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Chapter 6

AQUATIC HAZARD OF SELENIUM POLLUTION FROM COAL MINING

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ABSTRACT

Selenium is a chemical element that is found in coal in small amounts. The potential for environmental problems begins when coal-bearing strata are exposed to air and water during the mining process, and when coal is washed prior to transport and distribution. This can mobilize selenium and form contaminated leachate and liquid waste, which often becomes a source of pollution to nearby surface waters. Once in the aquatic environment, selenium can rapidly bioaccumulate in food chains and reach levels that are toxic to aquatic life. Because of bioaccumulation, a small amount of selenium in water can translate to a significant environmental hazard. Case examples show that selenium from coal mining can result in a variety of impacts to fish, ranging from subtle effects on growth to severe deformities and complete reproductive failure. However, despite this negative implication, coal mining can be compatible with environmental needs if adequate steps are taken to prevent or reduce hazard. For prospective mines, this involves conducting a detailed site assessment and then matching operational parameters with environmental requirements. For active or decommissioned mines it is necessary to formulate and implement appropriate waste management and site reclamation plans.

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INTRODUCTION

What Is Selenium and Why Is It a Concern?

Selenium is a naturally occurring chemical element in coal that can be released during the mining process and find its way into nearby aquatic habitats. Selenium in raw coal and overburden is leached out when these materials are exposed to air and water, and the leachate can pose a significant environmental hazard (Lemly 1985a). Once in the aquatic environment, waterborne selenium can enter the food chain and reach levels that are toxic to fish and wildlife (Figure 1). Impacts may be rapid and severe, eliminating entire communities of fish and causing total reproductive failure in aquatic birds (Lemly 1985b, Ohlendorf 1989). Few environmental contaminants have the potential to affect aquatic resources on such a broad scale, and even fewer exhibit the complex aquatic cycling pathways and range of toxic effects that are characteristic of selenium. In recent years there has been an escalation in selenium pollution episodes associated with coal mining in North America and elsewhere (Lemly 2004), which has caused substantial environmental liability issues for coal mining companies, and resulted in regulatory intervention by water quality authorities, natural resource management agencies, and the courts (see for example BC Ministry of Environment 2008, US District Court 2008). With the potential for negative impacts on the coal mining industry as well as the environment, it is essential to recognize and address the selenium threat in the context of active, prospective, and decommissioned mines.

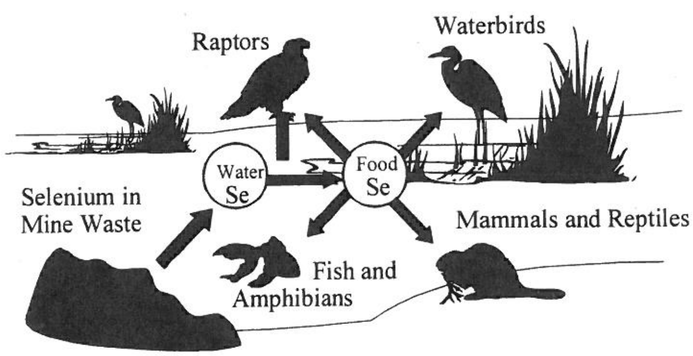

Figure 1. Pathways for selenium movement from coal mine wastes, bioaccumulation in food chains, and dietary exposure of fish and wildlife populations.

Background on Selenium Bioaccumulation, Cycling, and Toxicity

The most important principle to understand when evaluating the hazard of selenium from coal mining is its ability to bioaccumulate. This means that a low concentration of selenium in water has the potential to increase by several orders of magnitude by the time it reaches fish and wildlife. For example, a water concentration of 10 ug/L (micrograms per liter or parts-per- billion) can increase to over 5,000 times that amount in fish tissues. Bioaccumulation causes otherwise harmless concentrations of selenium to reach toxic levels. Although fish do take up some selenium directly from water, most of it comes from their diet.

Therefore, in order to protect fish from selenium poisoning it is essential to keep waterborne selenium below levels that cause bioaccumulation in the food chain (Lemly and Smith 1987). Another important principle is that selenium can cycle in aquatic habitats by moving in and out of sediments. A large portion of the total selenium in a stream or reservoir may be present in sediments, deposited directly from water or from plants and animals as they die and decompose. However, this pool of selenium is not permanently removed from the system. Biological activity, water chemistry changes, and physical disturbance can mobilize selenium back into water and organisms. This means that the selenium in sediments remains active, and provides a significant source of pollution to bottom-dwelling invertebrates and the fish that feed on them. Case studies show that selenium in sediments can recycle into the water and food chain for decades after selenium inputs are stopped (Lemly 1997).

