SELENIUM MONITORING AND MANAGEMENT – NEW MINES

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ABSTRACT

Selenium is a contaminant of particular concern for coal, phosphate, uranium and some precious and base metal mines. Regulators require reasonable assurances that environmental risks will be detected and ameliorated. Proponents require reasonable assurances regarding potential future liabilities. Provision of such assurances requires: identification of receptors of potential concern (for monitoring and investigative studies); generic and specific guiding principles; a three-tiered strategy (potential risk of impact? → realistic risk of impact? → any necessary management actions?); and, adaptive management. Primary levels of protection should be based on both appropriate whole body tissue (not water) guidelines (the present BC interim tissue guideline value does not appear to be appropriate), and background data (which can be naturally elevated). Background data should be used, where appropriate, as site-specific initial guidelines within the tiered strategy.

INTRODUCTION

Selenium is an essential element but, like all substances, is toxic at elevated concentrations. It has two different modes of toxic action in the aquatic environment. Acute toxicity occurs at relatively high water-borne selenium concentrations via similar mechanisms as the toxic responses of other inorganic substances such as metals. Specifically, uptake is via the gills or other respiratory structures with consequent disruption of physiological processes. Available scientific data indicate that chronic toxicity in the aquatic environment is restricted to fish and waterbirds and is related not to water column inorganic Se concentrations, but rather to organo-selenium body burdens, which are derived from dietary sources (USEPA 1998a).

Mining for coal, phosphate, uranium and some precious and base metals accelerates the natural release of selenium from rocks containing naturally elevated concentrations. There presently is no set approach for assessing the risks from selenium for new mines. The purpose of this paper is to propose such an approach via a framework that follows the Canadian and U.S. ecological risk assessment (ERA) paradigm (CCME 1996; USEPA 1998b): it considers available information (Problem Formulation), Exposure and Effects to provide a Risk Characterization.

RECEPTORS OF POTENTIAL CONCERN

There are five environmental receptors of potential concern (ROPCs) related to selenium in the aquatic environment: (1) Water – the initial route of entry for selenium into the aquatic environment; (2) Periphyton – a key food chain component and vector for selenium to fish and waterbirds; (3) Benthos – another key food chain component and vector for selenium to fish and waterbirds; (4) Fish – reproduction may be affected by dietary uptake of selenium; (5) Waterbirds – reproduction may also be affected by dietary uptake of selenium.

The following receptors are not considered ROPCs for reasons outlined. Humans – Se typically does not pose a human health risk. Sediment – measuring selenium concentrations in sediments is not a reliable indicator of selenium impacts on aquatic biota because the route of exposure is dietary rather than by exposure to contaminated sediments. Terrestrial Wildlife – the primary risk to terrestrial wildlife is from consumption of plant species that have accumulated selenium to toxic levels. There presently are no data for evaluating the significance of elevated Se concentrations in plants. The best approach is to monitor the health of ungulates (e.g., sheep and elk), including early warning signs such as cracking of hooves or unexplained hair loss. Amphibians – the scientific literature does not presently identify selenium as a potential threat to amphibians as it does for fish and waterbirds. Amphibians are subject to a wide variety of other stressors that can impact their populations, both natural and anthropogenic (e.g., climate variation, eutrophication, pesticides), and populations can be highly variable year-to-year even in reference areas (where selenium concentrations are at background). At present amphibians are not considered to be primary ROPCs related to selenium, nor suitable biota to monitor relative to potential selenium effects. However, studies being conducted in 2005 on spotted frogs in the Elk River Valley may provide information requiring a reassessment of amphibians as ROPCs.

GUIDING PRINCIPLES

Generic Guiding Principles

The following Generic Guiding Principles should be followed. First, short and long-term goals in areas affected by selenium should include protecting, maintaining and sustaining populations of fish and other aquatic organisms, including regional biodiversity. Second, the primary focus should be on reproductive success of fish and waterbirds exposed to selenium via dietary uptake. Third, water quality guidelines are not an appropriate tool to determine selenium effects (the primary exposure route is dietary). Fourth, risk should be assessed site-specifically, since there are no universally accepted threshold values. Fifth, total selenium concentrations should be measured in water and in aquatic biota. Sixth, although the primary concern for selenium toxicity to fish and waterbirds is in lentic, not lotic waters, both should be monitored.

