Alouette Project Water Use Plan

Kokanee Age Structure Analysis

Implementation Year 5

Reference: ALUMON-6

Alouette Lake WUP Monitor 6: Kokanee Population Analysis

Study Period: 2012 - 2013

Redfish Consulting
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Alouette Kokanee Age structure Analysis

(ALUMON#6)-2013

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ALOUETTE KOKANEE AGE STRUCTURE ANALYSIS (ALUMON#6)-2013

March 2014

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And

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Cover Photo: 'Photo of the Alouette Reservoir during the fall of 2012.' Photograph taken on the 9th of October 2013 by Greg Andrusak.

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EXECUTIVE SUMMARY

This report summarizes results of the sixth year of a multi-year investigation referred to as the Kokanee Age Structure Population Analysis aimed at addressing potential impacts of reservoir operations on the Alouette Reservoir kokanee population. This study is one component of the monitoring program developed under the BC Hydro Alouette Reservoir Water Use Plan (WUP) aimed at determining whether the current kokanee population is demonstrating recruitment limitation and whether any identified recruitment limitation is related to reservoir operations. Three questions to be addressed by this study include: 1) is the existing kokanee population in the Alouette Lake Reservoir recruitment limited? 2) if there is evidence of a recruitment constraint to productivity, is it linked to reservoir operations? and 3) if found linked to reservoir operation, what is the nature of the relationship and can it guide development of alternative mitigative reservoir operations?

Lack of data on the kokanee spawning population in the Alouette Lake Reservoir (ALR) required the use of gillnet and hydroacoustics data in development of models to assess whether the population is recruitment limited and whether reservoir fluctuations during the spawning and incubation period impact subsequent fry and adult abundance. This model based approach utilized a size-at-age model of kokanee collected from gillnet data from 2000-2013 to determine if the population's size-at-age is stable or decreasing with optimized reservoir productivity. Analysis of the size-at-age modeling indicates potential compensatory mechanisms regulating age 3+ kokanee. The kokanee population has undergone a substantial increase since 2000, while the average kokanee size from 2000 to 2004 has subsequently declined before stabilizing at the present level around which there are inter-annual fluctuations. However, the relation between abundance and size of kokanee in the reservoir is relatively weak and not significant and this suggests that other factors related to reservoir productivity and/or food quality maybe influencing the compensatory mechanisms.

Stock recruitment models were developed in a Bayesian framework for interpreting the effect of reservoir fluctuations on fry abundance. Analysis revealed that modeling the contribution of spawning stock (age 2+ and 3+) to the age-0 population, using a non-linear Beverton-Holt relationship, predicted the average carrying capacity of fry of 168,114 (95% CRI 129,691-235,038). This spawner-recruit model also predicted that severe reservoir drawdown <u>may</u> limit

recruitment and the reproductive success of the ALR kokanee population. In contrast, the second model analyzed age 0 (fry) and age 1+ (recruits) and the predicted outcome was a peak recruitment of 49,061 (95% CRI 36,126-73,333) age 1+. The second model indicates that elevation changes during the kokanee spawning and rearing period does not limit recruitment of kokanee at the age 1+ stage. Both models indicated that density dependent factors likely regulate the population abundance of both age-0 and age-1 fish. As with previous years, estimated age 0+ and age 1+ numbers are considered conservative since separation of age classes from hydroacoustic data may not be reliable.

Analysis of data suggests that the ALR kokanee population is likely regulated by compensatory mechanisms. Size-at-age analysis suggests that hypothesis one ($H_0 1$) under the first management question cannot be rejected since the data displays a size structure that has stabilized after initial increases under higher lake productivity. In addition, the Hierarchical Bayesian stock recruitment model results also failed to reject hypotheses two ($H_0 2$) and three ($H_0 3$) under management questions two and three. However, it is important to note the model identified the possibility of a recruitment limitation to the ALR kokanee population due to reservoir operations, not previously observed. Potential for emigrations of kokanee from reservoir operations, specifically through the spillway during volitional migration success studies may also impact the kokanee population which could potentially persist through that cohort's life stage. However, it is acknowledged that there is considerable uncertainty in modeling the kokanee data which can ultimately limit the ability to detect impacts from reservoir operations. On the other hand, limited spawning habitat in this reservoir also cannot be ruled out due as a limiting factor to kokanee recruitment within the ALR. Despite the limitations of the hydroacoustics data, the information is deemed adequate enough for modeling purposes to gain informative insights into some of the mechanisms regulating the kokanee population on ALR.

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INTRODUCTION

The Kokanee Age Structure Population Analysis (ALUMON #6) is a multi-year study to address potential impacts of reservoir operations on the reservoirs' kokanee (*Oncorhynchus nerka*) population (BC Hydro, 2009). As part of the under the Alouette Reservoir Water Use Plan (WUP), the focus of the study is to address whether the current kokanee population is recruitment limited and whether any identified recruitment limitation on reproductive success is related to BC Hydro dam operations. The reservoir has demonstrated an increase in productivity and fish abundance since the implementation of the nutrient restoration program in 1999 (Herbert et al., 2013), but there is a concern that reservoir operations may be limiting the kokanee population from reaching full capacity as a result of BC Hydro operations. Confounding the ability to assess the effects of hydro operations on the kokanee population has been the deliberate release of nerkids from the reservoir through water withdrawals at the dam spillway and the planned re-introduction of anadromized kokanee/sockeye (Plate et al., 2014) .

Kokanee populations are often regulated by density dependent processes which display compensatory growth responses to variations in stock densities (Rieman and Myers, 1992). As well, the carrying capacity of the lacustrine environment which they inhabit is often regulated by "bottom up" processes associated with lake/reservoir productivity (Rieman and Myers, 1992). However, reservoir formation and operations have adverse “footprint” and “operational” effects upon fish populations over time (Matzinger et al., 2007; Moody et al., 2007; Stockner et al., 2005, 2000). Determining whether reservoir operations could potentially limit recruitment of Alouette kokanee through impacts to reproductive success under increased productivity, are key management questions under the ALR WUP.

With the exception of McCusker et al. (2003), assessment of possible impacts of reservoir operations on the kokanee population has been limited and has relied upon analysis of information from available hydroacoustic and gillnet data obtained in the reservoir (MFLNRO and MOE data on file; Andrusak and Irvine 2013). However, in the fall of 2012, surveys were conducted in order to determine spawner timing and abundance, and redd abundance and distribution in the Alouette Reservoir (Andrusak and Irvine, 2013), similar to that on the West Arm of Kootenay Lake (Andrusak and Andrusak, 2013). The 2012 snorkel survey results were limited with no spawners observed resulting in no new information on the shore spawning population of kokanee in the reservoir (Andrusak and Irvine, 2013) .

The 2013 study is a summary of results over the past five years and is part of the larger monitoring protocol developed by the Alouette Water Use Plan Consultative Committee under the Alouette Reservoir Water Use Plan (WUP). In this years' report, a hierarchical Bayesian analysis was conducted, utilizing a stock recruitment model and a size-at-age model, from hydroacoustic and gillnet survey data (1998-2013) collected on the reservoir to address management questions posed by the ALR WUP described below.

Management Questions and Hypotheses

The management questions outlined in the WUP terms of reference were as follows:

1) Is the existing kokanee population in the Alouette Lake Reservoir recruitment limited?

2) If there is evidence of a recruitment constraint to productivity, can it be linked to reservoir operations, in particular the extent of reservoir fluctuations during the spawning and incubation period (deemed to be mid-October to the end of February)? and;

3) If found linked to reservoir operation, what is the nature of the relationship and can it guide the development of possible mitigative reservoir operations?

The key uncertainty identified is in the relationship between reservoir operations and recruitment potential of kokanee in Alouette Lake reservoir.

The hypotheses that flow from these management questions are:

$H_0$1: Once standing crop has stabilized with the annual addition of fertilizer, the size-at-age of the kokanee population remains stable or decreases with time.

$H_0$2: Drops in fry abundance, relative to estimates in previous years and to that predicted by estimates of mature kokanee, are uncorrelated with the extent of the reservoir fluctuations during the spawning and incubation period.

$H_0$3: Drops in fry abundance observed in one year do not persist through time to cause an impact on the abundance of mature kokanee.

BACKGROUND

The Alouette Reservoir is a comparatively small system with a sizeable average drawdown of nearly 6 m. Fish surveys that are on-going indicate that kokanee are the most abundant sport fish followed by rainbow trout with non-game fish seemingly far more abundant, particularly peamouth chub (*Mylocheilus caurinus*), northern pike minnow (*Ptychocheilus oregonensis*), redside shiner (*Richardsonius balteatus*) and various species of sucker (*Catostomus spp.*) [Harris et al. 2013]. Annual nutrient additions to the reservoir commencing in 1999 resulted in an initial response in kokanee growth and abundance that has since stabilized at slightly higher levels than the pre-nutrient era (Herbert et al., 2013). Re-andromization of sockeye salmon has recently been documented (Plate et al., 2014) and their planned releases into the reservoir complicate assessment of reservoir operations on the kokanee population thus future study will necessarily reference the nerkid population rather than simply kokanee. i.e. attempting to separate kokanee from juvenile sockeye would be difficult, very expensive and regardless, both are subject to the same influences of reservoir operations.

Generally speaking reservoir operations tend to impact the lower reaches of spawning streams especially for those fish species that spawn in the spring when reservoirs are usually low but filling with capture of spring runoff. i.e. redds are subjected to inundation that often results in lower egg-to-fry survival. Fall spawning fish such as kokanee are faced with receding reservoir levels and this is particularly problematic for shore spawning kokanee as documented on Okanagan Lake (Andrusak et al., 2005) and the West Arm of Kootenay Lake (Andrusak 2013). Assessment of Alouette Lake Reservoir influences on kokanee production has been severely limited due to the lack of information on kokanee spawning and spawner metrics. The only observations of spawning was by McCusker et al. (2003) who observed limited shore spawning at depths at least 5 m below average full pool. No estimates of spawner numbers or their metrics such as length or fecundity have been reported. Furthermore, no stream spawning has been recorded and a follow up snorkel survey of the shore line by Andrusak and Irvine (2013) proved to be inconclusive with no spawning observed at depths < 5 m. Deep water spawning must be the norm inferred from recent observations of tagged sockeye salmon located at depths of about 30 m (Plate et al., 2014). Deep water (30-50 m) kokanee spawning has also been confirmed in East Barriere Lake (Andrusak and Morris, 2005) while (Morris and Caverly, 2004) found kokanee spawning at depths of 20-70 m in Anderson and Seton lakes believed to be attracted to thermal plumes that would have temperatures suitable for successful spawning.

