Supporting Climate Change Adaptation Actions for the Conservation of the Threatened Cowichan Lake Lamprey Through Low Cost Monitoring of Critical Habitat

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ABSTRACT

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Cowichan Lake Lamprey (Vancouver Lamprey) is a threatened species, endemic to three interconnected lakes on Vancouver Island, British Columbia. Cowichan Lake, one of the lakes in which this species resides, is a water reservoir managed to meet the downstream conservation and anthropogenic needs of the watershed. Although Cowichan Lake Lamprey and its critical habitat are protected under the *Species At Risk Act,* the water and habitat needs for this species have not been considered in water management plans. With increased demands for water supply coupled with changes in precipitation and recharge due to climate change, options are needed to help manage the water resource better to conserve both lake and river ecosystems and aquatic species which depend on them for survival. Therefore, aerial surveys were trialed as a non-invasive method to quantify the relationship between the availability of spawning and early rearing habitat, and lake water levels, which depend on meteorological variables and anthropogenic control. Based on this preliminary study, spawning and early rearing habitat availability for Cowichan Lake Lamprey can be maintained above 50% if the weir that regulates release of water from the lake maintains water levels above the 1 m mark at the weir.

RÉSUMÉ

Wade, J., Dealy, L., Stephen, C, Lewis, T., and Grant, P. 2021. Supporting climate change adaptation actions for the conservation of the threatened Cowichan Lake Lamprey through low cost monitoring of critical habitat. Can. Manuscr. Rep. Fish. Aquat. Sci. 3227: vi + 17 p.

La lamproie du lac Cowichan (lamproie de Vancouver) est une espèce menacée, endémique à trois lacs interreliés de l'île de Vancouver, en Colombie-Britannique. Le lac Cowichan, l'un des lacs où réside cette espèce, est un réservoir d'eau géré pour répondre aux besoins de conservation et aux besoins anthropiques en aval dans le bassin versant. Bien que la lamproie du lac Cowichan et son habitat essentiel soient protégés par la *Loi sur les espèces en péril*, les besoins en eau et en habitat de cette espèce n'ont pas été pris en compte dans les plans de gestion de l'eau. Compte tenu de la demande accrue d'approvisionnement en eau, de même que des changements dans les précipitations et la recharge engendrés par les changements climatiques, il faut trouver des solutions pour mieux gérer les ressources en eau si l'on veut conserver les écosystèmes des lacs et des rivières et les espèces aquatiques qui en dépendent pour leur survie. Par conséquent, des relevés aériens ont été mis à l'essai comme méthode non invasive pour quantifier la relation entre la disponibilité de l'habitat nécessaire pour la fraie et les premiers stades de croissance d'une part, et les niveaux d'eau du lac d'autre part, qui dépendent des variables météorologiques et du contrôle anthropique. D'après cette étude préliminaire, la disponibilité de l'habitat nécessaire pour la fraie et les premiers stades de croissance de la lamproie du lac Cowichan peut être maintenue au-dessus de 50 % si le déversoir qui régule la libération de l'eau du lac maintient les niveaux d'eau au-dessus de la marque de un mètre au déversoir.

INTRODUCTION

Conservation success is increasingly measured by not only the removal of the threat of extinction but also by the development of self-sustaining, healthy, resilient populations (Stephen and Wade, 2018). A prominent threat hindering species in meeting these goals for conservation success, is climate change. As climate change is now agreed to be inevitable, adaptation actions are needed. Climate change adaptation involves reducing risk and predisposition to be adversely affected by climate change by building capacity to cope with climate impacts and mobilizing that capacity by implementing decisions and actions (Nobel et al., 2014). Climate change adaptation requires adjustments in natural and human systems in response to actual or expected climate change impacts, to moderate harm or exploit beneficial opportunities (IPCC, 2007).

Cowichan Lake Lamprey, also known as the Vancouver Lamprey, (*Entosphenus macrostomus*) is an endemic, freshwater, parasitic fish found only in Cowichan, Bear and Mesachie lakes in British Columbia, Canada. This species is listed as threatened under Schedule 1 of Canada's *Species at Risk Act* (SARA) due to being restricted in range and threatened by ongoing declines in habitat quality and quantity from water management, and droughts which are increasing in frequency due to climate change. Since being first described in 1982 (Beamish, 1982), research to understand the basic biology of the species has been limited. However, there is information to inform habitat requirements for the species, including descriptions of spawning habitat and nest building (Wade et al., 2018). Unlike other freshwater, parasitic lamprey species, spawning adults and ammocoetes (larvae) of Cowichan Lake Lamprey are thought to be dependent on alluvial fan habitat, shallow riparian habitats and mouths of inflowing rivers and streams for spawning and early rearing (Wade et al., 2018; Beamish and Wade, 2008). To date, there is no evidence of Cowichan Lake Lamprey spawning further upstream than a few hundred meters from the alluvial fans. Although not sedentary, ammocoetes spend most of this life stage burrowed in the sediment feeding on detritus. Ensuring early rearing habitat is available and maintained by sufficient water levels is therefore important for the survival of Cowichan Lake Lamprey. Critical habitat, defined in SARA as the habitat necessary for the survival or recovery of a species, has therefore been identified for Cowichan Lake Lamprey as Cowichan, Bear and Mesachie lakes in their entirety, the adjoining waterways, and 100 m upstream of tributaries into the lakes (MacConnachie and Wade, 2016; DFO, 2019).

