The Use of Groundwater Upwelling Areas by Interior Fraser Coho

Authors:
E. McGrath
Okanagan Nation Alliance Fisheries Department
and
M.Walsh
Secwepemc Fisheries Commission

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Okanagan Nation Alliance
105-3500 Carrington Road
Westbank, BC V4T 3C1
Phone: (250) 707-0095
Fax: (250) 707-0166

Secwepemc Fisheries Commission
680 Athabasca Street W.
Kamloops, BC V2H 1C4
Phone: (778) 471-8200
Fax: (778) 471-5804

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EXECUTIVE SUMMARY

Summer water temperatures in the Southern Interior region of British Columbia frequently approach or exceed the upper thermal limits of salmonids and there is concern for the sustained existence of many populations. This study investigated the effects of groundwater upwelling on juvenile coho summer and winter rearing habitat. Juvenile sampling was undertaken in both summer and winter over several years at paired groundwater and control sites. Mini-piezometers were installed at the groundwater sites to estimate upward groundwater fluxes. Linear and Binomial Mixed Modeling indicates that juvenile coho made preferential use of groundwater upwelling areas during both summer and winter. Temperatures in all of the groundwater areas remained up to 11.5°C cooler than control sites during the summer and slightly warmer at most sites during the winter. The results of this study indicate that groundwater needs to be regulated and protected to reduce potentially harmful temperature effects on coho populations in the Interior of BC.

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1.0 Introduction

1.1 Project Background

The Southern Interior of British Columbia (BC) is home to a large number of important salmon producing streams, many of which provide important rearing habitat for stream-rearing juvenile salmon. A combination of semi-arid climatic conditions, naturally low summer flows and high summer temperatures and high human water demand contribute to high summer stream temperatures throughout this region. The impact of human water use is both through direct withdrawal from surface waters and through groundwater pumping, which can lower the water table and subsequently reduce stream baseflows.

Summer water temperatures in this region frequently approach the upper thermal limits of salmonids (Mathews et al., 2007) and there is concern for the sustained existence of many populations (Walthers & Nener, 2000). Groundwater temperatures remain relatively stable throughout the year; therefore, groundwater seeping into the streambed may moderate stream temperatures and provide cold water thermal refuge for temperature stressed salmonids (Nielsen et al., 1994; Ebersole et al., 2001; Baird & Krueger, 2003; Tobias, 2006; Power et al., 1999). Likewise, groundwater seeps may create warm-water patches during the winter which remain ice-free and provide preferred overwinter habitat for salmonids.

Besides its contribution to stream flows and its thermal benefits, groundwater is an important pathway of nutrient input to streams (Power et al., 1999). Consequently, groundwater is important to the maintenance of fish populations in many streams. In the BC Interior, groundwater and surface water interactions and their impact on fish habitat have been identified as an important knowledge gap for understanding how Endangered Interior Fraser Coho Salmon (*Oncorhynchus kisutch*), as designated by the Committee on the Status of Wildlife in Canada (COSEWIC 2002), use their available habitat and what may be the cause of decline in their abundance (Interior Fraser Coho Recovery Team, 2006).

This report summarizes a five-year collaborative effort between First Nations, government, academia and non-profit organizations aimed at understanding the role of groundwater for the freshwater habitat needs of juvenile endangered Interior Fraser River Coho Salmon. This study addresses two knowledge gaps identified in the *"Conservation Strategy for Coho Salmon, Interior Fraser River Populations"* (Interior Fraser Coho Recovery Team, 2006a): (1) determining what constitutes as important habitat for Interior Fraser Coho populations and (2) the relationship between, and the importance of, groundwater and surface water sources. Most research on Coho Salmon has been conducted on coastal populations. As a result, management decisions are frequently based on results from coastal studies, even though recent evidence suggests that life histories may differ substantially between coastal and interior Coho populations (McRae, 2009; Warren, 2010).

Past years of this project focused primarily on investigating whether groundwater upwelling areas in streams provide thermal refuge to juvenile Coho during periods of summer heat stress. In Year 5 the study was expanded to include juvenile winter habitat selection to provide a comprehensive understanding of the role groundwater plays in the freshwater life history of Interior Fraser Coho salmon. Our findings will provide the basis for sound management strategies of groundwater resources in light of their importance for instream salmonid habitat.

1.2 Project Objectives

The goals for the final year of this study were to determine:

1) If juvenile coho make preferential use of groundwater upwelling areas during periods of heat stress during the summer;
2) Quantify the groundwater flux into upwelling areas and;
3) If juvenile coho make preferential use of groundwater sites for overwintering.

2.0 METHODS

2.1 Study Sites

Figure 1: Study site in the Nicola River.

The study area was located within the Fraser River upstream of Hells Gate in the Fraser Canyon, where known populations of Interior Fraser Coho are distributed. Groundwater study sites were identified in Year 1 of this study (2007) using Forward Looking Thermal Infrared (FLIR) imagery and ground-based surveys with handheld temperature probes (Davis & Wright, 2007). A total of 18 study sites were established. Each study site consisted of one groundwater-influenced site and one control site having similar habitat characteristics. Sites were located in the Thompson River watershed (at Nicola River [Figure 1], Coldwater River, Deadman River, Louis Creek, Bessette Creek, Harris Creek and Duteau Creek) and in the Quesnel River watershed at McKinley Creek. Sites were further refined after the first year and over subsequent years of this study (Walsh, 2009; Sampson, 2010).

All sites monitored over the past 4 years of this study were inspected for their suitability for this coho-habitat use analysis and selected based on the following criteria:

- standardized survey protocols were followed at all times;
- a full record of stream temperatures and juvenile salmon use data was available;
- groundwater and control site showed a temperature difference >1°C;
- the number of juvenile salmonid observations was sufficient for statistical analysis.

Based on these criteria, a total of six paired (groundwater and control) sites were selected for inclusion in the final analysis (Table 1). The last year (Year 5) continued monitoring of the Deadman, Louis, and Nicola streams.

Table 1: Study sites included in the final coho-habitat use analysis.

Site*		Years	Sample events
Duteau Creek	4.7	2008	3
Deadman River	14.2	2008, 2009, 2011	12
Louis Creek	13.9	2008, 2009, 2011	12
	16.2	2009, 2011	7
	25.5	2008, 2009, 2011	14
Nicola River	21.7	2008, 2009, 2011	12

*the number value denotes the distance, in kilometers, the site is located from the confluence

2.2 Data Collection

2.2.1 Groundwater Flow

Mini-piezometers were used to measure the vertical hydraulic gradient (VHG) and hydraulic conductivity (K_h) of the streambed at each groundwater study site (Lee and Cherry, 1978). Duteau Creek was not sampled. The mini-piezometers consisted of 1.5 m long sections of 6.35 mm (0.25 inch) outside diameter (0.43 mm or 0.17 inch inside diameter) polyvinyl chloride (PVC) tubing perforated with 24 evenly spaced holes over the bottom 5 cm of each piezometer. The perforated section was wrapped with landscape filter cloth secured with electrical tape to prevent entry of fine sediment.

Figure 2: Piezometer with differing water level (higher) from stream level

Mini-piezometers were installed in the substrate to a depth of 30 to 50 cm at each study site. Installation was completed by first installing a steel pipe casing plugged at the bottom with a bolt. The bolt was then tapped out using a thin metal rod. The piezometer was then inserted and the casing was slowly removed while holding the piezometer in place, leaving only the piezometer in the streambed.

After installation, each piezometer was developed to ensure communication with the streambed by rapidly drawing out water with a syringe. An equilibration period was observed during which water levels within the piezometer were recorded at one-minute intervals until no change was detected between measurements.

A manometer was used to measure the differences in water level between the piezometer and stream (Figure 2), termed head difference, necessary for calculating Vertical Hydraulic Gradient. The manometer was constructed from polyethylene tubing mounted onto plywood with a meter stick. The mini-piezometer tube was connected to the manometer as was a tube inserted into the stream water. Water from the two tubes was drawn up into the manometer using a syringe. The difference in water level between the stream (h_1) and the piezometer (h_2) was then read off the meter stick.

Hydraulic conductivity of the streambed refers to the ease at which fluid is transferred through the sediment. It was estimated at each study site using a falling-head slug test (Freeze and Cherry, 1979). During the test, a known volume of water was added to the piezometer and the drop in water level was recorded over time. The small diameter of the piezometer tubing made the addition of water difficult; therefore, water was drawn up into the piezometer using a syringe instead.

2.2.2 Temperature

Stream temperatures were recorded during the summer and winter study periods using temperature loggers (HOBO U22 Water Temp Pro V2, Onset Computer Corporation) accurate to 0.2°C over the range of 0° to 50° C with a resolution of 0.02°C at 25°C (http://www.onsetcomp.com/products/data-loggers/u22-001). The loggers were installed within each groundwater and control site and pre-programmed to record hourly stream water temperatures in degrees Celsius. The temperature loggers were secured within an open PVC pipe for protection against damage caused by the elements and the PVC-temperature logger unit was secured at the site using aircraft cable secured to a permanent landscape structure (mature tree) or a wooden stake. The location of the submerged logger was designated with a wooden stake embedded in the stream bank.

Figure 3: Temperature logger retrieval in winter (Louis Creek), 2011/12.

Once the temperature loggers were retrieved from the study sites (Figure 3) the raw data was downloaded on the computer using specified software (HOBOWare Lite version

2.3.0, Onset Computer Corporation) and converted to Microsoft Excel format for analysis purposes.

Summer water temperatures were recorded between July and September while winter temperatures were recorded between October and February.

2.2.3 Coho Habitat Use

Juvenile Coho habitat use surveys were conducted in the summer and the winter.

During the summers of 2008 and 2009, underwater observations via snorkeling were conducted to survey juvenile Coho habitat use in the study sites (Table 1). Each paired site was snorkeled on two to six occasions per summer between July and September. Snorkels at each site were conducted in the late afternoon when stream temperatures reached their peak and again just before midnight. During each snorkel, fish were identified to species and counted. A total of 174 snorkels were conducted at six paired sites (Table 1). Detailed snorkel survey methodology is described in O'Neal (2007).

Figure 4: Juvenile coho captured in Louis Creek, winter 2011/12.

Figure 5: trapping in Louis Creek in 2011/12.

During winter of 2011/2012, juvenile trapping using Gee traps was conducted at each of the five (5) study sites within the groundwater and control sites (Figure 4 and Figure 5); Duteau Creek was not included (Table 1). Traps were baited with cat food and set overnight for 14 to 25 hrs. Upon retrieval, all fish captured were tallied up by species and released.

Habitat data was collected at the paired sites and included habitat type (e.g., riffle), dominant substrate size, percent cover, and wetted width. Additional habitat data collected for the winter analysis included dissolved oxygen (DO), pH, flow rate and depth. Instantaneous water temperature and the maximum/minimum temperature observed within the three days preceding each sampling event were obtained from the temperature loggers installed at each site.

