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# Evaluation of the Hazard Quotient Method for Risk Assessment of Selenium

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**Environmental contamination with selenium from industrial and agricultural sources has poisoned fish and wildlife at several locations in the United States. Monitoring and risk assessment activities are currently being conducted by many state and Federal agencies. The U.S. Environmental Protection Agency (EPA) recommends a hazard quotient (HQ) method (waterborne concentration divided by the national water quality criterion) to assess the toxic threat of individual waterborne elements, including selenium. An evaluation of the EPA HQ method was conducted by comparing it to a recently published protocol (Protocol) for selenium assessment. Hazard estimates obtained using HQ were found to be invalid because the EPA water quality criterion is outdated, and the procedure uses mean rather than maximum waterborne concentrations. The HQ method seriously underestimates hazard and could lead to risk management decisions that would not protect fish and wildlife from selenium toxicity. The Protocol method provides an accurate assessment because it evaluates hazard by examining multiple exposure pathways on a site-specific basis. Until a revised (lowered) national water quality criterion is available, the EPA HQ method should not be used for selenium. Even then, with the availability of the Protocol, HQ analysis should be restricted to data sets where water is the primary or sole source of information on environmental concentrations of selenium.** 

## INTRODUCTION

The importance of selenium as an environmental contaminant has gained widespread attention among natural resource managers and water quality regulators in the United States during the past two decades. Selenium mobilized from the combustion of coal at electric generating stations has contaminated several major reservoirs, leading to reproductive failure and elimination of entire communities of fish (Cumbie and Van Horn, 1978; Garrett and Inman, 1984; Woock and Summers, 1984; Woock *et al.*, 1985; Lemly, 1985a, 1993c). Irrigation of seleniferous soils has produced subsurface drainage that contaminated wetlands and poisoned fish and migratory birds at several locations in the western United States (Lemly *et al.*, 1993, Lemly, 1994; Presser, 1994; Presser *et al.*, 1994). The U.S. Environmental Protection Agency (EPA) and some states have formulated and adopted increasingly restrictive water quality standards for selenium because of these incidents of environmental contamination (e.g., NCDEM, 1986; U.S. EPA, 1987; CEPA, 1992).

Many Federal and state natural resource management agencies have implemented contaminant monitoring programs to measure selenium concentrations in water, sediments, and aquatic biota. Once these data are collected it is important to conduct an overall evaluation and determine the degree of hazard or risk present in order to identify appropriate management actions. The EPA has published a risk assessment framework to provide guidance in this process (U.S. EPA, 1992). The EPA advocates the use of hazard quotients (HQ; waterborne concentration divided by the national water quality criterion) to assess the toxic threat of individual waterborne elements, including selenium. The HQ approach is generally recognized as a good method to use when there is an EPA water quality criterion for the substance under evaluation. It has been widely applied to aquatic risk assessments in the United States for the past decade.

An alternative procedure for aquatic hazard assessment of selenium has recently been published (Lemly, 1995). Known as the Protocol method, it focuses on food-chain bioaccumulation and reproductive impairment in fish and aquatic birds. Whereas the HQ method uses information on waterborne selenium alone, the Protocol uses selenium concentrations in five ecosystem components; water, sediment, benthic macroinvertebrates, fish eggs, and aquatic bird eggs.

With two different approaches for selenium assessment now available, there is a need to compare them and determine if one produces more accurate estimates of hazard than the other. This paper reports the results of such a comparison. Selenium monitoring data from three sites, representing wetlands, riverine systems, and reservoirs, were evaluated with both HQ analysis and the Protocol method. The resultant hazard estimates were checked for validity by comparing them to known evidence of selenium toxicity to fish and wildlife at the field sites.

