THE EFFECT OF FOREST HARVESTING ON STREAMFLOW RECESSION CURVES AT CARNATION CREEK, BRITISH COLUMBIA.

by

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Abstract

At the Carnation Creek Experimental Watershed on southwestern Vancouver Island, British Columbia, the effect of harvesting, regeneration and road building were analyzed through the use of stream discharge data collected at a weir on the catchment outlet. The study was separated into a Pre-Logging period from 1971-1975, Logging from 1976-1981, and two Post-Logging periods from 1982-1985 and 1985-90 respectively. The current study focussed on the effects of harvesting on streamflow recession curves, which are an indicator of the ability of coastal watersheds to maintain low flows (base-flow) during the water-limited dry season. Approximately 30 years of discharge data along with rainfall and temperature were segmented into corresponding forestry operation periods. Using the linear relationship between $\log[|dQ/dt|]$ and $\log[Q_m]$ according to storage-discharge theory, multiple linear models were created and a regression was used to investigate the significance of each of the forestry operations. It was found that the effect of the roads increased lateral slope interception of sub-surface flow and directed water along the ditch systems to the channel at a greater rate, steepening the recession curves at all discharge levels in the short term, but only persisting at low discharge levels. Harvesting increased the water table height, because of the reduction in transpiration via loss of interception, and low flows and total flows increased over both post-logging periods, which partially offset the effect the roads had on the recession. Regeneration began to occur over the harvested sections of the catchment and it was found their effect between post-logging periods was only significant with the inclusions of extremely low discharge levels. However, a second logging pass in 1987, removing 21% of the forested catchment in the headwaters is believed to have confounded the regeneration effects.

KEYWORDS: discharge, low flows, hydrograph, logging, roads, ditches, culvert, watershed, catchment, riparian harvest, cut-block, riparian buffer.

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1. Introduction

There have been numerous studies showing that forest harvesting can increase: annual water yield, water table levels, and overland flow (Smerdon *et al.*, 2009; Hetherington *et al*., 1998; Hicks *et al.*, 1991; Keppeler and Ziemer, 1990; Harr *et al.*, 1979). Harr (1979) reported that summer low flows increased almost four-fold following clear-cut harvest in a Western Oregon watershed. Additionally, road construction has been shown to reduce basin lag time and increase catchment connectivity (Hetherington *et al*., 1998). The vegetation removal effects have been seen to persist for one to two decades, and streamflow return to pre-logging levels is not guaranteed. This is due to the interaction between site geologic, vegetative, and climatic characteristics (Keppeler and Ziemer, 1990). The potential effect of forest harvesting on low flows is of particular interest for natural resource managers because low flow periods are associated with limited availability of water resources for human use, reduction of habitat availability for fish and other aquatic organisms, and an increased risk of elevated stream temperatures which can threaten the survival of many aquatic species (Price, 2011; Smerdon *et al*., 2009; Brandes *et al.*, 2005). A greater knowledge of forest harvesting effects on low flows is fundamental to developing and continuing the sustainability and practicality of coastal watershed management.

An important tool in understanding the low flow hydrology of a catchment is the streamflow recession curve, which is the portion of a streamflow hydrograph where discharge decreases steadily during periods of little or no precipitation (Smakhtin, 2001). Recession curves are useful indicators of a catchment's ability to release water stored as soil moisture and groundwater over extended periods of time, thus maintaining flow and aquatic habitat during periods of dry weather. In particular, the slope of the recession curve is a measure of how quickly water is released from storage within the catchment (Waterloo *et al*., 2007; Moore, 1997). It is influenced by soil characteristics, such as depth and permeability, hillslope gradients, the nature of the underlying bedrock, and the effects of evapotranspiration (Tallaksen, 1995).

Forest harvesting results in a reduction in vegetative transpiration and interception and loss of precipitation, at least over the short term, allowing more water to infiltrate into the soil and flow by subsurface flow paths to the stream channel (Smerdon *et al.*, 2009; Waterloo *et al.*, 2007). Forest harvesting can therefore result in increased soil moisture storage (Smakhtin, 2001) and higher water tables (Smerdon *et al.*, 2009; Hetherington *et al*., 1998; Hicks *et al*. 1991; Keppeler and Ziemer, 1990). Consequently, forest harvesting should generate increases in both annual water yield and low flows, as was found by Keppeler and Ziemer (1990) and Hicks *et al*. (1991), among others. However, as a forest regenerates, increases in transpiration and interception loss can become greater than a mature forest, especially for early seral stage deciduous species, resulting in more extreme low flows over the medium term (e.g., Hicks *et al*., 1991). Waterloo *et al.* (2007) found during their study that even with higher rainfalls the lowest flows coincided with forested catchments, due to their large uptake of water in the hydrologic cycle. Forest cover increases basin storage by augmenting the infiltration rate into the soil, despite increased interception. However, by extracting water from the soil that would otherwise continue to maintain flows during periods of dry weather, forest transpiration increases the rate of streamflow recession (Federer, 1973). Therefore, the removal of forest cover should result in less steep recessions, at least for the first few years or so following logging. Over the medium to longer term, recession curves generally become steeper as the forest regenerates.

Roads across hillslopes can intercept subsurface flow and redirect it to ditches and culverts and eventually to the stream at a much faster rate than it would in the absence of roads (Winkler *et al.*, 2011). Furthermore, due to the low permeability of road surfaces, much of the precipitation falling onto roads can also be directed as overland flow to ditches. Roads can thus result in decreased travel times and greater connectivity of the land to the channel network, producing faster streamflow response to rainstorms, as well as greater peak discharge. This redirection of flow also means that less water follows the slow subsurface pathways that supply the low flows during recession periods. The increased responsiveness of the catchment is opposite to the effect of harvesting. Therefore, the construction of logging roads is expected to result in a steepening of recession curves that persist through time (assuming the roads are not rehabilitated).

Analyses of the stream discharge data aims to separate the effects of the harvesting by growing season and non-growing season (summer and winter). During winter, the transpiration is severely reduced, so the effect of roads on the landscape can be isolated. If there is a significant recession curve steepening in winter, then it can be assumed that the roads are responsible (1). Comparing early post-logging discharge data with pre-logging data in the growing season should show a partial offset of recession curve steepening due to reduced transpiration. However, regeneration will increase transpiration and steepen the curve. If there is significant differences between pre-logging and post-logging and post-logging 1 to 2 growing season periods, then the effect of harvesting and forest regeneration is likely culpable (2). Moreover, the logging roads and culverts can be thought of as permanent additions to the landscape and hydrologic regime and their effects should persist through time. If there are no changes to the recession data in the non-growing season over the post-logging period, then it is probable that the effect of roads does not vary significantly over that time (3).

2. Methods

2.1 Study Site

This study draws upon data collected at the Carnation Creek Experimental Watershed, a single-watershed experiment site located near the southwestern coast of Vancouver Island, BC. The Carnation Creek experiment was initiated by the Department of Fisheries and Oceans (DFO), and is continued today as a part of the Forest-Fish Interaction Program (FFIP) conducted by the Research Branch of the B. C. Ministry of Forests. It was originally conducted to explore the effects of clear-cutting on coastal watersheds stream channel morphology and fish populations. It has grown into a long-term multidisciplinary study, which is continuing to investigate the effects of forestry-related operations on coastal catchments (Province of British Columbia, 2009). Over 200 papers have been published on the data collected from this site and the results and implications from the studies influenced the Forest Practices Code (FPC), later superseded by the Forest and Range Practices Act (*ibid*).

