Prepared in cooperation with the Montana Department of Environmental Quality

Understanding and Documenting the Scientific Basis of Selenium Ecological Protection in Support of Site-Specific Guidelines Development for Lake Koocanusa, Montana, U.S.A., and British Columbia, Canada

Open-File Report 2020–1098

U.S. Department of the Interior
U.S. Geological Survey

Cover. Photograph showing Libby Dam on the Kootenai River near Libby, Montana. Photograph by U.S. Army Corps of Engineers, Seattle District Public Affairs Office.

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DAVID BERNHARDT, Secretary

U.S. Geological Survey
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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
acre-foot (acre-ft)	1,233	cubic meter (m^3)
acre-foot (acre-ft)	0.001233	cubic hectometer (hm^3)

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
meter (m)	3.281	foot (ft)
meter (m)	1.094	yard (yd)
	Area	
square kilometer (km^2)	247.1	acre
square kilometer (km^2)	0.3861	square mile (mi^2)
	Flow rate	
cubic meter per second (m^3/s)	70.07	acre-foot per day (acre-ft/d)
	Mass	
kilogram (kg)	2.205	pound avoirdupois (lb)

Supplemental Information

Concentrations of chemical constituents in water are given in either micrograms per gram (µg/g) or micrograms per liter (µg/L).

A water year is the period from October 1 to September 30 and is designated by the year in which it ends; for example, water year 2019 was from October 1, 2018, to September 30, 2019.

Abbreviations

>	greater than
<	less than
AE	assimilation efficiency
BAP	bioaccumulation potential
CF	tissue-to-tissue conversion factor
dw	dry weight
EC	effect concentration or level of toxicity (for example, an EC10 is the toxicant concentration that causes a 10-percent effect in the endpoint of interest such as incidence of larval fish deformity in the case of selenium
ESA	Endangered Species Act
GSI	gonadosomatic index
IFM	invertebrate to fish model
K_d	environmental partitioning factor
MTDEQ	Montana Department of Environmental Quality
MTFWP	Montana Department of Fish, Wildlife and Parks
n	number of samples
RG_DSELK	downstream Elk River
SOE	south of Elk
SPM	suspended particulate material
TFM	trophic-level (predator to forage) fish model
TL	trophic level
TTF	trophic transfer factor
USFWS	U.S. Fish and Wildlife Service
USGS	U.S. Geological Survey
wb	whole body

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Abstract

Modeling of ecosystems is a part of the U.S. Environmental Protection Agency's protocol for developing site-specific selenium guidelines for protection of aquatic life. Selenium as an environmental contaminant is known to bioaccumulate and cause reproductive effects in fish and wildlife. Here we apply a modeling methodology—ecosystem-scale selenium modeling—to understand and document the scientific basis for predicting and validating ecological protection for Lake Koocanusa, a transboundary reservoir between Montana and British Columbia. A comprehensive set of site-specific data compiled from public databases (Federal, State, and Provincial) and reports by Teck Coal Ltd., is available in a companion U.S. Geological Survey data release. The tissue guideline used within modeling here to assess protection is the U.S. Environmental Protection Agency's national selenium guideline for whole-body fish (dry weight); however, other numeric values for a whole-body guideline or other tissue types may be assumed if applicable tissue-to-tissue conversion factors are available.

We consider the report assembled here as a working document that presents a model that can effectively address and structure the needs of (1) scientific understanding in representing the lake's ecosystem and selenium biodynamics and (2) policy and management development during a decision-making process, but it is open to modification and updating as more ecologically detailed data become available. The approach brings together the main concerns involved in selenium toxicity: likelihood of high exposure, inherent species sensitivity, and close connectivity of ecosystem characteristics and behavioral ecology of predators. Detailed site-specific modeling equations are provided to document the linked factors that determine the responses of ecosystems to selenium. A series of scenarios quantifies the implications of choices of site-specific variables including food-web species, bioavailability of particulate material, and partitioning between the dissolved and particulate phases at the base of food webs. A gradient mapping tool applied to Lake Koocanusa provides a precedent for ecosystem-scale modeling of lakes by recognizing the importance of lake strata and hydrodynamics as components of modeling.

Data requirements for ecosystem modeling, including ecological and hydrological process information fundamental to the dietary biodynamics of selenium in site-specific food webs, were assessed as a precursor to model validation for Lake Koocanusa. Understanding these relationships is necessary to connect modeling outcomes to reproductive effects and establish boundaries, in the case of Lake Koocanusa, for the influences of dam operation, fish-community viability, and its Clean Water Act impaired 303(d)-listing status on ecosystem function.

We find that an assemblage of conditions affects the representation of Lake Koocanusa's ecosystem within modeling scenarios but that the constructed gradient maps, mechanistic model, and associated bioaccumulation potentials portray and quantify the variables that are determinative to protection of predator species. Ecological and hydrological sorting of compiled individual data points on a site- and species-specific basis helps identify and address model uncertainties. Sources of uncertainty include (1) the scarcity of data for some environmental media compartments across time and locations, (2) the complexity of hydrodynamic conditions that can lead to seasonal ecological disconnects such as in selenium partitioning from water into particulates, and (3) the functional status of Lake Koocanusa's ecosystem because of cumulative effects of various environmental stresses (for example, fish-community changes, flow regime changes, parasites, gonadal dysfunction, and increasing mining input-selenium concentrations since 1984). To this last point, it is important to determine where Lake Koocanusa is in an impairment-restoration cycle so as not to base protection on survivor bias, the maintenance of a currently degraded ecosystem, or normalized toxicity. In a broader context, one of the overall consequences of revised selenium regulations is that their derivation is now dependent on being able to define and understand the status of the ecosystem on which protection is based.

Introduction

The objective of this work is to document the scientific basis of selenium ecological protection in support of the development of selenium guidelines for Lake Koocanusa (fig. 1). Both the British Columbia Ministry of Environment and Climate Change Strategy (hereafter referred to as "BCMOE") and the U.S. Environmental Protection Agency (hereafter referred to as "USEPA") provide guidance for recently revised selenium regulations that recognizes the importance of linking the primacy of a fish tissue toxicity guideline with the practicality of a water-column guideline through a site-specific modeled ecosystem (BCMOE, 2014; USEPA, 2016a). The overall goal of this work is to provide an ecosystem-scale model that illustrates the site-specific range of potential selenium exposure and bioaccumulation that can inform the basis for regulatory decision-making by the State and the Province.

Explicit goals related to modeling as expressed at the conception of this work and embedded in a cooperative funding agreement between the U.S. Geological Survey (USGS) and the Montana Department of Environmental Quality (MTDEQ) are as follows:

- consideration of ecologically significant species and those important to stakeholders;
- protection of 100 percent of the fish species in the reservoir assuming a reproductive endpoint from reproductively mature females that are feeding in an ecosystem that functions as a lentic reservoir;
- long-term protection for fish in all parts of the reservoir during all phases of reservoir operation, all selenium loading profiles, and all water years (precipitation/runoff scenarios);
- protection of ecosystems during maximum dietary selenium exposure (that is, feeding within a benthic food web); and
- protection of downstream uses including protection of the endangered Kootenai River *Acipenser transmontanus* (white sturgeon).

As a working document, the report integrates information, data, and graphs from the following:

- Teck Coal Ltd., Lake Koocanusa Monitoring Reports, 2014–16 and 2018 (Teck Coal Ltd., 2018a, 2019);
- Lotic Environmental Ltd., Lake Koocanusa Food Webs (Baranowska and Robinson 2017; Baranowska, 2018);
- USGS data release (Presser and others, 2018; https://doi.org/10.5066/P9HB5S5F) that includes data from sample collection in 2015–17 and a plan designed for ecosystem-scale selenium sample collection for Lake Koocanusa;
- a modeling methodology that is well documented in the literature (for example, Presser and Luoma, 2010a); and
- a methodology for sampling and analysis of suspended particulate material (SPM) that was implemented specifically for Lake Koocanusa (Presser and others, 2018).

Presented here in support of modeling are the following:

- USGS data release (Presser and Naftz, 2020; https://doi.org/10.5066/P9VXYSNZ) that is specific to the basis of ecosystem-scale selenium modeling;
- summary tables that characterize and justify site- and species-specific choices in model development;
- spreadsheets that show model scenarios and computations for validation of ecosystem selenium concentrations and prediction of protective dissolved selenium concentrations based on those scenarios;
- a series of lake contours or gradient maps for 2017 showing observed dissolved and SPM selenium concentrations and calculated environmental partitioning factors (K_d values);
- observed dissolved selenium concentration cross sections specific to lake strata and location that address both north-to-south and depth selenium gradients for April–October (2016–19); and
- supplemental data that may help identify additional predator, contaminant, and stressor pathways in the future (Presser and Naftz, 2020).

Hence, there are a number of ways to build upon the structure and templates presented here as data-collection efforts go forward and model runs are needed to test the implications of additional site-specific variables.

This report is in answer to a specified need by MTDEQ and other stakeholders concerning the derivation of site-specific aquatic-life protection for Lake Koocanusa. That need was to model the ecosystem in terms of selenium dietary biodynamics and provide modeling spreadsheets as an interactive way for stakeholders to participate in scenario building within a decision analysis structure (Jenni and others, 2017). The audience for this work is expected to be somewhat familiar with the environmental setting, regulatory issues, and the transboundary nature of the work. As such, this work cuts across Federal, State and Provincial boundaries and, hence, agency protocols. In this regard, terms such as criterion, standard, and guideline, which are specific to regulatory agencies cited in this report, are collectively referred to here as "guideline." The guidelines cited are those recommended on a national basis by the USEPA through the Clean Water Act section 304(a) or on a Provincial basis by BCMOE (USEPA, 2016a; BCMOE, 2014). For fish tissue, the whole-body (wb) selenium guidelines are as follows: USEPA, 8.5 micrograms

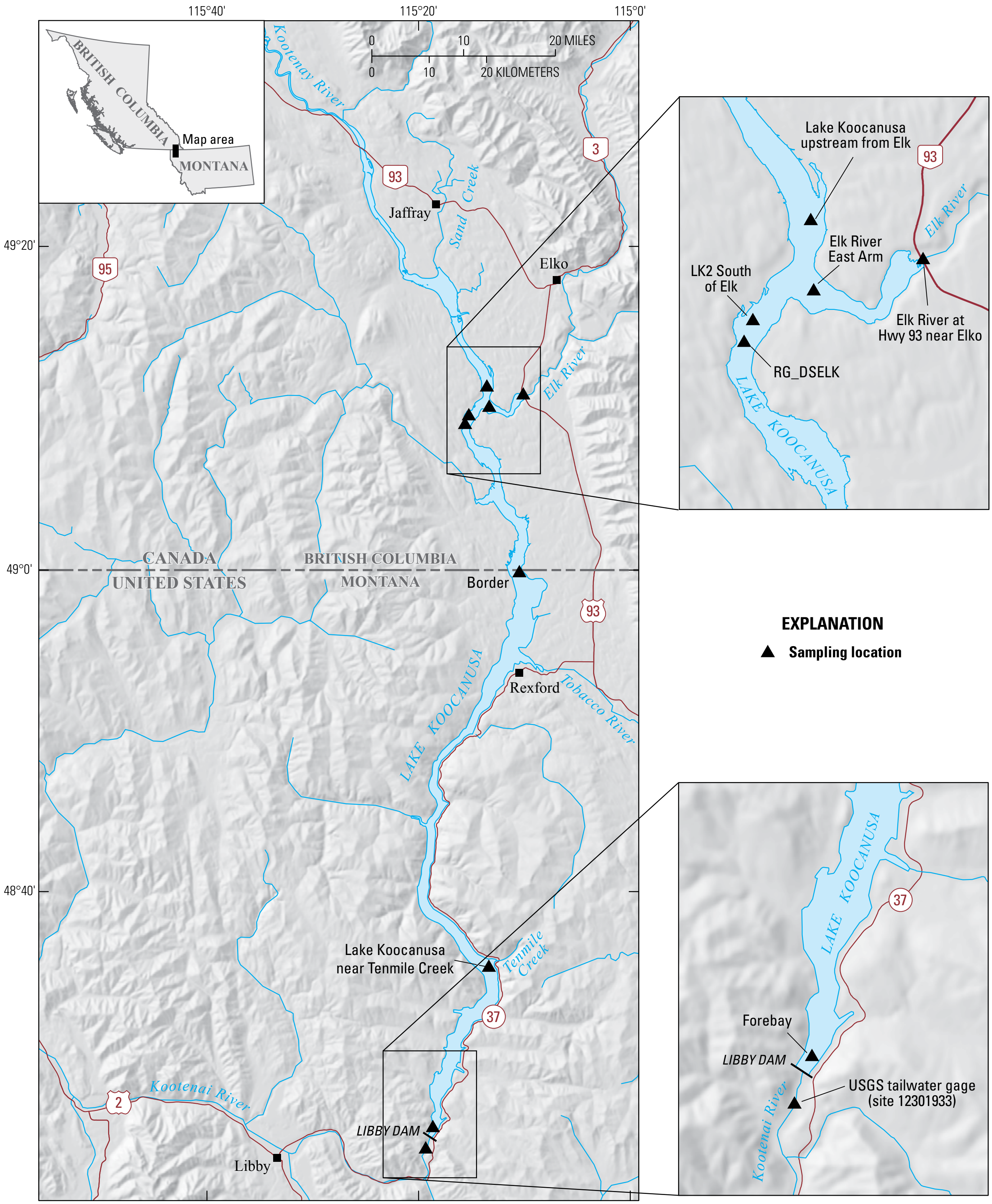


Figure 1. Study areas map of Lake Koocanusa showing locations of Libby Dam, the border between Montana and British Columbia, and the Elk River, which discharges selenium from five coal mines in British Columbia into the reservoir (see figures 11*A*–*F* for all sampling locations).

per gram dry weight (µg/g dw), and BCMOE, 4 µg/g dw. These regulatory guidelines and their derivation (for example, exposure-response curves) are not addressed here in any detail. However, it should be kept in mind when modeling that protection goals associated with these guidelines differ (for example, through application of an uncertainty factor; consideration of wildlife in addition to fish). The citations mentioned previously also document additional recommended national or Provincial water-column and diet guidelines for selenium that are used in this report.

Integration of available datasets within modeling for Lake Koocanusa was affected as we attempted to sort through fundamental landscape and ecosystem function alterations known to be caused by Libby Dam itself to establish sensitive locations and timing with which to inform regulatory and management actions. New sampling methods and tools also were implemented during the length of this project in response to ecosystem conditions assessed during our study. For example, collection of SPM, as the phase of particulate material most relevant to modeling of the base of food webs, was adapted for an oligotrophic lake setting of as much as 315 feet (ft) of depth. Additionally, a gradient mapping tool was formulated and applied to spatially integrate the influence of variables such as hydrodynamics and selenium source inputs within the lake. The generated plots illustrate the type of conceptualization and quantification that is possible to support food-web modeling of lake settings in comparison to stream-network or estuarine systems (Presser, 2013; Presser and Luoma, 2013). Overall, some tolerance is needed to accept these interim efforts as they are meant, as a way to move forward when encountering unforeseen uncertainty in ecosystem functioning and health.

As part of future monitoring to support ecosystem-scale modeling and constrain uncertainty within regulatory and management actions, the USGS deployed a monitoring platform in August 2019 at the U.S. and Canada border (fig. 1). In addition to standard, hourly limnological profiles that can be viewed in near-real time, filtered water samples are collected on a daily time step from four depths and preserved for selenium analysis (USGS site 12300110; https://nwis.waterdata.usgs.gov/usa/nwis/qwdata/?site_no=12300110). Similar equipment was deployed within the existing tailwater gaging station below Libby Dam (USGS site 12301933; https://nwis.waterdata.usgs.gov/usa/nwis/qwdata/?site_no=12301933). This station provides (1) coordinated monitoring for a second downstream location of the reservoir and (2) information on the variability of selenium inputs to the downstream lotic habitats of the Kootenai River. Hence, with the addition of these datasets in the future, the distribution of selenium concentrations with time and depth during varying hydrodynamic conditions (for example, spring freshet, fall turnover, density driven currents) can inform modeling scenarios.

Setting and Ecosystem

Lake Koocanusa is a transboundary reservoir between Montana and British Columbia created by the impoundment of the Kootenai River when Libby Dam was built in 1972 (Bonneville Power Administration and others, 1995) (fig. 1). Its construction was authorized as part of a treaty between the United States and Canada for cooperative development of flood storage, hydroelectric power generation, and recreation within the Columbia River Basin. The drainage area captured by the dam is 8,985 square miles (mi^2) and reservoir capacity is 6.0 million acre-feet (https://www.nwd-wc.usace.army.mil/dd/common/projects/www/lib.html). The reservoir is 90 miles (mi) in length, with 48 mi on the Montana side and 42 mi on the British Columbia side. Full-pool elevation is 2,459 ft, with a maximum depth of 350 ft at the forebay (Easthouse, 2013). Minimum pool is 2,287 ft, with drawdown occurring approximately from November to May (see also Presser and others, 2018, figs. 11, 13, 15). As part of the Columbia River Basin, many ecological studies were completed before and after impoundment. The status of the lake is currently monitored by (1) the U.S. Army Corps of Engineers for parameters critical to meeting management goals including flow, water quality, and productivity (https://www.nwd-wc.usace.army.mil/ftppub/water_quality/tdg/#LBQM) and (2) the USGS for outflow (river discharge) from the dam (https://waterdata.usgs.gov/nwis/uv/?site_no=12301933&agency_cd=USGS). Beginning in 2019, the USGS also monitors water quality and selenium concentrations at the international boundary (site number 12300110) and below Libby Dam (site number 12301933).

The Kootenai River drainage basin has its origin in British Columbia and is located within the Northern Rocky Mountain physiographic province (Woods and Falter, 1982). The basin lies within a latitude range of 48–51 degrees north, which is at the edge of the boreal (that is, high latitude) zone of climate classification. Lake Koocanusa's Trophic State Index fluctuates between oligotrophic and mesotrophic. This index compares lakes according to their summer (June–September) biological productivity on a scale of 0–100. At the lower end of the scale (oligotrophic, less than [<] 40), a lake would have low productivity, high water clarity, and low nutrients.

The Fording River and Elk River watersheds (240 and 1,718 mi^2, respectively) of the Kootenai River Basin are the sources of selenium to Lake Koocanusa. Drainage from five surface coal mines is transported by these rivers under permits administered by the BCMOE (Teck Coal Ltd., 2014; BCMOE, 2018). Mining of this mineral resource is through a technique similar to mountaintop removal that requires large-scale storage of selenium-enriched waste rock in valley drainages or open pits. Management of selenium risk is necessary once these waste rocks are exposed, oxidation to mobile selenate occurs, and the resulting leachate interfaces with the environment (Presser and others, 2004; Presser, 2013). Since 1984, selenium concentrations in the Elk River measured at a station 2.2 mi above its discharge into Lake Koocanusa (that is, at Highway 93) show a continuing increase as mines have expanded (https://www.canada.ca/en/environment-climate-change/services/freshwater-quality-monitoring/online-data.html) (fig. 2*A*). Selenium concentrations in the Elk River have exceeded BCMOE's Provincial guideline of 2 micrograms per liter (µg/L) for protection of aquatic life (Nagpal and Howell, 2001; BCMOE, 2014) since 1993 and the USEPA's guideline of 3.1 µg/L for lotic waters (USEPA, 2016a) since 2002 on a seasonal basis. In terms of maxima, selenium concentrations at this site exceeded 8 µg/L in February 2014 and April 2018. This upward trend has created a nonsteady state for dissolved selenium in the lake that the ecosystem is responding to throughout this 35-year period. The USEPA (2016a) describes concerns about site-specific derivations under new input conditions that lead to nonsteady-state conditions and recommends a series of steps that involve investigating the dynamics of selenium bioaccumulation within such an ecosystem. Expansion of mining is ongoing, and management plans for selenium call for a doubling of the amount of waste-rock storage by 2023 (Teck Coal Ltd., 2014).

A snapshot in 2014 of selenium concentrations farther downstream (1) in the Elk River at its mouth (fig. 1) shows a range of concentrations of 3.2–8.5 µg/L at the surface from January to December (fig. 2*B*) and (2) in the east arm (fig. 1), where the Elk River discharge enters into the reservoir, shows a range of 0.8–3.8 µg/L at different depths in May–November of 2014 (fig. 2*C*). A study in 2018 addressed riverine mixing within the reservoir during three pool conditions (low, intermediate, high). Specific conductance and temperature elucidated the density gradient from the river input to the order station (that is, permitted water-quality site; RG_DSELK [downstream Elk River]) at approximately 4.4 mi downstream (fig. 1) (Teck Coal Ltd., 2018b). The Elk River discharge is characterized by elevated specific conductance and cooler water temperatures compared to reservoir waters, thus setting up the potential for characteristic density-layering effects. Profiles of the east arm of the reservoir indicate that the Elk River waters were generally confined to bottom contours, but downstream mixing took place as river water rose to midcolumn. Confinement of river-water mixing to the eastern side of channelized flow also occurred until below RG_DSELK.

Lake Koocanusa's highly modified hydrological and ecological systems contribute to the interpretation of how its ecosystems are functioning, especially here, in terms of the fundamental processing of selenium. In general, Lake Koocanusa has the traditional problems associated with dam management for power generation in that large elevation changes (for example, 140–170 ft below full pool) occur during drawdown and refilling operations (Bonneville Power Administration and others, 1995). A series of hydrographs illustrate the magnitude of these types of changes (that is, elevation, discharge) specific to Lake Koocanusa in 2015–17 (Presser and others, 2018, figs. 11–16). An example of this type of disturbance specific to the species of the lake is that

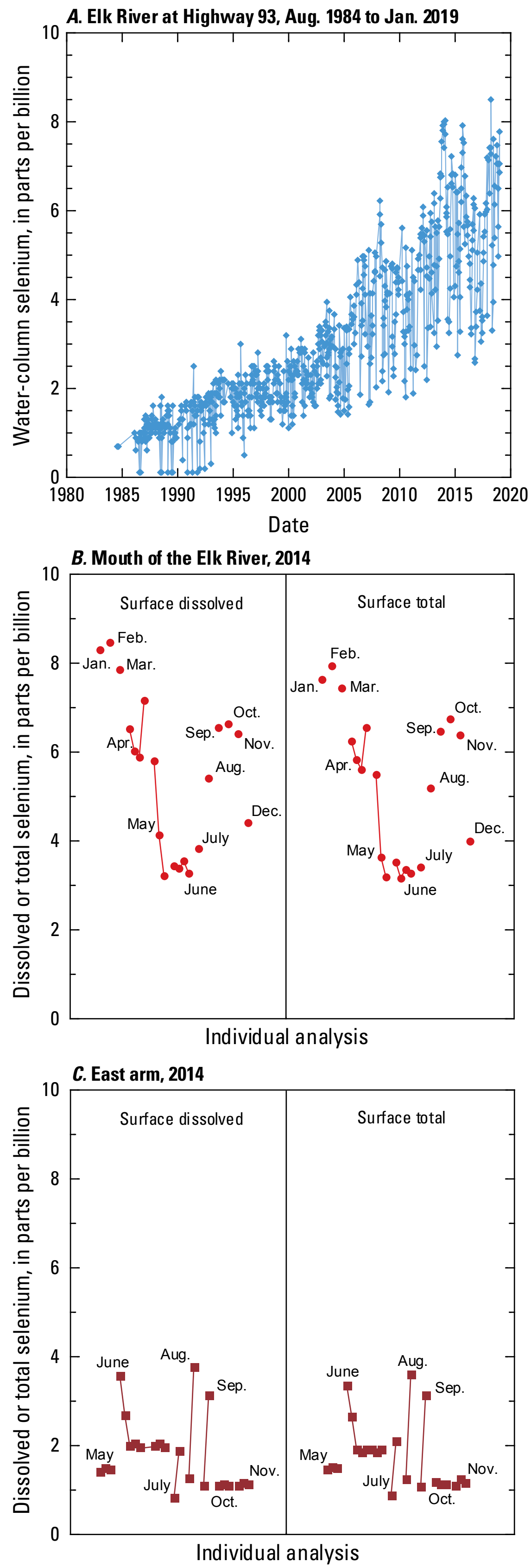


Figure 2. Water-column selenium concentrations for sites on the Elk River. *A*, for the Elk River at Highway 93 from 1984 to 2019; *B*, the mouth of the Elk River in 2014; *C*, the east arm in 2014.

the spawning time of *Lota lota* (burbot) coincides with the timing of maximum drawdown in Lake Koocanusa (Teck Coal Ltd., 2015).

