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Derivation of site-specific selenium water quality criteria: A comparison of two methods and regulatory implications

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Abstract

In 2016, the US Environmental Protection Agency (USEPA) issued revised aquatic life water quality criteria for selenium (Se). The criteria ("elements") consisted of threshold concentrations applicable to fish tissue (three tissue types, though the egg and ovary tissue takes precedence over the whole-body and muscle tissue thresholds), and water column. The agency rationalized that measured concentrations of Se in fish tissue were more predictive of potential adverse reproductive effects than those measured in external media. The agency provided two mechanisms for derivation of site-specific Se water criteria: a bioaccumulation factor (BAF) approach, and a partitioning-based bioaccumulation model approach. The use of either approach assumes that fish tissue concentrations exceed one or more of the tissue criteria. We compared the two approaches using fish tissue samples from various species in the Ohio River to evaluate resulting similarities and differences in the calculated Se water quality criteria. Fish (five species) were collected near two coal-fired power plants at sites unaffected by Se from wastewater discharges. Using results for all species and all sites combined, the resulting site-specific Se criteria for the BAF and partitioning-based model approach (median values) were 2.0 and 1.5 μg/L, respectively. Considering all species, resulting criteria differed little between the two power plant locations. Resulting criteria for both methods were strongly influenced by a small (less than detection) background Se water concentration. At least for the upper Ohio River, the BAF approach (requiring less input data) seems adequate for derivation of site-specific Se water criteria. In the current study, however, none of the tissue samples exceeded USEPA's tissue criteria. Thus, the decision to derive site-specific Se water quality criteria should be evaluated on a case-by-case basis, because the process may result in either a more stringent or less stringent value, wholly dependent on local factors. *Integr Environ Assess Manag* 2021;00:1–8. © 2021 SETAC

KEYWORDS: Bioaccumulation, Mechanistic model, Selenium, Site-specific criteria

INTRODUCTION

The release of selenium (Se) from mining activities and various industrial sources is a concern from an ecological standpoint. Though Se is an essential metabolic nutrient for vertebrates, marginally increased concentrations (above background levels) can lead to potential adverse effects to Se-sensitive biota under certain exposure regimes (Simmons & Wallschlager, 2005). In 1987, the US Environmental Protection Agency (USEPA) issued a nationally recommended chronic aquatic life water quality criterion of 5 μg/L (USEPA, 1987). Although this value was based on a field study at one coal-fired power plant cooling lake, it was generally assumed to be protective of most waterbody types.

Subsequently, several laboratory studies have indicated the toxicological mechanism of Se: the maternal transfer of organic Se forms to eggs resulting in reproductive adverse effects (e.g., Cleveland et al., 1993; Hermanutz et al., 1992). A meeting of experts held in 2009 resulted in a recommendation that the risk of Se exposure be evaluated by measuring Se in internal tissues, most notably levels in egg and ovary tissue (Chapman et al., 2010). Assessing risk of potential Se adverse effects to Se-sensitive biota using traditional water column concentrations, it was concluded, imparts considerable uncertainty, such as unknown temporal fluctuations.

In 2016, USEPA issued revised nationally recommended aquatic life criteria for Se. The criteria were intended to protect Se-sensitive fish species. They were derived based on laboratory studies that reported reproductive adverse effects caused by dietary exposure (USEPA, 2016). The criteria ("elements") consisted of thresholds for fish tissue (egg and ovary, muscle, and whole body) and water column values (1.5 μg/L for lentic waters; 3.1 μg/L for lotic waters). The criterion document delineated that compliance with the tissue criteria took precedence over evaluations of compliance with the water criteria. In instances where

