae *Platymonas* sp.

Brine fly larvae were collected for testing from White Rock Bay on the north shore of Antelope Island. Larvae were identified to species by Chadwick and Associates in Littleton (CO, USA). Test organisms were held in GSL water in 40-L aquaria at 12°C for eight weeks prior to testing. During holding, 40 ml of 3.5×10^6 cells/ml solution of *Dunaliella viridis* were

added weekly to the aquaria. Forty-eight hours prior to testing, larvae were acclimated to the test temperature of 25°C. Four replicate 1-L beakers with 800 ml of test solution were tested at each of five Se concentrations (207, 346, 576, 960, 1,600 mg/L Se nominal) and a control. Test organisms were not fed during testing.

Chronic testing. The methods for conducting the chronic brine shrimp life-cycle test were previously described in Brix et al. [13]. Briefly, this 28-d test measured survival, growth, and reproduction of the parental generation, and survival and growth of the F_1 generation. The test was conducted under intermittent flow-through conditions beginning with brine shrimp nauplii <24 h old. After 11 d, brine shrimp matured sexually and began pairing for mating. At this time, a random subsample from each test concentration was collected and weighed (dry). Six adult pairs for each test concentration were then monitored for reproduction until day 28 when surviving shrimp were measured for dry weight. For each test concentration (0, 3.8, 7.5, 15, 30, 60 mg/L Se nominal), randomly selected nauplii (F_1 generation) from the pairs were subjected to the same conditions as the parental generation for 11 d, with survival and dry weight being monitored for comparison with the parental generation.

The experimental design for the algae toxicity test followed U.S. EPA [14] and European Union [15], except for the dilution media, which was GSL water passed through a 1-μm filter. In this test, 1×10^4 cells of *D. viridis* from a culture in log-phase growth were inoculated into 125-ml test flasks with 50 ml of test solution. Test flasks were placed on a shaker table rotated at 100 cpm. Each test concentration (0, 15.6, 26, 43, 72, 120, 200 mg/L Se nominal) consisted of 16 replicates and every 24 h, four of the replicates were terminated, whereupon water quality was monitored and cell densities measured using a Hach 300 spectrophotometer (Loveland, CO, USA). The spectrophotometer was calibrated against known cell density stocks of *D. viridis*.

Analytical chemistry. For all tests, water quality parameters (temperature, salinity, pH, and dissolved oxygen) were measured daily in one replicate of each treatment and control. Samples from each concentration were collected for Se analysis at test initiation and termination using the hydride generation method of Cutter [16]. The exception to this sampling regime was the chronic brine shrimp study where selenium samples were collected on a weekly basis.

Data analysis. All data were analyzed using mean measured test concentrations. For the acute brine fly and brine shrimp tests, statistical analyses were conducted using the statistical computer package TOXIS® [17] to estimate the median lethal concentration (LC50) and its 95% confidence interval, as well as the no-observed-effect concentration (NOEC) and lowest-observed-effect concentration (LOEC). The NOEC and LOEC were determined by Steel's many–one rank test and the LC50 was estimated by probit analysis.

The statistical evaluation of the chronic brine shrimp results included testing for differences between the treatments and controls at reproductive pairing (day 11), day 21, and day 28 by parametric or nonparametric methods depending on whether data met normality and homogeneity assumptions. If the data met the assumptions of normality and homogeneity, an analysis of variance was computed to determine whether any differences existed among levels (concentrations or generations). If either of the assumptions could not be met, the nonparametric Kruskal-Wallis test was used to test for differences. The statistics were calculated using Statgraphics [18].

For the chronic algae tests, statistical analyses for the NOEC and LOEC were conducted using SPSS® [19] in accordance with procedures described in European Union [15]. Specific growth rate and cumulative area under the curve were calculated for each replicate, as were summary statistics for each time period. The statistical computer package TOXIS [17] was used to estimate the median effective concentration (EC50) value and the 95% confidence interval based on results from specific growth rate and cumulative area under the growth curve calculations.