Specific Guiding Principles

The following four Specific Guiding Principles should be followed to ensure adequate protection of fish and waterbirds.

Specific Guiding Principle 1

For fish and waterbirds, two levels of protection should be set: (1) an appropriate level of protection below which there is reasonable certainty that there will be no adverse effects, and above which there may or may not be effects; (2) a lower level of protection (e.g., on the order of 75-80% of the primary protective level) intended, if exceeded, to trigger focused investigations to determine whether or not there will be effects, well in advance of exceedance of the primary level of protection (Figure 1).

Specific Guiding Principle 2

Determination of the primary level of protection should involve consideration of both background data, and appropriate and relevant information from other studies. There is general agreement that environmental protection in Se-contaminated systems requires a tissue-based, not a water-based, generic guideline value (Hamilton 2002; Sappington 2002; USEPA 2002, 2004). However, there is not agreement as to what this generic value should be. For fish, USEPA (2002, 2004) suggests that an appropriately protective value would be 7.9 mg/Kg dry weight (dw) in whole tissue. However, Hamilton (2002) suggests an appropriate whole body national (US) tissue-based value should be 4 mg/kg dw. Site-specific guideline values may be higher than such generic values.

Recent effects-based studies on trout in both Alberta (rainbow trout, *Oncorhynchus mykiss* and brook trout, *Salvelinus fontinalis* – Holm 2002; Holm et al. 2003, 2005) and British Columbia (cutthroat trout, *Oncorhynchus clarki lewisi* – Kennedy et al. 2000) indicate that the USEPA (2002, 2004) value provides conservative protection for trout in northern waters (Chapman and McPherson 2004; Table 1). In other words, whole body selenium concentrations < 7.9 mg/kg dw will not result in adverse effects to these trout species; higher concentrations may or may not result in adverse effects. The 7.9 mg/kg dw USEPA (2002, 2004) value should be considered as a potential primary protective level, but needs to be considered in the light of baseline data.

Figure 1. Two levels of protection based on Se tissue levels and possible trend lines. Line A has crossed the conservative, lower level of protection and triggered focused investigations. Trends shown in Lines B and D do not appear to be of concern; however, Line C may be of future concern due to its increasing slope in comparison to the leveling out of Line B.

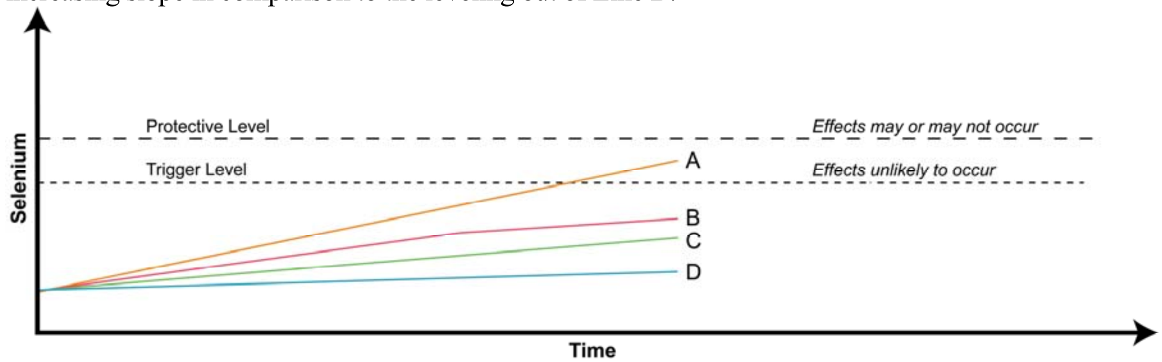


Table 1. Trout sensitivity to selenium.