STUDY AREA

Alouette Lake Reservoir

Alouette Lake Reservoir (ALR) was created with the construction of a low level dam at the south end of the lake from 1925 to 1928. The reservoir is 1656 ha in area at full pool and has an average drawdown range of 5.7 m (2002-2011). ALR is located in the Coast Mountains at 49°17′N, 122°29′W, about 16 km northeast of Maple Ridge, in a steep-sided glacial trench (Figure 1; BC MOE on file). The reservoir is comprised of two basins separated by a narrow section approximately 9 km upstream from the dam. Alouette Reservoir elevations range between the normal maximum elevation of 125.51 m at full pool (Figure 2), above which water flows over the crest of the dam spillway, and the minimum elevation of 112.6 m near low pool (Figure 3), based on licensed storage, providing 147 x 10^6 m^3 of active storage volume (Table 1). The normal operating minimum is 116 m due to turbidity problems with the low level outlet flows when the reservoir level drops below 116 m (BC Hydro, 1996). A spring surface release occurs from April 15th to June 14th to allow for the experimental release of kokanee smolts. The reservoir elevation is kept above 122.5 m from June 15th to Labour Day (Sept 5th) for recreational purposes. The new water use plan allows for a short shoulder season where the reservoir elevation will be at 121.25 until September 15.

Table 1. Alouette Reservoir morphometric information. Source: Burrard Power Company (1923), BCF (1980), BC Hydro Survey and Photogrammetric Dept.

Metric	Original Lakes	Full Pool	Minimum Operating Level	Basin North	Basin South
Surface elevation (m)	113	125.51	112.6	123[a]	123[a]
Area (ha)	1,410	1,656	1,507	491	1,131
Total volume (m^3 x 10^6)		1,306	1,151		
Active volume (m^3 x 10^6)		147	0		
Length, max (km)			17[b]	6.7	10
Width, max (km)			1.6[b]	1.2	1.6
Width, mean (km)		0.95	0.87	0.73	1.13
Depth, max (m)		152	141	149	138
Depth, mean (m)		78.4	77.2		
Shoreline (km)			37.5[b]		

[a] average summer elevation
[b] from BCF map at reservoir elevation of approx. 117 m.

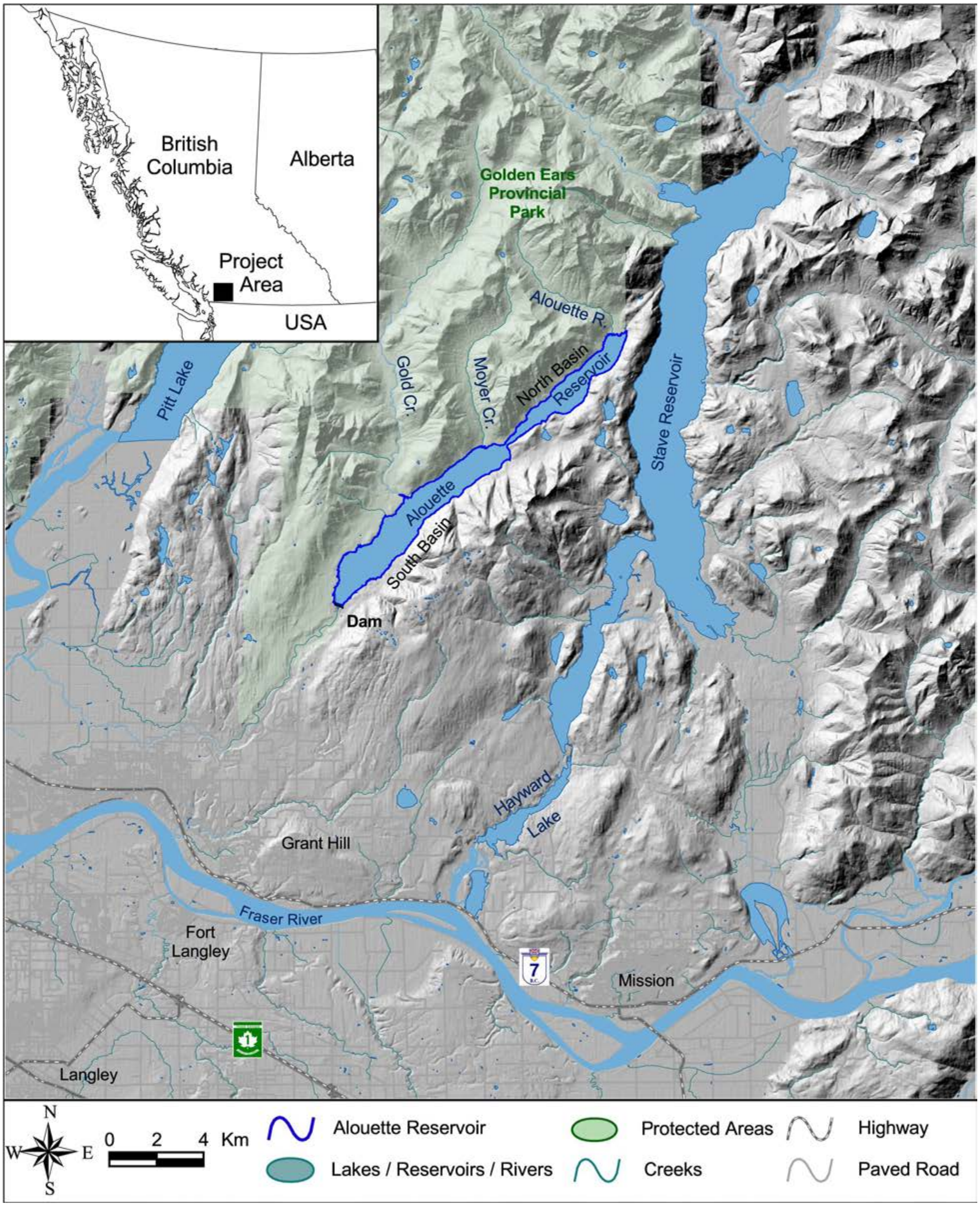

Figure 1. Location of Alouette Lake Reservoir.

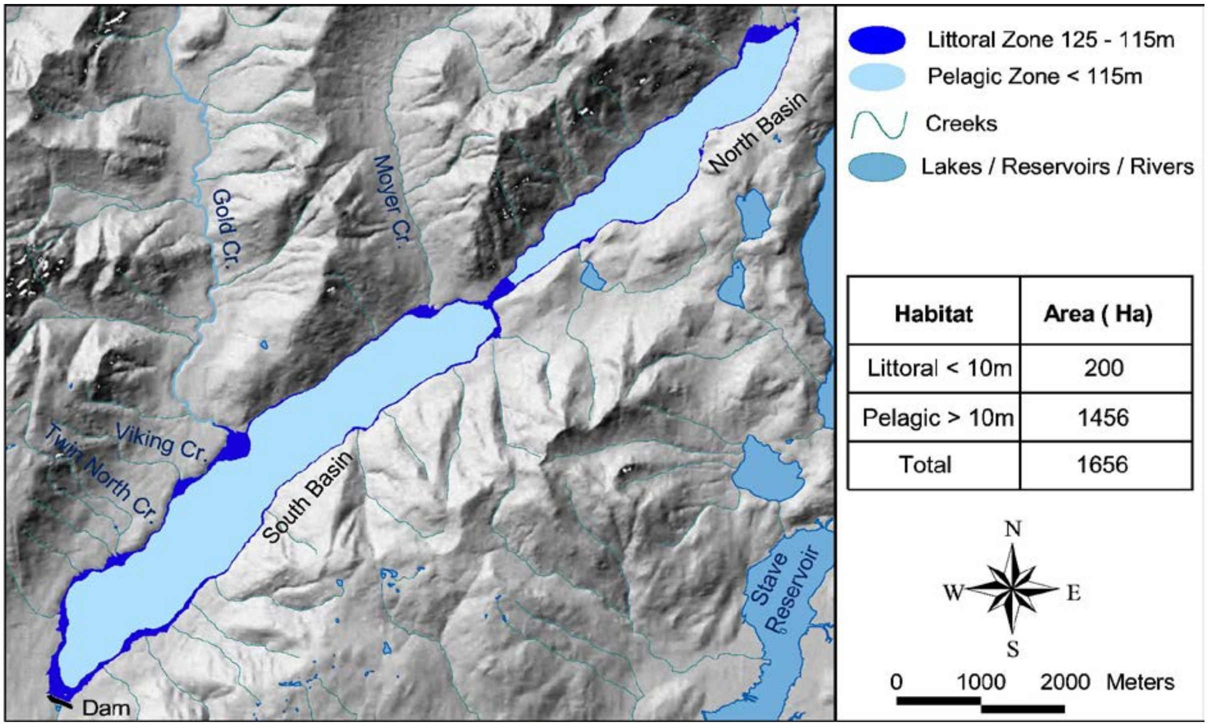

Figure 2. Maximum operating level (125 m) for Alouette Lakes Reservoir**.**

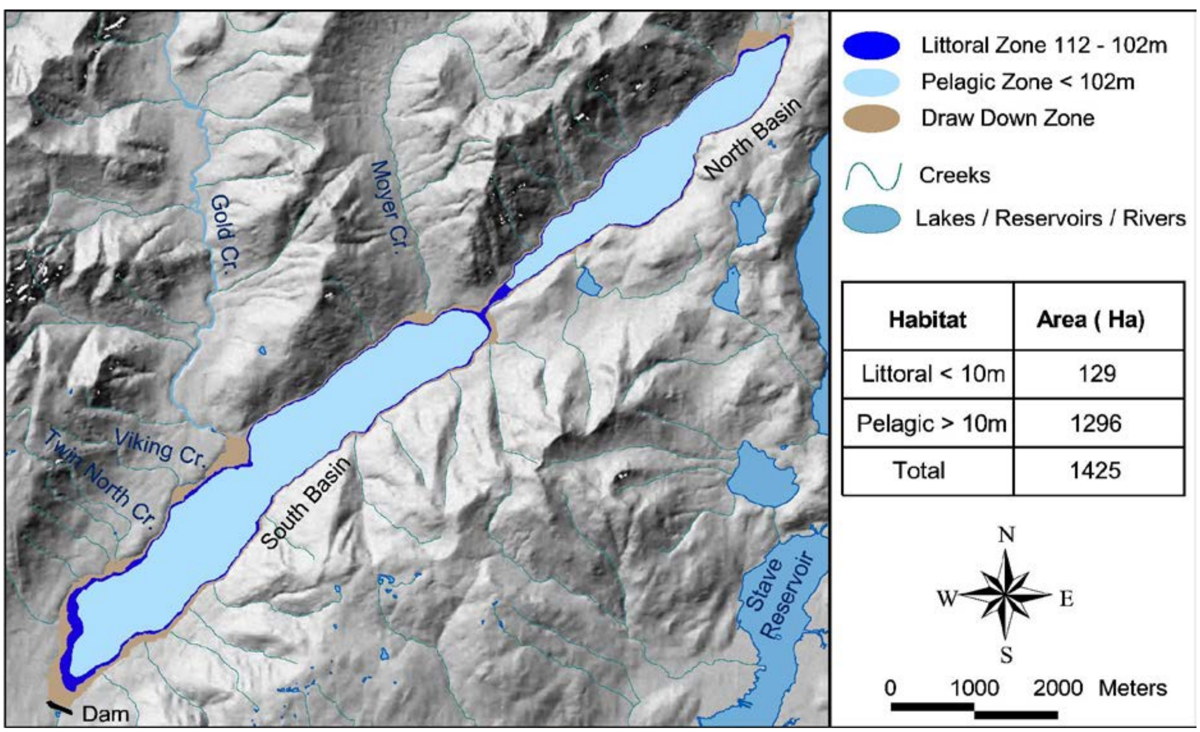

Figure 3. Minimum operating level (112 m) for Alouette Lakes Reservoir. Note drawdown zone and/or potential zone of impact for shore spawning kokanee.

