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SELENIUM IN THE ELK RIVER BASIN, BRITISH COLUMBIA - A REVIEW OF FINDINGS AND DISCUSSION OF IMPLICATIONS FOR ASSESSMENT AND MANAGEMENT

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ABSTRACT

Despite 100 to 200 fold increases in waterborne selenium below coal mine operations in the Elk River basin, concentrations in sediments, attached algae, aquatic insects and fish tissues were only 2 to 5 times greater than reference sites. Selenium concentrations in Westslope cutthroat trout skeletal muscle and liver were higher in the near field populations and exceeded published toxic effects thresholds for fish tissue. Further study in 1998 compared the frequency of embryonic deformities and mortalities with the; Se concentration in the eggs of individual female cutthroat trout in an exposed and a reference population. Egg selenium concentrations ranged from 2.0 to 8.8 μg/g dry wt. in reference fish, and 8.7 to 81.3 μg/g dry wt. in exposed fish. Both reference and exposed populations showed low frequencies of deformities (<2.5%) and occasional high frequencies of mortalities (up to 100%) but no correlation with egg selenium. The lack of response in this population of cutthroat trout suggests an evolved tolerance to selenium at levels reported elsewhere to cause significant toxic effects. The findings of the Elk River studies provide evidence that development and application of universal criteria must be done with great caution. Management decisions made on residue data alone may be unnecessarily under or over protective. At this stage it appears necessary that site specific studies must be carried out to verify the absence: or presence of effects.

BACKGROUND

Selenium contamination of surface waters from human activities falls into two categories. The first could be described as accelerated mobilization of *in situ* minerals and would include mining in Se bearing strata, and the irrigation of seleniferous soils. The second includes industrial effluents, usually those associated with fossil fuels such as oil refineries or coal fired power plants.

Although Se is an essential micronutrient for most vertebrates it becomes toxic at amounts not much higher than required quantities. In two well documented cases, Belews Lake, North Carolina and Kesterson National Wildlife Refuge, California, water borne Se at relatively low concentrations (<20 μg/L) caused severe toxic response in fish and birds, extirpating a number of species. The mode of toxicity of Se is somewhat unusual compared with other metal/metalloids. The primary pathway of bioaccumulation in fish and aquatic birds is through the diet not directly from the water (Lemly 1993). Bioaccumulated Se has little effect on the adult female but maternal transfer to the egg yolk causes teratogenic malformations in the embryo which may be immediately fatal or lead to premature death through impaired fitness (Lemly 1993).

The release of significant quantities of selenium into surface waters from coal mines in the Elk River Basin, British Columbia, was discovered in 1995, during an unrelated assessment for an effluent permit amendment. Concentrations of total Se above mining operations were <1 μg/L while immediately below the mine levels were 25 μg/L. Tailings and settling ponds contained 50 μg/L. The current national and British Columbia guideline for the protection of aquatic life is 1 μg/L total Se (CCME 1999, Nagpal et. al. 1995), and is under review.

Assessment of selenium in the Elk River began in 1996, with the sampling of water, sediment and biota throughout the upper basin. The report on this work (McDonald and Strosher 1998) recommended several follow-up studies, the most important of these being the examination for toxic effects in the embryos of cutthroat trout obtained from exposed and reference sites. Se bioaccumulation was clearly occurring in fish captured below the mines at levels that exceeded published toxic effects thresholds (Lemly 1993), although interestingly some fish tissues from reference sites also exceeded these thresholds. Anecdotal evidence that fish populations were apparently healthy and no toxic effects had ever been reported was considered an inadequate basis to conclude that no effects were occurring. The mode of toxic response to Se is such that serious loss of embryos can occur with the surviving adults showing no apparent effects (Lemly and Smith 1987, Lemly 1997).

This paper summarizes the two previous studies in the Elk River (McDonald and Strosher 1998, Kennedy et.al. 2000) and discusses the implications of these findings on the broader topic of managing Se contamination of surface waters.

RESULTS

The location of the most important sampling sites from both the 1996 survey (McDonald and Strosher 1998) and the 1998 embryo study (Kennedy et. al. 2000) are noted on Figure 1. Fish tissue samples in 1996 were collected from a remote site in the upper Elk River (Elk 96, reference), the Fording River immediately downstream of an operating coal mine (Fording 96, near-field), and from the lower Elk River (Elk 96, far-field). In June 1998 spawning cutthroat trout *(Oncorhynchus clarki lewisf)* were trapped at Connor Lake (Connor 98, reference) and on the Fording River approximately 3 km below the 1996 site (Fording 98, near-field) (see Figure 1).