Cowichan Lake is a large (6204 ha) regulated body of water which reaches a maximum depth of 152 m (MacConnachie and Wade, 2016). This lake flows into Cowichan River through a controlled weir which was constructed in 1957 at the confluence of Cowichan River and Cowichan Lake, in order for the lake to serve as a reservoir to meet downstream ecological and anthropogenic water needs (MacConnachie and Wade, 2016) (Figure 1). The weir is operated based on four goals: (i) maintain full storage behind the weir until July 9th if possible; (ii) maintain an optimum 25 cm/sec prior to May 1st if conditions allow; (iii) maintain a minimum of 15 cm/sec in Cowichan River prior to June 15th; and (iv) maintain a minimum 7 cm/sec June 15th to the end of the weir control period typically around November 1st (Weir Operation Guidelines, 2008). There are provisions in the operational procedure for the weir which allow for river flow reductions in drought conditions. These provisions however are made when drought conditions are already occurring, not as preventative measures for predicted summer droughts.

Weir management protocols recognize that low summer lake levels impact the ability to meet the ecological and anthropogenic water needs downstream. However, the impacts of those management decisions on Cowichan Lake Lamprey as well as larger scale impacts on lake and river ecology have not been largely considered. The exception being when emergency pumping permits have been approved to pump water from Cowichan Lake, over the weir to go below zero storage, into Cowichan River. In this case, there has been a requirement to monitor some aspects of lake ecology such as nearshore temperature and oxygen levels.

Due to increasing water demands and reductions in water storage, work is underway to construct a higher weir to hold back more water in the lake for use during times of drought. This is a complicated, multi-stakeholder undertaking which will take many years to complete. In the interim, there is a desire to manage the water resource taking into account the ecosystem values of both the river and lake. The inclusion of Cowichan Lake Lamprey and its habitat requirements are an essential component of the lake ecosystem and therefore provision for their conservation is overdue.

Aspects of species life history, including timing of spawning and early rearing can also make Cowichan Lake Lamprey more or less susceptible to the impacts of climate change, droughts and water management issues. Although knowledge gaps for the life history of this species exist, Cowichan Lake Lamprey have been reported in spawning condition as early as May 3rd and as late as August 18th (Beamish and Wade, 2008). Based on other lamprey species, Beamish and Wade (2008) estimated that Cowichan Lake Lamprey ammocoetes may spend five or more years in this stage of development before metamorphosing into a parasitic adult. This also aligns with life history knowledge for other lamprey species in which the ammocoete stage ranges from two and a half years for Miller Lake Lamprey (*Entosphenus minimus*), to seven years for both Silver Lamprey (*Ichthyomyzon unicuspis*), and Chestnut Lamprey (*I. castaneus*) (summarized in Wade, 2019).

Recent changes in weather patterns have increased the frequency and severity of droughts in the late spring and summer during the spawning and early rearing period, which have been compounded by recent higher than average temperatures impacting western Canada (CVRD 2021). Climate change models also suggest water storage will decrease, with reduced snowpack and precipitation in the winter storage period resulting in shortfalls in summer water supply (CVRD 2021). Key to climate change adaption is resilience. Resilience, health and welfare mean matching the species' reality to its evolved needs (Stephen and Wade, 2018). This means climate adaptions will be needed to protect critical habitat and ensure the survival and persistence of the Cowichan Lake Lamprey.

With the critical habitat identified and protected under SARA, water user plans should consider river and lake ecosystems, and in particular the water and habitat requirements of Cowichan Lake Lamprey. Building on work published in Chaudhuri et al. (2020) that was specific to one site in Cowichan Lake, our objective was to determine if a relationship between available critical habitat and metrics used by water managers could be identified for all of Cowichan Lake, using low-cost drone technology and if such a relationship could provide an indicator that could be used by the water board for adaptive management of both river and lake habitats. In order to do so, additional sites were sampled to those reported in Chaudhuri et al. (2020) to expand and a refinement of image capture and image analyses. As little investment is available for management or science of this species, low cost methods to assess and monitor their habitats are critically needed for evidence based management.

METHODS

SITES AND IMAGE CAPTURE

Cowichan Lake Lamprey have been found only in three interconnected lakes on Vancouver Island and in the lower reaches of streams flowing into these lakes. As Bear Lake is contiguous with Cowichan Lake, for the purposes of this study we will consider it a part of Cowichan Lake.

Because nest building by spawning lamprey has only been identified in the alluvial fan areas (Wade et al., 2018) these areas were targeted for surveys in 2017, 2018 and 2019. The data and results presented here include surveys at four different sites over these three years. Dates are provided in the results section. Spawning and early rearing areas were mapped using a DJI Mavic Pro drone (unmanned aerial vehicle) for image acquisition from late spring to early fall/winter at the confluence of Cowichan Lake with Cottonwood Creek, Robertson River, Shaw Creek and Nixon Creek (Figure 1).