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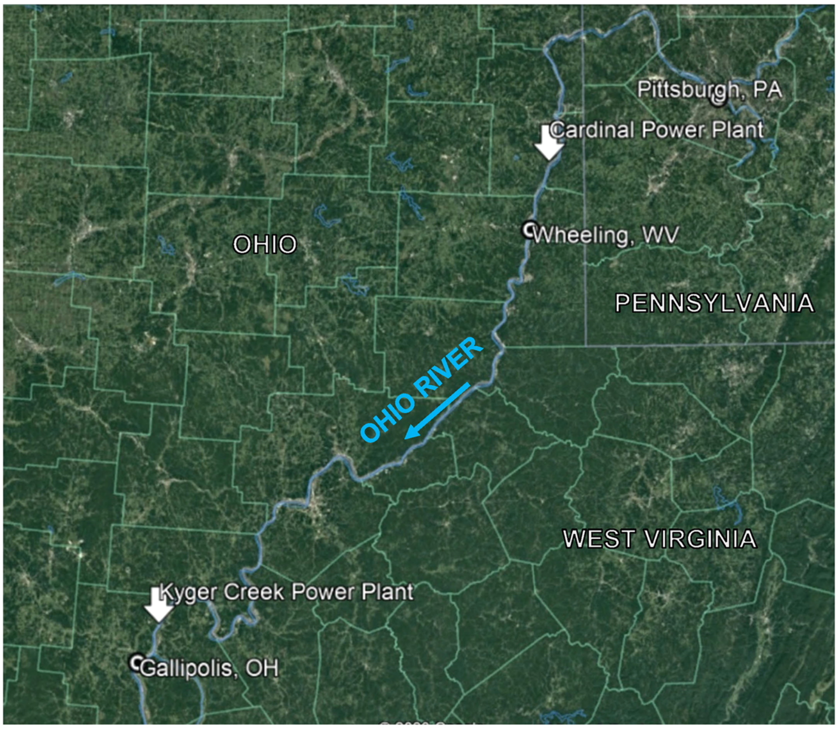

FIGURE 1 Location of Cardinal and Kyger Creek power plant sites on the upper Ohio River

compliance with a tissue criterion was not achieved, USEPA provided guidance on the derivation of site-specific water criteria whether the site-specific water criterion is less stringent or more stringent than the USEPA-recommended water criteria. Three approaches were indicated for development of site-specific water criteria (which would not result in exceedance of the applicable tissue criterion): the Recalculation Procedure (USEPA, 2013), the bioaccumulation factor (BAF) calculation, and a mechanistic bioaccumulation model (following Presser & Luoma, 2010).

In the Ohio River, fish tissue Se concentrations (mostly muscle samples) rarely exceed USEPA's recommended tissue criteria (ORSANCO, 2020; Reash et al., 2015, 2019); similarly, according to ORSANCO, analytical data water Se concentrations in the river do not exceed the USEPA-recommended lotic water quality criterion (3.1 μg/L). Nevertheless, in this study we sought to compare resulting site-specific Se water quality criteria at two sampling locations using the BAF and mechanistic modeling approaches, assuming that one or more fish tissue criteria have been exceeded. Although these approaches differ in sampling requirements, some reports have argued that the resulting criteria should not differ significantly (EPRI, 2018; USEPA, 2016). Although the Recalculation Procedure was considered to derive the site-specific water criteria, removal of Se-sensitive sunfish species (e.g., bluegill [*Lepomis macrochirus*] and largemouth bass [*Micropterus salmoides*]) could not be justified, because these species are common and persistent in the Ohio River. Moreover, making decisions to remove or retain certain species using the Recalculation Procedure is not, in many cases, straightforward (USEPA, 2013).

MATERIALS AND METHODS

Field sampling

Fish, periphyton, and water samples were collected near two coal-fired power plants on the Ohio River: at River Mile 76 (Buckeye Power Company Cardinal Plant, just downstream of Brilliant, OH), and at River Mile 260 (Ohio Valley Electric Corporation Kyger Creek Plant, just downstream of Pomeroy, OH; Figure 1). Biological communities near the two power plants have been well characterized during 30+ years of sampling (e.g., Lohner & Dixon, 2013).

Water samples were collected at power plant intake (ambient river) locations. Parameters measured were total dissolved solids (TDS; Standard Methods 2540C), total hardness (Standard Methods 2340B), sulfate (USEPA Method 300.1), total Se (USEPA Method 200.8), and dissolved Se (USEPA Method 200.8 after filtration). Samples were collected during August–October 2019. At Cardinal Plant, the analysis of total and dissolved Se measurements was excluded because of an unacceptably high method detection limit (MDL) used by the analytical laboratory (17.5 μg/L). Se measurements for this location were, therefore, based on results of ORSANCO "clean hands" sampling at the nearest upstream and downstream navigation lock and dam (L&D) locations (New Cumberland and Pike Island L&D; ORSANCO, 2020). At these locations, the reported MDL was 1.0 μg/L.