In 1996 water, sediment, algae and benthic invertebrate samples were collected at sites shown on Figure 1 plus several other sites within this area. Finally, total Se has been monitored bi-weekly at the mouth of the Elk River, 130 km downstream of the coal mines, since 1986 as part of a larger federal/provincial trend monitoring program.

<u>Water Sampling</u>

Twelve years of total Se monitoring at the mouth of the Elk River show a rising trend, from 0.1 μg/L in 1986 to over 2 μg/L in 1998 (Figure 2). Analysis of all these samples has been performed at the National Laboratory for Environmental Testing in Burlington, ON employing a hydride generation method with a minimum detection limit of 0.1 μg/L.

In 1996, water column selenium at all reference sites was consistently below the 1 μg/L detection limit. Two reference site samples, at which a 0.1 μg/L detection limit method was employed, had concentrations of 0.1 and 0.2 μg/L total Se. In major streams below the coal mines concentrations were found from 5 to 20 μg/L, while some smaller tributaries within the mines had ranged up to 315 μg/L.

Total Se concentrations in the river at the exposed fish capture site in 1998 were 13 μg/L, and this was during spring high water. Two samples taken at the Connor Lake reference site, one from near-shore and one from the inflow stream the fish were spawning in, both contained <0.1 μg/L total Se.