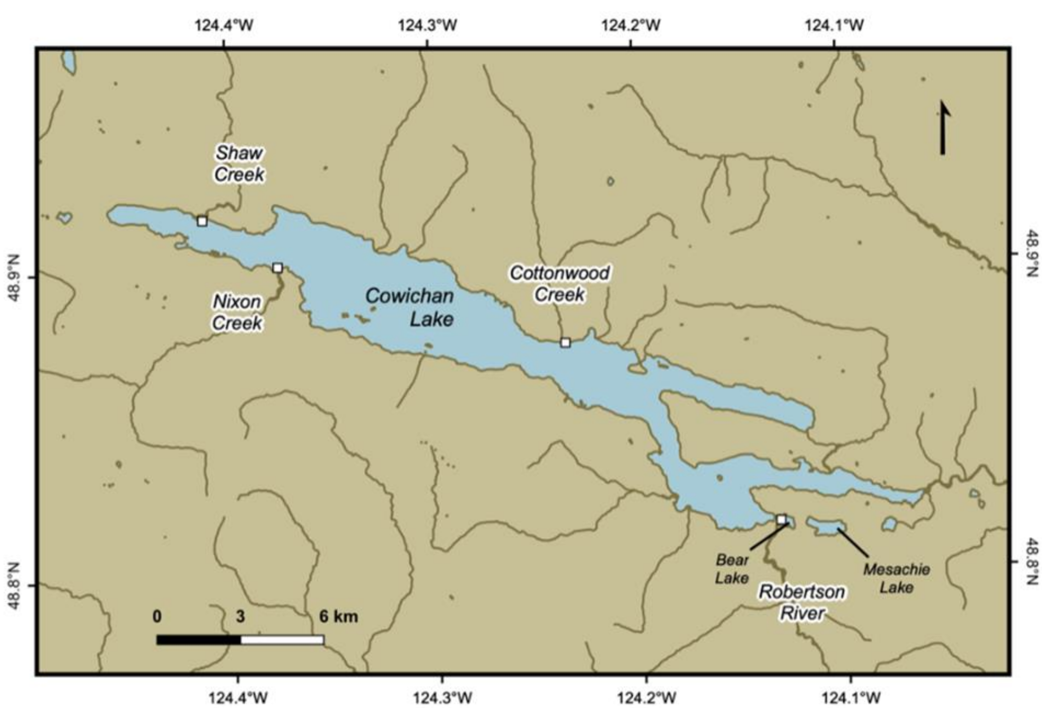

Figure 1. Map indicating sites where aerial drone images were taken to monitor spawning and early rearing habitat of Cowichan Lake Lamprey (2017–2019 inclusive).

IMAGE ANALYSES

Habitat delineation

To delineate habitat suitable for spawning and early rearing at each of the four sites, an outline was drawn on a representative image of each site. Because these delineations were created using limited research and expert opinion, the criteria on which they were based should be revisited as new information becomes available. Additionally, the size and substrate composition of the alluvial fans will change overtime, potentially resulting in changes to delineation of habitats over greater time scales. When delineating habitat for this study, the following information was considered:

1. Cowichan Lake Lamprey have only been observed constructing nests and spawning in alluvial fan areas (Wade et al., 2018; Beamish and Wade, 2008).
2. Cowichan Lake Lamprey have been found in the lower reaches of tributaries to Cowichan and Mesachie lakes, but to date, no spawning in these areas has been observed. If these areas are used for spawning and early rearing, they are not considered suitable habitat as these tributaries regularly dry up in the summer during spawning season.
3. Adults need access to certain substrates (sand and pebbles) to use for nest-building. As such, we have assumed that areas which are predominantly large cobble and/or boulders would not be suitable spawning and early rearing habitat.
4. Use of alluvial fan areas and mouths of streams for early rearing is also supported through observations of small ammocoetes (<2 cm), which have been found in or near these habitat types (Wade and MacConnachie, 2016).

Available habitat

A standardized habitat delineation for each site (Figure 2) was digitized using GIMP-2.10 (GNU Image Manipulation Program) in order to calculate the available spawning and early rearing area (i.e., percentage of wetted area) within these zones.