Given the variable retention and flushing times, residence time of water in the lake also varies. Woods (1982) calculated a range of annual hydraulic residence times of 1.7–7.5 months during initial conditions after dam construction (1972–80). Holderman and others (2009) cite 5.5 months based on a mean annual discharge of 440 cubic meters per second. The U.S. Army Corps of Engineers (Easthouse, 2013) cites a mean water residence time of approximately 9 months. Residence time profiles, if measured on a monthly time scale, could further elucidate a connection to lake productivity and, hence, ecosystem function (see later discussion, "Transboundary Metadata and Suspended Particulate Material Sampling" section).

Hauer and Stanford (1997) referred to the large-scale effects of river regulation on the ecology of the Kootenai River Basin as a functional reset of a river continuum. Impacts include decreases in (1) production of zooplankton and benthic invertebrates and (2) availability of terrestrial insects, especially when refill is not achieved (Bonneville Power Association and others, 1995, appendix K). Decreases in prey organisms can, in turn, lead to decreased fish growth. Impacts also affect the extent and quality of shoreline and littoral habitats, which can contribute to reduced nesting for birds and spawning areas for fish.

Phytoplankton and invertebrate densities (Presser and Naftz, 2020) elucidate shifts in taxa and provide measures of seasonal productivity for Lake Koocanusa (figs. 3–5). For example, diatoms dominated in 2014 and 2015 with a substantial shift to dominance by dinoflagellates in 2016 and 2017 (fig. 3). Yearly macrozooplankton (that is, excluding rotifers) densities (150-micron net) show dominance by the copepod Cyclops from 2009 to 2015 (fig. 4; Dunnigan and others, 2017). Mean densities for that period show productivity peaks in May and August, but the most recent profile in 2015 shows a series of peaks occurring during May, July, August, and September. Zooplankton densities (63-micron net) at three reservoir locations show rotifers dominate most profiles as increases occur from the border location to sites farther downstream towards the forebay of the dam (fig. 5*A*, *B*, and *C*). Experimental data for farm-raised fish show rotifers to be a nonnutrient food, low in selenium (for example, Mæhre and others, 2012); therefore, dilution of selenium in a composite sample of zooplankton could take place if a large number of rotifers were present compared to other zooplankton taxa.

Abundance data for macroinvertebrates in Lake Koocanusa are less available. Chisholm and others (1989) report large density peaks of aquatic macroinvertebrates in April–May, and to a lesser extent in August, based on a seasonal study of limnetic and nearshore habitats in 1983–87. For terrestrial macroinvertebrates, a peak in August dominates the 1983–87 profile. Also for this period, the density of individual invertebrate taxa, in decreasing order, was Hymenoptera (ants), aquatic dipterans (midges), Homoptera (leafhoppers), Coleoptera (beetles), Hemiptera (corixids, aphids), and Arachnida (spiders, ticks, mites) (Richards, 1997).

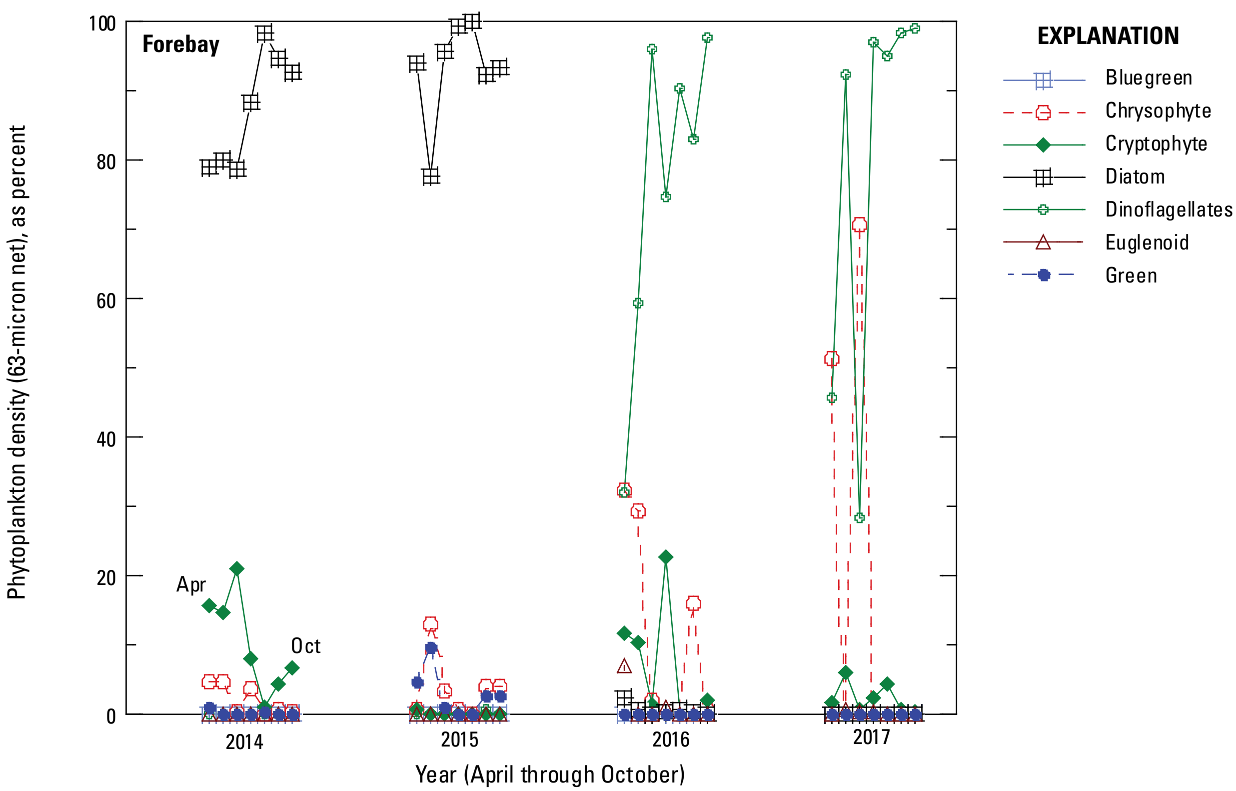


Figure 3. Phytoplankton profiles at the forebay for 2014–17.

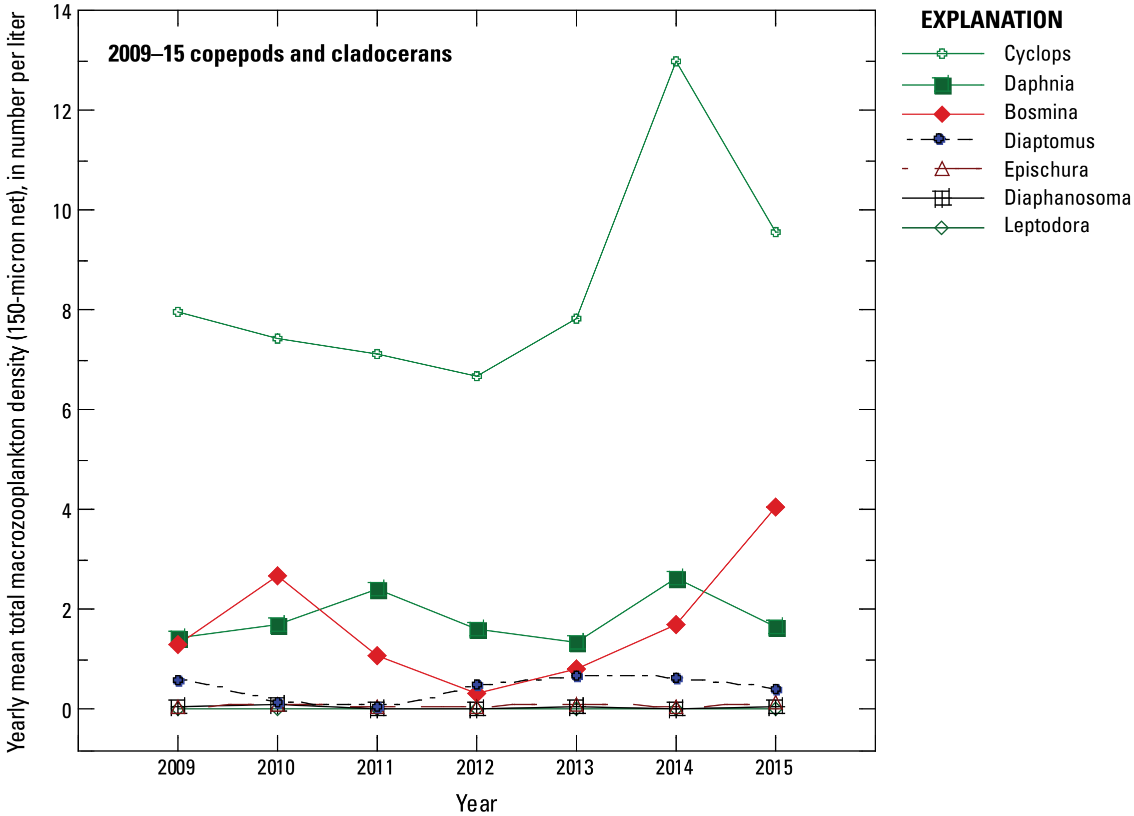


Figure 4. Macrozooplankton profiles (150-micron net) for 2009–15.

Specific to Lake Koocanusa for fish-community fluctuations, *Oncorhynchus mykiss* (rainbow trout), *Oncorhynchus clarki lewisi* (Westslope cutthroat trout), and *Prosopium williamsoni* (mountain whitefish) all demonstrated substantial decreases in abundance after construction of the dam caused a habitat shift from riverine to lacustrine, whereas *Mylocheilus caurinus* (peamouth chub) and *Ptychocheilus oregonensis* (northern pikeminnow) (that is, smaller bodied fish) have gone from rare during predam conditions to abundant during postdam conditions (Dunnigan and others, 2017). During the period 1979–85, inadvertent introduction of nonnative *Oncorhynchus nerka* (kokanee), stocking of hatchery rainbow trout, and invasion by *Perca flavescens* (yellow perch) all have added to the disruption of fish-community profiles and of species composition of zooplankton and invertebrate food sources. In 1985, kokanee accounted for 96 percent of the number of fish harvested from the reservoir (Chisholm and Hamlin, 1987). The Montana Department of Fish, Wildlife and Parks (MTFWP) introduced rainbow trout to feed on kokanee with goals of (1) reducing the number of kokanee and thereby increasing the size of trout and (2) providing a trophy fishery as trout attained an ultimate large size. Kokanee are also an important food source for *Salvelinus confluentus* (bull trout) and burbot.

Species of fish currently monitored, their histories, and important traits and characteristics are listed in table 1 (available for download at https://doi.org/10.3133/ofr20201098) and discussed in more detail later. Percentage composition of species in spring and fall from 2009 to 2016 is shown in figure 6*A* and *B* (Presser and Naftz, 2020). Peamouth chub, northern pikeminnow, and *Catostomus macrocheilus* (largescale sucker) are dominant in spring, with the remaining species making up <10 percent of totals. In fall, peamouth chub, northern pikeminnow, and kokanee dominate, with the remaining species again making up <10 percent of totals. Tracking of hatchery rainbow trout shows few fish of the approximately 30,000 to 90,000 stocked per year since 2001 are caught in nets (2.2 fish, mean) (Dunnigan and others, 2017, 2020; Presser and Naftz, 2020), which leads to the supposition that hatchery fish do not thrive or recruit.

Mitigation of the effects of Libby Dam on the lake's ecosystem is an ongoing effort since its construction in 1972. Focus in terms of fish is on (1) stream habitat enhancement or restoration; (2) removal of nonnative species; (3) protection of subwatersheds supporting native species; (4) assessment of burbot stock, restored natives, and hatchery fish (for example, hybridization between Westslope cutthroat trout and rainbow trout); and (5) increasing the productivity of fish populations

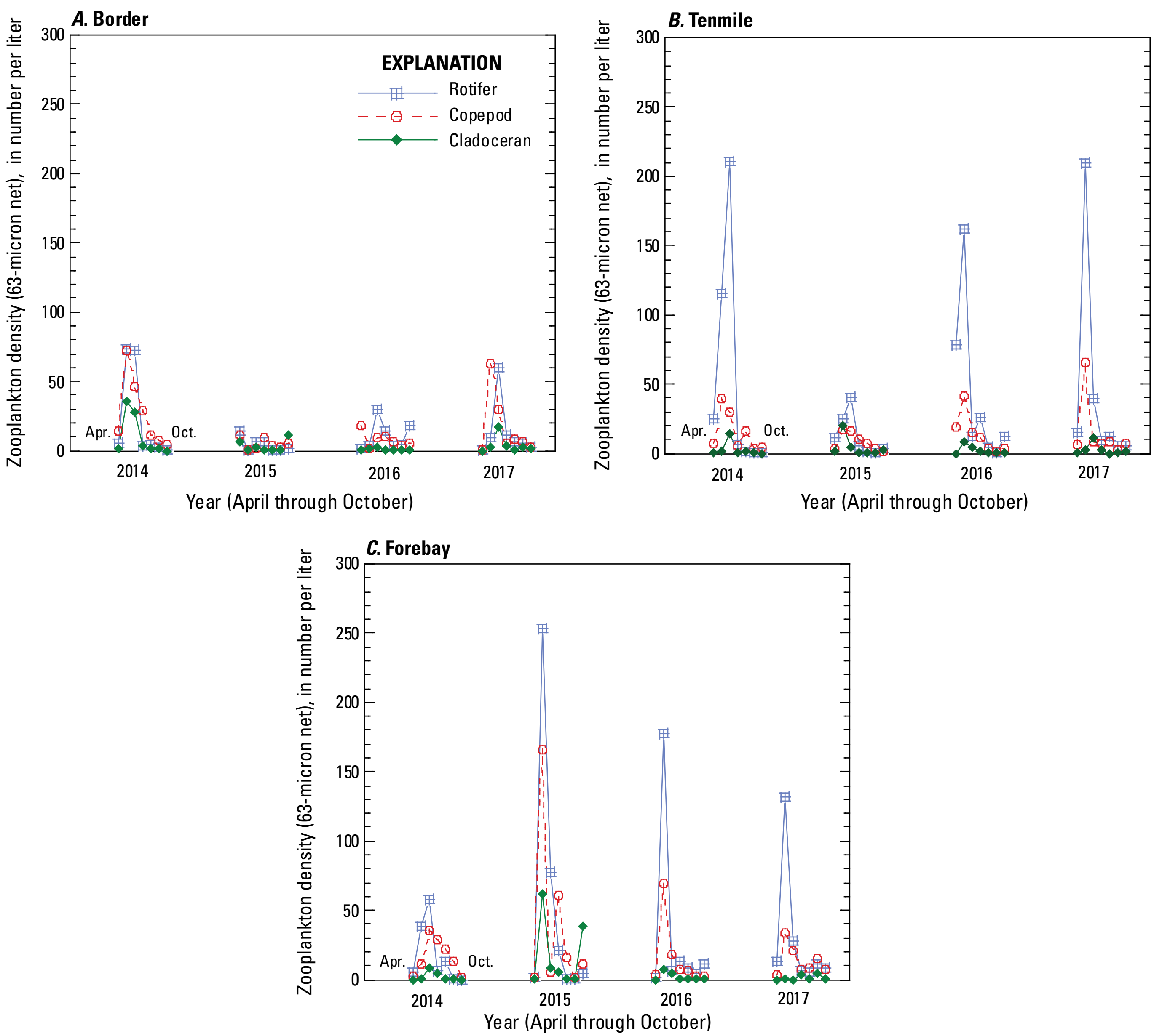


Figure 5. Zooplankton densities for 2014–17 (63-micron net). *A*, at the border; *B*, at Tenmile; *C*, at the forebay.

to help recruitment to adult stages (Dunnigan and others, 2017). The Kootenai River below the dam (that is, tailwater fishery) benefits from entrainment of kokanee through the dam because the fish become food for the river's population of rainbow trout; however, entrainment is detrimental to kokanee themselves.

Mitigation actions for minimizing the effects of Libby Dam operations that are temporal in nature include managing (1) downstream effects in the Kootenai River where the endangered white sturgeon and culturally sensitive burbot reside (for example, U.S. Fish and Wildlife Service [USFWS], 1999; Idaho Department of Fish and Game, 2008) and (2) tributary habitats for spawning (Dunnigan and others, 2017). Libby Dam has a selective withdrawal system that allows dam operators to mimic the natural annual temperature regime in the dam discharge in comparison to a traditional dam release of the hypolimnial layer (that is, bottom water). Hence, overall management of the Lake Koocanusa ecosystem is highly dependent on actions directed towards downstream mitigation.

The British Columbia side of Lake Koocanusa offers comparatively less elevation changes than the Montana side; hence, the ecological values of the northern reservoir shoreline (that is, foreshore as described here) areas for birds

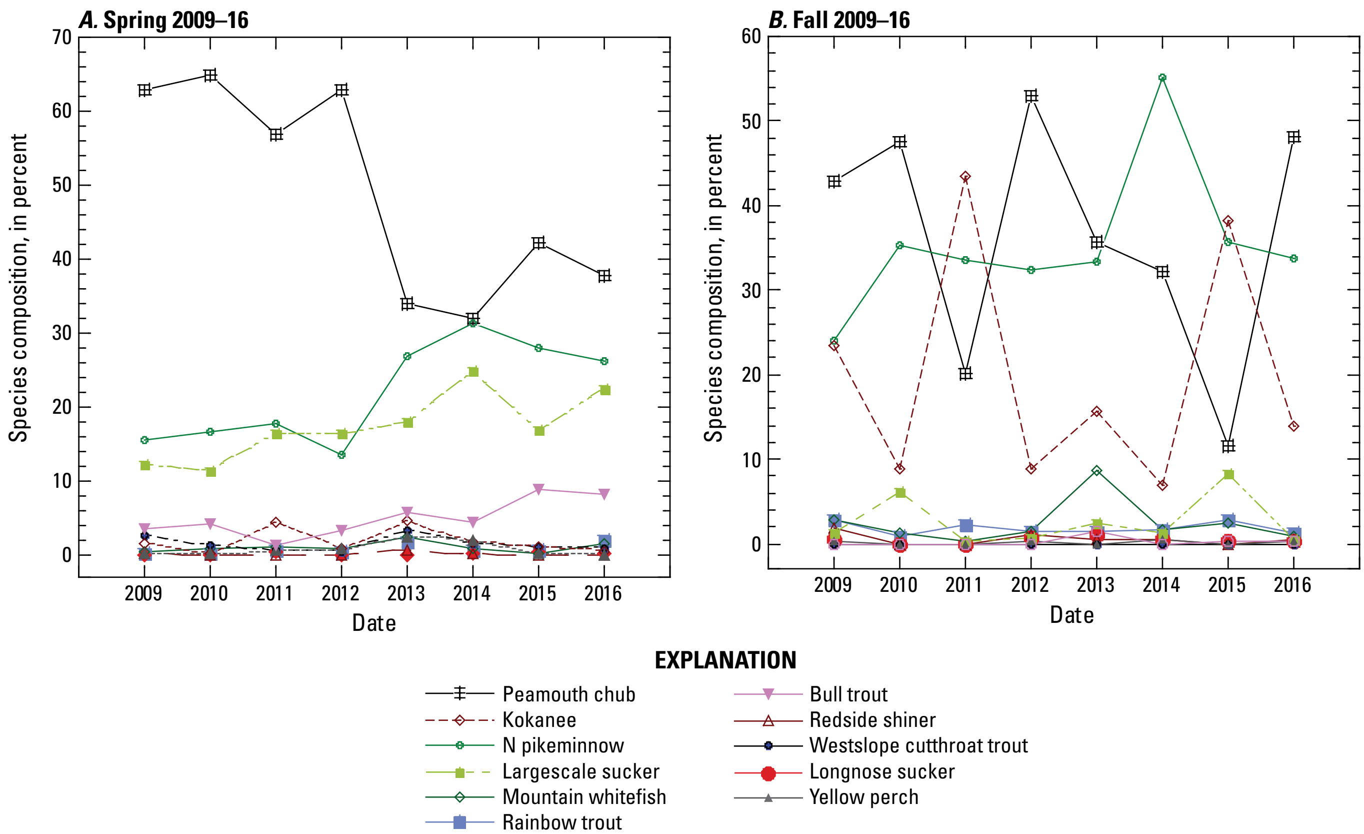


Figure 6. Percent composition of major fish species. *A*, in spring 2009–16; *B*, in fall 2009–16.

increase for such activities as foraging, migratory staging, and nesting/breeding (VAST Resource Solutions Inc., 2017). A list of recently observed birds for the British Columbia side foreshore areas includes species such as geese, grebes, loons, and mergansers and many migrating duck species (VAST Resource Solutions Inc., 2017, appendix C). A listing of bird species from eBird in 2016 for sites across the entire reservoir including Libby Dam (VAST Resource Solutions Inc., 2017, appendix D) shows an extensive array of aquatic, riparian, shore, and wetland species that are protected under the Migratory Bird Treaty Act.