METHODS

Gillnet data

Gillnet data collected from 1998 to 2013, was used to assess the influence of various factors on kokanee size-at-age (Figure 4). Near-shore gillnetting was completed from 1998 to 2009, as part of the reservoir nutrient restoration program (RNRP), to assess the response to fertilization (Harris et al., 2013). In the fall of 2008 and 2009, gillnetting methodology included pelagic netting overlapped by near-shore netting to assess changes in methods. The pelagic netting (WUP) methods were designed to corroborate the hydro-acoustic data in order to address the WUP management questions and this pelagic netting approach will be used in future sampling. The effect of netting methods was assessed to see if there is a difference between the two methods in their size selectivity.

Captured kokanee were aged using scales collected during 1998-2013. The actual data analyzed excluded the 4+ and 5+ aged fish due to small sample sizes. Of the > 1,300 fish that have been aged using scales over the course of the study, 3 were classified as age 5+ fish and 94 as age 4+ fish. Kokanee older than 3+ only comprised 7.2% of the aged population. The sex of the fish was also modeled to account for any dimorphism due to gender. The analysis only considered data from 3+ year old fish, considered the most common age at which sexual maturity is reached in this system and the age on which previous analyses have been completed (see Harris et al., 2013).

In order to scale the size-at-age of kokanee in relation to the nutrient loading (and associated productivity) of the reservoir resulting from the fertilization program, a loading coefficient was modeled. The fertilization program commenced in 1999, so data prior to 1999 were excluded. The nutrient data quantified the kilos per year of agricultural grade liquid ammonium polyphosphate and urea-ammonium nitrate added to the system. In order to calculate the nutrient loading scalar, the ratio of added N:P was averaged over the last three years of the fertilization program in order to obtain an optimum ratio for the added fertilizers. This optimum ratio was calculated as 7.45 for the years of 2009-2013 inclusive. This is the same optimum ratio as for the previous three-year period of 2008-2010 inclusive. This value was then multiplied by the nutrient with the lower value in the ratio (P) in order to scale the two nutrients. The minimum scaled total N or total P was then selected for each year as a gross estimate of nutrient loading for inclusion in the model.

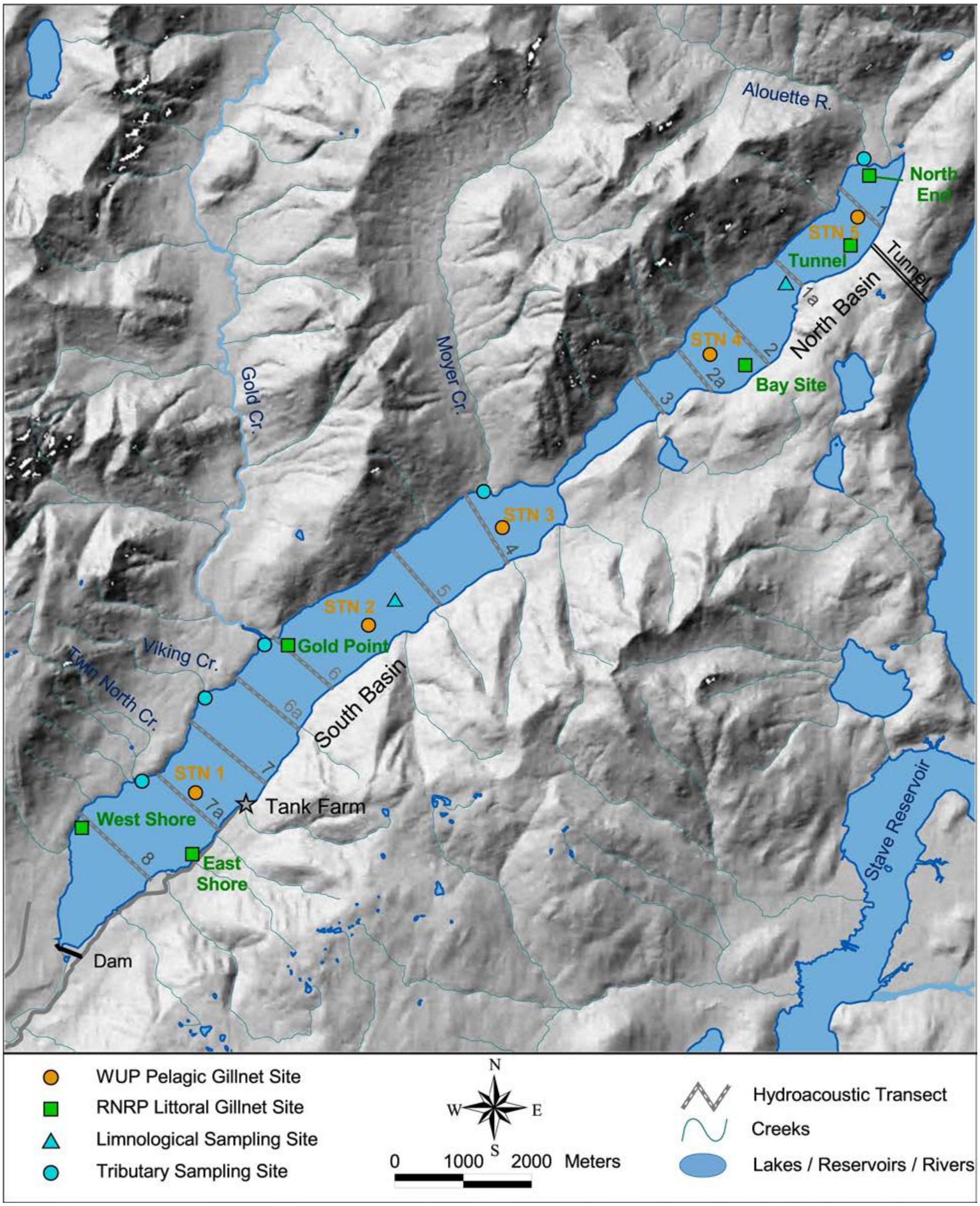

Figure 4. Locations for pelagic gillnetting (WUP; 2008-2013), littoral gillnetting (RNRP; 1998-2009), reservoir water sampling and tributary water sampling on the Alouette Lakes Reservoir

There are several definitions that could be utilized to define the point at which standing crop stabilized in Alouette Lake Reservoir. The most logical point when a stabilized standing crop would occur would likely be the point at which the fertilizer program was refined to address the concern of nitrogen limitation in 2003 (Harris et al. 2007). However, this would leave only 9 years of data with which to fit a model with five fixed effects and two random effects, which becomes somewhat marginal. In order to maximize the data, the first year in which the nutrient loading coefficient was above 24,000 was selected. Since 2000, the nutrient loading coefficient has remained within the range of 24,000-31,935 with an average value of 28,008 therefore selecting 2000 as the starting point for analysis gives three more years of data for model fitting.

Timing and location of sampling can add substantial variation to gillnetting data. To determine if the time of year of gillnetting affected the size-at-age of kokanee captured, day of year for each date when gill netting was completed was modeled. Due to the seasonal nature of the sampling, the data for day of year were clustered during three times in the year with the bulk of the data split between two time periods rather than spread throughout the year. Inter-annual variability and sampling location were also modeled.

Hydroacoustic data

Hydroacoustic data collected from 2001-2013 was used to provide the limnetic abundance of kokanee in the Alouette Lake Reservoir. The hydroacoustic data collected prior to 2001 were not used as they were not considered equivalent for this purpose due the different hydroacoustic equipment (single beam vs. split beam) used (Tyler Weir, MFLNRO Stock Assessment Biologist, Victoria BC, pers. comm.). Acoustic data are collected at 12 transect locations evenly spaced along the length within the north and south basins of Alouette Lake Reservoir (Figure 4).

Acoustic data (2001-2013) was collected using a Simrad model EK60 120 KHz split beam system. The downward looking transducer was towed on a planer alongside the boat at a depth of 1 m, and data were collected continuously along survey lines at 2-5 pings$\cdot s^{-1}$ while cruising at ~2 $m \cdot s^{-1}$. Navigation was by radar, GPS, and a 1:75,000 Canadian Hydrographics bathymetric chart. Echograms for each transect were analyzed from surface to 50 m depth in 10 equal depth layers (allowing an exclusion zone of surface to 3 m in the shallowest layer). The fish densities in number$\cdot$ha^{-1} for each transect and depth strata were output in 1-decibel (dB) size groups and compiled on an Excel spreadsheet. Further detail of hydroacoustic survey methods can be found in Harris et al., (2013).

The hydroacoustic data was interpreted and analyzed from transect information taken from a depth layer > 10 m (2001-2011 & 2013) and > 5 m (2012) which comprise the majority of kokanee (Herbert et al., 2013). Assignment of target strength to age of kokanee varied by year and age class of kokanee from 2001-2013 (see section below). As well, in order to account for the proportion of kokanee recruits in the limnetic area > 10 m obtained from trawl sampling, a scaling factor of 0.92 was used to multiply the number of fish in the decibel ranges used. While there are year specific estimates for the proportion of kokanee recruits from the trawl sampling within the limnetic area (> 10 m), only the average of 0.92 was utilized for the purpose of this analysis since trawl information had not been analyzed at time of writing.

Management hypotheses 2 and 3 required assessing whether reservoir operations affect recruitment so the abundance data were modeled in relation to a measure of reservoir fluctuations. The reservoir operations were incorporated into the analysis by calculating the sum of all declines in the reservoir level over the spawning and incubation period for each year. Increases in the reservoir level were not considered to be an issue since dewatering of redds and reduction of rearing habitat would not occur.

Limitations and Data Assumptions

All data for the modeling of recruitment and its relationship to reservoir productivity were provided by the Ministry of Environment and the Ministry of Forests, Lands and Natural Resource Operations (MFLNRO). Data included hydrologic and nutrient loading information as well as fish biometrics, gillnet catches, daily reservoir elevations and hydroacoustic estimates.

