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ASSESSMENT OF CALCITE DEPOSITION ON FISH AND FISH HABITAT FROM COAL MINING IN BRITISH COLUMBIA, CANADA

CONTEXT

The Elk River watershed upstream of Sparwood has an area of 2,809 km^2 and provides habitat for various salmonids, including Mountain Whitefish (*Prosopium williamsoni*), Westslope Cutthroat Trout (*Oncorhynchus clarkii lewisi),* and Bull Trout (*Salvelinus confluentus*), all of which can be impacted from changes in water quality and fish habitat. Westslope Cutthroat Trout (Pacific populations) are listed as Special Concern under the *Species at Risk Act* (DFO 2017). Bull Trout (Pacific population) are designated as Special Concern by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) and on the British Columbia Conservation Data Centre's Blue List.

Drainage from coal mine waste rock spoils has elevated levels of calcium and carbonate that create conditions suitable for calcite precipitation or build-up in downstream areas (EVWQP 2014). Calcite can cement streambed rocks together and alter various natural ecological functions that are required for maintenance of fish habitat and can therefore present a potential threat to the health of fish and fish habitat. To address trends of increasing contaminants and calcite formation potentially causing impairment of ecosystem health from coal mining, the Province of British Columbia issued a Ministerial Order to complete an Elk Valley Area Based Management Plan, which was completed in 2014 (EVWQP 2014) and revised in 2025 (EVWQP 2025). The plan establishes a framework that, among its multiple objectives, includes water quality targets for calcite with the intent of improving water quality and reducing the rate of calcite formation.

The Department of Fisheries and Oceans (DFO) Fish and Fish Habitat Protection Program (FFHPP) is concerned that calcite deposition may be impacting fish and fish habitat downstream of coal mines. To assess the impact, FFHPP requires robust scientific field methods to establish whether calcite deposition from coal mining has impaired the natural ecological functions within streams across broad geographic areas.

FFHPP is requesting DFO Science to conduct a review of the literature to determine the key ecological functions at risk from calcite deposition in streams, and to evaluate the efficacy of monitoring protocols for assessing calcite impacts to natural ecological functions. The advice arising from this Canadian Science Advisory Secretariat (CSAS) Science Response is intended to identify potential gaps and identify additional methods to support a practical field assessment of impacts to fish habitat from calcite deposition.

Objectives

The specific objectives of this review are to:

1. Complete a comprehensive literature review of impacts on ecological functions in salmonid habitat from calcite deposition.

2. Review the methods for measuring and monitoring calcite in the Elk Valley Water Quality Plan (EVWQP 2014; Annex J.1, EVWQP 2025) to:
    a. determine which components are suitable for assessing impacts to ecological functions from calcite; and
    b. identify any gaps and/or limitations requiring supplemental field techniques, using the results from the literature review.
3. Recommend procedures for practical field assessment methods for monitoring and identification of impacts to fish habitat from calcite deposition.

This Science Response Report results from the regional peer review of April 15, 2026 on Assessment of Calcite Deposition on Fish and Fish Habitat from Coal Mining in British Columbia, Canada.

BACKGROUND

Limestone, dolomite, and other calcium-rich sediments are abundant in the geological formations of Western Canada and North America. These include the well-known bedrocks of the Rocky Mountains and allied ranges, but also the other accretion zones in the Western Cordillera (Fischl 1985). The Foreland Belt is the easternmost of these zones in British Columbia (BC) and contains high-quality calcium sedimentary units that are utilized in commercial cement production at the BC-Alberta Border (e.g., LaFarge plant in Exshaw Alberta). Within the Foreland Belt, the Palliser formation also contains high-quality seams of coal sought for use in metallurgical industries and is mined in the East Kootenays. Other significant mining in the Foreland Belt includes both thermal and metallurgical coal mining near Hinton, Alberta, and metallurgical coal in the Gates Formation near Tumbler Ridge, BC. There are inactive thermal coal sites on Vancouver Island, near Quinsam, BC. Matheson et al. (1994) detail several major coal fields in BC, which are widespread such that occurrences also include all of the tectonic accretion zones forming the province's geology. Coal seams are frequently overlain by calcareous deposits where they occur.

Calcareous sediments, when weathered by surface water and associated geochemical processes, can form aqueous carbonate solutions with potential to form accretionary precipitate downstream when the right conditions are present. Because coal and other mining operations form waste rock piles with high surface area and modified hydrological pathways, through which surface water can migrate in altered patterns, the risk of forming these aqueous solutions is concurrent with mining activity. Significant amounts of precipitates have been documented as a consequence of mines in both the Kootenay area of BC and the McLeod River area of Alberta. In some cases a monitoring and remediation plan has been included as a required activity in provincial permitting. In this Science Response we discuss several possible consequences to fish and fish habitat from this phenomenon and make recommendations for filling knowledge gaps and for monitoring and field assessment of impacts. Although the emphasis is on coal-mining activity in Eastern BC, the prevalence of calcium-rich bedrocks throughout Western North America means that precipitates could be a risk in mining operations elsewhere.

ANALYSIS AND RESPONSE

Objective 1: Background on Various Elements Associated with Calcite Effects

Salmonid fishes are an important and diverse component of the aquatic fauna of the Western Cordillera (Roberge et al. 2002). They include a number of anadromous species (e.g., Pink, Sockeye, Coho, Chum, Chinook) that can reach very large sizes, potamodromous species

(e.g., Westslope Cutthroat Trout, Bull Trout) that are typically smaller, but still among the larger fishes in the environments where they occur, and species that possess both anadromous and potamodromous forms (e.g., Steelhead (anadromous Rainbow Trout), sea-run Coastal Cutthroat Trout, and Kokanee (landlocked Sockeye)). Salmonids are characterized by complicated life histories and remarkable interspecies and interpopulation behavioural plasticity. Because of their size and habit, they are important cultural, commercial, and sport species and often the focus of dedicated management and regulatory effort. Many salmonids in the Western Cordillera and worldwide have shown dramatic declining population trends beginning in the latter half of the twentieth century. These changes have been linked to increased climate variability and its interaction with a myriad of other factors in a cumulative effects fashion (e.g., Crozier and Siegel 2023).

Salmonids complete their life history through five distinct stages: egg, alevin, fry, parr, and adult. Both anadromous and potamodromous forms rely on freshwater habitat to support all five stages. Salmonids are classical r-strategists, producing a large number of eggs with low survival, rapid development, and relatively short overall lifespans. Eggs are almost always laid in freshwater environments, either in a broadcast effort (e.g., Mountain Whitefish) or as substrate spawners (most other species). Both of these behaviours rely on specific gravel / substrate specifications that provide a variety of functions for eggs and alevin, including predator and hydraulic protection, gas exchange, and temperature regulation. The interstitial spaces where eggs are deposited between gravel particles are important individual nursery sites, and must also be supplied with water that is free of fines that can accumulate in these spaces and foul their functions (Groot and Margolis 1991).

Substrate spawners most often dig redds, or nests, before laying eggs and are known to choose specific locations. Most species use natal homing as one way of selecting these conditions which also include specific (often shallow) depths, temperatures, water clarity, and rates of flow. Because subsequent fish development will occur downstream, there is a migration and passage requirement for both anadromous and potamodromous life cycle completion (Groot and Margolis 1991).

Alevins will utilize these same characteristics of streambed substrate to complete yolk absorption, relying on interstitial spacing and stability to survive transition to free-swimming fry (Kennedy 2008).

Fry and parr stages are free-swimming, free-feeding (often predatory) forms with distinct morphology, including progressively larger size, striping, feeding habits, and associated habitat requirements. Parr and later 1+ juveniles begin to move away from hatching locations seeking resources in different environments that their larger size both allows and requires (Kennedy 2008).

Lotic Mesohabitats and Their Use by Salmonid Life History Classes

Lotic waters have been characterized by their component hydromorphological units, or mesohabitats. While a number of classification systems have been proposed (Wegscheider et. al 2020), an early and simple approach that considered salmonids in small streams is relevant here (Bisson et al. 1982). That system recognizes three main units: pools, riffles, and glides. Each of these can be further classified according to finer hydrological features. Riffles for example are further given as low gradient riffles, rapids, and cascades. Bisson et al. (1982) provide evidence of ecological relevance to juvenile coho, cutthroat trout, and steelhead in the 0+ /1+ age categories. Pools likewise are given with six different categories, united by their formation from complex structures, often with forms of overhangs, which are important hunting and refuge areas for developing juveniles. Glides are recognized as a more simple and uniform habitat, often occurring in transition from pools to riffles. Glides typically have the longest,

uninterrupted forms. The frequency and size of each of these mesohabitat types varies with overall stream magnitude (stream order), as well as channel gradient, sediment supply, and structural controls (e.g., large woody debris). Undercut banks are noted as a feature that can occur in multiple habitat types and are important to rearing juveniles for the same provisions of cover, hydrological slowing, and feeding. Spawning (and larval rearing) occurs with specific flow and (often shallow) depth preferences, often at the tail end of pools and riffles (e.g., McPhail and Baxter 1996).

Individual size and movement affect how salmonids use the variety of instream habitats, and the complexity is further compounded by life history polymorphism with the possibility of fluvial, adfluvial, and resident behaviours between populations within a species (e.g., Muhlfeld and Marotz 2005). Further, there is evidence that these populations can overlap spatially and interact with one another (Campbell et al. 2019). Strongly adfluvial populations use a wide range of habitats, and are subject to the vulnerability of migration stress and a reliance on a broader range of habitat sequences to complete their life history. Resident behaviours risk relying on a narrow geographic scope and are more vulnerable to catastrophic events.

Westslope Cutthroat Trout (*Oncorhynchus clarkii lewisi* (Girard))

Westslope Cutthroat Trout (WCT) is one of fourteen alopatrically distributed subspecies of Cutthroat in western North America. In Canada, it is listed as Threatened (Alberta population) and Special Concern (BC / Pacific populations) under the *Species at Risk Act* (COSEWIC 2016). Average population sizes are considered to be small compared with other salmonids and there is documented evidence of numerous declines and extirpations (COSEWIC 2016). One of the most significant threats to WCT is genetic introgression from introduced Rainbow Trout, and the Pacific populations of WCT have been documented to contain the most genetically intact genome. These populations are contained in the upper reaches of the Kootenay River system (Taylor et al. 2003), where the presence of migration barriers and quality habitat are thought to have prevented introgression (Muhlfeld et al. 2009, Rubidge and Taylor 2005, also see Schmetterling 2001).

While WCT populations have been documented in fluvial, adfluvial, and resident polymorphs, Pacific populations showing high genetic quality occur in cold, high-elevation waters and show a tendency toward resident forms. It is thought that the ability to adapt to these conditions has shielded them from introgression, referred to as an elevation refugium (Paul and Post 2001). WCT are thought to be relatively sensitive to habitat disturbance, especially that disturbing water quality; degradation and loss of habitat are considered important to documented population declines including promotion of introgression.

Bull Trout (*Salvelinus confluentus* (Suckley))

Bull Trout are a char, closely related to Dolly Varden. Adults are among the larger fish in the freshwater communities they are found in, and both adults and juveniles are significant predators in those systems. Bull Trout are widely distributed, abundant in all major drainages of western North America, including waters of the Yukon, Mackenzie, Columbia, and Fraser Rivers, but most often present in small, discrete populations. Unlike Cutthroat, subspeciation is not recognized, though there are two major genetic lineages recognized: an inland variant and a coastal variant. In Canada, for conservation purposes, COSEWIC recognizes five distinct designatable units (DU), based on COSEWIC's National Freshwater Biogeographic Zones. Two are listed as Special Concern under the *Species at Risk Act* (SARA), one (Yukon) is data deficient, and one (Saskatchewan-Nelson) is listed as Threatened. The Pacific population, which is most relevant to this Science Response, has been assessed as Special Concern by COSEWIC and under consideration for listing under SARA. This status recommendation was

based on known vulnerability to a wide range of anthropogenic threats that are known to be increasing, and not because of existing range or population declines (COSEWIC 2025).

The Threatened status of the Saskatchewan-Nelson DU is attributed to habitat fragmentation, reduction, and erosion of quality as a result of natural resource development. The requirement for this species to have a combination of high-quality rearing habitat and connectivity between its discrete population units is considered unique among peer freshwater species. The maintenance of fish passage that avoids isolating discrete population units, as well as the maintenance/recovery of spawning and rearing habitat, are considered important recovery objectives (COSEWIC 2025). Johnston et al. (2007) documented population recovery limited by egg-early juvenile survival, noting from other observations that the result was influenced by intraspecific competition for daytime refugia (which can include cover, hydrological, and food web quality).

Mountain Whitefish (*Prosopium williamsoni* (Girard))

Mountain Whitefish is a widely distributed species in Western North America, ranging from the southern Yukon Territory to the northern end of the Great Basin, and east to approximately the border of Alberta and Saskatchewan (McPhail and Troffe 1998). In its range it is documented as abundant almost everywhere and has not been considered by COSEWIC as a species of concern for assessment. Adults are relatively long-lived (to 15 years), and have a strong habit of returning to summer foraging sites. Spawning migrations occur annually, usually downstream from foraging sites, and this combination of longevity and repeated migration tracking has allowed scales and later otoliths to be used as environmental records of various conditions, including contaminants.

Although many of the habitat requirements of this species are similar to Westslope Cutthroat Trout and Bull Trout (cold, clean water, spawning gravels, etc.), it is reported to be more tolerant of environmental variation, and found in a wider range of flow and elevation types. Some of the life history features that are attributed to its apparent robustness include a high number of eggs per spawn, the habit of broadcast fertilization (though still in gravel substrates), and the habit of being substrate (bottom) feeding rather than drift feeding (though there are drift feeding morphotypes in some populations).

On emergence, fry move to faster waters and feed on aquatic insects including a diet of up to 57% chironomid larvae as well as mayflies, but shifting toward the latter with increasing growth. Adults have a gregarious rather than solitary habit, found in groups at the bottoms of riffles, or surrounding woody debris (McPhail and Troffe 1998). Highest mortality, like most salmonids, occurs in embryonic/ emergent stages. Little is published about vulnerability of later life history stages.

Calcite Precipitation Dynamics

Calcium carbonate precipitation in lotic environments is fundamentally a physicochemical process governed by carbonate thermodynamics and reaction kinetics, in which dissolved calcium (Ca^{2+}) and carbonate species (e.g., CO_3^{2-}) combine to form solid calcium carbonate ($CaCO_3$). Precipitation occurs when waters become supersaturated with respect to calcite, most commonly in response to changes in solution chemistry, pH, temperature, hydrodynamic conditions, ionic strength, or biotic influences. Calcite precipitation has the potential to influence channel morphology, substrate characteristics, and water chemistry, while also affecting sediment dynamics, carbon cycling, and ecological function (Teng et al. 2000, Thomas 2007, Morse et al. 2007, Deocampo 2010). To understand carbonate mineral formation and its potential implications, it is essential to examine the physicochemical conditions enabling calcium

carbonate to precipitate from aqueous solutions, including thermodynamic controls on saturation state and the kinetic and mechanistic factors regulating nucleation and crystal growth.

This section synthesizes the fundamental mechanisms and drivers of calcium carbonate mineralization in freshwater systems, specifically focusing on lotic environments. Emphasis is placed on the interplay between thermodynamic supersaturation, CO_2 exchange, hydrodynamics, temperature, solution chemistry, biotic influences, and kinetic constraints that regulate precipitation across spatial and temporal scales characteristic of rivers and streams.