Selenium exerts two main types of effects on fish: (1) direct toxicity to juveniles and adults, and (2) reproductive impacts from selenium that is passed from parents to offspring in eggs. Both of these modes of toxicity can occur at the same time so the threat from selenium poisoning is multifaceted. Type 1 toxicity can begin to occur if concentrations in the food chain reach 3 ug/g dw (micrograms per gram or parts-per-million, dry weight) and whole-body residues in fish reach 4 ug/g dw (Cleveland et al. 1993, Lemly 1993a, Hamilton 2003). This form of selenium poisoning involves changes in physiology that causes damage to gills and internal organs, ultimately resulting in death of the fish (Sorensen 1986). There may be no outwardly visible symptoms in this type of selenium toxicity or, if selenium concentrations are high enough, some fish may appear swollen from accumulation of fluid (edema) or have cloudy lenses (cataracts) in their eyes (Lemly 2002a). Type 2 effects occur when selenium present in egg yolk is absorbed by the developing embryo. A variety of developmental abnormalities can result in newly hatched larval fish, such as teratogenic deformities of the spine, head, and fins (Lemly 1993b, see Figure 2). Other toxic symptoms include hemorrhaging and swelling or edema (Gillespie and Baumann 1986, Hermanutz et al. 1993, see Figure 2). Most of these effects are lethal because they either kill young fish just after hatching or, in the case of some teratogenic deformities, prevent them from feeding normally and escaping predators as they grow (see Figures 3-4). Type 2 effects (reproductive failure) begin to occur at egg selenium concentrations of about 9 ug/g dw, which is equivalent to about 16 ug/g dw whole-body in the parent (Coyle et al. 1993, Hermanutz et al. 1993). Adult fish may be unaffected by selenium concentrations that impair their ability to reproduce so the threat of selenium impacts on a fish population must be assessed by something more than routine monitoring surveys, that is, simply finding fish does not indicate the absence of selenium toxicity (Lemly 2002b). Waterborne concentrations of selenium in the 1-5 ug/L range can bioaccumulate and begin the Type 1 and/or Type 2 effects. The exact number is site-specific, and depends on the kind of aquatic system (stream, reservoir, wetland), its biological productivity, and the chemical form of selenium present in the water. Case studies show that if waterborne selenium reaches 10 ug/L, complete reproductive failure can occur in reservoirs, and reproduction may be reduced by 40% in streams (Cumbie and Van Horn 1978, Lemly 1985b, Gillespie and Baumann 1986, Hermanutz et al. 1993). Selenium concentrations in coal mine wastewater can far exceed these toxic thresholds, and are particularly high in coal cleaning process water (up to 63 ug/L) and coal cleaning solid waste leachate (up to 570 ug/L, Lemly 1985a).

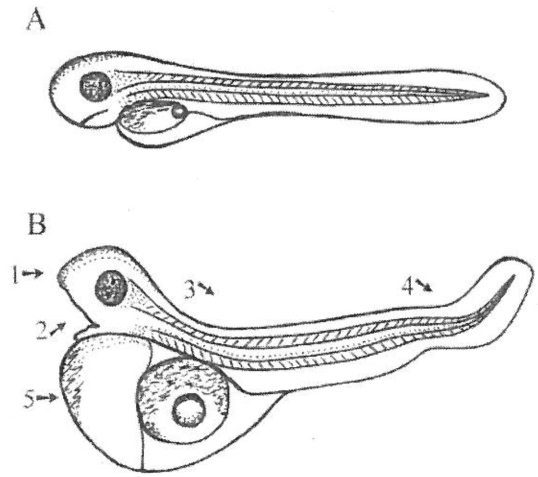

Figure 2. Typical appearance of larval fish at about 2-4 days after hatching. (A) Normal larva with yolk absorption nearing completion and straight, developing spine, (B) Abnormal development due to selenium-induced terata: (1) deformed, pointed head; (2) deformed, gaping lower jaw; (3) kyphosis (curvature of the thoracic region of the spine); (4) lordosis (concave curvature of the lumbar and/or caudal region of the spine). Other symptoms of selenium poisoning that usually accompany terata include (5) edema (swollen, fluid-filled abdomen) and delayed yolk absorption (drawing by A.D. Lemly).