Recent refinement of the method used to analyze the hydroacoustics data provided by MFLNRO staff has improved the ability to synthesize kokanee population dynamics on ALR. Target strength (dB) ranges based on kokanee size-at-age information from trawl surveys have increased the ability to understand the kokanee age structure in the reservoir. While improvements have been made analyses of hydroacoustic and trawl data are still confronted by substantial uncertainties confounded by a number of factors including: 1) temporal and spatial distribution of other species in the pelagic zone, 2) losses of a proportion of the population due to entrainment 3) inability of hydroacoustics to separate older kokanee age classes (e.g. 2+ vs. 3+), 4) limited ability of trawling to obtain accurate species compositional estimates under low densities a and 5) lack of information on kokanee spawning population distribution and abundance (Herbert et al., 2013).

In the absence of kokanee spawner biological, distribution and abundance data, several assumptions have been made. These include:

- Age at maturity as derived from the hydroacoustic data was defined as age 2+ (three summers of growth) and age 3+ fish (four summers of growth); age at maturity from the gillnet data was defined as age 3+ fish unless otherwise noted;
- Spawning habitat is assumed not to be limiting;
- Gillnet data are representative of the actual proportions of age 1-3 fish but does not account for the selectivity of gillnets and the bias associated with sampling using this method ;
- Inherent limitations in the equipment/software and inadequate size separation between older age classes of kokanee affect the ability to accurately estimate age structure for larger (1, 2 and 3+) kokanee using hydroacoustic data alone. These shortcomings may affect the reliability of the estimates, however given the lack of ancillary information this was considered the only viable alternative in addressing the management questions on ALR.
- Acoustic estimates from 2001-2008 assumed that 92% of all targets -61 to -48 dB range were kokanee fry (0+), targets -47 to -40 dB range were kokanee (1+) and targets -39 to -33 dB range were kokanee (2+ and 3+); from 10-50 m depths;
- Acoustic estimates in 2009-2011 assumed that 92% of all targets -61 to -46 dB range were kokanee fry (0+), targets -45 to -40 dB range were kokanee (1+) and targets -39 to -33 dB range were kokanee (2+ and 3+); from 10-50 m depths;
- Acoustic estimates in 2012 assumed that 92% of all targets -64 to -49 dB range were kokanee fry (0+), targets -48 to -42 dB range were kokanee (1+) and targets --41 to -33 dB range were kokanee (2+ and 3+); from 5-50 m depths;

- Acoustic estimates in 2013 assumed that 92% of all targets -64 to -47 dB range were kokanee fry (0+), targets -46 to -42 dB range were kokanee (1+) and targets --41 to -33 dB range were kokanee (2+ and 3+); from 10-50 m depths;
- 2012 hydroacoustic surveys were conducted in July compared to other years when survey was conducted in October. The July 2012 thermocline was higher than observed during October surveys in previous years. Pelagic gillnetting verified that the kokanee were concurrently higher in the water column as well, and confirmed that kokanee were exclusively present below 5 meters in 2012.
- Out-migrating kokanee at the dam spillway are representative of age structure in the reservoir in early spring before young-of-the-year (YOY) fry emerge; and
- Acoustic estimates were derived from data collected > 10 m (2001-2011 & 2013) and > 5 m (2012) because these data were considered good indicators of kokanee abundance during this time period and were likely to be less confounded by species distribution overlap (see Harris et al., 2013).

Analysis

Hierarchical Bayesian models (HBM) were fitted to: a) the size-at-age data from gill netting and b) the stock-recruitment data from the hydroacoustic data using R version 3.0.2 (R Core Development Team, 2013) and JAGS 3.3.0 (Plummer, 2012) which interfaced with each other via the jaggernaut (Thorley, 2014) R package , see Appendix 1). Additional information on hierarchical Bayesian modelling in the BUGS language is detailed in Kéry and Schaub (2011).

The models assumed vague (low information) prior distributions (Kéry and Schaub, 2011). The posterior distributions were estimated from a minimum of 10,000 Markov Chain Monte Carlo (MCMC) samples thinned from the second halves of three chains (Kéry and Schaub, 2011). Model convergence was confirmed by ensuring that Rhat was less than 1.1 for each of the parameters in the model (Kéry and Schaub, 2011). Model adequacy was confirmed by examination of residual plots.

The posterior distributions of the fixed parameters discussed in Kéry and Schaub (2011) are summarized below in terms of a *point* estimate (mean), *lower* and *upper* 95% credibility limits

(2.5th and 97.5th percentiles), the standard deviation (*SD*), percent relative *error* (half the 95% credibility interval as a percent of the point estimate) and significance (Kéry and Schaub, 2011).

The model results are displayed graphically by plotting the relationships between particular variables and the response (with 95% credible intervals) with the remaining variables held constant. In general, continuous and discrete fixed variables are held constant at their mean and first level values respectively while random variables are held constant at their typical values [expected values of the underlying hyper-distributions] (Kéry and Schaub, 2011). Where informative the influence of particular variables is expressed in terms of the effect size (i.e., percent change in the response variable) with 95% credible intervals (Bradford et al., 2005). Plots were produced using the ggplot2 R package (Wickham, 2009).

Size-at-Age

The size-at-age of 3+ kokanee from gill net samples was analyzed using a hierarchical Bayesian generalized mixed effects model. To assess the size-at-age of kokanee in relation to the nutrient loading and reservoir productivity a loading coefficient was modeled. The posterior distributions for the fixed parameters used in the size-at-age model are detailed in Table 2. Full model details are provided in Appendix 1.

Key assumptions of the size-at-age model include: 1) The productivity was calculated as the N:P ratio of 7.45 during 2008-2013 multiplied by the nutrient with the lower value in the ratio which was P. -Standing crop was considered to be stabilized in the year 2000 once the coefficient exceeded 24,000; 2) Size-at-age varies with productivity, the type of net set and a second order polynomial on year and 3) Size-at-age varies randomly with year and location within year.

Preliminary analyses indicated that the sex of the fish, day of the year and location were not significant predictors of size-at-age.

Table 2. The posterior distributions for the fixed parameters used in the size at age Bayesian model See Appendix 3 for full model details.

Variable/Parameter	Description
bLength	Intercept for log(eLength)
bLengthFYear[i]	Effect of i*th* FYear on log(eLength)
bLengthLocationFYear[i, j]	Effect of i*th* Location in j*th* FYear on log(eLength)
bLengthNetSet[i]	Effect of i*th* NetSet on log(eLength)
bLengthProductivity	Effect of Productivity on log(eLength)
bLengthYear	Effect of Year on log(eLength)
bLengthYear2	Quadratic effect of Year on log(eLength)
eLength[i]	Predicted length of the i*th* fish
FYear[i]	Year of capture of i*th* fish as a factor
Length[i]	Length of i*th* fish
Location[i]	Location of netting of i*th* fish
NetSet[i]	The net set type the i*th* fish was caught using
Productivity[i]	Centered productivity of year of capture of i*th* fish
sLength	SD of log-normally distributed residual lengths
Year[i]	Standardised year of capture of i*th* fish

Stock-Recruitment

Stock recruitment analysis has a particular data requirement of accurate and precise measures of the reproductive productivity of the mature population. While the best measure of this is the number of eggs spawned, alternative measures of spawning stock that are commonly used include average fecundity by age and proportion of each age class in a population, multiplying the number of mature females by the average fecundity or total biomass of mature individuals or an index of abundance of mature fish (Walters and Martell, 2004). Stock recruitment also requires an estimate of recruitment where this can refer to either the life stage at which the fish first become vulnerable to fishing gear or the population still alive any set time after the egg stage (Walters and Martell, 2004). All of these measures introduce uncertainty into the analysis before even beginning to assess recruitment (Walters and Martell, 2004).

The data used for stock-recruitment analysis (spawner to fry) were obtained through hydroacoustic surveys completed in water depths 10 m or greater from 2002-2011 & 2013. Data in 2012 was analyzed from 5-50 m. Spawners were defined as fish that were classified as age-2+ or age-3+ fish and recruits were fish classified as Age-0+ from the acoustic decibel ranges used by MNFLRO. To assess whether declines in fry abundance persist through time and cause an impact on the abundance of mature kokanee a stock-recruitment model was also developed where age-0 fish were the stock and age-1 fish were considered the recruits. This analysis provided an estimation of the carrying capacity of age-1 fish.

The spawner to fry and fry to age-1 data were analyzed using a Bayesian Beverton-Holt stock-recruitment model. A better understanding of the Beverton-Holt stock-recruitment model can be found in Myers (2001). A further understanding of the Beverton-Holt stock-recruitment model with a Bayesian inference is detailed in Michielsens and McAllister, 2004.

The posterior distributions for the fixed parameters used in the stock-recruitment model are detailed in Table 3. Full model details are provided in Appendix 1. Key assumptions of the stock-recruitment model include: 1) Fry numbers were multiplied by 0.92 to correct for non-kokanee detections; 2) Recruitment varies with stock as described by a Beverton-Holt curve; 3) Recruitment varies with the sum of all reservoir elevation declines from Oct 15 to Feb 28 and 4) The residual variation in recruitment is log-normally distributed.

Table 3. The posterior distributions for the fixed parameters used in the stock-recruitment Bayesian model. See Appendix 3 for full model details.

Variable/Parameter	Description
bAlpha	Density independent slope near Stock = 0
bAlphaPrior	Prior mean for bAlpha
bBeta	Density dependent parameter
bElevationalDrop	Effect of Elevational Drop on log(eRecruits)
ElevationalDrop[i]	Sum of reservoir drops from October to February
eRecruits[i]	Predicted number of recruits for i*th* stock
Recruits[i]	Number of recruits for i*th* stock
sRecruits	SD of log-normally distributed residual variation in Recruits
Stock[i]	The abundance of the i*th* stock

RESULTS

Reservoir Elevation 2013

The 2013 average reservoir elevation was 121.8 m (GSC), almost identical to the long term mean of 121.7 m since 1984 (Figure 5). Average reservoir drawdown was 5.03 m in 2013, slightly higher than 4.4 m drawdown in 2012 (Appendix 2). The reservoir was at an average annual elevation of 122.8 m (GSC) during the months of fertilization, usually late April-September (MOE on file). Following this period and similar to previous years (Herbert et al., 2013), the reservoir elevation declined precipitously as a result of operations. Significantly, the decline in reservoir elevation during the fall coincides with the spawning and incubation period (mid-October to the end of February) for shoal spawning kokanee in the reservoir as detailed in Figure 6 (BC Hydro 2009).