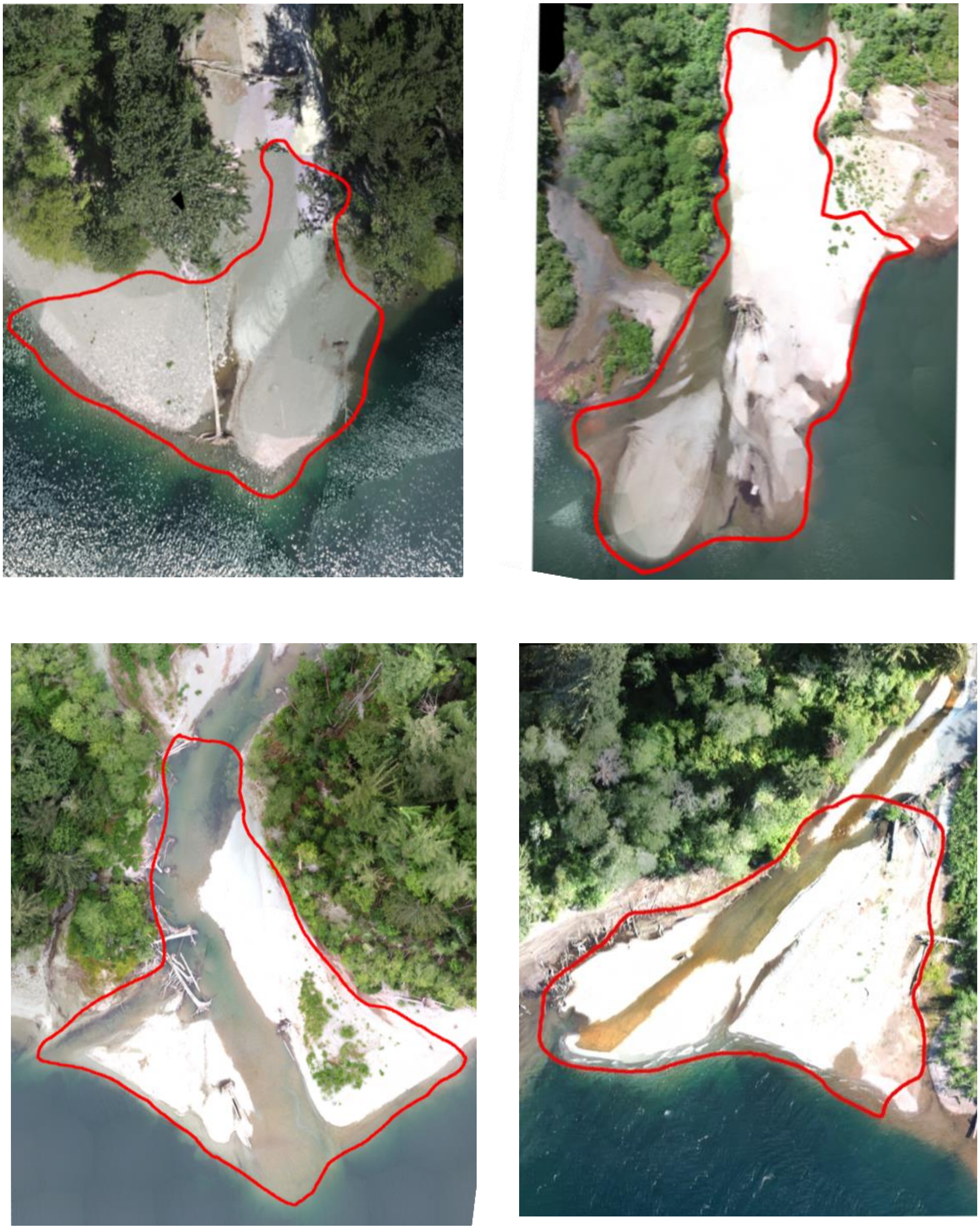

Figure 2. Delineated spawning and early rearing areas for Cowichan Lake Lamprey. Top left= Cottonwood Creek, Top right= Robertson River, Bottom left= Shaw Creek, Bottom right=Nixon Creek.

A sample is defined as an event when multiple images were captured at similar estimated elevations at a specific site on a given day. These sites include the convergence of Cowichan Lake with Cottonwood Creek, Robertson River, Shaw Creek and Nixon Creek. Images which fully overlapped with the habitat delineation areas in Figure 2 were selected for analysis. When necessary, multiple images were combined in GIMP-2.10 to create a composite image that completely overlapped the delineated area for that site. To achieve this, permanent and semi-permanent features such as log piles and tree lines were used to line up images as required.

Once aligned, the delineated area was selected from the original or composite image. Visibly wet areas were then selected using the Paintbrush tool. Only wet areas contiguous with the Lake were included. For example, pools of water surrounded by dry land were not included in the calculation of available habitat as lamprey could not access the area (although it is recognized that they may be stranded in this pool). Using the Histogram function, the amount of wetted area in relation to the entire delineated area was calculated as percentage of available habitat.

The percentage of available habitat derived from image analysis was examined in relation to the corresponding average daily water level at the weir (m) on that sample day. Water level data at the weir were obtained from the Environment Canada Weather Office, station name Cowichan Lake Near Lake Cowichan (https://wateroffice.ec.gc.ca/index_e.html).