Physical and Chemical Properties of Calcium Carbonates

Calcium carbonate is a ubiquitous mineral in natural and anthropogenically influenced systems, with physical and chemical properties that strongly influence its behaviour in aqueous environments (Morse et al. 2007, Ford and Williams 2007, Deocampo 2010). Calcium carbonate ($CaCO_3$) occurs in three principal anhydrous polymorphs: calcite, aragonite, and vaterite (Kabalah-Amitai et al. 2013, Vereshchagin et al. 2023, Santos et al. 2023). Although these polymorphs share an identical chemical composition, they differ in crystal structure, resulting in distinct thermodynamic stabilities, solubilities, and precipitation behaviours.

Calcite is the most common and thermodynamically stable polymorph of calcium carbonate (Deocampo 2010, Santos et al. 2023). Its stability reflects the energetically favorable arrangement of ions within its rhombohedral crystal lattice (Santos et al. 2023). Consequently, calcite is the dominant polymorph in most freshwater carbonate deposits (Thomas 2007, Santos et al. 2023). Aragonite crystallizes in the orthorhombic crystal system and is metastable under typical freshwater conditions, meaning that it is not the most thermodynamically stable polymorph, but can persist for extended periods because transformation to calcite is kinetically inhibited. Aragonite may form preferentially under elevated pressures, higher temperatures (over 50 C°), or in waters with elevated magnesium concentrations (Mejri et al. 2014). Vaterite is the least stable anhydrous polymorph and is comparatively rare in natural aqueous environments. It has a hexagonal crystal structure (Kabalah-Amitai et al. 2013) and typically transforms rapidly to calcite or aragonite (Thomas 2007).

In lotic systems, calcite precipitates from supersaturated water under varying conditions, producing diverse physical forms influenced by flow dynamics, temperature, water chemistry, and biological activity (Ford and Williams 2007, Balci et al. 2018). Over time, continuous precipitation can accumulate thicker deposits through repeated layering, but the resulting morphology depends on the environment, abiotic and biotic processes, leading to distinct textures and structures.

Thin layers or crusts are common, forming smooth, hard coatings (typically 1–10 mm thick) on streambeds, rocks, or vegetation in turbulent zones. Prolonged deposition can thicken these into concretions of laminated sheets over the stream substrate (Herman and Lorah 1987, Dreybrodt et al. 1992, Ford and Williams 2007, Deocampo 2010).

Tufa deposits represent a more porous form of calcite that develops at ambient (cooler) temperatures, often as mounds, terraces, barriers, or layered growths (Ford and Pedley 1996, Ford and Williams 2007, Deocampo 2010). These are heavily biologically influenced, incorporating microbes, algae, or other macrophytes and organisms that facilitate calcite nucleation via photosynthesis or metabolism. Continuous buildup creates irregular, organic-rich structures with voids from decaying biota, resulting in a hard, porous texture distinct from denser, abiotic forms.

Travertine deposits are dense, crystalline carbonates that form in warmer, thermal spring-fed or geothermal-influenced streams, appearing as stepped terraces, dams, or cave-like features. Primarily abiotic, they rely on chemical precipitation with minimal biological input, leading to

banded, uniform layers that thicken over time but lack the porosity of tufas (Ford and Pedley 1996, Dreybrodt et al. 1997, Decampo 2010).

These forms of calcite can vary in morphology due to site-specific conditions and over time, with thicker accumulations emerging from sustained supersaturation over years (Herman and Lorah 1987, Dreybrodt et al. 1992, Deocampo 2010).

Precipitation Thermodynamics and Kinetics of Calcite

Calcite precipitation represents a fundamental physicochemical process in freshwater environments, where dissolved calcium (Ca^{2+}) and carbonate (CO_3^{2-}) ions combine to form solid calcium carbonate ($CaCO_3$). The simplest stoichiometric representation of precipitation is the reaction of calcium ions with carbonate ions: $Ca^{2+} + CO_3^{2-} \rightleftharpoons CaCO_3$ (s) (Dreybrodt et al. 1997).

Calcite's stability in freshwater is defined by its solubility. In low-ionic-strength, freshwater calcite is thermodynamically stable but can dissolve or precipitate based on saturation index, influenced by pH, temperature, CO_2 degassing, and other abiotic and biotic factors (Herman and Lorah 1987, Hodell et al. 1998, Dreybrodt et al. 1992, Deocampo 2010, Balci et al. 2018).

Saturation State

The saturation state of a mineral describes the thermodynamic tendency of an aqueous solution to dissolve or precipitate that mineral. It quantifies how far the solution is from chemical equilibrium with the mineral. At equilibrium, the rates of dissolution and precipitation are equal, and the solution is said to be saturated. If the solution is undersaturated, dissolution is favored; if supersaturated, precipitation is thermodynamically possible (Dreybrodt et al. 1997, Deocampo 2010).

For any mineral, the saturation state is calculated as the ratio of the effective concentrations of the ions involved in the mineral's dissolution reaction, to the thermodynamic solubility product, which is the equilibrium constant for that reaction at a given temperature and pressure. This ratio is commonly expressed as the saturation state or index Ω (omega), where values less than one indicate undersaturation (conditions favoring dissolution), values equal to one indicate equilibrium, and values greater than one indicate supersaturation, under which calcite precipitation is thermodynamically favorable (Deocampo 2010).

However, while saturation state establishes the thermodynamic feasibility of precipitation, it does not ensure that precipitation will happen and supersaturation alone does not guarantee that precipitation will occur or the rate that it will occur kinetically (Dreybrodt et al. 1997, Deocampo 2010).

Numerous laboratory and field studies demonstrate that calcite precipitation is often kinetically inhibited at low to moderate supersaturation, particularly in dilute freshwater systems. This inhibition reflects the presence of nucleation barriers, limited reactive surface area, and the adsorption of inhibitory solutes such as magnesium, phosphate, sulfate, and dissolved organic matter (Lebrón and Suárez 1996, Lebrón and Suárez 1998). As a result, natural waters may remain supersaturated with respect to calcite for extended periods without measurable precipitation, especially where residence times are short or suitable nucleation surfaces are scarce. Therefore, the relationship between saturation state and precipitation rate is non-linear and mechanistically complex.

Even when calcite precipitation is thermodynamically favourable ($\Omega > 1$), precipitation rates are not determined by saturation state alone. Calcite growth kinetics also depend on solution stoichiometry, particularly the relative activities of carbonate and calcium ions (Gebrehiwet et al. 2012). Experimental work demonstrates that varying the carbonate-to-calcium activity ratio at constant saturation state can produce substantial differences in precipitation rates, indicating

that Ω does not uniquely define kinetic behaviour (Gebrehiwet et al. 2012). This effect is particularly relevant in lotic systems, where processes such as CO_2 degassing, pH elevation, dilution, and mixing can alter carbonate speciation and ion activity (i.e., elevate CO_3^{2-} availability without altering Ca^{2+} concentrations), potentially accelerating precipitation kinetics even at similar Ω values (Herman and Lorah 1987, Lorah and Herman 1988, Dreybrodt et al. 1992). As a result, hydrologically driven shifts in carbonate chemistry may enhance or suppress precipitation even when Ω remains similar, contributing to spatial and temporal variability in calcite deposition dynamics.

Therefore, in lotic environments, the saturation state (Ω) provides the essential thermodynamic framework for calcite precipitation, but it must be considered alongside kinetic barriers and hydrodynamic conditions to fully understand the processes of nucleation and crystal growth.

Nucleation and Crystal Growth

Nucleation represents the initiating step in calcite precipitation, where dissolved ions in a supersaturated solution (Ω > 1) assemble to form stable crystal embryos. This process is inherently kinetic and requires overcoming an energy barrier associated with the creation of a new solid–liquid interface (Teng et al. 1999, Teng et al. 2000). In freshwater systems, homogeneous nucleation (i.e., occurring uniformly within solution) is rare, as it requires supersaturation levels far greater than those typically encountered in natural waters (Reddy and Nacollas 1971, Thomas 2007). Instead, calcite precipitation in freshwater environments is dominated by heterogeneous nucleation, which occurs on pre-existing surfaces such as sediment grains (including suspended fine sediments), bedrock, biofilms, macrophytes, and anthropogenic substrates (Amor et al. 2004). These surfaces lower the energetic barrier to nucleation by providing structural templates, surface defects, or chemically favorable sites that stabilize incipient nuclei and facilitate subsequent crystal growth (Thomas 2007). Despite decades of experimental and theoretical work, however, the molecular-scale mechanisms governing calcite nucleation and early growth remain incompletely resolved, particularly under environmentally relevant conditions (Bergwerff and van Paassen 2021, Broad et al. 2022, Escoffier et al. 2023).

Nucleation thresholds in natural systems are therefore highly variable and cannot be defined by a single, universal saturation state. Instead, they depend strongly on substrate properties, including surface roughness, mineralogy, crystallographic orientation, and the presence of biological coatings. In addition, a range of dissolved constituents can inhibit nucleation by adsorbing to reactive surface sites or interfering with ion attachment. Magnesium (Mg^{2+}), phosphate (PO_4^{3-}), sulfate (SO_4^{2-}), and dissolved organic matter are particularly effective inhibitors, capable of elevating nucleation thresholds and allowing supersaturated waters to persist in a metastable state for extended periods without measurable precipitation (Lebrón and Suárez 1996, Lebrón and Suárez 1998). This behaviour is especially pronounced in dilute or organic-rich freshwater systems and is well documented in both experimental and field studies (Reddy and Nacollas 1971, Zhang and Dawe 2000, Thomas 2007). Such kinetic inhibition is a defining characteristic of freshwater carbonate chemistry and underscores that supersaturation alone is insufficient to predict precipitation (Teng et al. 1999, Teng et al 2000, Bergwerff and van Paassen 2021, Broad et al. 2022).

Once nucleation has occurred, calcite growth proceeds at the crystal–water interface through surface-controlled processes that are governed by surface reaction kinetics that include ion adsorption from solution, partial dehydration of hydrated ions prior to lattice incorporation, and step propagation at energetically favorable sites. Crystal growth is concentrated at defects, steps, and kink sites, where incorporation of calcium and carbonate ions is most favorable (Broad et al. 2022). The density and activity of these sites exert strong control over growth rates

and crystal morphology. Environmental factors such as pH, temperature, solution composition, and biological, further influence growth by modifying ion speciation, surface reactivity, and the effectiveness of inhibitory species (Broad et al. 2022).

In flowing freshwater systems, the combined effects of variable nucleation thresholds, surface-controlled growth mechanisms, and biotic and abiotic inhibitors have the potential to result in spatially heterogeneous and episodic calcite precipitation. While supersaturation defines the thermodynamic potential for precipitation, it is the interplay of nucleation pathways, surface processes, and kinetic inhibition that determines whether and where calcite precipitation is realized in lotic environments (Teng et al. 1999, Teng et al 2000, Balci et al. 2018, Bergwerff and van Paassen 2021, Broad et al. 2022).

Temperature

Calcite precipitation in freshwater systems is governed by a complex interplay of biotic and abiotic factors that influence both thermodynamic equilibria (e.g., solubility and saturation state) and kinetic processes (e.g., nucleation thresholds, crystal growth rates, and inhibition) (Sanjuan and Girard 1996, Deocampo 2010, Balci et al. 2018, Vereshchagin et al. 2023). Among these drivers, temperature is particularly influential because it acts simultaneously on multiple components of the precipitation process. Specifically, temperature affects the equilibrium chemistry that determines calcite saturation state, modifies the intrinsic rates of surface reactions governing nucleation and crystal growth, and alters physical transport processes, including diffusion and gas exchange, that regulate how rapidly supersaturation develops. As a result, the net influence of temperature on calcite precipitation is inherently multifaceted and context dependent (Stewart 1988, Balci et al. 2018, Liptak 2000, Ohlendorf and Sturm 2001, Mejri et al. 2014, Bergwerff and van Paassen 2021).

The most fundamental influence of temperature on calcite precipitation operates through thermodynamics of the $CaCO_3$–CO_2–H_2O system. Calcite solubility and saturation state vary systematically with temperature, and accurate evaluation of saturation therefore requires temperature-dependent equilibrium constants and aqueous speciation calculations (Plummer et al. 1978, Plummer and Busenberg 1982). In freshwater systems open to the atmosphere, temperature also exerts an important indirect control through its effect on CO_2 solubility. As temperature increases, the solubility of CO_2 in water decreases, promoting CO_2 degassing to the atmosphere. The resulting loss of dissolved CO_2 raises pH and shifts carbonate speciation toward carbonate ions (CO_3^{2-}), thereby increasing calcite saturation state (Ω). Consequently, warming can enhance the thermodynamic potential for calcite precipitation even in the absence of changes in calcium concentration (Strong and Eadie 1978, Herman and Lorah 1987, Stewart 1988, Hodell et al. 1998, Liptak 2000, Ohlendorf and Sturm 2001). This effect can act synergistically with other biotic and abiotic processes, together promoting elevated pH and higher Ω under warm, productive conditions (Teng et al. 2000). It is also important to recognize that temperature-driven changes in carbonate chemistry may be influenced by seasonal variability in source water composition, including processes governing carbonate dissolution in contributing materials, where factors such as snow cover can limit gas exchange and elevate CO_2, and enhance carbonic acid-driven dissolution.

In addition to its thermodynamic effects, temperature directly influences the intrinsic kinetics of calcite precipitation. Surface-controlled processes governing nucleation and crystal growth generally accelerate with increasing temperature as activation energy barriers are reduced and molecular mobility increases (Teng et al. 2000, Mejri et al. 2014). Experimental and surface-based studies demonstrate that, at a given saturation state, calcite growth rates often increase with temperature, although the magnitude of this response depends on the dominant growth mechanism, surface structure, and solution chemistry (Teng et al. 2000, Mejri et al. 2014).

Importantly, temperature also modifies the effectiveness of kinetic inhibitors and impurities, complicating simple expectations of faster precipitation under warmer conditions (Wasylenki et al. 2005, Bergwerff and van Paassen 2021). In natural freshwater systems where such inhibitors are commonly present, warming does not necessarily result in proportionally faster precipitation. Instead, temperature may alter which surface processes are rate-limiting, shift dominant growth regimes, or change impurity incorporation behaviour, leading to non-linear or even counterintuitive responses (Balci et al. 2018).

Given the potential for temperature to simultaneously influence equilibrium chemistry, surface kinetics, inhibition processes, and physical transport, changes in calcite precipitation cannot be attributed to temperature in isolation. Robust interpretation of temperature effects on calcite precipitation therefore requires integrated consideration of pH, dissolved inorganic carbon, calcium concentration, CO_2 exchange, and hydrodynamic conditions, rather than treating temperature as an independent predictor (Lebrón and Suárez 1998).

Climate change is expected to add further complexity through projected regional warming and shifts in hydrograph characteristics. Rising air and water temperatures, earlier spring freshets, reduced summer baseflows, and more frequent or prolonged low-flow periods will modify stream thermal regimes and flow patterns in ways that alter both the timing and intensity of calcite precipitation. The net influence of climate change on calcite dynamics is therefore highly context-dependent, arising from interactions among temperature, discharge regime, and gas exchange processes. This underscores the importance of interpreting long-term calcite trends within an integrated hydroclimatic framework.

pH Mechanisms

pH serves as one of the most influential controls on calcite precipitation, acting as a key regulator of carbon dynamics in freshwater systems (Khan et al. 2020). In lotic environments, pH governs carbonate speciation (the distribution of dissolved carbon forms such as CO_2, HCO_3^-, and CO_3^{2-}), the saturation state (Ω), and the kinetics of mineral nucleation (initial crystal formation) and growth. Given that pH can fluctuate rapidly due to CO_2 exchange, biological activity (e.g., photosynthesis or respiration), and hydrodynamic conditions (e.g., turbulence), it functions as the proximate driver connecting physical and biological processes to calcite precipitation in these dynamic settings (Ruiz-Agudo et al. 2011, Gebrehiwet et al. 2012, Khan et al. 2020, Khan et al. 2021, Many et al. 2024).