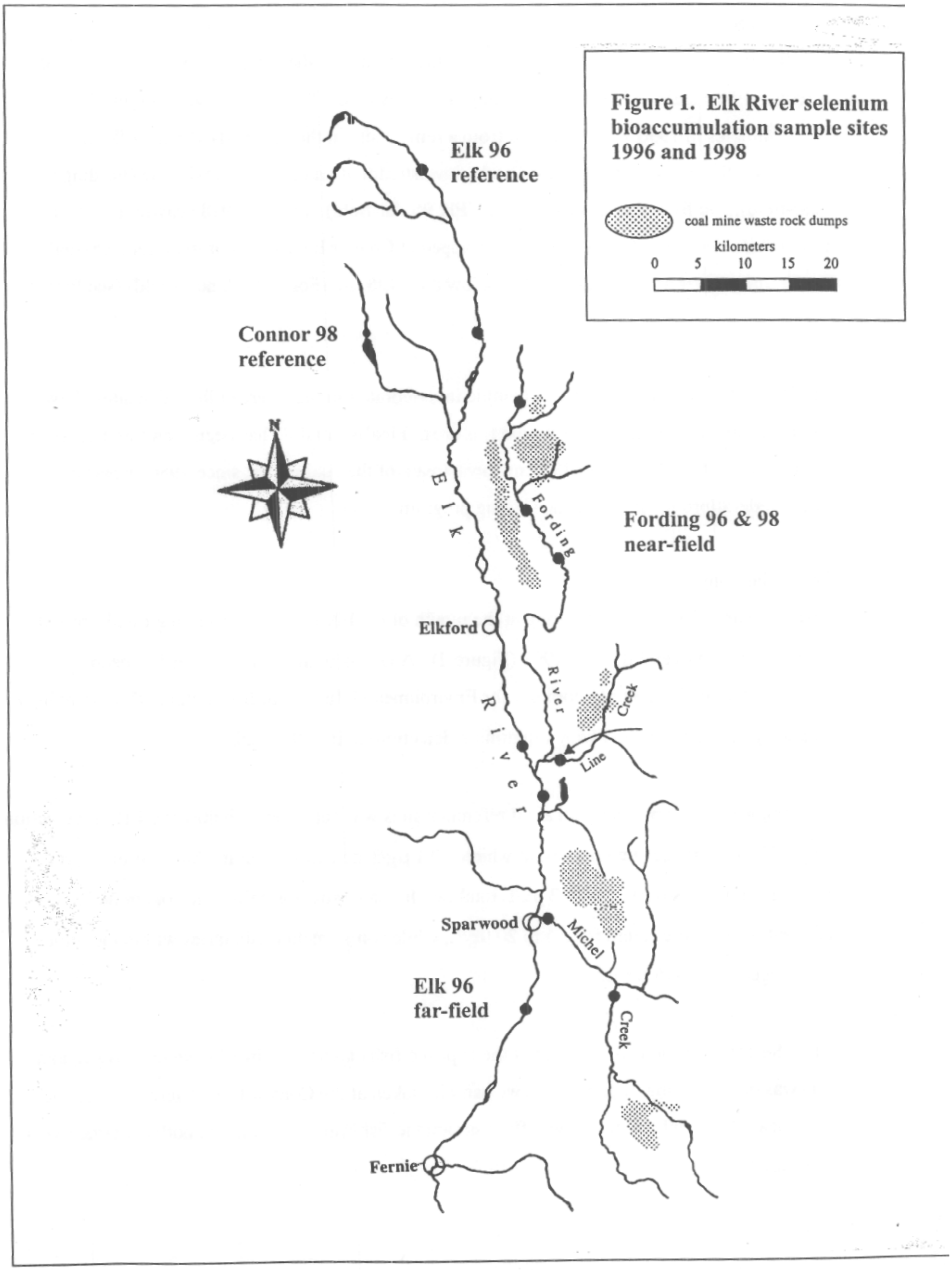


Figure 1. Elk River selenium bioaccumulation sample sites 1996 and 1998

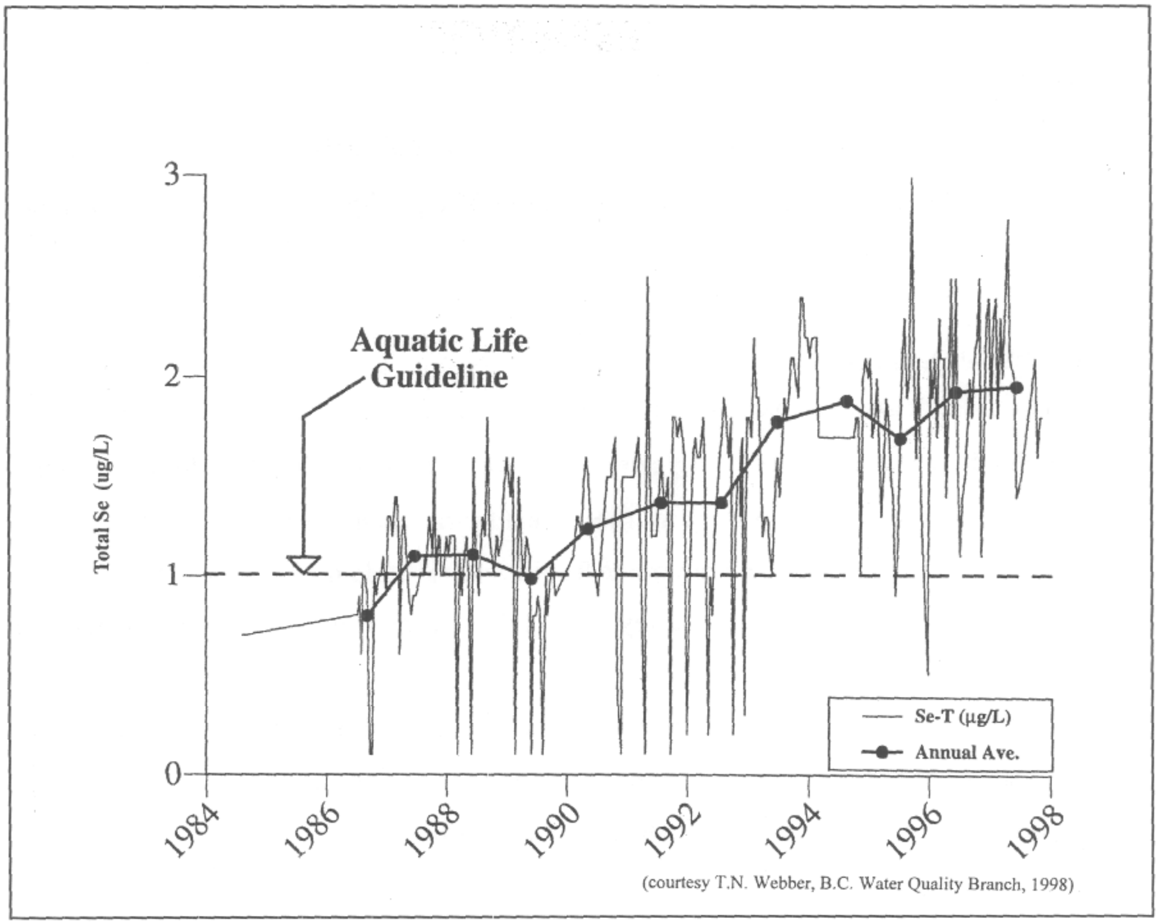


Figure 2. Total Selenium (ug/L). Elk River at Phillips Bridge (Highway 93).