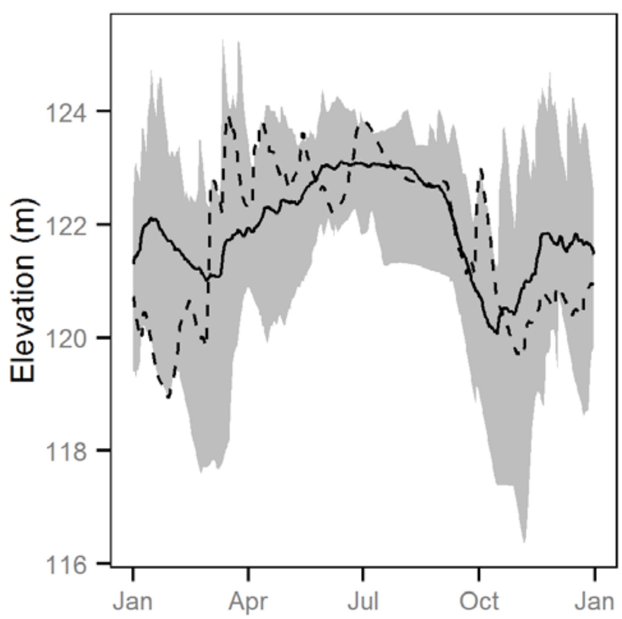

Figure 5. Elevation in meters vs. month in Alouette Reservoir for the 2001-2013. The minimum and maximum daily elevation are plotted with the grey band and the mean daily elevation over years with the solid black line and the mean daily elevation in 2013 with the dashed black line.

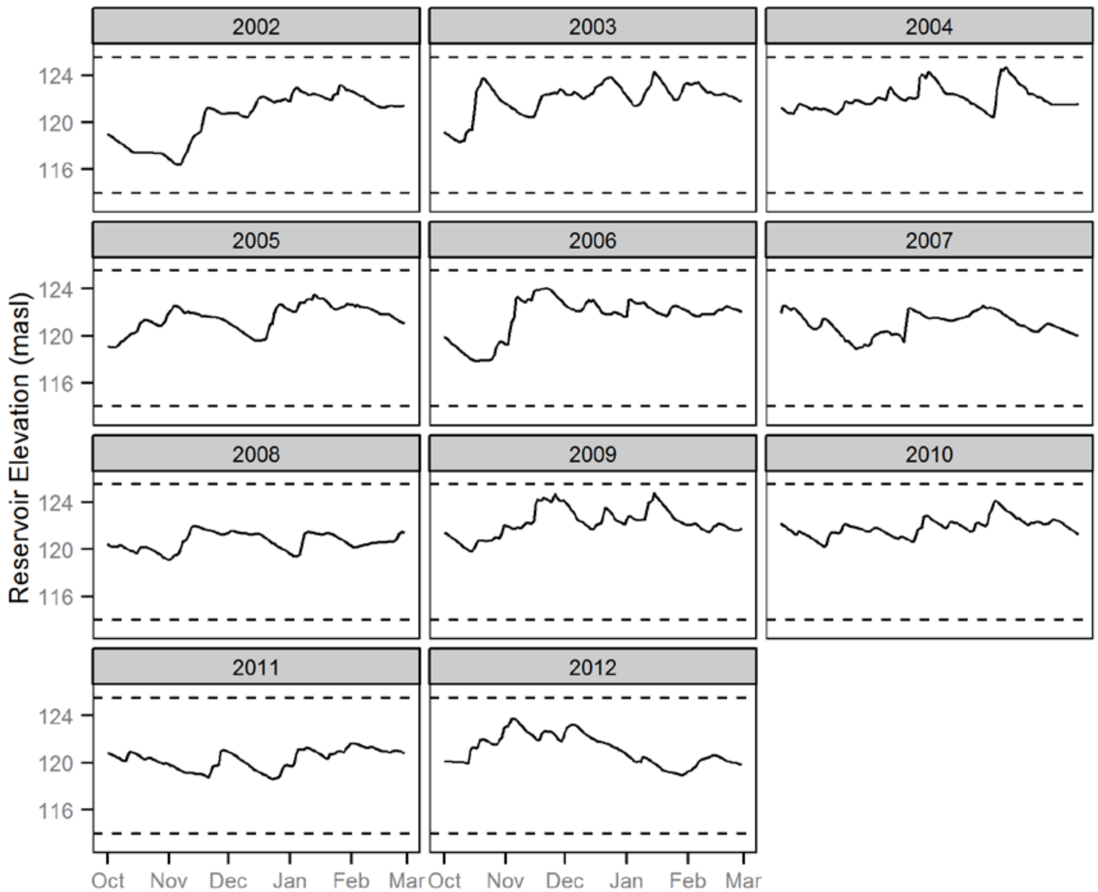

Figure 6. Alouette reservoir elevation in meters by month during the spawning and incubation season (October 15- February 28) for kokanee from 2002-2012. Note-data is displayed by spawning year.

Analysis

Size-at-Age

An assessment was conducted of size-at-age in ALR gillnet captured kokanee (age-3) obtained during 1998-2013 (Figure 7). Observed size data demonstrates an immediate increase following the commencement of the nutrient addition program in 1999 (Figure 7). However, more recently, the size-at-age information suggests a stable pattern has emerged since 2003, with an average size near 250 mm (Figure 7). The apparent larger size of kokanee from 2000-2002 corresponds to when kokanee abundance was considerably lower than the current estimates in reservoir (see below).

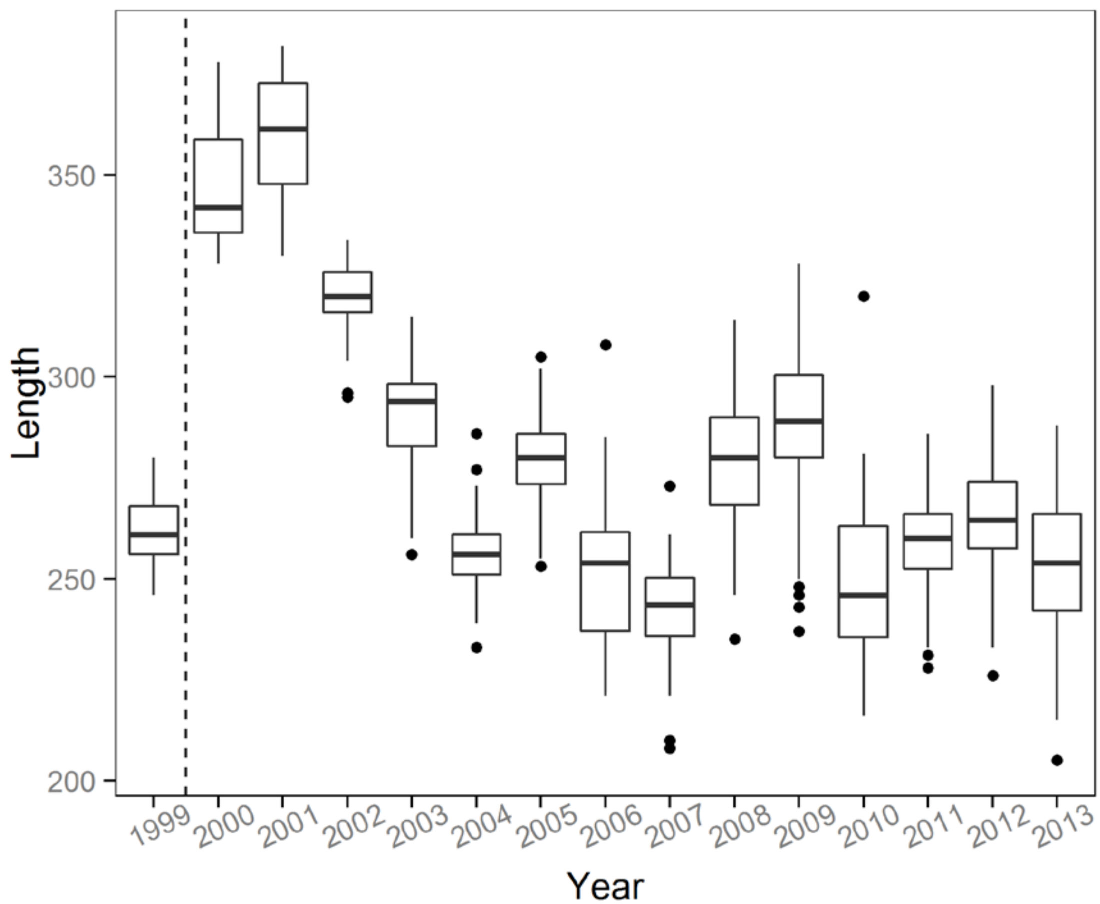

Figure 7. Boxplots of three year old kokanee captured with gillnets on Alouette Lake Reservoir from 1998-2013. The fertilization period begins in 1999, as indicated by the dashed line and the change in netting methods occurred in 2008. Data used in the analysis span from 2000-2013 and are to the right of the dashed line.

The results determined from the mixed effects size-at-age model, in relation to the nutrient loading and reservoir productivity, suggest a similar pattern to the observed data (Figure 7). Model results indicate that size-at-age has significantly declined since 2000. In fact, the estimated length of kokanee has declined from 347 mm in 2000 to 277 mm in 2013 (**Table 4**). The model also indicated that the productivity (N:P ratio) was not a significant predictor of kokanee length, but does indicate a slight positive trend in length as productivity increases (Figure 8; Appendix 3). It should be noted that the model did not account for variation in fish density over time which is known to affect kokanee size (Rieman and Myers 1992). Results may also be somewhat confounded by the fact that the two gillnetting programs (RNRP vs. WUP) indicate a significant difference in size of fish captured (Appendix 3).

Table 4. Predicted size at age data for 2000-2013 from Bayesian model.

Year	Estimate	Lower 95% CRI	Upper 95% CRI	SD	Error
2000	347.4	323.1	378.2	13.8	8
2001	359.9	341.3	377.5	9.6	5
2002	315.9	296.6	338.8	10.8	7
2003	288.9	276.2	301.5	6.6	4
2004	260.5	242.0	279.0	10.0	7
2005	277.5	256.1	297.8	10.7	8
2006	255.6	245.9	266.6	5.4	4
2007	242.5	234.3	251.6	4.3	4
2008	286.0	277.0	295.3	4.6	3
2009	287.7	279.5	296.1	4.1	3
2010	269.7	257.7	282.4	6.4	5
2011	279.5	266.8	292.5	6.7	5
2012	287.5	274.1	302.6	7.2	5
2013	277.3	264.8	290.6	6.6	5

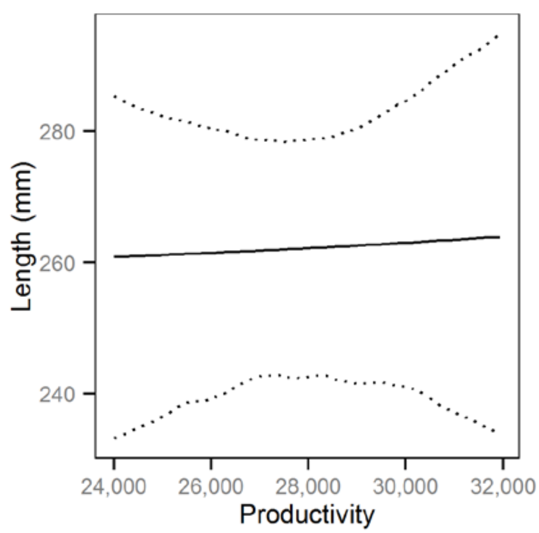

Figure 8. Relationship between productivity (N:P ratio) and length of age-3 kokanee captured in gillnets from 200-2013 in ALR. Dotted lines indicate 95% CRI.