Egg/Ovary Se (mg/kg dw)	**Holm (2002); Holm et al. (2003, 2005)**		**Kennedy et al. (2000)**	**USEPA (2004)**
	Rainbow trout*	Brook trout*	Cutthroat Trout**	Whole body 7.9 µg/g dw ***
Effects "Threshold"	10.2 to 25.6	>18.5 to >20	>21.2	17

* assuming 61% moisture content; ** measured moisture content; ***using the procedure in USEPA (2004) to convert to an egg/ovary value.

Similarly, for waterbirds eggs, toxicity reference values (TRVs) from the literature, which range from 6 mg/kg dw (USDOI 1998) to 12 mg/kg dw (Adams et al. 2003) should be considered, together with background data, to determine an appropriate primary level of protection.

To develop proposed levels for defining baseline conditions for new mines, a control chart approach is recommended. This approach is commonly used by analytical laboratories to define warning and control limits for quality control (QC) samples, and also by toxicity testing laboratories for monitoring reference toxicant test performance (Environment Canada 1990). The mean and SD are used to define a normal variability range for each data set. In the case of reference toxicant data, at least 5 data points are usually needed to establish the control chart but 15 to 20 data points may be needed to determine that the observed variability between results is representative (variability in analytical or reference toxicant data is generally expected to decrease over time and then stabilize). On the control chart, warning limits are set at ±2SD (the 95% confidence limits) and control limits are set at ±3SD (the 99% confidence limits). At the 95% confidence level, 1 in 20 data points (5%) can be expected to fall outside the warning limits due to chance alone. At the 99% confidence level, the probability of a data point falling outside the control limits due to chance alone is much lower (1 in 333 data points, or 0.3%).

A factor to consider when interpreting control chart data is the size of the warning and control limits. If data are highly variable, the ±2SD and ±3SD values may be so wide that the limits are never exceeded and are of little value in defining normal data variability and identifying atypical data. Conversely, if data variability is low then the warning and control limits will be narrow and a relatively small increase in variability can result in a limit being exceeded. In the case of reference toxicant data interpretation, Environment Canada (1990) suggested CV values of 20 to 30% as a target, while BSAB (1994) classified CVs <35% as excellent in terms of data variability.

The use of this control chart approach is illustrated using background data from three coal mines in the Tumbler Ridge area, BC (Figure 2). Whole body analyses of slimy sculpins showed relatively low variability (i.e., CVs ranged from 4 to 25%), indicating that sample sizes of five fish per station were reasonable for defining baseline sculpin tissue selenium concentrations. There was no relationship between sculpin age and tissue selenium concentrations, which also supports the use of this relatively small sample size. The overall mean tissue selenium concentration for all sculpin samples from all stations was 1.25 mg/kg ww, exceeding the 1.0 mg/kg ww BCMWLAP (2001) interim guideline for whole-body tissue selenium and suggesting that this value is too low. In contrast, the overall mean tissue selenium concentration for all sculpin samples from all stations was 5.38 mg/kg dw, which did not exceed the proposed USEPA (2002, 2004) 7.9 mg/kg dw criterion for whole-body tissue selenium.

This control chart approach allows for a determination as to whether or not future data are representative of background conditions. Exceedance of the proposed levels would be an indication that data were not consistent with baseline conditions, but would not give any indication of the potential for adverse effects.

The sculpin data were also used to estimate the sample size required to allow determination of statistically significant differences in fish tissue data, either between stations or over time at the same station. Following the guidance provided by Environment Canada (2002) for metal mining environmental effects monitoring programs, α and β were set between 0.05 and 0.10 for detecting an effect, and the desired minimum detectible difference was set at 2SD from the mean. The values α and β represent the significance level of a comparison between two means, and provide information about the probability of committing a Type I and Type II error, respectively. A Type I error occurs when the null hypothesis of no difference is rejected, when in fact it is correct. A Type II error occurs when the null hypothesis of no difference is not rejected, when in fact a difference between means exists. The minimum sample size required to achieve the above parameters can be calculated as follows (Environment Canada 2002; Zar 1984):

$$n \geq 2*s^2*(t_\alpha + t_\beta)^2/\delta^2$$

where n = sample size

t_α = t value for a significance level of α (Probability of a Type I error, two-tailed)

t_β = t value for a significance level of β (Probability of a Tpe II error, one-tailed)

s = standard deviation, estimated from historical data

δ = Minimum detectible difference, or effect size

Setting δ at 2 SD as described above, the formula simplifies to become:

$$n \geq (t_\alpha + t_\beta)^2/2$$

An estimate for "n" is used in the first step, and the equation is solved iteratively after the initial calculation. Results of the calculation are as follows:

A	B			
	0.01	**0.05**	**0.10**	**0.20**
0.01	14	11	10	8
0.05	11	8	7	5
0.10	9	7	5	4

In order to be able to determine statistically significant differences between samples, based on an effect size of 2SD, the number of samples required depends on the desired values used for α and β. For example, if these are both set to 0.05, then 8 replicates would be required, but if they are set to 0.10, then 5 replicates would be required.

Specific Guiding Principle 3

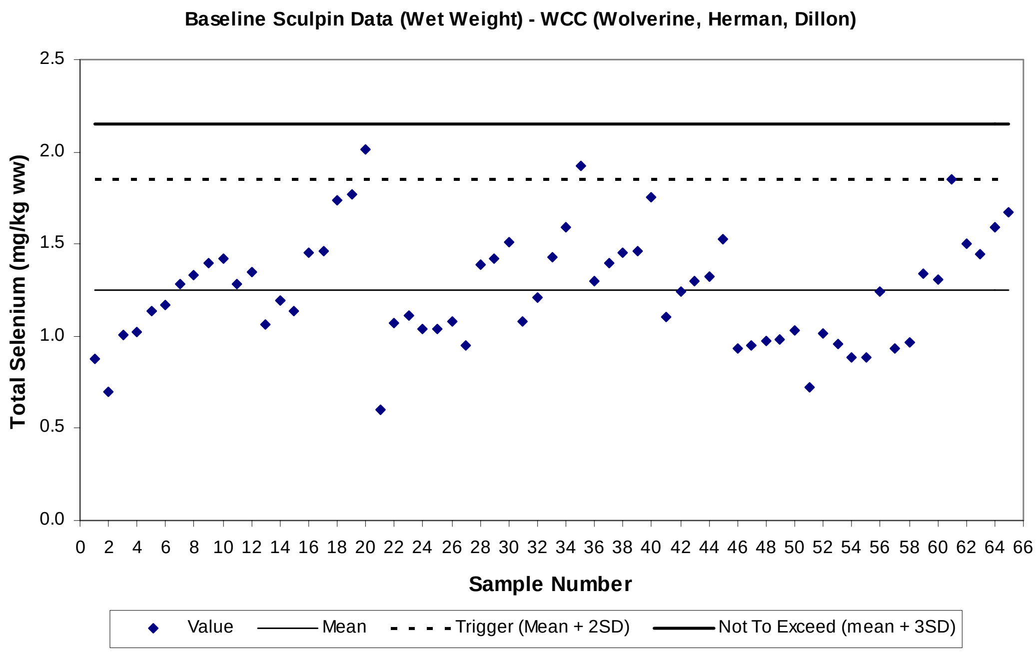
Monitoring data should be compared to the two levels of protection in a tiered strategy, of which monitoring is Tier 1 (Is there a potential risk of impact?); both the trend of the monitoring data and their proximity to the lower level of protection should be examined as part of the determination as to whether or not to proceed to Tier 2 (Is there a realistic risk of impact?).