Carnation Creek has a drainage area of 11 km^2 and has a main channel length of approximately 7.8 km. The site falls within the Coastal Western Hemlock zone (CWH), receiving around 2100 to 5000 mm of precipitation every year with 95% of that falling as rain primarily in the fall and winter months. Scrivener (1975) reported that after intense storms, the annual precipitation leaving this catchment as runoff could be up to 90%.

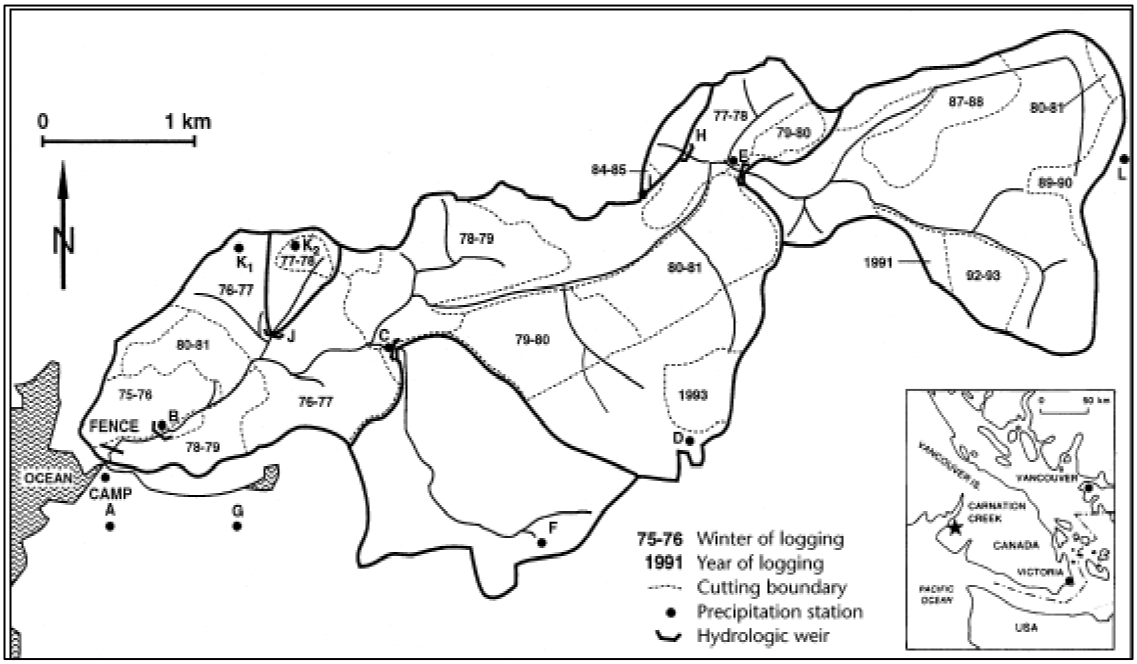

Figure 1. A Map showing the Carnation Creek watershed with an inset showing its location on southwestern Vancouver Island. The climate stations (A-L), the years of harvest, harvest boundaries, hydrologic weir locations and their sub-catchment basins are shown. From Hetherington et al. (1998).

The terrain is fairly rough, maintaining steep gradients up to 80% and an elevation ranging from 0 to 800 masl. The soil profile is a shallow ~ 0.7 m veneer with a coarse textured colluvium, and some variable dense till deposits found overlying bedrock. The last 3 km of stream before the outlet is a floodplain, which is composed of a gravelly alluvium (Hartman and Scrivener, 1990). The soil drains rapidly and extremely well, with preferential flow pathways and large macro-pores allowing quick movement of water through the sub-surface system to the channel network (Fannin *et al*., 2000).

The original mature tree species found in the catchment were Western red cedar (*Thuja plicata*), Sitka spruce (*Picea sitchensis*), amabilis fir (*Abies amabalis*), Douglas-fir (*Pseudotsuga menziesii*) and Western hemlock (*Tsuga heterophylla*). Red alder (*Alnus rubra*) and Bigleaf maple (*Acer macrophyllum*) were the dominant riparian tree species (Province of British Columbia, 2009; Hartman and Scrivener, 1990).

Stream assessments found several species of anadromous salmonids, *Oncorhynchus keta, O. kisutch, O. mykiss, O. clarki, Cottus aleuticus* and *C. asper,* inhabiting the lower reaches of the stream, as well as a land locked population of cutthroat trout (*O. clarki*) upstream in the catchment (Province of British Columbia, 2009).

2.2 Data Collection

Permanent weirs and climate stations have been in continuous operation since April 1971, collecting data on water temperature, depth, and stream discharge. Temperature and 24 hour precipitation measurements were obtained from 10 sites in and around the catchment study area. They were serviced weekly and recalibrated monthly if necessary. Weighing precipitation gauges were favoured over tipping buckets. The data was transferred to digital records for analysis, and the precipitation had a measurement error of ± 0.2 mm (Hartman and Scrivener, 1990).

Stream discharge data from the original study was obtained from 5 different weirs around the catchment, but for our purposes we only used the discharge data from the V-notch weir at Station B collected with *Stevens* digital recorders. The stage-discharge curves developed for each weir were calibrated and updated frequently to ensure instrument precision.

2.3 Forest Operations

Construction of roads began in January 1975, and were usually built far from the stream (Hartman and Scrivener, 1990). They used D-8 Caterpillars, shovels, and rock drills to construct the majority of the roads. The roads were fully benched and consisted of a very coarse gravel that overlaid the bedrock.

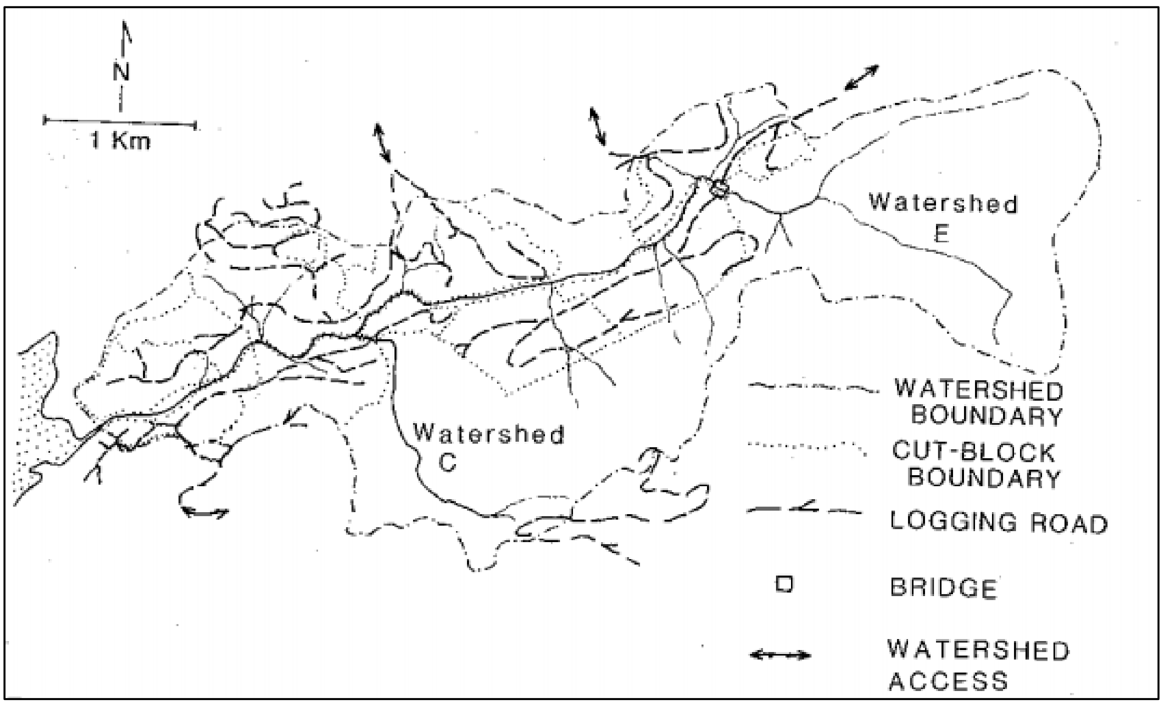

Figure 2. The logging roads and bridge network of the Carnation Creek catchment site. From Hartman and Scrivener (1990).

