Assessment of Historic Distribution of Anadromous Salmonids in the Ash River Watershed Using Stable Isotope Analysis of Lake Sediments

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Executive Summary

We used stable isotope analysis of lake sediments in conjunction with radioisotope dating techniques to help resolve an ongoing controversy regarding presence of anadromous salmonids prior to hydropower development in the Ash River watershed, British Columbia. Profundal sediments were sampled from Elsie and Oshinow Lakes, upstream of Elsie Dam, Dickson and McLaughlin Lakes, downstream of the dam, and Nahmint and Nimnim Lakes, which are outside the Ash River watershed but nearby. Reductions in $\partial^{15}N$ are apparent in Elsie, Oshinow and McLaughlin Lakes and are approximately coincident with hydropower development in the Ash watershed. There is a hint of a similar trend in Dickson Lake, and trends in Nimnim and Nahmint Lakes do not appear to be correlated with timing of hydropower development. Statistical comparisons of $\partial^{15}N$ concentrations in sediment samples prior to vs. after the year of dam formation indicate statistically significant declines of ^{15}N in Elsie, Oshinow and McLaughlin Lakes. Using a model to estimate escapement, Oshinow and Dickson Lakes both show lower levels of escapement after dam formation. In Oshinow this change is very dramatic, falling from escapements that were commonly 500 to 1100 fish, to 60 or fewer fish. Pre-dam escapements for Dickson Lake are occasionally above 100 fish, while post-dam records are usually below 50 fish. Inferred escapement for Elsie Lake suggests that pre-dam abundance was commonly higher than 400 fish and up to almost 900 fish. Post-dam escapements for Elsie Lake are likely to be confounded by the direct effects of damming. Nahmint, Nimnim and McLaughlin Lakes show relatively little change in escapement over time. Based on salmonid life histories and migration patterns in nearby watersheds, the most likely candidates for species that accessed lakes in the Ash watershed are steelhead, coho, chinook and possibly sockeye. Pacific lamprey are also known to have ascended the Ash watershed prior to hydropower development. Our results support the hypothesis of a loss of anadromous salmon production from the Ash River system as a result of dam construction and operation. Alternate hypotheses are discussed and rejected.

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INTRODUCTION

Dams have numerous effects on physical and ecological processes in streams (Baxter 1977, Ligon et al. 1995). Two of the most substantial effects for fish are physical disruption of migration and changes to the natural flow regime. Physical barriers at dams without passage facilities can fragment populations (e.g., Neraas and Spruell 2001, Schmetterling 2003) and in the case of migrating species can "orphan" productive habitat (e.g., Gregory et al. 2002). Alterations to the natural flow regime occur when water is diverted into or out of a watershed, or when water is stored and subsequently released in a pattern that is not natural. When the timing and magnitude of flows are altered, ecological productivity of habitats is often affected (Poff et al. 1997, Richter et al. 1997). Flows and related cues are used by fish to time migration (Quinn and Adams 1996 , Quinn et al. 1997), and some habitats are accessible only at certain flows (Quinn 2005). Altered flow regimes can therefore influence migration patterns, and affect access to some habitats.

Pacific salmon (*Oncorhynchus* spp.) are anadromous. They mature in the ocean and return to natal freshwater streams where they reproduce and die. Anadromous salmonids accumulate about 99% of their adult biomass in the marine environment (Groot and Margolis 1991). On their return they transport substantial biomass into freshwater systems in their somatic and gonadal tissue. As a result, the nutrients originating from carcasses of postspawning adults are almost exclusively of marine origin. These marine-derived nutrients are incorporated into aquatic and riparian food webs, and often represent significant sources of nutrients to coastal oligotrophic systems (Stockner 2001). Because there are no other widespread natural processes that move nutrients from the ocean to freshwater in large quantities, the presence of marine-derived nutrients can usually be assumed to originate from anadromous fish.

Stable isotopes of nitrogen can be used to track and quantify marine-derived nutrient inputs in freshwater systems. ^{15}N and ^{14}N are both incorporated into body tissues as organisms grow. Metabolic biases result in increased ^{15}N:^{14}N in higher trophic levels and under some conditions of nutrient limitation, but biomass from the ocean is typically much richer in ^{15}N than biomass from terrestrial or freshwater habitats. ^{15}N concentrations can therefore be used to track inputs of marine-derived nutrients into freshwater and terrestrial systems. Lake sediments archive this information, because organic matter continuously settles to the bottom (Finney et al. 2000). The relative abundance of ^{15}N vs. ^{14}N in profundal lake sediments thus provides an indicator of salmon presence. When combined with radioisotope-dating techniques and vertical subsampling of a sediment core, it is possible to assess not just historic salmon presence but trends in abundance also (e.g., Finney et al. 2000, Finney 2002), although it should be noted that these techniques for paleoecological reconstruction cannot apparently be applied universally (Hobbs and Wolfe 2007).

In the Ash River watershed, British Columbia, there has been ongoing controversy regarding the presence of anadromous salmonids prior to hydropower development. The Ash River is a tributary to the Stamp River, which itself is tributary to the Somass River (Figure 1). The Stamp and Somass are important salmon streams on the west coast of Vancouver Island, with stocks of steelhead, coho, chinook, sockeye, chum and pink salmon. The Ash River has abundant stocks of steelhead, coho, and chinook, but they are currently restricted to portions of the river downstream of a hydropower facility. Historic sampling indicated an absence of anadromous salmon above Dickson Falls (Anonymous 1953 and 1954 cited in Griffith 1993), which is immediately downstream of Elsie Dam at the outlet of Elsie Lake. However, sampling prior to hydropower development was not intensive and the findings contradict oral history of the Hupacasath First Nation. Recent observations of coho salmon juveniles above Dickson Falls (Michael McCulloch, BC Ministry of Environment, personal communication) have intensified the debate about fish distribution prior to hydropower development. The anadromous Pacific lamprey (*Lampetra tridentata*) was known to ascend the system beyond the current site of Elsie Dam (Beamish and Northcote 1989), but is the only species confirmed to do so.

In this study we use stable isotope analysis of lake sediments to investigate the historic presence of anadromous salmonids in the Ash River watershed. We examined two lakes upstream of Elsie Dam, two lakes downstream, and two lakes that are outside the Ash River watershed but nearby (Figure 1). Our objectives were to assess whether anadromous salmonids were historically present above Elsie Dam, whether presence or absence was correlated with timing of dam construction, and whether flow regulation has influenced downstream distribution of anadromous salmonids. We use a recently developed model to place bounds on escapements to each lake.

Goals and Objectives

The Ash watershed is a substantial sub-basin of the Somass-Stamp system, which supports five species of Pacific salmon (coho, chinook, sockeye, chum, and pink) and steelhead trout, resident salmonids (cutthroat, rainbow and Dolly Varden), and several non-salmonid species (sculpins, lamprey and pumpkinseed; BC Fisheries et al. 2000). Four significant, natural barriers exist on the Ash River: Lanternman Falls (~ 5.5 km upstream of the Ash River – Stamp River confluence), Dickson Falls (a further 4.5 km upstream), Ash Island Falls (just upstream of Dickson Falls), and a rock falls barrier at the full pool elevation of Elsie Lake Reservoir. In addition to the natural barriers, Elsie Lake Dam (~ 25 km upstream of the confluence) has no passage facilities.