2.3 Analysis

2.3.1 Groundwater Flow

Specific discharge (v) is the flow rate of groundwater into the stream or the streambed, measured in m/s per m^2 of streambed. It is calculated by multiplying the hydraulic conductivity of the streambed (K_h) [m/s] by the Vertical Hydraulic Gradient (VHG) between the stream and the streambed:

$v = K_h * VHG$ (Fetter, 2001)

The VHG is positive where groundwater is upwelling into the stream and negative where groundwater is downwelling into the bed. The VHG of the streambed was calculated by the formula:

$$VHG = \frac{\Delta h}{L}$$

where $\Delta h = h_2 - h_1$ known as head difference
L = distance below streambed to top of piezometer screen

Standard calculation of K_h requires that the drop in water level is recorded over time. Since all piezometers equilibrated too rapidly to do so, K_h was estimated using the following modified equation by Baxter et al. (2003):

$$K = \left[\frac{(0.2501)(d_{piezometer})}{\Delta t}\right]\left[log_e \frac{h_0}{h}\right]$$

where $d_{piezometer}$ = inside diameter of the piezometer
Δt = time elapsed between addition of water and equilibration
h_0 = water level after water was added
h = water level at equilibrium

This equation assumes homogeneous and isotropic flow conditions.

2.3.2 Temperature

Water temperatures were plotted and average daily maximum temperatures in July and August (2008 and 2009 data) were calculated. In addition, the absolute maximum reached during the entire season was calculated. For the winter 2011/2 data, average daily minimum data for December, January and February were calculated as well as the absolute minimum reached.

2.3.3 Coho - Habitat Relations

Juvenile Coho catch data collected during the habitat use surveys were standardized between sites by converting to densities (snorkel survey data collected in the summer of 2008 and 2009) and Catch Per Unit Effort (CPUE) (Gee minnow trap data collected in the winter of 2011/2012), according to the following formulas:

$$Coho\ Density = \frac{\#\ coho\ observed}{area\ snorkeled}$$

$$CPUE = \frac{=\#\ of\ Coho\ captured}{\#\ of\ traps * trap\ duration\ (hrs)}$$

The data was also translated into presence (1) / absence (0) format for analysis in a logistic regression model.

The relationship between habitat variables and the two coho abundance metrics were analyzed in a Gaussian Linear Mixed Model. The presence / absence data was analyzed in a Binomial Linear Mixed Model with a logistic link function. Mixed models were selected to accommodate the grouping structure of the data and the repeated observations at the same sites over the course of the study period. A total of 12 habitat variables representing a range of habitat conditions were assessed (Table 2). The data was analyzed using the statistical software R (R Development Core Team, 2012) and the function *glmer()* in the library *lme4* (Bates et al., 2011). Coho densities and CPUE were square root transformed to achieve normality.

Table 2: Variables included in the regression models.

Dependent variables	Predictors (Fixed Effects)	Random Effects
• coho density (summer data) • CPUE (winter data) • coho presence/absence (both)	• groundwater/control • instantaneous temperature • maximum temperature in the three days preceding the sampling date (summer only) • groundwater area • habitat type (riffle, glide, pool) • maximum depth • cover (% of total area) • substrate (sand, gravel, cobble) • wetted width • pH (winter only) • DO (winter only) • flow velocity (winter only)	• stream • location • time of day • date • year

3.0 RESULTS

3.1 Groundwater Flow

Groundwater was confirmed to be discharging to the stream at all of the five sites sampled. Groundwater flux rates were highest at the Louis Creek 16.2 and lowest at Louis Creek 25.5 (Table 3). Groundwater flux per square meter of streambed reached from a high of 6143 L/day at Nicola River to a low of 291L/day (Louis Creek).

Table 3: Groundwater flow metrics estimated for Louis Creek, Nicola River and Deadman River.

Site	Vertical Hydraulic Gradient	Hydraulic Conductivity (m/s)	Upward Groundwater Flux/m^2 (m/s)
Louis			
13.9	0.127	2.16×10^{-4}	2.73×10^{-5}
16.2	0.159	4.47×10^{-4}	7.11×10^{-5}
25.5	0.114	2.94×10^{-5}	3.36×10^{-6}
Deadman			
14.2	0.070	3.78×10^{-5}	2.65×10^{-6}
Nicola			
21.7	0.293	9.20×10^{-5}	2.70×10^{-5}

3.2 Temperature

3.2.1 Summer

Summer water temperatures were lower in 2008 than 2009 but all sites exceeded the optimum thermal range for coho rearing (<16.0°C; Oliver and Fidler, 2001). Summer maximum daily temperatures (July and August) were consistently lower at the groundwater sites than the control sites (Table 4; Figure A1 to A9, Appendix A). The largest difference was observed in the Nicola River (2009) where maximum daily temperatures were on average 11.5°C lower in the groundwater upwelling area than the control. The smallest difference of 2.7°C was observed at site Louis Creek 16.2.

Table 4: Summer water temperatures at the groundwater and control sites.

Site	Maximum temperature reached (°C)					
	2008			2009		
	Groundwater	Control	Temperature difference (°C)[a]	Groundwater	Control	Temperature difference (°C)[a]
Louis						
13.9	12.2	21.5	6.3	22.9	25.5	7.8
16.2	-	-	-	20.9	23.2	2.7
25.5	7.0	18.5	9.3	13.2	20.5	10.2
Deadman						
14.2	15.0	20.3	3.6	16.2	22.6	3.8
Nicola						
21.7	18.9	25.1	7.1	17.3	27.9	11.5

a average difference in maximum daily temperature between July 1 and August 31

3.2.2 Winter

Winter water temperatures at the groundwater sites were consistently higher than the control sites (Figure A10 to A14, Appendix A) except for one site (Louis Creek 13.9) but the absolute minimum temperatures reached were not substantially different (Table 5). The largest difference was observed at Deadman River where minimum daily temperatures from December to February were on average 2.6 °C higher in the groundwater upwelling area than the control.

Table 5: Winter temperatures at the groundwater and control sites

Site	Minimum temperature reached (°C)		
	2011/12		
	Groundwater	Control	Temperature difference (°C)[a]
Louis			
13.9	-0.26	-0.06	-0.09
16.2	no data	0.00	no data
25.5	0.02	-0.12	1.87
Deadman			
14.2	2.56	1.24	2.60
Nicola			
21.7	-0.14	-0.09	1.50

a average difference in minimum daily temperature between December 1, 2011 and February 23, 2012

3.3 Coho Habitat Use

3.3.1 Summer

A total of 3,520 coho salmon were observed during the summer study period. Other salmonid species captured included Chinook salmon and rainbow trout. Coho observations were generally greater at night (after 6 PM) than the afternoon (before 6 PM) (Figure 6).

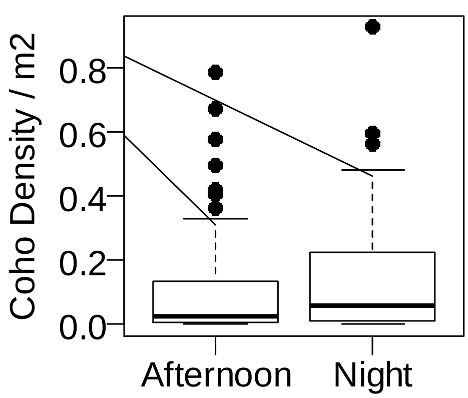


Figure 6: Coho Density (#/m^2) observed in the afternoon and at night during the summer of 2008 and 2009.

The Linear Mixed Model indicates that coho density at groundwater sites was significantly higher than at control sites (0.14 coho/m^2 vs. 0.10 coho/m^2, respectively; $p<0.001$) (Table 6). The only significant habitat predictor was the size of the groundwater upwelling area, with a predicted decrease in coho density with increasing area. However, the effect of size of the area predictor was small (-0.001 coho/m^2). All regression results and diagnostics are presented in Appendix B.

Daytime and night data was inspected separately, demonstrating that during the day there was no significant difference between coho density at groundwater and control sites (0.10 coho/m^2 vs. 0.11 coho/m^2, respectively; $p=0.62$). However; there was a significant difference at night when coho density was higher at the groundwater sites (0.17 coho/m^2 vs. 0.10 coho/m^2, respectively; $p<0.001$). Instantaneous and 3-day maximum temperatures were both negatively related to coho density and were lower at groundwater than control sites. Other significant habitat predictors during the night included area and substrate size. Coho density was significantly lower at sites with gravel than those with cobble (0.06 coho/m^2 vs. 0.14 coho/m^2; $p<0.001$). Similar to the pooled day and nighttime data discussed above, the effect size of area was very small (<-0.001), meaning that $\sqrt{coho/m^2}$ decreased by less than 0.001 for each additional square meter in size of the groundwater area.

Table 6: Significant predictors of coho density (square root) during the summer of 2008 and 2009.

Predictor	**Slope estimate**	**p-value**
Day and night combined		
groundwater	0.080	<0.001
area	<-0.001	0.013
Night only		
groundwater	0.124	<0.001
area	<-0.001	0.010
instantaneous temperature	-0.009	0.019
3 day maximum temperature	-0.007	0.028
substrate cobble	0.216	<0.001

Binomial Mixed Modeling indicates that the probability of encountering coho at groundwater sites was significantly higher than at control sites. When day and night data were combined, coho were 3.6 times more likely to be present at a groundwater site than a control site ($p<0.001$) (Table 7). The odds increased to 5.5 during the night ($p<0.001$) when coho were found to be more active (Figure 6). The only significant habitat predictors were instantaneous temperature and 3-day maximum temperature. In both cases, the probability of encountering coho decreased at higher temperatures Cover ($p=0.07$) and substrate ($p=0.08$) were almost significant predictors.

Table 7: Significant predictors of coho presence/absence during the summer of 2008 and 2009.

Predictor	Slope estimate	p-value
Day and night combined		
groundwater	1.28	<0.001
Night only		
groundwater	1.75	<0.001
instantaneous temperature	-0.138	0.008
3 day maximum temperature	-0.102	0.018

3.3.2 Winter

A total of 55 coho were captured during the winter study period as well as 13 Chinook and 66 rainbow trout. The instantaneous water temperatures measured at the beginning of each sampling event were higher at groundwater than control sites (3.38°C vs. 1.51°C, respectively). Coho CPUE was significantly greater at groundwater sites (0.046 coho/hr) than control sites (0.01 coho/hr) (p=0.040; Table 8, Figure 7). Instantaneous temperature (p=0.028) and habitat type (p=0.026) were also significant predictors of coho CPUE. Coho CPUE increased with higher temperatures and was significantly higher at sites where riffle was the dominant habitat unit rather than pool or glide.