The lake encompasses transboundary migratory routes and is a part of the Pacific Flyway. Northbound migration occurs from mid-April through mid-May. Southbound migration begins in mid-August for many shorebirds such as sandpipers, plovers, and dowitchers. Species that breed close to the lake's shores are *Actitis macularius* (spotted sandpiper), *Charadrius vociferus* (killdeer), and *Numenius americanus* (long-billed curlew). Upland wildlife that use the foreshore include songbirds (warblers, sparrows, flycatchers). Raptors utilizing the lake are *Falco peregrinus* (peregrine falcon), *Haliaeetus leucocephalus* (bald eagle), and *Pandion haliaetus* (osprey). Zones of sensitivity include specific protection rationales: active nesting for bank swallow and long-billed curlew; and designated Wildlife Habitat Areas for *Melanerpes lewis* (Lewis's woodpecker) and long-billed curlew (VAST Resource Solutions Inc., 2017). Selenium was analyzed in (1) spotted sandpiper eggs at the mouth of the Elk River in 2013–14 and (2) killdeer eggs in 2016 (Presser and Naftz, 2020). The maximum concentration in spotted sandpiper eggs was 8.4 µg/g dw (number of samples [*n*] =17), which exceeds the USFWS EC00 of 5.5 µg/g dw and EC10 of 7.7 µg/g dw for sensitive species (Presser and Luoma, 2010b). The maximum concentration in killdeer eggs was 3.7 µg/g dw (*n*=4).

Overarching Federal and State Policies for Ecosystem Setting and Species

The MTDEQ has identified Lake Koocanusa as threatened by selenium sources outside the State of Montana's jurisdiction or borders and listed the water body as impaired under section 303(d) of the U.S. Clean Water Act in 2012 (MTDEQ 303(d) list [MTDEQ, 2018]). The lake was identified as not fully supporting aquatic life as a beneficial use because of selenium, but also because of flow regime modifications. The current State regulation for selenium is through an aquatic-life standard of 5 µg/L (chronic) and 20 µg/L (acute) (MTDEQ, 2019). For comparison, the current aquatic-life guidelines are 1.5 µg/L for lentic waters of the United States (USEPA, 2016a) and 2 µg/L for waters of British Columbia (Nagpal and Howell, 2001; BCMOE, 2014).

In the 303(d)-list assessment record for Lake Koocanusa, selenium loads were estimated to increase by an average of 376 kilograms per year (kg/yr) or 19.7 percent per year, with planned mine expansions and new mines adding to that trend in the future. Loads measured in 2017 in connection with British Columbia's permit monitoring show a total input of 10,398 kg/yr based on monthly selenium concentrations at the mouth of the Elk River and extrapolated daily flow measurements (Teck Coal Ltd., 2018b). The two highest monthly inputs are approximately 2,400 kilograms during May and June. Establishment of a total maximum daily load as part of State regulatory actions is required, but the status of attainment is currently unassigned, and its priority is listed as low. The assessment unit is only that part of the lake located in the United States. Additionally, in consideration of permitting, a mixing zone of approximately 4.4 mi extends between the Elk River input and the permit sampling location RG_DSELK (fig. 1). Technically, mixing zones are not applicable in U.S. regulation of contaminants that bioaccumulate such as selenium (USEPA, 2016d).

Qualifying statements about the regulatory status of Lake Koocanusa (that is, the source of pollution is not controlled by actions of a locally issued discharge permit and pollutant loads are increasing) introduce the question of whether permits for the coal mines in British Columbia will be adjusted based on selenium guidelines adopted by the State of Montana. In this regard, Lake Koocanusa is subject to transboundary regulations: namely, the Boundary Waters Treaty Act of 1909 between Canada and the United States. The treaty establishes (1) an International Joint Commission to carry out the provisions of the act when requested by national governments and (2) a framework for dealing with disputes. The U.S. State Department, U.S. Department of the Interior, and USEPA, along with their Canadian counterparts, are actively engaged in this transboundary issue, but not to the point of referring the issue to the International Joint Commission.

The USFWS lists bull trout as threatened and designated Lake Koocanusa as critical habitat for this species (USFWS, 1998). In Montana, this species is considered a "species of concern," and in British Columbia, bull trout is blue listed (that is, a species of special concern). Westslope cutthroat trout is a species of concern in Montana and is blue listed in British Columbia. Burbot is red listed (that is, potentially extirpated, endangered, or threatened) in British Columbia, with lower Kootenay River populations designated as critically imperiled (Teck Coal Ltd., 2018a; BCMOE, 2015). Burbot also is considered culturally important to native Tribes, with resources being actively dedicated to its preservation, especially below Libby Dam (Idaho Department of Fish and Game, 2008).

White sturgeon do not inhabit Lake Koocanusa, but in 1999, the USFWS published a recovery plan for the Kootenai River population of endangered white sturgeon that depends on the implementation of a long-term flow strategy for Libby Dam (USFWS, 1999). Thus, the selenium guidelines for Lake Koocanusa are required to protect the downstream use of provision of habitat for white sturgeon under the requirements of the Endangered Species Act (ESA). For ESA-listed species, a site-specific guideline can only be approved by the USEPA if the guideline either would not harm a single individual of any listed species or would harm so few individuals as to avoid a jeopardy biological opinion under section 7 of the ESA. If even one individual could reasonably be expected to be harmed (as might be the case for a guideline that is based on an EC10 level of toxicity), at a minimum, a formal biological opinion would need to be prepared by USFWS and an incidental-take statement would be required. The opinion could include perpetual-monitoring requirements for the documentation of compliance with the incidental-take statement. Additionally, a guideline could not adversely modify any critical habitat, which would include perturbations of food webs.

Methods—Modeling, Contours, and Cross Sections

The derivation of the methodology used here and the need for regulatory revision of selenium protection is extensively documented in Reiley and others (2003), Luoma and Rainbow (2005), Luoma and Presser (2009), Chapman and others (2010), and Presser and Luoma (2010a). Examples of the site-specific application of ecosystem-scale selenium modeling are available for the coal mining regions of southern West Virginia and several regions of San Francisco Bay affected by discharges from oil refineries, agriculture, and municipalities (Presser, 2013; Presser and Luoma, 2013; Luoma and Presser, 2018). The USEPA's national guidelines (2016a) and those developed for California (USEPA, 2018) used an approach based on ecosystem-scale modeling.

Jenni and others (2017) describe an ecosystem-scale modeling framework applicable to Lake Koocanusa. Their report (1) serves as a coherent and consistent structure for organizing relevant scientific information within modeling parameters, (2) provides an appropriate context for interpreting new information as datasets and site parameters are developed, and (3) identifies data and science gaps that limit understanding of the implications of alternative selenium guidelines. Also available is an initial assessment of a site-specific monitoring design that meets the data needs of modeling selenium in Lake Koocanusa (Presser and others, 2018). This sampling matrix focuses on (1) spatially and temporally paired samples of environmental media (water, particulates, prey and predator tissue), (2) a site nearest the source of selenium entering Lake Koocanusa from the Elk River in British Columbia, and (3) sites at the forebay of Libby Dam and at the international border in the United States.

Ecosystem-scale selenium modeling conceptualizes and quantifies the site-specific variables that determine the effects of selenium (Presser and Luoma, 2010a) (fig. 7). Used optimally, the model provides a tool for framing a site-specific ecological problem or occurrence of selenium exposure, quantifying exposure within that ecosystem, and narrowing uncertainties about how to protect it by understanding the specifics of the underlying system ecology, biogeochemistry, and hydrology.

This mechanistic approach uses dietary selenium biodynamics to explain bioaccumulation and predict responses in ecosystems to selenium (note: all environmental media selenium concentrations are expressed as micrograms per gram dw except dissolved selenium, which is expressed as micrograms per liter). Dietary selenium biodynamics establish that (1) invertebrates biomagnify selenium (influx is greater than efflux) from particulate material at the base of the food web by as much as 38-fold depending on species-specific differences in dietary assimilation efficiency (AE) and the rate constant of loss and (2) dietary transfer of invertebrate selenium to fish species (as measured in wb dw tissue) has a median of approximately one, which reflects a cumulative preservation of selenium. Thus, trophic transfer from particulate material, based on dietary selenium concentrations and feeding, controls bioaccumulation within an ecosystem. The mechanistic dietary transfer model was validated through use of datasets from 29 historical and recent field case studies of selenium-exposed sites (Presser and Luoma, 2010a).

Choices explicit to running the model that are critical to deriving site-specific protection are (1) the choice of fish species, which determines the food web through which selenium is modeled; (2) the choice of food web, which determines the particulate material to prey kinetics of bioaccumulation; (3) the characterization of the type (for example, SPM, bed sediment) and bioavailability (for example, selenium speciation) of particulate material, which determines exposure at the base of the food web; and (4) the metric describing partitioning between particulate material and dissolved selenium concentrations, which is specific to the attributes of the hydrologic setting. Overall, the approach illustrates that environmentally safe dissolved selenium concentrations will differ among ecosystems depending on the ecological pathways and biogeochemical conditions in that system.

The constructed model here is first run in validation mode. For Lake Koocanusa, this model uses an observed SPM selenium concentration and categorized food-web types, with their associated trophic transfer factors (*TTFs*), to predict selenium concentrations in prey and predators. The predictions are then compared to observed selenium concentrations. The equation as applied to Lake Koocanusa is

$$C_{Se\ fish\ wb} = (C_{Se\ SPM})\ (TTF_{invertebrate})\ (TTF_{fish\ wb}) \quad (1)$$

where

$C_{Se\ x}$ is the selenium concentration in SPM, invertebrate, or fish (wb);

$TTF_{invertebrate} = C_{Se\ invertebrate} \div C_{Se\ SPM}$; and

$TTF_{fish\ wb} = C_{Se\ fish\ wb} \div C_{Se\ invertebrate}$.

As stated previously, the main mathematically determinative variables are the type of particulate material used to represent the ecosystem, the selenium concentration in the particulate material, and the taxa or species of the invertebrate consuming that food. The effect of multistep food webs that include forage fish as additional prey (that is, trophic level 3 to trophic level 4 [TL3 to TL4] food webs) and the bioavailability of selenium to the invertebrate (that is, selenium speciation of the particulate material) also may be quantified through additional equation components (Presser and Luoma, 2010a).

The model is then run in translation mode, which addresses the regulatory aspects of modeling. Here, an assumed fish tissue selenium guideline ($C_{fish\ Se\ guideline\ wb}$) and an observed environmental partitioning factor [$K_{d\ SPM} = (C_{Se\ SPM}/C_{Se\ dissolved})$ (1,000)] indicative of hydrological setting characteristics are used to predict a dissolved selenium concentration ($C_{Se\ dissolved}$) that is protective of the site-specific ecosystem. The equation as applied to Lake Koocanusa is

$$C_{Se\ dissolved} = C_{fish\ Se\ guideline\ wb} \div [(TTF_{fish\ wb})\ (TTF_{invertebrate})\ (K_{d\ SPM})] \quad (2)$$

where

$(K_{d\ SPM})\ (C_{dissolved})$ is substituted for $C_{Se\ SPM}$ and the equation is solved for $C_{Se\ dissolved}$.

$K_{d\ SPM}$ reflects the efficiency of environmental partitioning of selenium from the dissolved phase to the chosen particulate phase (Presser and Luoma, 2010a). In the modeling here, wb fish tissue is used as the endpoint ($C_{fish\ Se\ guideline\ wb}$), but egg-ovary tissue can be substituted if tissue-to-tissue conversion factors (CFs) are available (Janz and others, 2010; USEPA, 2016a, b). Thus, the predicted dissolved selenium concentration would quantify the ecosystem condition where fish would adhere to the assumed tissue guideline.

A series of modeling scenarios are used throughout the modeling process based on a range of choices that are informed by selenium science and stakeholders' decisions. Through both data utilization, as described below, and scenario development, sensitive locations, timing, and food webs can be identified to understand the maximum selenium bioaccumulation potential (BAP) and, hence, the focus of effective regulation and management.

The contouring package in OriginPro (v. 9.1, 2014) software was used to construct gradient plots of monitoring data from Lake Koocanusa. The triangulation method was used to contour the data. Selected polygons (for example, dissolved selenium concentrations greater than [>] 1.0 µg/L) from the gradient plots were extracted with the digitizer tool for x- (distance from Libby Dam) and y- (depth below water surface) coordinates from each monthly concentration gradient map. The absolute area of each polygon was calculated using the polygon area calculator.

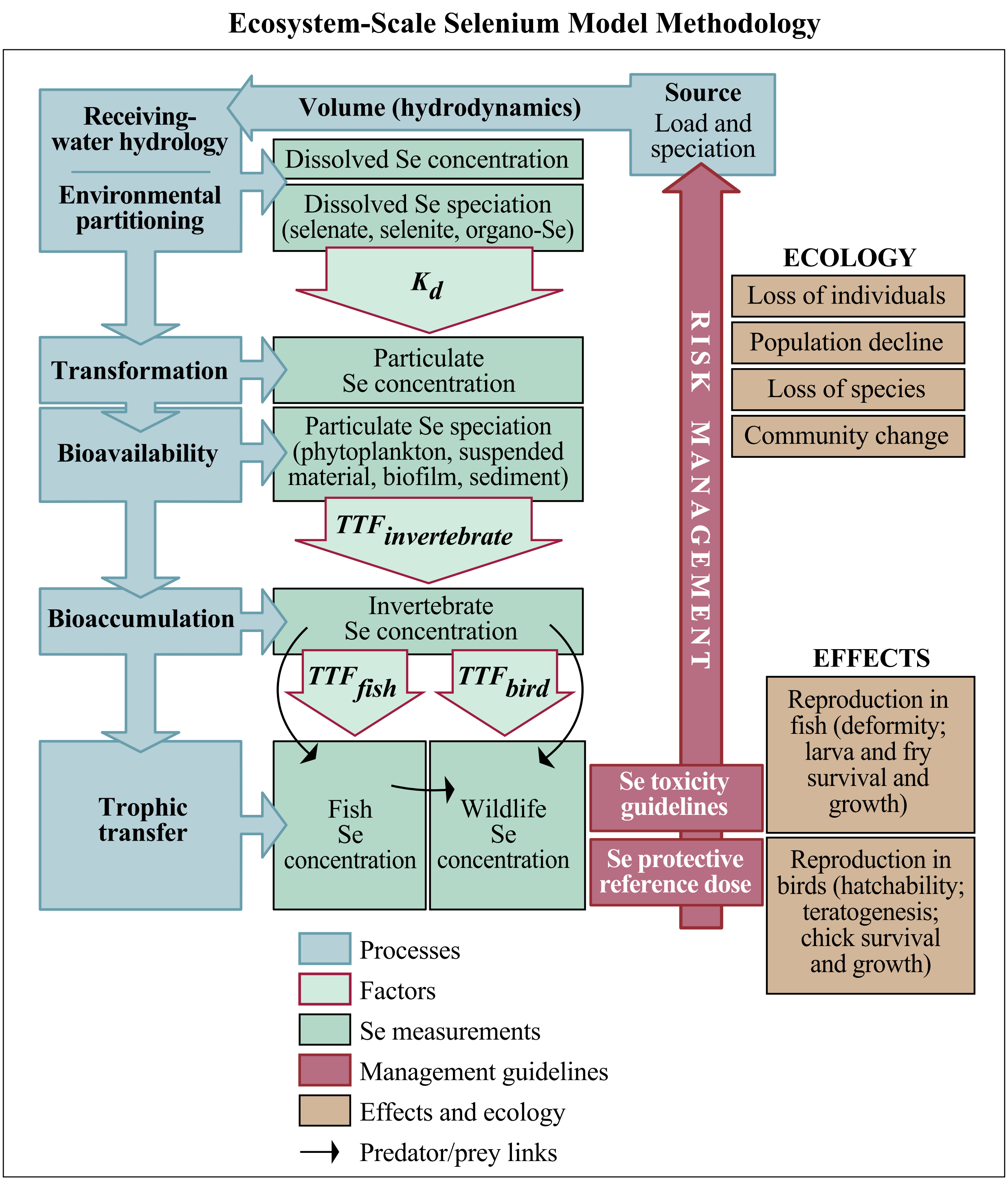


Figure 7. Ecosystem-scale selenium model methodology. The model conceptualizes processes and parameters important for quantifying and understanding the effects of selenium in the environment. The model can be applied to forecast exposure and to evaluate the implications of management or regulatory choices. [K_d, empirically determined environmental partitioning factor between water and particulate material; *TTF*, biodynamic food-web transfer factor between an animal and its food; Se, selenium (adapted from Presser and Luoma, 2010a)]

Supporting Data—Scope of Studies and Study Area

Sets of site-specific data support and give context to ecosystem-scale selenium modeling in this interpretative report (Presser and Naftz, 2020). These data were compiled from publicly available databases of Federal, State, and Provincial agencies and reports by Teck Coal Ltd. Some sets of raw data that helped inform the data presented in Presser and Naftz (2020) are available from MTDEQ (lakekoocanusaconservation.pbworks.com). The spreadsheets within our compilation are designed in an ecosystem-component format to assist modeling. Water-quality data are generically termed as "water column" for descriptive purposes below, but the data themselves are specific to dissolved (filtered) or total (unfiltered) samples. Reservoir sampling sites extend from the Elk River input in the north to the forebay in the south (see fig. 1 and figs. 8–11 for detailed maps of water-quality, invertebrate, and fish sampling locations).

Categories of data compiled in the companion USGS data release (Presser and Naftz, 2020) are as follows:

1. water-column selenium concentrations (2008–18),
2. recent USGS border platform water-column selenium concentrations (2019),
3. water-column selenium concentrations for the Elk River at Highway 93 (August 1984–January 2019),
4. spatially and temporally paired water-column and SPM selenium concentrations (2015–18),
5. recent detailed south of Elk (SOE) water-column selenium concentrations (2017–18),
6. dissolved selenium speciation (2015–16),
7. productivity (phytoplankton density) (2014–17),
8. zooplankton selenium concentrations (three net sizes) (2008, 2004–19),
9. zooplankton taxa metrics (2014–18),
10. invertebrate selenium concentrations (2013–16; 2018),
11. invertebrate taxa metric (2014–16; 2018),
12. dietary metrics for fish (percent of diet; relative importance index) (historical),
13. invertebrate taxa in fish stomachs (2017–18),
14. fish selenium concentrations (egg-ovary) (2008; 2013; 2014–18),
15. fish species abundance (2009–16) and fish catches (2014–16; 2018),
16. number of stocked fish (1988–2016),
17. annex—bird egg selenium concentrations (2013, 2014, 2016),

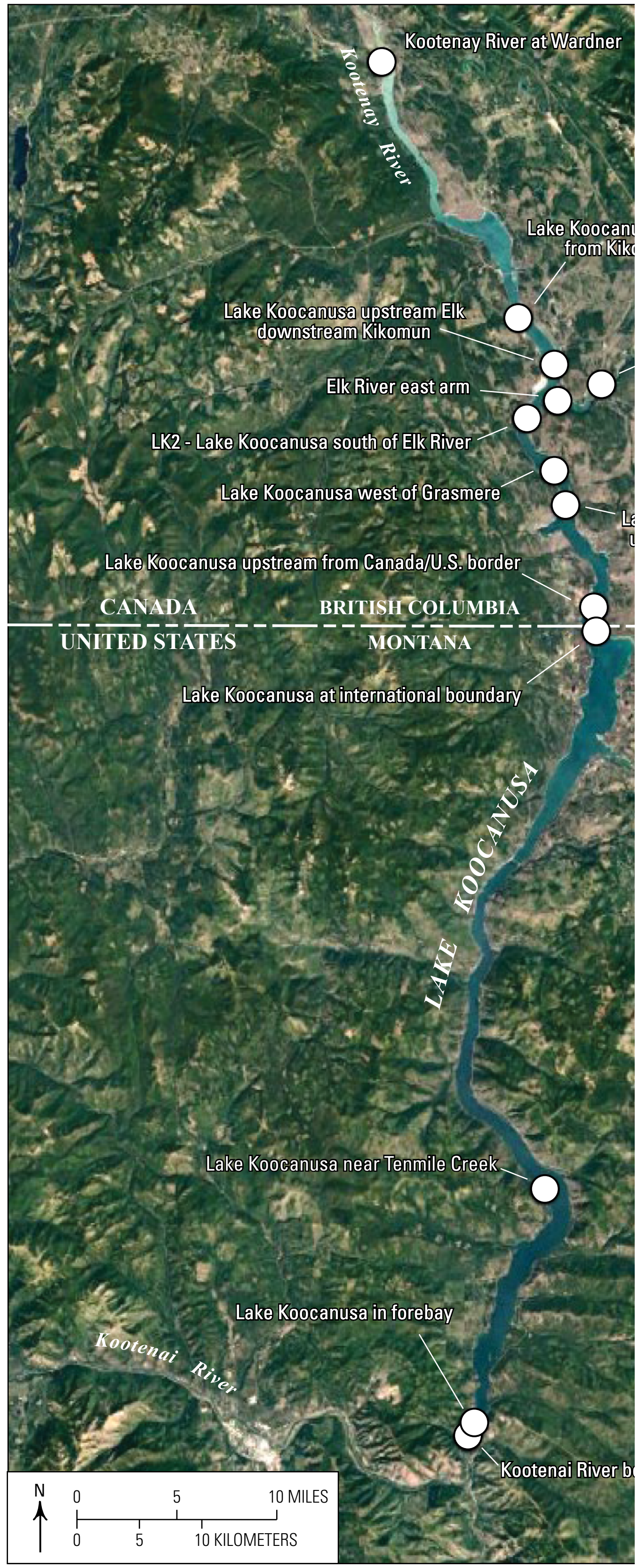


Figure 8. Location of sites where water quality and (or) suspended particulate material samples were collected from Lake Koocanusa, Elk River, and the Kootenai River, Montana, and Kootenay River, British Columbia.