Riparian harvest treatments included a 1300 m long leave-strip where between 1-70 m widths of riparian forest was left intact from the catchment outlet upstream. Directly upstream from the leave strip was a 900 m long clear-cut treatment, removing all riparian vegetation. The timber was felled and yarded onto and across the stream and all valuable logs were removed from the channel. This was designated as an "intensive clear-cut" treatment. Extending 900 m beyond the first clear-cut was a "careful clear-cutting" treatment, where no activity was permitted in the creek, and small streamside vegetation was retained (Province of British Columbia, 2009). A cable and metal grapple system was used to yard the merchantable material to the roads. However, at several of the bottom valley sites, skidders with rubber low-pressure tires were used for transportation. Slash was mostly piled and burned on site, with some broadcast burning on slopes. Some of the soils were scarified and some untouched, depending on their aspect and location within the catchment (Hartman and Scrivener, 1990). Through 1976-81, 41% of catchment was harvested, focussing on the valley bottoms. In 1987, a further 21% of the catchment was harvested, focussing on the headwaters and slopes (Province of British Columbia, 2009).

Reforestation efforts took place a year after harvest periods, with the primary seedling species being Douglas-fir, western red cedar, amabilis fir, western hemlock and Sitka spruce. In contrast, some sites received only natural regeneration (Hartman and Scrivener, 1990).

2.4 Analysis

All of the data processing and analysis was conducted using the R programming language (R Development Core Team, 2011). The first step in the analysis was to identify recession periods in the streamflow records. In order to qualify as part of the recession, two criteria were to be stipulated. Firstly, there should be no precipitation on the current or preceding days. Secondly, the stream discharge on the current day had to be less than the discharge of the previous day.

Theoretical considerations and empirical studies indicate that the relation between the absolute value of the rate of change of daily discharge ($|dQ/dt|$) and the mean daily discharge (Q_m) should follow a power law (Brutsaert and Nieber, 1977). Thus, a plot of $|dQ/dt|$ against Q_m on a log-log axes will follow a linear relationship according to storage-discharge theory. Therefore, $\log(|dQ/dt|)$ is used here as the response variable and $\log(Q_m)$ used as a covariate. Initial analysis indicated some nonlinearity in the relation between $\log(|dQ/dt|)$ and $\log(Q_m)$ over the full range of discharge. Therefore, data were stratified by discharge ranges, within which the relation was visually close to linear.

To account for the effect of transpiration on recession rates, daily maximum air temperature (T_{max}, °C) was included as a predictor variable, as transpiration rates should be correlated with air temperature. To account for changes associated with forest harvesting, the time series was split into four periods: (1) pre-harvest, “Pre” (1970 to 1975); (2) during-harvest, “Logging” (1976 to 1981); (3) initial post-harvest, “Post 1” (1982 to 1984); and (4) later post-harvest, “Post 2” (1985 to 1990). The analysis periods differed in the number and distribution of extremely low streamflow values. To minimize the effect of these differences on the analysis, the data were subsetted again to remove days on which Q_m was equal to and below 0.02 m^3s^{-1}. This removed 89 observations from the data set.

The analysis involved fitting a series of linear models relating $\log(|dQ/dt|)$ to $\log(Q_m)$, T_{max} and P, where P is a factor representing period, with four levels (Pre, Logging, Post 1 and Post 2). To account for seasonal variations in transpiration rates, data were classified into two seasons (*S*), summer and winter, with analyses being conducted separately for each season. Summer included the period from May to September, while winter extended from December to February. This resulted in the exclusion of quite a few data points, but the reasoning behind this was to separate the growing season, in which transpiration could be significant, from a mid-winter period when transpiration is likely to be negligible (Shimokura and Shibano, 2003).

In addition to a residual analysis to determine if the assumptions of multiple linear regression (MLR) have been met, we also calculated a variance inflation factor (VIF) for each of our models' parameter coefficients in order to account for the adverse effects of multicollinearity (Graham, 2003; Farrar and Glauber, 1967).

Type III partial sum of squares F-tests were conducted on constructed models through the exclusion of *P* variables for the purpose of observing their significance (Kozak *et al.*, 2008). All statistical significances of p-values were compared using an alpha (α) level of 0.05, but additional alpha p-values are listed for convenience.

3. Results

Looking at the mean annual precipitation (MAP) in Fig. 2 shows that there is some slight variation in rainfall between periods. There appears to be a trend towards a decreasing MAP over the study period. However, since the linear models we constructed included Q_m as a covariate, we assumed that any changes in precipitation would be correlated and described using the mean discharge. The maximum and minimum mean annual temperatures (MAT) graphs (Fig. 3) show that there are no clear deviations to temperature in summer; however there are some increasing temperatures in winter. This possibility will be accounted for in our linear model with the inclusion of T_{max} as an additional covariate, because we assume that it will be the maximum temperature that will have more weight on the evapotranspiration effect on the recession curves. A short study period with multiple catchments would have eliminated possible errors from climate variables and trends. However, a long-term study allowed the correlation between climate variations to be recorded with a larger dataset, and greater statistical power was achieved (Hartman and Scrivener, 1990).