DATA ANALYSIS

The linear relationship between water level at the weir and percentage of available habitat was analysed using Standardised Major Axis (SMA) estimation created by the function SMA within the package smatr using program R (Warton et al., 2006; Warton et al., 2012; R Core Team, 2021). Within smatr SMA tests can perform bivariate line fits with differences among two or more fitted slopes, evaluate slopes that share a common elevation, and test whether slopes fitted to groups are significantly separated along the common slope (Warton et al., 2012). The SMA estimation used herein assumed a linear relationship between y and x as; $Y = \alpha + \beta X$, with the relationships becoming linear on the log-scale after transformation as:

$$\log y = \log \gamma + \beta \log x$$

An advantage of using SMA to test for common linear slope relations is its inclusion of fitting factor groups for y against x (Dunn and Smyth, 1996; Warton and Weber, 2002; Warton et al., 2006). SMA can also utilise Huber's M estimation in place of a least squares method using a robust function in order to make the fit of the model more inclusive for marginal outliers (Taskinen and Warton, 2011). Likelihood ratio tests also evaluate the slope fit offering 95% confidence intervals for the coefficient estimates. The independent model used herein was written as:

```
ft1 = sma(Habitat ~ WeirHT, data = Allom, log = "xy", robust = TRUE)…
```

reflecting a typical GLM (general linear model) style model formula using habitat as the response column and water level at the weir as the predictor variable, log-transformed in both axis, and setting Huber's M robust estimation.

Differences between historical years of water level at the weir were investigated using ANOVA using the aov command in base R (R Core Team, 2021). Boxplots of ANOVA results were designed using package ggplot2 (Wickham, 2016). Data frame matrix manipulation was performed in package dplyr (Wickham et al., 2021). R code for the model run is presented in the Appendix.

RESULTS

From June 2017 to October 2019, a total of 59 sample events occurred at the following sites: the convergence of Cowichan Lake with Cottonwood Creek, Robertson River, Shaw Creek and Nixon Creek (**Error! Reference source not found.**). In 2017, samples were taken on three dates, one in June, September and December. In 2018, samples were taken from March to October, and in 2019, from June to October.

Table 1. Coverage of spawning and early rearing habitat (%) at four sampling sites in Cowichan Lake in 2017–2019 with corresponding average daily water level at the weir (m) as reported at https://wateroffice.ec.gc.ca/index_e.html. Blank cells indicate no images were taken.

Date of sample		Average daily water level at the weir (m)	% Habitat coverage			
			Cottonwood Creek	Robertson River	Shaw Creek	Nixon Creek
2017	June 25	1.42	68	96	83	
	September 4	0.82	34	96	61	
	December 9	2.23	84	96	100	
2018	March 10	1.1	57	81	73	
	April 26	1.62	75	98	88	
	June 3	1.25	67	92	81	
	June 27	1.06	55	68	74	
	August 4	0.79	23	55	63	
	August 14	0.71	27	48	61	
	September 6	0.54	21	42	60	
	October 18	0.77	50	57	63	
2019	June 3	0.74	27	29		
	June 4	0.72	28			41
	June 7	0.69	18			
	June 18	0.64		23		31
	June 25	0.6		21		

	July 2	0.59	17	21		14
	July 19	0.54		17		12
	August 6	0.49	14	14		10
	August 29	0.36		7		
	September 4	0.32	10	6		6
	September 26	0.6	38	37		36
	October 12	0.65	33	40		43

Summary results for each site show that there were differences in percentage of available habitat between sites across all sample events, but that these differences were not statistically significant (Figure 3). Cottonwood Creek site and Nixon Creek site were found to have the lowest amount of available habitat and Robertson River and Shaw Creek the highest.

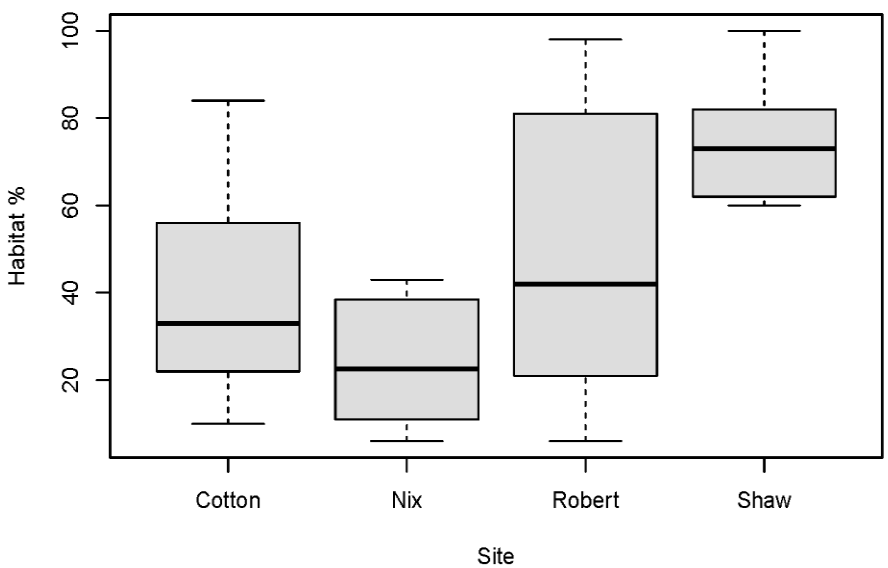

Figure 3. Summary boxplots of percentage of available habitat across sites (Cottonwood Creek, Nixon Creek, Robertson River, and Shaw Creek) for all sample events.