While kokanee size-at-age data suggests a substantial decline in size since 2003, kokanee abundance estimates determined from hydroacoustic data (2002-2013) demonstrates an increasing trend up to 2012 (Figure 9). In 2013, estimated kokanee abundance demonstrated a substantial decline compared to the last five years, and especially compared to 2012 (Figure 9). Size-at-age data from spawners does not indicate a strong correlation between kokanee length and abundance (Figure 10). However, the simple linear model did not assess variables that accounted for time dependence or lags often associated with density dependent growth responses, commonly observed in many nerkid populations (Rieman and Myers, 1992). As well, competition and growth between and within cohorts may be important factors in regulating the size-at-age of kokanee within ALR (Myers 2001; Myers et al. 1997). Clearly, kokanee size was smaller in 2013 following the high abundance of kokanee in 2012 (Figure 10). Conversely, kokanee were larger when total abundance was lower in the reservoir, especially in 2002 and 2003 (Figure 10). It should be noted that kokanee abundance data does not encompass the entire range of years due to differences between single beam (1998-2000) and split beam (2001-2013) acoustic technology.

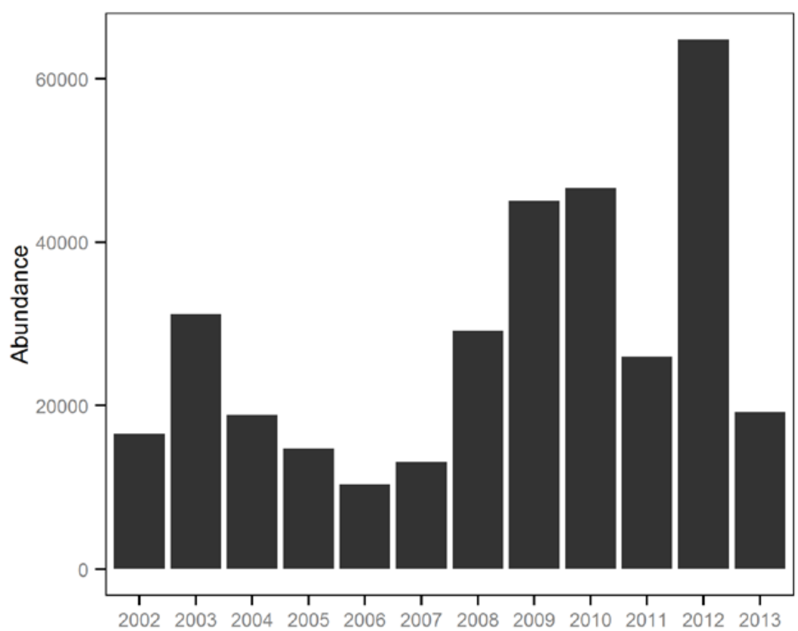

Figure 9. Abundance of two and three year old kokanee from 2002-2013 as assessed from hydroacoustic data.

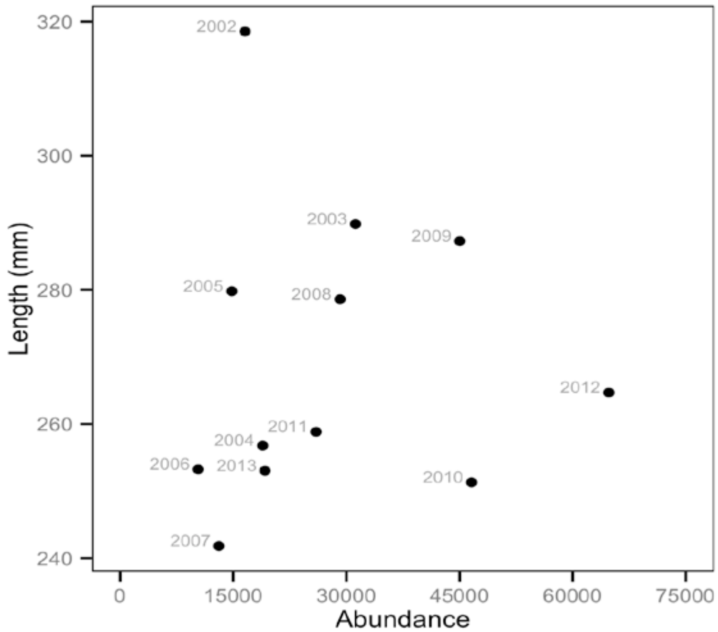

Figure 10. Length (mm) vs. abundance of kokanee from 2002-2013 as assessed from hydroacoustic and gillnetting data.

Stock Recruitment

Two models were used to determine the stock-recruitment relationship for ALR kokanee. Results from the first stock recruitment model, used to assess the spawner recruitment relationship from age-2 and -3 fish (spawners) to age-0 fish (recruits) for kokanee, predicts an average carrying capacity of fry of 168,114 (95% CRI 129,691-235,038) in ALR (Table 5; Figure 11). This predicted number is intermediate to the range of estimates made by Andrusak and Irvine (2013). The model assumes a density dependent response where the relationship between the spawners and the recruits is non-linear and reaches and asymptotic level in which recruitment does not increase with further increases in spawners. The spawner-recruit model also predicted that severe declines in reservoir drawdowns, using the sum of the declines during the spawning and incubation period (October 15-February 28), may limit recruitment and the reproductive success of the ALR kokanee population (Figure 12). This possible limitation had not been previously detected in recent reports for ALUMON#6 WUP. However it is important to note the relationship was not considered significant and demonstrated substantial uncertainty (Figure 12; Appendix 3).

Table 5. Estimated carrying capacity of age 0 and age 1 from Beverton-Holt stock recruitment model.

Age class	Estimate	Lower 95% CRI	Upper 95% CRI	SD	Error
age 0	168,115	129,691	235,038	26,693	31
age 1	49,062	36,126	73,331	10,275	38

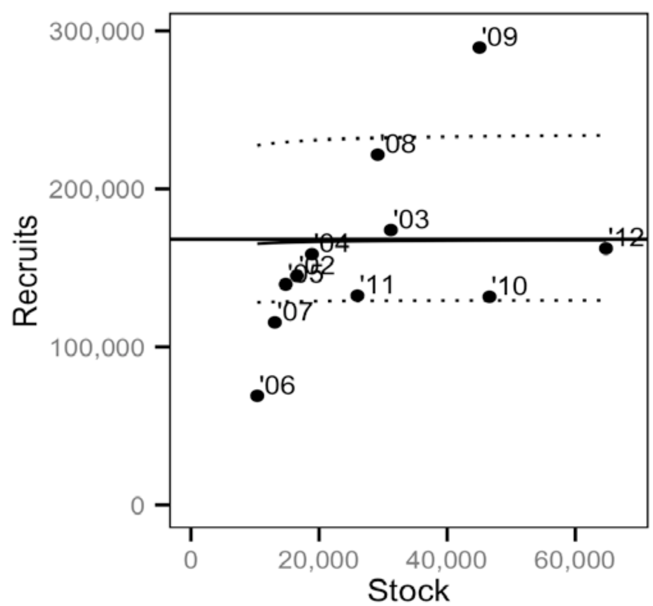

Figure 11. Stock recruitment model for kokanee in Alouette Lakes Reservoir, where stock as spawners (age-2 and 3) in relation to recruits (age-0 or fry). Points are labeled with the year in which sampling for the spawners occurred. Dotted lines indicate 95% CRI. The null model prediction assuming full density dependence is plotted with the solid horizontal line near the fitted line.

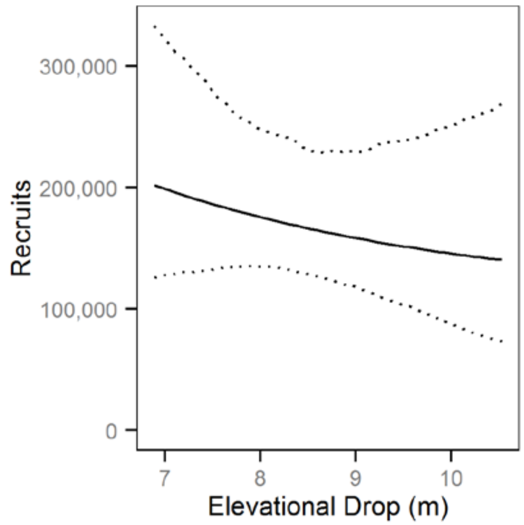

Figure 12. Predicted influence of reservoir fluctuations (sum of all drops) during the spawning and incubation period for recruits of kokanee (age 0) in Alouette Lakes Reservoir from stock recruitment model.

The second stock recruitment model, used to assess the spawner recruitment relationship from age-0 (fry) to age-1 fish (recruits) for kokanee, predicts an average carrying capacity of age 1 of 49,061 (95% CRI 36,126-73,333) in ALR (Table 5; Figure 13). Once again the model indicates a density dependent response where the relationship between age 0 and age 1+ is non-linear and reaches and asymptotic level in which age 1+ recruitment does not increase with further increases in age 0 fry. In contrast to the first stock recruitment model (previous section), the second stock recruitment model indicates that severe drops in reservoir elevation, using the sum of drops during the spawning and incubation period (October 15-February 28), does not limit recruitment of kokanee at the age 1+ stage (Figure 13). However, similar to the first model, there was substantial uncertainty in the model estimates (Figure 13; Appendix 3). It should also be noted that the stock recruitment model did not account for nerkid out-migrations from the reservoir through water withdrawals at the dam spillway.