Historic sampling indicated an absence of anadromous stocks above Dickson Falls (Anonymous 1953 and 1954 cited in Griffith 1993). However, this sampling was not extensive and the findings contradict Hupacasath oral history. In 1975-76 Dickson Falls was altered with selective blasting to facilitate passage of summer steelhead, but it has generally been believed that the passage improvements aided only steelhead. Since that time there has been ongoing debate about the historic distribution of fish in the Ash system, and the responsibilities of BC Hydro and fisheries agencies to address fish passage issues in the Ash River. Recent observations of coho juveniles above Dickson Falls (Michael McCulloch, BC Ministry of Environment, personal communication) have intensified the debate about historic fish distribution prior to hydropower development. The aim of this project was to clarify historic distribution of anadromous salmonids in this system, through the use of stable isotope analysis of lake sediment cores.

To date much of the discussion about fish passage on the Ash River has focussed on assessment of historic conditions and whether and to what extent different fish species ascended above some of the barriers. There has been no resolution of this issue in part because there has been no empirical way to address the question. This project proposed to obtain sediment samples from several lakes in the Ash watershed and to examine the sediments using stable isotope analysis. This technique can be used to assess the relative presence of marine-derived nitrogen sources in freshwater, and has been successfully used to assess historic salmonid abundance in coastal BC lakes (e.g., Gregory-Eaves et al. 2003, Holtham et al. 2004). It will be used here to assess historic presence or absence of salmon within different portions of the Ash watershed. Results of the study will feed directly into ongoing decision processes regarding fish passage on the Ash River, and help define boundaries for BC Hydro responsibilities.

Activities proposed here meet each of the three main BCRP program objectives described on the BCRP website.

Program Objective 1 - Addressing Footprint Impacts
The project addresses footprint impacts and limiting factors identified in the Ash River Watershed Strategic Plan by helping to clarify historic fish passage in the Ash River. The study will therefore also help to clarify the biological impacts of the BC Hydro Ash River Project, and provide context for mitigation and compensation.

Program Objective 2 - Creating Other Benefits
The proposed activities provide value-added benefits as defined by the BCRP Board. The project will enhance awareness, appreciation and understanding of fish and their habitats and lead to greater stewardship of natural resources. Stewardship will be enhanced because Hupacasath and other stakeholders will participate directly in the project.

Program Objective 3 - Involving First Nations, the Public, and Agencies in Collaborative Decision Making. This objective of the program was met because Hupacasath participated directly in all phases of the project, which will foster development of First Nations partnerships with BC Hydro and agencies in the realm of decision-making and natural resource management.

STUDY AREA

The Ash River watershed covers an area of 379.5 km^2 in the transition zone between wet west coast and drier east coast regions of central Vancouver Island, British Columbia (Figure 1). Winters are cool and wet, and summers are warm and dry. During winter, moist air flows inland from the sea, and west-facing slopes receive prolonged, heavy rains, which spill over to the east-facing slopes. Most winter precipitation falls as rain rather than snow, resulting in highly variable streamflows with peak discharges from November to February. Snowmelt from higher elevations cause additional peak flows from May to July. Low flows typically occur in August and September.

The headwaters of the Ash River are in Strathcona Provincial Park, and most of the remainder is private forest land and crown land. Approximately 4% of the watershed is Alpine Tundra, 16% Mountain Hemlock, and 80% is in the Coastal Western Hemlock Biogeoclimatic Zone (Environment Canada 2005). 38% of the watershed is old-growth forest (>140 years old, >6 m tall), and 35.5% is young forest (<140 years old, >6 m tall; Environment Canada 2005). A little more than 13% of the watershed has been logged in the last 20 years. The landscape is rugged and mountainous, with peaks in the upper watershed that exceed 2000 m elevation; despite its proximity to the ocean the mean watershed elevation is 700 m.

Total length of the Ash River including lakes and reservoirs is more than 60 km. There are four significant, natural barriers to fish migration: Lanternman Falls (4.7 m stepped bedrock falls, ~ 5.5 km upstream of the Ash– Stamp confluence), Dickson Falls (9.24 m stepped bedrock falls, ~ 10.9 km upstream of the Ash– Stamp confluence), Ash Island Falls (a series of three falls of 5.8 m total, just upstream of Dickson Falls), and a rock falls barrier near the inlet to Elsie Lake. Dickson Falls represents the most serious natural obstacle, and has been noted as an obstacle to the passage of coho salmon (Province of British Columbia 2007; Burt and Lewis 2004), summer steelhead (Province of British Columbia 2007) and Pacific lamprey (Beamish and Northcote 1989). Selective blasting of Dickson Falls was carried out by the BC Fish and Wildlife Branch in 1977 and 1978 in an attempt to improve passage conditions for anadromous salmonids. Elsie Dam is the only non-natural barrier and has no fish passage facilities.

The Ash River hydropower facility consists of Elsie Lake Reservoir, which was created following the construction of Elsie Dam at the outlet of Elsie Lake (i.e., the Ash River) and four saddle dams. Construction of the dam began in 1957, was completed in July 1958, and the hydropower facility began operation in 1959 (BC Fisheries et al. 2000). Water is diverted from Elsie Lake Reservoir through a 4 km tunnel and 3.4 km penstock, dropping 248 m to a 25.2 MW powerhouse located on the north shore of Great Central Lake. The plant usually operates at maximum capacity (10.7 m^3 sec^{-1}) except in late summer when inflows are low and a one- to two-week maintenance outage occurs. The natural mean discharge of the Ash River is 20.7 m^3 sec^{-1} at the outlet of Elsie Lake Reservoir, and the regulated mean discharge is 9.5 m^3 sec^{-1}.

There are three natural lakes on the mainstem, Oshinow, Elsie and Dickson Lakes. Dickson Lake, approximately 10 km upstream of the Ash River – Stamp River confluence, is about 1.5 km long and 0.5 km wide. It is a broad, shallow, dendritic lake with substantial wetland areas. Elsie Lake, approximately 15 km further upstream, is an impounded natural lake with water elevations now controlled by Elsie Lake Dam. The reservoir is about 7 km long by 1 km wide, and has a maximum depth of 30 m and an annual drawdown of about 15 m. Elsie Lake was 271 ha prior to impoundment; the current surface area is 672 ha. Oshinow Lake, 13 km upstream of Elsie Lake, is a natural, steep-sided lake about 5 km long and 0.6 km wide. In addition to lakes on the Ash mainstem there are several smaller lakes on tributaries (e.g., Ash, Lois, McLaughlin, Turnbull, Moran, and Toy Lakes). This study focused on two lakes upstream of Elsie Dam, Elsie and Oshinow Lakes, two lakes downstream of the dam, Dickson and McLaughlin Lakes, and two lakes from nearby watersheds, Nahmint and Nimnim Lakes. Biophysical information for the lakes is summarized in Table 1 and locations are shown in Figure 1.

METHODS

Sediment Cores.— Sediment samples were collected from the deepest regions of the six lakes in June 2006 using a three-inch diameter sediment corer. Each core was sectioned at 2.5 mm intervals using a vertical extruder. Sections were placed in individual sample bags and kept refrigerated until lab analyses could be completed.