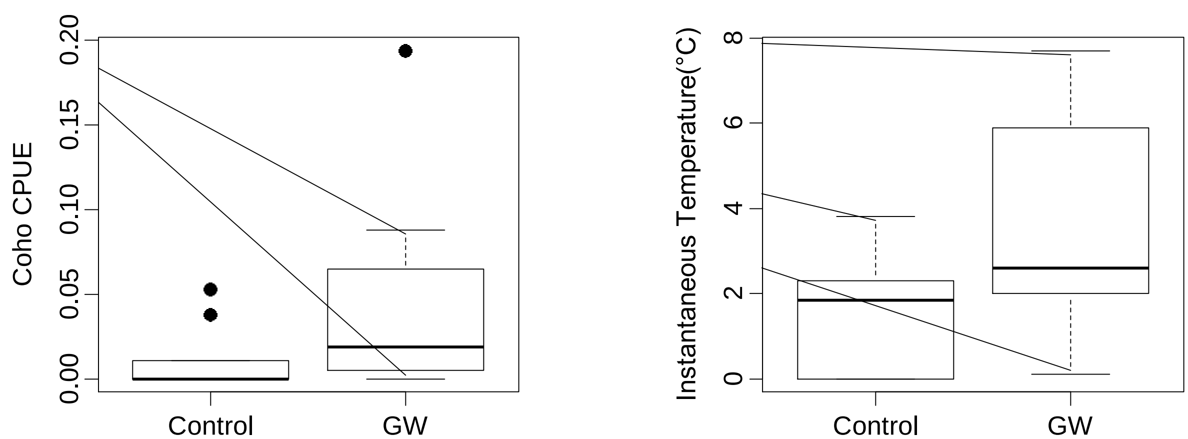


Figure 7: Coho CPUE and instantaneous temperature at groundwater and control sites during the winter of 2011.

Table 8: Significant predictors of coho density (square root) during the winter of 2011/12.

Predictor	Slope estimate	p-value
groundwater	0.103	0.040
habitat type	0.133	0.026
instantaneous temperature	0.032	0.028

4.0 DISCUSSION AND RECOMMENDATIONS

This study confirmed that juvenile coho in the interior of BC make preferential use of groundwater upwelling areas in both summer and winter seasons. Summer stream temperatures exceeded coho optimum temperature limits (<16°C) in all of the study streams. During both seasons, temperatures were more favorable for coho rearing at the groundwater than the control sites (e.g., lower temperatures in the summer and higher in the winter). However, the temperature difference was far more pronounced during the summer.

Temperature was the only consistently significant predictor of salmonid abundance through the seasons. Other habitat predictors including area and substrate (summer), and habitat type (winter) were significant in some models but the effect size of the area predictor was very small. In the case of substrate and habitat type, the number of observations in the respective significant types (cobble and riffle) was substantially greater than others, which may have led to the significant result. It is therefore concluded that it is primarily the thermal benefit that led to a higher abundance of coho at the groundwater sites rather than a difference in habitat parameters.

Groundwater upwelling rates between study sites varied and both the highest and lowest flux was found in Louis Creek. Interestingly, the site with the highest groundwater flux showed the smallest summer temperature difference between groundwater and control site (Louis Creek 16.2; 2.7°C). However, the site with the second highest flux showed the largest temperature difference (Nicola River; 11.5°C). This demonstrates that the moderating effect of groundwater inflow on stream temperature does not depend entirely on the magnitude of the flux. Other determining factors include flow velocity, depth, and shading.

The moderating effect of groundwater flow on stream temperatures was less pronounced in the winter at all sites, indicating that the thermal benefits of groundwater may be seasonal in some areas. Nonetheless, most of the groundwater sites were 1 to 2°C warmer than control sites.

This project demonstrates the difficulty in finding appropriate study sites for groundwater-related stream studies. It took several years to identify and refine sites with a sufficient difference in temperatures and other favorable conditions for the project. This difficulty was further exacerbated by the Endangered conservation status of coho. Low coho escapements in the past decade have resulted in low juvenile densities in many streams, making it difficult to find study sites with sufficient abundances for analysis.

Winter sampling for juvenile coho is difficult because of their reduced activity at low temperatures. It is recommended that future studies expand on winter study sites and sampling frequency to ensure a sufficient number of observations. During the summer it was observed that coho are more active at night, making nighttime sampling more advisable.

Continuing this study over several years was very useful as it ensured that both warm (e.g., 2009) and cool years (e.g., 2008) were captured. During cool years, the difference in juvenile abundance between groundwater and control sites may not be as pronounced as during very warm years. In addition, as brood abundances vary, juvenile densities may vary from year to year. It is recommended to choose study sites that have relatively large and consistent escapements every year.

It is recommended that an additional study be undertaken to assess the importance of groundwater in redd site selection by Interior Fraser Coho. Recently published research (McRae, 2009) indicates that upwelling groundwater plays an important role in spawning site selection of Interior Fraser Coho Salmon. Regional DFO stock assessment biologists have emphasized the importance of research initiatives that clarify the role of groundwater in spawning site selection on a larger spatial scale. The methodology for this study would include the installation of mini-piezometers immediately adjacent to confirmed Coho redds and nearby unused but suitable redd sites, and the collection of habitat data for statistical comparison. Expanding the study to adult spawning site selection would result in knowledge on the role groundwater plays in the egg, fry, rearing and spawning life stages of Interior Fraser Coho.

The results of this study indicate that groundwater needs to be regulated and protected to reduce potentially harmful temperature effects on coho populations in the Interior of BC. Excessive groundwater pumping has led to a lowering of groundwater levels in many areas, leading to lower stream baseflows and a reduction in cool groundwater seeps during the summer, which this study demonstrated constitute preferred habitat for coho and may provide critical thermal refuge for coho. The modernization of BC's water act provides an opportunity for protecting this resource along with the endangered Interior Fraser Coho populations that depend upon it.

5.0 REFERENCES

Bates, D., Maechler, M. and B. Bolker. 2011. *lme4: Linear mixed-effects models using S4 classes*. R package version 0.999375-42. Retrieved from: http://CRAN.R-project.org/package=lme4

Baxter C., Hauer, R.F. and W. W. Woessner. 2003. Measuring groundwater-stream water exchange: New techniques for installing minipiezometers and estimating hydraulic conductivity. *Transactions of the American Fisheries Society* 132:493-502.

Davis, C and H. Wright. 2007. Groundwater habitat interaction for Interior Fraser Coho study. Okanagan Nation Alliance, Westbank, B.C. Prepared for Fraser Salmon and Watershed Program – Fraser Basin Initiative.

Fetter, C. W. 2001. Applied hydrogeology (4th Ed.). New Jersey: Prentice Hall.

Freeze, R.A. and J.A. Cherry. 1979. Groundwater. Prentice-Hall, Inc. Englewood Cliffs, NJ. 604 p.

Interior Fraser Coho Recovery Team. 2006. Species at risk proposed recovery strategy: coho salmon (*Interior Fraser River populations*), *Oncorhynchus kisutch*. Fisheries and Oceans Canada. 137 p.

Interior Fraser Coho Recovery Team. 2006a. Conservation Strategy for Coho Salmon, Interior Fraser River Populations. Fisheries and Oceans Canada.

Lee, D.R. and J.A. Cherry. 1978. A field exercise on groundwater flow using seepage meters and mini-piezometers. Journal of Geological Education 27:6-10.

Matthews, M., Glova, G., & Sampson, T. 2007. Nicola River watershed stream temperatures, July-October 2006. Submitted to the Pacific Salmon Foundation. 25p.

McRae, C.J. 2009. Spawning site selection and the influence of incubation environment on larval success in Interior Fraser Coho. Master's Thesis, University of Northern British Columbia, Prince George, BC. 121 p.

Nielsen, J.L., Lisle, T.E., & Ozaki, V. 1994. Thermally stratified pools and their use by steelhead in northern California streams. *Transactions of the American Fisheries Society*, 123, 613-626. As cited in: Ebersole et al., (2001); Baird & Krueger (2003); Tobias (2006) and; Power et al., (1999).

Oliver, G. G. and L. E. Fidler. 2001. Towards a water quality guideline for temperature in the Province of British Columbia. Prepared for the BC Ministry of Environment, Lands and Parks, Water Management Branch, Water Quality Section.

O'Neal. J. S. 2007. Snorkel Surveys. In D. H. Johnson, B.M. Shrier, J.S. ONeal, J.A. Knutzen, X. Augerot, T.A. ONeil, and T.N. Pearsons (eds) Salmonid Field Protocols Handbook: Techniques for assessing status and trends in salmon and trout populations. American Fisheries Society, Bethesda, Maryland. Pp 325-339. As cited in Davis & Wright, 2007.

Power, G., Brown, R.S., & Imhof, J.G. 1999. Groundwater and fish – insights from northern North America. Hydrological Processes, 13, 401-422.

R Development Core Team. 2012. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0, URL http://www.R-project.org/.

Sampson, T. 2010. Groundwater Habitat Interactions for Interior Fraser Coho – Year 3 (2009) Project Final Report. Nicola Tribal Association - Nicola Watershed Stewardship and Fisheries Authority, Merritt, BC. Prepared for Pacific Salmon Foundation - Fraser Salmon and Watersheds Program.

Walsh, M. 2009. Groundwater Habitat Interactions for Interior Fraser Coho Study – Year 2. Secwepemc Fisheries Commission, Kamloops, BC. Prepared for Fraser Salmon and Watershed Program – Fraser Basin Initiative.

Walthers, L.C., & Nener, J.C. 2000. Water temperature monitoring in selected Thompson River tributaries, B.C., 1996: implications of measured temperatures for anadromous salmonids. *Canadian Technical Report of Fisheries and Aquatic Sciences*, 2306. 69 p.

Warren, K.D. 2010. University of Northern British Columbia Masters Candidate. University of Northern British Columbia, Prince George, British Columbia.

Appendix A

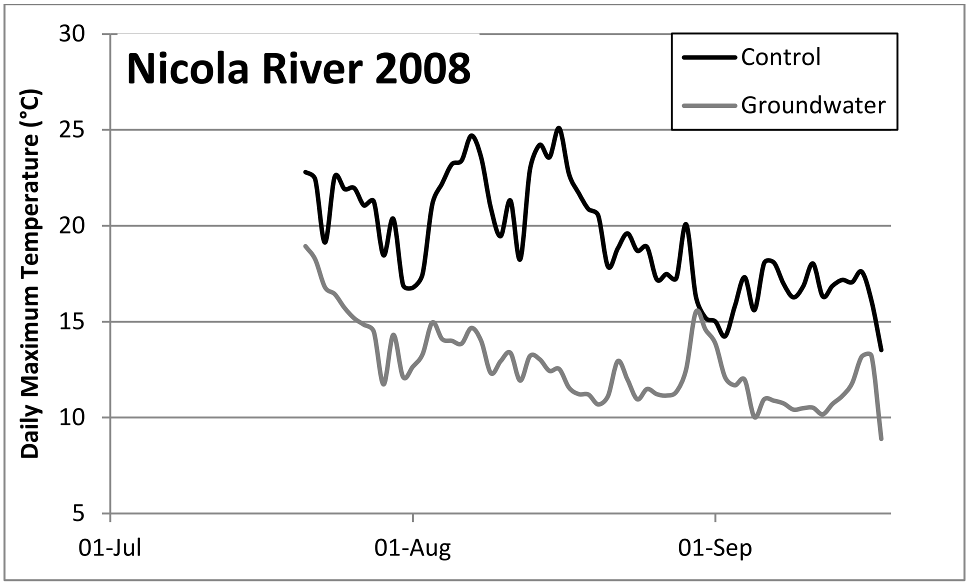


Figure A1: Nicola River daily maximum temperatures at the groundwater and control site in the summer of 2008.