The primary effect of pH on calcite precipitation stems from its control over dissolved inorganic carbon speciation in the freshwater carbonate system. As pH rises, carbonate equilibria shift from dissolved CO_2 and bicarbonate (HCO_3^-) toward carbonate ions (CO_3^{2-}) (Ruiz-Agudo et al. 2011, Khan et al. 2020). As the calcite saturation state (Ω) directly depends on carbonate ion activity, even modest pH increases (typically on the order of ~0.2–0.5 units) can lead to substantial rises in Ω due to this non-linear relationship (Neal et al. 2002). Although numerically small, even these small shifts can substantially alter carbonate equilibria and produce disproportionately large increases in calcite saturation state (Ω) and thereby promote precipitation (Neal et al. 2002). This explains why calcite precipitation is often associated with localized or transient pH elevations rather than gradual changes in calcium concentration (Lorah and Herman 1988, Teng et al. 2000).

Beyond influencing saturation state, pH also affects calcite precipitation by altering nucleation thresholds and crystal growth rates. Even when $\Omega > 1$ (indicating supersaturation), precipitation may not occur if kinetic barriers to nucleation are not overcome. Higher pH reduces these barriers by increasing carbonate availability, increasing the likelihood of successful ion-ion interactions at surfaces (Gebrehiwet et al. 2012). Consequently, nucleation thresholds are often overcome during rapid pH spikes, such as those from daytime photosynthesis or in zones of

intense CO_2 degassing associated with turbulent flow, leading to episodic precipitation events (Dreybrodt et al. 1992).

Experimental studies further reveal that calcite precipitation rates can vary significantly at constant saturation state when pH is adjusted, reflecting changes in carbonate ion activity and surface reaction pathways (Teng et al. 2000). This underscores that pH is an independent kinetic control that influences when and where calcite precipitation initiates (Gebrehiwet et al. 2012).

Additionally, pH modulates the effectiveness of kinetic inhibitors that suppress calcite precipitation (Lebrón and Suárez 1996). For example, experimental studies show that phosphate inhibition of calcite precipitation is more effective at lower pH, where carbonate availability is reduced and competitive adsorption at growth sites is enhanced (Reddy and Hoch 2001, Hoch et al. 2000). Similarly, dissolved organic matter can alter surface charge and hydration in a pH dependent manner, further complicating precipitation behaviour in natural waters. These interactions help explain why calcite precipitation is commonly suppressed in organic rich streams, even under conditions of apparent supersaturation (Lebrón and Suárez 1998).

In flowing freshwater systems, pH varies dynamically over diel, seasonal, and spatial scales, positioning it as a central variable for calcite precipitation (Stewart 1988, Cicerone et al. 1999, Escoffier et al. 2023). Daytime photosynthesis elevates pH by consuming CO_2, while nighttime respiration lowers pH through CO_2 production; turbulence-driven CO_2 degassing can also elevate pH, resulting in changes over short distances (Herman and Lorah 1987, Lorah and Herman 1988, Dreybrodt et al. 1992). As a consequence, calcite precipitation in lotic environments tends to be spatially heterogeneous and episodic, occurring preferentially where and when pH increases sufficiently to elevate saturation state and overcome kinetic inhibition. This sensitivity helps explain why calcite supersaturation and precipitation frequently develop downstream in turbulent stream reaches, riffles, and cascades, where enhanced gas exchange promotes CO_2 loss to the atmosphere (Lorah and Herman 1988).

Taken together, the literature demonstrates that pH acts as both a thermodynamic and kinetic control on calcite precipitation, by regulating carbonate speciation, nucleation thresholds, growth mechanisms, and inhibitor effectiveness. Consequently, interpretation of calcite precipitation in lotic environments requires consideration of pH dynamics alongside other interacting factors including temperature, hydrodynamic conditions, and solution chemistry.

Primary Productivity

Primary productivity, the biological process by which organisms like algae, macrophytes, periphyton, and cyanobacteria convert sunlight, CO_2, and nutrients into organic matter through photosynthesis, can modulate the thermodynamics and kinetics of calcite precipitation by altering water chemistry (Rupp and Adams 1981, Dittrich and Obst 2004, Balci et al. 2018, Khan et al. 2021, Escoffier et al. 2023). This modulation primarily occurs through the uptake of dissolved CO_2 during photosynthesis, which raises pH and shifts carbonate speciation toward increased CO_3^{2-} ions, thereby elevating the saturation state (Ω) and promoting precipitation. In productive streams, this biological process can synergistically interact with physical drivers such as turbulence, which enhances CO_2 degassing from the water surface, further amplifying supersaturation and the potential for calcite precipitation. Conversely, respiration, the metabolic process where organisms break down organic matter to release energy, releases CO_2 back into solution, lowering pH and reducing Ω, thereby favoring calcite dissolution or suppressing precipitation (Liptak 2000, Deocampo 2010, Khan et al. 2020, Many et al. 2024).

The balance between photosynthesis and respiration often results in diel cycles in pH and saturation state in productive streams, with daytime peaks in productivity driving precipitation and nighttime respiration potentially leading to partial dissolution (Cicerone et al. 1999, Escoffier et al. 2023). These cycles can also manifest over short spatial scales, such as in riffles or pools, where variations in flow velocity, light exposure, and nutrient availability influence productivity gradients and localized calcite formation.

Seasonal warming, especially during summer low-flow periods, commonly coincides with enhanced photosynthetic activity, diel pH elevation, and increased gas exchange efficiency, collectively promoting higher saturation states and increasing the likelihood of calcite precipitation (Cicerone et al. 1999, Escoffier et al. 2023). The role of aquatic metabolism in calcite precipitation implies that changes in community structure and ecosystem processes, which affect primary productivity, can also influence saturation and precipitation of calcite, in addition to altering water chemistry (Cicerone et al. 1999).

Periphyton and cyanobacteria are particularly important drivers of calcite precipitation in lotic systems, as they are widespread, metabolically active, provide abundant heterogeneous nucleation sites (surfaces for crystal initiation), and are closely coupled to mineral substrates (Balci et al. 2018, Dittrich and Obst 2004). Their photosynthetic activity can elevate pH at the water-substrate interface, creating microscale chemical conditions favorable for calcite nucleation and growth, often resulting in biomineralized structures like tufa deposits or encrustations on streambeds and macrophytes (Dittrich and Obst 2004).

Collectively, these processes demonstrate that primary productivity influences calcite precipitation primarily through indirect geochemical pathways, rather than through direct biological mineralization (Dreybrodt et al. 1997). By regulating CO_2 availability, pH, and carbonate speciation, and by providing reactive surfaces for nucleation, photosynthetic organisms play a contributing role in determining when and where calcite precipitation occurs in freshwater, particularly in lotic environments where biological and physical controls are tightly coupled.

Role of Dissolved Impurities and Kinetic Inhibitors

The chemical composition of lotic systems reflects the integrated influence of multiple natural and anthropogenic processes operating across their contributing catchments. Stream and river chemistry is shaped by mineral dissolution and precipitation, oxidation–reduction reactions, ion exchange, and biological activity, as well as by terrestrial (e.g., groundwater and surface runoff from upland source areas) and atmospheric inputs delivered through the drainage network (Thomas 2007). Because lotic systems are open, dynamic, and connected to their surrounding landscapes, their chemical signatures often vary spatially and temporally in response to hydrologic conditions, land use, and climatic factors (Stendera et al. 2012).

Within this chemical context, certain dissolved ions and organic compounds can act as kinetic inhibitors to calcite precipitation, significantly reducing crystal nucleation and growth rates, even when the water is supersaturated ($\Omega > 1$). Calcite precipitation can also sequester and remove these ions from solution, which in the case of nutrients can impact primary productivity (Vereshchagin et al. 2023). Although Magnesium and Phosphate are discussed in more detail below, a wide range of dissolved ions and organic additives are known to influence calcite precipitation kinetics (Vereshchagin et al. 2023). The effects of these impurities on nucleation thresholds, growth mechanisms, and crystal morphology have attracted sustained research attention for decades and remain central to understanding carbonate mineralization in natural freshwater systems (Vereshchagin et al. 2023).

Magnesium ions (Mg^{2+}) are one of the strongest and most studied inhibitors of calcite precipitation (Nyirő-Kósa et al. 2018, Davis et al. 2000, Wasylenki et al. 2005, Morse et al. 2007, Deocampo 2010, Xu and Higgins 2011, Vereshchagin et al. 2023, Santos et al. 2023). They work by adsorbing (sticking) to the crystal surface, blocking sites where new ions would attach, and sometimes incorporating into the calcite structure, which makes the mineral less stable and slows growth. Even low concentrations of Mg^{2+} can reduce dissolution and growth rates. This inhibition is more pronounced when sulfate (SO_4^{2-}), another kinetic inhibitor, is also present and they form ion pairs ($MgSO_4$) that enhance the blocking effect on calcite surfaces (Nielsen et al. 2016). In natural streams, high Mg^{2+} from dolomite-rich rocks can prevent rapid calcite formation, explaining why some supersaturated waters don't precipitate much calcite.

Phosphate ions (PO_4^{3-}, derived from phosphorus) are effective kinetic inhibitors of calcite precipitation. Numerous experimental studies have demonstrated that even low concentrations of phosphate can significantly reduce calcite nucleation and growth rates by blocking reactive sites on calcite surfaces (Reddy and Nancollas 1971, Ishikawa and Ichikuni 1981, Giannimaras and Koutsoukos 1987, Lebrón and Suárez 1998, Lin and Singer 2006). This surface-site blocking increases the effective kinetic barrier to both nucleation and subsequent crystal growth, allowing waters to remain supersaturated with respect to calcite without precipitation.

Phosphorus is an essential element for all living organisms, forming key components of nucleic acids, phospholipid membranes, and energy transfer molecules like ATP. In aquatic ecosystems its availability often determines ecosystem dynamics (Cicerone et al. 1999, Elser et al. 2007, Corman 2025). When scarce, phosphorus availability can limit biological growth by constraining photosynthesis in primary producers thereby reducing overall primary productivity (Elser et al. 2007, Corman 2025). When abundant, phosphorus availability can cause eutrophication characterized by excessive algal blooms, oxygen depletion and habitat degradation (Lin and Singer 2006, Smith and Schindler 2009, Corman 2025). Given the fundamental role of phosphorus in aquatic ecosystems, its co-precipitation dynamics with calcium carbonate ($CaCO_3$) are particularly relevant. The effect of calcite precipitation on freshwater phosphorus dynamics has been well studied (Ishikawa and Ichikuni 1981, Hodell et al. 1998, Liptak 2000, Corman 2025). Calcite and other solid-phase carbonates can reduce the availability of potentially limiting nutrients such as phosphorus and iron, biologically active organic compounds (vitamins, amino acids, fatty acids, and so on), and potentially toxic trace metals (Cicerone et al. 1999). Calcite precipitation can influence nutrient dynamics by sequestering bioavailable phosphorus through adsorption onto crystal surfaces or co-precipitation with calcium-bearing phosphate phases, thereby potentially reducing dissolved phosphorus concentrations and exerting negative feedback on primary productivity (Corman 2025). However, phosphorus retention associated with calcite is not necessarily permanent. Adsorbed or co-precipitated phosphate can be remobilized during periods of calcite dissolution, which may occur in response to declining pH, elevated CO_2 concentrations, temperature-driven changes in solubility, or shifts in hydrologic conditions that alter saturation state. Consequently, phosphorus–carbonate interactions in lotic systems are dynamic, with sequestration and release occurring under different chemical regimes.

At the same time, elevated pH under alkaline conditions can enhance primary production by increasing the availability of bicarbonate (HCO_3^-) as an inorganic carbon source for photosynthesis (Lay and Ward 1987, Lebrón and Suárez 1998, Almodóvar et al. 2006, Kaushal et al. 2013). These contrasting processes underscore the context-dependent nature of carbonate–nutrient interactions in streams: calcite precipitation may temporarily reduce phosphorus availability, while concurrent shifts in carbonate chemistry can stimulate autotrophic productivity. The net ecological outcome therefore depends on the balance among carbonate saturation state, hydrologic conditions, biological uptake, and dissolution dynamics.

In lotic systems, the dual role of phosphate as both a nutrient and a kinetic inhibitor of calcite precipitation highlights the interdependent feedback between biogeochemical cycling and mineral precipitation processes. Phosphate can suppress calcite precipitation even under conditions of apparent supersaturation, while calcite precipitation can, in turn, reduce phosphorus availability to primary producers. This feedback has the potential to influence nutrient dynamics, food-web structure, and ecosystem health in streams and rivers. Accordingly, understanding these interactions is essential for interpreting calcite precipitation patterns and for assessing the broader ecological consequences of carbonate mineralization in lotic systems and their effects on nutrient cycling, food webs, and ecosystem health (Jeziorski et al. 2008, Weyhenmeyer et al. 2019, Corman 2025).

Overall, calcite precipitation in lotic environments is strongly influenced by dissolved impurities. Interactions between inhibitors, mineral surfaces, and aqueous ions can significantly reduce precipitation rates and promote spatially heterogeneous or patchy deposition. Understanding the role of such inhibitors is therefore critical for interpreting variability in calcite accumulation and for assessing how carbonate precipitation may alter streambed structure and habitat conditions.

Hydrological Context

Lotic systems are inherently dynamic, with hydrologic and geomorphic conditions that vary over space and time. Fluctuations in discharge, channel morphology, and flow regime can rapidly alter stream chemistry, causing rivers to shift between conditions that favor calcite precipitation and those that suppress it, sometimes within the same reach on short timescales.

Hydrodynamic conditions play a critical role in mediating these chemical responses, primarily through their influence on air–water gas exchange. In many carbonate-precipitating streams, CO_2 degassing is the dominant physical mechanism driving increases in pH and calcite saturation state (Ω). Turbulent flow accelerates gas exchange, promoting rapid CO_2 evasion from the water column, shifting carbonate speciation toward CO_3^{2-}, elevating Ω, and thereby increasing the potential for calcite precipitation (Herman and Lorah 1987, Herman and Lorah 1988, Lorah and Herman 1988, Dreybrodt et al. 1992, Zhang et al. 2021).

The efficiency of CO_2 exchange is quantified by the gas transfer velocity (k), which integrates the effects of turbulence, surface renewal, and channel morphology (Raymond et al. 2012, Marx et al. 2017, Rocher-Ros et al. 2019). Values of k vary widely within and among streams and generally increase with discharge and channel slope (Raymond et al. 2012, Marx et al. 2017, Zhang et al. 2021). Consequently, periods of elevated flow can either promote or inhibit calcite precipitation, depending on whether enhanced CO_2 degassing and mixing outweigh the counteracting effects of dilution and reduced residence time (Herman and Lorah 1987, Dreybrodt et al. 1992).

Overall, the hydrogeochemical context of lotic systems demonstrates that calcite precipitation is a highly dynamic process that responds to flow regime, seasonality, and stream hydraulics. Turbulence and gas exchange act as key amplifiers of supersaturation, interacting with biological processes, temperature, pH, kinetic inhibition, and other factors to produce spatially heterogeneous patterns of carbonate deposition.