Elemental Analysis.— Sediment samples were analyzed for stable nitrogen and carbon isotopes, and percent organic C and N. Elemental analysis was conducted at the Biogeochemistry Facility, School of Earth and Oceans Science, University of Victoria. Sediment sections were subsampled, dried at 80 ˚C, then ground with mortar and pestle. Samples wrapped in tin capsules were dropped onto an oxidation column packed with chromium oxide and cobaltous/ic oxide at 1020 ˚C. Combustion products were carried by a helium stream through a second reduction column packed with copper at 700 ˚C, and finally a magnesium perchlorate water trap. All samples were run on a Fisons NA1500 elemental analyzer, interfaced to a Thermo Delta Plus XL and ConFlo II. IRMS calculations for $\partial^{13}C$ and $\partial^{15}N$ were referenced to an in-house standard of acetanilide, run as a sample. Calculated error for this standard is ± 0.15 ‰ (± 1 sd) for $\partial^{15}N$ and $\partial^{13}C$. We ran three samples in each lake with and without carbonate extraction to assess the potential influence of carbonates on isotope results. Laboratory quality control procedures included replicate analyses of some samples. Replicate samples for these runs were taken from the same core depth in each core.

Geochronology Methods.— Geochronologies were determined using radioisotope (^{210}Pb) analyses conducted by MyCore Scientific Inc. Sections from the following depths (cm) were analysed from each core: 0, 1, 2, 3, 5, 7, 10, 13, 16, 19, 22, 25, 28, 31, 35. ^{210}Po was measured by isotope dilution alpha spectrometry. Details of sample preparation and analysis are presented in Flynn (1968) and Evans and Rigler (1980) with modifications described in Cornett et al. (1984) and Rowan et al. (1995). ^{210}Pb activities were estimated using cumulative dry mass (Binford 1990), and the constant rate of supply (CRS) model was used to estimate the ages of sedimentary layers (Appleby et al. 1979). Dating of sections between those directly sampled for ^{210}Pb analyses were estimated by linear interpolation.

Analysis of Elemental Results.— Stable isotope data and C:N ratios were analysed separately for each lake. Statistical comparisons were made of values prior to and after 1958 (the year of Elsie Dam completion) using Welch-modified t-tests (Insightful 2004). The Welch modification does not assume equal variances in samples groups.

Escapement Modeling.— Escapement estimates for each of the study lakes were developed using a multiple linear regression model based on sedimentary ^{15}N, C:N and escapement (Bos 2007). The model replicates predictions of the more complex model of Brahney et al. (2006), but does not require picking individual cladoceran remains from lake sediment. The model predicts escapement (log escapement ha^{-1}) using variation in sedimentary C:N to account for changes in N-limitation within lakes and its effect on deposition of N-isotopes to lake sediments (Brahney et al. 2006). Within the calibration set of lakes, the relationship between predicted and measured escapement is quite strong ($R^2 = 0.77$, n = 15). The prediction equation is:

$$\log escapement = \frac{(^{15}\mathrm{N} - 5.102) + (0.228 \times C{:}N)}{(5.548 \times C{:}N) + \log surface\ area}$$

RESULTS

Elemental Analysis.— Laboratory analysis of sediments proceeded using standard methods and presented no unique problems. Replicate samples were within ranges specified by laboratory quality control procedures. Replicates treated with acid to remove carbonates were not significantly different within lakes, although differences existed among lakes (Table 2).

Geochronologies.— ^{210}Pb activities reached background at approximately 13 cm in cores from Elsie, Dickson and Oshinow, 16 cm in Dickson, and 19 cm in Nahmint and Nimnim Lakes. ^{210}Pb activities generally decreased exponentially, consistent with the constant rate of supply model (Appleby 2001). Some departure from a log-linear profile was evident in the Nahmint and McLaughlin cores. The profile for Nahmint Lake dropped quickly between 5 and 19 cm (i.e., prior to ~1990), and between 5 and 11 cm (prior to ~1960) in the McLaughlin core. These shifts appear to be related to changes in sedimentation rate, though may also be caused by mixing of sediments within these depths.

Analysis of Elemental Results.— ∂^{15}N levels are consistently low in the six study lakes, with the lowest levels observed in Oshinow and Nahmint Lakes, and the highest levels observed in Elsie and Nimnim Lakes. Trends in ∂^{15}N in the six study lakes are presented in Figure 2. Reductions in ∂^{15}N are apparent in Elsie, Oshinow and McLaughlin Lakes and are approximately coincident with construction and operation of hydropower development in the Ash watershed. There is a hint of a similar trend in Dickson Lake, but overall variability in $\partial^{15}N$ is greater making trend detection difficult. $\partial^{15}N$ trends in Nimnim and Nahmint Lakes indicate historic variability, but the trends do not appear to be correlated with timing of hydropower development in the Ash watershed.

Statistical comparisons of $\partial^{15}N$ concentrations in sediment samples prior to vs. after 1958 are presented in Table 2. Results of t-tests indicate statistically significant declines of ^{15}N in Elsie, Oshinow and McLaughlin Lakes.

Trends of C:N in the six study lakes are presented in Figure 3. Trends in Elsie, McLaughlin and Nahmint Lakes indicate approximately constant C:N, with occasional spikes or reductions. A progressive reduction in C:N is indicated in Nimnim and Oshinow Lakes, but the trend shows no apparent correlation with the date of hydropower development in the Ash watershed. Prior to about 1900, Dickson Lake sediments show high C:N, which declines rapidly thereafter but remains relatively constant after about 1925.

C:N ratios are significantly and negatively correlated with $\partial^{15}N$ concentrations in sediments from Dickson, Elsie and McLaughlin Lakes (Table 3). Correlations are not statistically significant in the other three lakes.

Escapement Estimates.— Estimates of historic escapement are generally more variable than the $\partial^{15}N$ trends. Nahmint, Nimnim and McLaughlin Lakes show relatively little change in escapement over time. In McLaughlin Lake pre-dam escapements are inferred to be very low ($<$ 5 fish yr^{-1}). There is a decrease in escapement coincident with dam formation, followed by an increase near the top of the core. The maximum escapement inferred is 18 fish $year^{-1}$, which is still very low and likely within the error of the model for a lake with no or few anadromous fish. This increase also corresponds to a sharp increase in C:N. Nahmint and Nimnim Lakes have similar trends with relatively low levels of escapement (2 to 104 fish for Nimnim and 25 to 350 fish for Nahmint) throughout the record, excluding outliers. Both lakes show departures to much higher levels of escapement, however these are coincident with spikes in C:N that are not accompanied by changes in $\partial^{15}N$. Oshinow and Dickson Lakes both show lower levels of escapement after dam formation. In Oshinow this change is very dramatic. Pre-dam escapements to Oshinow were variable, but escapements of 500 to 1100 fish were common. After construction of the dam, inferred escapement drops quickly and is generally below 60 fish. Inferred escapements for Dickson Lake are more variable and low throughout the record. Pre-dam escapements are only occasionally above 100 fish, while post-dam records are commonly below 50 fish. Inferred escapement for Elsie Lake, based on a pre-impoundment lake size of 271 ha, suggests that pre-dam escapements were commonly higher than 400 fish and could be as high as almost 900 fish. Post-dam escapements for Elsie Lake are likely to be confounded by the direct effects of damming.