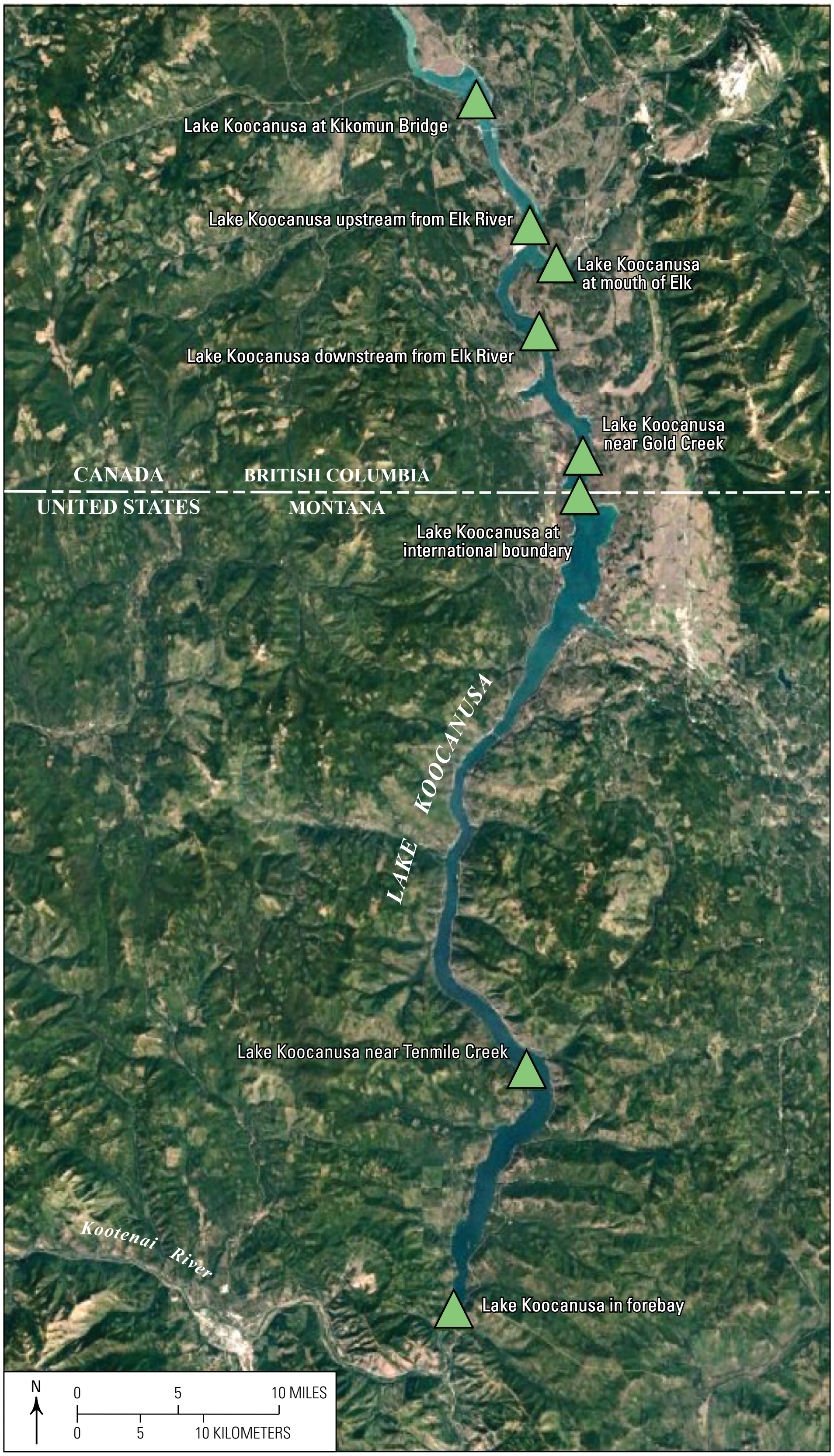


Figure 9. Location of sites where zooplankton samples were collected from Lake Koocanusa, Montana and British Columbia. Sample locations north of the international boundary may vary slightly depending on reservoir levels and other variables when the sample(s) were collected.

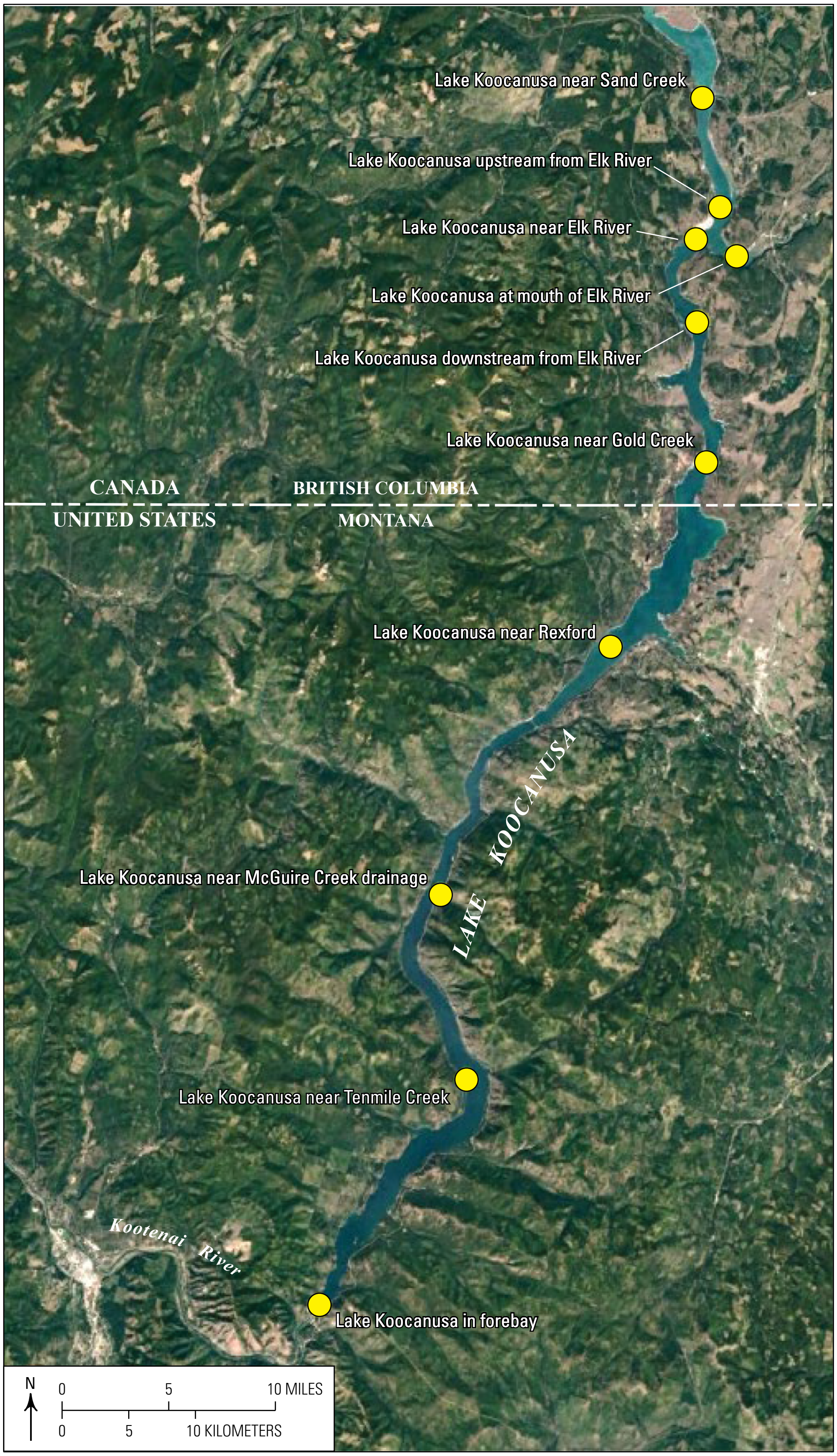


Figure 10. Location of sites where invertebrate samples were collected from Lake Koocanusa, Montana and British Columbia. Sample location(s) may vary slightly depending on reservoir levels and other variables when the sample(s) were collected.

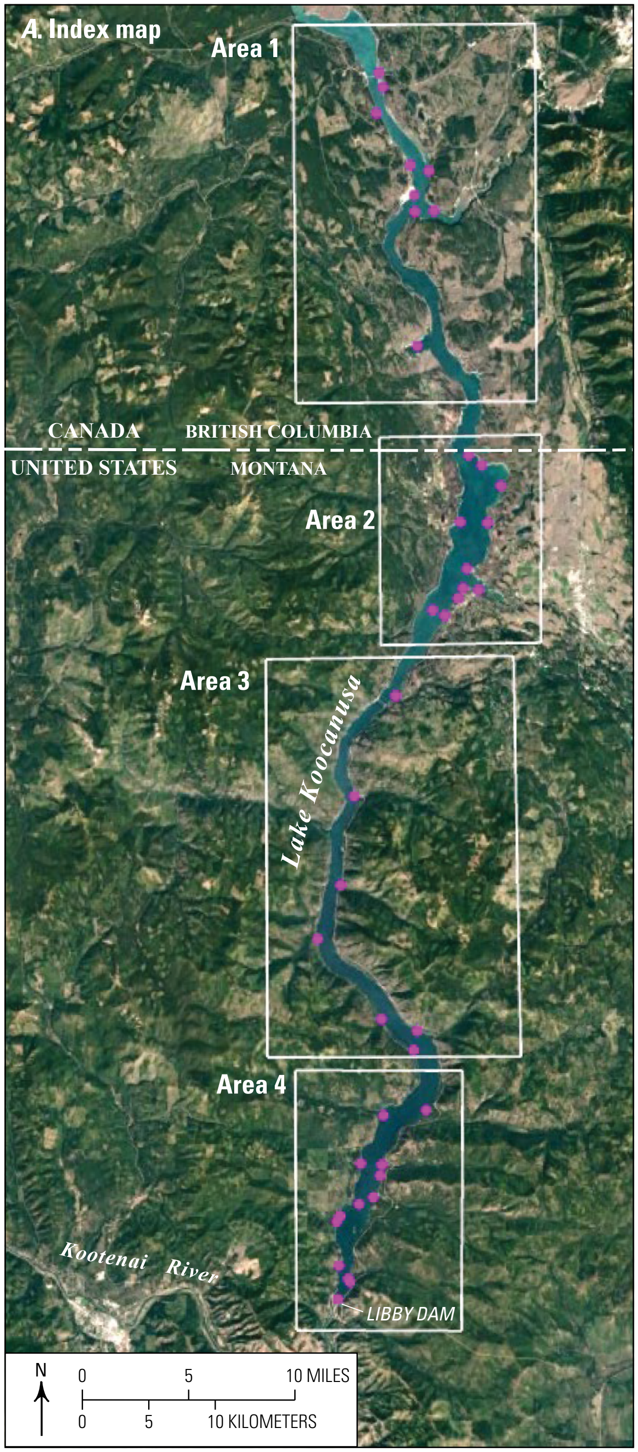
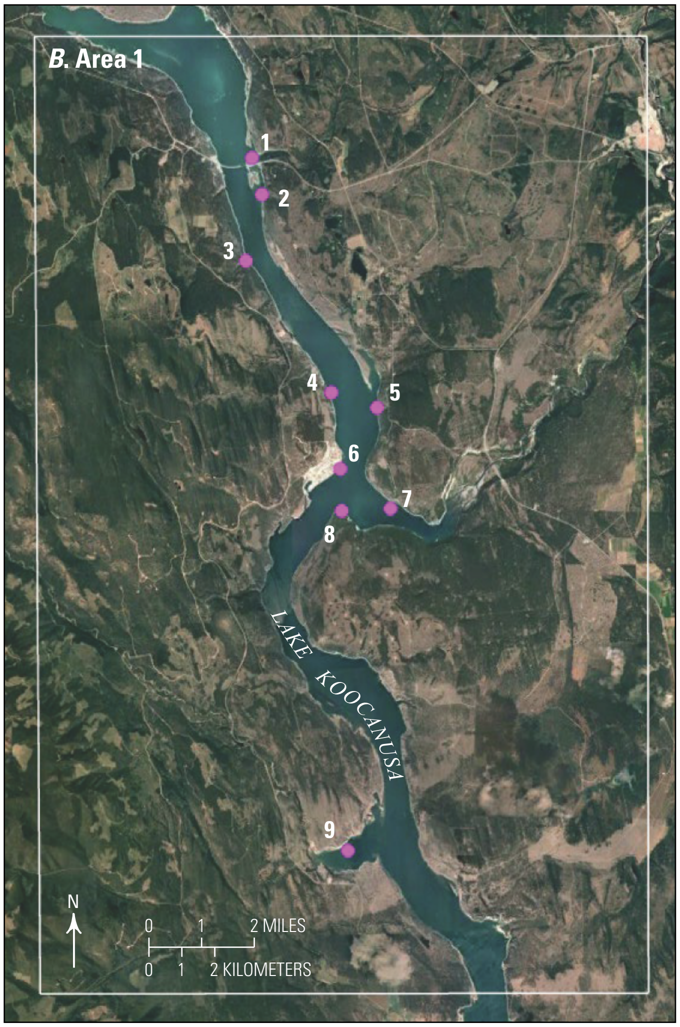
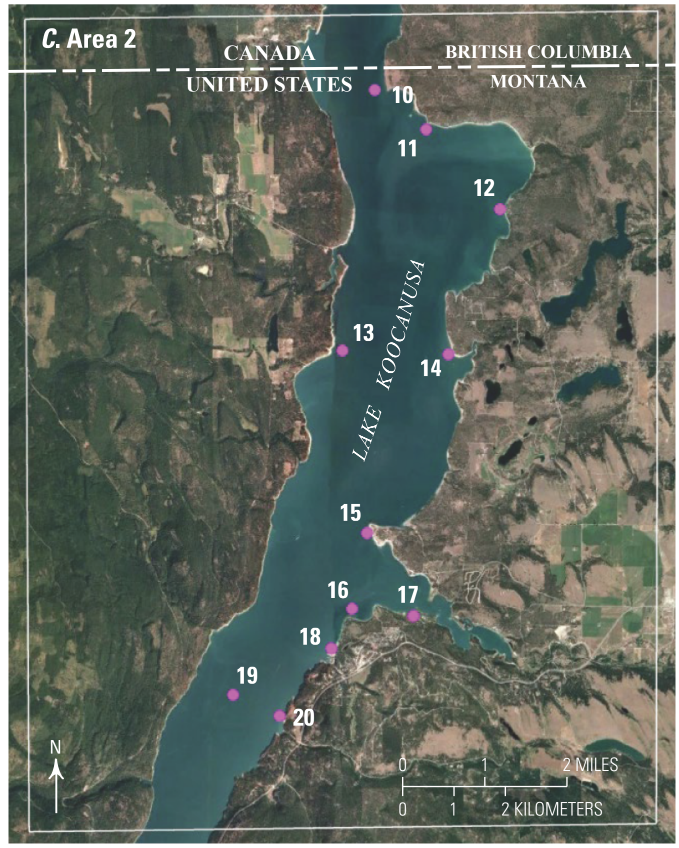


Figure 11. Location of sites (circles) where fish samples were collected from Lake Koocanusa. *A*, index map; *B*, Lake Koocanusa, British Columbia, area 1; *C*, Lake Koocanusa, Montana, area 2; *D*, Lake Koocanusa, Mont., area 3; *E*, Lake Koocanusa, Mont., area 4; *F*, Lake Koocanusa, British Columbia and Montana, areas 1–4 showing gill-net locations (triangles) used by Montana Fish, Wildlife and Parks.



EXPLANATION

1. Lake Koocanusa near Sand Creek
2. Lake Koocanusa south of Kikomun Road bridge
3. Lake Koocanusa near Kikomun Creek Provincial Park
4. Lake Koocanusa north of cabin
5. Lake Koocanusa across from campground
6. Lake Koocanusa at cabin
7. Lake Koocanusa south of Elk River
8. Lake Koocanusa at south point of Elk River drainage
9. Lake Koocanusa near Gold Creek



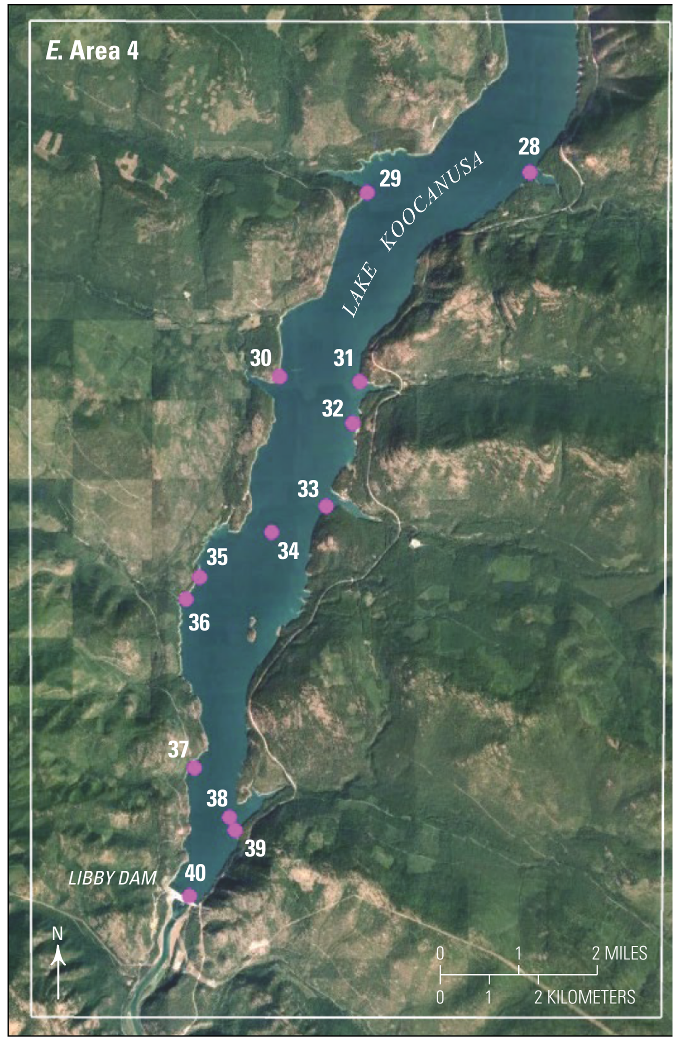
EXPLANATION

10. Lake Koocanusa at international boundary
11. Lake Koocanusa north of Sophie Creek drainage
12. Lake Koocanusa south of Sophie Creek drainage
13. Lake Koocanusa near Young Creek drainage
14. Lake Koocanusa North Point Murray
15. Lake Koocanusa at north point of Tobacco River drainage
16. Lake Koocanusa at south point of Tobacco River drainage
17. Lake Koocanusa near Tobacco River drainage
18. Lake Koocanusa farther south of Tobacco River drainage
19. Lake Koocanusa near Rexford
20. Lake Koocanusa North Black Lake

Figure 11. —Continued

EXPLANATION

21. Lake Koocanusa near Pinkham Creek drainage
22. Lake Koocanusa near Sutton Creek drainage
23. Lake Koocanusa near McGuire Creek drainage
24. Lake Koocanusa near Parsnip Creek drainage
25. Lake Koocanusa near Ural Creek drainage
26. Lake Koocanusa near Tenmile Creek drainage
27. Lake Koocanusa near Tenmile Creek



EXPLANATION

28. Lake Koocanusa near Fivemile Creek drainage
29. Lake Koocanusa near Bristow Creek drainage
30. Lake Koocanusa north of Barron Creek drainage
31. Lake Koocanusa north of Warland Creek drainage
32. Lake Koocanusa near Warland Creek drainage
33. Lake Koocanusa near Cripple Horse Creek drainage
34. Lake Koocanusa near McGillivray campground
35. Lake Koocanusa north of Jackson Creek drainage
36. Lake Koocanusa near Jackson Creek drainage
37. Lake Koocanusa near Peace Creek drainage
38. Lake Koocanusa near Canyon Creek drainage
39. Lake Koocanusa south of Canyon Creek drainage
40. Lake Koocanusa in forebay

Figure 11. —Continued

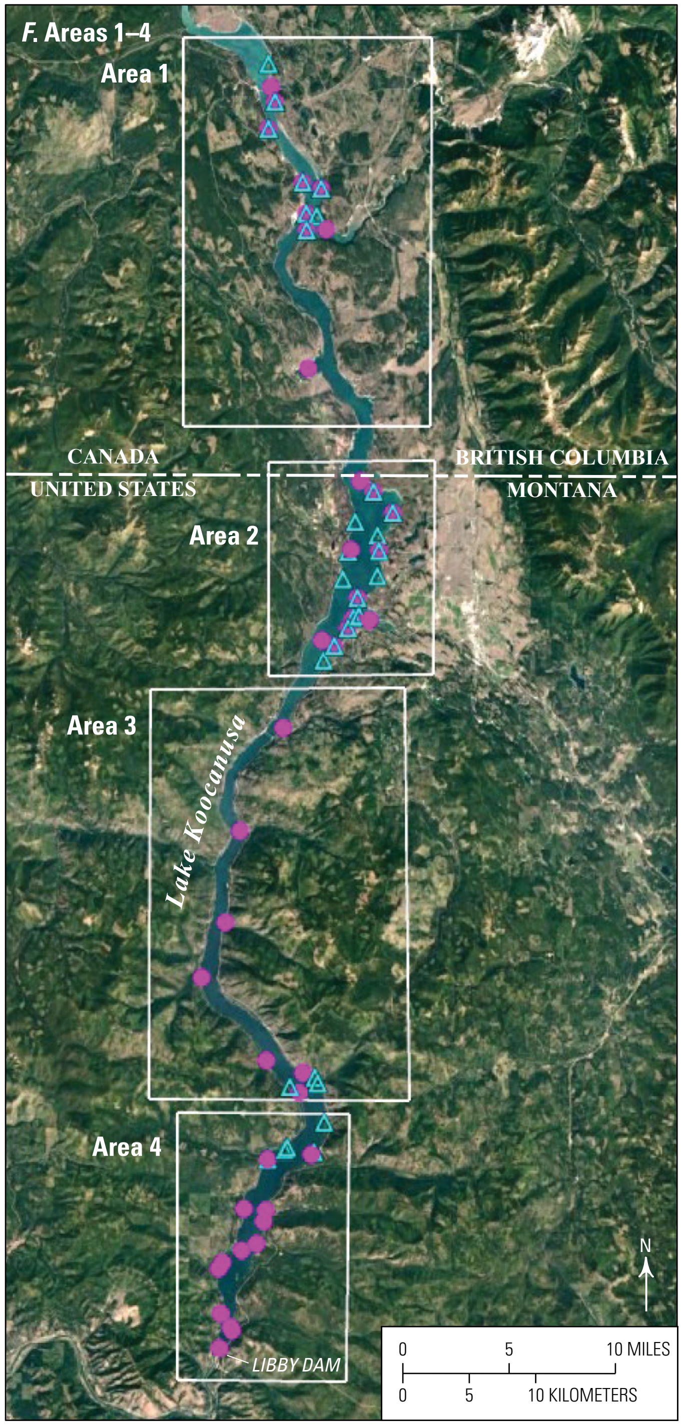


Figure 11. —Continued

18. annex—fish mercury concentrations (muscle) (2013–18), and
19. annex—the State of Montana's human health consumption advisories for mercury and selenium (2014).

Transboundary Metadata and Suspended Particulate Material Sampling

Metadata within Presser and Naftz (2020) give details of sampling and analysis methodologies for each category of data. Methodologies are specific to collection agency because of the transboundary nature of monitoring. Discussions are currently proceeding among Federal, Provincial, and State agencies about a potential transition to applying consistent monitoring protocols to ensure consistency in sample and data collection on both sides of the border.

It is important to note here that key to the data-collection effort to support modeling of Lake Koocanusa was the introduction of sampling of SPM on the Montana side in 2015 and on the British Columbia side in 2017. A selenium concentration in SPM is used to initiate modeling as the diet of invertebrates at the base of the food web, and its characterization is important in representing the dynamics of the system (Presser and Luoma, 2010a). The oligotrophic/mesotrophic nature of Lake Koocanusa requires collecting large-volume water samples and using an efficient concentrating technique (that is, ultracentrifugation) to obtain a sufficient mass of SPM for chemical analysis (Horowitz,1986; Horowitz and others, 2001, 2008). This approach provides an integrated range of particle sizes representational of (1) seasonal sources, (2) hydrological transport conditions, and (3) the dynamics of ecological selenium processing within Lake Koocanusa.