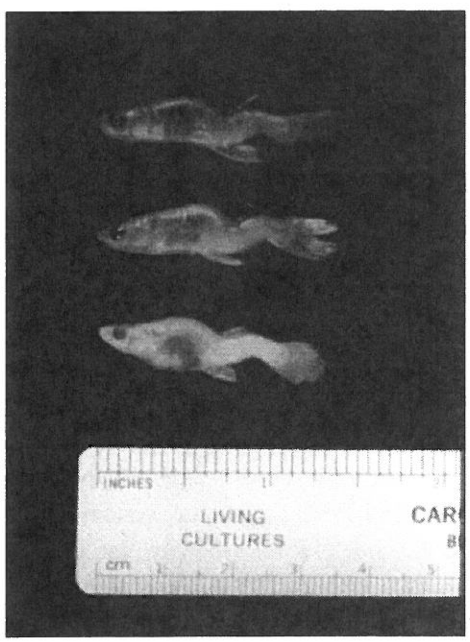

Figure 3. One of the most common and outwardly visible teratogenic effects of selenium in fish is deformity of the spine. Shown here are examples of dorso-ventral abnormalities known as kyphosis and lordosis (photo by A.D. Lemly).

Figure 4. Lateral curvature of the spine (scoliosis) caused by exposure to elevated selenium. Individual on the right is normal (photo by A.D. Lemly).

Case Examples of Impacts on Fish

Elk Valley, British Columbia, Canada

The Elk River watershed is located in the extreme southeastern portion of the province and lies in an area of naturally seleniferous soils and underlying coal deposits known as the Kootenay geological formation. Recent studies have determined that elevated concentrations of selenium are present in some areas of the watershed (EVS 2002a). Five active open-pit coal mines operate within the watershed and produce wastewaters containing selenium in concentrations that can exceed 200 ug/L (EVS 2002a, 2002b). Elevated selenium is present in water, sediments, and biota downstream of the mines relative to undisturbed sites (EVS 2004, Minnow 2004, 2007, Orr et al. 2006, Golder 2007). Experimental reproduction studies using field-exposed fish show that selenium toxicity associated with coal mine discharges has taken place in populations of cutthroat trout (Oncorhynchus clarki lewisi, Rudolph et al. 2006) and longnose sucker (Catostomus catostomus, Minnow 2005, 2006) in the Elk River watershed. Figures 5-6 illustrate the magnitude of these effects. The severity of impacts increases as egg selenium concentrations rise, culminating in complete reproductive failure.

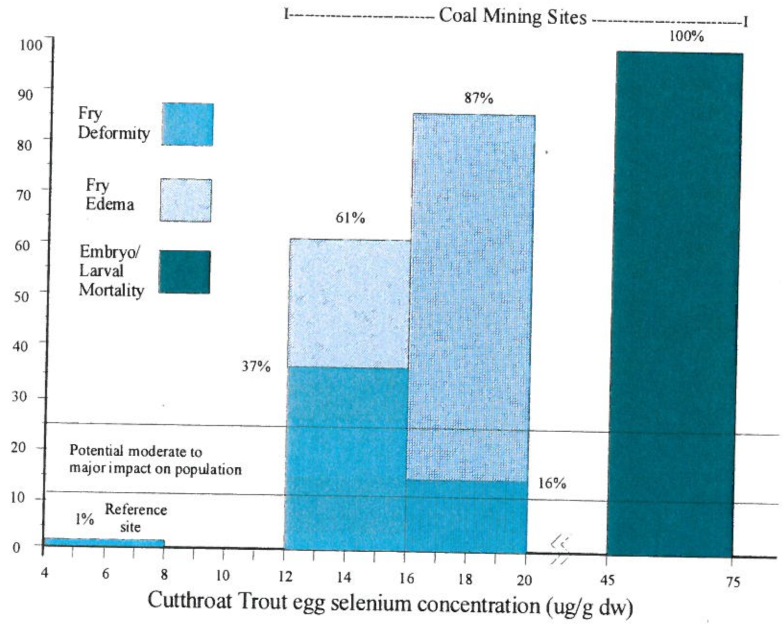

Figure 5. Effects of selenium on reproductive success in Westslope Cutthroat Trout (Oncorhynchus clarki lewisi) exposed to coal mining effluents in the Elk River watershed, British Columbia, Canada (data compiled from Rudolph et al. 2006). An effect level of 12-25 % or greater would be expected to result in moderate to major impacts on the population.