DISCUSSION

Trends in $\partial^{15}N$ in sediments from Elsie, Oshinow and McLaughlin Lakes indicate recent reductions in levels of ^{15}N, which is consistent with the hypothesis of historic escapement of anadromous salmonids to these systems. Furthermore, the timing of ^{15}N reductions is consistent with the hypothesis that hydropower development on the Ash River has caused reductions or extirpations of stocks that accessed these portions of the Ash watershed. Reductions or extirpations of stocks appear to have occurred both downstream and upstream of Elsie Dam. The stocks were sufficiently abundant to produce detectable trends in $\partial^{15}N$ in lake sediments, but escapement models indicate the runs were likely of modest size.

Candidate Species.— Present day barriers to fish migration on the Ash River are not trivial, and it seems likely that these barriers historically restricted access for some species. It is also quite possible that suitable passage conditions varied from year to year. The falls are apparently not passable under most present-day flows, so flows in some years may have limited or even precluded passage for some species and may have affected run strength to the upper watershed.

The five species of Pacific salmon present in British Columbia have different habitat requirements for rearing and spawning (Groot and Margolis 1991). Coho salmon (*O. kisutch*) are capable of surmounting considerable physical obstacles and reach locations that may be inaccessible to other salmon. They use small headwater streams, which they may share with only migrant steelhead or resident cutthroat trout. They rear in freshwater for a year or more before migrating to the ocean, where they rear for at least 18 months. Chinook salmon (*O. tsawytscha*) are most closely related to coho and have broad habitat requirements. They will spawn in small tributaries two to three metres wide and in the mainstem of large rivers, and depending on the stock, rear in freshwater for a year or migrate directly to the ocean after emergence. Sockeye salmon (*O. nerka*) are primarily anadromous, but there are distinct populations called kokanee that mature, spawn, and die in freshwater without a period of sea life. Typically, juvenile anadromous sockeye utilize lakes as rearing habitat for one to three years after hatching. Pink salmon (*O. gorbuscha*) and chum salmon (*O. keta*) make less extensive migrations into freshwater for spawning than do the other species and therefore tend to occur at lower elevations or the lower reaches of rivers. Upon emergence from the gravel, pink and chum salmon fry migrate quickly to sea. Steelhead trout (*Oncorhynchus mykiss*) are an anadromous life history form of rainbow trout, and are themselves often divided into two variants: summer and winter steelhead. Both forms spawn in the spring but differ in the timing of their return to freshwater. Summer steelhead are often found in systems with barriers that are only passable under certain flow conditions — conditions that often preclude other anadromous salmonids due to the lack of passable flows during typical salmon run timing. Unlike salmon, steelhead may return to the ocean and spawn again in the future, although a portion of the population typically die on or near the spawning grounds.

Based on salmonid life histories and migration patterns in nearby watersheds, the most likely candidates for species that accessed lakes in the Ash watershed are steelhead, coho, chinook and possibly sockeye. The case for steelhead is likely the strongest, given the broad timing of their migrations and multiple life history forms that are adapted to timing of flow-dependent barriers. Coho salmon are known to be excellent swimmers and jumpers and potential access to the upper Ash by this species is corroborated by the recent capture of coho juveniles above Dickson Falls (Michael McCulloch, BC Ministry of Environment, personal communication). Chinook salmon have swimming and jumping abilities that are similar to coho (Bjornn and Reiser 1991) and may have accessed portions of the Ash above existing barriers. It is possible that sockeye also utilized these lakes. Kokanee are present in low numbers in Elsie Lake, based on anecdotal reports and capture of a single individual following a reservoir spill event in 2001 (Smith 2001), though they have not been captured in gill nets during nine different sampling events between 1952 and 2003 (Lewis and Ganshorn 2004). There are other watersheds on Vancouver Island with populations of kokanee but no runs of sockeye salmon, so it is possible that the absence of sockeye in the Ash watershed is not correlated with hydropower development. Given known swimming speeds and jumping abilities (Bjornn and Reiser 1991), it is unlikely that pink and chum accessed these lakes in the recent past. Lastly, it has been noted that Pacific lamprey were able to ascend the Ash watershed prior to hydropower development. It is possible that this was the only anadromous species to do so, though this is unlikely, as we are aware of no watersheds in British Columbia where Pacific lamprey occur in the absence of anadromous salmonids. Presence of Pacific lamprey is an excellent indicator of chinook salmon habitat (R. Beamish, Fisheries and Oceans Canada, personal communication).

Escapement Estimates.— The physical disruption of fish migration is a well-known impact from dam construction, and dam operations often affect downstream habitat quantity and quality. Results from the study lakes support the hypothesis of a loss of anadromous salmon production from the Ash River system as a result of dam construction and operation, and modest and variable escapements of salmon before Elsie Dam.

Oshinow Lake, located upstream of Elsie Dam, shows the strongest response to dam formation. Prior to the dam, it is likely that 500 to 1100 fish commonly spawned in or above the lake. After dam construction, escapement to Oshinow dropped precipitously to around 50 fish per year. Given the error in the regression model, this represents effectively no anadromous fish reaching the lake after Elsie Dam was constructed, and agrees with our knowledge of the dam as a complete barrier.

Elsie Lake is the only other lake located above Elsie Dam. However, the dam is located directly on the outlet of the lake and the lake has been directly affected by changes in lake levels, shoreline flooding and water level control. These factors all have the potential to directly influence C:N and ^{15}N levels and make Elsie Lake a poor candidate for reconstructing escapement after dam formation. Prior to the dam, inferred escapement to Elsie is 133 to 896 fish $year^{-1}$.

Dickson Lake is downstream of the dam and shows a weak but consistent response to dam formation. The overall pattern for Dickson Lake is that escapements greater than 100 fish are inferred at times prior to Elsie Dam, but no escapements of that magnitude occur after dam formation. Escapement estimates for Dickson Lake are highly variable throughout the core, which may in part be due to its small size and the high flow-though from the Ash River. High flows in the Ash River would reduce time for sequestration of ^{15}N from salmon, whereas low flushing rates would likely result in greater deposition of ^{15}N to the sediments. Flows could also affect fish passage at Dickson Falls, and in years of poor passage, restrict fish bound for Elsie and Oshinow, and thereby increase spawning in the lower Ash and nutrient inputs to Dickson Lake.

The three control lakes Nimnim, Nahmint, and McLaughlin, all show relatively small changes in inferred escapement, with the exception of a few radical departures for one or several data points. This same phenomena is also observed for one point in Oshinow Lake and several points in Elsie Lake after dam formation. It is unlikely that these deviations represent real departures, and instead reflect inclusion of terrestrial material high in C:N. The escapement model is sensitive to large changes in C:N and was derived primarily with larger lakes where export of terrestrial material to profundal sediments is less likely. Some terrestrial materials have much higher C:N and consequently macrofossils such as conifer needles, grass or woody debris in bulk sediment samples can produce erroneous model inferences. However, these samples can be identified by their large changes in C:N with little change or a decrease in the $\partial^{15}N$ value. Replicate samples at the affected intervals may resolve the discrepancy with other escapement values.