SPM samples were spatially and temporally matched to water samples to enable calculation of K_d (Presser and others, 2018; Presser and Naftz, 2020). K_d operationally defines the instantaneous partitioning of selenium between particulate and dissolved phases. This metric is driven by the residence time of water and, as such, offers a quantitative factor representing competing hydrologic and biogeochemical processes at work in complex aquatic systems (Presser and Luoma, 2010a). Monthly dissolved selenium concentrations, even if not paired with an SPM concentration, also are compiled as part of Presser and Naftz (2020) to further elucidate the impacts of hydrodynamics.

From 2015 to 2017 on the Montana side, paired samples were collected at two locations (forebay and international boundary) and at two depths (epilimnion, 3 meters (m) below lake surface; hypolimnion, 3 m above lake bottom). The number of SPM sampling times per year varied (2015, n=3; 2016, n=4; 2017, n=7), thus limiting direct comparative profiles. In 2018, paired sampling on the Montana side focused on concentrations for the epilimnion at the border, Tenmile, and forebay sites in May, June, and September (n=9). In 2019, sampling occurred at the border and forebay for May, July, and September for two depths except for the forebay in September (n=11). For the British Columbia side, sampling events at SOE occurred in June, July, and September in 2017 at three depths (n=9) and in June–October in 2018 at the epilimnion (n=5). SPM data for 2019 were delayed and are not included here.

A Lake-Gradient Approach to Support Modeling and Resulting Decisions on Data Reduction

A dynamic, working system view of Lake Koocanusa during 2017 was developed from (1) detailed bar graphs for observed dissolved and SPM selenium concentrations specific to epilimnion and hypolimnion strata for SOE, border, and forebay sites (Presser and others, 2018; figs. 5–9) and (2) depth-dimensional gradient maps of observed dissolved and SPM selenium concentrations and calculated K_d values for sites at the SOE, border, and forebay (fig. 12*A*, *B*, *C*). The distribution of selenium in the lake, as illustrated in these figures, is influenced by hydrodynamics and source loading conditions of the lake. Specifically these conditions (1) drive environmental partitioning and may under some instances disconnect the particulate material and the water column as rapid flow transitions occur (Presser and others, 2018, figs. 11–16) or riverine conditions interface with the reservoir (for example, extensive range of K_d values for SOE) and (2) underlie the fundamental functioning of ecosystems that are portrayed and quantified in selenium modeling. These data and figures illustrate that (1) a distinct spring contaminant plume in dissolved selenium occurs at 13 m, with a similar plume occurring in fall at 21 m; (2) for both the epilimnion and hypolimnion, selenium concentrations in SPM at the forebay are generally greater than those at the border, with the trend reversing for dissolved selenium (that is, border is greater than forebay); (3) for SPM selenium concentrations in the forebay, the epilimnion generally exceeds the hypolimnion, but for dissolved selenium concentrations, the hypolimnion generally exceeds the epilimnion; and (4) patterns for K_d are similar to that for selenium concentrations in SPM.

The dynamic nature of Lake Koocanusa is an important consideration because (1) modeling is initiated through choice of SPM selenium concentrations and (2) site-specific water-column selenium concentrations are derived for regulatory purposes that are a function of both the choice of K_d and the food web. Hence, concentration gradient maps specific to lake strata and location can narrow uncertainty both in terms of selenium source and hydrodynamic effects. These gradient maps also help explain temporal variability of (1) dissolved selenium concentrations during April and May when snowmelt and drawdown are occurring and (2) SPM selenium concentrations during June, July, and August when biological productivity is elevated.

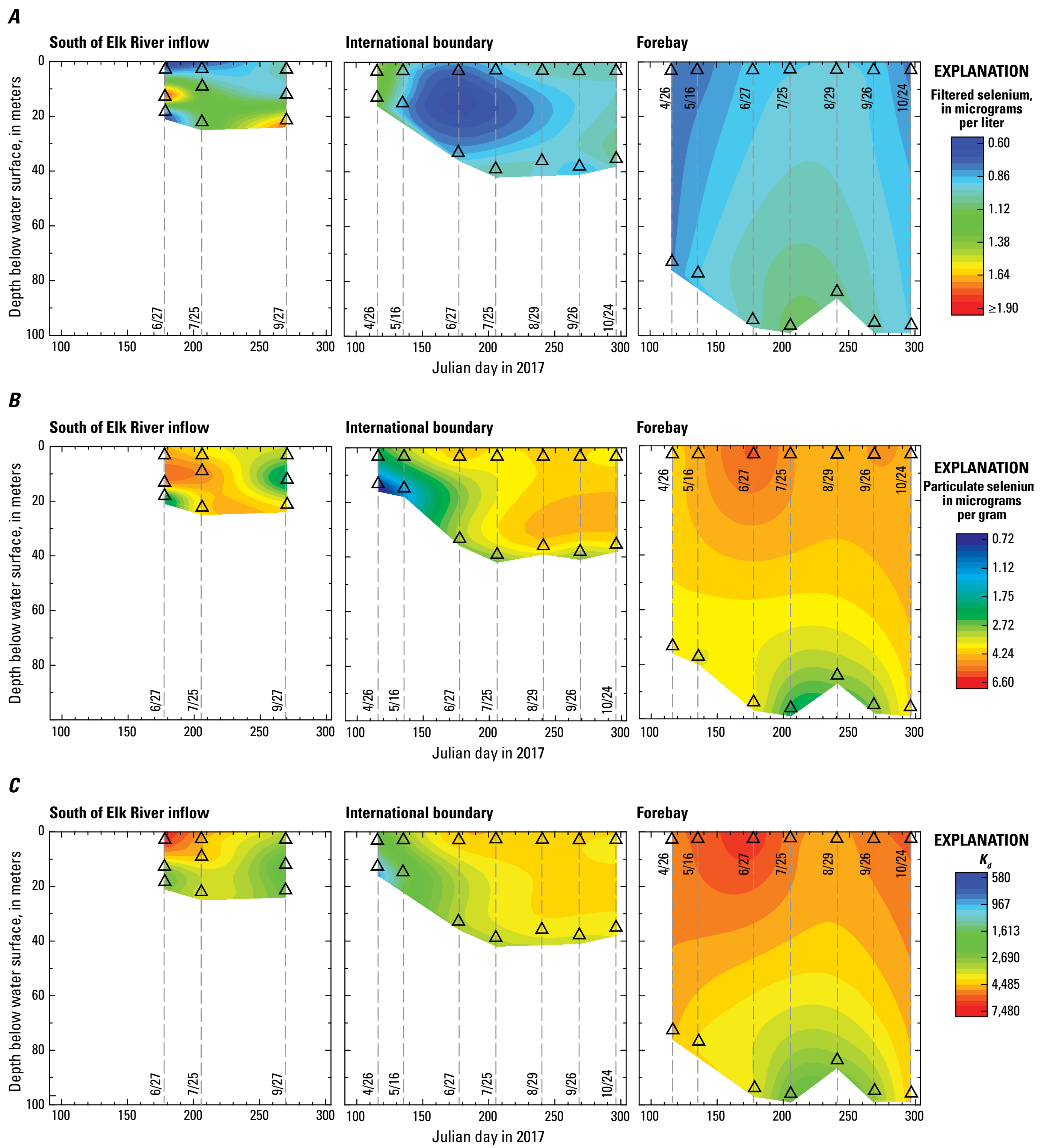


Figure 12. Depth-specific gradients across three reservoir monitoring sites in 2017. *A*, for dissolved selenium concentrations; *B*, for suspended particulate material selenium concentrations; *C*, for environmental partitioning factor (K_d) values (that is, partitioning factor between the dissolved phase and particulate phase). [triangles denote sample depth; dashed lines denote when samples were collected: date (mm/dd) and Julian day (2017)]

Given the importance of the dimensional nature of dissolved and SPM selenium concentrations in the lake as delineated above, the decision here, at this stage of knowledge for the lake, was not to statistically reduce datasets but rather to consider each paired sampling event and consequent K_d calculation as an independent scenario. Overall, a gradient-specific approach helps conceptualize potential seasonal and spatial interactions with food webs and inform modeling in terms of sensitive times and locations when considering regulatory and management options.

Data Utility for Modeling—Field Collection and Selenium Analysis of Invertebrates and Fish

Divergent goals for monitoring of Lake Koocanusa impinged on data usefulness for the dietary biodynamic modeling of selenium. In general, existing monitoring programs were not adjusted to protocols based on the ecosystem aspects of selenium modeling and, thus, do not provide essential spatially and temporally coordinated samples of ecosystem compartments that are important to narrowing modeling uncertainty. Further, species or taxa specificity, sampling of reproductive tissue in game fish species, and a gradient approach for a defined source of selenium contamination were not important design elements of monitoring. Rather, sampling programs were maintained at current objectives that pertain to (1) age, health, and recruitment of fish species; (2) fish-community aspects; (3) set times and sites for reservoir-reach scale sampling or broadly defined upstream-to-downstream sampling at the Elk River input; and (4) separate schedules and sites for sampling each media type. For example, fish sampling by MTFWP took place at a site designated as “Canada,” which is mainly above the Elk River discharge, the source of selenium (Presser and Naftz, 2020) (fig. 11*F*). On the British Columbia side, monitoring of zooplankton and invertebrate as food sources identified taxa, but selenium concentrations were analyzed on composited samples. Fish monitoring, which occurs on a 3-year cycle in Montana, also was not adjusted to accommodate matching fish samples with the scheduled intensive sampling of SPM in 2017. Additionally, selenium speciation for particulate material was not analyzed as part of monitoring. This parameter is important for determining the bioavailability of SPM selenium to prey species within a biodynamic model (Presser and Luoma, 2010a).

Listed in table 1 are the species of fish important to the Lake Koocanusa ecosystem and past decisions concerning field sampling of fish (for example, seasonal timing, type of tissue, number of samples per species) that took place during 2008–18 at sites on both sides of the border. The components of table 1 also address the broader context of connecting to the reproductive nature of selenium’s toxicity as a requirement of regulatory policy. Specifically, as described by Janz (2011), selenium is an environmental reproductive toxicant for fish with a characteristic suite of early life-stage deformities resulting from maternal transfer of selenium-methionine to yolk proteins during vitellogenesis and subsequent selenium exposure during yolk resorption by developing larvae.

There is an important distinction in terms of derivation of tissue selenium guidelines themselves (that is, construction of toxic-response curves) and their subsequent connection to bioaccumulation equations in order to derive or predict site-specific dietary and dissolved selenium concentrations. The primacy of egg tissue as a guideline is related to its reliability for prediction of effects (Lemly and Skorupa, 2007; Chapman and others, 2010; USFWS, 2012; USEPA, 2016a). The interconnectedness or partitioning of selenium concentrations among diet, egg, and wb selenium concentrations in fish is complex, although there is causality between diet and both egg and wb tissue selenium concentrations. The derived connection used by the USEPA in modeling and translating tissue guidelines is mainly between diet and wb concentrations (for example, 89 percent in field exposure scenarios) with a CF that is species specific in order to convert wb to egg-ovary concentrations (USEPA 2016a, b, c, d, 2018). Hence, the practical consequence of the USEPA’s approach is that the diet to egg relationship is not defined as a primary relationship in fish when modeling the dietary transfer of selenium to connect to a water-column selenium concentration. However, studies have addressed the necessity of an internally consistent equilibrium relationship between wb and egg selenium concentrations based on dietary exposures, as would be expected in nature (Chapman and others, 2010). Additionally, few laboratory data are available to directly connect trophic transfer of selenium from diet to egg tissue.

To further inform our discussion here, excerpts relating the ecotoxicology of selenium to (1) fish tissue monitoring guidance for the implementation of site-specific selenium guidelines (USEPA, 2016b) and (2) tissue-to-tissue conversion relationships (Janz and others, 2010) are given in table 2. These rationales shed light on questions concerning (1) muscle tissue as an unacceptable surrogate for egg tissue and consequent connection to reproductive effects; (2) the importance of gravid females and sampling of expressed eggs; (3) problematic interpretations of data for combined egg-ovary tissue, in general, and specifically for nonsynchronous spawners like cyprinids; and (4) timing for preference of wb sample collection versus egg sample collection. The implications of the compiled information (1) as part of food-web and hydrological model inputs and (2) as to their ecological relevance in representing and quantifying fundamental processing of selenium are discussed below in the larger context of the status of the Lake Koocanusa ecosystem.

Table 2. Excerpts concerning ecotoxicology and fish tissue monitoring or tissue-to-tissue relationships.

Excerpts (U.S. Environmental Protection Agency, 2016b)
Egg-ovary sampling including temporal factors associated with spawning
When using egg-ovary tissue for the implementation of the selenium criterion, States and authorized Tribes must be careful to consider the difficulty in timing egg-ovary sampling with spawning periods.
The only appropriate time to collect egg-ovary tissue from suitable species is when the female is gravid in the pre-spawn stage, just before mating and spawning. This is typically a very small window (see appendix B) of time for most synchronous species.
An egg-ovary tissue sample from a female that is not gravid will not be representative for monitoring and assessment when compared with gravid egg-ovary results because the egg-ovary tissues represent the potential selenium load available to eggs and larvae through maternal transfer.
Egg-ovary tissue is the preferable tissue to collect because the egg-ovary tissue of pre-spawn, reproductively mature (also called “gravid” or “vitellogenic”) females will give the most accurate view of potential selenium hazard to reproduction.
Egg-ovary tissue (which refers to eggs, ovaries, or both) data provide point measurements that reflect integrative dietary accumulation, transfer, and deposition of selenium over time and space in female fish at a given site.
Research has shown that selenium concentrations in egg-ovary tissue is strongly correlated with selenium in the maternal diet, which is transferred from the adult female during vitellogenesis.
It is the selenium concentration in eggs that drives early life-stage toxicity, so adult female fish must be collected during the late vitellogenic or preovulatory periods of oogenesis for this criterion to be scientifically and toxicologically meaningful.
Timing errors related to fish reproduction may result in data that falsely indicate the selenium criterion is being met.
Most fish species that are synchronous spawners do so in the spring, whereas fish tissue collection for advisories typically occurs in the late summer or early fall, when contaminant loads in the edible portion of the fish are highest. If an agency is limited to sampling outside of the pre-spawning period due to resource constraints, that will need to be considered when incorporating selenium fish tissue monitoring into the existing programs, or when developing a new program (for example, sampling whole-body or muscle tissue instead of egg-ovary tissue).
For egg-ovary tissue sampling, agencies with fish tissue monitoring responsibilities should consult with a State fisheries biologist to determine the appropriate time for sampling specific species in their region in order to capture the specimens in their pre-spawning phase. These regional experts will be familiar with the local species and able to use their best professional judgment to determine which are appropriate for selenium sampling and the appropriate sampling time frame based on spawning season.
Monitoring programs should sample for reproductively mature females from iteroparous fish species (that is, fish that have multiple reproductive life cycles over the course of its lifetime) that are single batch (synchronous) or multiple batch (asynchronous) spawners.
Fish species that spawn multiple times per season (asynchronous; for example, species in the family Cyprinidae) have variable cycles of oogenesis and, thus, special care should be taken when using these for egg-ovary monitoring as the pre-spawn window can be hard to predict.
Egg maturation may occur well before, immediately prior to, or during the spawning season.
For example, *Lepomis cyanellus* (Green Sunfish) can spawn multiple times per season (Osmundson and Skorupa 2011, Chapman and others, 2010).
For many fish species, vitellogenesis can occur over several months prior to spawning, with a relatively large amount of yolk deposited into eggs (Osmundson and Skorupa 2011).
It is also possible that species with relatively large eggs and yolks deposit more selenium in their eggs than species with smaller eggs and yolks (Osmundson and Skorupa 2011).
Selenium concentrations in the eggs and ovarian tissues are expected to be at their maximum level when eggs have maximum levels of vitellogenin prior to spawning; therefore, egg-ovary tissue samples collected outside of the pre-spawn window are not suitable for assessment in comparison to the national egg-ovary fish tissue criterion element.
Reproductively mature females of most fish species, except indeterminate spawning species and viviparous species (that is, live bearing), will produce eggs that can be sampled for selenium. Appendix A of this document (i.e., USEPA, 2016b) presents egg and ovary collection and sample preparation methods.
The egg-ovary tissue element has primacy over all other elements; thus, when available, it is the ultimate arbiter for compliance with the selenium water-quality criterion. Most States and authorized Tribes do not currently collect egg-ovary tissue as part of their regular monitoring programs. The USEPA recognizes that many States and authorized Tribes may not have the resources to augment their existing monitoring programs to include egg-ovary tissue collection. Although egg-ovary tissue remains the preferable tissue type, whole-body or muscle samples can be used as an alternative.

Table 2. Excerpts concerning ecotoxicology and fish tissue monitoring or tissue-to-tissue relationships.—Continued

Excerpts (U.S. Environmental Protection Agency, 2016b)
Fish species selection—Fish body size
It is difficult to collect egg-ovary (or muscle) tissue samples from small fish species (for example, certain species in the family Cyprinidae or Cyprinodontidae) because the amount of tissue available for analysis is small, and many of these species are asynchronous spawners that do not have a large number or biomass of eggs at any one time.
Whole-body sampling
Measuring selenium concentration in ovarian tissue during other periods of oogenesis will be much less informative. Summer and fall may be prime periods for whole-body and muscle tissue collection due to the engorgement of populations to replenish fat and energy reserves post-spawn.
If agency resources limit fish tissue collection to times outside of these species-specific windows connected to spawning periods, then the only appropriate samples to collect are whole-body and muscle tissue. Target fish species collected in the fall may be common to selenium monitoring and human health risk assessment. In this case, muscle tissue can be composited and evaluated for selenium in addition to contaminants of interest for fish consumption advisories.
The USEPA is aware that some States and authorized Tribes make use of muscle plugs in their monitoring programs. However, it is important to remember that contaminant concentrations can vary considerably depending on where the plug is collected. Plugs provide very small tissue quantities (about 1 gram of tissue per fish) and, therefore, not enough biomass for possible reanalysis or quality assurance/quality control considerations. In addition, relatively small individuals may not recover from a muscle plug biopsy punch. Care should be taken to ensure that the sampling protocols involving plugs have a sound scientific basis and that there is enough tissue for the analytical method.
Seasonal considerations are less stringent for whole-body and muscle tissue sampling. Seasonal collection of whole-body or muscle fish tissue samples should be timed to avoid the pre-spawning influence on selenium tissue concentrations, particularly for females, since enhanced depuration of selenium from tissue stores may occur during vitellogenesis prior to spawning (USEPA, 2016a).
Excerpts (Janz and others, 2010)
Section 6.4.5.1 Selenium Concentration Relationships between Fish Tissue (pages 167–168).
Therefore, tissue-tissue relationships should not be used generically to derive tissue-based selenium toxicity thresholds.
However, even within a species tissue-tissue, extrapolations should ideally be site-specific because individuals show considerable intraspecific variation in the ratio between egg/ovary and whole-body selenium.
If no species-specific tissue-tissue relationship is available, it is not possible to use adult tissue selenium [as opposed to eggs] to reliably estimate potential early life-stage exposure [*text in brackets is for clarification purposes*].

Influence of Ecosystem Characteristics on Selenium—Status of Ecosystems and Data Limitations for Modeling

The 12 species of fish considered for modeling are bull trout, burbot, kokanee, *Catostomus catostomus* (longnose sucker), largescale sucker, mountain whitefish, northern pikeminnow, peamouth chub, rainbow trout (wild strain), *Richardsonius balteatus* (redside shiner), Westslope cutthroat trout, and yellow perch (table 1). Fish characteristics used to ecologically sort these fish species to support modeling include (1) family; (2) origin and function (native, nonnative; game, nongame; introduced, invasive); (3) association of dietary habitat and life cycle; (4) species status, history, and abundance; (5) sampled tissue variations; (6) number of egg-ovary samples per species; (7) observations concerning female ripeness; (8) availability of a gonadosomatic index (GSI) metric; and (9) spawning type (for example, nonsynchronous spawning for cyprinids), location, and timing (table 1). Additionally, a diagram explicit to the life cycle of Lake Koocanusa fish species and their potential exposure opportunities was constructed by Baranowska and Robinson in 2017. This array of information (that is, a “fish grid”) helps identify the who, when, where, and why of exposure during the life cycle of species that can inform goals for monitoring and help interface with modeling (Presser and Luoma, 2013).

Restricting available observed data based on these listed fish factors yielded few species and few selenium concentrations per species (that is, a reduced fish-selenium-concentration database in Presser and Naftz, 2020) on which to validate model predictions. Species-specific factors that were found to limit the utility of available data as the basis of a dietary biodynamic selenium model are included in table 1. Overarching concepts that limit data utility relate to (1) dysfunctional selenium dietary bioaccumulation and tissue partitioning that affect tissue-to-tissue relationships, (2) effects to gonadal development, (3) uncertainty in connections to reproductive effects, and (4) sampling protocols not being designed for a known source gradient (that is, geographic focusing). Species-specific limiting factors are (1) timing of egg sampling when sampling is through net hauls of many species; (2) muscle plug sampling of game fish species, rather than egg or wb sampling; (3) egg-ovary selenium concentrations reported for nonripe or undeveloped ovaries as indicated by field observation or GSI values <1, especially in nonsynchronous spawners; (4) a high incidence of intestinal tapeworms in cyprinids; (5) ingestion of nematodes in trout; (6) a low number of samples for species important to representation of the lake's ecosystem; (7) no fish samples at ecologically important sites (for example, forebay, SOE) for species important to Lake Koocanusa; and (8) elevated mercury concentrations (Teck Coal Ltd., 2018a, 2019) that are known to cause antagonistic/synergistic effects within fish affected by selenium (for example, redistribution of selenium within tissues) (table 1). Individual discussions of these topics are beyond the scope of this report; however, selected literature citations concerning GSI, parasitism, and mercury/selenium interactions are included in a separate "Supplementary References" section in the appendix.

In sum, these identified ecosystem influences define and justify the constraining choices that were made for use of selenium concentration data for various fish species. For the future, modifying sampling protocols to accommodate these types of identified vulnerabilities and focusing modeling on exposures important to species of known concern would lower uncertainty and identify potential ecological bottlenecks (most sensitive species at time and place of greatest exposure) for Lake Koocanusa. To this point, selenium concentrations in ovaries of the few samples available of Westslope cutthroat trout (n=2) and rainbow trout (n=11) ranged from 5.6 to 19.8 µg/g dw, but none were downstream from the Elk River. Even fewer samples are available to assess bull trout (n=2) and burbot (n=3).

Diet Component Analysis and Categorization of Fish Species

Stomach content data for fish collected by the MTFWP from 1982 to 1992 are summarized in Baranowska and Robinson (2017) and Baranowska (2018). Results are either based on calculation of a relative importance index or percentage of biomass for each prey item. Detailed field methods and calculations are given in Dalbey and others (1998) and Chisholm and others (1989) and are summarized in Baranowska and Robinson (2017) and Baranowska (2018).