## DESCRIPTION OF ASSESSMENT METHODS

The HQ approach compares environmental concentrations of a contaminant with a measured effect or no-effect level in



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test organisms. Theoretically, any sample matrix could be used if there was sufficient toxicity data available to provide a reliable interpretation; for example, water, sediments, and/or biological tissues. The EPA method (U.S. EPA, 1992) focuses on water as the sample matrix. For selenium, HQ is calculated by dividing the mean measured or expected environmental waterborne concentration of selenium by the EPA national water quality criterion for chronic exposure (5 $\mu$g/liter). The rationale of this technique is that if waterborne concentrations of selenium exceed the criterion, imminent hazard exists. If concentrations are below the criterion then minimal hazard is expected. This method provides a quantitative estimate of the hazard associated with single chemicals or elements, primarily from a waterborne route of exposure. However, the EPA process for deriving national water quality criteria does allow for inclusion of data that would account for bioaccumulation. In the case of selenium, field data on food-chain transfer and reproductive toxicity to fish were included in the derivation and were largely responsible for the criterion being lowered to its current value of 5 $\mu$g/liter (U.S. EPA, 1987). Guidelines for interpreting HQ calculations are:

HQ = <0.1, no hazard exists
HQ = 0.1–1.0, hazard is low
HQ = 1.1–10, hazard is moderate
HQ = >10, hazard is high

The Protocol method (Lemly, 1995) establishes a separate hazard rating for five ecosystem components (water, sediments, benthic macroinvertebrates, fish, aquatic birds) based on where the highest concentrations of selenium fall on corresponding hazard profiles given in the Protocol. The hazard profiles were developed from a comprehensive synthesis of field and laboratory data on selenium cycling, food-chain bioaccumulation, and reproductive toxicity to fish and aquatic birds. These biological endpoints are the most sensitive indicators for predicting ecosystem-level impacts of selenium contamination (Lemly, 1993a). Numerical scores are assigned according to the hazard ratings: none = 1; minimal = 2; low = 3; moderate = 4; high = 5. A final ecosystem-level hazard assessment is determined by adding the scores for each ecosystem component and comparing the total to the following evaluation criteria: no hazard = 5; minimal hazard = 6–8; low hazard = 9–11; moderate hazard = 12–15; high hazard = 16–25.

In some situations it may be difficult or impossible to obtain adequate data for all five ecosystem components, particularly when the method is applied to monitoring data that have already been collected. In his original description of the Protocol method, Lemly indicated that the procedure could be used for incomplete data sets, i.e., one or more ecosystem components missing. However, no details were given on how to calculate final hazard ratings. Guidelines for that process are given here as new information. When selenium data is missing for one ecosystem component, the following evaluation criteria should be used: no hazard = 4; minimal hazard = 5–7; low hazard = 8–10; moderate hazard = 11–14; high hazard = 15–20.

These criteria were not derived by prorating the numbers in the other set (e.g., subtracting 5 from high hazard, 4 from moderate hazard, 3 from low hazard, 2 from minimal hazard, and 1 from no hazard). For both sets of final hazard numbers, the intervals are based on the scores for the individual ecosystem components but they are not a simple average or midpoint. For example, a final hazard rating of ‘‘high’’ can occur even though each of the individual components was rated ‘‘moderate.’’ The rationale for this is that three distinct routes of exposure are possible for selenium; water, planktonic food-chain, and detrital food-chain. Based on field evidence of bioaccumulation and toxic effects, the hazard of all three together should be greater than if each is present separately. Thus, the aggregate hazard for the ecosystem as a whole can be greater than the hazard for individual components. This is analogous to synergism, i.e., the parts (hazard) are not simply additive.

The Protocol should not be used if data are missing for more than one ecosystem component. Accepting only three components could mean that data for both fish and birds were absent. The objective of the Protocol is to estimate ecosystem-level hazard by focusing on bioaccumulation in fish and aquatic birds. If one of these components is missing, the predictive power of the assessment will not be as strong as if both are included but it can still be done. However, if both are missing, the procedure does not meet its objective and, therefore, is invalid. One other precaution is necessary. Substitution of an ecosystem component for one that was not specified for use in the Protocol, for example, zooplankton instead of benthic macroinvertebrates, should not be done because the hazard profiles given in the original description were constructed for use with the indicated ecosystem components only. Substitutions will invalidate the results.