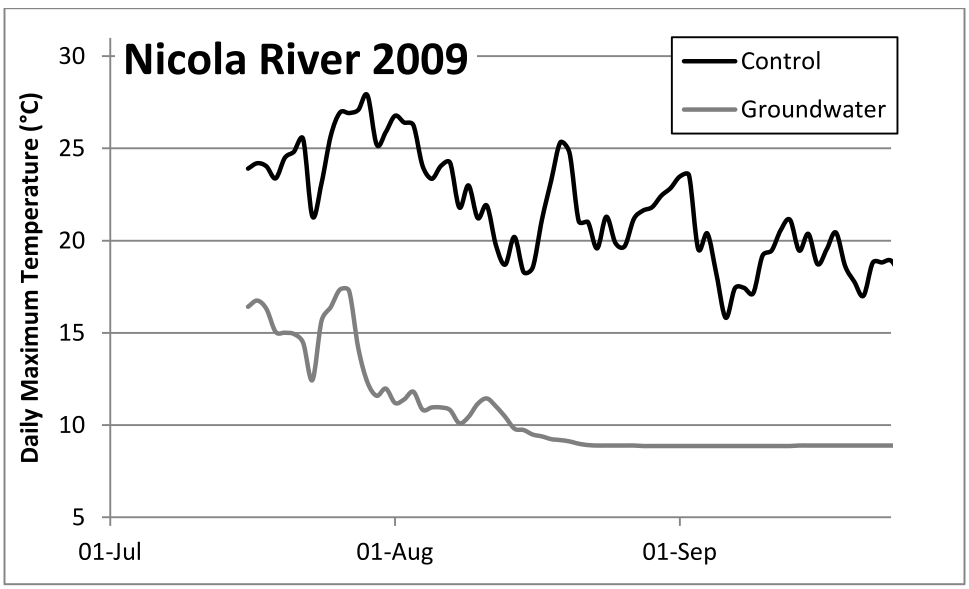


Figure A2: Nicola River daily maximum temperatures at the groundwater and control site in the summer of 2009.

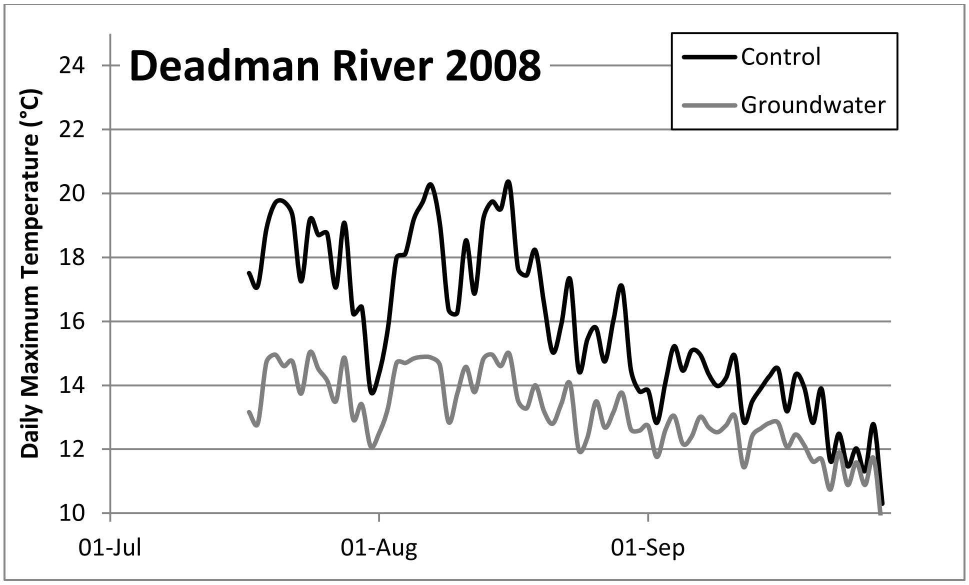


Figure A3: Deadman River daily maximum temperatures at the groundwater and control site in the summer of 2008.

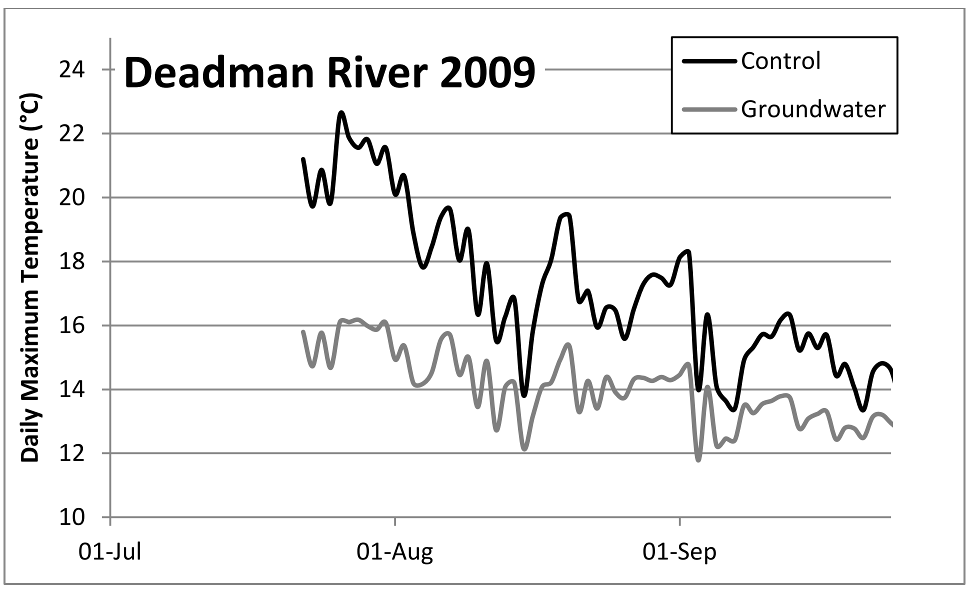


Figure A4: Deadman River daily maximum temperatures at the groundwater and control site in the summer of 2009.

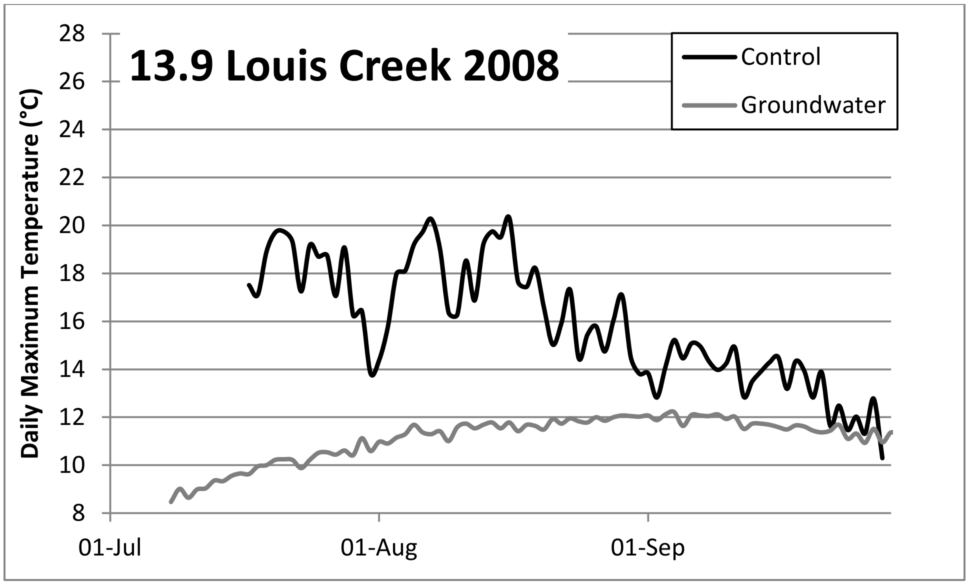


Figure A5: Louis Creek 13.9 daily maximum temperatures at the groundwater and control site in the summer of 2008.

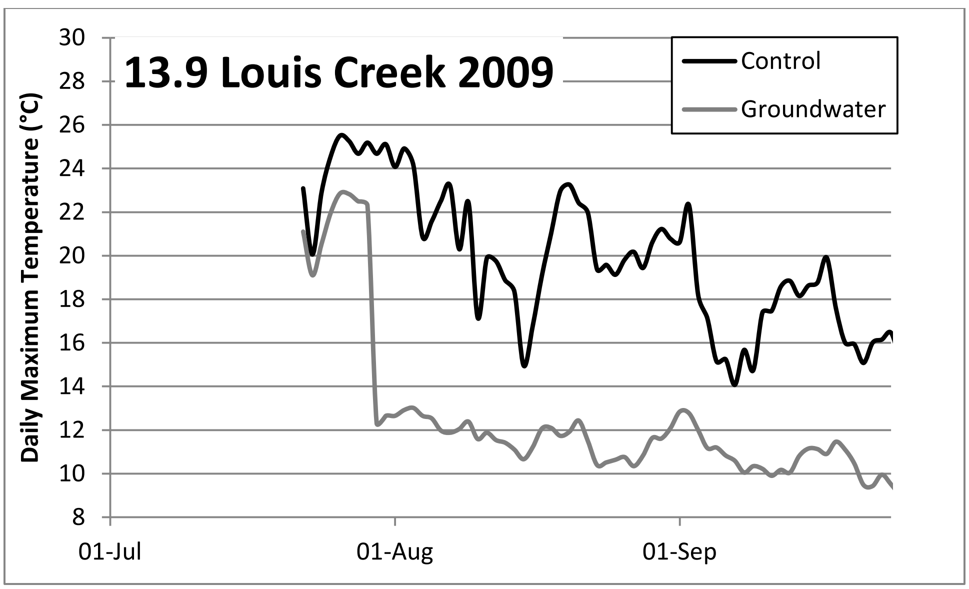


Figure A6: Louis Creek 13.9 daily maximum temperatures at the groundwater and control site in the summer of 2009.

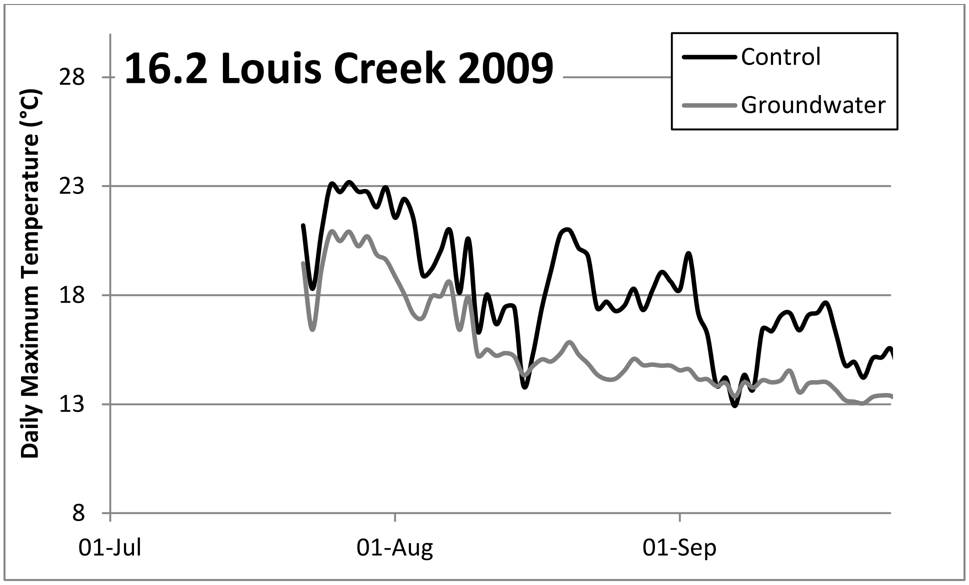


Figure A7: Louis Creek 16.2 daily maximum temperatures at the groundwater and control site in the summer of 2009.