Calcite Precipitation Gradients

Calcite precipitation downstream of anthropogenic sources, such as mine waste-rock spoils, is highly site-specific due to substantial variations in source chemistry, evolving hydrogeochemical conditions along the flow path, and other interacting influences (Brierley 1994, Dreybrodt et al. 1997, Nordstrom et al. 2015, Gadikota 2021, Cravotta 2021). Drainage from waste rock piles at several mines in BC exhibit wide variability, influenced by local geology, weathering climate,

mineralogy, geochemistry, hydrogeology, as well as diurnal and seasonal fluctuations (Brierley 1994). Predicting drainage quantity and quality is thus challenging and context-dependent (Brierley 1994, Webb and Sasowsky 1994, Balci et al. 2018, Vriens et al. 2020). More broadly, mine drainage systems can produce waters ranging from acidic to neutral or alkaline, with corresponding differences in concentrations of dissolved calcium (Ca^{2+}), carbonate species, and CO_2 (Brierley 1994, Nordstrom et al. 2015, Balci et al. 2018). As waters flow downstream, changes in stream chemistry and hydrology can either promote or suppress calcite precipitation (Brierley 1994, Nordstrom et al. 2015, Balci et al. 2018).

Abongwa et al. (2016) examined carbonate precipitation from neutral mine drainage discharges into a series of stilling ponds, as it evolved over a distance of about 562 m during interaction with atmospheric CO_2. Site-specific conditions resulted in pH increasing spatially along the flow path due to CO_2 outgassing, thereby promoting calcite precipitation and causing a decrease in Ca^{2+} concentrations. Abongwa et al. (2016) estimated that over the 562 m distance, 20% of the carbon was lost to CO_2 outgassing, 12% was sequestered as calcite precipitate, and 68% was exported further downstream. However, the hydraulic and geochemical conditions associated with ponded systems differ from those in flowing stream channels, and thus the observed precipitation dynamics may not be directly transferable to lotic environments.

Despite such observations, the literature remains limited when it comes to quantitative, process-based characterisation of calcite precipitation gradients, particularly in flowing (lotic) systems. While systems in closer proximity to a source may exhibit higher calcite saturation states and increased thermodynamic potential for precipitation, supersaturation alone does not ensure that precipitation will occur. Therefore, precipitation gradients are likely not reliably predictable solely as a function of distance from the source, as distance is not a mechanistic control but rather a proxy for multiple interacting dynamic processes that vary across space and time. Saturation state (Ω), pH, CO_2 degassing rates, turbulence, dilution, kinetic inhibitors, temperature, and primary productivity can all fluctuate spatially and temporally. The cumulative impact of these variables can result in reach-specific and process-driven gradients which can vary widely across streams and watersheds.

Effective prediction requires integrated, site-specific modeling that accounts for both thermodynamic and kinetic controls on carbonate dynamics. Nevertheless, predictive reliability remains constrained by data limitations, inherent uncertainties, and scale-dependent processes.

Impacts of Calcite on Salmonids and their Habitat

Water Quality/Chemical and Food Web Impacts

The thermodynamic conditions for calcium carbonate precipitation are characterized by a slightly elevated, but stable/buffered pH, and dynamic concentrations of carbonic acid, CO_2, and calcium. One significant consequence of the precipitation dynamic is a co-precipitation of orthophosphate, potentially limiting photosynthetic production and the associated evolution of O_2 (in the form of dissolved oxygen (DO)). Factors that can modify the extent of this phenomenon include water temperature, flow and aeration, as well as ambient nutrient status beyond calcite-specific influences. For example, broader changes in water chemistry associated with mining activities in the Elk Valley (e.g., phosphate, nitrate, sulfate, and other constituents) might interact with calcite-specific processes such as phosphorus co-precipitation, influencing overall nutrient dynamics. As well, the formation of periphyton-calcification complexes in lotic systems could be influenced by phosphate and other nutrient changes, forming localized trophic dynamics capable of influencing both food and oxygen availability. *Didymosphenia geminata* (Lyngbye; Schmidt) is a known component of periphyton and associated biogenic crusts in this area (Larratt and Self 2021), and has an irregular response to phosphorus reduction where its filamentous growth form (and hence photosynthetic productivity) is increased, especially in

stoichiometric conditions of high N:P ratios. Blooms of this species can produce excessive filamentous growth and have been suspected to be deleterious to fish through its influence on shifting invertebrate production from large macroinvertebrates to midge species, by simplifying physical heterogeneity, reducing availability of free oxygen when eutrophication conditions emerge, and by congesting potential spawning locations.

The prevalence of cyanobacteria is also an indication that complicated producer-consumer effects might be at play (Kleintech et al. 2017). Cyanobacterial proliferation has been cited as a symptom of phosphorous depletion and related macrophyte reductions (Corman 2025). Cyanobacteria are present in the biogenic matts in Elk watershed and explored as a possible stressor for Westslope Cutthroat Trout, though with no conclusion to support detrimental effects (Larratt and Self 2021).

Physical Impacts

The suite of suspected physical processes affecting fish stem from the escalating impact of deposition as it reaches concretion either as fully mineralized hardpan on streambeds, or the expression of tufa-like scale forms surrounding steeper stream gradients.

Literature documenting calcite-specific impacts to fish and fish habitat is limited, and dominated by (valuable) hypothetical discussion in consultant reporting for mining operations (e.g., Barret et al. 2016, Cope et al. (2016, 2018, 2020), Hocking et al. 2022, Larratt and Self 2021). Data in these studies are field-based observations with some actual fish observations but no experimental controls. Still, they represent a body of developed thinking on the subject, basing hypothetical discussions on a strong body of literature relating analogous physical and biological stresses to salmonid responses.

The most subtle form of deposition, a veneer of calcite on pre-existing riverbed cobbles and gravels, is likely also the most widespread. At the localized scale (e.g., mesohabitat to microhabitat scale within the stream channel) of consideration, no negative effects to fish have been attributed to this form (though see concerns proposed later on regarding landscape-level nutrient impacts). The formation of any of the pebble-like calcite structures (clasts, oolites, oncoids, etc.) likewise has no attributed impacts, except where they can be seen as contributing to further concretion reflecting a balance between calcite precipitation and physical reworking processes such as abrasion and sediment transport.

Where particles begin to bind to one another with calcite acting as a cement, a series of suspected impacts have been proposed:

Simplification of existing riverbed structure

Natural riverbeds in the Western Cordillera are porous, dynamic, and relatively variable in space and time, being composed of sedimentary and organic materials in a variety of states of decomposition that provide interstitial spacing between fragments. Water and gas exchange with the hyporheic zone is an important feature of this structure and well-documented to provide renewable water quality elements for fish, particularly an ongoing supply of dissolved oxygen. Riverine structure enhances vertical exchange of materials between hyporheic zone, and other river channel elements (e.g., Montgomery and Buffington 1997). Free-moving fragments also provide interstitial space that can provide contained structure for successful development of fish eggs through gas exchange and protection from hydraulic stress, micro-entrapment of organic materials to serve in food web production, rearing and feeding sites for macroinvertebrates, and the prevention of blanket siltation from distribution of fine sediments. Progressive cementation by calcite deposition erodes this structure, binding fragments together, reducing gas exchange (Wright et al. 2018), and potentially exposing surfaces to accumulation of sediments and preventing manipulation by fish that seek to build redds.

Changes to surface rugosity

Structure in lotic habitat is an important feature for a variety of reasons. While rough but mobile sediments form channel structure that fish can move within and manipulate, armoring by calcification can eliminate important vertical elements as previously discussed. This is a type of interstitial simplification, uniting mobile elements and eliminating important textures. In contrast, finer surface texturing as a result of calcite deposition could have different effects.

During a 2025 field visit in the Kootenay region of BC, DFO personnel examined examples of tufa-like concretions, noting horizontally-spanning forms with distinct, rugged surface textures. These tufa deposits can be described as having a scabrous surface, with sharp, angular ridges and projections. In places, the concretion type spanned entire widths of small channels, leading upstream toward strong vertical concretions of the same type at cascades. In general, and especially during low flows, surfaces like this can be expected to impede passage of larger fish. In some cases formations showed phytoclastic character, although the morphology of these deposits varied and likely reflects a balance between calcite precipitation and physical reworking processes such as abrasion and sediment transport.

In its most extreme forms, calcite cementing or concretion can form solid hardpans on river bottoms, simple in broad form, relatively non-porous, hydrologically convective, and generally non-conducive to fish production through the elimination of required habitats to complete life histories. Additionally, concreted structures can be expected to reduce fish passage and migration: tufa concretion at steep cascades form rigid vertical structures that can be expected to challenge fish passage in low water conditions. Pre-calcification flow structures and their functions to fish including riffle-glide-pool exchanges can be expected to deteriorate with increasing levels of calcification and especially where concretion forms. Table 1 highlights proposed calcite effects on typical salmonid life history stages, and notes special cases where impacts could be expected to be unique for focal species Bull Trout, Mountain Whitefish, and Westslope Cutthroat Trout.

Table 1. Proposed calcite effects on salmonid life cycle stages with emphasis on Bull Trout, Mountain Whitefish, and Westslope Cutthroat Trout

Life History Stage	Primary Calcite Mechanism	Physical/Chemical Impact	Biological Consequence	Species specific considerations
Egg	Infilling of Interstitial Space	Reduced hydraulic conductivity; restricted hyporheic exchange	Decreased dissolved oxygen delivery; increased embryo mortality	-
Alevin	Infilling of Interstitial Space	Sealing of the gravel surface; restriction of movement	Entombment within the substrate; accumulation of toxic metabolic wastes; delayed emergence	-
Fry	Microhabitat Degradation	Loss of shallow-water cover and interstitial refugia; shift in prey community	Increased vulnerability to predation and high-flow displacement; reduced survival	Habitat loss may compound Bull Trout interspecific competition

Life History Stage	Primary Calcite Mechanism	Physical/Chemical Impact	Biological Consequence	Species specific considerations
Parr	Habitat Simplification	Permanent loss of overwintering refuge; shift in prey community	Reduced growth rates due to loss of macroinvertebrate prey (EPT); Movement barrier	Whitefish subject to reduction in substrate feeding
Adult	Substrate Concretion	Hardening of spawning gravels; loss of mobile substrate; Increased hydrological conductivity; Movement barrier; shift in prey community and habitat distribution	Reduced redd density; mechanical impedance of excavation; displacement to marginal habitat; Barrier to migration; egg displacement	Whitefish subject to reduction in substrate feeding; Bull Trout habitat / inter-population fragmentation and restricted access to smaller tributaries during late summer and fall low-flow migration periods

Potential Effects of Calcite Precipitation on Sediment Transport

In alluvial streams, channel morphology and aquatic habitat are maintained through continuous cycles of erosion, sediment transport, and deposition. These processes regulate sediment mobility, grain-size distribution, and scour–fill dynamics, thereby governing the formation and persistence of key habitat features (Harrison et al. 2011, Wohl et al. 2015). For salmonids and other aquatic organisms, sediment mobility is fundamental to maintaining clean, oxygenated spawning gravels, limiting fine-sediment accumulation during incubation, and creating dynamic refuge and foraging habitats across life stages (Lisle and Lewis 1992, Cienciala and Hassan 2013, Schindler Wildhaber et al. 2014). Sustained reductions in sediment mobility therefore impair the geomorphic processes that underpin ecological function. In this way, sediment transport provides a direct mechanistic link between fluvial dynamics and habitat quality, such that disruptions to sediment mobility can alter both channel form and biological suitability across multiple life stages.

Calcite precipitation has the potential to disrupt these processes by modifying sediment particle surfaces and cementing adjacent grains, effectively increasing substrate cohesion and resistance to entrainment. Although direct empirical evidence linking calcite precipitation to altered sediment transport remains limited, the mechanistic basis for such effects is well established. Where calcite forms cemented or semi-cemented layers that persist under local flow and sediment transport conditions, erosion and deposition processes may be locally suppressed, reducing substrate turnover and limiting the recruitment of new, mobile sediments. This can produce spatially heterogeneous zones of reduced sediment mobility and localized loss of spawning and rearing habitat, even where adjacent channel areas remain fully alluvial. However, the ecological effect of such features depends on their extent and whether they alter habitat continuity or fish passage. In some settings, increased substrate cohesion and localized bed hardening may also contribute to channel-scale adjustments, such as the development of grade controls or shifts in lateral channel mobility, depending on flow regime and geomorphic context.

Pathways of Effects

Pathways of Effects (PoE) are a way of standardizing communication about the relationships between works, undertakings, and activities (WUA; under the habitat protection provisions of the *Fisheries Act*), the stressors generated by WUA, and the resulting impacts on fish or fish habitat (endpoints). PoE diagrams are used by DFO staff in various stages of regulatory review.

Simplified diagrams are currently used (Brownscombe and Smokorowski 2021), though more elaborate schemes are proposed in DFO (2014). Early use of PoE diagrams was circa 2005 and supported an ecosystem-based management (EBM) framework and planning process for regulatory actions, as well as a risk management framework. Eventually, 20 different diagrams had been produced and accepted for national use, describing an array of WUA and associated impacts. These were subsequently collapsed to four nationally endorsed diagrams (Brownscombe and Smokorowski 2021).

Of these four, the diagram for land-based effects is pertinent here (Figure 1). Mine spoils and water flowing through them to produce downstream calcification potential can be generalized as an alteration of land drainage patterns (stressor 5 from left in Figure 1). While this approach can help to communicate the fundamental context in which an impact is being considered, the simplified models have a tendency to underrepresent real-world complexity. Brownscombe and Smokorowski (2021) note that diagrams more closely representing ecosystem models with an enhanced number of pathways operating in multiple directions might be necessary to properly approach modern regulatory problems like cumulative effects. As well, earlier efforts to use PoE for planning and EBM considerations (DFO 2014) indicate an original intention to use them in a broad and detailed fashion.

A proposed diagram for the effects of mine-related aquatic calcification is given in Figure 2 and shows how adapting a national model to a specialized context can be useful. While the diagram isn't overly prescriptive in its representation of the ecosystem in which it is set, it does help place a number of complicated sequences into a pictorial guide that can quickly communicate a suite of regulatory concerns.

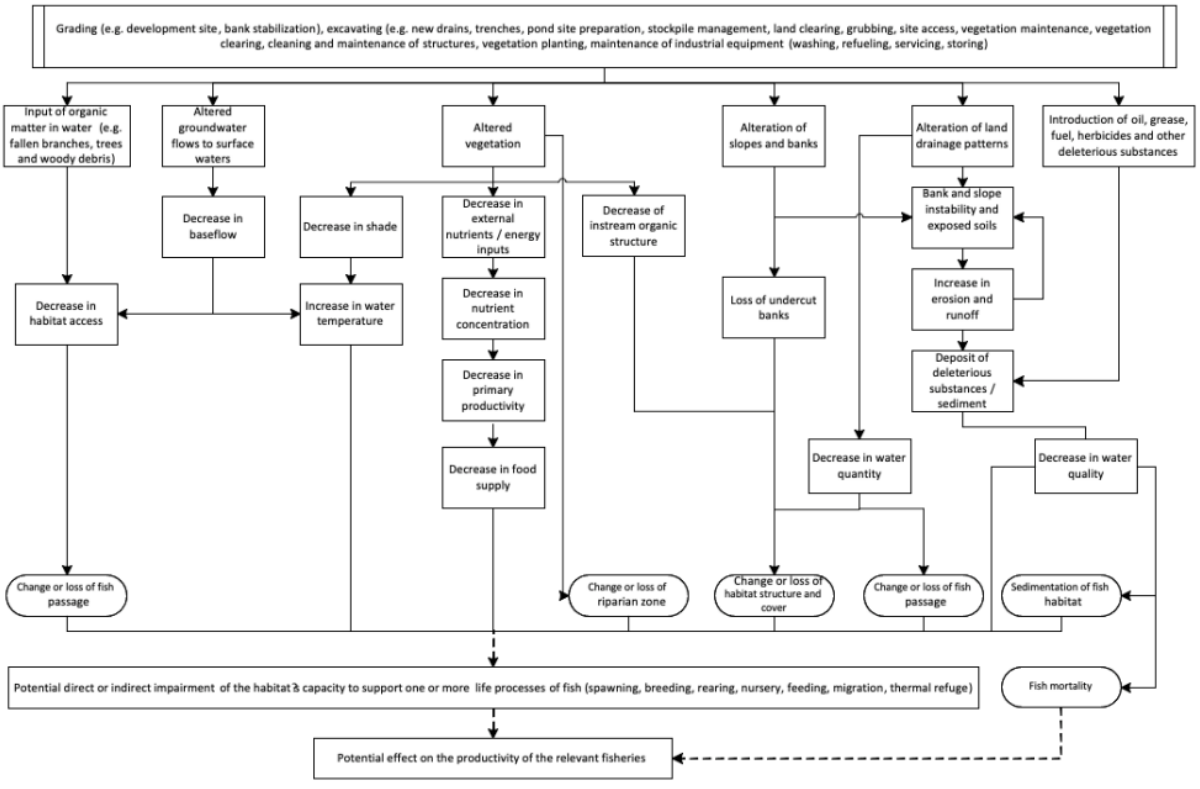


Figure 1. National PoE diagram for land-based WUA (taken from Brownscombe and Smokorowski 2021).