## DATA USED IN THE EVALUATION

Selenium data from three ecologically distinct systems were used: wetlands (Stephens *et al.*, 1988, 1992; Hoffman *et al.*, 1990; Pelz and Waddell, 1991; Waddell and Stanger, 1992), rivers (Finger, 1995), and reservoirs (Lemly, 1993c, in press). Selenium concentrations in whole-body fish samples and aquatic bird livers were converted to equivalent egg concentrations (whole-body values × 3.3 for fish; liver values × 0.33 for birds; Lemly, 1995) for use in the Protocol method.

## RESULTS

Analyses by the two methods are given in Table 1. The Protocol indicated greater hazard than HQ for all locations except Leota Bottom and High Rock Lake, which are considered to be uncontaminated reference sites (Stephens *et al.*, 1992; Lemly, in press). In four cases, no hazard was indicated by HQ, whereas moderate to high hazard was indicated by the Protocol. At these four locations, concentrations of selenium in

**TABLE 1**
**Hazard Assessment of Selenium Using Protocol and HQ Methods**

| Site and ecosystem component | Selenium concentration[a] | Protocol Method | | | | HQ Method | |
|---|---|---|---|---|---|---|---|
| | | Evaluation by component | | Total for the site | | | |
| | | Hazard | Score | Score | Hazard | HQ | Hazard |
| | | | Wetlands | | | | |
| Leota Bottom, UT | | | | | | | |
| Water | <1–3 | Low | 3 | | | 0.23 | |
| Sediments | 0.7–1.0 | None | 1 | 11 | Low | — | Low |
| Invertebrates | 1.0–3.0 | Minimal | 2 | | | — | |
| Fish eggs | 2.0–4.0 | Minimal | 2 | | | — | |
| Bird eggs | 2.0–7.0 | Low | 3 | | | — | |
| Roadside Ponds, UT | | | | | | | |
| Water | 9–93 | High | 5 | | | 5.6 | |
| Sediments | 7–41 | High | 5 | 25 | High | — | Moderate |
| Invertebrates | 12–72 | High | 5 | | | — | |
| Fish eggs | 75–120 | High | 5 | | | — | |
| Bird eggs | 12–120 | High | 5 | | | — | |
| Sheppard Bottom, UT | | | | | | | |
| Water | 3–4 | Moderate | 4 | | | 0.61 | |
| Sediments | 0.6–3.0 | Low | 3 | 21 | High | — | Low |
| Invertebrates | 3.0–33 | High | 5 | | | — | |
| Fish eggs | 8–27 | High | 5 | | | — | |
| Bird eggs | 1–17 | Moderate | 4 | | | — | |
| Stillwater WMA,[b] NV | | | | | | | |
| Water | <1 | None | 1 | | | 0.05 | |
| Sediments | 0.2–0.8 | None | 1 | 15 | Moderate | — | None |
| Invertebrates | 0.3–7.0 | High | 5 | | | — | |
| Fish eggs | 2.9–12.2 | Moderate | 4 | | | — | |
| Bird eggs | 0.9–10.6 | Low | 3 | | | — | |
| Fernley WMA, NV | | | | | | | |
| Water | <1 | None | 1 | | | 0.04 | |
| Sediments | 0.1–0.6 | None | 1 | 16 | High | — | None |
| Invertebrates | 3.5–13.0 | High | 5 | | | — | |
| Fish eggs | 10.8–36.3 | High | 5 | | | — | |
| Bird eggs | 1.9–13.0 | Moderate | 4 | | | — | |
| Humboldt WMA, NV | | | | | | | |
| Water | <1 | None | 1 | | | 0.04 | |
| Sediments | 0.3–1.2 | Minimal | 2 | 16 | High | — | None |
| Invertebrates | 2.5–5.1 | High | 5 | | | — | |
| Fish eggs | 6.3–12.9 | Moderate | 4 | | | — | |
| Bird eggs | 2.3–15.8 | Moderate | 4 | | | — | |
| | | | Rivers | | | | |
| Animas River, CO, NM | | | | | | | |
| Water | 1–20 | High | 5 | | | 0.28 | |
| Sediments | 0.1–2.3 | Low | 3 | 14 | Moderate | — | Low |
| Invertebrates | 1.8–2.9 | Minimal | 2 | | | — | |
| Fish eggs | 3.0–15.8 | Moderate | 4 | | | — | |
| La Plata River, CO, NM | | | | | | | |
| Water | 1–12 | High | 5 | | | 0.22 | |
| Sediments | 0.1–0.95 | None | 1 | 13 | Moderate | — | Low |
| Invertebrates | 1.1–2.2 | Minimal | 2 | | | — | |
| Fish eggs | 2.6–39.6 | High | 5 | | | — | |
| Mancos River, CO, NM | | | | | | | |
| Water | 2–29 | High | 5 | | | 2.1 | |
| Sediments | 0.2–0.8 | None | 1 | 16 | High | — | Moderate |
| Invertebrates | 1.8–11.2 | High | 5 | | | — | |
| Fish eggs | 5.6–46.2 | High | 5 | | | — | |