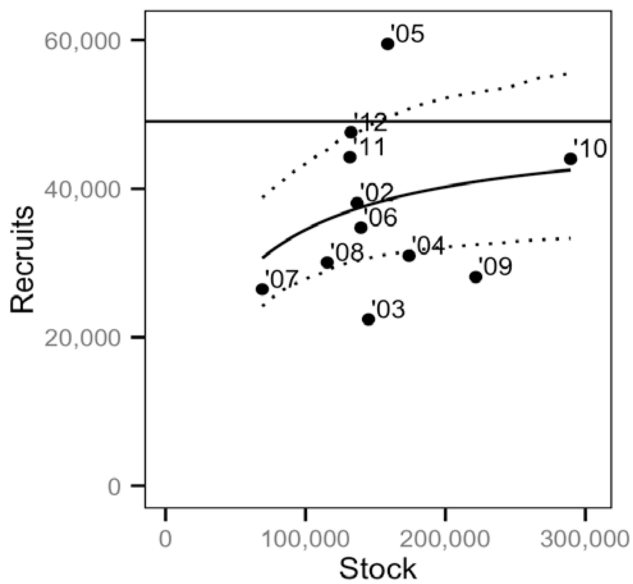

Figure 13. Stock recruitment relationship for kokanee in Alouette Lakes Reservoir, where age 1+ are recruits and age 0 are stock. The year label is for the year in which the age-0 fish were enumerated and the age-1 fish are from the subsequent year. Dotted lines indicate 95% CRI. The null model prediction assuming full density dependence is plotted with the solid horizontal line.

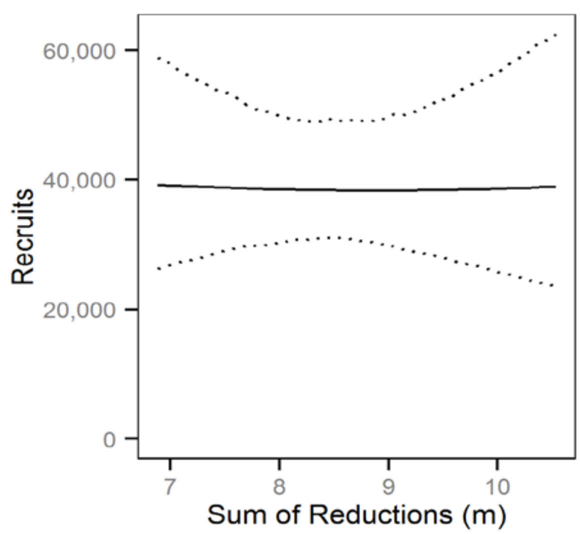

Figure 14. Predicted influence of reservoir fluctuations (sum of all drops) during the spawning and incubation period for recruits of kokanee (age 1+) in Alouette Lakes Reservoir from stock recruitment model.

DISCUSSION

Transformation of lakes into reservoirs managed for hydroelectric demands is well known to have profound effects upon the natural processes of lake limnology and the aquatic ecosystem they support (Moody et al., 2007; Utzig and Schmidt, 2011). In British Columbia reservoirs have been investigated to understand if and how much reservoir operations have the potential to have adverse effects on fish distribution and abundance (Ashley et al., 1997; Ney, 1996; Stockner et al., 2005, 2000; Utzig and Schmidt, 2011). Ecological effects can be evidenced from both footprint and operational impacts associated with the impoundment/inundation phase and with the water regulation phase of hydroelectric operations. After impoundment, reservoirs often demonstrate an increase in productivity followed by a substantial decline in productivity, often coined “boom and bust” periods (Ney, 1996; Stockner et al., 2000). Operational impacts from water level fluctuation, results in a loss of production in the littoral areas of many small reservoirs and has been cited as factor in reducing productivity in reservoirs (Wetzel, 2001).Understanding both footprint and operational impacts on fish populations can often be obscure and unclear. Due to the large spatial and temporal aspects of these systems, they often require years of investigation to determine real impacts.

The ALUMON#6 WUP study has relied solely on two sources of data (gillnet and hydroacoustic) to assess the influence of reservoir operations on the kokanee population mainly due to the paucity of data on the distribution and abundance of the spawning population. As a result, analysis involved fitting size-at-age data to an age model based on the gill net data to determine if the population’s size-at-age is stable or decreasing with optimized reservoir productivity. In addition, a kokanee stock-recruitment model was also developed from hydroacoustic data to assess if reservoir fluctuations affected fry abundance and whether any decline in fry abundance persisted thus affecting the numbers of older age classes. Invariably, these analyses are fraught with numerous assumptions based on the available but limited data and indicate substantial uncertainty in the derived model results.

Similar to previous years, the size-at-age modeling confirmed the immediate size increase following the commencement of the nutrient addition program in 1999. In recent years the size-at-age information indicates a stable pattern exists with average spawner size ~277 mm. The initial larger size of kokanee from 2000-2002 corresponded to when kokanee abundance was considerably lower than the present day estimates (Herbert et al., 2013). Size-at-age data from spawners does not indicate a strong correlation between kokanee length and abundance. This is an unexpected outcome since kokanee populations are usually regulated by density dependent processes (Hyatt and Stockner, 1985; Rieman and Myers, 1992; Rose et al., 2001). Clearly, kokanee mean size was smaller in 2013 following the high abundance of kokanee in 2012. Conversely, kokanee were larger when total abundance was lower in the reservoir, especially in 2002 and 2003 (Figure 10). Interestingly the model suggests that productivity (N:P ratio) was not a significant predictor of kokanee length, although it does indicate a slight positive trend in length as productivity increases. Future assessment of size at age data should include changes in stock densities as a predictor variable on kokanee length over time.

Unlike previous years reporting (Andrusak and Irvine, 2013), the current stock recruitment models were developed in a Bayesian framework for interpreting the effect of reservoir fluctuations on fry abundance. The Bayesian inference can be more flexible and interpretable for management purposes and is often better at representing the uncertainty (Michielsens and McAllister, 2004; Punt and Punt, 1997). Analysis revealed that modeling the contribution of spawning stock (age 2+ and 3+) to the age-0 population, using a non-linear Beverton-Holt relationship, predicted the average carrying capacity of fry of 168,114 (95% CRI 129,691-235,038). This spawner-recruit model also predicted that severe reservoir drawdown <u>may</u> limit recruitment and the reproductive success of the ALR kokanee population. This possible limitation had not been detected in earlier analysis and caution should be considered since the relationship indicated substantial uncertainty and was not statistically significant. The second model analyzed age 0 (fry) and age 1+ (recruits) and the predicted outcome was a peak recruitment of 49,061 (95% CRI 36,126-73,333) age 1+. As well, this estimate is much higher than the 2012 estimate of ~25,000 age 1+ detailed in Andrusak and Irvine (2013). In contrast to the first stock recruitment model, the second model indicates that severe elevation changes during the kokanee spawning and rearing period does <u>not</u> limit recruitment of kokanee at the age 1+ stage. Both models indicated that density dependent factors likely regulate the population abundance of both age-0 and age-1 fish. As with previous years, estimated age 0+ and age 1+ numbers are considered conservative since separation of age classes from hydroacoustic data may not be reliable.

The relative survival from age-0 to age-1 fish was estimated to be 36 % in 2012, slightly higher than the 34% in 2011, with both years' estimates higher than the average of 26% (2002-2012) and that previously reported in (Andrusak and Irvine, 2013). To date it is still unclear as to the mechanisms driving the variable rates of relative survival in ALR. At least in one instance there was some indication of an increase in survival in 2007 when densities of age-0 fish were the lowest in the reservoir in part due to a large outmigration of age 1 the spring (Plate et al., 2014). The low densities in that year class coincide with a large out-migration (n=62,923) of juvenile kokanee from the reservoir during surface flow releases from the Alouette Dam, mostly age-1 kokanee (Mathews et al., 2013;Table 6). Since 2007 the estimated out-migration has decreased with very low numbers during the last two years (Table 6). Nonetheless, it is believed that the direct loss of kokanee through the spillway and the diversion tunnel (Squires and Bruce, 2009) could potentially provide some compensatory increase in survival for kokanee remaining in the reservoir, since densities potentially can be substantially reduced. Future assessment of large out-migrations of kokanee from the reservoir may be beneficial in understanding the underlying mechanisms regulating the kokanee population on ALR while providing important answers for addressing water management questions.

Table 6. Mark-recapture estimates of *O. nerka* out-migrating the Alouette Reservoir from Plate et al. (2014).

Year	Estimate	95% CI	% of Age 1	% Age 2 & 3
2005	7,900	na	96%	4%
2006	5,064	na	94%	6%
2007	62,923	48,436 – 77,410	91%	9%
2008	7,712	6,682 – 8,742	72%	28%
2009	4,287	3,833 – 4,741	95%	5%
2010	14,201	13,624 – 14,778	68%	32%
2011	35,542	34,034 – 37,051	96%	4%
2012	720	348-1,108	29%	72%
2013	6,179	5,350-7,008		

For the first time during the period of study the stock recruit analysis offers the possibility that reservoir operations might be impacting kokanee fry production. The size at age model results infer that factors such as reservoir productivity, food quality and or possibly reservoir operations are speculated as possibly influencing the compensatory mechanisms (Herbert et al., 2013; Rieman and Myers, 1992). Nonetheless, it is acknowledged that there is substantial uncertainty associated with the results and further refinement of these of the modelling and analyses is recommended. For example, the model did not assess variables that account for time dependence or lags often associated with density dependent growth responses, commonly observed in many nerkid populations (Myers et al., 1997; Rieman and Myers, 1992)..

Finally, competition and growth between and within cohorts may be important factors in regulating the size-at-age of kokanee within ALR (Myers 2001; Myers et al. 1997), similar to that observed on Quesnel Lake (Dolighan et al. 2012).

Reservoir operations during the kokanee spawning and egg incubation window has the potential to impact the kokanee population on ALR, similar to that observed on the West Arm of Kootenay Lake (Andrusak and Andrusak 2013). For this very reason, the drawdown on the West Arm of Kootenay Lake was recommended to commence before the spawning period so that when spawning does begin the lake level is lower than the normal operating level during the winter months (Andrusak and Andrusak 2013). i.e. spawning occurs at the lower lake level rather than at the high lake level only to have redds stranded when drawdown occurs.. With the exception of observations cited in McCusker et al. (2003), observations suggest that the spawning occurs at deep (20-40 m) water depths (Plate et al. 2014). Similar observations of kokanee spawning at depths beyond the areas of reservoir drawdown have been documented on Seaton and Anderson Reservoir (Morris and Caverly 2004)

Spillway releases from the dam during the spring have occurred since 2005 and were implemented to determine the volitional migration success of *O. nerka* from the reservoir (Mathews et al., 2013). It is suspected that spillway releases have the potential to impact to the kokanee population due to the high proportion of age 1 fish that emigrate. An average of ~17,000 nerkids per year has emigrated from ALR since 2005, not a small number if the reservoir estimates are anywhere near correct (Plate et al., 2014). However, as previously discussed, there is the possibility that a compensatory benefit in growth and survival from the annual loss of kokanee from the reservoir. These potential benefits may provide the ability of regulatory agencies (MOE and DFO) to meet the management objectives for the restoration of the ALR and the Alouette River Sockeye Re-Anadromization Project (Plate et al., 2014).