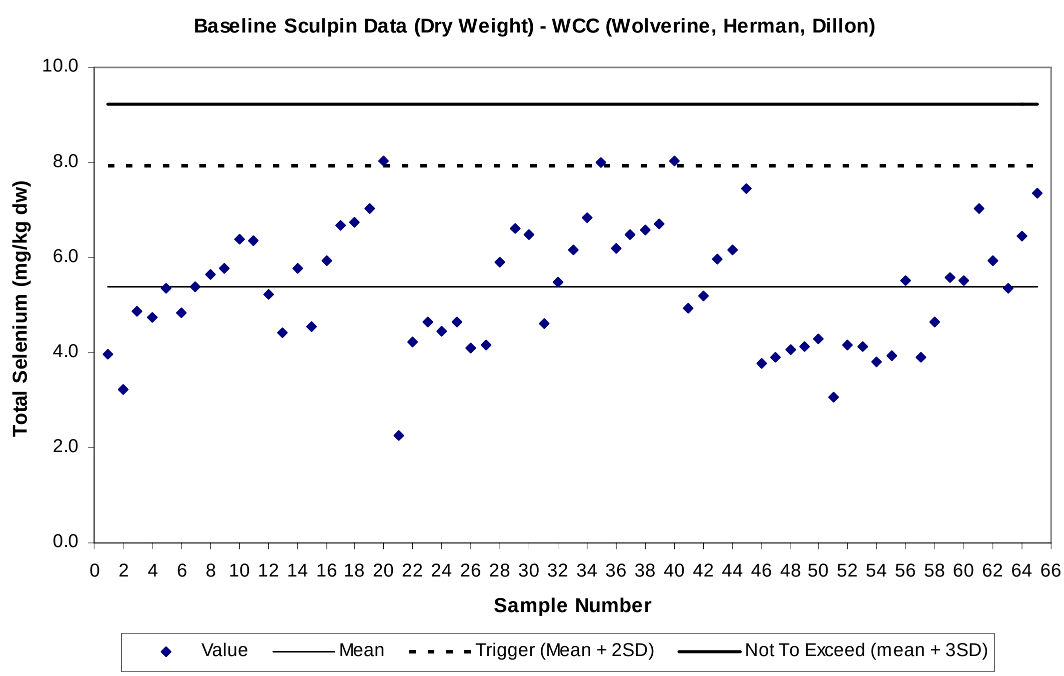
Effectively, this strategy follows the ERA paradigm for screening assessments, where a hazard quotient (HQ) is developed by dividing measured environmental concentrations [in this case, fish whole body and waterbird egg selenium body burdens – Tier 1) by predicted no effect concentrations. A HQ < 1 indicates negligible risk. A HQ > 1 indicates potential risk; further investigation (Tier 2) is required to determine whether or not a risk actually exists.

Specific Guiding Principle 4

Determinations as to whether or not to proceed to Tier 3 will be based on a determination of realistic potential for impacts, not solely on potential or demonstrated effects. An effect is defined as a change to a ROPC related to selenium released as a result of mining activities. For instance, selenium could, as has been documented in the Elk River Valley (Harding et al. 2005) be associated with reduced hatchability of spotted sandpipers (*Actitis macularia*). However, since this effect did not result in any changes to overall productivity, which was in fact higher than the regional average, this effect did not result in an impact. An impact is defined as an effect that adversely affects the utility or viability of a ROPC. An effect is not necessarily a negative impact; an effect may be neutral or even positive. The latter possibility (positive effects) is particularly relevant in the case of selenium, which is an essential element.

Figure 2. Proposed baseline tissue selenium limits for sculpin (wet weight and dry weight) – Western Coal's Herman, Dillon and Wolverine Mines (combined). Note that baseline data generally exceed the BCMWLAP (2001) interim whole body tissue guideline (1 mg/kg ww) but only rarely exceed the USEPA (2002, 2004) draft whole body tissue criterion (7.9 mg/kg dw).