**TABLE 1—***Continued*

| Site and ecosystem component | Selenium concentration[a] | Protocol Method: Evaluation by component: Hazard | Score | Total for the site: Score | Hazard | HQ Method: HQ | Hazard |
|---|---|---|---|---|---|---|---|
| | | | Reservoirs | | | | |
| Belews Lake, NC | | | | | | | |
| Water | <1 | None | 1 | | | 0.08 | |
| Sediments | 0.1–4.3 | High | 5 | 18 | High | — | None |
| Invertebrates | 2.0–5.9 | High | 5 | | | — | |
| Fish eggs | 3.6–12.8 | Moderate | 4 | | | — | |
| Bird eggs | 2.5–11.0 | Low | 3 | | | — | |
| High Rock Lake, NC | | | | | | | |
| Water | <1 | None | 1 | | | 0.03 | |
| Sediments | 0.1–0.3 | None | 1 | 5 | None | — | None |
| Invertebrates | 0.9–1.5 | None | 1 | | | — | |
| Fish eggs | 1.4–2.9 | None | 1 | | | — | |
| Bird eggs | 1.7–2.9 | None | 1 | | | — | |

[a] Selenium concentrations in $\mu$g/liter (parts per billion) for water; $\mu$g/g (parts per million) dry weight for sediments, invertebrates, and eggs.
[b] WMA denotes wildlife management area.

water were very low, but were elevated in one or more of the other ecosystem components used in the Protocol.

The comparison evaluated the Protocol method for eight sites where full data sets were available (all five ecosystem components), as well as three sites where one component was missing (aquatic bird eggs). The results were similar in all cases; the Protocol consistently indicated greater hazard than HQ.

## DISCUSSION

The data sets used in this analysis represent a wide range of ecological conditions, ranging from shallow freshwater marshes to large riverine and reservoir systems. They also represent a range in the level of selenium contamination—from clean reference sites to heavily contaminated wetlands. This range of conditions should cover the spectrum of pathways by which selenium cycles, accumulates, and causes toxicity in aquatic habitats. It is important to examine different conditions because a dominant pathway in one system may be relatively insignificant in another (Lemly and Smith, 1987). Hazard assessment methods that are overly sensitive to one particular pathway will give biased or unreliable risk estimates. The data sets examined should provide a good perspective from which to judge the performance of the two assessment methods.