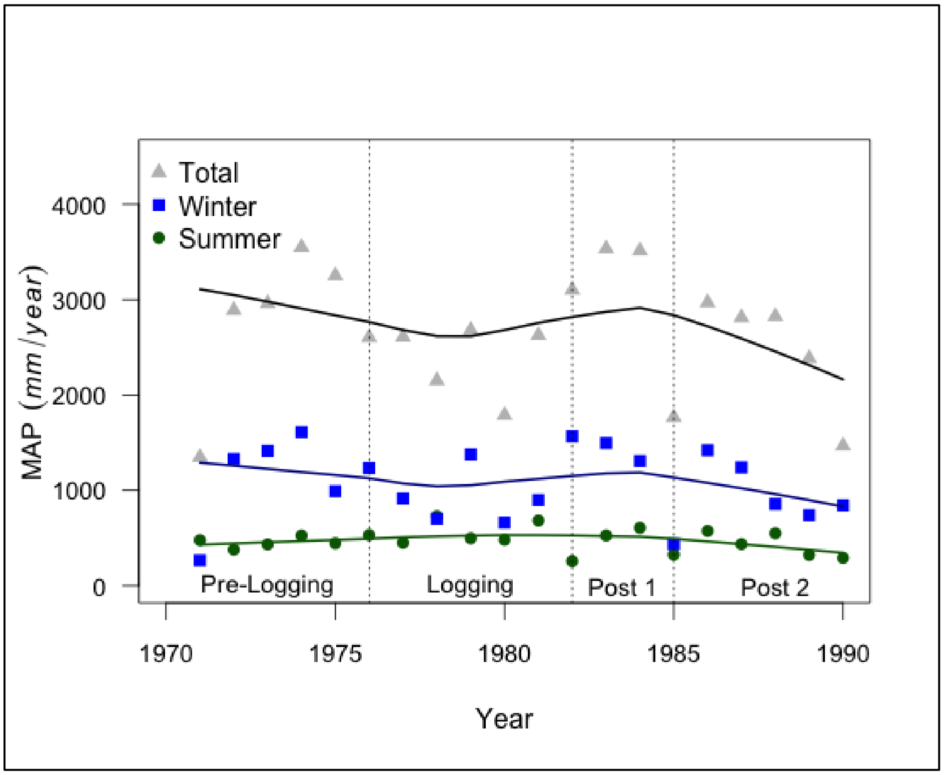

Figure 3. The Mean Annual Precipitation (MAP) over the entire duration of the study, split into the harvest periods. Lowess regression lines were fitted to the data to show the variation over time and between the periods.

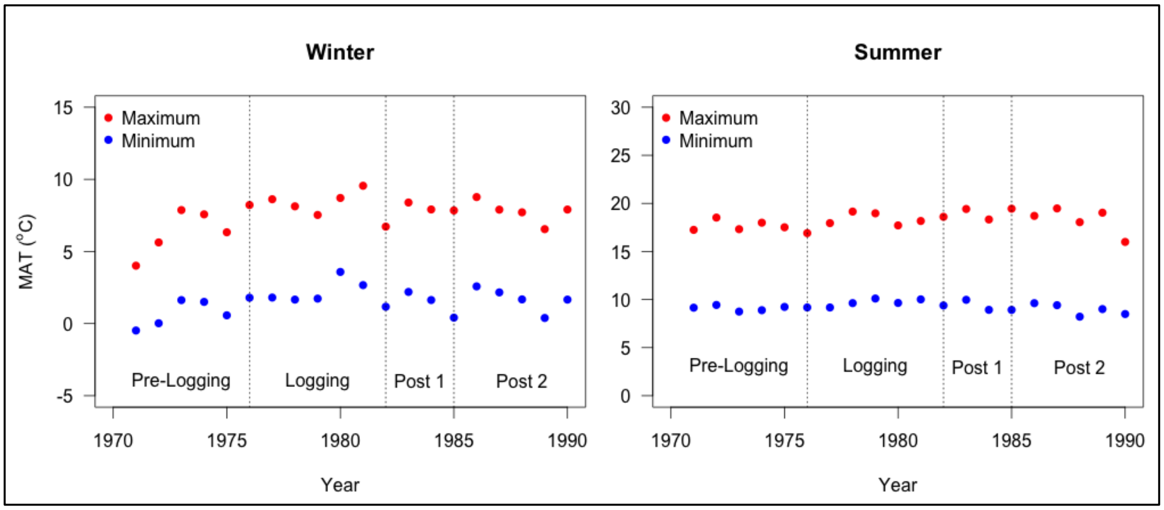

Figure 4. The maximum and minimum mean annual temperatures over the study period, separated into non-growing and growing season. The harvest periods were defined.

3.1 Regression Assumptions

In Appendix A, the residuals plots for log(Q_m) and T_{max} are given for the linear models, which are separated by growing and non-growing season, and discharge level. They show that that there is independence of observations and equal error residual variance around the lines. The winter data deviated slightly from equal variance around the line and had several large outliers. This could be due to the reduced number of sample data because of the strict season requirements. The results of Shapiro-Wilk normality tests are located in Appendix B. A few of the linear models had p-values below the set alpha level of 0.05 and this meant that they had failed to meet the normality assumption. When normality of the error residuals is not satisfied, this can greatly bias the significance of the variable in the model as well as the parameter coefficient estimates.

3.2 Variance Inflation Factor

When we initially performed our ANOVA tests on the models we included Q_m, T_{max} and P and all the interactions between them. However, we noticed that some of the model parameters (Q_m, T_{max} and *P)* were non-significant predictors of the response variables. An example of this is below from a comparison between Pre and Logging Low discharge level.

```
Model 1: log(dQ/dt) ~ log(Qm) * Tmax
Model 2: log(dQ/dt) ~ log(Qm) * Tmax * P

  Res.Df    RSS Df Sum of Sq      F  Pr(>F)
1     46 14.973
2     42 11.121  4     3.852 3.6369 0.01241 *
---
Call:
lm(formula = log(dQ/dt) ~ log(Qm) * Tmax* P)

Residuals:
     Min       1Q   Median       3Q      Max
-1.14873 -0.28499  0.00001  0.36418  0.89659

Coefficients:
              Estimate   Std. Error  t value  Pr(>|t|)
(Intercept)    21.1888    10.7142   1.978    0.0546 .
log(Qm)        -4.4771     3.0709  -1.458    0.1523
Tmax           -1.1444     0.5863  -1.952    0.0576 .
P2            -29.3751    24.3688  -1.205    0.2348
log(Qm):Tm      0.3367     0.1685   1.998    0.0522 .
log(Qm):P2      9.4920     7.6003   1.249    0.2186
Tmax:P2         1.4588     1.1944   1.221    0.2288
log(Qm):Tmax:P2 -0.4581    0.3711  -1.235    0.2239
---
```

RSE 0.5146, 42DF, R_2=0.3905,R^2_a: 0.2889,F=3.843 7 and 42DF, p-value: 0.002583

There is significant difference between the models (p-value = 0.012) attributed to period, yet in the model, all the parameters involving period are non-significant. We deduced that this was due to a strong interaction between T_{max} and log(Q_m). We performed variance inflation factors (VIF) - which detect for multicollinearity - on the models and found that each of them had significant correlation. Where a VIF value of 5 or 10 indicated high levels of interaction between the terms, we found levels of 1000 and higher (O'Brien, 2007). The VIF values for all the parameters of the Full model can be found in Appendix C. Graham (2003) and Farrar and Glauber (1967) report that multicollinearity can lead to improper inferences with respect to coefficient estimates, but the predictive power of the model is not hindered. Due to the redundancy effect of including T_{max} in the model, it was removed to increase the validity of the specific predictor variable ($log(Q_m)$).