Analysis of data suggests that the ALR kokanee population is likely regulated by compensatory mechanisms, similar to other kokanee populations (Harris et al., 2013; Schindler et al., 2013, 2014). Size-at-age analysis suggests that hypothesis one (H_01) under the first ALUMON management question cannot be rejected since the data displays a size structure that has stabilized after initial increases under higher lake productivity. In addition, the Hierarchical Bayesian stock recruitment model results also failed to reject hypotheses two (H_02) and three (H_03) under management questions two and three. However, it is important to qualify the fact the model identified the possibility of a recruitment limitation to the ALR kokanee population due to reservoir operations, not previously observed. The latter null hypotheses are ($H_0$2 and $H_0$3) somewhat problematic due to the nature of such dichotomous tests, similar to that detailed in Bradford et al. (2005). Potential for emigrations of kokanee from reservoir operations and specifically through the spillway during volitional migration success studies may also impact the kokanee population which likely persists through that cohort's life stage. However, it is acknowledged that there is considerable uncertainty in modeling the kokanee data which can ultimately limit the ability to detect impacts from reservoir operations. On the other hand, limited spawning habitat in this reservoir also cannot be ruled out due as a limiting factor to kokanee recruitment within the ALR. To date no stream spawning has been observed (Plate et al., 2014), the 2012 snorkel survey did not detect any shallow (< 5 m) water spawning (Andrusak and Irvine, 2013) and the extent of deep water spawning appears scattered (Plate et al., 2014). In summary, it would be ideal to have far better data on the spawning population however it is acknowledged that obtaining this data would be very expensive. Despite the limitations of the hydroacoustics data, this information is deemed adequate enough for modeling purposes to gain informative insights into some of the mechanisms regulating the kokanee population on ALR.

RECOMMENDATIONS

A number of data gaps have been identified and recommended actions to address these gaps are outlined in brief below. These include:

- Fisheries work should be directed at obtaining kokanee spawner numbers, size-at-maturity and fecundity.
- In the BC Hydro TOR, a study plan was proposed where gillnet sampling would only occur every other year (BC Hydro 2009). It is strongly recommended that this study design not be implemented. Annual information is important for answering the questions of interest about recruitment and the carrying capacity of the system.
- Future analyses of these data would benefit from refining the hierarchical Bayesian framework where model fits are robust to low sample sizes, confidence intervals are more readily calculated and prior information can be incorporated.
- Pelagic gillnet sampling should continue to allow for the discernment of species composition and proportions of kokanee by depth. This work should continue so more accurate estimates of kokanee numbers and ages can be incorporated into the analysis
- In the analysis assessing whether kokanee size-at-age is stable or decreasing, variable starting points for the data could be explored to address the problems with nitrogen limitation that were identified in 2002 (Harris et al. 2007) to better reflect the ‘stable state’ when there are sufficient years of data to do so.
- Kokanee density information could also be incorporated in future years of analysis to model some of the variability in size-at-age.
- To obtain a better understanding of the mechanisms and processes driving the patterns in the size-at-age data, growth information from kokanee cohorts should be modeled for each year in relation to the productivity and fish numbers in the system
- Entrainment losses through the spillway and the tunnel may need to be estimated in order to correct for biomass lost from the reservoir. This has been partially addressed by incorporating the information from reports documenting the outmigration of kokanee and other species through the spillway (Mathews and Bocking 2010). Squires and Bruce, (2009) provided a qualitative review of entrainment losses through the northern tunnel. Including information on potential fish entrainment through the northern end of the reservoir would improve our understanding of the kokanee population dynamics on the reservoir.

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Appendix 1 Model Code

JAGS distributions, functions and operators used in the models are defined in the first three tables below. For additional information on the JAGS dialect of the BUGS language see the JAGS User Manual (Plummer, 2012). The other subsections provide the variable and parameter definitions and JAGS model code for the analyses.

JAGS Distributions

Distribution	Description
dlnorm(mu, sd^-2)	Log-normal distribution
dnorm(mu, sd^-2)	Normal distribution
dunif(a, b)	Uniform distribution

JAGS Functions

Function	Description
length(x)	Length of vector *x*
log(x)	Natural logarithm of *x*
T(x,y)	Truncate distribution so that values lie between *x* and *y*

JAGS Operators

Operator	Description
<-	Deterministic relationship
~	Stochastic relationship
1:n	Vector of integers from *1* to *n*
a[1:n]	Subset of first *n* values in *a*
for (i in 1:n) {...}	Repeat *...* for *1* to *n* times incrementing *i* each time
x^y	Power where *x* is raised to the power of *y*

Size-At-Age - Model 1

```
model {
 bLength ~ dnorm(5, 5^-2)

 bLengthYear ~ dnorm(0, 5^-2)
 bLengthYear2 ~ dnorm(0, 5^-2)

 bLengthProductivity ~ dnorm(0, 5^-2)

 bLengthNetSet[1] <- 0
 for(i in 2:nNetSet) {
  bLengthNetSet[i] ~ dnorm(0, 5^-2)
 }

 sLengthFYear ~ dunif(0, 5)
 for (i in 1:nFYear) {
    bLengthFYear[i] ~ dnorm(0, sLengthFYear^-2)
 }

 sLengthLocationFYear ~ dunif(0, 5)
 for (i in 1:nLocation) {
  for(j in 1:nFYear) {
    bLengthLocationFYear[i, j] ~ dnorm(0, sLengthLocationFYear^-2)
  }
 }

 sLength ~ dunif(0, 5)
 for(i in 1:length(Length)){
  log(eLength[i]) <- bLength
         + bLengthYear * Year[i]
         + bLengthYear2 * Year[i]^2
         + bLengthProductivity * Productivity[i]
         + bLengthNetSet[NetSet[i]]
         + bLengthFYear[FYear[i]]
         + bLengthLocationFYear[Location[i], FYear[i]]

  Length[i] ~ dlnorm(log(eLength[i]), sLength^-2)
 }
}
```

Stock-Recruitment - Model 1

```
model {

  bElevationalDrop ~ dnorm(0, 5^-2)
  bAlpha ~ dnorm(AlphaPrior[1], (AlphaPrior[1] / 2)^-2) T(0, AlphaPrior[1] * 2)
  bBeta ~ dunif(0, 0.01)

  sRecruits ~ dunif(0, 5)
  for (i in 1:length(Stock)) {
    log(eRecruits[i]) <- log(bAlpha * Stock[i] / (1 + bBeta * Stock[i]))
                 + bElevationalDrop * ElevationalDrop[i]

    Recruits[i] ~ dlnorm(log(eRecruits[i]), sRecruits^-2)
  }
}
```

Appendix 2 ALR Elevation 1984-2013

Year	Maximum Elevation (m)	Minimum. Elevation (m)	Reservoir Draw (m)	Mean Elevation (m)	SD
1984	124.99	117.73	7.26	122.04	1.85
1985	124.71	116.57	8.15	121.66	2.38
1986	125.68	118.03	7.65	122.68	1.51
1987	124.57	115.84	8.73	121.34	2.14
1988	124.85	118.39	6.46	121.73	1.84
1989	124.37	118.28	6.09	122.26	1.25
1990	124.74	116.04	8.70	120.25	2.20
1991	124.24	116.10	8.14	119.95	2.19
1992	122.77	116.00	6.77	118.90	1.98
1993	124.89	116.18	8.72	120.10	2.69
1994	125.27	117.07	8.20	121.88	2.09
1995	126.14	119.21	6.93	122.96	1.30
1996	124.64	120.70	3.94	122.13	0.62
1997	125.08	120.11	4.97	122.50	1.08
1998	124.03	117.24	6.79	121.81	1.51
1999	124.45	119.50	4.95	122.40	1.09
2000	124.43	118.92	5.51	121.27	1.46
2001	123.95	117.62	6.33	121.33	1.60
2002	124.39	116.37	8.02	121.76	1.95
2003	124.30	118.34	5.96	122.13	1.06
2004	124.32	120.22	4.10	122.16	0.89
2005	124.63	118.84	5.79	121.78	1.11
2006	124.08	117.84	6.25	121.54	1.27
2007	125.29	118.85	6.44	122.40	1.19
2008	124.27	119.09	5.18	121.96	1.40
2009	124.72	119.41	5.31	122.27	1.18
2010	124.74	120.22	4.52	122.30	0.80
2011	124.12	118.61	5.51	121.92	1.43
2012	124.09	119.69	4.40	122.21	1.09
2013	123.96	118.94	5.03	121.82	1.38

Appendix 3 Parameter Estimates

Parameter Estimates-Size-At-Age

Parameter	Estimate	Lower	Upper	SD	Error	Significance
bLength	5.568e+00	5.4915256	5.630e+00	3.418e-02	1	0.0000
bLengthNetSet[2]	-7.910e-02	-0.1130719	-4.551e-02	1.735e-02	43	0.0000
bLengthProductivity	1.429e-06	-0.0000186	2.295e-05	1.024e-05	1454	0.8870
bLengthYear	5.656e-03	-0.0581960	7.223e-02	3.199e-02	1153	0.8192
bLengthYear2	7.062e-02	0.0211546	1.208e-01	2.535e-02	71	0.0000
sLength	4.963e-02	0.0469977	5.244e-02	1.423e-03	5	0.0000
sLengthFYear	7.814e-02	0.0479856	1.299e-01	2.130e-02	52	0.0000
sLengthLocationFYear	2.895e-02	0.0207121	3.927e-02	4.829e-03	32	0.0000

Rhat	Iterations
1.1	80000

Parameter Estimates-Stock-Recruitment (Spawners To Fry)

Parameter	Estimate	Lower	Upper	SD	Error	Significance
bAlpha	992.583342	373.071724	1.564e+03	3.190e+02	60	0.0000
bBeta	0.006569	0.002406	9.818e-03	2.084e-03	56	0.0000
bElevationalDrop	-0.105172	-0.382908	1.626e-01	1.357e-01	259	0.4291
sRecruits	0.418885	0.258863	7.043e-01	1.224e-01	53	0.0000

Rhat	Iterations
1.04	10000

Parameter Estimates Stock-Recruitment (Fry To Age-1)

Parameter	Estimate	Lower	Upper	SD	Error	Significance
bAlpha	1.254e+00	5.832e-01	1.899e+00	3.614e-01	52	0.0000
bBeta	2.886e-05	9.140e-06	5.053e-05	1.098e-05	72	0.0000
bElevationalDrop	-5.505e-03	-2.176e-01	2.044e-01	1.053e-01	3832	0.9341
sRecruits	3.433e-01	2.117e-01	5.714e-01	9.703e-02	52	0.0000

Rhat	Iterations
1.01	10000