Hazard estimates from HQ analysis were consistently lower, usually much lower, than those generated from the Protocol. Information on the toxic effects of selenium to fish and wildlife at the field sites can be used to check the results and determine which method produced the most valid estimates of hazard. *Example 1:* The contaminated sites in Utah (Roadside Ponds and Sheppard Bottom) have produced acute and chronic selenium toxicosis and reproductive impairment in fish and aquatic birds (Waddell and Stanger, 1992; Hamilton *et al.*, 1996). These biological effects demonstrate that the hazard from selenium is high. The Protocol indicated high hazard at both sites, whereas HQ indicated low to moderate hazard. *Example 2:* Decreased survival of juvenile ducks due to selenium in the diet, and associated decreases in waterfowl production were identified at Fernley, Humboldt, and Stillwater wildlife management areas in Nevada. Irrigation drainage containing high concentrations of selenium was determined to be toxic to young fish and other aquatic organisms (Hallock and Hallock, 1993). Collectively, the toxic effect of selenium at these sites was not as great as for the Utah sites, but it still represents a significant biological hazard. The Protocol rating indicated high hazard for two sites (Fernley and Humboldt) and moderate hazard for the other (Stillwater). The HQ analysis indicated that no hazard was present at any of the sites. *Example 3:* Belews Lake has a well documented history of selenium-induced teratogenesis and reproductive impairment in fish (Lemly, 1985a, 1993c). Selenium concentrations are somewhat elevated in bird eggs but reproductive impairment has not been found (Lemly, in press). The toxic effect of selenium on fish has been devastating (16 species were eliminated) and persistent, indicating high hazard for the site. The Protocol gave a high hazard rating for Belews Lake, whereas HQ analysis indicated that no hazard was present.

Hazard estimates from HQ analysis were incorrect for two reasons: (1) because of shortcomings in the EPA water quality criterion, and (2) because of a basic flaw in the HQ approach, as it applies to selenium. The EPA water quality criterion used in the procedure is badly outdated. Although the criterion (5 $\mu$g/liter) was developed using field data that reflected current (pre-1988) information on bioaccumulation, more recent information indicates that 5 $\mu$g/liter is too high to protect sensitive species of fish and wildlife from reproductive toxicity and the effects of Winter Stress Syndrome (Lemly, 1993a, 1993b; Skorupa and Ohlendorf, 1991). This criterion is now almost 10 years old and several research studies and reviews published recently indicate that the number should probably be somewhere in the 1–2 $\mu$g/liter range, especially for wetlands and impoundments where bioaccumulation is maximized (e.g., Lemly, 1993a, 1993c; Peterson and Nebeker, 1992; Skorupa and Ohlendorf, 1991). Had a value of 2 $\mu$g/liter, for example, been used instead of 5 $\mu$g/liter, the HQ numbers would be quite different and the hazard estimates would more closely match those indicated by the Protocol for sites in Utah and New Mexico. Thus, as it is currently practiced, HQ analysis will consistently underestimate selenium hazard because it relies on an invalid EPA water quality criterion.

A basic flaw with the HQ method is that it uses geometric mean waterborne concentrations of selenium. A large part of the selenium bioaccumulation and associated toxic impact to fish and wildlife in an aquatic system can result from one-time or periodic waterborne inputs that have high concentrations relative to the long-term mean (Garrett and Inman, 1984; Sorensen, 1988; Presser *et al.*, 1994). On a mass-balance basis, these spikes in concentration deliver a disproportionately large amount of selenium that can load sediments and be cycled into detrital food chains long after the waterborne spike is gone (Lemly and Smith, 1987). Once in the aquatic system, this ‘‘pulse’’ of selenium may be all that is necessary to rapidly escalate bioaccumulation and cause a cascade of impacts. The toxicity threshold for selenium is very steep. An increase of only a few micrograms per liter, which may represent the difference between mean and maximum concentrations in HQ analysis, can cause a totally different, much more serious impact on fish and wildlife (Lemly, 1985b, 1993a; Skorupa and Ohlendorf, 1991). It is critical to capture this underlying principle of selenium ecotoxicology when conducting hazard analyses and risk assessments. Relying on mean waterborne concentrations diminishes and masks the importance of the peaks in terms of selenium loading, bioaccumulation, and toxic threat. Results are biased and hazard is seriously underestimated. This could lead to risk management decisions that would not protect fish and wildlife from selenium toxicity. In order to make the best decisions, risk managers need to know what the maximum hazard is, not the mean hazard. Thus, it is essential to estimate hazard using the highest concentrations of selenium measured in the samples. The EPA HQ approach does not do this.