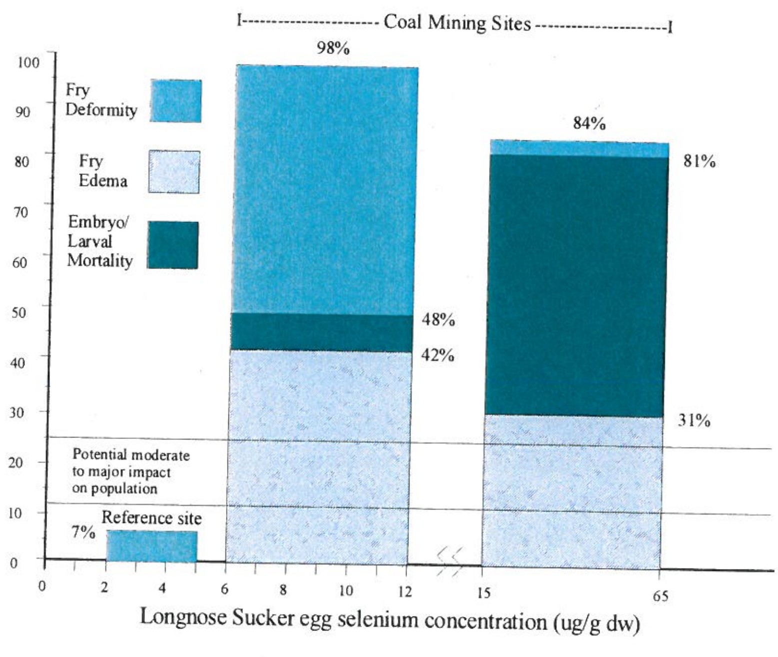

Figure 6. Effects of selenium on reproductive success in Longnose Sucker (Catostomus catostomus) exposed to coal mining effluents in the Elk River watershed, British Columbia, Canada (data compiled from Minnow 2005, 2006). An effect level of 12-25 % or greater would be expected to result in moderate to major impacts on the population.

Mud River Watershed, West Virginia, USA

Coal mining has a long history in this state but until recently, little attention was paid to water quality issues other than acid drainage and sedimentation. Selenium was raised as a concern by local and regional nonprofit environmental conservation groups in the 1990's. Subsequent water quality monitoring conducted as part of mine wastewater discharge permit requirements under USEPA's National Pollution Discharge Elimination System revealed that frequent violations of the surface water quality criterion (5 ug/L) were taking place (WVDEP 2007a). This led the West Virginia Department of Environmental Protection to initiate an aquatic monitoring program aimed at evaluating the extent and severity of selenium pollution from coal mining (WVDEP 2007b). Results of this effort in one of the key mining areas (Mud River watershed) are depicted in Figures 7-10, and reveal that selenium levels in water, fish tissue, and invertebrate food organisms exceed toxic thresholds for fish. As a supplement to this routine monitoring, a fish reproduction study was conducted in 2007 to determine if selenium-related abnormalities were present in the fish population of Upper Mud River Reservoir in Lincoln County (WVDEP 2007c). This reservoir receives selenium-laden discharges from a surface coal mining complex that has several active mine sites upstream in the watershed. The tell-tale signs of selenium toxicity (spinal deformity and edema) were evident in larval fish, indicating that significant biological impacts have occurred. Figures 11-12 illustrate the appearance of normal and affected individuals from this study.

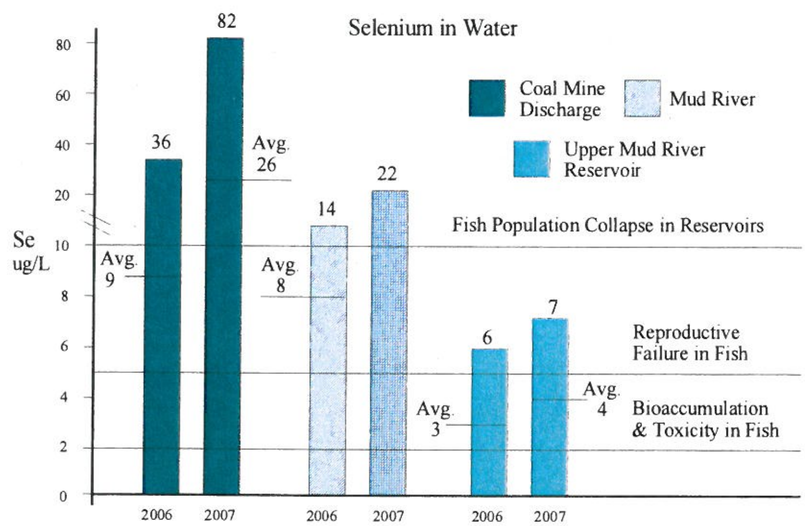

Figure 7. Selenium concentrations (ug/L or parts-per-billion) measured in coal mine discharges and surface waters of the Mud River ecosystem, West Virginia, relative to levels that can bioaccumulate and become toxic to fish (data compiled from WVDEP 2007a, 2007b).