With the exception of the above mentioned intervals, escapement estimates to McLaughlin Lake are very low (1 to 18 fish) and do not represent a large contribution of marine-derived nutrients to the lake. The $\partial^{15}N$ data and escapement modeling indicate a decline in abundance immediately post-dam formation, and the faint signal is consistent with the small size of the lake and lack of a well-defined inlet channel that could be used for spawning. The lake is likely suitable rearing habitat for coho, but none of the other anadromous species. Available data indicate only non-anadromous species in this part of the Ash (Province of British Columbia 2007) and we had originally selected the lake as a downstream control. The decline in $\partial^{15}N$ coincident with construction of Elsie Dam underscores the notion that migration conditions for fish may be impacted well downstream of dam facilities and impacts may occur in tributaries as well as mainstem areas. However, the signals are faint and the results should be interpreted cautiously.

Throughout their records, Nimnim and Nahmint show little change in escapement , with the exception of the large departures accompanying large C:N values mentioned above. Escapement estimates for Nahmint range from 3 to 382 fish and would represent insignificant anadromous migration for such a large lake. The upper Nahmint watershed, where Nahmint Lake is located, is known to be almost exclusively a steelhead system, and has escapements typically on the order predicted by our model (Province of British Columbia 2007). In Nimnim, the escapement estimates range from 2 to 63 fish year^{-1}, ignoring the spike in the middle of the record. These low levels are within the error of the model and likely represent no significant levels of anadromous fish entering the lake. Nimnim Lake is in the headwaters of a watershed adjacent to the Ash, and is believed to be well above anadromous access. It is possible that historic stocking in this system (Province of British Columbia 2007) has influenced $\partial^{15}N$ trends.

The escapement estimates for Oshinow, Elsie and Dickson are consistent with life-history patterns of salmon species in the area. Significant migration barriers exist on the Ash River, the relatively small and variable escapements that are inferred are consistent with limited numbers of coho, steelhead and potentially chinook reaching the upper reaches of the Ash watershed. It is unlikely that large numbers of sockeye reached the lakes because a stronger ^{15}N signal and larger inferred escapements would be expected, especially since this species often spawns in lakes and contributes its carcasses directly into the lakes.

Alternate Hypotheses.— We have interpreted the results from this study as an indication that hydropower development resulted in declines or extirpations of salmon stocks in parts of the Ash watershed, but alternate hypotheses should be evaluated before accepting this interpretation. The main alternative explanations include regional declines in salmon stocks unrelated to hydropower development, effects of land use on sedimentation and ^{15}N inputs, and possible discrepancies in ^{210}Pb dating of these cores.

Regional declines and extirpations of salmon stocks have occurred throughout western North America in relation to harvest, habitat changes and climatic influences (Slaney et al. 1996, Beamish et al. 1997, Bradford and Irvine 2000, Gresh et al. 2000). Harvest rates have varied considerably among watersheds, but have historically been in excess of 50% for some stocks (Hyatt and Steer 1987, Walters and Staley 1987, Beamish et al. 1997) which has led to declines, extinctions and alterations in numerous stocks (e.g., Bradford and Irvine 2000). We cannot exclude the possibility that overharvest led to loss or decline in Ash watershed salmon stocks, but this influence seems unlikely to explain the sudden, coincident decline in ^{15}N inputs detected in these lake sediments. Stocks that decline from overharvest generally decline over a period of one or more decades (e.g., Bradford and Irvine 2000, COSEWIC 2003) and abundance through the period of decline is often more variable than the precipitous abundance changes inferred from $\partial^{15}N$ trends in our lake sediment samples. The influence of fishing on Ash stocks would almost certainly be coincident with fishing of stocks in the Stamp-Somass system. Yet, we are aware of no information indicating a sudden, large decline in abundance of Stamp-Somass stocks within the time frame of this study. In fact, available estimates indicate relatively constant sockeye returns in this region (i.e., Barkley Sound) from the 1920s through the 1960s, followed by a period of large increases associated with habitat and hatchery enhancements (Hyatt and Steer 1987). The lack of coincident declines in Stamp-Somass stocks is evidence that the cause(s) of decline in Ash stocks is likely specific to the Ash watershed.

Influences of climate and land use also seem unlikely to explain the rapid, coincident decline of $\partial^{15}N$ observed in Ash lake sediments. Ocean conditions exert an influence on run strength, and conditions are known to be related to the Pacific Decadal Oscillation (Beamish et al. 1997), El Niño and other large-scale climate patterns. However, the changes in abundance related to these mechanisms tend to be more subtle, and are unlikely to lead to a sudden, dramatic change in abundance. An examination of sediments in nearby Hobiton Lake (Holtham et al. 2004) indicated no precipitous decline in abundance over the same period, further indicating that the influence on ^{15}N levels in Ash sediments may not be from a broadly geographical influence. Climate changes have also likely influenced freshwater survival rates as hydrographs in the region show detectable changes in duration of summer low flow period and declines in summer base flows (Leith and Whitfield 1998). However, the link to fish production is weak and would nevertheless be expected to be gradual, rather than the than the precipitous abundance changes inferred from $\partial^{15}N$ trends observed in these lake sediments. Land use may also have had an influence, as much of the region is subject to intensive forest harvesting. However, like other influences discussed here, changes in land use are likely to have led to gradual changes in fish production, rather than sudden, sharp declines. We believe that harvest, climate changes and land use are unlikely explanations for the dramatic decline in $\partial^{15}N$ levels observed in sediments from three of four lakes in the Ash watershed.

The interpretation of rapid declines in $\partial^{15}N$ and the temporal coincidence with hydropower development is in part dependent on adequate dating of sections within our sediment cores. Ideal conditions for ^{210}Pb dating include seepage inflows, constant sedimentation rates and an absence of sediment mixing (Appleby 2001). Our cores were taken from the deepest portions of the study lakes, which are the areas of the profundal zone most likely to satisfy these preferred conditions for analysis. But some of the study lakes are small and shallow, and it is possible that the pelagic areas of some of the lakes are subject to influences of strong inflow currents and events on adjacent lands. For example, the ^{210}Pb profiles showed departures from the ideal log-linear relationship, particularly the profiles from McLaughlin and Nahmint Lakes. These profiles had "kinks" that indicate some sediment mixing, perhaps due to previous slumping of profundal sediments or sediment focussing from intensive inflows. However, the CRS model for dating sediments is remarkably robust, as shown by Appleby et al. (1979), and it is unlikely that additional sampling would markedly improve the confidence in our dating data. The strong concordance in timing of $\partial^{15}N$ declines among lakes in the Ash watershed, and the very different temporal patterns observed in the control lakes (Nimnim and Nahmint) indicates that the dating procedure is sufficient to describe similarities and differences in trends among lakes, and the timing of declines is repeatable across the three lakes that showed declines.

Conclusion.— The physical disruption of fish migration is a well-known impact associated with the construction of dams. Stable isotope trends in lake sediments within the Ash watershed indicate declines in ^{15}N, a marine-derived nutrient associated with anadromous fish. The timing of this decline is broadly concurrent with the known timing of hydropower development on the Ash River. We interpret these data as strong evidence that anadromous fish were extirpated from the upper Ash River due to lack of adequate fish passage facilities in the hydropower dam. Our data also provide evidence that migration to areas downstream of the dam were affected, likely by changes in flow regime. Studies similar to ours have been most commonly carried out on large lakes with abundant runs of sockeye (e.g., Finney et al. 2000, Finney 2002, Holtham et al. 2004). The stable isotope signals in our study lakes were detectable with standard techniques despite the relatively small size of the lakes, their high flushing rate, and run sizes that were likely relatively modest. Our results suggest that it should be possible to further explore trends of smaller salmonid stocks associated with trends in fishing, land use and water use to understand historic abundance and distribution of Pacific salmon stocks.