Field bioaccumulation study

To evaluate the potential for Se in mining effluent to bioaccumulate in aquatic organisms that might be fed upon by migratory shorebirds, a field program was implemented to sample water and colocated brine shrimp at various locations relative to the mining effluent discharge (Fig. 1). Two sampling events (June and August) were undertaken to characterize Se concentrations in water and biota. The sampling times were selected based on previous studies indicating brine shrimp densities were highest in the lake during this time frame. However, because brine shrimp were not found at most stations in the discharge channel during the August sampling event, only results for the June sampling event and a single sampling station (station 7) with brine shrimp present during the August sampling event are presented.

Surface samples were collected because preliminary sampling efforts indicated the majority of brine shrimp occurred in the upper water column. Water depth along the sampling transect varied from 0.5 to 1.5 m. Grab water samples were collected using a battery-powered peristaltic pump and methods consistent with U.S. EPA [20]. Samples were collected within the channel midway between the banks wherever possible.

When present, brine shrimp were collected at the same time and place as water samples to evaluate the relationship between water and tissue Se concentrations. Brine shrimp were collected using a dip net with a 15- × 30-cm basket constructed of 500-μm Nitex™ screen (Safar, Depew, NY, USA). The dip net was slowly trawled through the water column approximately 15 cm below the water surface until the net contained sufficient specimens (5 g wet wt) for analysis.

Total recoverable and dissolved Se were measured in water samples at the Kennecott Environmental Laboratory using the hydride generation method of Cutter [16] with an analytical detection limit of 2 μg/L Se. Total selenium was determined on the tissue digestate by hydride generation–atomic fluorescence spectrometry. A total reduction/oxidation digestion, converting all forms to selenium (IV), was accomplished by boiling the digested sample in 4M HCl with potassium persulfate. The analytical detection limit in tissues was 0.5 mg/kg dry weight.

RESULTS

Analytical chemistry

In the acute brine shrimp study, mean measured test concentrations were 86 to 98% of nominal with within-treatment coefficients of variation (variability over time) ranging from 10 to 19%. In the acute brine fly study, mean measured test concentration ranged from 114 to 125% of nominal with within

Table 2. Summary of acute toxicity test results (all values are mg/L Se)

Species	Se form	LC50[a] (95% CL)[b]	NOEC[c]	LOEC[d]
Artemia franciscana	Selenate	78 (71–86)	51	71
Ephydra cinerea	Selenate	490 (445–542)	369	691

[a] Median lethal concentration.
[b] Confidence levels.
[c] No-observed-effect concentration.
[d] Lowest-observed-effect concentration.

treatment coefficients of variation ranging from 7 to 17%. In the chronic *D. viridis* study, mean measured test concentrations were 67 to 70% of nominal with within-treatment coefficients of variation ranging from 4 to 7%. Finally, in the chronic brine shrimp study, mean measured test concentrations were 79 to 126% of nominal with within-treatment coefficients of variation ranging from 11 to 20%. All toxicity test results were analyzed using mean measured Se concentrations.

Toxicity testing

Well-defined concentration–response relationships were observed for all of the studies. For the acute brine fly study, a 96-h LC50 of 495 mg/L Se was estimated. The brine shrimp 96-h LC50 of 78 mg/L indicated it was substantially more sensitive than the brine fly (Table 2). In the chronic *D. viridis* study, 96-h EC50s of 45 and 32 mg/L were observed for the specific growth and area under the curve endpoints, respectively (Table 3). The NOEC was 11 mg/L for both endpoints. A number of different endpoints were evaluated in the chronic brine shrimp study. Day 11 growth of the parental generation and day 21 reproduction were comparable in sensitivity and were the most sensitive endpoints evaluated. For both, the NOEC was 3 mg/L Se and the LOEC 8 mg/L Se (Table 4). Overall, these two endpoints for the brine shrimp were also the most sensitive of any endpoint and species evaluated.

Water quality parameters were within expected ranges for all studies (Table 1). Measured dissolved oxygen concentrations ranged from 1.8 to 6.0 mg/L; these concentrations are lower than what is typically considered acceptable in toxicity tests. The low dissolved oxygen values measured during testing are a result of the hypersalinity of the test solutions, which limits oxygen solubility. Dissolved oxygen saturation at salinities of 100 to 150 g/L range from 3.6 to 5.0 mg/L, depending on salinity and test temperature (supersaturated values were measured in the study with *D. viridis* as will typically occur in algal assays). The measured values in the tests were typically >60% saturation, which is acceptable for toxicity tests. For comparison, the southern arm of the GSL has a dissolved oxygen saturation of 2.0 mg/L, which is lower than the range of 3.6 to 5.0 mg/L provided above because the lake is at an elevation of 4,200 ft [8], whereas the tests were performed in a laboratory at sea level. The dissolved oxygen concentrations in these tests are characteristic of what these organisms normally encounter in the environment.