Bottom Sediment

In 1996 fine bottom sediments, sampled in depositional parts of stream channels, yielded Se concentrations from 0.5 to 1.28 µg/g dry wt. at reference sites (n = 4), 1.53 to 2.41 µg/g dry wt at near-field sites (n = 4), and 0.7 to 1.18 µg/g dry wt. at far-field sites. This represents up to a 5-fold increase from reference to exposed sites.

In 1998 a bottom sediment sample at the Connor Lake reference site (near shore) had 2.0 µg Se/g dry wt. while a sample from the creek flowing into the lake, where the fish spawn, had 4.2 µg/g dry wt. Note that this latter reference stream feeding a remote alpine lake, contained more Se than sites immediately below the coal mines.

Algae

Algae attached to bottom substrate (periphyton) followed a similar pattern as sediment, ranging from 0.31 μg Se/g dry wt. at the reference site to 1.56 μg/g dry wt. at the highest near-field site (n=6), a 5 fold increase.

Food-Chain Organisms

Benthic invertebrate samples (mixed taxa) from two reference sites in 1996 had Se concentrations of 2.74 and 6.84 μg/g dry wt. These compared with near-field samples that ranged from 6.82 to 10.7 μg/g dry wt. (n = 3) and far-field samples that were 4.29 and 4.62 μg/g dry wt. (n = 2). This represents anywhere from a zero to 4-fold increase in the Se content of benthic invertebrates, which form a key, but not the sole, component in the diet of cutthroat trout.

In 1998 samples of net zooplankton and Gammarid amphipods from the Connor Lake reference site contained 1.03 and 2.66 μg Se/g dry wt. respectively. These organisms form a substantial portion of the diet of the fish from which eggs were taken.

McDonald and Strosher (1998) pointed out that the magnitude of bioaccumulation of Se in exposed reaches, at most a 5 fold increase over reference sites, was much lower than the increases observed in the water column, 100 to 200 fold.

Fish

Cutthroat trout were selected as the test species based on their presence in all reaches studied. Selenium tissue analyses at the five sampling sites from both the 1996 and 1998 studies are shown in Figure 3 (skeletal muscle) and Figure 4 (liver). There are three observations that can be made from data for both these tissues. First, exposed sites are consistently higher than reference sites, indicating that the Se released from the coal mines is being bioaccumulated by this species of fish. Second, the content of Se in each tissue varies much more from fish to fish at exposed sites than at reference sites. Individual analyses have been plotted to show that the distribution across the range is not uniform, in fact there are one or two fish with tissue Se much higher than the rest. Third, toxic effects thresholds (TET) published by Lemly (1993), which have become the benchmark for evaluating potential Se toxicity, were exceeded. The TET for muscle (8 μg/g dry wt.) was exceeded by most of the fish from the exposed sites (Figure 3). The TET for liver