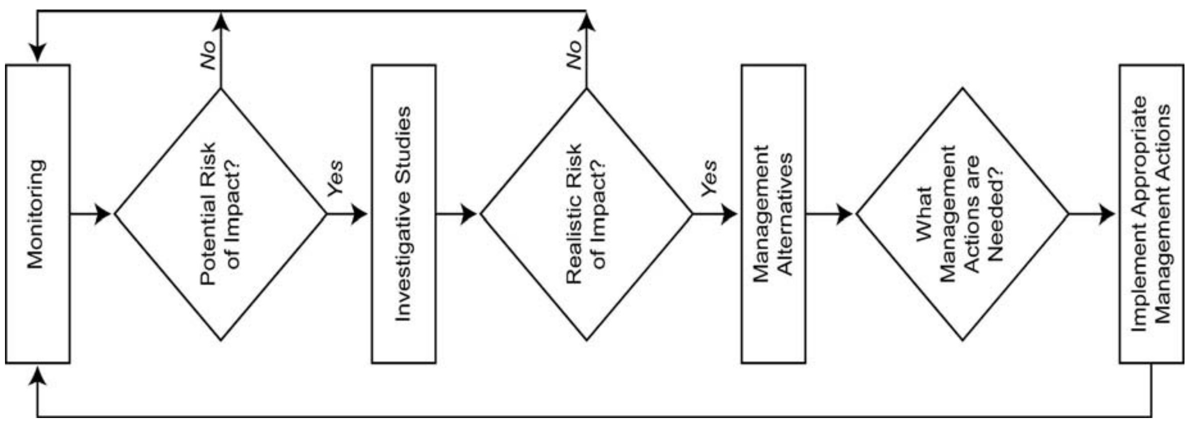




SELENIUM MONITORING AND MANAGEMENT PROGRAM

A tiered strategy should be followed for selenium monitoring and management following the Generic and Specific Guiding Principles as applied to the ROPCs. This strategy is designed to (Figure 3): Tier 1 - determine trends in selenium concentrations in water and biota, assess the status and health of resident fish and waterbirds populations on an on-going basis, and assess sources - to provide early warning of potential selenium toxicity before such is manifest and determine whether or not such toxicity may be manifest; Tier 2 - to conduct any necessary investigative studies should there be a potential for selenium toxicity (effects) resulting in impacts; and, Tier 3 - should there be a reasonable potential for impacts, to ensure that appropriate and timely management actions are taken.

Figure 3. Selenium Monitoring and Management Strategy



<u>Tier 1: Is There a Potential Risk of Impact(s)?</u>

This initial tier will involve three types of investigations: sources of selenium; concentrations of selenium in water and biota; and, the status and health of resident fish populations. Effectively this tier focuses on sources, exposure to selenium (if exposure does not occur or does not occur to a sufficient level, adverse effects will not occur), and on the health of sensitive resident biota (the "gold standard" relative to potential selenium effects).

Sources

Investigations should include determinations as to whether or not there are particular areas of the mine where selenium is consistently released, such that these releases can (a) be reasonably reduced by management interventions, and (b) reductions can be reasonably expected to reduce any realistically potential impacts. Investigations should also be conducted to determine lentic areas where inorganic selenium may be converted into organic selenium, the primary contaminant of concern (COC). Such investigations should also determine the relative proportion of lotic compared to lentic areas and their locations relative to selenium discharges from the mining operations. Ideally, information gathered over time as the mine develops and enters full production, will be used to make predictions regarding selenium inputs (water) through mine life. Similar predictions should be made, as possible, with regard to selenium concentrations in biota (see Exposure, below), following generation of a long enough (i.e., several years) data base.

Exposure

Although water is not the exposure route of concern, it is the primary source for selenium from coal mining entering the aquatic environment. Significant increases in water column selenium concentrations above baseline can indicate potential for additional food chain exposures. Accordingly, water quality monitoring should be conducted to determine any trends. Effectively, this monitoring will provide information regarding any changes that may affect the biota (early warning) as well as an evaluation of the efficacy of any management efforts to reduce Se concentrations from mining (Sources, above). Sampling should be conducted at appropriate exposed and reference locations during high, low and intermediate flow conditions. Both selenium concentrations and loadings (based on flow measurements) should be determined.

Because the primary route of exposure for selenium is via the food chain, determination of food chains and monitoring of key components of those food chains is critical. Because of the importance of dietary uptake of Se, conceptual diagrams detailing the major food chains to key fish and waterbirds should be determined based on available generic and site-specific information, and include consideration of potential seasonal changes. They will form the basis for assuring that monitoring is appropriate, and should be updated periodically as and if new information becomes available.

The food chain conceptual diagrams are used to identify major direct and indirect food chain items for key fish and waterbirds, for which Se tissue concentrations should be determined. Typically, both periphyton and benthic invertebrates are included as primary food chain biota for which Se tissue concentrations should be determined. Because tissue selenium concentrations will not change as rapidly as water concentrations, monitoring should be conducted once yearly and possibly at larger intervals subsequently, dependent on whether any accumulations of selenium are determined and whether selenium concentrations in the water column increase (and the level of any such increase).