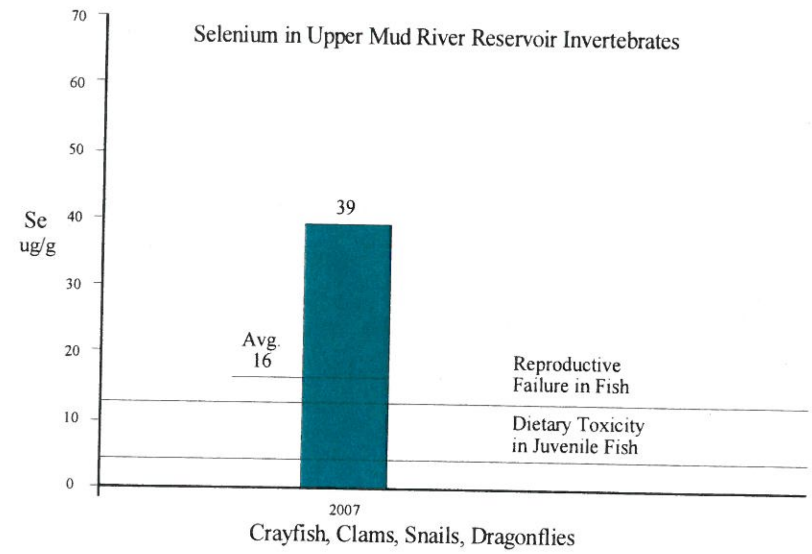

Figure 8. Selenium concentrations (ug/g or parts-per-million, dry weight) in fish food organisms of Upper Mud River Reservoir, West Virgina, relative to known toxic effect levels (data compiled from WVDEP 2007b).

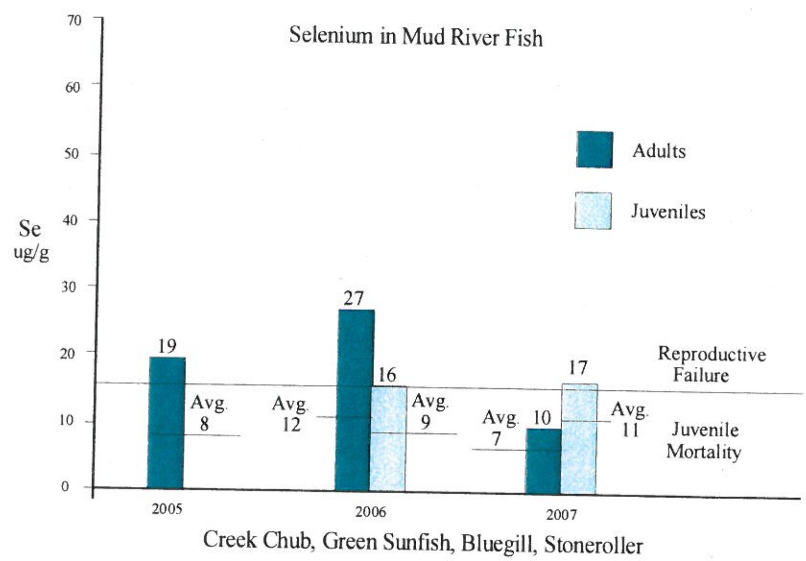

Figure 9. Selenium concentrations (ug/g or parts-per-million, dry weight) in fish from Mud River, West Virginia, relative to known toxic effect levels (data compiled from WVDEP 2007b; data are for creek chub, Semotilus atromaculatus, bluegill, Lepomis macrochirus, green sunfish, Lepomis cyanellus, and stoneroller, Campostoma anomalum).