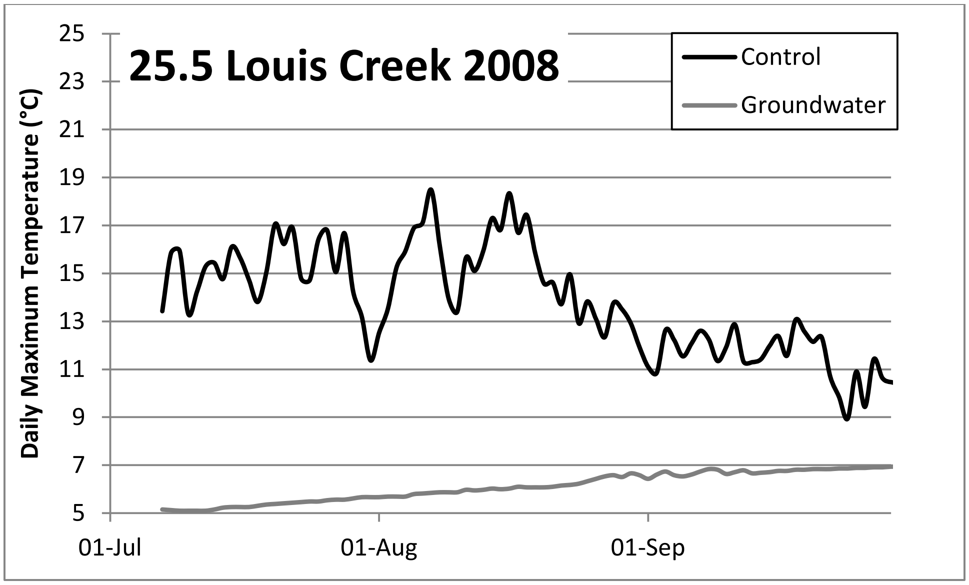


Figure A8: Louis Creek 25.5 daily maximum temperatures at the groundwater and control site in the summer of 2008.

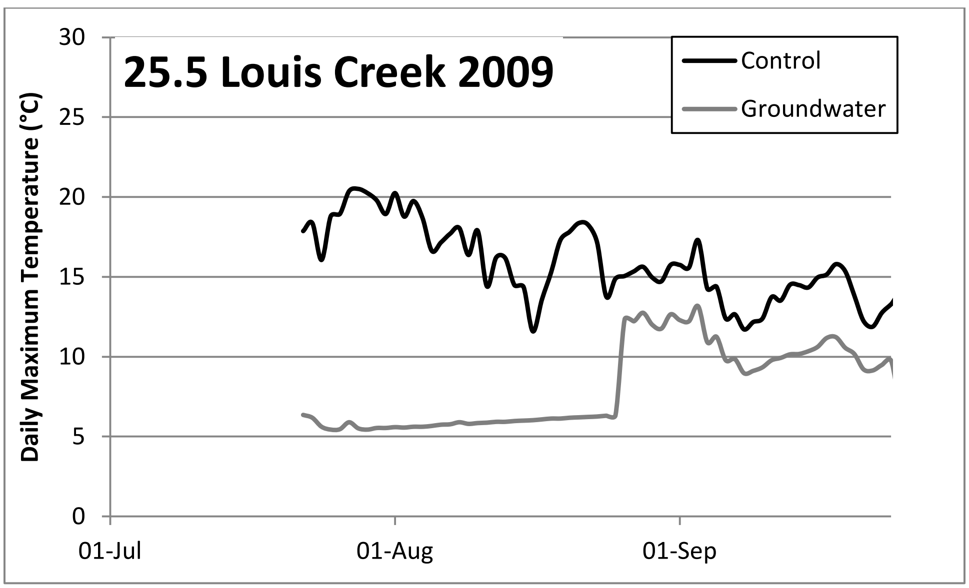


Figure A9: Louis Creek 25.5 daily maximum temperatures at the groundwater and control site in the summer of 2009.

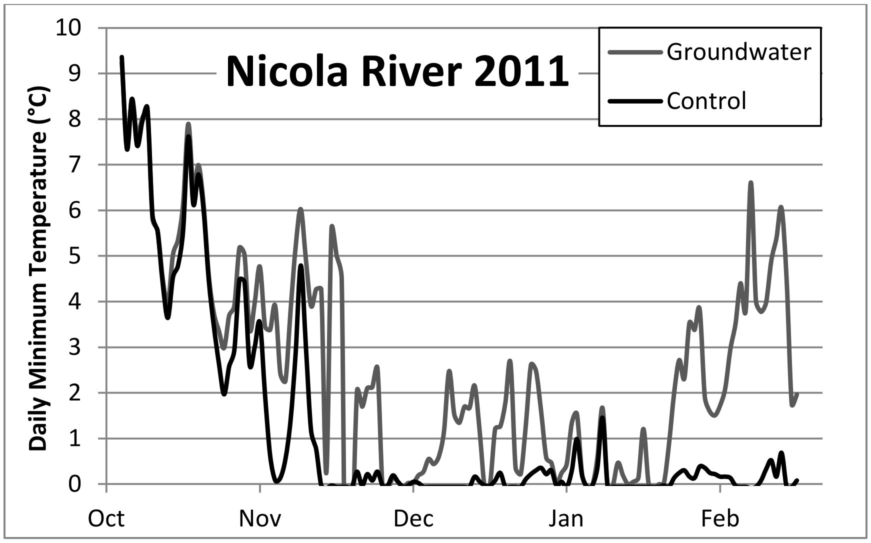


Figure A10: Nicola River daily minimum temperatures at the groundwater and control site in the winter of 2011.

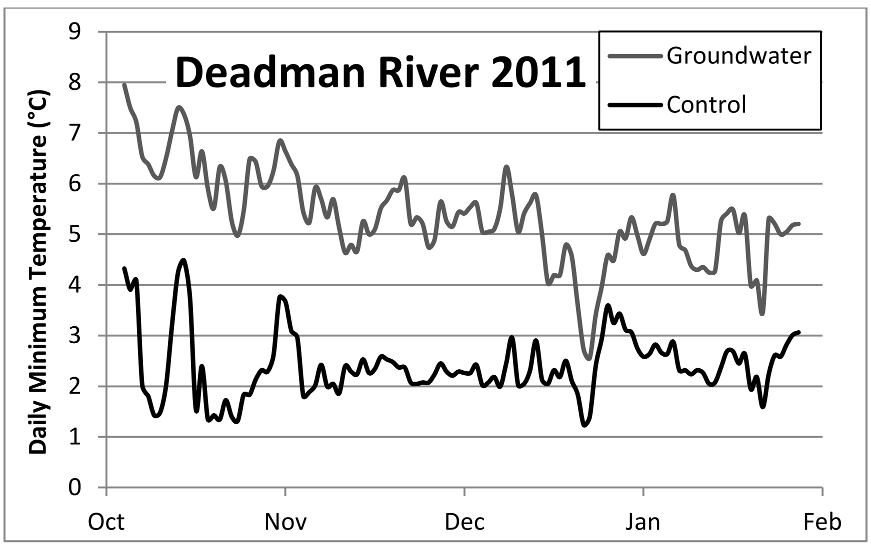


Figure A11: Deadman River daily minimum temperatures at the groundwater and control site in the winter of 2011.

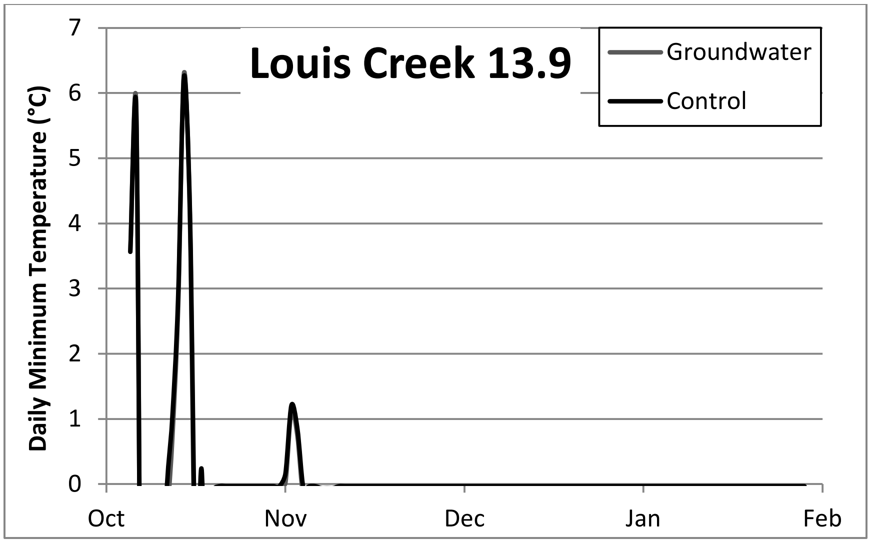


Figure A12: Louis Creek 13.9 daily minimum temperatures at the groundwater and control site in the winter of 2011.

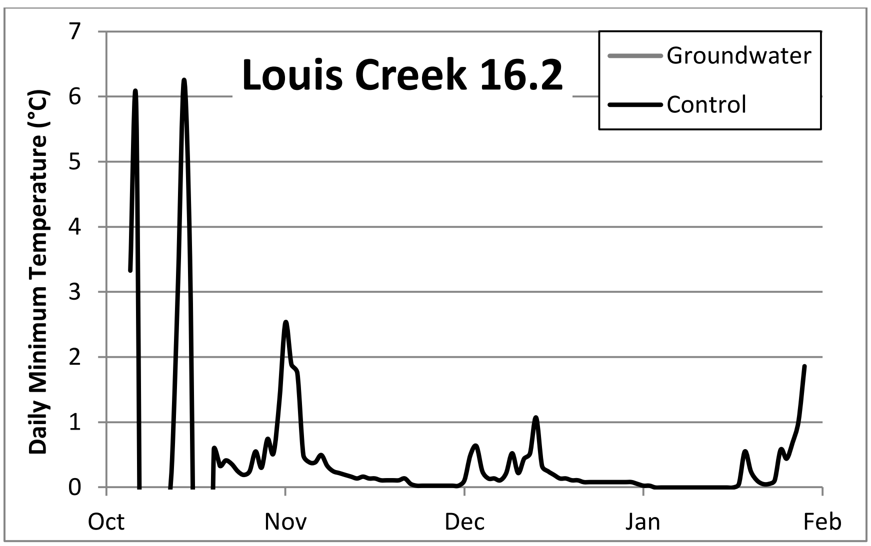


Figure A 13: Louis Creek 16.2 daily minimum temperatures at the groundwater and control site in the winter of 2011.