At Kyger Creek Plant, ambient Se water samples were collected at the power plant river intake. Other Se water analyses—performed by ORSANCO—were also obtained from the nearest upstream and downstream navigation L&D locations (Bellville and R.C. Byrd L&D). The MDL for these Se samples was also 1.0 μg/L. Kyger Creek Plant is located in the R.C. Byrd navigation pool. During August–October 2019, the mean monthly flow rate at the R.C. Byrd L&D varied between 629 and 864 m^3/s (ORSANCO, 2020).

The mechanistic bioaccumulation model—to derive a protective site-specific water Se criterion—requires a measure of Se in water and particulate matter. Particulate matter is generally described as the elements in a food web that accumulate dissolved trace elements from the water; examples include algae, detritus, periphyton, and sediment materials (USEPA, 2016). In this study, periphyton samples were collected at both power plant locations during August and October. Two replicate samples were collected during each sampling event (total $N = 8$). Scalpels were used to scrape periphyton into plastic bags. The samples were then frozen before transport to an analytical laboratory. In the laboratory, Se content (mg/kg dry weight) was measured using USEPA Method 6020.

Fish species collected for tissue Se analysis were based on USEPA (2016) recommendations. Sunfish species had top priority, notably bluegill and largemouth bass. These species have laboratory-based toxicity thresholds for reproductive success; the calculated chronic EC_{10} values for reproductive effects indicate that bluegill is the second most sensitive species and largemouth bass has sensitivity similar to trout in the genus *Oncorhynchus* (USEPA, 2016). Sturgeon and salmon or trout species—taxa that are sensitive to Se exposure—are not present in the upper Ohio River.

Fish were collected at both locations via night electrofishing at sampling sites unaffected by wastewater discharges. At both sites, the fish species collected were golden redhorse (*Moxostoma erythrurum*), bluegill, largemouth bass, and sauger (*Sander canadense*). At Kyger Creek Plant spotted bass samples (*Micropterus punctatus*) were also collected. Fish length (total length, mm) and weight (g) were measured at the time of capture. Fillets were scaled and the skin-on samples consisted, in most cases, of a composite of three fish. Water temperature (°C), dissolved oxygen (DO; mg/L) and specific conductivity (μmhos/cm) were measured at each fish sampling location during the August and October sampling events.

Frozen composite samples were shipped to Pace Analytical Laboratories in Green Bay, WI. Samples were homogenized (Standard Methods 2540G) and analyzed for percent moisture (ASTM Method D2974-87) and total Se (USEPA Method 6020). Quality-assurance and/or quality-control analyses conducted on each shipped batch included analysis of method blanks, duplicates, matrix spikes, and matrix spike duplicates. A detectable concentration was that measured at or above the MDL.

Calculation of site-specific Se water criteria

For each species-specific composite tissue sample, a BAF was calculated as the ratio of the concentration of Se in tissue to the concentration of Se in background water samples. At both power plant locations, the ambient water concentration was set at 0.5 μg/L (1/2 the MDL value of 1.0 μg/L). Although using an assumed "fixed" water concentration results in uncertainty regarding the actual average concentration, the method used by ORSANCO to analyze total Se (USEPA Method 200.8) is an approved sensitive method. The species-specific, site-specific Se water quality criterion was then calculated as:

$$\text{Site specific Se concentration}_{\text{water},\mu g/L} = \frac{\text{USEPA tissue criterion (mg/kg dry wt.)}}{\text{BAF(L/kg)}}$$

For calculating the mechanistic model-based, site-specific Se water quality criterion, we used equations provided by Presser and Luoma (2010) and USEPA (2016). The equation we used was:

$$\text{Site-specific Se water concentration}_{\text{water},\mu g/L} = \frac{\text{USEPA tissue criterion}}{\text{TTF}^{\text{composite}} \times \text{EF}}$$

where the USEPA tissue criterion was either 8.5 mg/kg dry weight (whole-body samples) or 11.3 mg/kg dry weight (muscle samples). The composite trophic transfer factor ($TTF^{composite}$) value is a numerical value that designates the BAF of Se from water to particulates and particulates to primary consumers; primary consumers to secondary consumers; and from secondary consumers to fish when $TTF^{composite}$ values exceed 1.0. These values were obtained from (mostly) field studies as reported by USEPA (2016). For golden redhorse, a $TTF^{composite}$ value for a related species (black redhorse; *Moxostoma duquesnei*) was used. Similarly, a $TTF^{composite}$ value for walleye (*Sander vitreus*), was used as a surrogate for sauger. The enrichment factor (EF) was calculated as the arithmetic average of the periphyton Se concentration (at each power plant site) divided by the average Se water concentration (0.5 μg/L at both power plant locations).