3.3 Discharge Levels

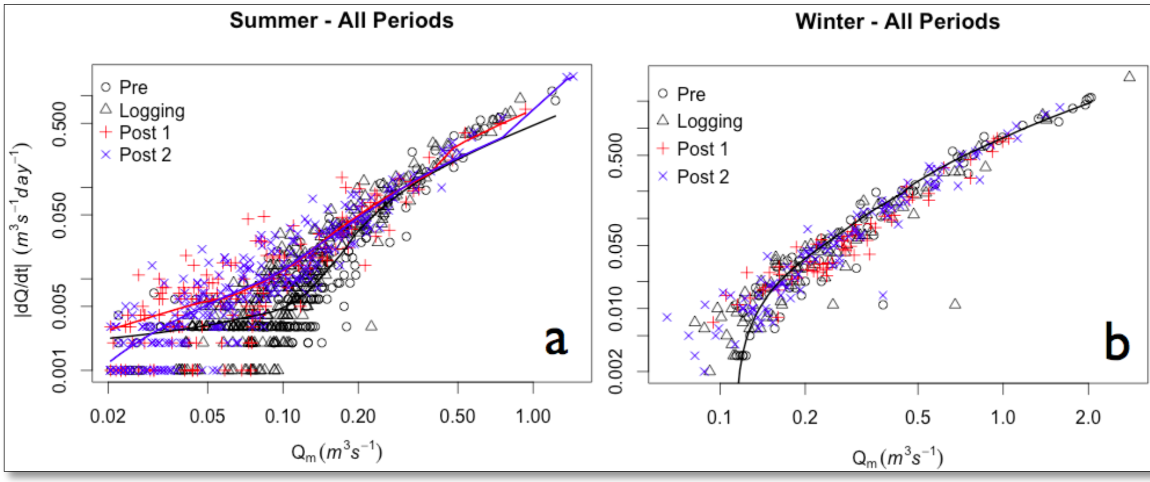

Figure 5. The Summer (A) and Winter (B) mean discharge against the rate of the change in daily discharge for all periods.

Initial graphs of the stream discharge data were very complicated and convoluted. In order to retrieve some semblance of order and results from the data, the period comparison was limited to two, and discharge levels were separated. The ultimate goal was to be able to fit linear models to the data, and the discharge levels were founded on trends garnered from Fig. 5 above. In summer, a $Q_m \geq 0.25$ m^3s^{-1} appeared to show similar results, so this was accorded High. Additionally, 0.020 m^3s^{-1} < $Q_m \leq 0.05$ m^3s^{-1} and 0.050 m^3s^{-1} < Q_m < 0.25 m^3s^{-1} were labeled Low and Medium respectively. The winter data did not show as much variation over the mean discharge (Q_m), so they were segmented into only two discharge levels, Low, where 0.020 m^3s^{-1} < $Q_m \leq$ 0.25 m^3s^{-1} and High, where Q_m > 0.25 m^3s^{-1}. Using this method allowed us to develop specific linear models to each comparison and discern significant differences between them.

Table 1. The p-value results from the type III ANOVA F-tests comparing all the periods and discharge levels. [a] **Discharge levels are defined in section 3.2.** [b] **Reduced model is the Full model without third order interactions e.g. $Q_m{:}T_{max}{:}P$.** [c] **Simple model has removed T_{max}.** [d] **Simple model with data points where $Q_m \leq 0.02$ m^{3}s^{-1} are included in the regression.**

Season	Period Comparison	Discharge Level [a]	Full Model	Reduced Model [b]	Simple Model [c]	Simple Model [d]
Summer	Pre vs. Post 1	All	6.213e-14 ***	2.277e-14 ***	2.804e-15 ***	-----------
-----------	Pre vs. Post 1	Low	0.4893	0.5412	0.3706	0.01078 *
-----------	Pre vs. Post 1	Medium	1.144e-14 ***	8.907e-15 ***	1.613e-15 ***	-----------
-----------	Pre vs. Post 1	High	0.5246	0.5942	0.7263	-----------
-----------	Pre vs. Post 2	All	2.2e-16 ***	2.2e-16 ***	< 2.2e-16 ***	-----------
-----------	Pre vs. Post 2	Low	0.76	0.8833	0.9986	0.02809 *
-----------	Pre vs. Post 2	Medium	2.2e-16 ***	2.2e-16 ***	< 2.2e-16 ***	-----------
-----------	Pre vs. Post 2	High	0.4701	0.3859	0.2287	-----------
-----------	Pre vs. Logging	All	3.226e-08 ***	7.862e-09 ***	3.45e-06 ***	-----------
-----------	Pre vs. Logging	Low	0.01241 *	0.009826 **	0.01225 *	0.008687 **
-----------	Pre vs. Logging	Medium	2.865e-07 ***	1.314e-07 ***	3.277e-08 ***	-----------
-----------	Pre vs. Logging	High	0.1214	0.08754	0.05453 .	-----------
-----------	Logging vs. Post 1	All	2.2e-16 ***	2.2e-16 ***	< 2.2e-16 ***	-----------
-----------	Logging vs. Post 1	Low	0.001788 **	0.000641 ***	0.000264 ***	0.0001311 ***
-----------	Logging vs. Post 1	Medium	2.362e-09 ***	8.9e-10 ***	4.391e-10 ***	-----------
-----------	Logging vs. Post 1	High	0.03023 *	0.02101 *	0.07944 .	-----------
-----------	Logging vs. Post 2	All	2.2e-16 ***	2.2e-16 ***	< 2.2e-16 ***	-----------
-----------	Logging vs. Post 2	Low	0.001006 **	0.000393 ***	0.0001548 ***	0.009235 **
-----------	Logging vs. Post 2	Medium	2.2e-16 ***	2.2e-16 ***	2.2e-16 ***	-----------
-----------	Logging vs. Post 2	High	0.917	0.8109	0.9203	-----------
-----------	Post 1 vs. Post 2	All	0.1278	0.1087	0.1346	-----------
-----------	Post 1 vs. Post 2	Low	0.3634	0.2517	0.09923 .	0.02724 *
-----------	Post 1 vs. Post 2	Medium	0.1228	0.8767	0.9125	-----------
-----------	Post 1 vs. Post 2	High	0.3098	0.2569	0.2535	-----------
Winter	Pre vs. Post 1	All	0.0005184 ***	0.0005605 ***	0.0003253 ***	-----------
-----------	Pre vs. Post 1	Low	0.0009649 ***	0.0003459 ***	6.272e-05 ***	-----------
-----------	Pre vs. Post 1	High	0.13	0.08707 .	0.03284 *	-----------
-----------	Pre vs. Post 2	All	0.001338 **	0.0008018 ***	0.01114 *	-----------
-----------	Pre vs. Post 2	Low	0.0008471 ***	0.0004193 ***	0.002013 **	-----------
-----------	Pre vs. Post 2	High	0.4404	0.522	0.3531	-----------
-----------	Pre vs. Logging	All	0.01109 *	0.04163 *	0.03998 *	-----------
-----------	Pre vs. Logging	Low	0.007551 **	0.003261 **	0.01691 *	-----------
-----------	Pre vs. Logging	High	0.1218	0.07402 .	0.2124	-----------
-----------	Logging vs. Post 1	All	0.4265	0.5397	0.3563	-----------
-----------	Logging vs. Post 1	Low	0.644	0.4716	0.01549 *	-----------
-----------	Logging vs. Post 1	High	0.6769	0.505	0.9203	-----------
-----------	Logging vs. Post 2	All	0.02201 *	0.06787 .	0.5619	-----------
-----------	Logging vs. Post 2	Low	0.838	0.7457	0.5692	-----------
-----------	Logging vs. Post 2	High	0.03151 *	0.01463 *	0.6468	-----------
-----------	Post 1 vs. Post 2	All	0.1559	0.1242	0.1005	-----------
-----------	Post 1 vs. Post 2	Low	0.6855	0.5428	0.09106	-----------
-----------	Post 1 vs. Post 2	High	0.2436	0.1608	0.1943	-----------

Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

3.4 Road Effects

The results of the significance tests for the winter period comparisons shown in Table 1 allow us to secularize the road effects on the recession streamflows. Pre and Post 1 comparisons were found to be significant at a Low discharge level for all model types, but only significant in the High discharge level with the simplified model. Pre vs. Post 2 was only significant in all models at Low and there was a significant difference between the Logging vs Post 1 period at Low for the simple model. Pre and Logging was found to have a p-value ≈ 0.017 at Low discharge and there was no difference between the post-logging periods at any discharge level or model. However, it should be noted that Pre vs. Post 1 Low and Pre vs. Logging Low linear models did not satisfy the Shapiro-Wilk tests for normality (Appendix B).