Water level at the weir varied across sample events, decreasing during summer months (i.e., 0.32 m in August 2019) correlating to summer drought conditions and increasing during fall and winter months (i.e., 2.23 m in December 2017), correlating to the winter storage period. Using average daily water level at the weir (data are reported at https://wateroffice.ec.gc.ca/index_e.html) there was a trend of decreasing water levels across years 2017–2019 particularly during May–August when water levels are regulated and Cowichan Lake Lamprey require sufficient water levels to cover spawning and rearing habitat (F=260.1, df=2, $P<0.05$) (Figure 4). However, differences between 2017 and 2018 were less pronounced than in 2019, and show inherent annual variability.

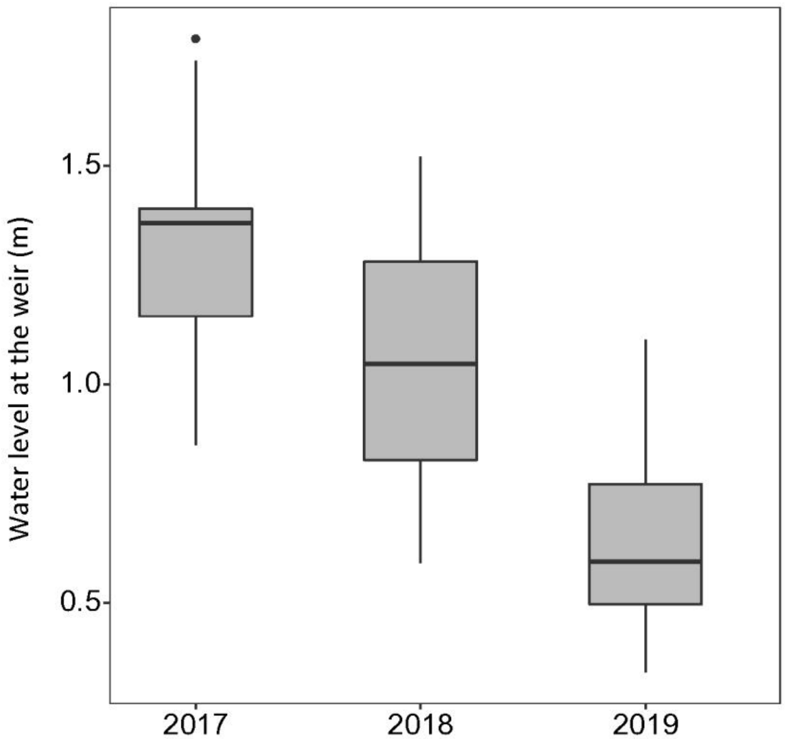

Figure 4. Summary boxplot of average daily water level at the weir (m) from May–August for 2017–2019.

The relationship between water level at the weir and percent of available habitat was calculated using SMA with fit results, residual-fit and quantile plotting presented in Figure 5; and coefficients in Table 2. Plots of fits (Figure 5) showed an appreciable model fit with very strong quantile plots and negligible fanning in residual-fits (ft1, df 5.0, AIC 110.2). Fit of the model was significant at R-squared: 0.719, $p<0.05$. Results show clearly that across all sites and sample events, that water level at the weir has a significant effect on percentage of available habitat.

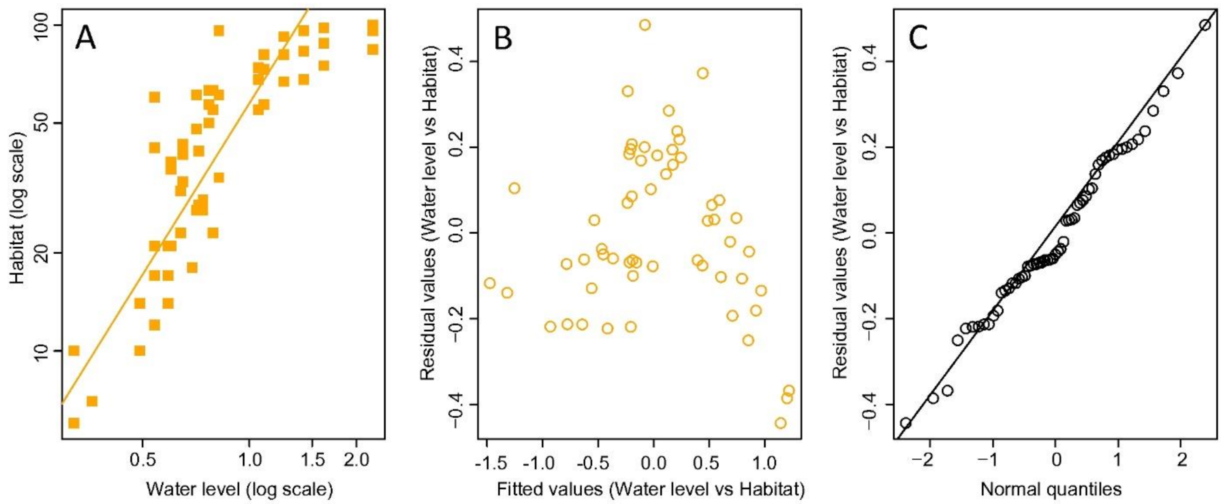

Figure 5. The relationship between water level at the weir and percent of available habitat was calculated using SMA model with log scale fit results (A), residual fitted values (B), quantile plot (C).