RECOMMENDATIONS

Recommendations based on results of this project include acknowledgement of historic fish distributions in the Ash River watershed and incorporation of the findings into ongoing decision processes for fish passage options at the Ash hydropower facility.

ACKNOWLEDGEMENTS

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TABLES

Table 1. Summary of biophysical features of the six study lakes. Species recorded are those noted in the BC Ministry of Environment fish observation database, and do not necessarily include historic presence. CAS = slimy sculpin (*Cottus asper*), CT = cutthroat trout, DV = Dolly Varden, KO = kokanee, RB = rainbow trout, ST = steelhead. Some observations may have occurred after stocking programs. Elsie Lake data are post-impoundment observations; pre-impoundment lake area was 271 ha.

Lake	Elevation (m)	Area (ha)	Max depth (m)	Mean depth (m)	Species recorded
Dickson	201	119.4	16	4.9	DV, RB, ST
Elsie	337	672	20.7	7.8	CT, RB, ST
Oshinow	414	263.5	81	42.2	CT, RB
McLaughlin	219	41.1	27.7	10.2	CT, DV
Nimnim	469	44.9	24.4	6.4	RB, ST
Nahmint	106	799	150	78.8	CT, DV, KO, CAS, RB, ST

Table 2. Two-way ANOVA comparing replicates treated with acid for carbonate extraction.

Source of variation	df	MS	F	P
Acid Treatment	1	0.632	3.320	0.081
Lake	5	10.044	52.750	3.64E-12
Interaction	5	0.234	1.231	0.325
Total	35			

Table 3. Welch-modified t-tests comparing $\partial^{15}N$ in sediments prior to and after 1958.

Lake	Mean before 1958	Mean after 1958	t	df	p
Dickson	1.765	1.694	0.526	17.53	0.606
Elsie	2.195	1.827	2.948	12.52	0.0117
Oshinow	1.223	0.664	4.393	21.065	0.0003
McLaughlin	1.812	1.472	4.487	12.578	0.0007

Nimnim	2.301	2.429	-1.548	23.93	0.135
Nahmint	-0.871	-1.286	1.410	15.726	0.178

Table 4. Pearson correlations between C:N ratios and $\partial^{15}N$ concentrations in lake sediments.

Lake	**r**	**t**	**df**	**p**
Dickson	-0.688	-4.446	22	0.0002
Elsie	-0.696	-4.646	23	0.0001
Oshinow	0.17	0.915	28	0.368
McLaughlin	-0.544	-3.04	22	0.006
Nimnim	0.009	0.0454	25	0.964
Nahmint	-0.325	-1.375	16	0.188

FIGURES

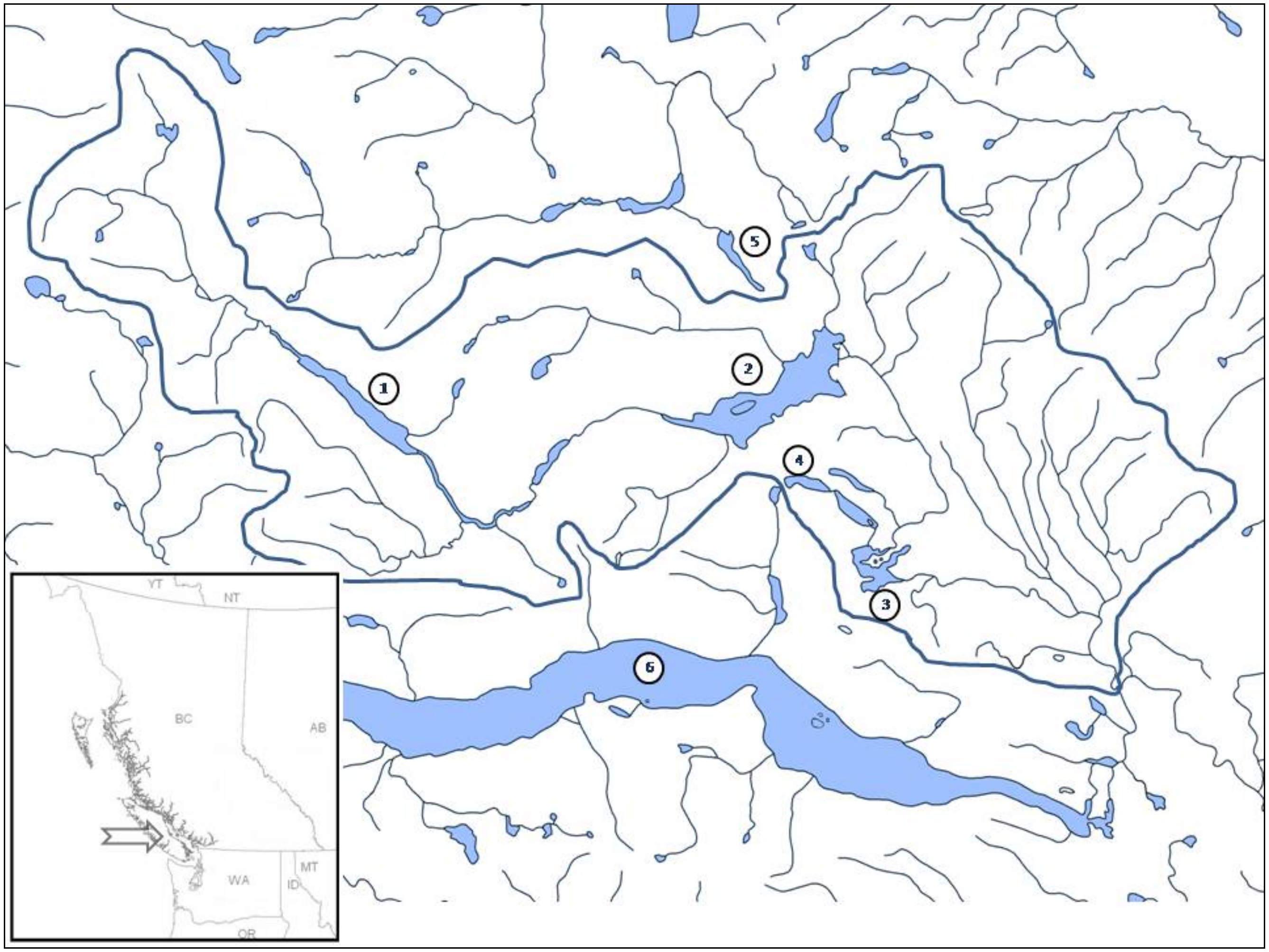

Figure 1. Approximate watershed boundary for the Ash watershed, with key streams and lakes indicated. Inset indicates the approximate location of the watershed on Vancouver Island. 1. Oshinow Lake, 2. Elsie Lake Reservoir, 3. Dickson Lake, 4. McLaughlin Lake, 5. Nimnim Lake, 6. Great Central Lake. Not shown in the figure is Nahmint Lake, which is morphologically similar to Oshinow. The outlet of Nahmint Lake is 21.8 km south of the outlet of Great Central Lake.