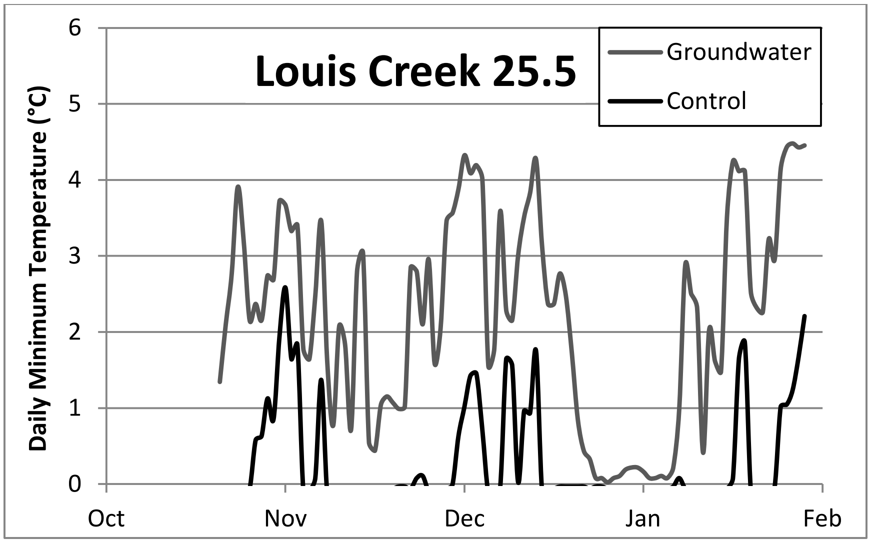


Figure A14: Louis Creek daily minimum temperatures at the groundwater and control site in the winter of 2011.

Appendix B – Regression Results and Diagnostics

Linear Mixed Models – Summer

Linear mixed model fit by REML (p-values from comparing nested models fit by maximum likelihood)

Formula: CohoRoot ~ **GW** + **Area** + (1 | Year) + (1 | Stream) + (1 | Location) + (1 | Date)

AIC	BIC	logLik	deviance	REMLdev
-110.2	-84.97	63.12	-152.7	-126.2

Random effects:

Groups	Name	Variance	Std.Dev.
Date	(Intercept)	8.60E-03	9.28E-02
Location	(Intercept)	7.11E-03	8.43E-02
Stream	(Intercept)	6.08E-16	2.47E-08
Year	(Intercept)	7.12E-03	8.44E-02
Residual		1.87E-02	1.37E-01

Number of obs: 174, groups: Date, 28; Location, 6; Stream, 4; Year, 2

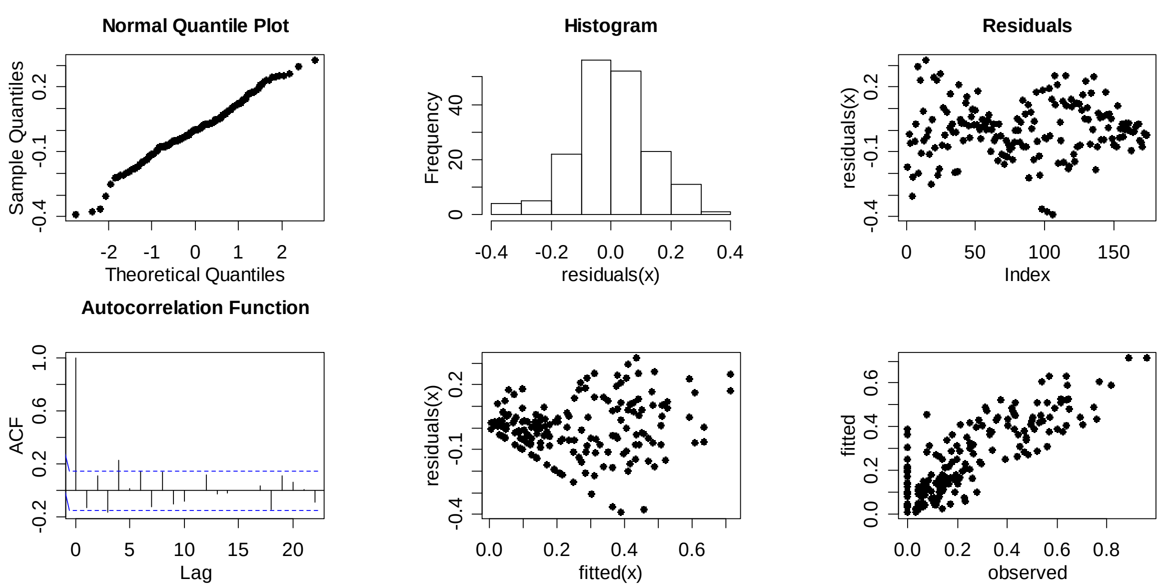
Fixed effects:

	Estimate	Std. error	t-value	p.value.LRT
(Intercept)	3.07E-01	7.83E-02	3.92E+00	1.50E-02
GW	8.05E-02	2.25E-02	3.57E+00	0.00E+00
Area	-2.18E-04	7.85E-05	-2.77E+00	1.30E-02

Correlation of Fixed Effects:

	(Intr)	GW
GW	0.015	
Area	-0.351	-0.39

Shapiro-Wilk normality test
data: residuals(x)
W = 0.9869, p-value = 0.1054



Linear mixed model fit by REML (p-values from comparing nested models fit by maximum likelihood)

Formula: CohoRoot ~ **GW** + **Area** + (1 | Year) + (1 | Stream) + (1 | Location) + (1 | Date)

Data: salmondata **Subset: Time2 == "Late"**

AIC	BIC	logLik	deviance	REMLdev
-60.19	-39.84	38.09	-101.7	-76.19

Random effects:

Groups	Name	Variance	Std.Dev.
Date	(Intercept)	4.93E-03	7.02E-02
Location	(Intercept)	1.23E-02	1.11E-01
Stream	(Intercept)	3.39E-03	5.82E-02
Year	(Intercept)	0.004191	6.47E-02
Residual		0.013785	0.117409

Fixed effects:

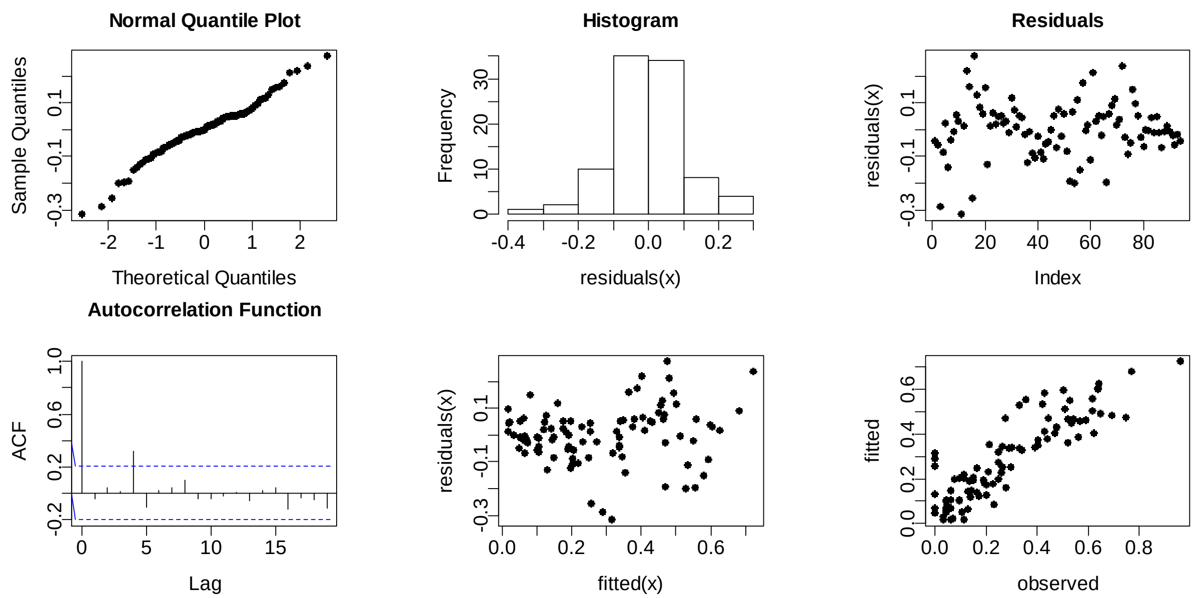
	Estimate	Std. error	t-value	p.value.LRT
(Intercept)	0.30873	0.0855065	3.611	0.012
GW	0.1237354	0.0272116	4.547	0
Area	-0.0002791	0.0001047	-2.665	0.01

Number of obs: 94, groups: Date, 27; Location, 6; Stream, 4; Year, 2

Correlation of Fixed Effects:

	(Intr)	GW
GW	0.074	
Area	-0.439	-0.456

Shapiro-Wilk normality test
data: residuals(x)
W = 0.9731, p-value = 0.05



Linear mixed model fit by REML (p-values from comparing nested models fit by maximum likelihood)

Formula: CohoRoot ~ **InstTemp** + (1 | Year) + (1 | Stream) + (1 | Location) + (1 | Date)

Data: salmondata **Subset: Time2 == "Late"**

AIC	BIC	logLik	deviance	REMLdev
-61.72	-43.92	37.86	-88.35	-75.72

Random effects:

Groups	Name	Variance	Std.Dev.
Date	(Intercept)	5.52E-03	7.43E-02
Location	(Intercept)	1.95E-02	1.40E-01
Stream	(Intercept)	9.22E-04	3.04E-02
Year	(Intercept)	0.005058	7.11E-02
Residual		0.015575	0.1248

Number of obs: 94, groups: Date, 27; Location, 6; Stream, 4; Year, 2

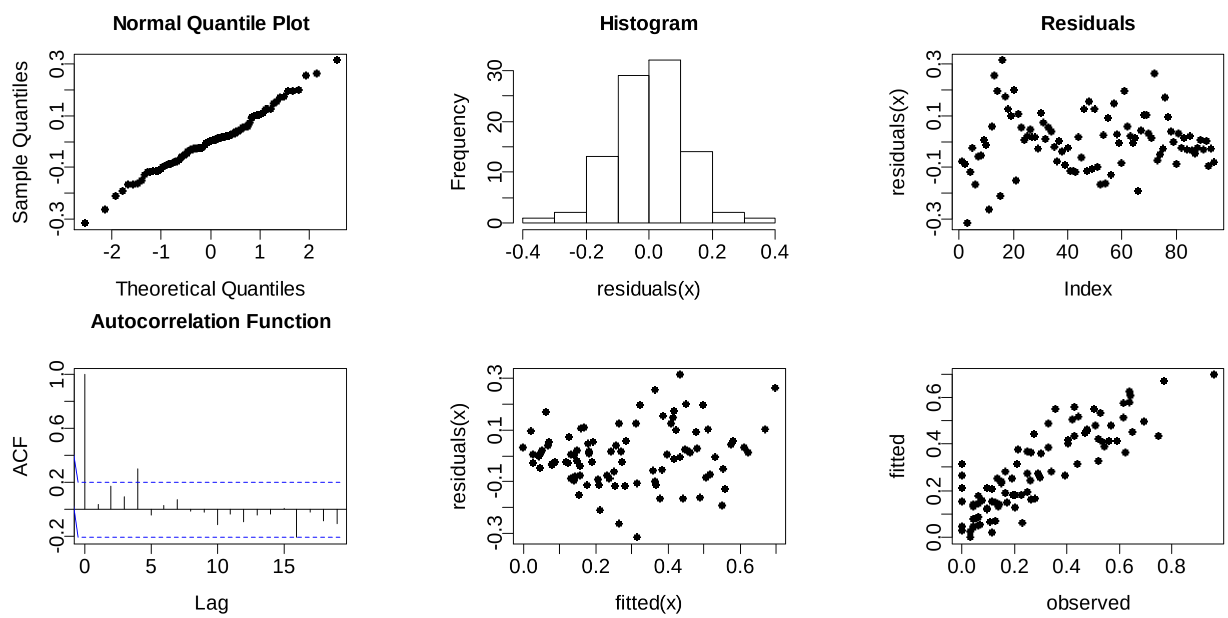
Fixed effects:

	Estimate	Std. error	t-value	p.value.LRT
(Intercept)	0.382727	0.095098	4.025	0.01
InstTemp	-0.008766	0.003568	-2.457	0.019

Correlation of Fixed Effects:

	(Intr)
InstTemp	-0.511

Shapiro-Wilk normality test
data: residuals(x)
W = 0.9874, p-value = 0.5139



Linear mixed model fit by REML (p-values from comparing nested models fit by maximum likelihood)

Formula: CohoRoot ~ **X3DayMax** + (1 | Year) + (1 | Stream) + (1 | Location) + (1 | Date)

Data: salmondata **Subset: Time2 == "Late"**

AIC	BIC	logLik	deviance	REMLdev
-58.67	-41.02	36.34	-85.5	-72.67

Random effects:

Groups	Name	Variance	Std.Dev.
Date	(Intercept)	5.17E-03	7.19E-02
Location	(Intercept)	2.04E-02	1.43E-01
Stream	(Intercept)	0.002495	4.99E-02
Year	(Intercept)	0.005584	0.074728
Residual		0.01573	0.12542

Number of obs: 92, groups: Date, 27; Location, 6; Stream, 4; Year, 2

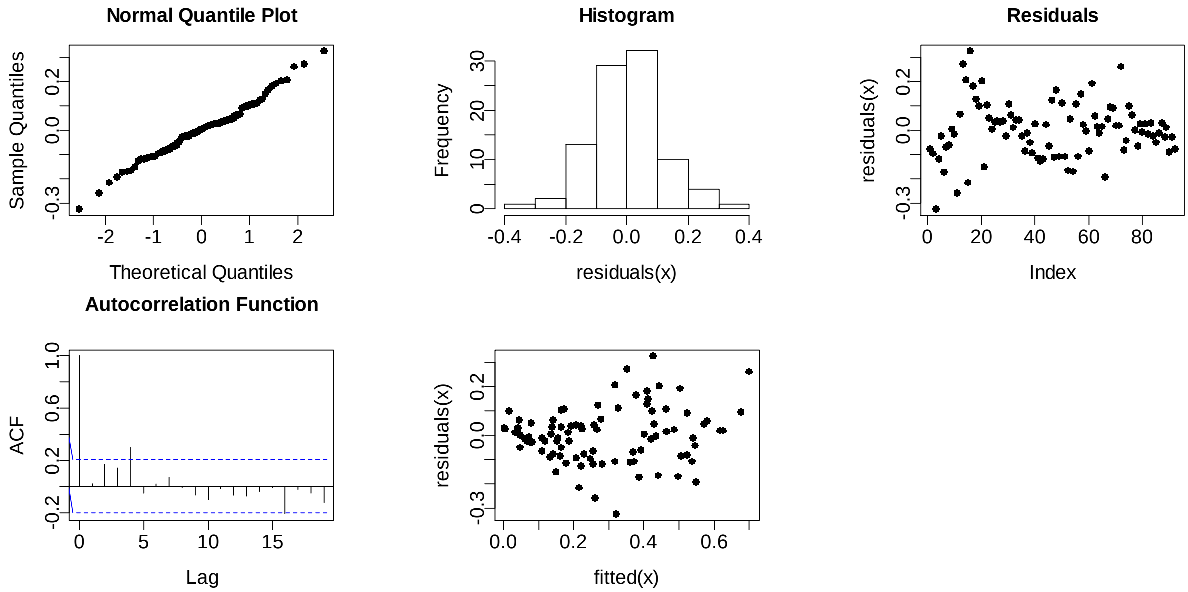
Fixed effects:

	Estimate	Std. error	t-value	p.value.LRT
(Intercept)	0.36768	0.099522	3.694	0.012
X3DayMax	-0.006974	0.003031	-2.301	0.028

Correlation of Fixed Effects:

	(Intr)
X3DayMax	-0.482

Shapiro-Wilk normality test
data: residuals(x)
W = 0.9858, p-value = 0.4232



Linear mixed model fit by REML (p-values from comparing nested models fit by maximum likelihood)

Formula: CohoRoot ~ **Cobble** + (1 | Year) + (1 | Stream) + (1 | Location) + (1 | Date)

Data: salmondata **Subset: Time2 == "Late"**

AIC	BIC	logLik	deviance	REMLdev
-78.08	-60.27	46.04	-99.36	-92.08

Random effects:

Groups	Name	Variance	Std.Dev.
Date	(Intercept)	5.70E-03	7.55E-02
Location	(Intercept)	2.79E-02	1.67E-01
Stream	(Intercept)	2.67E-15	5.17E-08
Year	(Intercept)	3.97E-03	6.30E-02
Residual		1.31E-02	1.15E-01

Number of obs: 94, groups: Date, 27; Location, 6; Stream, 4; Year, 2

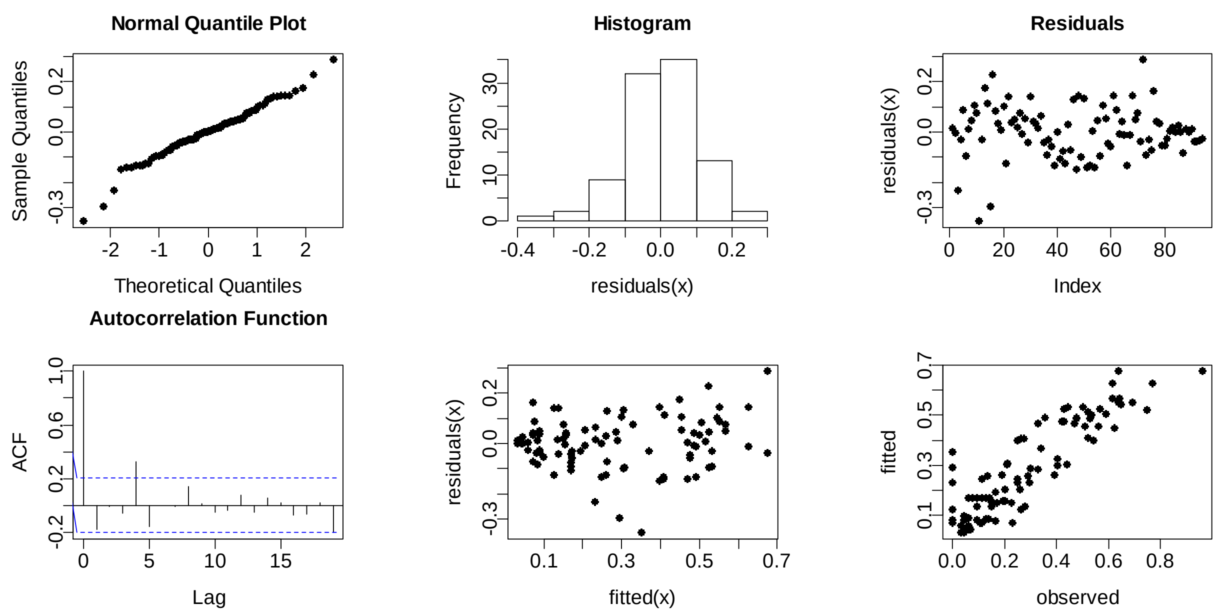
Fixed effects:

	Estimate	Std. error	t-value	p.value.LRT
(Intercept)	0.0969	0.09322	1.039	0.278
Cobble	0.21635	0.04961	4.361	0

Correlation of Fixed Effects:

	(Intr)
Cobble	-0.413

Shapiro-Wilk normality test
data: residuals(x) W = 0.976, p-value = 0.08071



Binomial Mixed Models – Summer

Generalized linear mixed model fit by the Laplace approximation (p-values from comparing nested models fit by maximum likelihood)

Formula: CoBin ~ **GW** + (1 | Year) + (1 | Stream) + (1 | Location) + (1 | Date)

Data: salmondata

AIC	BIC	logLik	deviance
236.2	255.1	-112.1	224.2

Random effects:

Groups	Name	Variance	Std.Dev.
Date	(Intercept)	0	0
Location	(Intercept)	0	0
Stream	(Intercept)	0	0
Year	(Intercept)	0	0

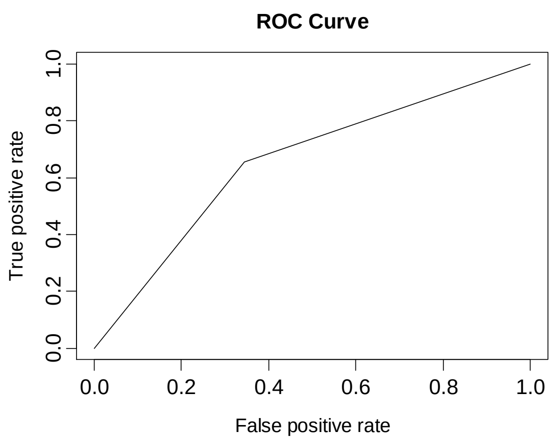
Number of obs: 174, groups: Date, 28; Location, 6; Stream, 4; Year, 2

Fixed effects:

	Estimate	Std. Error	z-value	Pr(>|z|)	p.value.LRT
(Intercept)	-6.42E-01	2.26E-01	-2.85E+00	4.43E-03	0.002
GW	1.28E+00	3.19E-01	4.02E+00	5.72E-05	0

Correlation of Fixed Effects:

	(Intr)
GW	-0.707



Generalized linear mixed model fit by the Laplace approximation

Formula: CoBin ~ **GW** + (1 | Year) + (1 | Stream) + (1 | Location) + (1 | Date)

Subset: Time2 == "Late"

AIC	BIC	logLik	deviance
126.5	141.8	-57.25	114.5

Random effects:

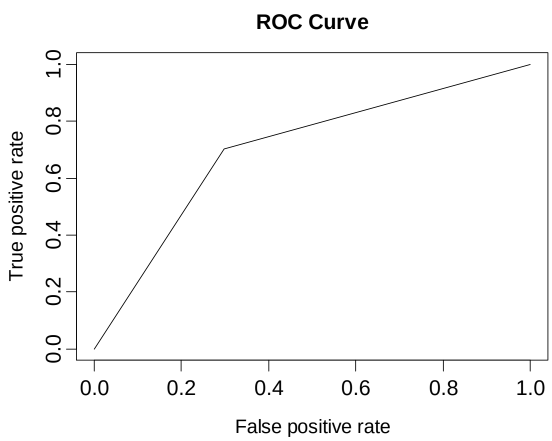
Groups	Name	Variance	Std.Dev.
Date	(Intercept)	4.95E-12	2.23E-06
Location	(Intercept)	0.00E+00	0.00E+00
Stream	(Intercept)	0.00E+00	0.00E+00
Year	(Intercept)	0.00E+00	0.00E+00