Table 2. Coefficients of elevation and slope fit of model; confidence intervals (CI) are at 95%.

Coefficients	**Elevation**	**Slope**
Estimate	1.759884	1.746619
lower limit	1.703964	1.506198
upper limit	1.815805	2.025415

The data also indicate that as average daily water level at the weir increases above 1 m, differences in percent of available habitat for lamprey spawning and early rearing habitat noticeably increase across all sites (Figure 5-A).

Habitat coverage (%) was also categorized into five ranges along with the corresponding range in average daily water level at the weir (m) for each site (Table 3). There were similar trends in water level across sites within each category of percent of available habitat. Data presented in this table also demonstrate that water levels at the weir above 1 m noticeably increase the percent of available habitat for Cowichan Lake Lamprey, as displayed in Figure 5-A.

Table 3. Categories of available habitat (%) coresponding to water levels at the weir (m) during May to August, across at four sites in Cowichan Lake (2017–2019).

Site	% available habitat (range)				
	0–20	21–40	41–60	61–80	81–100
	Range in water level at the weir in metres (number of samples)				
Cottonwood Creek	0.32–0.69 (4)	0.54–0.82 (8)	0.77–1.1 (3)	1.25–1.62 (3)	2.23 (1)
Robertson River	0.32–0.54 (4)	0.54–0.74 (7)	0.71–0.79 (3)	1.06 (1)	0.82–2.23 (6)
Shaw Creek			0.54 (1)	0.71–1.1 (6)	1.25–2.23 (4)
Nixon Creek	0.32–0.59 (4)	0.6–0.64 (2)	0.65–0.72 (2)		

DISCUSSION

Cowichan Lake Lamprey face many threats, the most immediate may be the impact of climate change in combination with water management decisions. Aspects of this species life history such as being semelparous, timing of spawning, extensive larval period, and being restricted in distribution to one watershed also make this species more susceptible to these threats. To conserve this species and foster a self-sustaining, healthy, resilient population we must find ways to reduce the risks of these harms and support climate change adaptation planning that balance the ecological needs of the species and the anthropogenic water needs downstream.

Cowichan Lake Lamprey are dependent on alluvial fan habitat, shallow riparian habitats and mouths of inflowing rivers and streams within Cowichan Lake for spawning and early rearing (Wade et al., 2018; Beamish and Wade, 2008). The relationship between lake water levels and available habitat for this species demonstrates the importance of the control and management of the weir for the survival of this species. It is therefore recommended that water levels at the weir should be maintained at 1 m or greater to ensure more than 50% of critical habitat is available for spawning and early rearing for Cowichan Lake Lamprey.

Winter precipitation is one of the major sources of water for the Cowichan Watershed.
Of particular concern is average daily water levels at the weir significantly decreased over 2017–2019 during May to August, when Cowichan Lake Lamprey require spawning and early rearing habitat. While inter-annual variation is expected, this finding highlights the reduction of available habitat over time and the importance of water management decisions for this species.

Weir management protocols recognize that low summer lake levels impact the ability to meet the ecological and anthropogenic water needs. While climate change adaptation requires adjustments in natural and human systems in response to actual or expected climate change impacts, to moderate harm or exploit beneficial opportunities (IPCC, 2007), there is currently limited ability to maintain lake levels during summer months. In order to provide greater flexibility to managers to maintain sufficient water levels during the summer, it is also recommended that goals of the weir operation allow greater flexibility to maintain full storage beyond July, and to restrict flows earlier to maintain water levels and storage. Weir operation should be flexible to adjust for inter-annual variation in storage and to take into consideration the spawning and rearing requirements of the Cowichan Lake Lamprey. Increasing the height of the weir to increase storage capacity is one way to achieve this and would improve the ability of managers to make water resource decisions to balance both ecological and anthropogenic water needs. In the interim, it is recommended that water levels at the weir should be maintained at 1 m or greater, to the extent possible, to ensure the survival and persistence of the threatened Cowichan Lake Lamprey. Use of water management tools, such as the Okanagan Fish-Water-Management Tool may also be of value in making real-time water management decisions to balance the ecological needs of the species and the anthropogenic water needs downstream, and support climate change adaptation planning.

This minimum water level recommendation is consistent with that reported by Chaudhuri et al. (2020), to maintain spawning and early rearing habitat for Cowichan Lamprey in the alluvial fan of Robertson River. This study expands on that work to identify minimum water levels required to maintain habitat for Cowichan Lake Lamprey across all major spawning and early rearing areas in Cowichan Lake (i.e., Cottonwood Creek, Nixon Creek Robertson River, and Shaw Creek).

As new information becomes available, and changes to the alluvial fans occur, the assumptions regarding spawning and early rearing habitat delineation and availability in relation to water management, may need to be updated. However, this study, demonstrates the utility of non-invasive drone technology in the ongoing monitoring of a cryptic species and its potential to provide direct and practical advice for watershed management and climate change adaptation planning.