The two primary ROPCs are fish and waterbirds, which are the biota that can be affected by selenium toxicity via food chain exposures. Accordingly, appropriate monitoring of selenium concentrations in both fish (whole body analyses per USEPA 2002, 2004) and waterbirds should be a primary component of Tier 1. The primary concern related to selenium toxicity for waterbirds (as for fish) is accumulation of selenium in eggs from maternal transfer, resulting in deformities or death of the developing birds. Accordingly, monitoring should involve collecting eggs from appropriate exposed waterbirds for selenium analyses once yearly and possibly at larger intervals subsequently, dependent on whether any accumulations of selenium are determined and whether selenium concentrations increase (and the level of any such increase – See Figure 1).

Status of Resident Fish and Waterbird Populations

Adverse effects of selenium will manifest as reproductive failures, typically resulting in changes to the proportion of young-of-the-year compared to other age classes. Thus, determining population status of fish relative to selenium will require: monitoring abundance and recruitment; ensuring that no shift in species distributions occurs that could be due to differential tolerances to selenium; and, ensuring that adequate reproduction is occurring to protect, maintain and sustain fish populations. Should there be evidence that adverse effects due to selenium are occurring to resident fish populations, further investigations should be conducted as outlined in Tier 2.

Because waterbirds have a very high mobility it is extremely difficult, at best, to evaluate their populations. Thus, similar population assessments cannot be conducted on waterbirds; instead, measurements of selenium egg concentrations should be supplemented by observations, during egg collections and analyses, of any abnormalities or mortalities that could be due to selenium. Should there be evidence of such effects, further investigations should be conducted as outlined in Tier 2.

Tier 2: Is There a Realistic Risk of Impact(s)?

Tier 2 has two components once entrance into this tier is triggered either by data on selenium body burdens, or by data on resident fish or waterbirds. The first component involves examination of relevant literature or case study information (e.g., from other areas) to determine whether, in the case of body burden data, the threshold used is appropriately realistic. For instance, available data for brook trout (Holm 2002; Holm et al. 2003, 2005) indicate that this species is relatively tolerant of selenium. For this species a threshold value applicable to other trout species is probably inappropriately low (Chapman and McPherson 2004; Table 1). In the case of resident fish population data, other potential causes (e.g., habitat changes, competition / predation) need to be considered based on both literature and regional information. In the case of deformities or mortalities in waterbird embryos / young, other potential causes (e.g., disease, predation) should be similarly considered.

If the first component of this tier indicates that an effect that has reasonable potential to result in an impact is occurring, then further investigative studies should be conducted to reduce uncertainty and allow for appropriate decision-making. Investigative studies might not be necessary in the case of resident fish population changes, if the evidence is reasonably convincing that these were due to selenium from mining activities. However, in the case of body burden exceedances of conservative, protective thresholds, laboratory (e.g., Kennedy et al. 2000; Holm et al. 2002; Holm et al. 2003, 2005) and / or field effects studies will likely be required.

All evidence considered in Tier 2 needs to be evaluated together with evidence from Tier 1 in a weight of evidence (WOE) assessment per Golder Associates (2005). Effectively, this evaluation comprises the Risk Characterization component of an ERA.

Tier 3: What Management Actions are Necessary When There is a Realistic Risk of Impact(s)?

This tier will only be triggered if the results of Tier 2 indicate that adverse effects are occurring to resident fish and/or waterbirds related to selenium, and there is reasonable certainty that, if appropriate management actions are not taken, impacts will ensue. This tier involves selection and evaluation of management alternatives. Components of this tier include determining: the specific potential impact (magnitude and significance); characteristics; selenium pathway(s); and, appropriate, available mitigation / compensation options. Based on this evaluation, the appropriate mitigation / compensation option(s) can be selected.

The choice of management action (Tables 2 and 3) will be determined based on specific circumstances but should follow an adaptive management approach. Adaptive management builds on current knowledge, and is guided by and adapted as necessary and appropriate by both the expanding general scientific knowledge base, and by site-specific findings. Adaptive management also follows from the risk assessment paradigm, which is the basis for the proposed approach for assessing the risks of selenium releases from new mines.