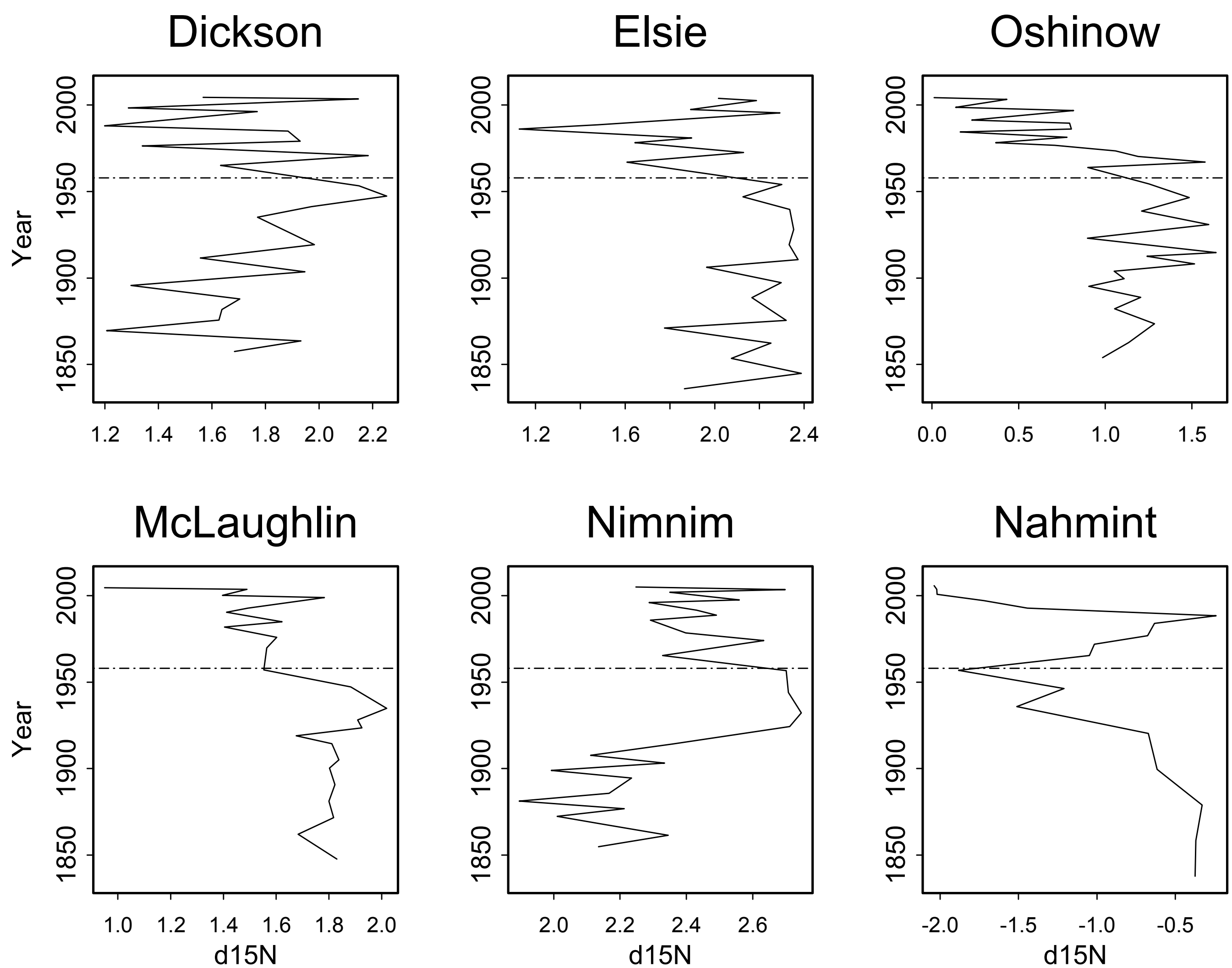

Figure 2. Trends in $\partial^{15}N$ for the six study lakes. Dates used are those calculated using the CRS model. The year of Elsie Dam commissioning, 1958, is indicated by a dashed horizontal line.

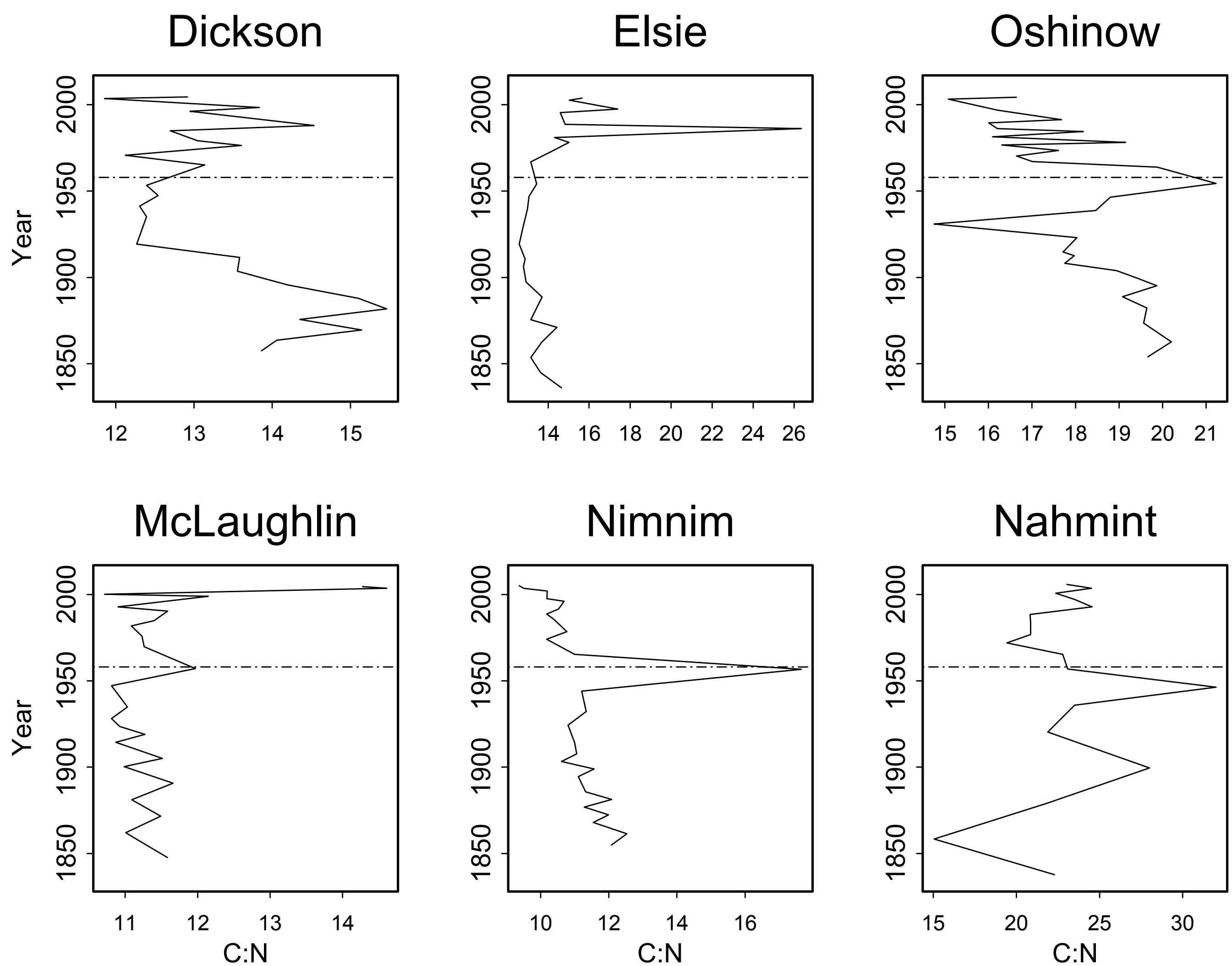

Figure 3. Trends in C to N ratios for the six study lakes. Dates used are those calculated using the CRS model. The year of Elsie Dam commissioning, 1958, is indicated by a dashed horizontal line.