Number of obs: 94, groups: Date, 27; Location, 6; Stream, 4; Year, 2

Fixed effects:

	Estimate	Std. Error	z-value	Pr(>|z|)
(Intercept)	-0.8574	0.319	-2.688	0.007181
GW	1.7149	0.4511	3.802	0.000144

	(Intr)
GW	-0.707



Generalized linear mixed model fit by the Laplace approximation (p-values from comparing nested models fit by maximum likelihood)

Formula: CoBin ~ **InstTemp** + (1 | Year) + (1 | Stream) + (1 | Location) + (1 | Date)

Data: salmondata **Subset: Time2 == "Late"**

AIC	BIC	logLik
134.5	149.8	-61.27

Random effects:

Groups	Name	Variance	Std.Dev.
Date	(Intercept)	0.00E+00	0.00E+00
Location	(Intercept)	0.00E+00	0.00E+00
Stream	(Intercept)	0.00E+00	0.00E+00
Year	(Intercept)	2.05E-10	1.43E-05

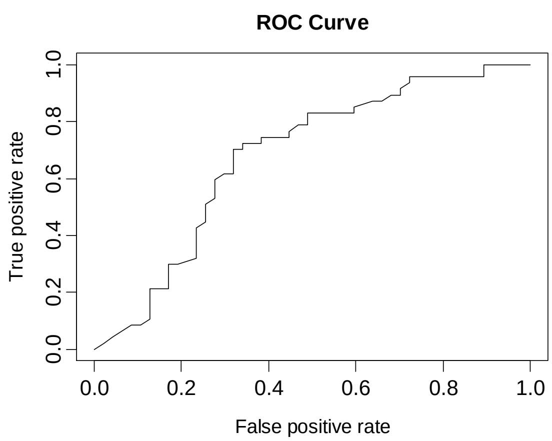
Number of obs: 94, groups: Date, 27; Location, 6; Stream, 4; Year, 2

Fixed effects:

	Estimate	Std. Error	z-value	Pr(>|z|)
(Intercept)	1.82238	0.72267	2.522	0.01168
InstTemp	-0.13807	0.05218	-2.646	0.00815

Correlation of Fixed Effects:

	(Intr)
InstTemp	-0.955



Generalized linear mixed model fit by the Laplace approximation

Formula: CoBin ~ **X3DayMax** + (1 | Year) + (1 | Stream) + (1 | Location) + (1 | Date)

Data: salmondata **Subset: Time2 == "Late"**

AIC	BIC	logLik	deviance
133.5	148.6	-60.73	121.5

Random effects:

Groups	Name	Variance	Std.Dev.
Date	(Intercept)	0.00E+00	0.00E+00
Location	(Intercept)	0.00E+00	0.00E+00
Stream	(Intercept)	1.89E-10	1.37E-05
Year	(Intercept)	0.00E+00	0.00E+00

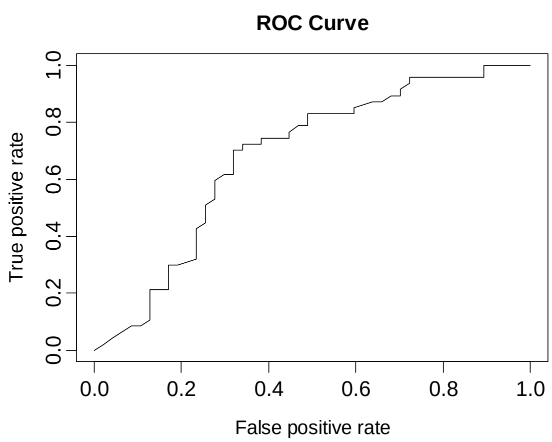
Number of obs: 92, groups: Date, 27; Location, 6; Stream, 4; Year, 2

Fixed effects:

	Estimate	Std. Error	z-value	Pr(>|z|)
(Intercept)	1.57714	0.70419	2.24	0.0251
X3DayMax	-0.1021	0.04316	-2.365	0.018

Correlation of Fixed Effects:

	(Intr)
X3DayMax	-0.952



Linear Mixed Models – Winter

Linear mixed model fit by REML (p-values from comparing nested models fit by maximum likelihood)

Formula: I(sqrt(CohoCPUE)) ~ **GW** + (1 | Date)

Data: salmondatawinter

AIC	BIC	logLik	deviance	REMLdev
-10.54	-6.977	9.269	-27.66	-18.54

Random effects:

Groups	Name	Variance	Std.Dev.
Date	(Intercept)	5.28E-03	0.072689
Residual		1.03E-02	1.01E-01

Number of obs: 18, groups: Date, 7

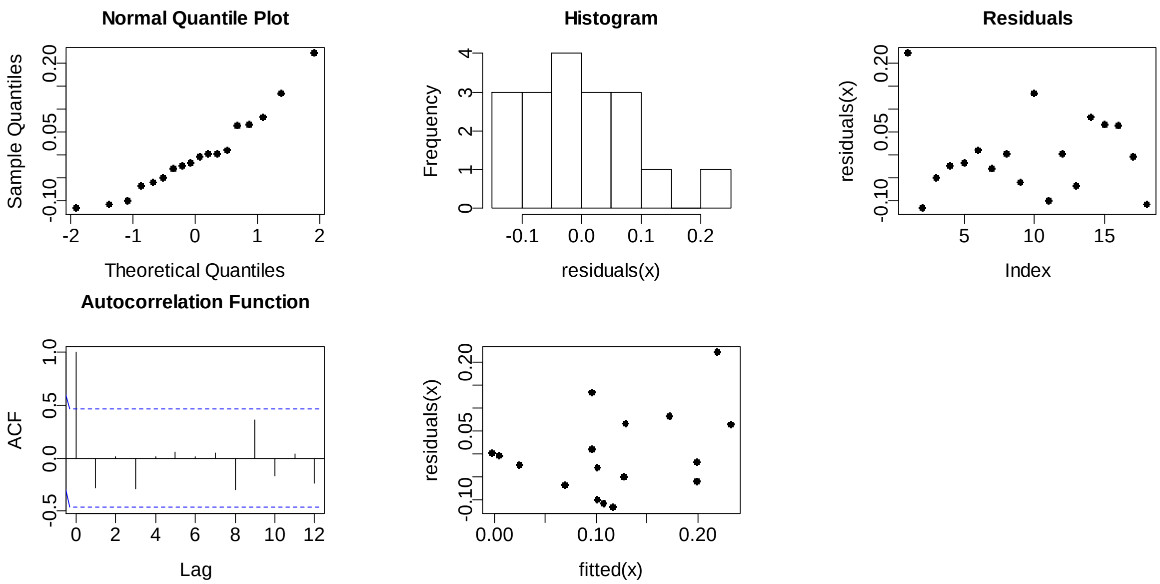
Fixed effects:

	Estimate	Std. Error	t-value	p.value.LRT
(Intercept)	0.06239	0.04397	1.419	0.144
GW	0.1033	0.0478	2.1611	0.04

Correlation of Fixed Effects:

	(Intr)
GW	-0.544

Shapiro-Wilk normality test
data: residuals(x) W = 0.9337, p-value = 0.2253



Linear mixed model fit by REML (p-values from comparing nested models fit by maximum likelihood)

Formula: I(sqrt(CohoCPUE)) ~ **InstTemp** + (1 | Date)

Data: salmondatawinter

AIC	BIC	logLik	deviance	REMLdev
-8.557	-4.995	8.278	-28.17	-16.56

Random effects:

Groups	Name	Variance	Std.Dev.
Date	(Intercept)	0.0057889	0.076085
Residual	0.009663	0.0983	

Number of obs: 18, groups: Date, 7

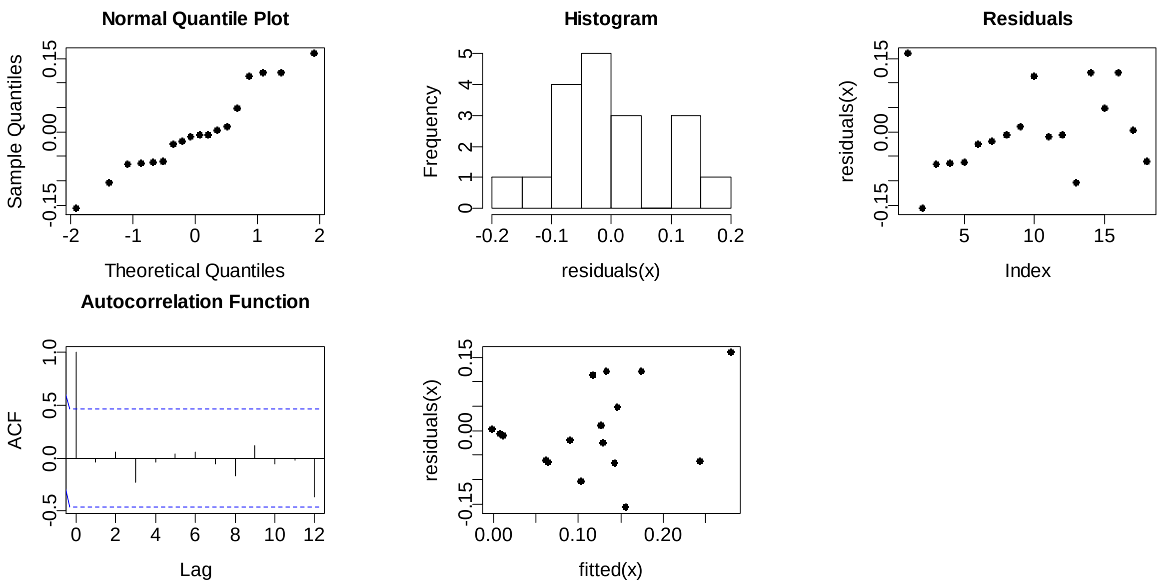
Fixed effects:

	Estimate	Std. Error	t-value	p.value.LRT
(Intercept)	0.033	0.05107	0.6461	0.454
InstTemp	0.03182	0.01362	2.3361	0.028

Correlation of Fixed Effects:

	(Intr)
InstTemp	-0.681

Shapiro-Wilk normality test
W = 0.9444, p-value = 0.3441



Linear mixed model fit by REML (p-values from comparing nested models fit by maximum likelihood)

Formula: I(sqrt(CohoCPUE)) ~ **HabType** + (1 | Date)

Data: salmondatawinter

AIC	BIC	logLik	deviance	REMLdev
-7.038	-2.587	8.519	-29.29	-17.04

Random effects:

Groups	Name	Variance	Std.Dev.
Date	(Intercept)	0.006983	0.083562
Residual		0.009131	0.095558

Number of obs: 18, groups: Date, 7

Fixed effects:

	Estimate	Std. Error	t-value	p.value.LRT
(Intercept)	0.03239	0.06055	0.5349	0.56
HabTypePool	0.02437	0.08618	0.2828	0.756
HabTypeRiffle	0.13251	0.0581	2.2806	0.026

Correlation of Fixed Effects:

	(Intr)	HbTypP
HabTypePool	-0.61	
HabTypeRffl	-0.725	0.581

Shapiro-Wilk normality test
data: residuals(x) W = 0.9271, p-value = 0.1728