Hazard profiles used in the Protocol method integrate updated information on selenium bioaccumulation and reproductive toxicity to fish and wildlife. Hazard is characterized in terms of the potential for food-chain bioaccumulation and reproductive impairment in fish and aquatic birds, which are the most sensitive biological responses for estimating ecosystem-level impacts of selenium contamination (Lemly, 1993a). Hazard estimates generated from the Protocol are not driven by a single number or water criterion for effect/no effect concentrations, as is the case for the HQ method. There is no implicit assumption or evaluation of toxicity related to direct waterborne exposure. Rather, water concentrations are used to estimate hazard associated with bioaccumulation in the planktonic food chain. Each of the ecosystem components used in the Protocol are given equal weighting so that spatial or temporal variation in the relative dominance of one selenium cycling pathway over another will be accounted for in the assessment. This is a key point that differentiates the two methods. The Protocol approach utilizes multiple parameters that determine selenium bioaccumulation and exposure on a site-specific basis, whereas the HQ method is more generic, and is tied to a single criterion that is assumed to be protective under all exposure conditions.

The Protocol's hazard estimates closely matched the field evidence of selenium toxicity; the HQ estimates did not. The inability of HQ to correctly assess hazard reflects the outdated EPA water quality criterion. Data from the field sites show, quite clearly, that bioaccumulation of selenium in aquatic food chains and resultant toxicity to fish and wildlife can occur when concentrations of waterborne selenium are well below the current U.S. national water quality criterion. This indicates that a revision (lowering) of the EPA criterion is necessary. Even then, there will likely be many locations where HQ will perform poorly, due to the potential for high selenium bioaccumulation with little detectable elevation in waterborne concentrations (e.g., the sites in Nevada). This condition can develop because of the presence of ultra-trace amounts ($<1$ $\mu$g/liter) of dissolved organic selenium that cause disproportionately high bioaccumulation relative to the inorganic forms of selenium (Besser *et al.*, 1989, 1993). Accounting for this scenario in selenium cycling is essential for accurate hazard assessment. The Protocol is sensitive to all of the bioaccumulation pathways for selenium, and its predictions are accurate when waterborne concentrations are not elevated.

Another problem with HQ analysis, due to its dependence on waterborne selenium, is that it does not accurately evaluate the success of remediation at contaminated sites. It is possible for waterborne selenium to fall substantially, with little or no accompanying reduction in the overall ecosystem-level hazard to fish and wildlife. For example, hazard to fish and aquatic birds remains high at Belews Lake, NC, because of selenium-laden sediments even though waterborne concentrations have dropped to near background levels because of remediation that eliminated selenium inputs (Lemly, 1993c, in press). The HQ ratings suggest that remediation has been successful and no hazard remains because waterborne selenium is well below the EPA criterion. However, this is clearly not the case. The Protocol correctly identified and rated the hazard that persists at this site; HQ analysis did not. Thus, there are several important limitations in the application of HQ analysis to aquatic risk assessment of selenium.

A possible criticism of the Protocol method is that it requires considerably more data than HQ (i.e., water, sediments, invertebrates, fish, and birds for the Protocol; just water for HQ). However, given the serious impacts of selenium on fish and wildlife that have resulted because of environmental management actions that were based on inadequate risk assessment (e.g., Lemly, 1985b, 1993; Lemly, 1994), the effort and expense is well justified from an ecological perspective. In order to adequately address environmental safety issues, risk assessment procedures that yield the most ecologically sound information are necessary. For aquatic hazard assessment of selenium, the method of choice is the Protocol.

## CONCLUSIONS

The differences in hazard indicated by the Protocol and HQ analysis have important implications for risk assessment of selenium and environmental planning in general. Until an updated EPA national water quality criterion is available, HQ analysis should not be used for selenium. Even then, with the availability of the Protocol, which addresses multiple exposure pathways on a site-specific basis, HQ analysis should only be applied to those data sets that have water as the primary or sole source of information on environmental concentrations of selenium.

Use of the Protocol can greatly reduce the level of uncertainty in risk assessment for selenium and lead to more effective risk management. This method can identify selenium as a concern early-on in the planning process so that alternative land and water management scenarios can be evaluated, hopefully minimizing risks to fish and wildlife.

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