Table 2. The estimated coefficients for the winter linear models, showing only periods where there was found to be significance when tested.

Period	*b0* *Intercept*	*b1* $|log(Q_m)|$
Pre-Logging Low	-1.62	3.22
Pre-Logging High	-0.09	2.20
Logging Low	-0.25	2.35
Post-Logging 1 Low	1.44	1.34
Post-Logging 1 High	0.29	2.11
Post-Logging 2 Low	0.15	2.10

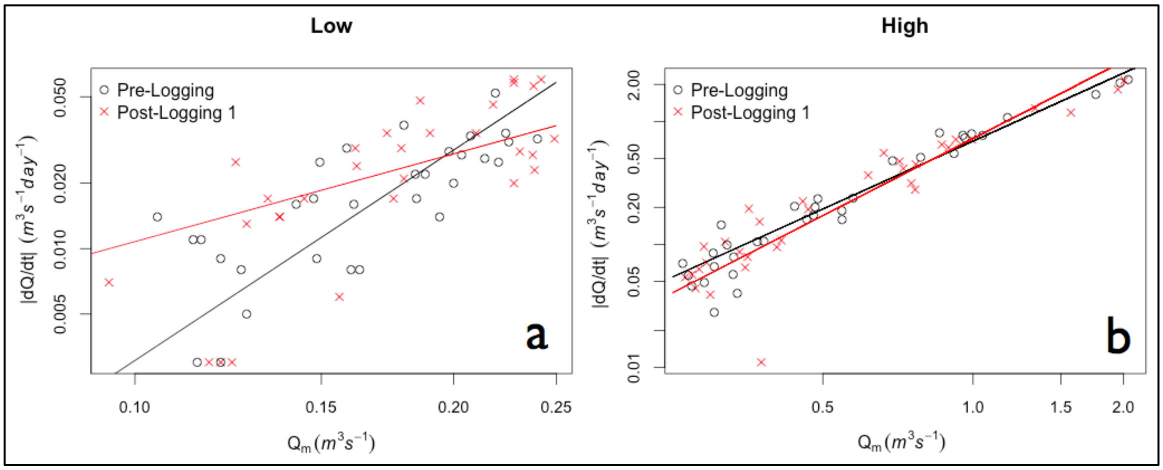

Figure 6. The pre-logging vs. the post-logging 1 period at both low (a) and high (b) discharge levels during the Winter.

Figure 6a show that as smaller mean discharges are reached, there is a greater difference in the |*dQ/dt*| between the Pre and Post 1 periods. During Post 1, |*dQ/dt*| decreases more slowly at a lower mean discharge.

3.5 Forest Harvest and Regeneration

The harvesting effects were studied by using a comparison between the Pre and Post 1 summer periods. F-tests were performed on these models (see Table 1) and it was found that there was a highly significant difference between the two periods at the Medium discharge level for all model types (Simple Model p-value = 1.6×10^{-15}). The mean discharge parameter coefficients were found to be 1.76 for Post 1, 1.84 for Pre and Post 2 was equal to 1.70. The intercept parameters for Pre, Post 1 and Post 2 were 1.1, 0.31, and 0.42. A graphical visualization of the harvest effects is seen in Figure 7.

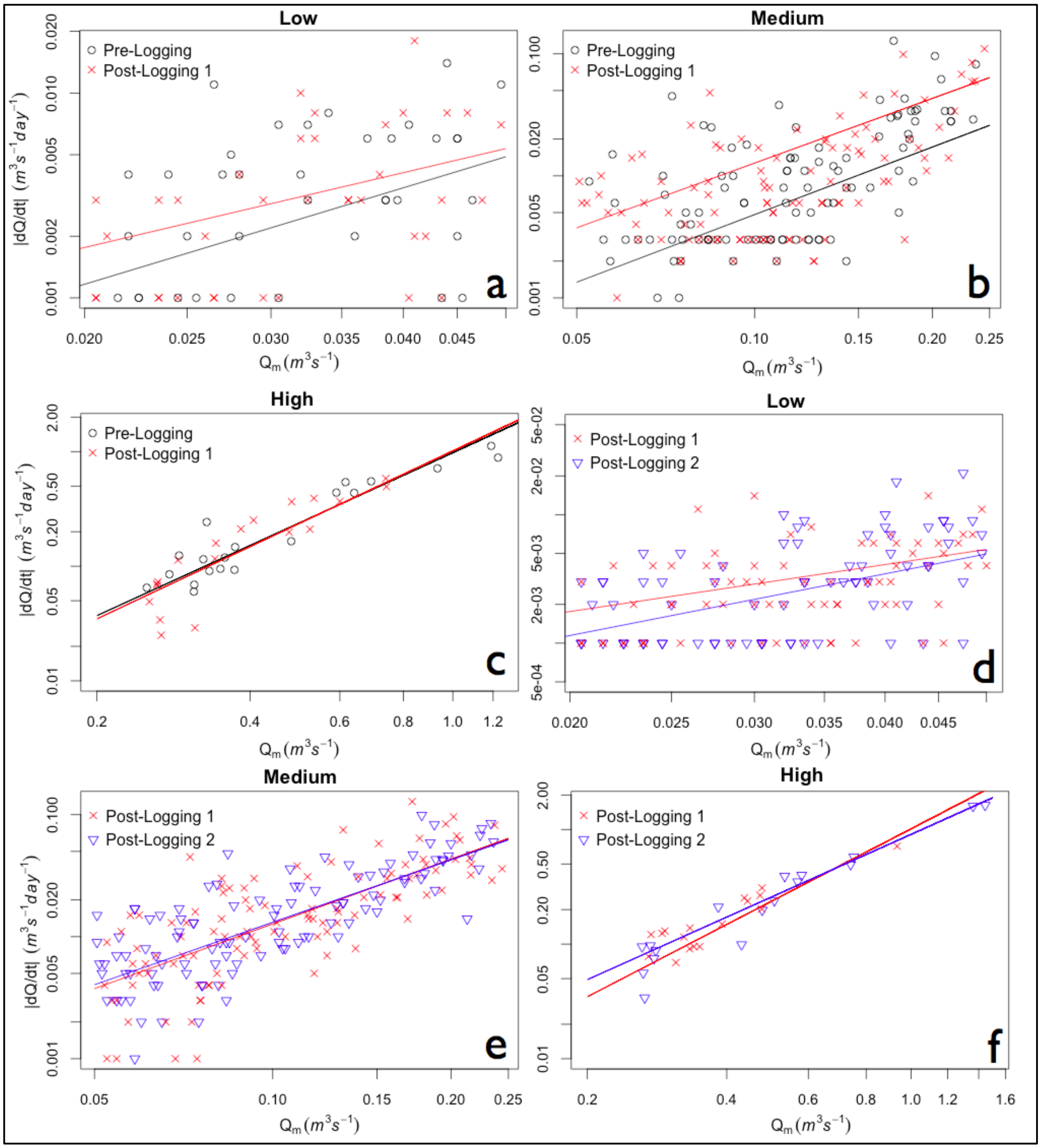

Figure 7. (a-c) The Pre and Post 1 growing season comparison showing non-significant differences for Low and High, but significance at Medium. (d-f) The comparison of Post-Logging 1 vs. Post-Logging 2 highlighting the effect of forest regeneration.