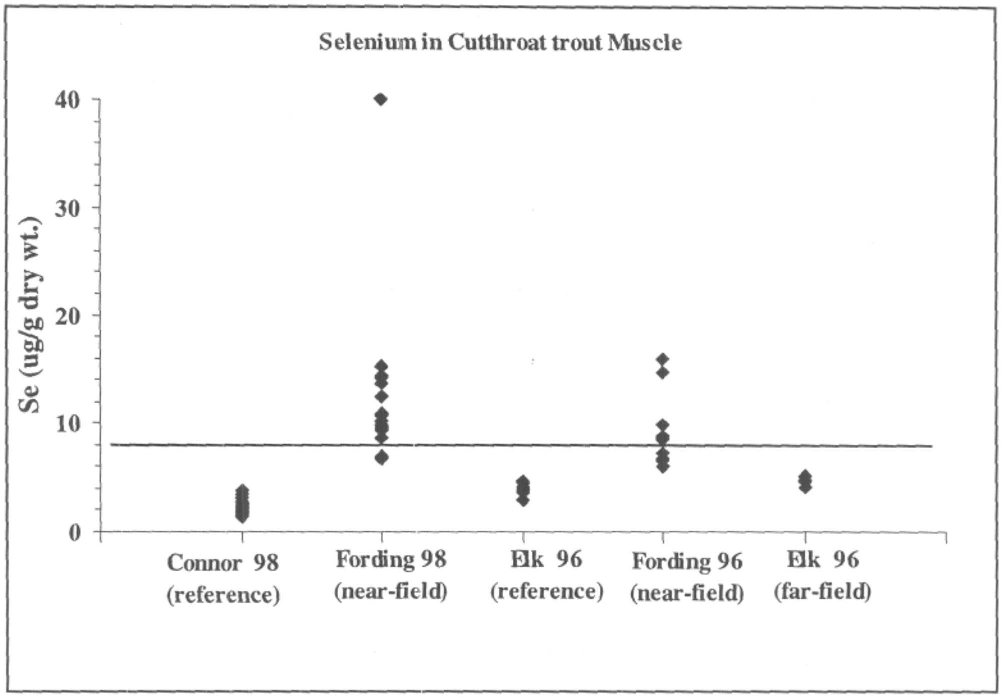


Figure 3. Selenium in cutthroat trout muscle. Sample size n= 19; 17; 10; 10; 5, Connor to Elk far-field, respectively. Horizontal line = Toxic effects threshold (Lemly 1993).

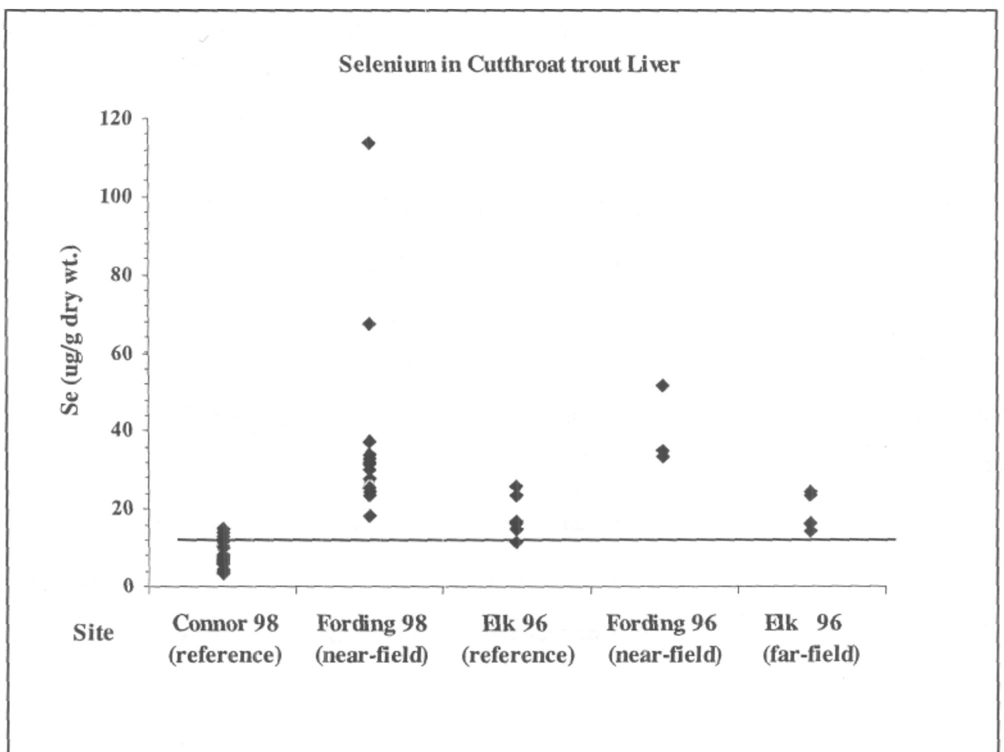
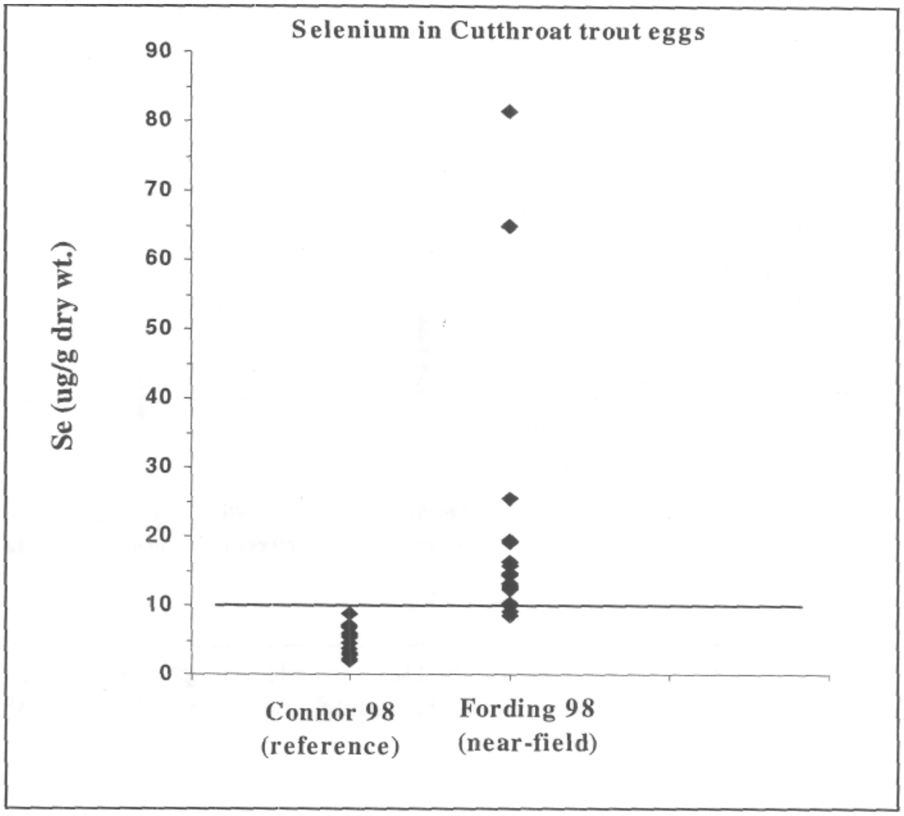