Table 3. Summary of chronic *Dunaliella viridis* toxicity test (all values are mg/L Se)

Evaluation	Specific growth	Cumulative area under growth curve
EC50 (95% CI)[a]	45 (36–71)	32 (28–36)
NOEC[a]	11	11
LOEC[a]	18	18
Chronic value	14	14

[a] Refer to Table 2 for definitions of acronyms.

Table 4. Summary of chronic *Artemia franciscana* toxicity test results (mg/L)

Endpoint	NOEC[a]	LOEC[a]
Survival—parental day 11	38	74
Survival—parental day 21	74	>74
Survival—parental day 28	74	>74
Growth—parental day 11	3	8
Growth—parental day 28	15	38
Reproduction—parental day 21	3	8
Reproduction—parental day 28	15	38
Survival—F_1	15	38
Growth—F_1	15	38

[a] Refer to Table 2 for definitions of acronyms.

Field bioaccumulation study

In the June sampling event, surface water Se concentrations generally decreased with distance from the outfall. Near the mouth of the outfall (station 1) concentrations were as high as 120 μg/L Se, but declined relatively rapidly to 2 μg/L Se at station 5 (790 m from the outfall) and beyond. Total recoverable and dissolved Se concentrations were essentially equivalent at all stations. This is expected for Se discharges in the form of selenate, as it does not readily adsorb to suspended solids [21,22].

Consistent with water concentrations, Se concentrations in brine shrimp from the June sampling event were highest near the outfall mouth, with concentrations as high as 15 mg/kg dry weight (Table 5). Also consistent with waterborne Se data, brine shrimp whole body concentrations dropped relatively rapidly to 2 to 3 mg/kg dry weight beginning at station 4. Selenium concentrations in brine shrimp collected from station 7 in August were also low (3 mg/kg dry wt).

DISCUSSION

Toxicity studies

The current U.S. EPA acute and chronic water quality criteria for Se in freshwater systems are 20 and 5 μg/L [23]. However, U.S. EPA has recently proposed a revised acute criterion for selenate of 185 μg/L and a chronic criterion based on a tissue residue concentration in fish of 7.9 mg/kg dry weight [24]. The lowest acute and chronic toxicity values mea-

Table 5. Summary of co-located selenium concentrations in surface water and brine shrimp

Sample date	Station	Total Se (μg/L)	Dissolved Se (μg/L)	Tissue Se (mg/kg dry wt)	BAF[a]
6/21/98	1	120	121	15.5	129
6/21/98	2	117	116	15.4	132
6/21/98	3	85	81	7.82	92
6/21/98	4	30	30	3.36	112
6/21/98	5	2	2	2.75	1,375
6/21/98	6	2	2	2.86	1,430
6/21/98	7	2	2	3.14	1,570
8/27/98	7	1	1	3.38	3,380

[a] BAF = bioaccumulation factor.

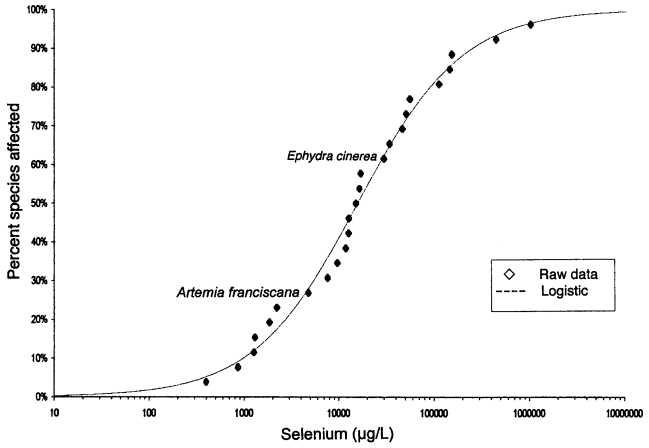

Fig. 2. Relative sensitivity of brine shrimp and brine flies compared to a freshwater species sensitivity distribution for selenate (sulfate-normalized).

sured in this study for biota resident to the GSL were one to two orders of magnitude higher than the proposed acute criterion. However, as discussed below, a close examination of the data indicates resident biota are actually average in sensitivity relative to other freshwater species that have been tested. We make these comparisons not as an argument that the freshwater water quality criteria is appropriate for the GSL, but simply to understand why biota resident to the GSL may appear to be relatively insensitive to Se.