Species-specific dietary data considered for each fish species modeled here are summarized as percentage of taxa-specific invertebrate biomass and relative importance index (Presser and Naftz, 2020). Percentage of biomass data are the most applicable for biodynamic modeling (Presser and Luoma, 2010a) and are used here as the basis for categorizing Lake Koocanusa fish species for modeling (table 3, available for download at https://doi.org/10.3133/ofr20201098). Recent selenium concentrations for invertebrate taxa in 2018 and a study of the contents of the stomachs of fish species caught in 2017 were also used to inform the categorization for modeling (Presser and Naftz, 2020). Chironomids in particular were key components of benthic Diptera larvae sampling. Teck Coal Ltd. (2018a, 2019) also found chironomids and mayflies as the dominant taxa for sites on the British Columbia side of the reservoir including the Elk River sites (Presser and Naftz, 2020). Finally, qualitative information on the density of different invertebrate taxa at certain sites were included as an additional basis for diet component analysis (Presser and Naftz, 2020).

The number of fish species of interest necessitated each fish species being assigned to a generalized food-web category for modeling to reduce the number of scenarios (table 4, available for download at https://doi.org/10.3133/ofr20201098). The resultant initial diet categorizations for invertivores (aquatic insects and zooplankton to fish) are as follows: 100-percent aquatic insect (rainbow trout, Westslope cutthroat trout, redside shiner, longnose sucker), 50-percent aquatic insect and 50-percent zooplankton (peamouth chub, largescale sucker, mountain whitefish), 75-percent zooplankton and 25-percent aquatic insect (rainbow trout December–March), and 100-percent zooplankton (kokanee). Categorization for TL4 (predator fish) to TL3 (forage fish) is specific to bull trout, burbot (winter and summer), and northern pikeminnow. In these scenarios, forage fish ingest a range of higher risk insectivores and lower risk planktivores (that is, 100-percent insectivores, 50-percent aquatic insect and 50-percent zooplankton, and 100-percent planktivores). Rainbow trout could be included in the last category if a scenario was desired to include adult rainbow trout switching to a diet of 100-percent kokanee. A food web consisting of 50-percent aquatic insects and 50-percent fish also can be considered for yellow perch as a combination of assimilation from two separate food webs (that is, the average of the two outcomes) but is not included here because of noninterest in using yellow perch as a species to represent Lake Koocanusa. These initial modeling categories can then be modified based on additional data collection or specific choices pertaining to decision-makers' goals for protection and representation of the ecosystem in their efforts to narrow uncertainty.

Modeling and Fish Scenario Development

The equation for prediction of a selenium concentration in fish ($C_{Se\ fish\ wb}$) is initialized from a selenium concentration in SPM ($C_{Se\ SPM}$) as diet for an assumed invertebrate prey taxon (eq. 2). The equation modified by assigning a percentage of bioavailability to the SPM is

$$C_{Se\ fish\ wb} = [(C_{Se\ SPM})\ (\text{percent bioavailability})]\ (TTF_{invertebrate})\ (TTF_{fish}). \tag{3}$$

For an aquatic insect food web that assumes 100-percent bioavailability of SPM, the numeric version of the equation is

$$C_{Se\ fish\ wb} = [(C_{Se\ SPM})\ (1.0)]\ (2.8)\ (1.1) \tag{4}$$

where

$TTF_{invertebrate}$ is the mean aquatic insect TTF of 2.8, which here also represents the $TTF_{chironomid}$ of 2.7; and

TTF_{fish} is the mean fish (wb) *TTF* of 1.1, which is based on 25 fish species (Presser and Luoma, 2010a).

Similarly, for a zooplankton food web, the numeric version of the equation is

$$C_{Se\ fish\ wb} = [(C_{Se\ SPM})\ (1.0)]\ (1.5)\ (1.1) \qquad (5)$$

where

$TTF_{invertebrate}$ is the mean freshwater zooplankton *TTF* of 1.5.

However, a more conservative choice would be a *TTF* of 1.9 that is specific to Daphnia (Presser and Luoma, 2010a).

Assimilation efficiencies (AEs) of different types of particulate matter can be considered in this type of equation to account for the site- or species-specific bioavailability of foods likely to be consumed by invertebrates. The selenium speciation of the particulate phase (that is, elemental selenium, adsorbed selenium, and organo-selenium), the type of particulate material (sediment, detritus, or algae), and the taxa of the invertebrate ingesting the particles all affect the efficiency of selenium assimilation as quantified in biodynamic modeling (Presser and Luoma, 2010a). For example, Schlekat and others (2004) determined an AE of 52 percent for the copepods *Tortanus* sp. and *Acartia* sp. at a specific efflux rate. Both elemental and adsorbed selenium are probably minor components of the food of most organisms. Assimilation of selenium is more efficient when animals ingest living food or detritus, both of which are dominated by organo-selenium. From these materials, AEs vary from 55 to 86 percent among species, with smaller differences among living food types such as different species of algae. Estimates of AE for specific types of particulate material are 15 percent for sediment, 35 percent for detritus, and 60 percent for algae.

A similar equation where an assumed, generalized SPM bioavailability of 60 percent is applied to an aquatic insect food web is

$$C_{Se\ fish\ wb} = [(C_{Se\ SPM})\ (0.6)]\ (2.8)\ (1.1). \qquad (6)$$

When applied to a zooplankton food web, the equation becomes

$$C_{Se\ fish\ wb} = [(C_{Se\ SPM})\ (0.6)]\ (1.5)\ (1.1). \qquad (7)$$

Modeling of selenium bioaccumulation also can represent a diet that includes a mixed proportion of prey in the diet through use of the equation

$$\begin{aligned} C_{Se\ fish\ wb} = (TTF_{invertebrate})\ [&(C_{Se\ invertebrate\ a})\ (\text{prey fraction a}) \\ &+ (C_{Se\ invertebrate\ b})\ (\text{prey fraction b}) \\ &+ (C_{Se\ invertebrate\ c})\ (\text{prey fraction c})]. \end{aligned} \qquad (8)$$

Accommodating longer food webs that contain more than one higher TL consumer (for example, forage fish being consumed by predatory fish) can be incorporated through additional *TTF* values.

For modeling of a food web with both a TL3 forage fish and a TL4 predatory fish, the equation is

$$\begin{aligned} C_{Se\ predator\ fish\ wb} = (TTF_{invertebrate})\ (C_{Se\ SPM})\ (TTF_{forage\ fish\ wb}) \\ (TTF_{predator\ fish\ wb}). \end{aligned} \qquad (9)$$

Species specificity in terms of TTF_{fish} for predator and forage fish can be addressed using factors compiled by the USEPA (2016a). The range of TTF_{fish} is narrow though for the species of Lake Koocanusa (0.88–1.46), so the quantitative effect of deviating from the mean factor of 1.1 is relatively small (see later discussion).

Model Validation

For the ecosystem-scale selenium modeling methodology, validation or estimation of uncertainty is through comparison of predicted prey and predator selenium concentrations with observed selenium concentrations. For Lake Koocanusa, the availability of SPM samples establishes the modeled sites as the forebay, border, and SOE. Availability of field data from the lake (1) establishes the validation of invertebrates and zooplankton and (2) excludes comparison to observed fish because of the factors specified in table 1 and discussed above.

For sites at the forebay, border, and SOE, observed selenium concentrations for invertebrates and zooplankton (Presser and Naftz, 2020) are compared to selenium concentrations predicted using the invertebrate model equation described earlier calculated for each observed SPM selenium concentration and for two SPM bioavailabilities (100 percent and 60 percent) (table 5, available for download at https://doi.org/10.3133/ofr20201098). The SPM selenium concentrations applied in validation are specific to the time period of sample collection and encompass the entire available dataset (Presser and Naftz, 2020). Selenium concentrations are specific to taxa of invertebrates in field samples from the Montana side but are composited samples from the British Columbia side (Presser and Naftz, 2020). Zooplankton sampling was executed using three net sizes (64-, 80-, and 150-micron nets) during a variety of months (Presser and Naftz, 2020).

Given the limited amount of field data and varied sampling methods and collection sites for invertebrates and zooplankton, comparison of ranges is more appropriate than statistical comparisons. Only one set of observations (May and September 2018, *n*=12) for invertebrates is available from a collective Tenmile/forebay and Rexford site on the Montana side due to the small mass of material available for analysis.

For validation, comparisons are to predicted selenium concentrations for 2015–18 (table 5). The range of observed selenium concentrations is 0.4–9.1 µg/g dw in 2018, whereas the range of predictions throughout all years at 100-percent bioavailability is 1.2–18.8 µg/g dw and at 60-percent bioavailability is 0.7–11.3 µg/g dw.

For the British Columbia side, observed ranges for invertebrates at the SOE site are 5.3–9.7 µg/g dw in 2013–16 (n=8) and 4.7–12 in 2018 (n=7). Predicted selenium concentrations at 100-percent bioavailability range from 3.8 to 15.5 µg/g dw in 2017 and 9.3–21 µg/g dw in 2018. At 60-percent bioavailability, the ranges are 2.3–9.3 µg/g dw in 2017 and 5.6–12.6 µg/g dw in 2018.

Validation for zooplankton is affected by the transitory nature of the zooplankton community and the variable field dataset available for comparison (figs. 4 and 5). Specific factors involved are use of different net sizes (64-, 80-, and 150-micron nets) for sampling and the variable uptake rate of selenium for different taxa that are composited for analysis. For example, rotifers are a major component of zooplankton sampled on the Montana side with density varying by site (fig. 5*A*, *B*, and *C*). In studies where rotifers were reared as food for fish larvae, rotifers were found to be devoid of selenium both prior and after enrichment and, thus, provided little nutrition to prey (for example, Mæhre and others, 2012).

For zooplankton on the Montana side (64- and 150-micron nets), comparisons for predictions at 60-percent bioavailability based on years when the most data were collected (2017–18) showed a range of 0.7–5.9 µg/g dw compared to an observed range of 0.3–4.4 µg/g dw. For zooplankton on the British Columbia side (80-micron net), the predicted range at 60-percent bioavailability was 1.2–6.7 µg/g dw compared to an observed range of 2.2–4.9 µg/g dw.

Dietary guidelines give context for the observed selenium concentrations in the aggregate for the site-specific food sources of Lake Koocanusa. The BCMOE currently has a dietary guideline of 4 µg/g (BCMOE, 2014), which is exceeded by the ranges of observations and predictions for Lake Koocanusa. The USFWS has derived a dietary guideline of 3.6 µg/g dw for both fish and birds at the EC00 level, of <4.9 at the EC10 level, and of 5.7 µg/g dw at the EC20 level (Presser and Luoma, 2010b). Again, the ranges of observations and predictions for Lake Koocanusa exceed those values.

Prediction of Protective Dissolved Selenium Concentrations—Invertebrate to Fish Model and Trophic-Level (Predatory to Forage) Fish Model

Two models for prediction of protective dissolved selenium concentrations were developed. The equation for the invertebrate to fish model (IFM) is

$$\text{predicted protective } C_{Se\ dissolved} = \text{fish guideline wb} / TTF_{fish} / [(TTF_{invert1} * \text{invert fraction1}) + (TTF_{invert2} * \text{invert fraction2})] / \text{SPM \% bioavailability} / (K_d/1{,}000). \quad (10)$$

The equation for the trophic-level (predatory to forage) fish model (TFM) is

$$\text{predicted protective } C_{Se\ dissolved} = \text{fish tissue guideline wb} / TTF_{fishTL4} / TTF_{fishTL3} [(TTF_{invert1} * \text{invert fraction1}) + (TTF_{invert2} * \text{invert fraction2})] / \text{SPM \% bioavailability} / (K_d/1{,}000). \quad (11)$$

Modeled Bioaccumulation Potentials for Lake Koocanusa

Equations to calculate selenium BAPs as an intermediate numeric endpoint independent of setting (that is, K_d) for each of these models are

$$BAP_{IFM} = (TTF_{fish}) [(TTF_{invert1} * \text{invert fraction1}) + (TTF_{invert2} * \text{invert fraction2})], \quad (12)$$

$$BAP_{TFM} = (TTF_{fishTL4}) (TTF_{fishTL3}) [(TTF_{invert1} * \text{invert fraction1}) + (TTF_{invert2} * \text{invert fraction2})]. \quad (13)$$

If SPM bioavailability (that is, with [w] bioavailability) is added as a factor in a composited BAP, then the equations are

$$BAP_{IFM} \text{ w SPM bioavailability} = (TTF_{fish}) [(TTF_{invert1} * \text{invert fraction1}) + (TTF_{invert2} * \text{invert fraction2})] (\text{SPM \% bioavailability}), \quad (14)$$

$$BAP_{TFM} \text{ w SPM bioavailability} = (TTF_{fishTL4}) (TTF_{fishTL3}) [(TTF_{invert1} * \text{invert fraction1}) + (TTF_{invert2} * \text{invert fraction2})] (\text{SPM \% bioavailability}). \quad (15)$$

Applying the BAP equations to the species and diet categorizations shown in table 4 allows development of a set of scenarios within each model (tables 6 and 7, available for download at https://doi.org/10.3133/ofr20201098). As noted previously, specific species and scenarios for the IFM model are as follows: 100-percent aquatic insect (rainbow trout, Westslope cutthroat trout, redside shiner, longnose sucker), 50-percent aquatic insect and 50-percent zooplankton (peamouth chub, largescale sucker, mountain whitefish), 75-percent zooplankton and 25-percent aquatic insect (rainbow trout December–March), and 100-percent zooplankton (kokanee). The TFM scenarios for bull trout, burbot (winter and summer), and northern pikeminnow are as follows: 100-percent insectivores, 50-percent aquatic insect and 50-percent zooplankton, and 100-percent planktivores. Rainbow trout could be included in the latter category if a scenario was desired to include adult rainbow trout switching to a diet of 100-percent kokanee compared to an insectivorous diet.

The BAPs for IFM food-web scenarios range from 3.08 to 1.65 at 100-percent bioavailability and from 1.85 to 0.99 for 60-percent bioavailability (table 6). The scenario of kokanee ingesting a diet of 100-percent zooplankton represents a scenario where no bioaccumulation (BAP <1) is taking place. For TFM food-web scenarios, BAPs range from 3.39 to 1.82 at 100-percent bioavailability and from 2.03 to 1.09 for 60-percent bioavailability (table 7). Again, this last scenario (bull trout and burbot ingesting a diet of 100-percent planktivorous forage fish) is at the cusp of no bioaccumulation occurring; hence, choice of a fish species and its food web to represent the lake is a critical decision.

Illustrated Scenarios—Prediction of Protection for Westslope Cutthroat Trout, Rainbow Trout, Redside Shiner, Longnose Sucker, Bull Trout, and Burbot

Translation model equations for the IFM and TFM food-web scenarios are then applied to sites at the forebay, border, and SOE where data for paired selenium concentrations of dissolved and SPM are available to calculate observed, instantaneous K_d values (that is, within a common set of K_d values) (tables 8 and 9, available for download at https://doi.org/10.3133/ofr20201098). Given the importance of the dimensional nature of dissolved particulate material and SPM selenium concentrations in the lake (fig. 12*A*, *B*, and *C*), the modeling here does not statistically reduce the K_d datasets; rather, each paired sampling event and consequent K_d calculation is considered as an independent scenario (n=87). Using this all-encompassing set of available K_d values specific to timing, depth, and location, the range of values shows that 69 percent of values lie between 3,017 and 5,977, with the interval between 4,071 and 4,975 containing the greatest percentage (29 percent) (tables 8 and 9). The smallest K_d value in the observed data is 424, but only three observations are less than a K_d value of 1,000. The greatest value is 7,475, and only three observations are greater than 7,000.

The predictions for the illustrated food-web scenarios focus on protection of Westslope cutthroat trout, rainbow trout, redside shiner, and longnose sucker using the IFM and protection of bull trout and burbot using the TFM in accordance with one of the objectives of the proposed modeling (that is, a maximum dietary exposure through feeding within a benthic food web). Two SPM bioavailability factors (100 percent and 60 percent) are used within each food-web scenario to quantify the efficiency of assimilation of SPM by invertebrates.

Predicted protective dissolved selenium concentrations are based on a fish tissue wb guideline of 8.5 µg/g dw as the endpoint (tables 8 and 9). Egg-ovary tissue can be substituted if applicable tissue-to-tissue CFs are available (that is, species-specific extrapolations at a minimum, but ideally site specific if ecosystems are not degraded). As stated previously, the derived dissolved selenium concentration would quantify the ecosystem condition where fish would adhere to an 8.5-µg/g wb tissue guideline. Modeling shows that 85–88 percent of predicted dissolved selenium concentrations are <1 µg/L for both the IFM and TFM with an assumption of 100-percent bioavailability. Using an assumption of 60-percent bioavailability, 46–60 percent of values are <1 µg/L. From the perspective of a dissolved selenium concentration of <1.5 µg/L, the corresponding outcome ranges would be 91–93 percent for 100-percent bioavailability and 78–85 percent for 60-percent bioavailability.

Species-Specific TTF_{fish} for Predator and Forage Fish

These models can be further refined by substituting a species-specific TTF_{fish} as provided by the USEPA (2016a). Using the IFM equation and an assumed K_d of 5,000, example scenarios for applicable fish species show the variation in predicted dissolved selenium concentrations when species-specific TTF_{fish} are applied and other modeling factors are held constant (table 10, available for download at https://doi.org/10.3133/ofr20201098).

Gradient Map Perspectives

Understanding the scientific basis of selenium ecological protection here includes connecting modeling outcomes and the representation of ecosystem conditions for Lake Koocanusa when deriving a water-column guideline or set of guidelines. The frequencies of occurrence of an assumed water-column condition, as discussed above, are only relevant within an understanding of the influences of hydrodynamics and source gradients on a chosen species and food web. Shown in figures 13–16 are a series of monthly (April–October) cross sections of observed dissolved selenium concentrations for 2016–19 that are examples of experimental plots of the type of conceptualization possible, but minimal data were available for building such plots. These constructs give time-, location-, and depth-specific contexts to conditions in the lake that overlap with modeling of food webs of the lake. The illustrated selenium cross sections are influenced by the hydrodynamic and biogeochemical cycles of the lake and the gradual dilution of selenium coming from the Elk River moving south in the lake; hence, comparison of dissolved selenium concentrations across years becomes meaningful when contoured to represent the dynamics of lake conditions. These contours also relate to interactions at the base of food webs and, hence, can elucidate modeling outcomes. These contours argue against using reductions of nonanchored (that is, nonlocation specific) dissolved selenium datasets because of the influences of the hydrologic setting of the lake, especially in terms of selection of K_d values for modeling predictions.

The constructs can be quantified by the cross-sectional area specific to a designated dissolved selenium concentration to illustrate existing conditions or adherence to a proposed guideline. In the example here, areas >1 µg/L are quantified for 2016–19 (fig. 17). Even though constructs are based on the relatively few available data points, seasonal trends are clear and the cross-sectional areas are seen to increase over the time period 2016–19. Hence, if choices need to be made as the development of guidelines proceeds, this would be a methodology to meaningfully constrain data with the goal of identifying the time and place of greatest selenium sensitivity (that is, the ecological bottleneck). Going forward, this type of contouring can be used to project the effect of increases or decreases based on the current dissolved selenium conditions developed here.

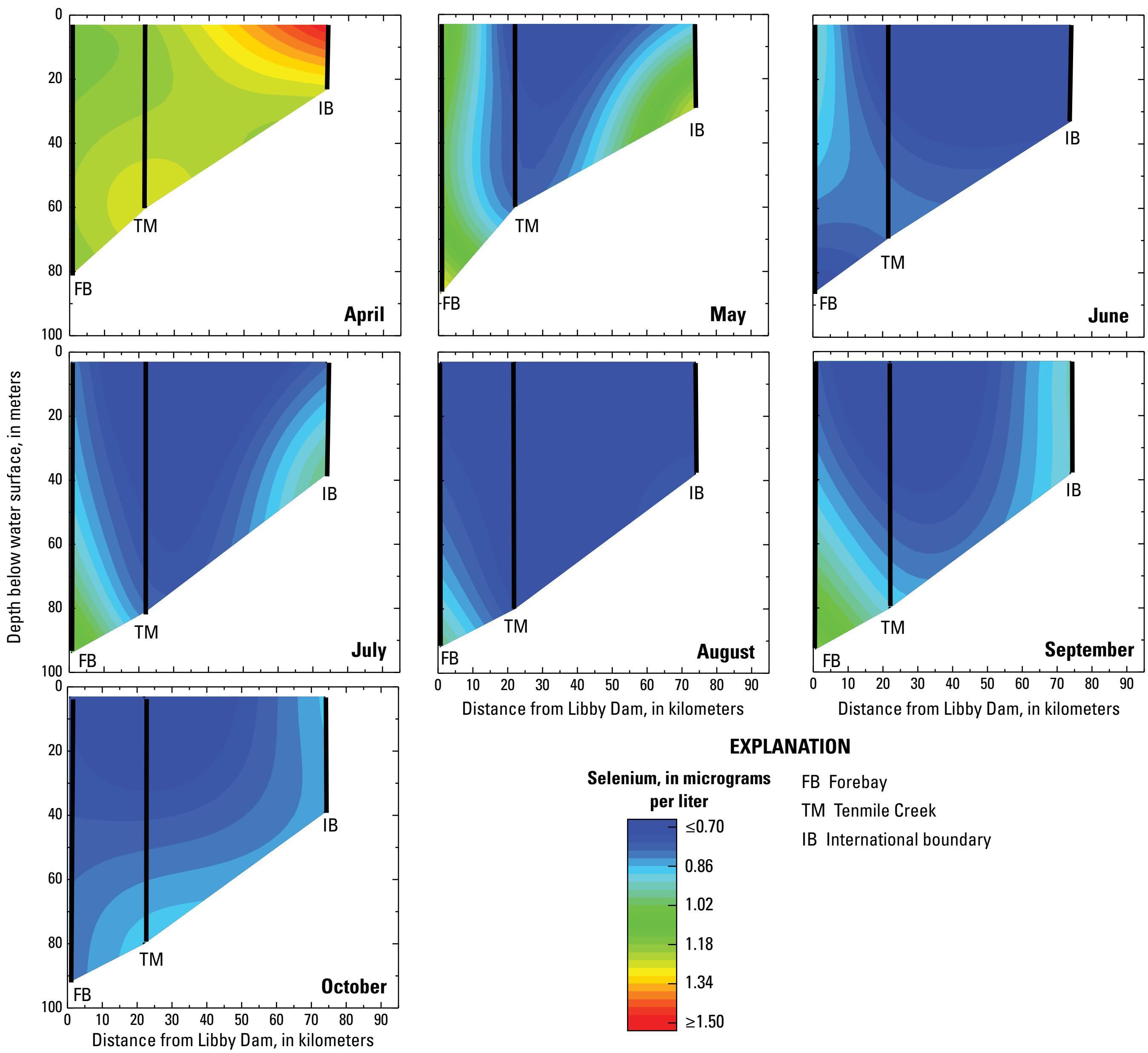


Figure 13. Cross sections of dissolved selenium concentrations from monitoring sites on Lake Koocanusa during calendar year 2016. Contours based on two samples from each site. April selenium concentrations from the international boundary site are based on unfiltered water samples.