RESULTS

Results of water sample analyses at power plant intake locations and proximal L&D locations are provided in Table 1. The samples collected at the power plant intake locations were typical of seasonal samples collected at the upstream and downstream L&D locations (ORSANCO, 2020). During fish collections in August 2019, the average water temperature was 27.2 °C at Cardinal Plant and 29.0 °C at

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TABLE 1 Results of water sample analyses at power plant intake and proximal lock and dam (L&D) locations

Location	Sample date	TDS (mg/L)	Total hardness (mg/L)	Total Se (μg/L)	Sulfate (mg/L)
Cardinal Plant intake	1 Aug. 2019	168	110	——[a]	59.4
Cardinal Plant intake	8 Aug. 2019	174	128	–	63.3
Cardinal Plant intake	15 Aug. 2019	172	124	–	63.7
Cardinal Plant intake	22 Aug. 2019	222	136	–	80.4
Cardinal Plant intake	29 Aug. 2019	230	140	–	93.9
Cardinal Plant intake	5 Sept. 2019	254	138	–	85
Cardinal Plant intake	12 Sept. 2019	188	120	–	80.4
Cardinal Plant intake	18 Sept. 2019	258	134	–	96.9
New Cumberland L&D	18 Sept. 2019	220	124	0.5[b]	71
Pike Island L&D	18 Sept. 2019	204	118	0.5	67.7
Cardinal Plant intake	20 Sept. 2019	258	134	–	78
Cardinal Plant intake	3 Oct. 2019	235	132	–	66.3
Cardinal Plant intake	9 Oct. 2019	346	144	–	72.8
Cardinal Plant intake	17 Oct. 2019	216	138	–	82.1
Kyger Creek Plant intake	3 Sept. 2019	262	140	0.4	76.1
Belleville L&D	19 Sept. 2019	256	140	0.5	84
R.C. Byrd L&D	19 Sept. 2019	320	140	0.5	80.9
Kyger Creek Plant intake	1 Oct. 2019	280	158	0.5	92.2

[a]Measured selenium value not valid owing to a very high MDL value.
[b]Value is equivalent to ½ the analytical MDL.

Kyger Creek Plant; average values during the October fish sampling event were 22.8 °C and 25.3 °C, respectively. DO levels ranged between 6.9 to 8.0 mg/L and specific conductivity levels ranged between 307 and 525 μmhos/cm. All total and dissolved Se values were reported as 0.5 μg/L.

Results of measured Se concentrations in fish tissue and periphyton samples are provided in Table 2. Results of all quality-assurance and/or quality-control analyses were within the acceptable criteria range. Considering both site locations, fish tissue Se ranged between 2.2 and 4.0 mg/kg; all reported concentrations were considerably smaller than the USEPA Se tissue criteria for both whole-body and muscle samples.

For periphyton samples collected at Cardinal Plant, the average Se concentration (average of two replicates) was 1.4 mg/kg (August) and 2.6 mg/kg (October), with an overall average of 2.0 mg/kg (all values in dry wt.). For samples collected near Kyger Creek Plant, the average concentration for samples collected in August was 5.3 mg/kg, whereas the average concentration for samples collected in October was 2.9 mg/kg; the overall average concentration was 4.1 mg/kg.

BAF values at Cardinal Plant—assuming an ambient water Se concentration of 0.5 μg/L—ranged between 5000 and 6600 L/kg (Table 3). The resulting aquatic life water quality criteria at this location ranged between 1.7 (golden redhorse and bluegill) and 2.3 μg/L (sauger). For all species combined, the median criterion value was 2.0 μg/L; a similar value (2.1 μg/L) was obtained when only sunfish species (bluegill and largemouth bass) were considered.