The primary factor causing biota to appear relatively insensitive to Se in these studies is the effect of ambient sulfate concentrations on selenate bioavailability. It is well recognized that sulfate reduces selenate bioavailability to a variety of organisms, including algae, bacteria, midges, daphnids, and brine shrimp [25–30]. Brix et al. [31] quantified this relationship by summarizing available data and conducting additional studies with amphipods, daphnids, and fish. From these studies, a log-linear relationship was developed for selenate bioavailability as a function of ambient sulfate concentration, similar to that derived for hardness and divalent cationic metals. This relationship is important when evaluating the toxicity data in this study because the ambient sulfate concentration in the GSL is 5,800 mg/L, high enough to significantly reduce selenate bioavailability.

To demonstrate this, the relative acute sensitivity of brine shrimp and brine flies was compared to freshwater species. The GSL species were compared to freshwater species rather than marine for two reasons. First, only one marine species has been tested for acute sensitivity to selenate. Second, the GSL is the remnant of a much larger freshwater lake and the resident biota are much more closely related to freshwater organisms than marine [32]. Toxicity data for freshwater species used in this comparison were from Table 4 in Brix et al. [31], who compiled available acute freshwater data meeting U.S. EPA test acceptability for deriving water quality criteria [9].

When the acute data from this study are plotted with available acute data and all data normalized for ambient sulfate concentrations using the regression equation of Brix et al. [31], brine shrimp and brine flies rank at the 29th and 63rd percentiles, respectively, of the species-sensitivity distribution (Fig. 2). The acute brine shrimp 96-h LC50 derived in this study is largely consistent with previous studies [25] that estimated 96-h LC50s of 1.4 and 82 mg/L Se at ambient sulfate concentrations of 50 and 14,000 mg/L, respectively.

Similar to results for the acute studies, the effect levels from the chronic *D. viridis* study are considerably higher than observed for other algal species that have been tested with selenate, although the amount of data available for comparison are relatively limited. For example, selenate chronic values for the freshwater green algae *Selenastrum capricornutum* and *Scenedesmus obliquus* are in the range of 0.1 to 0.3 mg/L Se [33], compared with 14 mg/L Se obtained for *D. viridis* in this study. Similar to invertebrates and fish, selenate toxicity to algae is also sulfate dependent [30]. Normalizing this value to 50 mg/L sulfate (generally comparable to standard freshwater algal test media) using the regression equation of Brix et al. [31] lowers the estimated chronic value for *D. viridis* to 0.85 mg/L. Given the limited number of species tested to date, it is difficult to say whether *D. viridis* is less sensitive than freshwater green algae.

In the chronic brine shrimp study, growth of the parental generation on day 11 and reproduction on day 21 were the two most sensitive endpoints, with both endpoints having a NOEC of 3 mg/L and LOEC of 8 mg/L Se. Hence, the chronic value for this study is the geometric mean of the NOEC and LOEC, 5 mg/L. Published data on the chronic sensitivity of other invertebrate species to selenate are limited to an LOEC of >0.7 mg/L for the amphipod *Hyalella azteca* [34].

Overall, the sensitivity of resident biota was relatively well characterized by the studies performed, although there are two uncertainties regarding this testing. First was the lack of testing of the corixid (*Trichocorixa verticalis*), which has sporadically been observed in the discharge channel perimeter. Although no standard toxicity testing with this species has been conducted, Thomas et al. [35] did assess the short-term (48 h) bioaccumulation of Se in *T. verticalis* by exposing organisms to Se concentrations as high as 1 mg/L with no effect on survival. Hence, the 48-h LC50 for this species is >1 mg/L Se. Second, only one algal species was tested, and a number of additional algal, diatom, and bacteria species occur in the lake. Though we can only speculate on the sensitivity of other unicellular organisms, it seems unlikely that they would be sensitive at levels more than an order of magnitude below those observed for *D. viridis*.