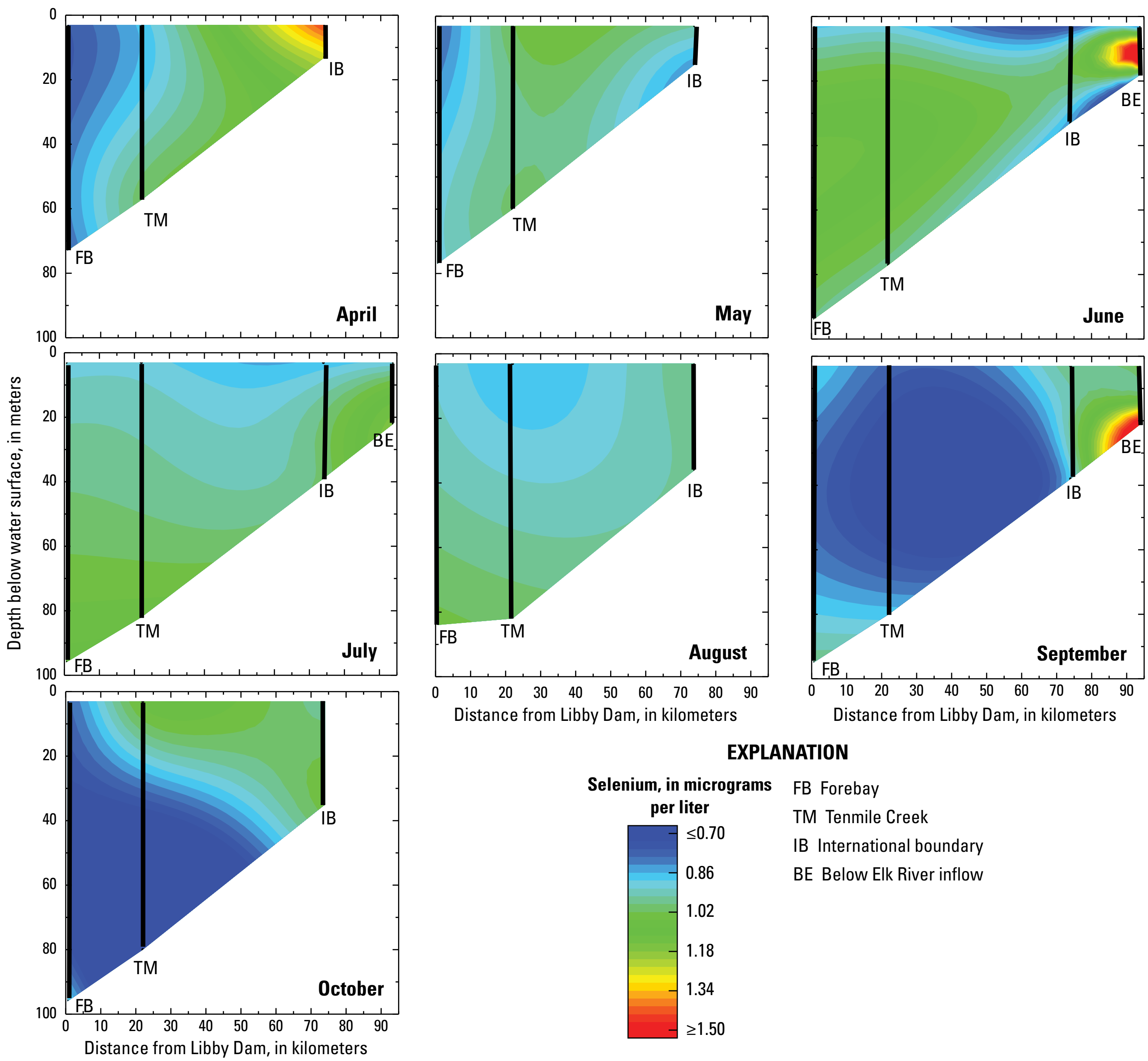


Figure 14. Cross sections of dissolved selenium concentrations from monitoring sites on Lake Koocanusa during calendar year 2017. Contours based on one to three samples from each site.

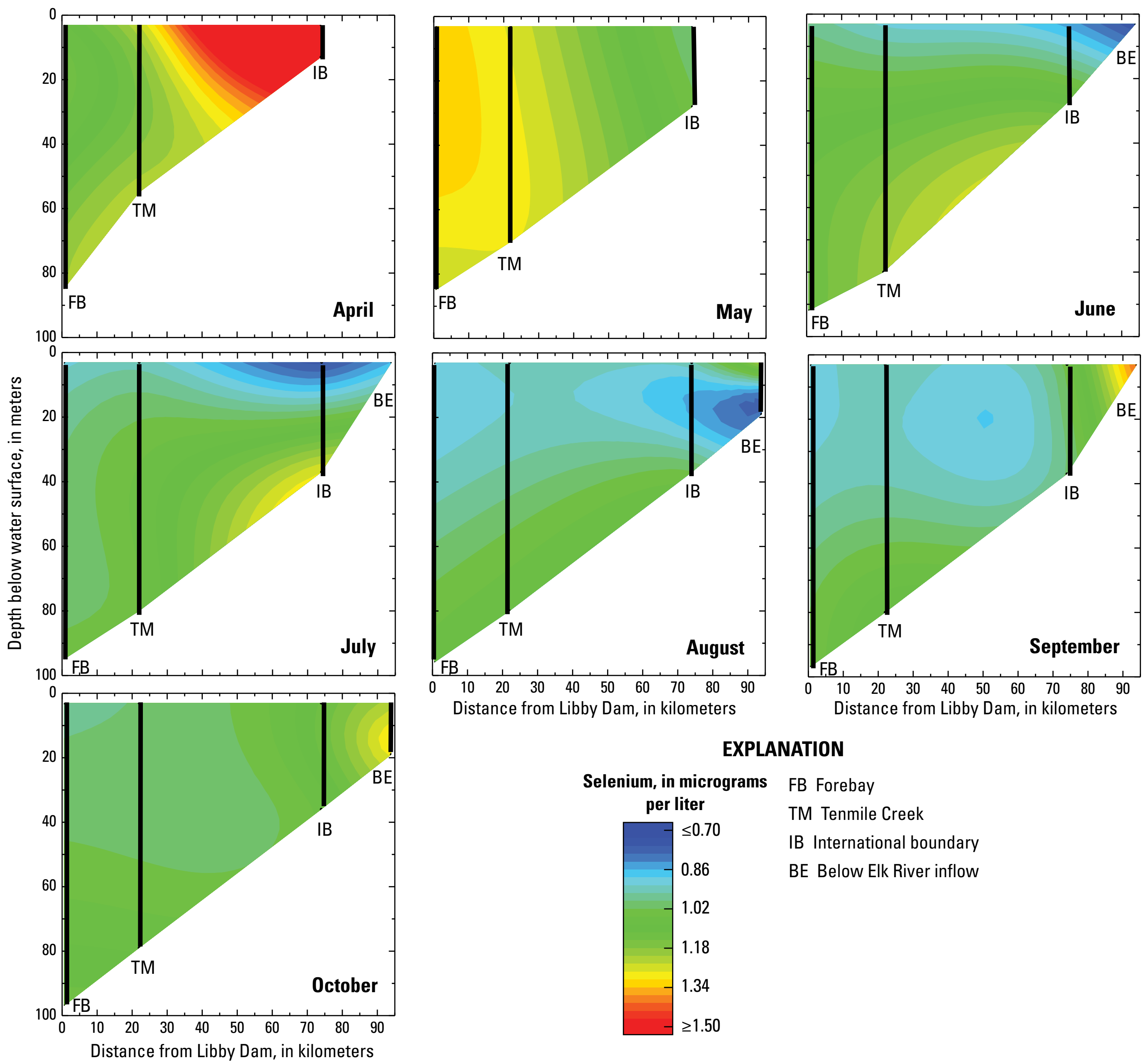


Figure 15. Cross sections of dissolved selenium concentrations from monitoring sites on Lake Koocanusa during calendar year 2018. Contours based on one to three samples from each site.

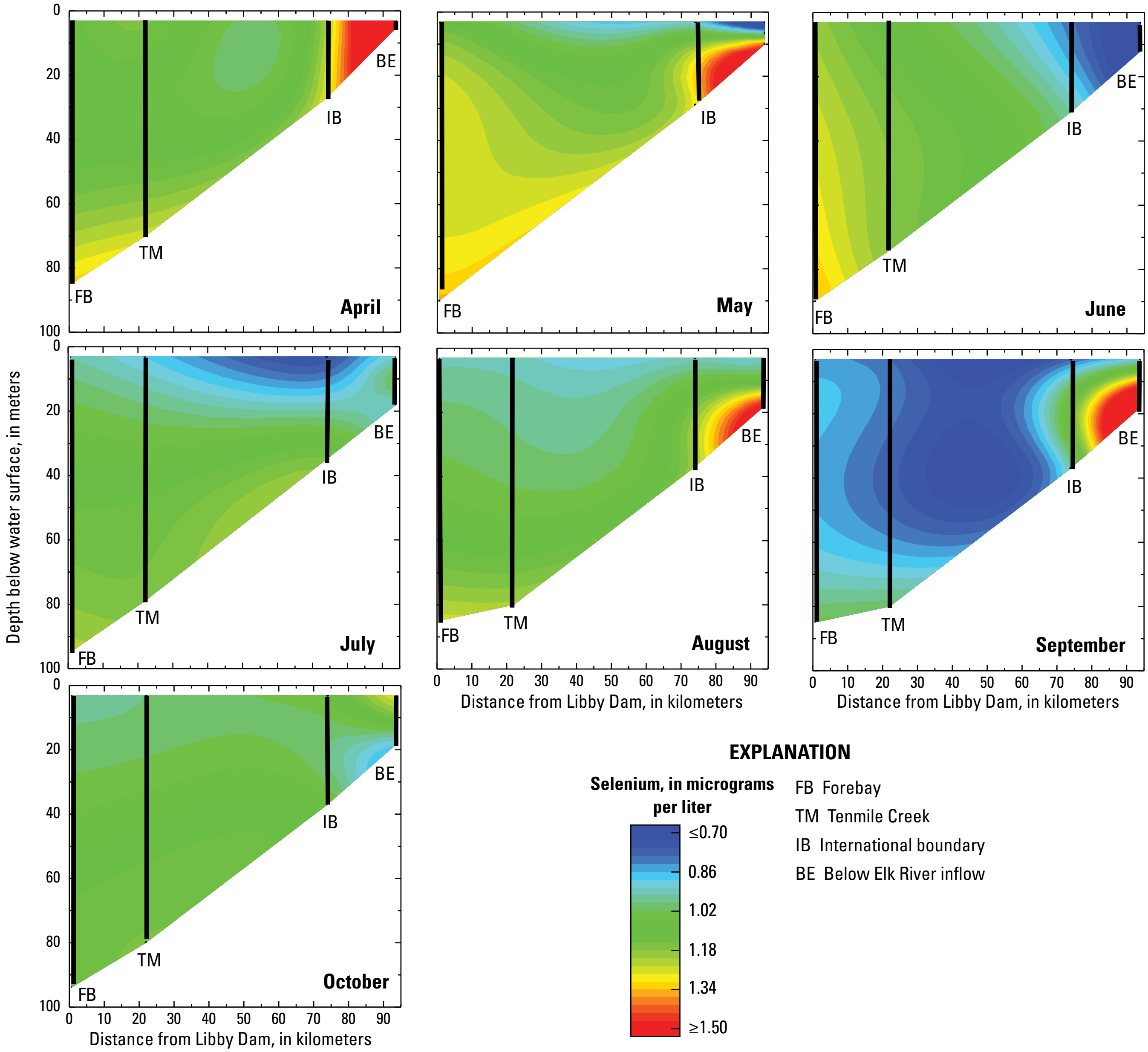


Figure 16. Cross sections of dissolved selenium concentrations from monitoring sites on Lake Koocanusa during calendar year 2019. Contours based on two to three samples from each site. No samples were collected from the Tenmile Creek site during May due to equipment problems.

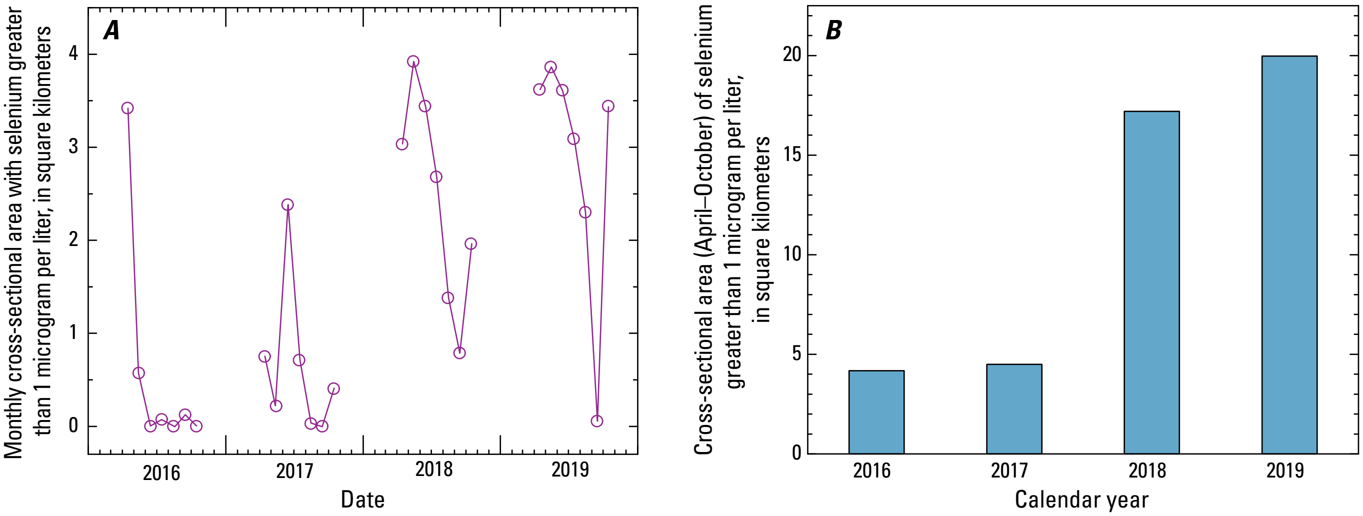


Figure 17. Graphs showing (*A*) monthly cross-sectional areas (2016–19, April–October) in Lake Koocanusa specific to a dissolved selenium concentration of greater than 1 microgram per liter for 2016–19 from the international boundary to Libby Dam and showing (*B*) annual summation of monthly cross-sectional areas specific to a dissolved selenium concentration of greater than 1 microgram per liter. Graph *B* indicates an annual increase from 2016 to 2019.

Conclusions

This working report and accompanying USGS data release (Presser and Naftz, 2020) provide the data, rationale, food-web modeling structure, and interactive spreadsheets for the quantitative derivation of site-specific selenium guidelines for Lake Koocanusa. Model scenarios and gradient maps presented here represent the lake's ecosystem that is the link between the designated protective fish-tissue selenium concentration guideline and the modeled predictions of protective dissolved selenium concentrations. Model predictions for protective dissolved selenium concentrations are specific to the USEPA's national guideline of 8.5 µg/g wb fish tissue, but the model outcomes can be modified to numerically support BCMOE's guideline of 4 µg/g wb by dividing by a factor of 2.125 (that is, 8.5/4). However, as stated previously, the tissue guidelines were derived with different protection goals.

Modeling of selenium overlays cumulative effects in the reservoir of (1) dam operation itself, (2) mitigation actions, and (3) its impaired selenium status for aquatic life designated in 2012 as coal mining continues to expand in the Elk Valley region of British Columbia over the last 35 years. Concerns encompass fish-community changes, flow regime changes, and such ecological stressors as parasitic infection, gonadal dysfunction, and mercury-selenium interactions. The cumulative effects related to fish species were found to have affected the fundamental processing of selenium through food webs, which did have ramifications for data utility, choices for model validation, and connection to a reproductive selenium endpoint.

Our previously listed goals (see "Introduction" section) guided our choices and assumptions used in illustrating Lake Koocanusa's ecosystem and modeling its dietary dynamics. Two models address protection of benthic feeders within the overall goal of identifying food webs with maximum BAPs (that is, maximum dietary exposure). As categorized and constructed, (1) the IFM protects a community of rainbow trout, Westslope cutthroat trout, redside shiner, and longnose sucker and (2) the TFM protects a community of bull trout and burbot. Constraining the variables for identification of sensitive locations and seasons to represent Lake Koocanusa led to a lake-gradient approach. In this approach, each paired sampling event of water-column and SPM and the consequent K_d calculation was considered as an independent scenario. Where data were most abundant for pivotal sites (forebay and SOE), temporal gradient maps of dissolved and SPM selenium concentrations and ecological partitioning factors (K_d values) specific to lake strata, hydrodynamics, and source gradient were constructed. These experimental plots show the kind of conceptualization possible when considering lake dynamics in general and connecting to selenium dynamics at the base of food webs in particular.

The results of our analysis and illustrated modeling scenarios show that at least 78 percent of predictions are <1.5 µg/L and at least 46 percent of predictions are <1 µg/L for protection of this community of core benthic feeders. The percentages are based on exposure through a 100-percent chironomid diet and two choices of bioavailability (100 percent and 60 percent for SPM); hence, these scenarios represent conservative, but realistic, choices within the set of 12 categorized fish species. Switching from an assumed guideline of 8.5 µg/g to 4 µg/g would decrease each individual model prediction, as stated previously, by a factor of approximately two.

To give context to this range of tested designated dissolved selenium concentrations, 1.5 µg/L is the USEPA's national guideline derived for lentic systems. The range in comparison to recent conditions in Lake Koocanusa (fig. 17) shows that during 2016 and 2017, cumulative cross-sectional areas with selenium concentrations exceeding 1 μg/L in the reservoir south of the international border were <5 square kilometers (km^2). During 2018, a more than threefold increase in the cross-sectional area (>15 km^2) exceeding 1 μg/L of dissolved selenium was observed, followed by a more than fourfold increase (about 20 km^2) in 2019. These recent increases in the proportion of the reservoir containing selenium concentrations exceeding 1 μg/L indicate a system that is not at a steady state and raises concerns over the likelihood of continuing future increases.

The outcomes of formal protocols (for example, the USEPA's recalculation procedure [USEPA, 2016d]) for addressing the ecotoxicological sensitivity of an assemblage of site-specific fish species are not publicly available for Lake Koocanusa. However, a practical, qualitative ranking of fish species can be achieved through the metric of vulnerability, which combines inherent selenium sensitivity and exposure through diet. This assessment is informed by (1) the site-specific analysis of the fish traits and connectivity to behavioral ecology of predators shown in table 1, (2) the ranking of fish species listed in USEPA (2016a, see table 3.1) and in other reviews (for example, Janz and others, 2010, see figures 6.4), and (3) recent studies of *Danio rerio* (zebrafish) documenting the elevated sensitivity of this species of Cyprinid (Thomas and Janz, 2014, 2015; Penglase and others, 2014a,b). Our example of ranking based on species vulnerability is included as a working part of this report, which can be updated in the future when a formal analysis by regulatory agencies is prepared as guideline development proceeds.

Near the top of a vulnerability ranking would be concern for the Cyprinids of Lake Koocanusa (that is, redside shiner, peamouth chub, and northern pikeminnow) based on sensitivity and for burbot given its demersal feeding and winter spawning period. Redside shiner and peamouth chub as representative of Cyprinids would be interesting choices of species to protect as examples of small-bodied fish with 100-percent and 50-percent benthic diets, respectively (table 4). Concern for burbot is also anecdotally corroborated by the lack of fish caught in recent monitoring efforts and the fact that extensive drawdown occurs during the spawning season for this species. White sturgeon, although not residing in the lake, does inhabit waters downstream from the dam and is the most toxicologically sensitive fish as ranked by the USEPA in its national guidance (USEPA, 2016a); hence, extending protection to waters and habitat immediately downstream from the dam would seem advisable. Less concern would be for bull trout and mountain whitefish, which appear at the bottom of the sensitivity ranking (USEPA, 2016a). This leaves considering protection for remaining species such as rainbow trout and Westslope cutthroat trout, which rank near the middle of the sensitivity scale and are benthic feeders. Here too for these species, the percentages of composition among Lake Koocanusa species are low during spring and fall (fig. 6*A*, *B*).

In sum, this subset of modeling variables, species, and attributes appears to meet the specific goals set out at the beginning, which also impinge on operational interests. These considerations connect to specific scenarios and supporting rationales to represent the system. Going forward, qualifying the status of the Lake Koocanusa ecosystem within an impairment-restoration cycle would acknowledge concerns about using current conditions as a baseline for regulatory actions because of possible survivor bias and normalization of ecosystem degradation and dysfunction. Considerations for future endpoint and modeling-related actions include development of (1) a series of health endpoints related not only to long-term exposure to selenium, but also to food sources and fish communities; (2) a coordinated selenium portal where data are arranged within a set format specific to Lake Koocanusa's food webs; (3) a comprehensive plan for taxa-specific selenium analysis of invertebrates; and (4) a strategy for filling the data gaps for selenium in samples of expressed eggs for fish species and studying the occurrence of deformities in developing larvae. In reference to these latter considerations, focus for monitoring would be on the main drivers of the outcomes of ecosystem-scale selenium modeling: (1) type of particulate material (SPM in the case here), (2) selenium concentration and speciation of the particulate material that is food for invertebrates, and (3) taxa of invertebrates consuming that food. Monitoring of dissolved selenium concentrations on a high-frequency basis (for example, USGS platform data) at several key sites across the reservoir would help to further develop seasonal spatial selenium gradients and to understand process-level relationships in order to pinpoint and assess sites consequential to defining future regulatory compliance.

References Cited

Baranowska, K., 2018, Koocanusa Reservoir food web amendment: Cranbrook, B.C., prepared by Lotic Environmental Ltd., 21 p.

Baranowska, K., and Robinson, M.D., 2017, Koocanusa Reservoir food web model—Final report: Cranbrook, B.C., prepared by Lotic Environmental Ltd., 48 p.

Bonneville Power Administration, U.S. Army Corps of Engineers, North Pacific Division, U.S. Department of Interior, and Bureau of Reclamation, Interagency Team, 1995, Columbia River System Operation Review—Final Environmental Impact Statement, appendix K, resident fish: U.S. Government Printing Office, No. DOE/EIS–0170, 297 p. [Also available at https://usace.contentdm.oclc.org/digital/collection/p16021coll7/id/6482/.]