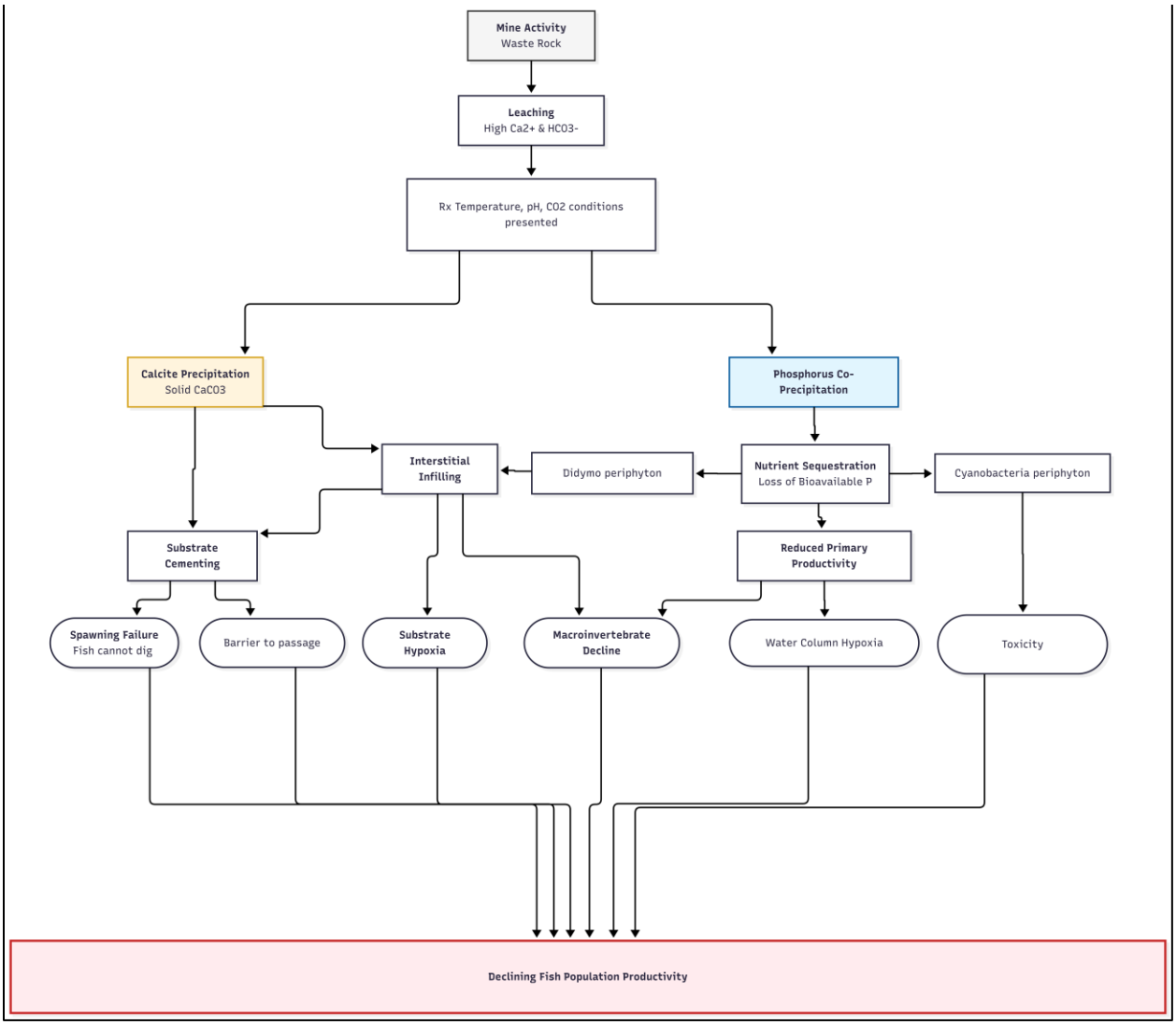


Figure 2. A proposed PoE diagram for effects of mining-related calcite precipitation on fish habitat. Square boxes represent stressors, bubbles represent endpoints, individual lines represent cause and effect relationships between stressors, and the downward trending set of boxes and lines together represent a PoE (after Brownscombe and Smokorowski 2021).

Brownscombe and Smokorowski (2021) further use the diagrams to communicate strength of evidence for the various pathways given in the national models they reviewed. This is an important consideration in regulatory approaches, and one that is not often made explicit. The categories of strength they invoke are: I. Strong, direct basis of support in scientific literature linking the pressure pathway to the endpoint, including numerous, robust studies and/or syntheses or meta-analyses, II. Direct basis of support in scientific literature linking the pressure pathway to the endpoint based on at least one robust study, III. Theoretical basis of support linking the pressure pathway to the endpoint, but no direct scientific evidence, and IV. No support found.

Components of Figure 2 that depict calcification processes leading to concretion and interstitial filling are considered well established and have an evidence ranking of I, with several independent studies supporting the reaction mechanics and surface precipitation effects in

surface waters. Below we focus on pathway components that lead to effects on fish and fish habitat.

Calcite Precipitation>Substrate Concretion> Spawning Failure (II)

There is one data set collected and reported for this pathway, which was subject to an internal peer review, having been reported as a consultant report (Hocking et al. 2022). This was a field observation study reporting correlational data in the form of observations and modeled responses indicating significant declines in the occurrence of spawning redds of Westslope Cutthroat Trout with increasing levels of mining-related substrate concretion. Because of similarities in spawning requirements among salmonids, the result can be considered strongly relevant to other salmonids. Broadcast spawners like Mountain Whitefish require similar resources, though how they would respond to surface concretion during spawning when compared to substrate spawners is unclear.

Substrate Concretion> Barrier to Fish Passage (III)

Calcite concretion as a barrier to fish passage has not been explicitly studied, though there are relatable studies from which negative effects can be expected. Scabrous surfaces in concrete structures designed to conduct fish passage are known to impede travel and to cause ventral wounding (Cox et al. 2003). Hydraulic conductivity (fast flows) in these same environments and in rivers will also impede fish passage, where baffles and other structures are implemented to create turbulence and reduce flow strength (Savoie et al. 2002). Lastly, concretion formation happens more frequently at cascades where reaction conditions are also more likely (Lahrichi et al. 2026). Artificial concreted barriers of various sizes are known to impede fish passage, and even relatively small in-stream features can influence movement and population structure under certain conditions (Wells et al. 2024). The extent to which a feature functions as a barrier depends on species-specific swimming capabilities (e.g., burst speed, jump height) and local hydraulic conditions, including pool depth, approach velocity, and barrier geometry.

Calcite Precipitation>Interstitial Filling>Substrate Hypoxia (II)

Interstitial filling resulting from calcite precipitation within the substrate (e.g., infilling and coating of existing pore spaces) is observable in the field where calcite precipitation occurs (Kuchapski and Rasmusen 2015), and is a logical precursor to concretion. The role this type of sedimentation plays with fish has been assumed from logical extension of more established studies about effects of other sediment on fish, especially for dissolved oxygen, where sediments restrict gas exchange and oxygen supply. Wright et al. (2018) examined dissolved oxygen in a dedicated study of field observations with various levels of calcite sediment and at various hyporheic depths. Again the study is not externally peer-reviewed and presents correlational data. They concluded that calcite and dissolved oxygen could be negatively correlated. However, this relationship reflects reductions in dissolved oxygen within the interstitial (subsurface) environment of the substrate, rather than the overlying water column, thereby potentially limiting oxygen availability within redds and other subsurface habitats. In their measurements, the strongest reductions in dissolved oxygen occurred at depths deeper than those typically excavated by Westslope Cutthroat Trout during redd construction. Therefore, while the results suggest that calcite-associated interstitial filling may reduce subsurface oxygen availability, the direct relevance of those observations to WCT egg and alevin incubation environments remains uncertain.

Calcite Precipitation>Interstitial Filling>Macroinvertebrate Decline (I)

Macroinvertebrate association to interstitial filling is the most supported line of evidence in Figure 2. Kuchapski and Rasmussen (2015) studied the issue directly at two sites in the Canadian Rockies and although they didn't specifically study interstitial filling they do provide

anecdotal comment on why it might be one of the factors responsible for the effects calcite has on aquatic macroinvertebrates that aren't favorable to fish diets (reduction in burrowing habit). A similar approach conducted at that time by Barrett et al. (2016) showed similar results and especially that concretion is associated with and might be affecting abundance of important prey items like mayflies, and otherwise shifting the species and family composition of invertebrate communities in ways that could negatively affect insectivorous fish. Many other studies have examined the importance of interstitial space in macroinvertebrate abundance and diversity with similar conclusions (e.g., Natsumeda and Iguchi 2019, Bylak and Kukula 2022). These localized changes in macroinvertebrate abundance and composition also have the potential to influence downstream productivity, as reductions in invertebrate production and altered hydraulic conditions could reduce drift and the downstream transport of prey resources, with potential implications for food availability in downstream reaches.

Phosphorous Co-precipitation>Nutrient Sequestration>*Didymosphina*>Interstitial Filling (III)

The suggestion that this pathway could be important in surface-mined landscapes is novel. As a pathway specific to calcite, this sequence has not been specifically studied, though there is published support for each of its steps. Phosphorous co-precipitation with calcite is well known, though its exact fate in being adsorbed and immediately released or sequestered in mineralization or other form depends on local conditions. However, concurrent calcite formation and phosphorous deficiency does occur (Corman 2025). For most aquatic biota phosphorous is a limiting nutrient and its deficiency will reduce growth. *Didysmosphina geminata* (Didymo), a documented inhabitant of biogenic calcite crusts in the Rocky Mountains (Larratt and Self 2021), will respond by producing a filamentous form that grows into thick mats on stream substrates. Specifically, this can be induced by a high N:P stoichiometric ratio. In its filamentous form Didymo can be a threat to substrate spawners through interstitial filling and impacts to other fish through changes to macroinvertebrate fauna (Root and O'Reilly 2012).

Phosphorous Co-precipitation>Nutrient Sequestration>Reduced Primary Productivity> Macroinvertebrate Decline (III)

Corman (2016) provides experimental evidence that phosphorous co-precipitation and subsequent sequestration can limit primary productivity in small streams. Relationships of primary productivity to macroinvertebrate species and community metrics in streams are variable but there are strong observational and experimental cases where the relationship in this pathway is established (e.g., Ferreira et al. 2015, Rosemond 2015).

Phosphorous Co-precipitation>Nutrient Sequestration>Reduced Primary Productivity> Water column Hypoxia (III)

While hypoxic hyporheic conditions have been associated with calcite (Wright et al. 2018), there are no data that suggest the water column in the systems under discussion is hypoxic. Still, this is a viable pathway that practitioners should be aware of and in the literature it is demonstrated simply as a deficit of photosynthetically generated oxygen compared to respiratory consumption (e.g., Diamond et al. 2023, Diamond et al. 2021).

Phosphorous Co-precipitation>Nutrient Sequestration>Cyanobacteria> Toxicity (III)

This is another pathway that has been proposed and hypothetically discussed (Larratt and Self 2021), based on known occurrence of cyanobacteria in biogenic mats studied in the Elk Valley, but with no evidence of effect. Nutrient limitation of phosphorous (and possible stoichiometric amplification of N:P) in generating biogenic mats that include both Didymo and cyanobacterial species is something that is supported in literature and could be an important landscape consequence of ongoing calcification.

A Note About Breaking Pathways

Although seldom promoted in literature on PoE, practitioners also know that pathways are represented as cause-and-effect sequences that can be 'broken'. The intent is to represent opportunities for practical intervention to alter the course of a sequence leading to a deleterious endpoint. These can be preventative intervention, or reactive mitigation. Anti-scalant solutions currently used to prevent further calcite are an intervention between leachate development and formation of reaction conditions (between two uppermost stressor boxes in Figure 2), thereby breaking the entire pathway. The higher up in the pathway a break can be made, the more dramatic will be its consequences to the cascade of effects represented lower in the diagram.

Objective 2: Overview of Calcite Monitoring Methods

The intent of this section is to provide a high-level overview of the calcite monitoring methods implemented under the 2014 and 2025 Elk Valley Water Quality Plans, to the extent necessary to support the objectives of this review. Comprehensive descriptions of monitoring protocols and methodological details are well documented in the 2014 Elk Valley Water Quality Plan and Annex J.1 (EVWQP 2014), the 2025 Elk Valley Water Quality Plan (EVWQP 2025), and technical reports such as Hocking et al. (2020, 2021, 2022), McCabe and Robinson (2020), Zathey et al. (2021), Smit and Robinson (2023, 2024), and Smit et al. 2025.

Summary of the Regulatory and Historical Context

The Elk Valley, located in southeastern BC, Canada, holds substantial economic, social, cultural, and ecological value. Coal mining has been a cornerstone of the region since 1898, with operations expanding significantly over time to meet global demand for high quality metallurgical (coking) coal. However, the growth and expansion in the scale of mining operations have resulted in increased generation of waste rock, which is a source of contaminants including selenium, nitrate, sulphate, cadmium, and calcite. Although mitigation measures have been implemented, waste rock remains a persistent source of these substances to aquatic systems.

Calcite accumulation emerged as a specific concern following observations of mineral precipitation and streambed concretion downstream of coal mining operations, raising concerns over potential long-term impacts to aquatic habitat structure and function. While calcite occurs naturally, mining activities can alter geochemical conditions in ways that can increase calcite precipitation and accumulation. However, at the time, scientific understanding of calcite precipitation dynamics in lotic systems and resulting ecological implications remained limited. There was no established regulatory framework, targets, or standardized monitoring methodology for assessing calcite occurrence, accumulation, or biological effects at either local or watershed scales.

Recognition of these concerns led to the issuance of Ministerial Order No. M113-2013 (Order M113) on April 15, 2013 by the BC Minister of Environment. Order M113 required development of an Area Based Management Plan that included the entirety of the Elk Valley watershed, with the objective of improving water quality and guiding future mine development. Notably, Order M113 identified calcite as one of the parameters requiring regional management and required actions to reduce the rate of calcite formation.