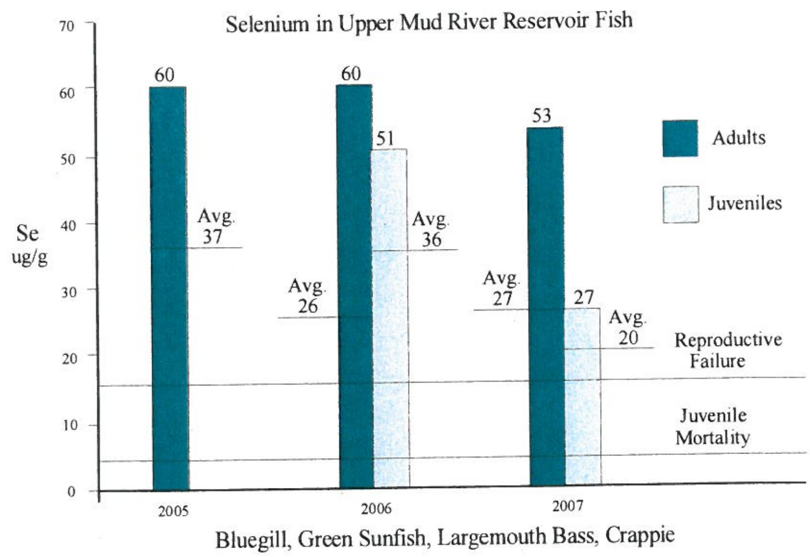

Figure 10. Selenium concentrations (ug/g or parts-per-million, dry weight) in fish from Upper Mud River Reservoir, West Virginia, relative to known toxic effect levels (data compiled from WVDEP 2007b; data are for bluegill, Lepomis macrochirus, green sunfish, Lepomis cyanellus, largemouth bass, Micropterus salmoides, and crappie, Pomoxis sp.).

Figure 11. Side view of normal fish larva from Upper Mud River Reservoir, West Virginia, June 2007 (photo by West Virginia Department of Environmental Protection). Note normal eye development, straight spine, and complete yolk absorption with no evidence of edema or a swollen, deformed yolk sac.

Figure 12. Side view of abnormal fish larva from Upper Mud River Reservoir, West Virginia, June 2007 (photo by West Virginia Department of Environmental Protection). Note the distended, fluid-filled yolk sac (edema) with delayed yolk absorption. This individual also has dorso-ventral curvature of the spine (kyphosis) and deformed pectoral fins and eyes (both eyes are on the same side of the head). All of these abnormalities are characteristic biomarkers of selenium poisoning.