The effect of the restored transpiration to the catchment can be observed by comparing the summer Post 1 and Post 2 periods. Figure 7 graphs d-f show the period comparison at all the discharge levels. However, the periods are not significantly different, with Low, Medium and High p-values ~ 0.10, 0.91, and 0.25 respectively (see Table 2).

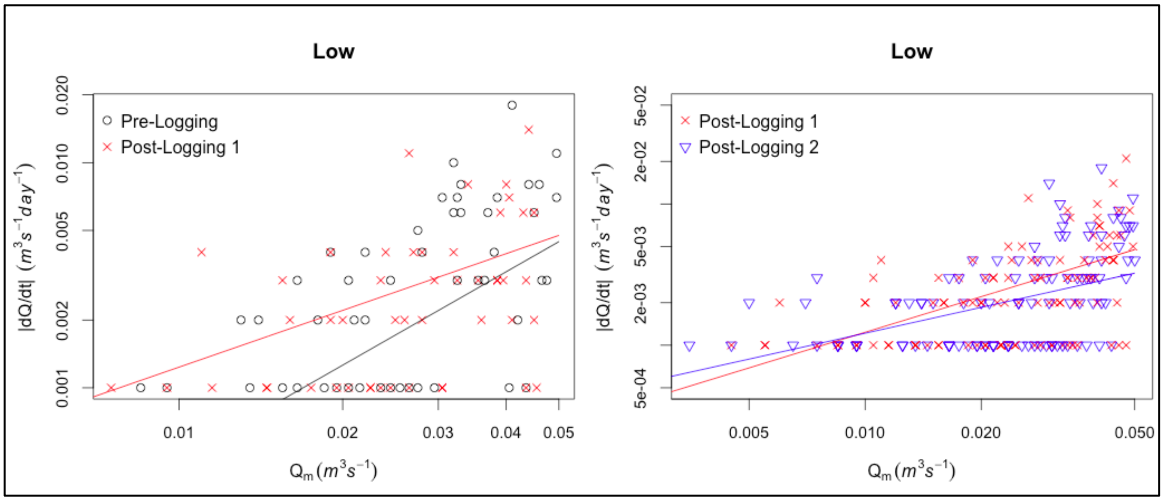

Figure 8. The low discharge level for Pre vs. Post 1 and Post 1 vs. Post 2, with the inclusion of Q_m data below 0.02 m^3s^{-1}.

The omittance of the data that fell below the mean discharge threshold, $Q_m > 0.02$ m^3s^{-1}, was due to the uneven distribution of those extremely low flows across the study periods. However, we did an analysis on the Low discharge levels, the only levels that would be affected, with the omitted values inserted back into the dataset and found that there was some very strong significance gained. Figure 8 above shows the Pre vs. Post 1 and Post 1 vs. Post 2 new graphs, which differ from the previous graphs in Figure 7. There is a greater separation between the Pre and Post 1 slopes, with the greatest change occurring in the post-logging periods The parameter estimates in Appendix D show that the new pre-logging slope is shallower compared to the original, 1.38 to 1.56. As well, the intercept doubles from 0.64 to 1.3. The new slopes for Post 1 and 2 are 0.84 and 0.61, compared to 1.2 and 1.6 with the data omitted. This led to Pre vs. Post 1, Pre vs. Post 2 and Post 1 vs. Post 2 comparisons becoming significantly different (Table 2).

4. Discussion

4.1 Road Effects

Figure 6a singles out the effect of the roads on the catchment and shows that from the pre period to the post 1 period there was a significant steepening of the recession curve. The road network created more hill flow mechanisms, Hortonian overland flow along the road surfaces and pathways (*i.e.* ditches) for the water to reach the stream. As well, the cut banks allowed the recapture of through-flow back into the ditch drainage system, which would otherwise slowly move downslope. The data indicates that during both High and Low discharge levels there are differences between the Pre and Post 1 periods, even though Figure 8b does not show this very clearly. Looking at the estimated coefficients for the comparison (Appendix D) shows that they are indeed similar, but there are enough data points to increase the degrees of freedom coupled with a strong normal distribution, both of which could increase the statistical power to detect even subtle changes to the streamflow (Table 2).

Roads and drainage systems are unique in that they persist on the landscape with a fixed effect. Unless the roads are dismantled and semi-natural drainage patterns are re-established, then the effect of the roads should not change over time. There were no significant differences between the post-logging periods during winter. This agrees with our hypothesis that the effect of the roads does not change over time. However, looking at Logging vs. Post 2 winter shows some significance at the High discharge level for the Full and Reduced models, unusual because there is no significance during the same level in the summer and none for the previous period of Post 1. Removal of the two highest outliers in the winter Logging vs. Post-Logging 2 yielded a non-significant p-value of 0.0517. There could be several explanations for this occurrence. It could possibly be attributed to additional road building and forest operation effects that would have taken place to allow for additional harvesting. A second pass of logging began in 1987, taking place in winter, so it is reasonable to assume that this could have had some effect on the stream discharge (*i.e.* diverting more water to ditches and culverts and faster flows to the stream). An additional explanation could have something to do with the decreased MAP occurring during the Post 2 period, compared to the Logging period. If there were overall less water flowing through the system then the data would show a lowered mean discharge. Then large events, like the ones we removed, would have a large effect, increasing the variance and mean, but would not be indicative of the actual site processes. However, given the high VIF values we found for those models parameters (Appendix C), the lack of normality (Appendix B), and the fact that once T_{max} was removed there was a definitive non-significance between the periods, we have reason to believe our hypothesis was correct in predicting a persistence of the effects of the roads over the course of the study period.

Looking at the coefficient estimates output in Appendix D shows that the winter Low Pre and Post 2 $log(Q_m)$ coefficients are 3.2 and 2.1 respectively. This means that because the slope was shallower throughout the Post 2 period, the rate of change in daily discharge continued at a higher level during the same mean discharge. With a p-value of 0.002, there appears to be a long-lasting effect of the roads in steepening the recession curve from pre-harvest levels.

It is interesting to note that there is no difference between the Pre vs. Post 2 High discharge level. This would seem to indicate that for a short period after road building, the effect on streamflow recession curves extended to all discharge levels, but after a time it is only noticeable at the lowest flows. Because the effect of the roads was not changing appreciably, and there was negligible evapotranspiration occurring, then the forest regeneration must have been extending beyond its transpirational effect.

4.2 Forest Harvest and Regeneration

The effect of the roads during the Post 1 period is similar to the transpirational effects of the forest cover observed in the pre-growing season, in that both steepened the recession curve during low mean discharges. As well, large woody debris (*LWD*) was removed systematically from the channel at most locations, so less blockage and sediment build up at those locations probably helped increase discharge levels during all periods (Province of British Columbia, 2009; Hetherington, 1988). Watersheds containing highly valuable fish populations and spawning grounds, endemic riparian species, or sensitive ecosystems in or downstream could be negatively affected by changes to the recession curves at low flows. At the Carnation Creek site there were actual increases in salmonid productivity as a result of slightly increased growing temperatures (Province of British Columbia, 2009).