Figure 4. Selenium in cutthroat trout liver. Sample size n= 20; 17; 8; 3; 4, Connor to Elk far-field, respectively. Horizontal Line = Toxic effects threshold (Lemly 1993).



Figures. Selenium in cutthroal: trout eggs. Sample size n=20; 17, Connor and Fording respectively. Horizontal line = toxic effects threshold (Lemly 1993)

(12 µg/g dry wt.) was exceeded by all of the samples from the exposed sites but, interestingly, also by most of the fish from the river reference site (Figure 4).

Egg Se concentrations from the 1998 study (Kennedy et. al. 2000) are shown in Figure 5. Again, individual analyses of each female's brood are presented to show the distribution across the range. Egg Se in the 20 fish from the reference site are distributed in a narrow range from 2.0 to 8.8 (µg/g dry wt. At the exposed or near-field site, however, 14 of the 17 fish ranged from 8.7 to 19.3 µg/g dry wt. with three outliers at 25.4, 64.8 and 81.3 µg/g dry wt. The egg/ovary TET (10µg/g dry wt.) (Lemly 1993) was exceeded by most of the fish at the exposed site and by none at the reference site.

Based on a comparison to Lemly's (1993) TET alone it would be easy to assume that embryos in the clutches of eggs illustrated in Figure 5 would be suffering from Se induced teratogenic toxicity, particularly the two highest Se broods, at 6 and 8 times the TET. This was not the case.

Figures 6 and 7 show the relationship between egg Se and percent deformities and mortalities prior to yolk absorption from Kennedy et. al. (2000). The exposure of the embryo to the Se in the yolk is the cause of teratogenic deformities and these effects effectively cease when external feeding begins (Lemly 1997). The percent deformities in even the highest egg Se brood was very low, <0.5%, and showed no correlation with egg Se content. Similarly, the percent mortalities, though high in three broods, were not correlated with egg Se. Indeed the three highest egg Se broods had similar numbers of mortalities to many of the reference fish (<10%). This is the most important finding of the studies conducted to date in the Elk River.

DISCUSSION

The studies that have thus far been conducted on Se in the Elk River have produced several important results. Some of these findings confirm what has already been reported in the literature, other results were quite unexpected and have significant implications for the understanding of the ecological effects of this unusual contaminant.