For samples collected at Kyger Creek Plant, species-specific BAF values ranged from 4400 to 8000 L/kg (Table 4). The resulting BAF-based water quality criteria ranged between 1.4 μg/L (largemouth bass) and 2.6 μg/L (bluegill). For all species combined, the resulting median site-specific water quality criterion was 1.9 μg/L. For the three sunfish species only, the resulting median site-specific water quality criterion was 2.2 μg/L.

Species-specific Se aquatic life criteria, based on the mechanistic model approach, are provided in Table 5. These values ranged from 1.2 μg/L (spotted bass) to 2.0 μg/L (golden redhorse). Considering all species from both locations, the median site-specific Se water quality criterion was 1.5 μg/L.

DISCUSSION

The concentration of Se in muscle tissue samples—for the current study—was generally smaller than levels reported for the same species in previous Ohio River studies, notably bluegill and sauger (ORSANCO, 2020; Reash et al., 2015, 2019). Moreover, the Se tissue concentrations reported in the current study—and in previous studies—are

TABLE 2 Selenium concentrations in fish and periphyton samples collected near Cardinal and Kyger Creek plants, 2019

Location	Species	Sample date	Mean total length (cm)	Se (mg/kg dry wt)	Mean species Se concentration (mg/kg dry wt)
Upstream Cardinal Plant	Golden redhorse	3 Aug. 2019	27.7	3.0[a]	3.3
	Golden redhorse	8 Oct. 2019	29.4	3.6[a]	
	Bluegill	3 Aug. 2019	11.1	2.3[b]	2.5
	Bluegill	7 Oct. 2019	11.4	2.7[b]	
	Largemouth bass	7 Oct. 2019	15.3	2.6[a]	2.6
	Sauger	3 Aug. 2019	25.2	2.4[a]	2.5
	Sauger	7 Oct. 2019	30.6	2.5[a]	
	Periphyton (2 replicates)	2 Aug. 2019	–	0.99–1.9	1.4
	Periphyton (2 replicates)	7 Oct. 2019	–	1.9–3.2	2.6
Upstream Kyger Creek Plant	Golden redhorse	3 Aug. 2019	28.9	3.3[a]	3.3
	Golden redhorse	4 Oct. 2019	32.0	3.2[a]	
	Bluegill	3 Aug. 2019	16.0	2.2[a]	2.2
	Bluegill	3 Aug. 2019	9.5	3.0[b]	2.5
	Bluegill	4 Oct. 2019	15.0	2.3[b]	
	Bluegill	4 Oct. 2019	10.4	2.2[b]	
	Spotted bass	3 Aug. 2019	25.0	2.6[a]	2.6
	Largemouth bass	5 Oct. 2019	17.4	4.0[a]	4.0
	Sauger	3 Aug. 2019	39.7	3.2[a]	2.8
	Sauger	5 Oct. 2019	41.0	2.9[a]	
	Sauger	5 Oct. 2019	20.6	2.4[a]	
	Periphyton (2 replicates)	4 Aug. 2019	–	3.3–7.3	5.3
	Periphyton (2 replicates)	5 Oct. 2019	–	2.2–3.6	2.9

[a]Skin-off fillet (muscle) sample.
[b]Whole-body sample.

all smaller than the USEPA-recommended muscle and whole-body criteria. Thus, considering the chemical and physical characteristics of the Ohio River, the concentrations of Se in fish tissue should not be a concern to stakeholders regarding potential population-level adverse effects. This is not to say that elevated concentrations of fish tissue Se could not occur in the immediate mixing zone of wastewater discharges, though most numeric water quality standards do not apply in these designated stream reaches.

The accumulation of waterborne Se by periphyton is influenced strongly by Se speciation and floral composition (Markwart et al., 2019; Riedel et al., 1991). Baines and Fisher (2001) reported that the taxonomic composition of marine phytoplankton influenced the bioconcentration of selenite (Se(IV)$^{+4}$). In the current study, no taxonomic or genetic analyses were conducted to distinguish potential differences in periphyton community composition.

The observation that the calculated median site-specific Se water quality criterion was virtually identical between the BAF and mechanistic model approaches was somewhat unexpected. As the BAF approach is conceptually and computationally simpler than the mechanistic model approach (i.e., the BAF approach does not require extensive knowledge of the physical, chemical, and biological characteristics in a given system), in large rivers such as the Ohio River this approach is probably preferred. Variable water Se concentrations, however, would inject some uncertainty in calculated BAF values for a given site.