How to Reduce Risks to Aquatic Life

For Coal Mines in the Planning Stage

Adequate pre-mine evaluation and planning are critical to prevent selenium pollution. Lemly (2007) provides a detailed procedure for accomplishing this task. The reader should refer to that publication for specific information, as only a general overview is given here. There are five major components to the procedure (Figure 13), which is designed to gather information on operational parameters of the proposed mine as well as key aspects of the physical, chemical, and biological environment surrounding it. 1) Geological assessment is the first step to understanding the environmental risk of selenium at prospective coal mines. It is essential to characterize the amount of selenium present in the geologic strata that are to be disturbed because once these materials are exposed to air and precipitation they can leach substantial quantities of selenium, which begins the mobilization process and threat to aquatic life. Because selenium concentrations vary widely in the target matrix and waste rock at a mine site, an accurate representation of the intended geographic area and depth of disturbance by mining must be made. This projection, in combination with analyses of selenium content and leachate parameters, will provide key information on selenium quantity and mobility. 2) Mine operation assessment is the next component. The disposal method(s) used for solid and liquid wastes at a mine greatly affect the potential amount of selenium released and thus the risk of ecological damage (Lemly 1994). It is important to know approximately how much excavated solid material will be exposed to weathering at any given time, as well as how much liquid will be produced, whether held in tailings ponds or directly discharged into receiving waters. The engineering design should be examined closely to provide waste volume estimates that are as accurate as possible. Once these numbers are obtained, some calculations will provide estimates of daily selenium production, that is, how much selenium is available for potential release to the surrounding environment. 3) Hydrological assessment is necessary to reveal key pathways for selenium movement and accumulation. The surface water hydrology of the basin surrounding the proposed mine must be carefully examined in order to identify all potential receiving waters for selenium discharges. Because of hydrological connections between the various aquatic habitats that may be present in a watershed basin, the toxic threat from selenium contamination is also connected. The hydrologically linked parts of a watershed that are down-gradient of the mine site, extending to the point at which outside water sources dominate the hydrology (for example, confluence of the watershed with a larger drainage basin) should be the area evaluated. This physical area constitutes a hydrological unit (HU). The protocol given by Lemly (2007) aims to protect the weakest link in the HU, that is, habitats where the risk of selenium accumulation and toxicity to aquatic life are greatest. In order for the assessment and resultant mine operation decisions to be environmentally sound it is necessary to map and characterize the aquatic system of the HU, estimate its selenium retention capacity, and project selenium concentrations in water and biota. 4) Biological assessment is needed because is important to have a complete inventory of the aquatic resources that may be threatened by mine development in order to obtain a comprehensive and ecologically relevant hazard assessment. This entails making a list of fish and aquatic-related wildlife present in the HU, characterizing fish and wildlife uses of the habitat (feeding, spawning, nesting, migratory stop-overs, etc.), and identifing biota of special concern such as endangered or threatened species and management priority species. It is also necessary to document the presence of, and habitat used by, selenium-sensitive species and identify habitats where bioaccumulation would likely be greatest, that is, in locations with high primary productivity and slow-moving or impounded waters (reservoirs, ponds, wetlands, marshes, etc.). The reason for collecting this information is so that any biological issues or concerns can be identified and factored into the formulation of a Total Maximum Daily Load (TMDL) of selenium that is sustainable for the HU. The TMDL will be useful as guidance for developing and refining mine operation parameters needed to meet environmental quality goals. Information from the biological assessment will also aid in focusing monitoring efforts on the habitats and species of greatest priority and sensitivity to selenium. 5) Hazard assessment is the final and most crucial step. At this point, having completed the preceding four steps, the planner/evaluator will have gathered all of the information necessary to evaluate the ecological risk posed by the prospective mine. Hazard is determined by comparing the projected water and tissue selenium concentrations to published toxicity levels and then rating the degree of hazard using interpretive guidelines (Lemly 2007). Five degrees of hazard are possible: none, minimal, low, moderate or high. The initial ratings may be modified based on other information such as presence of endangered or threatened species, resource management agency priorities, and other local, regional, or national regulatory control considerations. If the hazard level is low, moderate, or high, a TMDL needs to be developed and then reviewed in the context of the mine operation parameters to identify options for meeting environmental quality goals. If modifications are needed, there are several options for reducing the exposure and weathering of selenium-laden solid materials, and minimizing the amount of wastewater produced (Lemly 1994). Practices such as backfilling, water recirculation/reuse, and containment leaching are just a few of the possible ways to lower selenium discharges. Chemical/physical treatment of liquid waste to lower selenium concentrations in the discharge is another step that can be taken. Some flexibility on the part of the mining company may be all that is necessary to meet the TMDL and gain approval for the project. Monitoring of water, fish, and birds should be done once mining begins to verify that selenium levels in aquatic habitats remain at safe levels. Monitoring is needed to make sure that the mine is meeting its discharge limits and also as a check on how well the TMDL fits the ecosystem. The TMDL is generated from calculations that are based on projected selenium levels, not actual concentrations. Therefore, it may not be a perfect fit to the HU once site-specific environmental conditions that regulate selenium cycling and biological uptake come into play. It is possible that some adjustment of the TMDL may be necessary because of mine-related and/or environmental-related factors.

For Active Coal Mines

Waterborne selenium should be measured routinely as part of a mine's overall environmental accountability reporting. In the US, this would fall under the monitoring requirements for discharge permits issued as part of EPA's National Pollution Discharge Elimination System or other state and local monitoring efforts. If monitoring reveals elevated selenium concentrations in water (2 ug/L or greater), follow-up monitoring of biota is needed. If levels of selenium are also elevated in biota (3 ug/g dry weight in benthic invertebrates, 4 ug/g dw in fish whole-body samples or 8 ug/g dw in fish muscle fillets, 10 ug/g dw in fish eggs, 7 ug/g dw in aquatic bird eggs), steps should be taken to reduce wastewater and leachate discharges. This would typically involve the TMDL process discussed above, which would identify HU's and develop maximum sustainable discharge limits based on site-specific selenium retention capacity. There are several options for reducing selenium discharges. Perhaps the most basic is to simply reduce the amount of surface residuals, waste rock, and raw coal that are exposed to precipitation. This could involve increased use of backfilling for all solid wastes, and measures to reduce the residence time and aerial extent of tailings piles, raw coal storage areas, and cleaning/preparation/loading sites. Disposal of coal cleaning waste should be done so as to prevent movement of solids or liquids off-site, as this waste can contain very high concentrations of selenium. Recirculation and reuse of water should be done to the extent possible in order to reduce the amount of liquid waste produced. Finally, chemical and/or biological treatment can be used to remove selenium from liquid waste and precipitation-derived leachate before it is discharged to surface waters. The overall target should be a final effluent concentration of 5 ug/L or less. Success of treatment will depend on determining the chemical form of selenium in the wastewater and then matching an appropriate technology. For example, if it is predominantly selenite, treatment with ferrihydrite can reduce concentrations by 85-90%, and achieve final values in the range of 3-6 ug/L (Rosengrant and Fargo 1990). If it is selenate or organic, biological removal methods such as BSeM may be more effective and less expensive than chemical treatment. For more information on the use of ferrihydrite to pre-treat the discharge, see Rosengrant and Fargo