An overall assessment of the selenium toxicity data generated in this study indicates brine shrimp is the GSL's most sensitive species resident, with a chronic value of 5,000 µg/L Se. In comparison, selenium concentrations in the mine effluent typically range from 20 to 50 µg/L Se, approximately two orders of magnitude lower than those predicted to cause chronic effects. Accordingly, the direct effects of Se on resident biota are not the critical exposure pathway in deriving a site-specific water quality discharge limit for the GSL.

Bioaccumulation study

When whole body concentrations of Se in brine shrimp are plotted as a function of colocated waterborne Se concentrations, a relatively strong relationship is observed ($r^2 = 0.92$) (Fig. 3). Though the data suggest a curvilinear rather than linear relationship, we chose to use the linear relationship because it provides a more environmentally protective description of the water-to-tissue relationship. The GSL Se data (Table 5) also demonstrate an inverse relationship between waterborne exposure concentration and corresponding bioaccumulation factor that is frequently observed for metals [36,37].

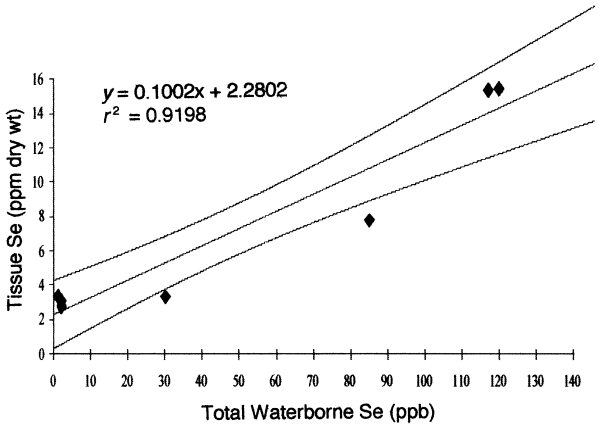

Fig. 3. Relationship between water column and whole body brine shrimp selenium concentrations.

Using this relationship, the site-specific waterborne Se concentration that results in the dietary threshold for aquatic-dependent birds can be estimated. For this assessment, we used a conservative avian dietary Se threshold of 5 mg/kg dry weight [38,39]. A dietary threshold for birds was used because they are considered to be more sensitive than other wildlife species. Using the equation for the linear regression model in Figure 2, the water Se concentration resulting in a brine shrimp selenium concentration of 5 mg/kg dry weight was back-calculated using the following equation:

$$\text{site-specific water quality standard} = \frac{\text{dietary threshold} - \text{intercept}}{\text{slope}}$$

where

$$\text{dietary threshold} = 5 \text{ mg/kg dry wt}$$

$$\text{intercept} = 2.2802$$

$$\text{slope} = 0.1002$$

Using this equation, a waterborne Se concentration of 27 μg/L was calculated as the maximum concentration that will not result in brine shrimp Se concentrations equal to or greater than the avian dietary threshold of 5 mg/kg dry weight. Given that this value is more than two orders of magnitude lower than the lowest effect level observed for direct Se toxicity to resident aquatic biota, Se bioaccumulation in brine shrimp and subsequent dietary toxicity to aquatic birds clearly represents the most critical exposure pathway. Consequently, a site-specific water quality discharge limit of 27 μg/L Se appears protective for aquatic species and sensitive wildlife for this site.

CONCLUSION

The GSL is a unique ecosystem in the United States for which there are no water quality criteria; existing freshwater or marine national water quality criteria are inappropriate due to the unique water quality characteristics and biota of the lake. We evaluated critical exposure pathways for Se released into this environment with the objective of setting a site-specific water quality discharge limit. Resident aquatic biota were found to be comparable in sensitivity to other species that have been tested, but naturally high ambient sulfate concentrations significantly reduce Se bioavailability in this environment. Field bioaccumulation data collected from the study site indicate that waterborne Se concentrations as high as 27 μg/L will not exceed the Se dietary threshold for aquatic birds that feed on resident biota. Therefore, 27 μg/L Se appears to be an appropriate site-specific water quality standard for the protection of aquatic biota and aquatic-dependent wildlife at this site via all exposure pathways.

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