One technical problem with the BAF approach, at least considering aquatic life exposure to Se and other trace

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TABLE 3 Calculated BAF-based site-specific Se water quality criteria for fish species collected near Cardinal Plant, 2019

Species	Tissue type	Mean Se concentration (mg/kg/dry wt)	USEPA tissue criterion (mg/kg dry wt)	Background water Se concentration (μg/L)	BAF (L/kg)	Site-specific water criterion (μg/L)
Golden redhorse	Fillet	3.3	11.3	0.5[a]	6600	1.7
Bluegill	Whole body	2.5	8.5	0.5[a]	5000	1.7
Largemouth bass	Fillet	2.6	11.3	0.5[a]	5200	2.2
Sauger	Fillet	2.5	11.3	0.5[a]	5000	2.3
Median site-specific Se criterion						2.0
Median site-specific criterion (sunfish species only)						2.1

[a]Equivalent to ½ the MDL of measured samples.

elements, is the observed inverse relationship between calculated BAFs and exposure concentration (DeForest et al., 2007). This significant relationship ($p < 0.05$) applies to both laboratory-based bioconcentration factors (BCFs) and field-based BAFs. As Se is an essential trace nutrient in vertebrates, the metalloid is assimilated more efficiently at small external concentrations. This could lead to an erroneous interpretation of BAF data, that is, reaching a conclusion that a high BAF value is caused by unmeasured elevated water column concentrations. The same inverse relationship has also been observed with water exposure concentration and calculated EF values. The adoption and implementation of tissue Se water quality criteria, as currently advocated by USEPA, would prevent possible erroneous assessments of BAF values where elevated water column Se concentrations are suspected, but not observed.

Both approaches used in the current study resulted in relatively stringent site-specific water quality criteria. USEPA (2016) issued proposed water criteria in addition to the tissue thresholds: 1.5 μg/L for lentic waters and 3.1 μg/L for lotic waters. Using a food web mechanistic modeling approach, DeForest et al. (2017) calculated Se screening guidelines for the protection of freshwater aquatic life. Their analysis resulted in waterborne guidelines for lentic waters (3.0 μg/L) and lotic waters (6.5 μg/L).

During most flow conditions, the Ohio River can be considered a lotic system. As an example, for the R.C. Byrd Navigational Pool the hydraulic residence time for the river ranges between 0.5 and 2.5 days (EPRI, 2013). This navigational pool is 67 km in length; the relatively short flushing rate, even during low-flow periods, does not suggest that the Ohio River has consistent lentic properties.

Since USEPA issued the final 2016 criteria guidance documents, there have been some cases where regulated industry stakeholders have sought approval of site-specific Se tissue or water column criteria. On July 9, 2019, USEPA Region 10 approved several proposed Se site-specific water column criteria for various Idaho streams based on site-specific BAF calculations. These site-specific criteria were largely less stringent than USEPA's recommended Se water criteria. Also in 2019, the Nevada Division of Environmental Protection approved several site-specific Se water column criteria, calculated using site-specific BAF data. The agency demonstrated that no sturgeon species are present in state waterbodies; thus the protective egg or ovary tissue criterion was adjusted when white sturgeon chronic toxicity data were removed. Finally, in 2019, the Minnesota Pollution Control Agency approved proposed site-specific Se water criteria for a limited 6-mile stretch of the lower Minnesota River (downstream of the Seneca Wastewater Treatment Plant to the confluence with the Mississippi River). These criteria (11.3 μg/L for the Minnesota River and 5.7 μg/L for two nearby oxbow lakes) were calculated using site-specific BAF data. Thus, these cases seem to demonstrate a preference to derive site-specific Se water criteria using the BAF approach.

TABLE 4 Calculated BAF-based Se site-specific aquatic life water quality criteria for fish collected near Kyger Creek Plant, 2019

Species	Mean Se tissue concentration (mg/kg dry wt)	USEPA tissue criterion (mg/kg dry wt)	Background water Se concentration (μg/L)	BAF (L/kg)	Site-specific water criterion (μg/L)
Golden redhorse	3.3[a]	11.3	0.5[b]	6600	1.7
Bluegill	2.2[a]	11.3	0.5	4400	2.6
	2.5[c]	8.5	0.5	5000	1.7
Spotted bass	2.6[a]	11.3	0.5	5200	2.8
Largemouth bass	4.0[a]	11.3	0.5	8000	1.4
Sauger	2.8[a]	11.3	0.5	5600	2.0
Median site-specific Se criterion					1.9
Median site-specific Se criterion—sunfish species only					2.6

[a]Se concentration in fillet (muscle) sample.
[b]Equivalent to ½ the MDL concentration of measured samples.
[c]Se concentration in whole-body sample.