In response, the 2014 Elk Valley Water Quality Plan (EVWQP 2014) was developed as an Area Based Management Plan, and approved on November 18, 2014, resulting in *Environmental Management Act* Permit 107517 being issued. Developed with input from stakeholders, the 2014 EVWQP established a framework that, among its multiple objectives, included water quality targets for chemical parameters, including calcite. The 2014 EVWQP further

acknowledged that the long-term target for calcite was interim, reflecting substantial uncertainty in both the mechanistic drivers of calcite precipitation and the relationship between observed calcite accumulation and biological effects. The plan anticipated that the long-term calcite target would be reviewed and refined as additional monitoring data, treatment experience, and aquatic effects information became available.

In July 2024, Ministerial Order No. M232-2024 (Order M232) was issued, requiring amendments to the 2014 EVWQP, and initiating development of the 2025 Elk Valley Water Quality Plan (EVWQP 2025). As part of these amendments Order M232 required a review and update of the calcite target to reflect new scientific information and experience gained since implementation of the 2014 EVWQP.

The resulting 2025 EVWQP, approved on July 30, 2025, amends and replaces the 2014 EVWQP as the updated Area Based Management Plan. Prepared by the BC Ministry of Environment and Parks in response to Order M232, the plan incorporates a revised calcite target and associated recommendations arising from the calcite review (EVWQP 2025).

Overview of the 2014 Elk Valley Water Quality Plan Monitoring Methods

The methods outlined in the 2014 Elk Valley Water Quality Plan (EVWQP 2014) were developed to quantify the spatial extent and relative rate of calcite formation downstream of mining operations, while also supporting evaluation of potential effects on aquatic habitat.

The monitoring program encompassed all mine exposed streams within the Designated Area (i.e., Elk River Watershed) that met the definition of fish habitat under the *Fisheries Act*. To provide comparative context, the 2014 EVWQP also identified a set of reference streams selected based on their anticipated long-term persistence and sufficient separation from existing and reasonably foreseeable mine development. These reference sites were intended to represent background calcite conditions against which mine influenced streams could be interpreted.

Streams were delineated into reaches, representing relatively homogeneous sections with respect to channel morphology, riparian cover, and flow characteristics, and were assumed to exhibit low intra-reach variability with respect to calcite deposition (EVWQP 2014; Annex J.1). Reach boundaries were delineated using existing, previously identified reach breaks derived from multiple sources (EVWQP 2014; Annex J.1). For streams without predetermined reach breaks, a GIS based analysis was conducted to identify significant changes in morphological variables, with reach boundaries subsequently verified or refined through field observations (EVWQP 2014; Annex J.1). To account for inherent variability within reaches, replicate sampling sites were established within each reach to improve the accuracy and reliability of calcite deposition estimates.

Depending on reach length, generally up to three sites were surveyed per reach, with reaches ≥300 m in length typically sampled at three systematically stratified locations corresponding to approximately 25, 50, and 75% of the total reach length. Results from individual sites were averaged to derive a single Calcite Index value per reach, providing information at a spatial resolution considered appropriate for informing management decisions. Monitoring at the habitat or mesohabitat scale (i.e., individual sites within a reach) was considered overly fine for the implementation of calcite mitigation actions (EVWQP 2014).

At the time the monitoring methods were developed, scientific understanding of the mechanisms driving calcite precipitation and the influence of interacting abiotic and biotic factors was limited. In the absence of standardized methods for measuring and monitoring calcite accumulation and streambed concretion, a modified Wolman pebble count (Wolman 1954, EVWQP 2014) was adopted to evaluate the extent of calcite at each site. This approach involved an observer

moving systematically across the sampling area and stopping to randomly select and assess individual substrate particles. Sampling continued until 100 particles with diameters >2 mm (e.g., pebbles) were evaluated using the Calcite Index.

The Calcite Index (CI) was calculated as the sum of two components: calcite presence (Cp), and calcite concretion (Cc), such that CI = Cp + Cc. Calcite presence was scored for each particle as binary (0 = no calcite observed; or 1 = calcite present), with site level Cp values ranging from 0 to 1 based on the proportion of particles exhibiting calcite. Calcite concretion quantified the degree to which particles were cemented into the substrate and was scored as 0 (negligible resistance), 1 (notable resistance but removable), or 2 (immovable or fully concreted). At the site level, Cc values ranged from 0 to 2 and were calculated as the mean concretion score across all particles sampled.

Accordingly, the Calcite Index is expressed on a scale from 0.0 (no calcite observed) to 3.0 (streambed fully concreted). Under the 2014 EVWQP, two management targets were established to support the identification and prioritization of streams for intervention in receiving environments that provide fish habitat or associated ecosystem functions. The long-term target was defined as a Calcite Index (CI) score of ≤0.50, with a 15-year timeline established for achievement. The medium-term target was based on a Calcite Concretion (Cc) score of ≥0.50 and was used to identify more heavily impacted streams requiring more immediate management actions, with a 10-year timeline for achieving this target.

Within the 2014 EVWQP, year-to-year changes in calcite conditions were to be quantified as the annual rate of calcite formation or dissolution. This rate was calculated using changes in the Calcite Index between consecutive monitoring years.

Outside of the 2014 EVWQP, which established the overarching monitoring framework, objectives, and core metrics, several field-based monitoring programs implemented additional methods to improve calcite monitoring and understanding of biological effects, which are discussed in more detail below (e.g., Hocking et al. 2020, 2021, 2022, McCabe and Robinson 2020, Zathey et al. 2021, Smit and Robinson 2023, 2024, Smit et al. 2025).

Overview of the 2025 Elk Valley Water Quality Plan Monitoring Methods

In response to Order M232, the 2025 EVWQP incorporated amendments in addition to recommendations from the calcite review conducted in 2024 (EVWQP 2025). This review represented the first formal re-evaluation of calcite site performance objectives since their establishment in 2014 and drew on emerging scientific understanding, more than a decade of calcite monitoring data, aquatic effects studies, and related research conducted in the Elk Valley.

The review concluded that calcite accumulation had increased across the watershed since 2014 and that the Calcite Index and calcite presence (Cp) metrics were limited in their ability to meaningfully characterize ecological risk or inform effective management (EVWQP 2025). Uncertainty was also identified in the spatial scale and statistical approach used to evaluate compliance with the existing medium- and long-term calcite objectives (EVWQP 2025). Although population level effects on Westslope Cutthroat Trout and benthic invertebrates remain uncertain, available biological effects studies indicated that calcite concretion levels below approximately 0.3 are likely protective of aquatic life (EVWQP 2025). The review further identified that evaluating calcite at the reach scale, rather than at the stream scale, would more accurately capture habitat level impacts (EVWQP 2025).

Collectively, these findings informed a refined approach to calcite management in the 2025 EVWQP. The updated plan shifts emphasis toward calcite concretion as the primary metric for

assessing calcite impacts, and establishes a single calcite target of ≤0.3 intended to be protective of aquatic life. This approach replaces the previous medium and long-term targets and removes specified timelines for target attainment, instead adopting a risk-based prioritization framework. Where calcite concretion exceeds the target, the intent is to limit further accumulation and to implement management actions over time, informed by site-specific risk and feasibility considerations.

Evaluation of the 2025 EVWQP Calcite Monitoring Methods

This section evaluates the calcite monitoring methods described in the 2025 EVWQP to determine which components are suitable for assessing impacts to ecological functions in lotic habitats and to identify gaps and limitations. The overall outcomes, objectives, and targets in the 2025 EVWQP provide a suitable framework for monitoring calcite accumulation, with an appropriate emphasis on calcite concretion as the primary mechanism through which calcite may impair aquatic habitat structure and function.

The calcite review conducted in 2024 (EVWQP 2025) produced a series of evidence-based recommendations that were incorporated into the updated plan and represent a substantive improvement over the 2014 framework. These revisions reflect advances in scientific understanding derived from more than a decade of monitoring and targeted research in the Elk Valley.

It is important to recognize that both the previous and current EVWQP address multiple water quality and aquatic ecosystem objectives across the entire Designated Area, of which calcite represents one component. Accordingly, while the plan provides a suitable framework, many of the detailed field procedures, sampling designs and analytical methods that have been developed to support implementation are documented in associated technical monitoring reports (e.g., Hocking et al. 2020, 2021, 2022, Zathey et al. 2021, Smit and Robinson 2023, 2024, Smit et al. 2025). Evaluation of calcite monitoring methods therefore draws on both the EVWQP and technical reports, to the extent necessary to meet the objectives of this review.

Given the limited and evolving body of literature on calcite precipitation in lotic systems, the absence of standardized monitoring methods, and the complexity of interacting abiotic and biotic factors that can enhance or suppress calcite formation and its ecological effects, continued monitoring and periodic methodological review remain warranted. Ongoing evaluation of calcite monitoring approaches will be important for improving interpretation of calcite dynamics, strengthening linkages to ecological function, and informing adaptive management within the Designated Area.

Importantly, these methods should be interpreted within a tiered framework. Broad-scale calcite monitoring is intended to identify and prioritize reaches where calcite levels may warrant further investigation, rather than to directly inform management actions. Detailed, site-specific assessments, conducted outside the core monitoring program, are required to characterize conditions at appropriate spatial scales and to support the design and implementation of management or remediation measures.

Suitable Components

Shift to Calcite Concretion (Cc) as the Primary Metric

A central change in the 2025 EVWQP is the shift away from the composite Calcite Index (CI) toward calcite concretion (Cc) as the primary evaluation parameter. This change aligns with the 2024 calcite review, which concluded that the Calcite Index (CI) and calcite presence (Cp) are not the most appropriate ecological parameters for interpreting impacts to aquatic life and informing calcite management (EVWQP 2025). The Calcite Index (CI) lacks a clear mechanistic

or ecological justification for combining these metrics additively. Calcite presence and calcite concretion are not independent indicators of impact, but rather represent correlated expressions of the same underlying precipitation process. As a result, summing these metrics introduces conceptual overlap and variable redundancy, and where CI is used as a response or explanatory variable in statistical analyses, can also contribute to collinearity-related interpretability issues, obscuring relationships between calcite conditions and biological responses.

Calcite concretion (Cc) is more directly aligned with plausible pathways of effects, as it has a clear mechanistic link to habitat degradation by representing the degree to which substrates are cemented. Increased cementation has the potential to occlude interstitial spaces, reduce refuge availability for aquatic organisms, limit hyporheic exchange, impair benthic invertebrate communities, obstruct fish movement and redd construction, and influence sediment transport and channel morphology. In contrast, calcite presence (Cp) primarily reflects surface scaling on substrate particles, for which evidence of measurable adverse effects and direct mechanistic linkages to habitat impairment is more limited. However, we recommend that both metrics continue to be used in monitoring because Cp can indicate new calcification, whether or not concretion has developed.

Calcite concretion (Cc) therefore represents the most appropriate and currently feasible metric for evaluating calcite-related habitat impacts in lotic systems. At present, no alternative metrics or standardized methods exist that directly quantify calcite-related habitat impairment in a manner that is both mechanistically relevant and suitable for routine field application. As such, the current approach reflects a necessary and pragmatic framework based on the best available science. Future method development, including more spatially explicit or area-based approaches, may improve the ability to quantify the extent and distribution of calcite impacts.

Biological Effects Monitoring

A central objective of the EVWQP is the protection of aquatic ecosystems and the development of an improved understanding of how calcite accumulation may influence the capacity of aquatic systems to support diverse communities of fish and other aquatic life.

In addition to the calcite monitoring methods outlined in the 2025 EVWQP, effort has been devoted to collecting data on complementary physicochemical parameters and biological responses (e.g., Hocking et al. 2020, 2022). These targeted studies provide important insight into how calcite accumulation might affect spawning habitat suitability and broader ecological function across spatial scales, and help link physical measures of calcite deposition to biologically meaningful outcomes.

Biological effects studies are critical for advancing collective understanding of calcite-related impacts, as they provide the empirical evidence needed to interpret monitoring metrics and targets, evaluate habitat-level consequences, and reduce uncertainty surrounding the ecological significance of calcite precipitation beyond substrate concretion alone.

To strengthen inference, biological effects studies should be designed to ensure that calcite concretion (Cc) is quantified at the same spatial scale as biological observations. This is particularly important given the localized and heterogeneous nature of calcite precipitation, where reach-averaged metrics may not adequately represent conditions experienced by organisms. Biological sampling should therefore be explicitly aligned with calcite measurements at appropriate spatial scales to ensure that observed responses can be directly linked to site-specific calcite conditions.

Study designs should expand biological effects monitoring across a broader range of taxa, life-history stages, and functional groups, beyond those currently emphasized, to improve detection

of differential sensitivities and better characterize population- and community-level responses to calcite-related habitat change. Incorporating appropriate reference and impacted sites is also essential to control for natural variability and isolate the influence of calcite from other biotic and abiotic drivers (e.g., temperature, flow, substrate composition, and habitat structure). Where feasible, paired or stratified sampling frameworks that capture gradients in calcite conditions across comparable habitats can further improve the ability to detect and interpret biological responses.

Consideration of relevant biotic and abiotic covariates will further strengthen inference by improving the ability to distinguish calcite-related effects from other sources of ecological variability. Collectively, these approaches will enhance statistical power, reduce confounding, and support more robust evaluation of calcite-related effects and associated thresholds, while improving confidence in the interpretation of ecological responses and management targets.

Gaps and Limitations

Calcite Concretion (Cc) as a Metric

Calcite concretion represents a relevant and mechanistically defensible metric for assessing physical habitat alteration associated with calcite deposition and is broadly consistent with approaches used in stream habitat assessments. However, while currently no other standardized methods exist specifically for assessing calcite concretion in lotic systems that are as practical and cost effective for routine field monitoring, important limitations remain. Calcite concretion is inherently a semi-quantitative, observer-based measure and is therefore subject to variability and potential observer bias during field assessment. Although standardized protocols and observer training have been implemented to reduce this variability (e.g., Smit and Robinson 2024), subjectivity in scoring degree of cementation cannot be fully eliminated. This semi-qualitative nature limits statistical power in detecting subtle trends, especially in low concretion reaches where small differences may obscure or exaggerate apparent changes over time.

In addition, calcite concretion reflects the physical expression of calcite accumulation but does not, on its own, resolve the broader set of chemical or biological processes that influence ecological response. As a result, interpretation of calcite concretion values in isolation is limited and requires further linking physical metrics to biological outcomes. Accordingly, assessment of calcite-related impacts should consider parallel evaluation of ecological condition alongside calcite concretion (Cc). Metrics of habitat suitability and ecosystem function, such as those informed by Proper Functioning Condition (PFC) principles, are particularly valuable for determining whether physical changes associated with calcite deposition translate into meaningful effects on fish and aquatic communities. Reliance on Cc alone may not capture the full ecological response, especially where biological processes (e.g., food web dynamics or habitat selection) mediate or amplify the effects of physical habitat alteration. Integration of physical and biological metrics is therefore necessary to support robust interpretation of calcite thresholds and overall stream health.

While calcite concretion (Cc) is supported as the primary metric for evaluating physical habitat alteration, there remains value in maintaining data collection on calcite presence (Cp) as a complementary indicator. Calcite presence can serve as an early signal of calcite formation in streams, providing contextual information on precipitation patterns and environmental conditions that may precede substrate cementation. Although Cp has limited direct biological relevance for adverse effects compared to Cc, it remains useful for characterizing the spatial extent of calcite occurrence across landscape scales and for interpreting broader geochemical conditions influencing aquatic habitats.

Calcite Target

The 2025 EVWQP establishes a calcite concretion (Cc) target of ≤0.3 intended to be generally protective of aquatic life at the reach scale. This threshold is informed primarily by biological effects studies, which remain relatively limited in scope but provide the best empirical evidence currently available to support target development (Barret et al. 2016, Hocking et al. 2022, EVWQP 2025).