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APPENDIX

R code of SMA analysis: Standardized Major Axis Testing

```
#data setup
setwd("~/RTodd/PaulWEIR")
Allom <- read.csv("~/RTodd/PaulWEIR/PaulWEIR2.csv", header=TRUE)
Allom$Year = as.factor(Allom$Year) #make year a factor and not numerical

#Some summary information:
sum.ft <- summary(Allom, maxsum = 1000)
write.csv(sum.ft, file = "summary_data.csv")

#Basic data visualisation - boxplots:
#pdf(file = "~/RTodd/PaulWEIR/VARboxplots.pdf", width = 7, height = 5)
par(mfrow=c(1,1))
boxplot(Habitat ~ Site, data = Allom, ylab="Habitat %")
#dev.off()

#Fit SMA - Habitat vs Weit HT (all site groups combined)
library(smatr)
ft1 <- sma(Habitat ~ WeirHT, log="xy", data=Allom, robust = TRUE)

#Plot SMA - Habitat vs Weit HT:
#pdf(file = "~/RTodd/PaulWEIR/SMAFitsPlot.pdf", width = 11, height = 5)
par(mfrow=c(1,3))
plot(ft1, pch = c(15,17,9,16), col = c("orange"),cex=1.8)
plot(ft1, which= "residual", col = c("orange"),cex=1.8)
plot(ft1, which= "qq",main = "",cex=1.8)
#dev.off()

summary(ft1) #Summary fits

#Fit SMA - Habitat vs Weit HT (all site groups individually)
ft2 <- sma(Habitat ~ WeirHT * Site, log="xy", data=Allom, robust = TRUE, multcomp=TRUE)

#Plot SMA - Habitat vs Weit HT:
#pdf(file = "~/RTodd/PaulWEIR/SMAFitsPlot.pdf", width = 11, height = 5)
par(mfrow=c(1,3))
plot(ft2, pch = c(15,17,9,16), col = c("orange","blue","red","green"),cex=1.8)
plot(ft2, which= "residual", col = c("orange","blue","red","green"),cex=1.8)
plot(ft2, which= "qq",main = "",cex=1.8)
#dev.off()

summary(ft2) #Summary fits
AIC(ft1,ft2) #AIC of ft1/ft2
```

```
#Multicomp matrix giving ANOVA significance p-values
multcompmatrix(ft2, sort = TRUE)
capture.output(multcompmatrix(ft2), file="ft2matrix.txt")
```

END

R code of ANOVA Historical Water Levels

```
#data setup - data frame organisation
setwd("~/RTodd/PaulWEIR")
Water <- read.csv("~/RTodd/PaulWEIR/PaulWEIR15to20.csv", header=TRUE)
Water$Year = as.factor(Water$Year) #make year a factor and not numerical
```

END

R code of ANOVA Anova of differences in Weir HT Years 2017-2019

```
#Subset of Years 2017-2019
Select <- data.frame(Water[c(732:1826),c(1:4)])
Select

#ANOVA TEST
AnYears = aov(Value ~ Year, data=Select)
summary(AnYears) #(F=61.95, df=2, P<0.05) significant difference

#pdf(file = "~/RTodd/PaulWEIR/ANOVA_boxplots1a.pdf", width = 6, height = 6)
library(ggplot2)
P <- ggplot(Select, aes(x = Value, y = Year, group=Year)) +
  geom_boxplot(fill="grey", width=0.5) +
  theme_bw()+
  labs(x = "Weir Height (m)", y = "", size=3)+
  ggtitle("")+
  theme(axis.text.x = element_text(size = 12, angle = 0, hjust = 0.5))+
  theme(axis.text.y = element_text(size = 12, angle = 0, hjust = 0.5))+
  theme(legend.position = "none")+
  theme(plot.title = element_text(hjust = 0.5))+
  coord_flip()
#  xlim(0,1)
P
#dev.off()
```

END

R code of ANOVA Anova of differences in Weir HT 2017-2019 + May-Aug ONLY

```
##Subset of Years 2017-2019 and May-August
library(dplyr)
Select2 = Select %>% filter((Select$Month == "May" | Select$Month == "June" | Select$Month
== "July" | Select$Month == "August"))

#ANOVA TEST
AnYearsSUM = aov(Value ~ Year, data=Select2)
summary(AnYearsSUM) #(F=260.1, df=2, P<0.05) significant difference

#pdf(file = "~/RTodd/PaulWEIR/ANOVA_boxplots1b.pdf", width = 6, height = 6)
library(ggplot2)
P <- ggplot(Select2, aes(x = Value, y = Year, group=Year)) +
  geom_boxplot(fill="grey",width=0.5) +
  theme_bw()+
  labs(x = "Weir Height (m)", y = "")+
  ggtitle("")+
  theme(axis.text.x = element_text(size = 12, angle = 0, hjust = 0.5))+
  theme(axis.text.y = element_text(size = 12, angle = 0, hjust = 0.5))+
  theme(legend.position = "none")+
  theme(plot.title = element_text(hjust = 0.5))+
  coord_flip()
#  xlim(0,1)
P
#dev.off()
```

END