There are only a few waterbody types where Se—released by anthropogenic activities—would be expected to cause elevated tissue concentrations. Lakes and reservoirs with very long hydraulic residence times (e.g., Belews Lake and Hyco Reservoir, NC; Skorupa, 1998), and effluent-dominated streams and rivers (e.g., Cianciolo et al., 2020; Reash et al., 2006) are two habitat types where adverse effects may be expected to occur.

In conclusion, we analyzed Se in water, periphyton, and fish tissue (fillet and whole body) to assess the similarity of calculated site-specific Se water quality criteria using a BAF and mechanistic model approach. There was little evidence of spatial effects (i.e., between the two study locations) and differences in tissue Se concentrations between species. The resulting criteria values were 1.5 μg/L total Se (mechanistic modeling) and 1.9 μg/L total Se (BAF approach). The very small ambient Se water concentration had a relatively strong influence on the calculated criteria but more so for the BAF approach. Any consideration to derive a site-specific water column Se criterion, at least for the Ohio

TABLE 5 Mechanistic model-based species-specific Se aquatic life criteria for fish collected from Cardinal and Kyger Creek plants, 2019

Species	Location	Tissue type	USEPA criterion (mg/kg dry wt)	TTF[a]	Average periphyton Se (mg/kg dry wt)	EF[b]	Site-specific water criterion (μg/L)	Species average criterion (μg/L)[c]
Golden redhorse	Cardinal	Fillet	11.3	1.10	2.0	4000	2.6	2.0
	Kyger Creek	Fillet	11.3	1.10	4.1	8200	1.3	
Bluegill	Cardinal	Whole body	8.5	1.03	2.0	4000	2.1	1.5
	Kyger Creek	Whole body	8.5	1.03	4.1	8200	1.0	
	Kyger Creek	Fillet	11.3	1.03	4.1	8200	1.3	
Spotted bass	Kyger Creek	Fillet	11.3	1.12	4.1	4000	1.2	1.2
Largemouth bass	Cardinal	Fillet	11.3	1.39	2.0	4000	2.0	1.5
	Kyger Creek	Fillet	11.3	1.39	4.1	8200	1.0	
Sauger	Cardinal	Fillet	11.3	1.60	2.0	4000	1.8	1.4
	Kyger Creek	Fillet	11.3	1.60	4.1	8200	0.9	

[a]Trophic transfer factor.
[b]Enrichment factor.
[c]Median and average Se site-specific water quality criterion (all species combined) = 1.5 μg/L.

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River, should be evaluated on a case-by-case basis, because the process may result in either more stringent or less stringent water values, depending on local factors that influence bioaccumulation.

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CONFLICT OF INTEREST

The authors declare that there are no conflict of interests. The peer review for this article was managed by the Editorial Board without the involvement of Robin J. Reash.

DATA AVAILABILITY STATEMENT

Data and associated meta-data and calculation tools are available by contacting Robin J Reash (robreash@gmail.com).

REFERENCES

Baines, S. B., & Fisher, N. S. (2001). Interspecific differences in the bioconcentration of selenite by phytoplankton and their ecological implications. *Marine Ecology Progress Series*, *213*, 1–12.

Chapman, P. M., Adams, W. J., Brooks, M. L., Delos, C. G., Luoma, S. N., Maher, W. A., Ohlendorf, H. M., Presser, T. S., & Shaw, D. P. (2010). Ecological assessment of selenium in the aquatic environment. SETAC Press.

Cianciolo, T. R., McLaughlin, D. L., Zipper, C. E., Timpano, A. J., Soucek, D. J., Whitmore, K. M., & Schoenholtz, S. H. (2020). Selenium bioaccumulation across trophic levels and along a longitudinal gradient in headwater streams. *Environmental Toxicology and Chemistry*, *39*, 692–704.