Barrett et al. (2016) identified changes in benthic invertebrate community composition across a calcite gradient, with responses occurring within the approximate range of 0.1–0.3 Cc. These results support the use of ≤0.3 Cc as a precautionary habitat-protection benchmark. However, the study is observational, site-specific, subject to confounding water quality variables, and focused primarily on benthic invertebrate responses. As such, it provides important evidence of biological sensitivity to calcite concretion, but does not fully resolve causal mechanisms, broader food-web effects, or responses across other taxa, stream types, seasons, or hydrological settings.

For Westslope Cutthroat Trout (WCT), evidence from Hocking et al. (2022) demonstrates a negative association between calcite concretion and the likelihood of redd presence. Streams containing observed redds exhibited lower mean concretion scores (approximately 0.08 Cc) compared to streams without redds (approximately 0.3 Cc; Hocking et al. 2022). However, modelled probabilities of redd presence across concretion bins indicate substantial uncertainty in this relationship, with the highest predicted probability (approximately 20%) occurring in the 0.25–0.5 Cc range (Hocking et al. 2022). These results indicate that while streams with redds tend to have lower average concretion, Westslope Cutthroat Trout redds occur across a broad range of calcite concretion values, including moderate levels of concretion. This pattern reflects both uncertainty in population level effects and the inherent complexity of spawning habitat selection. Multiple interacting factors such as natal homing behaviour, substrate size and composition, flow velocity, water temperature, channel morphology, size, cover, and riparian condition, are likely to influence spawning site selection and confound simple relationships between calcite concretion and redd presence. In addition, limitations of the available data, including the absence of direct assessments of redd quality or egg-to-fry survival, further constrain inference regarding demographic consequences.

Collectively, Barrett et al. (2016) and Hocking et al. (2022) provide valuable biological lines of evidence, but both are limited in their ability to define a precise effects threshold. The ≤0.3 Cc target therefore rests on a relatively narrow empirical foundation. Biological responses to calcite concretion are expected to vary across taxa, life stages, and environmental contexts, and neither study was designed to capture this variability across spatial or temporal scales. As a result, neither study alone establishes a definitive threshold at which calcite concretion results in population-level impairment. These limitations highlight the need for replication across taxa, additional streams, hydrological settings, habitat types, seasons, and biological endpoints. Further work linking calcite concretion to habitat suitability, benthic productivity, food-web dynamics, spawning success, egg-to-fry survival, and population-level outcomes would strengthen interpretation of the target. Further, the possibility of confounding variables like water quality factors is identified by Barrett et al. (2016), underscoring the need for properly controlled experimental designs where certainty of mechanistic causes is needed.

Overall, the ≤ 0.3 Cc target is reasonable and scientifically defensible based on the best available evidence. However, substantial uncertainty remains regarding population-level responses to calcite concretion thresholds and the degree to which the target is protective is likely to vary spatially and temporally in relation to stream-specific biotic and abiotic conditions. Accordingly, the target should be interpreted as a precautionary, habitat-based benchmark

rather than a definitive threshold for population effects, underscoring the need for continued research, complementary biological and habitat monitoring, across diverse environmental conditions, and adaptive refinement consistent with the plan's framework.

Spatial Considerations

Lotic systems are inherently dynamic, with hydrologic and geomorphic conditions varying across spatial and temporal scales. Fluctuations in discharge, channel morphology, flow regime, and interacting abiotic and biotic factors can rapidly alter stream chemistry, producing shifts between conditions that favor calcite precipitation and those that suppress it, sometimes within the same reach on short timescales. Consequently, the spatial scale at which calcite monitoring data are summarized, analyzed, and interpreted is a critical factor when evaluating heterogeneous patterns of calcite deposition in lotic environments.

Fine-scale measurements at the site or mesohabitat level are essential for identifying localized effects, characterizing spatial heterogeneity, and understanding mechanistic drivers of calcite precipitation that may not be apparent when data are aggregated at coarser scales. Averaging calcite concretion scores across multiple sites within a reach has the potential to mask localized areas of elevated concretion and dilute ecologically relevant signals, particularly when sites encompass contrasting mesohabitats (e.g., pools, glides, riffles, cascades, or falls) that exhibit different precipitation dynamics. This aggregation reduces sensitivity to fine-scale or emerging changes that may be relevant to localized habitat conditions and biological responses.

A related consideration is the spatial representation of sampling within sites. The modified Wolman pebble count provides a practical and repeatable method for quantifying calcite concretion; however, the standard approach (e.g., 100 particles) does not explicitly define the spatial area over which samples are collected. Without an associated measure of sampled area (e.g., channel width, sampled length, or defined polygon), interpretation of results is limited to relative, rather than spatially explicit, estimates of calcite extent. Incorporating a simple area-based descriptor alongside pebble count data would improve the ability to characterize the extent and distribution of calcite within and among sites, and support more robust comparisons across space and time.

At broader scales, interpretation of monitoring data depends on the validity of reach delineation. The current framework assumes that reaches represent relatively homogeneous sections of stream with respect to channel morphology, riparian cover, and flow characteristics, and therefore exhibit low intra-reach variability in calcite deposition. Under this assumption, systematic sampling at stratified locations (e.g., approximately 25%, 50%, and 75% of reach length) is appropriate. Existing analyses of intra-reach variability (Smit et al. 2025) indicate that the standard design of three sites per reach provides a reasonable balance between representativeness and efficiency under typical conditions, but its performance is dependent on the assumption of low intra-reach variability. However, where substantial variability in geomorphic or hydrologic conditions exists within a reach, this assumption may not hold, and reach-averaged metrics may obscure meaningful spatial patterns. In such cases, refinement of reach delineation, increased sampling density within reaches, or a greater emphasis on mesohabitat-scale sampling may be required to ensure that sampling units are comparable and ecologically meaningful.

Interpretation of fine-scale observations is strengthened when they are explicitly linked to broader spatial scales, including reaches, streams, and watersheds. Analyses at these scales are necessary for evaluating cumulative patterns, identifying areas of elevated risk, and assessing progress toward management objectives. Overall, current calcite monitoring is conducted at an appropriate spatial resolution to document patterns of calcite deposition and substrate concretion relevant to fish and fish habitat. While fundamental field methods do not

require modification, the spatial scale at which monitoring data are summarized, analyzed, and interpreted remains critical for drawing robust ecological and management conclusions.

Long-term consistency in sampling locations and mesohabitat types over time represents another important spatial consideration for reliable trend detection. Repeated sampling of the same fixed sites and equivalent mesohabitats within clearly delineated reach boundaries minimizes noise arising from spatial heterogeneity and increases confidence that observed changes reflect genuine temporal trends rather than differences in sampling location. The calcite monitoring program has largely addressed this through the establishment of permanent sampling sites within reaches and detailed documentation of associated mesohabitat types (e.g., Smit and Robinson 2024).

To support interpretation and improve transparency, calcite monitoring would benefit from more explicit spatial documentation and mapping. This includes clear delineation of reach boundaries, identification of sampling locations within those reaches, classification of mesohabitats, and recording of calcite morphological forms (e.g., calcified algae, calcareous laminate, calcified moss/tufa, barrage tufa, calcite scale, and insect tufa). Integration of these data into spatial mapping layers, alongside other relevant environmental variables, would enhance the ability to identify mechanistic drivers, highlight areas of elevated risk, and distinguish locations where calcite remains absent despite similar physical and geomorphic conditions. This approach would improve interpretation of calcite dynamics and support more effective evaluation of patterns across the landscape.

Statistical Considerations

The approach outlined in the 2014 EVWQP for monitoring year-to-year changes in calcite levels through the annual rate of formation or dissolution at the reach scale is not well-suited for detecting reliable trends over time. This method can conflate true temporal changes with sampling variability arising from differences in mesohabitat sampled, observer effects, and variable hydrological conditions, without explicitly quantifying uncertainty or providing confidence intervals for overall trends at reach, stream, or watershed levels. As a result, small interannual differences may be misinterpreted as meaningful change when they fall within the range of expected sampling and observation uncertainty inherent to dynamic lotic systems, limiting utility for assessing long-term progress toward calcite targets.

The Calcite Review component of the 2025 EVWQP includes a recommendation to apply a three-year moving average of calcite concretion relative to the target as an evaluation metric. This represents a clear improvement over the previous EVWQP approach by reducing sensitivity to short-term fluctuations arising from interannual variability, and observer-related variability inherent to calcite concretion as a subjective, semi-quantitative metric. By dampening noise and anomalous values, it provides a more stable representation of general conditions at the reach scale. However, this smoothing effect introduces an important limitation: a temporal lag in responsiveness. Sustained increases or decreases in calcite concretion may not be fully reflected in the three-year moving average until several years after the underlying change has occurred. Furthermore, it does not explicitly quantify statistical uncertainty or provide estimates of trend magnitude or significance. Accordingly, the three-year moving average is best interpreted as a complementary reporting tool rather than a primary analytical method. Statistical approaches that explicitly account for variability across pebbles, sites, reaches, and years would provide a more robust basis for assessing temporal trends, quantifying uncertainty, and evaluating progress toward calcite targets in a manner that more directly supports adaptive management.

It is important to note that while Permit 107517 does not prescribe a specific method for assessing calcite conditions, the regional calcite monitoring program applied a suite of

appropriate statistical analyses to evaluate reach scale trend detection, evaluation of interannual variability, and comparisons between mine-exposed and reference reaches (e.g., Smit and Robinson 2024, Smit et al. 2025). Primary methods included non-parametric Mann–Kendall trend analysis, one-way ANOVA (with Tukey's HSD post-hoc tests), ANCOVA, and separate linear regressions.

The Mann–Kendall test is well suited for environmental time-series data, as it is robust to non-normal distributions and outliers. The analysis produces Kendall's τ, a rank-based statistic describing the direction and relative strength of a monotonic association with time, along with a corresponding *p*-value for statistical significance. However, Mann–Kendall does not estimate the magnitude (rate) of change or provide confidence intervals around any trend slope. One-way ANOVA was appropriately applied was to test for differences in mean calcite metrics among years within reaches, which is useful for detecting interannual variability. Nevertheless, the parametric assumptions underlying ANOVA (e.g., normality and homogeneity of variances) may be only partially met for bounded, semi-quantitative metrics such as calcite concretion, which can influence inference. In such cases, non-parametric alternatives such as the Kruskal–Wallis test would generally be more robust.

Collectively, the statistical methods applied are appropriate and scientifically defensible for detecting temporal patterns and trends and contrasting exposed and reference conditions. However, the current analytical framework has limited capacity to quantify uncertainty, trend magnitude, or propagate variance across the hierarchical sampling structure, or generate reach-specific confidence or credible intervals around long-term trends. In particular, the practice of successive averaging of individual pebble scores to derive site-level scores, followed by averaging across sites to generate reach-level score removes information on variance at each level of the sampling hierarchy. While this approach produces stable summary metrics, it removes information on within-site and within-reach variability that is critical for formal uncertainty estimation and robust trend analysis. As a result, the ability to distinguish true temporal change from sampling variability or observation error is reduced, especially in systems characterized by high spatial heterogeneity. More advanced statistical approaches provide an opportunity to retain and explicitly model variability across nested spatial and temporal scales, thereby supporting more informative estimation of trends and associated uncertainty.

For example, Bayesian statistical approaches provide a robust framework for analysing calcite monitoring data in spatially heterogeneous and temporally variable lotic systems. These methods are particularly well suited to datasets characterized by limited or unbalanced sampling, bounded and non-normal response variables, heteroscedasticity, and multiple sources of uncertainty, including observation error, spatial heterogeneity, temporal variability, and autocorrelation. Hierarchical Bayesian models can explicitly represent nested spatial structure (e.g., sites within reaches within streams or watersheds), enabling estimation of spatial and temporal trends while appropriately accounting for variability across scales. By producing posterior probability distributions for parameters of interest, Bayesian analyses support probabilistic evaluation of change and threshold exceedance, with credible intervals that directly quantify uncertainty and more effectively distinguish meaningful trends from sampling variability and short-term environmental fluctuations (Feelders and van der Gaag 2012, Gelman et al. 2013, van de Schoot 2015, McNiesh 2016, Smid et al. 2020). What Bayesian methods require is not a specific number of years, but sufficient information in the data to estimate parameters of interest with useful precision. Accordingly, while these approaches can be applied to relatively short or unbalanced time series, the certainty of inferred trends and threshold exceedance will depend on the degree of temporal replication, the magnitude of the signal relative to background variability, and the complexity of the model structure. Therefore, considerations of

Bayesian analytical approaches may provide additional opportunities to strengthen statistical analysis.

In addition to statistical approaches, hydrogeochemical modelling provides a complementary, process-based line of evidence for understanding calcite precipitation in mining-influenced lotic systems. When paired with hydrological context, hydrogeochemical models can help address key uncertainties related to where, why, and under what conditions calcite precipitation occurs. These models integrate water chemistry data (e.g., calcium, alkalinity, dissolved inorganic carbon, pH, temperature, and major ions) to estimate carbonate speciation and saturation state, allowing evaluation of the thermodynamic potential for calcite precipitation under varying environmental conditions.

However, hydrogeochemical modelling should not replace field observation or biological assessment. Model outputs are constrained by data quality and underlying assumptions, and uncertainty may arise from limited spatial coverage, temporal variability (e.g., pH, CO_2 exchange), poorly resolved groundwater pathways, and unquantified kinetic controls (e.g., nucleation thresholds, inhibitors, biological influences). Accordingly, hydrogeochemical modelling is best viewed as a complementary tool for hypothesis development and interpretation of monitoring data, rather than a predictive or stand-alone method. Its value lies in identifying conditions under which calcite precipitation is feasible, but it does not directly quantify calcite occurrence, extent, or ecological impact.

Effectiveness Monitoring

Across conservation and environmental mitigation programs, effectiveness monitoring is widely recognized as a persistent knowledge gap that limits understanding of whether management actions achieve their intended outcomes. Although mitigation measures are often implemented to address identified stressors, limited post-implementation monitoring frequently constrains the ability to evaluate performance, learn from outcomes, and distinguish interventions that are effective from those that are ineffective or highly context-dependent. This limitation reduces opportunities to replicate successful mitigation approaches and to refine or adapt measures where outcomes fall short.

In the context of calcite precipitation in mining-influenced lotic systems, effectiveness monitoring is particularly important given the complexity of interacting physical, chemical, and biological processes. Mitigation actions such as chemical treatments (e.g., antiscalant dosing), physical modification or removal of cemented substrates, or alternative approaches, may produce immediate changes to water chemistry, channel hydraulics, sediment mobility, and flow pathways, and are intended to move systems toward more natural or less impacted conditions. However, improvements in biological use and ecosystem function may not occur synchronously with these physical changes and may exhibit temporal lags as habitats stabilize and biological communities respond.

Without systematic effectiveness monitoring that spans appropriate spatial and temporal scales, it remains difficult to determine whether observed biological responses reflect true recovery, delayed adjustment, or transient conditions following intervention. Recognizing and explicitly accounting for potential time lags between physical habitat modification and biological response is therefore essential for evaluating mitigation success, informing adaptive management, and making informed conclusions regarding the effectiveness of mitigation measures.

Objective 3: Practical Field Assessment

The strength of evidence for Pathways of Effects discussion (Figure 2 and associated interpretation) showed three strong areas of documentation for calcite effects on salmonid fish:

effects to passage, effects to recruitment, particularly spawning, and effects to macroinvertebrate communities. Without further study or data in calcite-affected areas, it is impossible to quantify the magnitude of effect these are having on fish populations, but there is enough evidence to support precautionary behaviour through prevention of further calcification and mitigation for existing calcification.