British Columbia Ministry of Environment [BCMOE], 2014, Ambient water quality guidelines for selenium technical report update: Water Protection and Sustainability Branch, Environmental Sustainability and Strategic Policy Division, Victoria, B.C., p. 1–270, accessed May 2020 at https://www2.gov.bc.ca/assets/gov/environment/air-land-water/water/waterquality/water-quality-guidelines/approved-wqgs/bc_moe_se_wqg.pdf.

British Columbia Ministry of Environment [BCMOE], 2015, Reports and references for *Lota lota* pop. 1 (Burbot, Lower Kootenay Population): Government of British Columbia web page, accessed May 2020 at http://a100.gov.bc.ca/pub/acat/public/viewReport.do?reportId=9720.

British Columbia Ministry of Environment [BCMOE], 2018, Environmental Management Act Permit 107517 and AMS107517, Authorizing Effluent Discharges from Five Steelmaking Coal Operations in the Elk Valley; British Columbia Gazette, Vol CLIV, No. 40, Victoria, B.C., 2014 and amended 2018, accessed May 2020 at https://www.bclaws.ca/civix/document/id/bcgaz1/bcgaz1/279370937.

Chapman, P.M., Adams, W.J., Brooks, M., Delos, C.G., Luoma, S.N., Maher, W.A., Ohlendorf, H.M., Presser, T.S., and Shaw, P., eds., 2010, Ecological assessment of selenium in the aquatic environment: Boca Raton, Fla., CRC Press, 368 p., https://doi.org/10.1201/EBK1439826775.

Chisholm, I., and Hamlin, P., 1987, 1985 Libby Reservoir Angler Census—May 13–October 31, 1987 [ie 1985]: Kalispell, Mont., Montana Department of Fish, Wildlife and Parks, Interim Report (No. DOE/BP–12660–4) 106 p. [Also available at https://www.osti.gov/biblio/5494223.]

Chisholm, I., Hensler, M.E., Hansen, B., and Skaar, D., 1989, Quantification of Libby Reservoir water levels needed to maintain or enhance reservoir fisheries—Methods and data summary, 1983–1987: Kalispell, Mont., Montana Fish, Wildlife, and Parks, Bonneville Power Administration Project no. 83–467, 272 p. [Also available at http://docs.streamnetlibrary.org/BPA_Fish_and_Wildlife/12660-5.pdf.]

Dalbey, S., DeShazer, J., Garrow, L., Hoffman, T., and Ostrowski, T., 1998, Quantification of Libby Reservoir water levels needed to maintain or enhance reservoir fisheries: Libby, Mont., Montana Fish, Wildlife, and Parks, Bonneville Power Administration Project no. 83–467, 117 p. [Also available at https://www.cbfish.org/Document.mvc/Viewer/12660-7.]

Dunnigan, J.L., DeShazer, J., Ostrowski, T., Benner, M., Lampton, J., Garrow, L., Tohtz, J., and Boyer, M., 2017, Mitigation for the construction and operation of Libby Dam—Annual Report 2016: Libby, Mont., Montana Fish, Wildlife and Parks, Bonneville Power Administration Project no. 1995–004–00, 270 p. [Also available at https://www.cbfish.org/Document.mvc/Viewer/P154535.]

Dunnigan, J.L., DeShazer, J., Ostrowski, T., Benner, M., Lampton, J., Garrow, L., Frye, J., Gabreski, C., and Boyer, M., 2020, Mitigation for the construction and operation of Libby Dam—Draft Annual Report 2019: Libby, Mont., Montana Fish, Wildlife and Parks, Bonneville Power Administration Project no. 1995–004–00, 365 p. [Also available at https://www.cbfish.org/Document.mvc/Viewer/P171660.]

Easthouse, K., 2013, Libby Dam—Kootenai River and Lake Koocanusa water quality sampling and analysis plan 2013: Seattle, Wash., U.S. Army Corps of Engineers, 20 p., accessed May 2020 at https://usace.contentdm.oclc.org/digital/collection/p266001coll1/id/8870.

Hauer, F.R., and Stanford, J.A., 1997, Long-term influence of Libby Dam operation on the ecology of macrozoobenthos of the Kootenai River, Montana and Idaho: Polson, Mont., Flathead Lake Biological Station, Open-File Report 141–97, 80 p.

Holderman, C., Hoyle, G., Hardy, R., Anders, P., Ward, P., and Yassien, H., 2009, Libby Dam Hydro-electric Project mitigation—Efforts for downstream ecosystem restoration: Vancouver, B.C., Section C–4 of 33d International Association of Hydraulic Engineering and Research Congress, p. 6214–6222.

Horowitz, A.J., 1986, Comparison of methods for the concentration of suspended sediment in river water of subsequent chemical analysis: Environmental Science & Technology, v. 20, no. 2, p. 155–160. [Also available at https://doi.org/10.1021/es00144a007.]

Horowitz, A.J., Elrick, K.A., and Smith, J.J., 2001, Estimating suspended sediment and trace element fluxes in large river basins—Methodological considerations as applied to the NASQAN programme: Hydrological Processes, v. 15, no. 7, p. 1107–1132. [Also available at https://doi.org/10.1002/hyp.206.]

Horowitz, A.J., Elrick, K.A., and Smith, J.J., 2008, Monitoring urban impacts on suspended sediment, trace element, and nutrient fluxes within the City of Atlanta, Georgia, USA—Program design, methodological considerations, and initial results: Hydrological Processes, v. 22, no. 10, p. 1473–1496. [Also available at https://doi.org/10.1002/hyp.6699.]

Idaho Department of Fish and Game, 2008, Ecosystem rehabilitation study of the Kootenai River Investigations: Boise, Idaho, Ecosystem Rehabilitation Project Progress Report 2005–2007, Idaho Department of Fish and Game report no. 08–11, 61 p.

Janz, D.M., 2011, Selenium, *in* Wood, C.W., Farrell, A.P., and Brauner, C.J., eds., Fish physiology—Homeostasis and toxicology of essential metals: Academic Press, v. 31, part A, p. 327–374. [Also available at https://doi.org/10.1016/S1546-5098(11)31007-2.]

Janz, D.M., DeForest, D.K., Brooks, M.L., Chapman, P.M., Gilron, G., Hoff, D., Hopkins, W.A., McIntyre, D.O., Mebane, C.A., Palace, V.P., Skorupa, J.P., and Wayland, M., 2010, Selenium toxicity to aquatic organisms, *in* Chapman, P.M., Adams, W.J., Brooks, M., Delos, C.G., Luoma, S.N., Maher, W.A., Ohlendorf, H.M., Presser, T.S., and Shaw, P., eds., Ecological assessment of selenium in the aquatic environment: Boca Raton, Fla., CRC Press, p. 141–231.

Jenni, K.E., Naftz, D.L., and Presser, T.S., 2017, Conceptual modeling framework to support development of site-specific selenium criteria for Lake Koocanusa, Montana, U.S.A., and British Columbia, Canada: U.S. Geological Survey Open-File Report 2017–1130, 14 p. [Also available at https://doi.org/10.3133/ofr20171130.]

Lemly, A.D., and Skorupa, J.P., 2007, Technical issues affecting the implementation of U.S. Environmental Protection Agency's proposed fish tissue-based aquatic criterion for selenium: Integrated Environmental Assessment and Management, v. 3, no. 4, p. 552–558. [Also available at https://doi.org/10.1897/IEAM_2007-024.1.]

Luoma, S.N., and Presser, T.S., 2009, Emerging opportunities in management of selenium contamination: Environmental Science & Technology, v. 43, no. 22, p. 8483–8487. [Also available at https://doi.org/10.1021/es900828h.]

Luoma, S.N., and Presser, T.S., 2018, Status of selenium in south San Francisco Bay—A basis for modeling potential guidelines to meet National tissue criteria for fish and a proposed wildlife criterion for birds: U.S. Geological Survey Open-File Report 2018–1105, 75 p. [Also available at https://doi.org/10.3133/ofr20181105.]

Luoma, S.N., and Rainbow, P.S., 2005, Why is metal bioaccumulation so variable? Biodynamics as a unifying concept: Environmental Science & Technology, v. 39, no. 7, p. 1921–1931. [Also available at https://doi.org/10.1021/es048947e.]

Mæhre, H.K., Hamre, K., and Elvevoll, E.O., 2012, Nutrient evaluation of rotifers and zooplankton—Feed for marine fish larvae: Aquaculture Nutrition, v. 19, no. 3, p. 301–311. [Also available at https://doi.org/10.1111/j.1365-2095.2012.00960.x.]

Montana Department of Environmental Quality [MTDEQ], 2018, Appendices A–J *of* Final 2018 water quality integrated report: Helena, Montana Department of Environmental Quality, 72 p., accessed May 2020, at http://deq.mt.gov/Water/Resources/report.

Montana Department of Environmental Quality [MTDEQ], 2019, Montana numeric water quality standards: Helena, Mont., Montana Department of Environmental Quality, Water Quality Planning Bureau, Water Quality Standards and Modeling Section, Circular DEQ–7, 80 p., accessed May 2020 at https://deq.mt.gov/Portals/112/Water/WQPB/Standards/PDF/DEQ7/DEQ-7.pdf.

Nagpal, N.K., and Howell, K., 2001, Water quality guidelines for selenium—Technical appendix: Victoria, B.C., Ministry of Water, Land and Air Protection, Water Protection Branch, 27 p., accessed May 2020 at http://www.speciation.net/Database/Links/Government-of-British-Columbia-Ministry-of-Environment-Water-Quality-Guidelines-for-Selenium-;i374.

Osmundson, B., and Skorupa, J., 2011, CO-Selenium in fish tissue—Prediction equations for conversion between whole body, muscle, and eggs: U.S. Fish and Wildlife Service, Project FFS ID 6F50, 49 p.

Penglase, S., Hamre, K., and Ellingsen, S., 2014a, Selenium and mercury have a synergistic negative effect on fish reproduction: Aquatic Toxicology (Amsterdam, Netherlands), v. 149, p. 16–24. [Also available at https://doi.org/10.1016/j.aquatox.2014.01.020.]

Penglase, S., Hamre, K., Rasinger, J.D., and Ellingsen, S., 2014b, Selenium status affects selenoprotein expression, reproduction, and F_1 generation locomotor activity in zebrafish (*Danio rerio*): British Journal of Nutrition, v. 111, no. 11, p. 1918–1931. [Also available at https://doi.org/10.1017/S000711451300439X.]

Presser, T.S., 2013, Selenium in ecosystems within the mountaintop coal mining and valley-fill region of southern West Virginia—Assessment and ecosystem-scale modeling: U.S. Geological Survey Professional Paper 1803, 86 p., accessed April 2020 at https://doi.org/10.3133/pp1803.

Presser, T.S., and Luoma, S.N., 2010a, A methodology for ecosystem-scale modeling of selenium: Integrated Environmental Assessment and Management, v. 6, no. 4, p. 685–710. [Also available at https://doi.org/10.1002/ieam.101.]

Presser, T.S., and Luoma, S.N., 2010b, Ecosystem-scale selenium modeling in support of fish and wildlife criteria development for the San Francisco Bay-Delta Estuary, California: U.S. Geological Survey Administrative Report, prepared for and released by U.S. Environmental Protection agency, Region 9, San Francisco, Calif., 46 p., accessed July 2020 at https://archive.epa.gov/region9/water/archive/web/pdf/selenium-modeling_admin-report.pdf.

Presser, T.S., and Luoma, S.N., 2013, Ecosystem-scale selenium model for the San Francisco Bay-Delta Regional Ecosystem Restoration Implementation Plan (DRERIP): San Francisco Estuary and Watershed Science, v. 11, no. 1, p. 1–39. [Also available at https://doi.org/10.15447/sfews.2013v11iss1art2.]

Presser, T.S., and Naftz, D.L., 2020, Selenium concentrations in food webs of Lake Koocanusa in the vicinity of Libby Dam (MT) and the Elk River (BC) as the basis for applying ecosystem-scale modeling, 2008–2018: U.S. Geological Survey data release, https://doi.org/10.5066/P9VXYSNZ.

Presser, T.S., Naftz, D.L., and Jenni, K.E., 2018, USGS measurements of dissolved and suspended particulate material selenium in Lake Koocanusa in the vicinity of Libby Dam (MT), 2015–2017 (update): U.S. Geological Survey data release, accessed May 2020 at https://doi.org/10.5066/P9HB5S5F.

Presser, T.S., Piper, D.Z., Bird, K.J., Skorupa, J.P., Hamilton, S.J., Detwiler, S.J., and Huebner, M.A., 2004, The Phosphoria Formation—A model for forecasting global selenium sources to the environment, *in* Hein, J.R., ed., Life cycle of the Phosphoria Formation—From deposition to the post-mining environment: New York, Elsevier, p. 299–319.

Reiley, M.C., Stubblefield, W.A., Adams, W.J., Di Toro, D.M., Hodson, P.V., Erickson, R.J., and Keating, F.J., Jr., eds., 2003, Reevaluation of the state of the science for water-quality criteria development: Pensacola, Fla., Society of Environmental Toxicology and Chemistry Press, 224 p.

Richards, D., 1997, Kootenai River biological baseline status report: Portland, Oreg., U.S. Department of Energy, Bonneville Power Administration, Environment, Fish and Wildlife, Project no. 94–49, 71 p. [Also available at https://www.cbfish.org/Document.mvc/Viewer/40364-1.]

Schlekat, C.E., Purkerson, D.G., and Luoma, S.N., 2004, Modeling selenium bioaccumulation through arthropod food webs in San Francisco Bay, California, USA: Environmental Toxicology and Chemistry, v. 23, no. 12, p. 3003–3010. [Also available at https://doi.org/10.1897/03-4.1.]

Teck Coal Ltd., 2014, Elk Valley Water Quality Plan: Sparwood, B.C., Teck Coal Ltd., 290 p., accessed May 2020 at https://www2.gov.bc.ca/gov/content/environment/waste-management/industrial-waste/mining-smelting/teck-area-based-management-plan.

Teck Coal Ltd., 2015, Burbot monitoring in Lake Koocanusa, 2014 and 2015: Sparwood, B.C., Teck Coal Ltd., prepared by Minnow Environmental, Inc., Georgetown, Ontario, 86 p.

Teck Coal Ltd., 2018a, Koocanusa Reservoir monitoring report, 2014 to 2016: Sparwood, B.C., Teck Coal Ltd., prepared by Minnow Environmental, Inc., 655 p., accessed May 2020 at https://www.teck.com/media/Koocanusa-Reservoir-Monitoring-Report,-2014-to-2016.pdf.

Teck Coal Ltd., 2018b, Permit 107517—2017 summary report of monitoring results in the Koocanusa Reservoir—Sparwood. B.C., Teck Coal Ltd., 97 p. [Also available at https://www.teck.com/media/Koocanusa-Water-Quality-2017-Report.pdf.]

Teck Coal Ltd., 2019, Koocanusa Reservoir monitoring report, 2018: Sparwood, B.C., Teck Coal Ltd., prepared by Minnow Environmental Inc., Georgetown, Ontario, 632 p., accessed May 2020 at https://www.teck.com/media/Koocanusa-Reservoir-Monitoring-2018-Report.pdf.

Thomas, J.K., and Janz, D.M., 2014, In ovo exposure to selenomethionine via maternal transfer increases developmental toxicities and impairs swim performance in F1 generation zebrafish (*Danio rerio*): Aquatic Toxicology (Amsterdam, Netherlands), v. 152, p. 20–29. [Also available at https://doi.org/10.1016/j.aquatox.2014.03.022.]

Thomas, J.K., and Janz, D.M., 2015, Developmental and persistent toxicities of maternally deposited selenomethionine in zebrafish (*Danio rerio*): Environmental Science & Technology, v. 49, no. 16, p. 10182–10189. [Also available at https://doi.org/10.1021/acs.est.5b02451.]

U.S. Environmental Protection Agency [USEPA], 2016a, Aquatic life ambient water quality criterion for selenium—Freshwater: Washington, D.C., U.S. Environmental Protection Agency, EPA 822–R–16–006), 807 p., accessed May 2020 at https://www.epa.gov/sites/production/files/2016-07/documents/aquatic_life_awqc_for_selenium_-_freshwater_2016.pdf.

U.S. Environmental Protection Agency [USEPA], 2016b, Technical support for fish tissue monitoring for implementation of EPA's 2016 selenium criterion: U.S. Environmental Protection Agency, EPA 820–F–16–007, 49 p., accessed May 2020 at https://archive.epa.gov/epa/sites/production/files/2016-10/documents/technical-support-fish-tissue-monitoring-selenium.pdf.

U.S. Environmental Protection Agency [USEPA], 2016c, Water quality standards—Establishment of revised numeric criteria for selenium for the San Francisco Bay and Delta, State of California: Federal Register, v. 81, no. 178, p. 46030–46042, accessed May 2020 at https://www.federalregister.gov/d/2016-22087.

U.S. Environmental Protection Agency [USEPA], 2016d, Technical support for adopting and implementing EPA's 2016 selenium criterion in water quality standards: Washington, D.C., U.S. Environmental Protection Agency, 16 p., accessed May 2020 at https://archive.epa.gov/epa/sites/production/files/2016-10/documents/technical-support-adoption-implementation-selenium.pdf.

U.S. Environmental Protection Agency [USEPA], 2018, Water quality standards—Establishment of a numeric criterion for selenium for the State of California: Federal Register, v. 83, no. 239, p. 64059–64078, accessed May 2020 at https://www.federalregister.gov/d/2018-26781.

U.S. Fish and Wildlife Service [USFWS], 1998, Endangered and threatened wildlife and plants—Determination of threatened status for the bull trout in the conterminous United States: Federal Register, v. 64, no. 210, p. 58910–58933, accessed May 2020 at https://www.federalregister.gov/d/99-28295.

U.S. Fish and Wildlife Service [USFWS], 1999, Recovery plan for the Kootenai River population of the white sturgeon (*Acipenser transmontanus*): Portland, Oreg., U.S. Fish and Wildlife Service, 96 p. plus appendixes.

U.S. Fish and Wildlife Service [USFWS], 2012, Technical Review—Smoky Canyon Mine site-specific selenium criterion report: Denver, Colo., Division of Environmental Quality, Environmental Contaminants Program, 154 p.

VAST Resource Solutions Inc, 2017, Lake Koocanusa foreshore inventory and mapping and aquatic habitat index: VAST Resource Solutions, Inc., prepared for East Kootenay Integrated Lake Management Partnership, 155 p., accessed May 2020 at https://westsidekoocanusa.wildapricot.org/resources/Documents/EKIMP%20ForeShore%20Mapping%20Mgmt_FINAL_Oct%2017.pdf.

Woods, P.F., 1982, Annual nutrient loadings, primary productivity, and trophic state of Lake Koocanusa, Montana and British Columbia, 1972–80: U.S. Geological Survey Professional Paper 1283, 24 p. [Also available at https://doi.org/10.3133/pp1283.]

Woods, P.F., and Falter, C.M., 1982, Limnological investigations—Lake Koocanusa, Montana—Part 4, factors controlling primary productivity: Seattle, Wash., U.S. Army Corps of Engineers, Special Report 82–15, 106 p., accessed May 2020 at https://hdl.handle.net/11681/12346.

Appendix Supplementary References

Tapeworm and Nematode

Carter, V., Pierce, R., Dufour, S., Arme, C., and Hoole, D., 2006, The tapeworm Ligula intestinalis (Cestoda—Pseudophyllidea) inhibits LH expression and puberty in its teleost host, Rutilus rutilus: Reproduction (Cambridge, England), v. 130, no. 6, p. 939–945. [Also available at https://doi.org/10.1530/rep.1.00742.]

Hursky, O., and Pietrock, M., 2015, Intestinal nematodes affect selenium bioaccumulation, oxidative stress biomarkers, and health parameters in juvenile rainbow trout (Oncorhynchus mykiss): Environmental Science & Technology, v. 49, no. 4, p. 2469–2476. [Also available at https://doi.org/10.1021/es5048792.]

Mahon, R., 1976, Effect of the cestode Ligula intestinalis on spottail shiners, Notropis hudsonius: Canadian Journal of Zoology, v. 54, no. 12, p. 2227–2229. [Also available at https://doi.org/10.1139/z76-254.]

Majdi, N., and Traunspurger, W., 2015, Free-living nematodes in the freshwater food web—A review: Journal of Nematology, v. 47, no. 1, p. 28–44.

Teck Coal Ltd., 2018a, Koocanusa Reservoir monitoring report, 2014 to 2016: Sparwood, B.C., Teck Coal Ltd., prepared by Minnow Environmental, Inc., 655 p., accessed May 2020 at https://www.teck.com/media/Koocanusa-Reservoir-Monitoring-Report,-2014-to-2016.pdf.

Mercury and Selenium

Canadian Council of Ministers of the Environment, 2000, Canadian tissue residue guidelines for the protection of wildlife consumers of aquatic biota—Methylmercury: Winnipeg, Ontario, Canadian Environmental Quality Guidelines, Canadian Council of Ministers of the Environment, 7 p.

Heinz, G.H., and Hoffman, D.J., 1998, Methylmercury chloride and selenomethionine interactions on health and reproduction in mallards: Environmental Toxicology and Chemistry, v. 17, no. 2, p. 139–145. [Also available at https://doi.org/10.1002/etc.5620170202.]

Montana Department of Fish, Wildlife and Parks, Montana Department of Environmental Quality, and Montana Department of Health and Human Services, 2014, Montana Sport Fish Consumption Guidelines (updated 2015): Montana Department of Fish, Wildlife and Parks, Montana Department of Environmental Quality, and Montana Department of Health and Human Services, 11 p.

Penglase, S., Hamre, K., and Ellingsen, S., 2014, Selenium and mercury have a synergistic negative effect on fish reproduction: Aquatic Toxicology, v. 149, p. 16–24. [Also available at https://doi.org/10.1016/j.aquatox.2014.01.020.]

Cyprinids

Janz, D.M., DeForest, D.K., Brooks, M.L., and Chapman, P.M., 2010, Selenium toxicity to aquatic organisms, *in* Chapman, P.M., Adams, W.J., Brooks, M.L., Delos, C.G., Luoma, S.N., Maher, W.A., Ohlendorf, H.M., Presser, T.S., and Shaw, D.P., eds., Ecological assessment of selenium in the aquatic environment: Pensacola, Fla., Society of Environmental Toxicology and Chemistry Press, p. 141–231.

U.S. Environmental Protection Agency, 2016, Technical support for fish tissue monitoring for implementation of EPA's 2016 selenium criterion: U.S. Environmental Protection Agency, EPA 820–F–16–007, 49 p., accessed May 2020 at https://archive.epa.gov/epa/sites/production/files/2016-10/documents/technical-support-fish-tissue-monitoring-selenium.pdf.

Rotifers

Mæhre, H.K., Hamre, K., and Elvevoll, E.O., 2012, Nutrient evaluation of rotifers and zooplankton—Feed for marine fish larvae: Aquaculture Nutrition, v. 19, no. 3, p. 301–311. [Also available at https://doi.org/10.1111/j.1365-2095.2012.00960.x.]

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