Cleveland, L., Little, E. E., Buckler, D. R., & Wiedmeyer, R. H. (1993). Toxicity and bioaccumulation of waterborne and dietary selenium in juvenile bluegill (*Lepomis macrochirus*). *Aquatic Toxicology*, *27*, 265–279.

DeForest, D. K., Brix, K. V., & Adams, W. J. (2007). Assessing metal bioaccumulation in aquatic environments: The inverse relationship between bioaccumulation factors, trophic transfer factors and exposure concentration. *Aquatic Toxicology*, *84*, 236–246.

DeForest, D. K., Brix, K. V., Elphick, J. R., Rickwood, C. J., deBruyn, A. M. H., Tear, L. M., Gilron, G., Hughes, S. A., & Adams, W. J. (2017). Lentic, lotic, and sulfate-dependent waterborne selenium screening guidelines for freshwater systems. *Environmental Toxicology and Chemistry*, *36*, 2503–2513.

EPRI. (2013). *Application of the dynamic mercury cycling model (D-MCM) to the Robert C. Byrd Pool, Ohio River* (Technical Report No. 1023762). Electric Power Research Institute.

EPRI. (2018). *Implementing the USEPA fish-tissue and water criteria for selenium*. (Technical Report No. 3002010888). Electric Power Research Institute.

Hermanutz, R. O., Allen, K. N., Roush, T. H., & Hedtke, S. F. (1992). Effects of elevated selenium concentrations on bluegills *Lepomis macrochirus* in outdoor experimental streams. *Environmental Toxicology and Chemistry*, *11*, 217–224.

Lohner, T. W., & Dixon, D. A. (2013). The value of long-term environmental monitoring programs: An Ohio River case study. *Environmental Monitoring and Assessment*, *185*, 9385–9396.

Markwart, B., Liber, K., Xie, Y., Raes, K., Hecker, M., Janz, D., & Doig, L. E. (2019). Selenium oxyanion bioconcentration in natural freshwater periphyton. *Ecotoxicogy and Environmental Safety*, *180*, 693–704.

ORSANCO. (2020). *Water quality and fish tissue data*. Ohio River Valley Water Sanitation Commission. www.orsanco.org/data/

Presser, T. S., & Luoma, S. N. (2010). A methodology for ecosystem-scale modeling of selenium. *Integrated Environmental Assessment and Management*, *6*, 685–710.

Reash, R. J., Brown, L., & Merritt, K. (2015). Mercury and other trace elements in Ohio River fish collected near coal-fired power plants: Interspecific patterns and consideration of consumption risks. *Integrated Environmental Assessment and Management*, *11*, 474–480.

Reash, R. J., Friedrich, L. A., Bock, M. J., Halden, N. M., & Palace, V. P. (2019). Selenium and mercury in freshwater fish muscle tissue and otoliths: A comparative analysis. *Environmental Toxicology and Chemistry*, *38*, 1467–1475.

Reash, R. J., Lohner, T. W., & Wood, K. V. (2006). Selenium and other trace metals in fish inhabiting a fly ash stream: Implications for regulatory tissue thresholds. *Environmental Pollution*, *142*, 397–408.

Riedel, G. F., Ferrier, D. P., & Sanders, J. G. (1991). Uptake of selenium by freshwater phytoplankton. *Water, Air, and Soil Pollution*, *57–58*, 23–30.

Simmons, D. B., & Wallschlager, D. (2005). A critical review of the biogeochemistry and ecotoxicology of selenium in lotic and lentic environments. *Environmental Toxicology and Chemistry*, *24*, 1331–1343.

Skorupa, J. P. (1998). Selenium poisoning in fish and wildlife in nature: Lessons learned from twelve real-world experiences. In W. T. Frankenberger, & R. A. Engberg (Eds.), *Environmental chemistry of selenium*. Marcel Dekker P 315–354.

USEPA. (1987). *Ambient water quality criteria for selenium – 1987*. EPA 440-5-87-006. US Environmental Protection Agency, Office of Water.

USEPA. (2013). *Revised deletion process for the site-specific recalculation procedure for aquatic life criteria*. EPA 823-T-13-001. US Environmental Protection Agency, Office of Water.

USEPA. (2016). *Aquatic life ambient criteria quality criterion for selenium – Freshwater*. EPA 822-R-16-006. US Environmental Protection Agency, Office of Water.