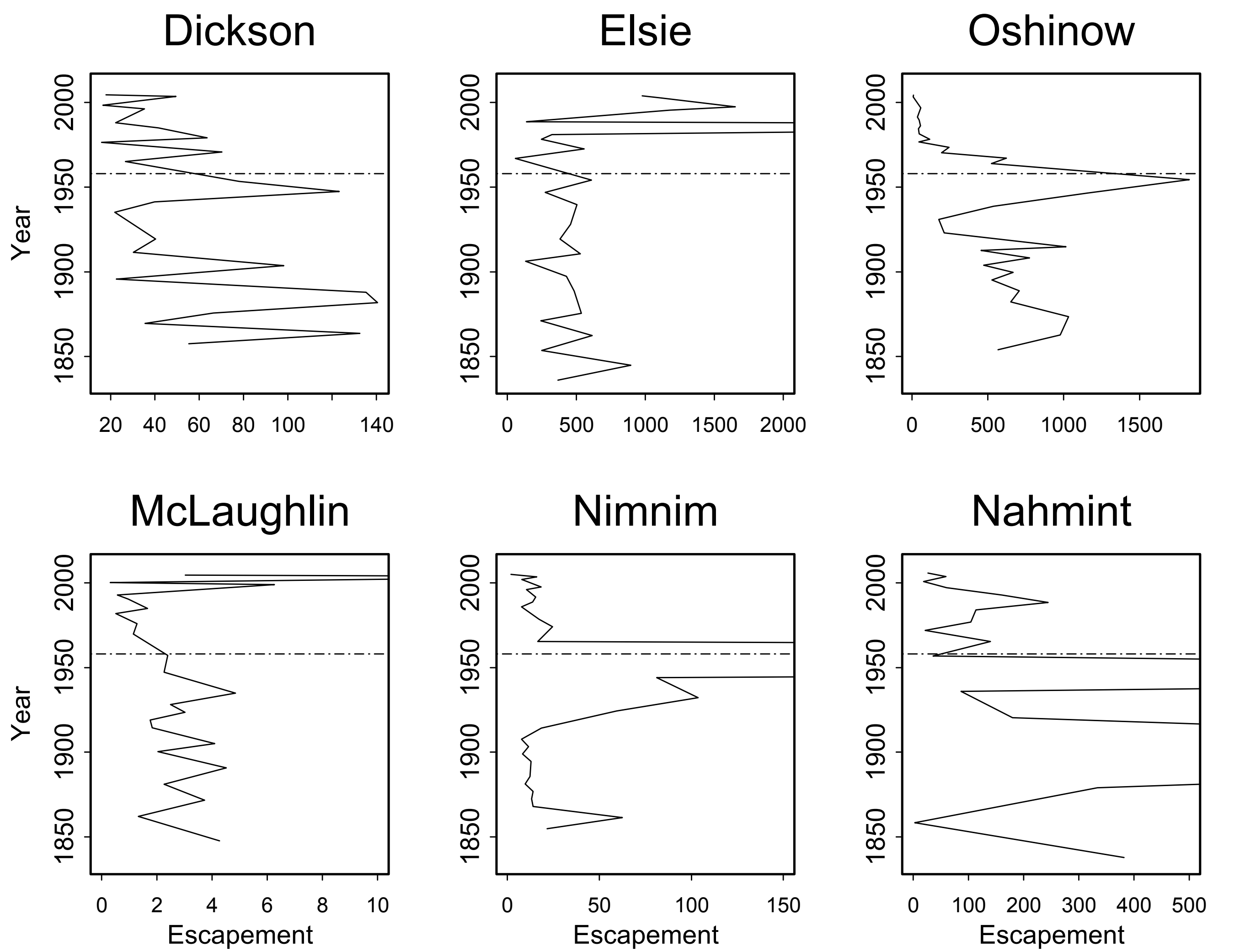

Figure 4. Trends in escapements for the six study lakes as calculated using the escapement model of Bos 2007. Dates used are those calculated using ^{210}Pb data and the CRS model. The year of Elsie Dam commissioning, 1958, is indicated by a dashed horizontal line. To show detail in trends at lower values, one outlier has been clipped from graphs of Elise, McLaughlin and Nimnim, and two outliers from Nahmint.

Appendix I. Financial Statement

Appendix II. Performance Measures-Actual Outcomes

Project # 06.Ash.04

Performance Measures – Target Outcomes												
			Habitat (m^2)									
Project Type	**Primary Habitat Benefit Targeted of Project (m^2)**	**Primary Target Species**	Estuarine	In-Stream Habitat – Mainstream	In-stream Habitat – Tributary	Riparian	Reservoir Shoreline Complexes	Riverine	Lowland Deciduous	Lowland Coniferous	Upland	Wetland
Impact Mitigation												
Fish passage technologies	Area of habitat made available to target species											
Drawdown zone revegetation/stabilization	Area turned into productive habitat											
Wildlife migration improvement	Area of habitat made available to target species											
Prevention of drowning of nests, nestlings	Area of wetland habitat created outside expected flood level (1:10 year)											
Habitat Conservation												
Habitat conserved – general	Functional habitat conserved/replaced through acquisition and mgmt											
	Functional habitat conserved by other measures (e.g. riprapping)											
Designated rare/special habitat	Rare/special habitat protected											
Maintain or Restore Habitat forming process												
Artificial gravel recruitment	Area of stream habitat improved by gravel plmt.											
Artificial wood debris recruitment	Area of stream habitat improved by LWD plcmt											
Small-scale complexing in existing habitats	Area increase in functional habitat through complexing											
Prescribed burns or other upland habitat enhancement for wildlife	Functional area of habitat improved											
Habitat Development												
New Habitat created	Functional area created											

Note: This was a research project and did not build physical works to restore or enhance habitat.

Appendix III. Confirmation of BCRP Recognition

This project is one of a suite of projects devoted to assessing passage feasibility on the Ash River in relation to hydropower development. The final report will be distributed to the Alberni Valley Aquatic Resource Group (AVARG), Ministry of Environment, Fisheries and Oceans Canada, and BC Hydro. The results will also be presented and discussed as part of a final meeting in relation to BCRP Project 05.Ash.04 (Ash River Passage Feasibility); participants in the meeting will include Hupacasath First Nation, AVARG, Ministry of Environment, Fisheries and Oceans Canada, and BC Hydro.

The results are currently being prepared for submission for publication in a scientific journal.