(1990). For comparison of ferrihydrite and less expensive biological options, including BSeM, see USEPA (2001) and Microbial Technologies (2005).

SELENIUM DECISION TREE FOR COAL MINES

1. GEOLOGICAL ASSESSMENT

▼

Core sampling and analysis of ore and overburden

▼	▼
≥1 µg/g Selenium	<1 µg/g Selenium
▼	▼
Passive leaching test	Begin mining
▼	▼
Selenium mobility characterization	Environmental monitoring

▼

2. MINE OPERATION ASSESSMENT

▼

Waste disposal methods

▼

Waste volume projection

▼

Daily selenium load projection

▼

3. HYDROLOGICAL ASSESSMENT

▼

Delineate and characterize Hydrological Unit (HU)

▼

Estimate selenium retention capacity of HU

▼

Projected selenium concentrations

▼

4. BIOLOGICAL ASSESSMENT

▼

Inventory of aquatic life present in HU

▼

Characterize sensitivity to selenium

▼

Identify priority species

▼

5. HAZARD ASSESSMENT

▼

Determine hazard level of projected selenium concentrations

▼	▼
High, moderate, or low hazard	Minimal or no hazard
▼	▼

Figure 13. Continued on next page.

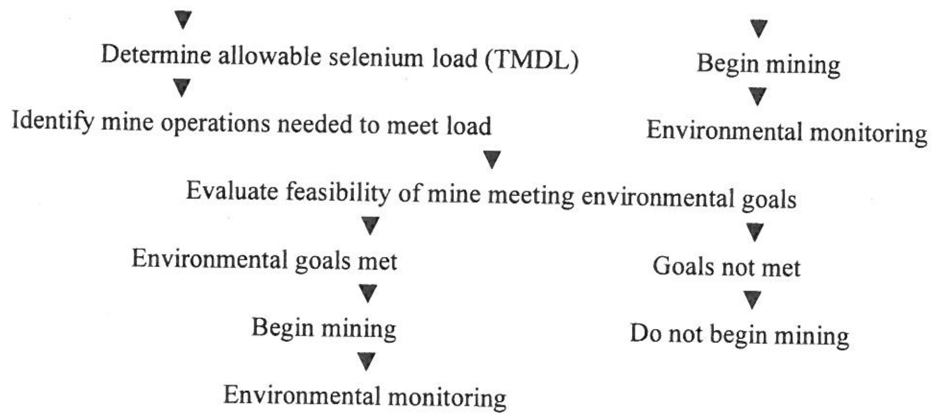

Figure 13. Framework for identifying and interpreting selenium hazards associated with coal mining.

For Decommissioned Coal Mines

Once a mine is closed, actions are necessary to reclaim and vegetate all exposed areas to stabilize them and minimize further leaching of selenium. However, it should be noted that even with typical mine reclamation and revegetation efforts there may still be substantial selenium exposure risks to upland wildlife and livestock (Steele 2003), that would have to be avoided through additional measures such as capping the waste spoils with several feet of clay to reduce water infiltration and prevent selenium uptake by plants, containment and treatment of leachate, etc. Thus, there may be a need for long-term site management and environmental monitoring at decommissioned coal mines.

Conclusion

Until recently, most environmental concerns associated with coal mining were focused on sedimentation and acid drainage. However, selenium pollution should also be a major concern and, in fact, all coal mines have the potential to release hazardous amounts of selenium. Case examples show that selenium pollution from coal mining is widespread, and is capable of causing extreme toxicity to fish. The need for coal as a source of energy is growing steadily, as is the need for coal mining companies to display prudent environmental stewardship. It is both essential and quite feasible to recognize and deal with selenium pollution from coal mining, thereby allowing expansion of the industry while also protecting aquatic life.

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