More granular assessment of per-area impact on fish habitat could draw on existing field assessment approaches used in regulatory and permitting contexts in Canada, including those utilizing Fish Habitat Assessment Protocols (FHAP) and proper functioning condition (PFC) principles. Adapting such procedures to assess calcite impacts is beyond the scope of this Science Response, but it is a potential way forward for describing effects, especially if calcification continues to increase in extent and existing calcification sites continue to concrete. PFC approaches are typically used in wetland-riparian assessments and have several geomorphological components as well as biotic ones (e.g., Swanson et al. 2017). Comparable approaches are also applied in programs such as the Provincial Forest and Range Evaluation Program (FREP) riparian assessments under the BC *Forest and Range Practices Ac*t (FRPA; e.g., see Tripp et al. 2025). Some of the goals of a PFC assessment are to describe:

- **Stream energy dissipation** during high-water (resisting excessive erosion)
- **Sediment** filtration and contribution to development of floodplains
- **Floodwater retention** and groundwater recharge
- **Maintain channel characteristics** and support biological attributes like fish and fish food webs

Qualitative PFC assessments rely on expert interdisciplinary knowledge and professional judgement across relevant biophysical disciplines. In this context, at least four areas of expertise should be considered: expertise on fish (and particularly expertise about specific species or populations of interest, e.g., Western Cutthroat Trout or Bull Trout); expertise on calcite form and trend of concretion under consideration, and expertise on geomorphic principles of the landscape of concern. In addition, hydrogeological expertise, including understanding of groundwater flow systems and reactive geochemistry, is important for interpreting the processes influencing calcite precipitation and its spatial distribution. Small headwater streams will have different geomorphic attributes and may exhibit different responses to calcite precipitation dynamics than large, mainstem reaches. Development of field assessments should start with limited field campaigns to map approaches against more established regimes like those developed for riparian systems. Ultimately, protocols would be designed to deliver an assessment of impact, risk of deteriorating function, and possible solutions for remediation.

However protocols develop, they will need to consider prioritized site selection. Below we give several considerations that will help rank sites for priority, based on risk of calcification to fish and fish habitat values.

How well have calcite formations been mapped and characterized?

Prioritizing sites for assessment assumes a complete knowledge of individual locations and their extent of calcification. Severity of impact includes level of concretion, but also extent of calcification laterally in the channel and, where appropriate, lengthwise along a reach or mesohabitat segment. Sites with more advanced concretion and/or aerial extent should receive priority for assessment.

Proper mapping and characterization can include using proper organizational segments. Characterizing a stream reach that includes a run ahead of a cascade and the cascade itself, for example, could be error prone. Cascades have dramatically increased risk of forming concretion and should always be considered as a discrete sampling feature. Runs, riffles, pools, and other mesohabitat features should likewise be considered separately from one another. Other reach selection methods might not align with fish life history use, leading to misalignment between calcite characterization and functional habitat status.

How well are calcite trends understood?

Calcite can have negative implications for fish in all stream mesohabitats, and levels of calcification and concretion can increase over time at any impacted site. Sites that are showing rapid increases in calcification should be a priority for assessment of function, especially if they are showing escalating concretion values nearing some of the concretion values seen as important thresholds to protect aquatic life.

How well are fish populations understood?

Where practicable, existing knowledge and available data on populations and habitat use by species and life history stage should be employed. This can also be accomplished through ongoing mapping and the use of mesohabitat segments as organizational units in the mapping. Fish with imperiled status and life history stages with heightened vulnerability should both be prioritized for assessment. Overlying calcite priority with fish priority can illuminate sites where calcite development has high-risk implications to habitat function. Non fish-bearing streams may also contribute to downstream productivity and food availability, and can therefore influence fish populations indirectly. Where these are associated with known fish distributions, and especially those of imperiled status, they should also receive priority.

Future Research Recommendations

Predicting Calcite Precipitation

Despite a good understanding of fundamental requirements for calcite precipitation, attempts at predicting within-stream or within-watershed patterns of precipitation do not appear in literature. Casual conversations with field practitioners have suggested to us that early attempts have met with little or no success. Still, the ability to understand better which landscape features promote precipitation and advanced concretion would be valuable. To demonstrate why this is important, we have detailed here the broad extent of landscape risk that exists for calcite formation in the calcareous geology of the Western Cordillera and in BC. Despite increased recognition of calcite impacts to fish and fish habitat since approximately 2010, and the inclusion of calcite monitoring requirements in some surface-mining permits in BC, calcite continues to be documented in additional mining areas. For example, calcite was reported during a routine inspection in the Tumbler Ridge area of BC in 2023, resulting in a 2024 calcite monitoring requirement under Provincial Permit 17679. This example illustrates that predictive tools at both coarse and fine spatial scales would help predict calcite formation risk and potential calcite impacts to fish, particularly where surface mining overlaps with calcareous bedrock substrates.

Incorporating water chemistry sampling (e.g., Ca^{2+}, CO_3^{2-}, pH, temperature) into carbonate saturation index calculations used to predict precipitation potential would help to understand the mechanistic drivers of calcite precipitation across dynamic abiotic and biotic conditions. Additionally, incorporating climate modeling to assess impact of altered temperature dynamics and hydrological regime changes may help inform adaptive management decisions.

Biological Effects and Physicochemical Indicators

Calcite precipitation in lotic systems underscores the need for continued, targeted biological effects monitoring (e.g., benthic invertebrate assemblages, spawning surveys, redd condition, and egg survival) as a vital complement to physical assessments of calcite concretion. Biological response data offer empirical context to interpret calcite metrics and targets to determine if accumulation levels yield ecologically significant impacts on fish and aquatic life, such as reduced spawning success or altered food webs.

The challenge lies in translating measurements of calcite precipitation and measures of concretion into an assessment of functional habitat impairment, rather than relying on physical indicators alone (e.g., extent to which calcite concretion alters habitat processes or functions required to support fish or fish habitat across relevant life stages). Of particular value is research targeting quantitative impacts to fish and fish habitat and directly considering calcite as a stressor under direct observation. Field experimentation that goes beyond observational studies to demonstrate effect magnitude and mechanics of cause would strengthen the management regime and lead to a better ability to develop assessment like PFC and FHAP.

Development of Functional Assessments

Development of a proper functioning condition (PFC) assessment or allied approach as previously described should be a priority. These will allow assessors and other practitioners to develop a common language to describe a variety of changes that could occur as a result of aquatic calcification and develop solutions for those effects.

PFC assessments have historically been multidisciplinary efforts integrating biological and physical criteria necessary for a specific ecological condition. Contrary to the sense that this could be a static state, conditions include the components to allow change and evolution that are supportive of biological values like fish species. While not exhaustive, some criteria that could be included in a calcite-oriented assessment protocol are:

- Overall distribution of concretion in a mesohabitat segment, including degree of embeddedness (Cc), total concretion area and concretion depth.
- Barriers to passage, including step-type formations at cascades, unnaturally rugged surface conditions, and increased flow velocity over concreted streambeds.
- Interference to natural channel evolution. Concretion has potential for both near and long-term influences on stream function, where more severe cases could change development of long-term channel morphology. In turn, important features like energy dissipation, flow volume and velocity, groundwater recharge, flood plain development, and others are implicated (e.g., see Schumm et al 1984).
- Anticipated fish habitat values based on physical and biological criteria established in literature from other kinds of fish habitat assessments. This component has a well-developed literature where many published approaches already exist. As an example, in BC the provincial *Forest and Range Practices Act* has an associated field protocol designed to rate lotic conditions for purposes of managing forestry impacts to aquatic values. This approach focuses on conditions affected by upland disturbances, particularly in-stream and riparian values (Tripp et al., 2025). A calcite-oriented approach could make use of some of the in-stream qualities, while adding geomorphic and other effects not considered in existing protocols.
- Known fish use by species and life history type, from fish surveys, where practical. While traditional PFC and allied protocols don’t consider fish observations, the possibility of an adapted approach that uses documented fish use should be considered.

Calcite Precipitation and Nutrient Dynamics

Calcite precipitation in lotic systems may influence nutrient dynamics through the adsorption and co-precipitation of phosphorus, thereby reducing dissolved phosphorus concentrations and potentially exerting negative feedback on primary productivity. Such reductions in phosphorus availability may have disproportionate ecological effects in oligotrophic or otherwise nutrient-limited streams.

Sustained low concentrations of bioavailable phosphorus have been associated with shifts in benthic algal assemblages and are widely hypothesized to favor the proliferation of *Didymosphenia geminata*, a species known to proliferate under low dissolved phosphorus conditions. Observations consistent with this potential linkage, including the co-occurrence of calcite concretion, benthic algal proliferation, and reduced macroinvertebrate presence, have been reported in the Fording River (Heidt 2022), although causal mechanisms remain uncertain.

Determining whether calcite-mediated phosphorus sequestration contributes meaningfully to nutrient limitation and associated biological responses in lotic environments represents a key research gap. Addressing this uncertainty will require integrated assessments of calcite precipitation, phosphorus speciation, and biological community structure to distinguish calcite-related nutrient effects from other drivers of phosphorus limitation.

Monitoring and Assessment Methods

A number of methodological approaches may provide additional insight into calcite precipitation dynamics and support continued refinement of monitoring and interpretation.

A key area for future work is the evaluation of spatial variability in calcite deposition within and among reaches. Current approaches involve successive averaging of individual particle (pebble) scores to derive site-level estimates, followed by averaging across sites to generate reach-level metrics. While this approach provides stable and comparable summary values, it may reduce the ability to explicitly quantify variability within sites and among sites within a reach. This information is important for characterizing spatial heterogeneity, supporting formal uncertainty estimation, and strengthening trend analysis. Existing datasets may provide an opportunity to evaluate the degree to which site-level variability influences reach-scale summaries, and to assess whether reach-averaged calcite concretion values adequately represent the extent and severity of calcite within a given reach. Such analyses could help inform the sensitivity and representativeness of current monitoring approaches, and identify situations where refinement of reach delineation or sampling design may improve alignment with ecologically meaningful spatial patterns.

Spatial Integration and Mapping

Improved spatial integration of monitoring data would further enhance interpretation. This includes explicit mapping of contributory material (calcareous rock spoils), calcite distribution in relation to reach boundaries, sampling locations, monitoring frequency, and environmental gradients across watersheds. Integration of calcite monitoring data with biological datasets (fish species and life-stage distribution, particularly) and spatially explicit environmental variables would support identification of patterns, evaluation of ecological risk, and improved interpretation of calcite impacts across spatial scales. An important component of this integration is understanding the functional role of individual stream reaches within the broader watershed (e.g., primary functions such as spawning, juvenile rearing, overwintering, or food production). Incorporating this functional context would allow calcite monitoring results to be interpreted relative to the ecological importance of affected habitats and support a more holistic and risk-informed approach to management and restoration prioritization. Incorporating spatial information on treatment locations (e.g., anti-scalant application areas) alongside consideration

of downstream zones of influence may provide useful context for interpreting observed patterns in calcite deposition. Future efforts to model risk of calcite precipitation/ risk to fish could be integrated with these approaches.

Emerging Remote Sensing Approaches

Drone (UAV) surveys combined with multispectral or hyperspectral imaging have shown promise for mapping surface calcite deposits and tufa formations in lentic environments, where clear water and stable surface conditions facilitate reliable visual and spectral interpretation (He et al. 2021, Zhang et al. 2024). However, their application to lotic systems remains largely unvalidated. In flowing streams, challenges including canopy cover, water surface reflectance, turbulence, variable water depth, and substrate heterogeneity significantly reduce detection accuracy and complicate differentiation of thin calcite veneers or tufa from natural calcareous substrates.

While drone-based methods are not currently suitable for routine monitoring of calcite deposition and concretion in streams, they warrant further research and development as a complementary reconnaissance tool. If validated, they could improve spatial coverage, reduce field effort in remote or hazardous areas, and help identify broad patterns of calcite occurrence to guide more targeted ground surveys.

CONCLUSIONS

Calcite precipitation in lotic systems is highly dynamic and controlled by a complex interplay of biotic and abiotic factors. These factors modulate the thermodynamics and kinetics of the process, generating spatially heterogeneous patterns of carbonate deposition. These factors make it difficult to predict where and how calcite will form.

The 2025 Elk Valley Water Quality Plan provides a suitable framework for monitoring calcite accumulation, with an appropriate emphasis on calcite concretion as the primary mechanism through which calcite may impair aquatic habitat structure and function. Current calcite monitoring is conducted at an appropriate spatial resolution, and while fundamental field methods do not require modification, the spatial scale at which monitoring data are summarized, analyzed, and interpreted remains critical for drawing robust ecological and management conclusions.

Overall, the ≤ 0.3 Cc target is reasonable and scientifically defensible based on the best available evidence. However, substantial uncertainty remains regarding population-level responses to calcite concretion thresholds. Accordingly, the target should be interpreted as a precautionary, habitat-based benchmark rather than a definitive threshold for population effects, underscoring the need for continued research, complementary biological and habitat monitoring, and adaptive refinement consistent with the plan’s framework.

The calcite concretion score is currently the only well-developed field metric available to field practitioners, but its use in determining trends in space and time is limited by current analytical approaches. Alternative approaches, including Bayesian-oriented methods, are suggested; however, their value depends on comprehensive datasets that retain spatial and temporal variability in the underlying observations. This is important for improving temporal trend detection, supporting more advanced interpretation of calcite precipitation dynamics across monitoring scales, and characterizing uncertainty around observed changes.

For salmonid fishes, mining-related calcification presents variable risks with emerging data describing these, especially the degree of concretion. Impacts to fish passage, redd density, and aquatic macroinvertebrates are supported broadly in scientific literature, but quantitative impacts to fish populations aren’t possible to determine at this time.

Mesohabitat units as the basis for sampling and reporting are recommended versus alternative reach delineation techniques. Mesohabitats align with fish habitat, fish behaviour, and calcite precipitation occurrence, where other reach concepts might not.

Permitted surface mining operations in landscapes capable of generating aquatic calcite precipitation should include a robust monitoring requirement following recommendations provided in this Science Response.

Future monitoring efforts should describe the overall aerial extent of calcification in the mine-affected landscape, particularly whether sites further downstream continue to show new development of calcite presence (whether or not the mine-affected aerial footprint is increasing). A monitoring program should be able to describe the overall distribution of calcite in the mine-affected landscape and the form in which it is present. Simple metrics like total affected area, total number of known sites, and calcite form will be useful in the context of novel knowledge about impacts to fish. The development of mapping and modeling tools that include elements of source material (rock spoils), known calcite formations, remediation efforts like anti-scaling sites, and fish distribution can be used to develop a risk-based site selection framework for monitoring and assessment. In some cases this effort can use existing datasets, but the exploratory use of drone mapping and allied remote sensing techniques should be included to increase efficiency of ongoing data collection. High-risk sites where advanced concretion and high fish values intersect should be prioritized for intensive monitoring and remediation. Tools to better map fish values and calcite development will be needed to achieve this.

Developing a calcite-oriented Proper Functioning Condition (PFC) assessment will help with more intensive consideration of evaluating impacts at appropriate locations. These are more intensive assessments utilizing multidisciplinary input where there is a high risk of calcite occurrence overlapping high fish values. The increased effort to undertake these can point to how calcite can affect fish values further to what a concretion score alone will provide. PFC assessments could be utilized to integrate such features as area of coverage and depth of calcite formation, risk to continued channel evolution, and more. An understanding of how calcite is comprehensively influencing function will help with determining both remediation and regulatory considerations like restoration and offsetting.

Knowledge gaps are highlighted that emerged from existing literature. Among these are the ability to predict calcite formation downstream of calcareous waste rock, the development of functional condition assessments, fundamental research on the principal effects to fish (spawning, passage and food web consequences), and landscape nutrient consequences.

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