Although based on limited data, the food-chain uptake of water borne Se in the Elk River is limited. A mixed sample of benthic invertebrates at the most exposed site, where total Se levels in the water are 20 to 25 μg/L, had 10.7 μg Se/g dry wt. This can be compared to 6.4 to 96.3 μg/g dry wt. in benthic invertebrates in Belews Lake (Hodson 1990) where water concentrations where 3 to 22 μg/L (Lemly 1985).

Despite this limited food-chain uptake, certain Westslope cutthroat trout were found to have bioaccumulated relatively high tissue Se residues. This fish species is an opportunistic feeder, taking whatever aquatic or terrestrial insects become available. This may explain the large range in tissue Se concentrations among fish trapped in the same location. Lemly and Smith (1987) discussed the greater potential for Se bioaccumulation in standing versus flowing water habitats but also pointed out that slower flowing sections of streams or side-channel marshes are at greater risk. In our studies the fish with the highest residues may have fed in stream reaches with higher Se bioaccumulation and/or relied less on the terrestrial component.

When, in 1996, we found bioaccumulation in fish occurring at levels exceeding published toxic thresholds, and with the knowledge that these fish populations were apparently healthy and no effects had ever been reported, we postulated that either toxic effects were cryptic or the fish had

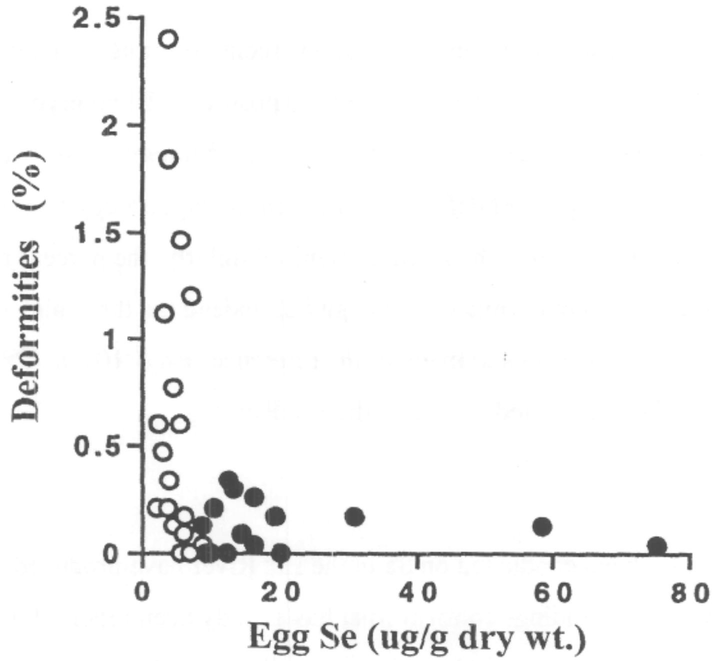


Figure 6. Egg Selenium concentration versus percent deformities in eggs and alevins. Reference = o; Exposed = • (Kennedy et. al. 2000).

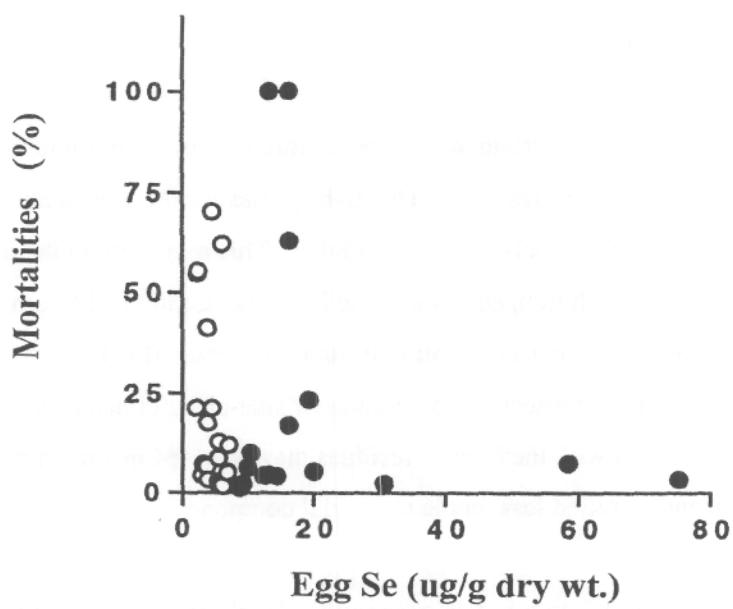


Figure 7. Egg Selenium concentration versus percent mortalities in eggs and alevins. Reference = o; Exposed = • (Kennedy et. al. 2000).