Table 2. Selenium Management Options

Management Options	Details	Feasibility	Comments
Subaqueous disposal	Waste rock is submerged to reduce oxidation rates	Depends on the availability of large waterbodies for all of the waste rock	Will reduce but not eliminate oxidation; can also maximize in-pit disposal of waste rock
Engineered soil covers	Waste rock is covered by clean soil to minimize water and oxygen interactions with oxidizing rock	Expensive if applied to large volumes of waste rock	Most effective if applied to rocks having the highest potential for selenium release
Landform design	Design out of pit dumps with aggressive dendritic drainage patterns to reduce infiltration of precipitation and encourage long-term designed surface runoff	Flexibility required in dump design	Increasing surface design may result in greater dump profile / footprint
Vegetation selection for reclaimed landforms	Selection of vegetation with high evapo-transpiration rates to reduce percolation of precipitation into dump formation	Reclamation commitments are often for the re-establishment to native ecosites; regulatory and stakeholder endorsement would be required for use of persistent agronomics in closure landscape	May necessitate non-native/agronomic species; efficacy of different native species available for re-vegetation would need to be explored
Rapid reclamation of out of pit dumps	Provide soil mantle and vegetative cover as soon as practicable to reduce precipitation infiltration into dump formation	Needs to be integrated with the mine plan	Feasible

Table 3. Selenium Treatment Options

<table>
<tr><th>Treatment Options</th><th>Details</th><th>Feasibility</th><th>Comments</th></tr>
<tr><td>Membrane filtration (reverse osmosis and nanofiltration)</td><td>Selenium concentrated into brine</td><td>Expensive and complex; nanofiltration not yet applied to operating mines; heating required in cold climates</td><td rowspan="2">Brine or acid solution must be disposed of (e.g., deep-injection, evaporation</td></tr>
<tr><td>Ion exchange</td><td>Selenium removed to synthetically produced organic resin which is regenerated with a strong acid solution</td><td>Not previously applied to selenium; only one known application to a [gold] mine</td></tr>
<tr><td>Iron coprecipitation</td><td rowspan="2">Work best for selenite (4+) not selenate (6+); the latter is the inorganic form associated with coal mines</td><td>Not specific for selenate; will not reduce selenium concentrations below about 12 µg/L</td><td rowspan="2">Pretreatment required to chemically reduce selenite (4+) to selenate (6+)</td></tr>
<tr><td>Catalyzed cementation</td><td>Not specific for selenate; no large-scale, commercial process available to reduce selenium concentrations below about 50 µg/L</td></tr>
<tr><td>Volatilization</td><td>Stimulation of bacterial volatilization</td><td>Only applied to sediments, not waters; variable results</td><td>Still an experimental technique</td></tr>
<tr><td>Bioreactor</td><td>Engineered structure holding microbes for wastewater treatment</td><td>Good selenium removal, reasonably cost effective</td><td>Applicable to focused water flows, not to diffuse flows</td></tr>
<tr><td>In-situ treatment</td><td>Treatment of selenium in groundwater via stimulation of bacterial activity</td><td>Good selenium removal, reasonably cost effective, but not applied to surface waters</td><td>Only applied full-scale at one mine site (in New Mexico)</td></tr>
<tr><td>Passive system (biopass)</td><td>Mine water flows through decaying organic matter in a sealed system</td><td>Not designed to treat selenium; only applicable to modest flows</td><td>Generally applied to abandoned, not operating mines</td></tr>
<tr><td>Treatment wetlands</td><td>Dissolved selenium is retained in the wetlands</td><td rowspan="2">Cannot operate in cold climates without heating; attract waterfowl which need to be deterred or selenium-related reproductive effects can occur</td><td rowspan="2">Require suitable land for the wetlands/ponds and for water storage during winter for summer treatment</td></tr>
<tr><td>Evaporation ponds</td><td>Natural evaporation in large ponds enhances volatilization</td></tr>
</table>

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