a higher tolerance to Se. The 1998 study was designed to determine if toxic effects, that could be overlooked in the wild, were present, and if so did they correlate with egg Se concentrations. The lack of toxicity, even at egg Se of 80 μg/g dry wt., leads us to conclude that this population of Westslope cutthroat trout has a tolerance to Se tissue levels that have proven toxic to other species and populations. We further hypothesize that this tolerance is related to the presence of Se in the geological formations in the valley and a greater exposure in the aquatic environment that may date back at least to the last ice age.

This hypothesis needs considerable additional testing, but if true the implications for the management of Se in aquatic systems are significant. These include:

- If fish, and presumably other vertebrates, can/do evolve a tolerance to Se in their native habitat, increases in waterborne Se can be expected to have less effect in seleniferous systems than in low Se areas. Human activities that release additional Se into surface waters in seleniferous regions (e.g. mining) may be expected to have less impact than the introduction of Se into low Se systems (industrial effluents).
- The introduction (stocking) of fish from a low to a higher Se habitat, even though the species is found in both systems, may fail. The stocked individuals may well survive but their offspring may not.
- The development and application of universal criteria for Se, in any matrix, must be done with great caution. The use of water-based criteria is complicated by the fact that bioaccumulation is heavily influenced by chemical speciation. Selenite is more readily bioaccumulated than selenate and organic forms to an even greater degree (Presser et. al. 1994). The relative proportions of Se species is dependent on the source (erosion sources are predominantly selenate, industrial effluents, mainly selenite) and the type of aquatic habitat (cycling in wetlands can convert selenate to selenite and organic forms). Tissue-based criteria would appear to avoid the complexities of bioaccumulation providing that a simple dose-response relationship exists across taxonomic groupings. If individual populations of fish and other vertebrates of the same species have different levels of tolerance to Se, tissue-based criteria must also be approached with caution. The case for site-specific toxicity assessments becomes decidedly stronger.

Future Research

The lack of toxic response in Elk River cutthroat trout, despite high concentrations of egg Se, is mainly based on samples from two fish (64 and 81 μg/g dry wt.), the other 15 samples ranging from 8 to 25 μg/g dry wt. More evidence is needed from fish in seleniferous systems with egg Se concentrations in this range or higher to corroborate or refute the hypothesis of adapted tolerance. Such information may be forthcoming as Alberta Environment is planning to conduct a similar study on rainbow trout that have been found to bioaccumulate Se being released from coal mines in the northwest part of the province.

Another opportunity to study Se body burden tolerance in a sub-species of cutthroat trout exists in the phosphate-mining district in the Blackfoot River watershed in Idaho. Selenium, mobilized into surface waters from waste spoils at open-pit phosphate mines, has been found to bioaccumulate in Yellowstone cutthroat trout *(Oncorhynchus clarki bouveri* Richardson) (Lemly 1999).

In the Elk Valley there is yet a need to examine Se bioaccumulation and effects in other species such as aquatic birds or amphibians. To assume that all exposed species are as apparently unaffected as cutthroat trout would not be prudent. Planning is underway for such work.

Final Comments

Sorensen (1991) stated "Se is considered both an essential element and a villainous killer among trace elements, depending upon the exposure concentration". Frankenberger and Engberg (1998), describing the nutritive and toxic nature of the element, stated "As we approach the millennium, selenium is arguably the naturally occurring trace constituent of greatest concern worldwide." In a recent invited debate/commentary Chapman (1999) asked for submissions from experts in the field to the charge "Selenium - A potential time bomb or just another contaminant?" Submitted papers ranged from "Selenium Impacts on Fish: An Insidious Time Bomb" (Lemly 1999), to "Selenium Was a Time Bomb" (Ohlendorf 1999), to "Critical Review of Proposed Residue-based Selenium Toxicity Thresholds for Freshwater Fish" (DeForest et. al. 1999).

That Se is a serious contaminant in aquatic systems that can cause severe toxic response in fish and wildlife is indisputable, but our findings suggest perhaps not at the same level of exposure in all environmental settings. The ecotoxicological complexities of this element dictate that thorough, well designed assessments of effects, or the lack thereof, are required in each instance of Se contamination before decisions can be made regarding remediation and management.

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