Because of forest harvesting, the percentage of precipitation falling on the catchment, which is subsequently being drawn out of the soil by hydraulic lifting associated with plant respiration, has been decreased. More water is able to infiltrate the groundwater system and feed the stream system through recession periods. However, the ability of the harvest to offset the effect of the roads is dependent on the mean discharge, and the reduction in transpiration is temporary as regeneration begins to establish around the catchment.

The difference between the Pre and Post 1 and 2 periods means that the effect of the roads is strong all year round, and because there is a decreasing slope in almost all comparisons from Pre, one can conclude that the reduced transpiration partly offsets the effect of the roads, but not completely. The one exception is Post 2 Low discharge level, where the slope had increased past the Pre levels - 1.56 to 1.59. I am skeptical of those results for a number of reasons. The first is due to the large number of points we omitted from the analysis. The distribution of extreme low flow data points among the periods was as follows: 7 points in late summer of Pre period, 21 in Post 1 period, and 60 in Post 2 period. They fell between June and October, with the majority of points coming during August. Because of the high concentration of low-flows occurring in the Post-Logging 2 period, the exclusion of these led to ignorance of information on low-flows, which may or may not have been the result of the roads and the forest regeneration. The second is that there was an additional 21% of the catchment harvested during the Post 2 period, which focussed on the headwaters. Without a control sub-catchment, or a group of sub-catchments that were able to account for the second logging pass, the results of the full interaction between harvesting and roads remains ambiguous.

In the comparison between the summer Post 1 and Post 2 periods there was found to be no significance. There are a number of possibilities for the lack of differences between the two periods in the Simple model. There could not be enough time difference between them, so that any increased steepening would not be noticeable. In addition to this, there could be a logarithmic increase in the effect of regeneration, so that as the time since the first establishment of the trees increases, the change in their regeneration effect becomes smaller. Eventually this would reach some asymptotic plateau where no change would take place. Such a phenomenon could very likely be the case as the roots of grasses, shrubs and the regenerating trees are able to remove most of the soil water for their respiration uses at only 5 years following disturbance (Winkler *et al.*, 2011). It is interesting to note that Hetherington *et al*. (1998) found that at the end of summer, the clear-cut areas soils were wetter than the forested soils. Even though forests may increase infiltration rates, provide cooler soil temperatures, and reduce solar radiation, the effect of their water requirements - especially during the water limited growing season - removes a large portion of the water in the upper soil profile. The Post 1 vs. Post 2 comparison with the omitted values yielded a significant relationship at the Low discharge level, p-value ≈ 0.027. The Post 2 slope estimate is shallower, indicating a steepened recession curve, which is what would be expected from a regenerating forest.

4.3 Study Limitations and Errors

Some improvements and errors to the study and analysis have been identified for the purposes of increasing applicability of the data, as well as for the transferability to other watersheds being managed in similar coastal forests around the world.

It would have been ideal to segment the harvest periods into more even lengths of time, the Post 1 and 2 periods more specifically. Additionally, we would have liked to exclude the data collected after 1987, when a second logging harvest was conducted on the catchment. Alternatively, there could be a short Logging 2 period followed by an additional Post 3 period added to the time series.

Looking back at Figure 4 shows the time of the clear-cuts was highly variable and patchy across the logging period. It was never a consistently applied effect, but instead had periods of regeneration, harvesting, and burning mixed throughout. It would be informative and useful to have a study on the specific effects of harvesting on recession curves by undergoing a full clear-cut during the first year and measuring the initial effect and the recovering hydrologic system.

There is a possibility that we could have used Mean Daily Flow (MDF) and obtained from Mean Annual Runoff (MAR) to observe changes to this low-flow indicator.

The separation of summer and winter periods could have been precisely calculated yearly by data when plant respiration started in the region, specifically defined per annum. Nevertheless, this would have accounted for only transpirational effects, as evaporation is possible year round.

Because the parameter coefficients had such high variance due to multicollinearity, the use of T_{max} was limited. I would have possibly liked to use T_{avg} or T_{min} to see if the VIFs were reduced. There is a technique called "regularization" via ridge regression, which penalizes parameter coefficient estimates that are too high. This reduces the variance in the parameter estimates and provides more meaning to the fitted linear models. Using that technique, we might have been able to continue using T_{max}.

4.4 Improvements to Research

Hetherington (1988) observed that errors in low measurements could have been confounded by a small leak in the weir and the resulting inaccuracy of low flow measurements. Using the Bamfield climate data for precipitation, daily temperature and discharge data to increase the data pool, or using it to remove outliers would have been helpful when analyzing streamflow data. There was a portion of the catchment that was left alone for the entirety of the study, so no forest management occurred in its reaches. It could have been used as a control, similar to a paired watershed, and comparisons made against on a temporal scale (Province of British Columbia, 2009). This could have improved the error due to climatic variation found in long-scale studies. As well, I would have liked to use the other weir data from around the experiment site, corresponding to separately managed sub-catchments.

Noteable would have been to see if a correlation exists between changes to tree volume, species type, and the resulting increase in depth and expanse of a soil water retaining layer following harvesting. Using the correlation to compare the different effects of forest management prescriptions: thinning, pruning, and fertilizer treatments would also have been interesting, but there might not be enough change to detect using streamflow data. However, if the treatments were large enough, the effect on $|dQ/dt|$ might be observable.

In the case of future watershed experiments, if possible, road building should commence for a cutblock. In this case harvesting would be delayed for a few years so that a pre-logging period could be observed isolating the effect of road building and culverts, separate from the effect of logging. This would be interesting, but might be a costly delay for the forest managers.

It would have been interesting to have obtained extended discharge data up to the present for the purpose of better understanding the effects of forest regeneration on recession curve steepening following forest harvest. Because of the small time frame (in regeneration terms) on the analyzed post-logging periods, the results are ambiguous.

An experimental design involving the road system of a cutblock being deactivated according to the Watershed Restoration Act (Atkins *et al*., 2001 in Jordan *et al*., 2010) would provide the opportunity to study the effect of road dismantling and the return time, in such a case, of natural flow paths. Discharge data could continue to be collected and observed to determine if the effect of filling in cut-banks and removing bridges and culverts would be able to bring the recession curve back to pre-logging levels. This could fuel research towards determining the time lengths of the restoration process and underscore the ecological responsibility that Forest Companies have for the land after harvesting, which includes “Free growing” status.

5. Conclusion

At the Carnation Creek Experimental Watershed site, stream discharge data was collected over a period of 30 years and separated by Pre-Logging, Logging, Post-Logging 1, and Post-Logging 2 times. The results showed clearly that the effect of roads, isolated in the non-growing season, had a large steepening effect on the recession curve and that it persisted year round. This steepening was affected at the low and high mean discharges during winter in the short term, but persisted only during the lowest flows in the long term. Forest harvesting, which focussed on the valley bottoms during the first pass, partially offset the steepening by the roads, but only at a medium discharge level. However, when extreme low-flow data was re-submitted into the linear models, both low and medium discharge levels were found to be significantly differ from pre-logging to the post-logging periods. This offset was only temporary as regeneration of the catchment began to steepen the curve once more. A significant effect of regeneration from post-logging period 1 to 2 was only acquired at the low discharge level with the inclusion of the omitted data. This is likely due to the catchment already reaching maximum transpiration effects in a short period. The research conducted at Carnation Creek sheds a stronger light on the lasting effect of forest harvest operations on coastal watersheds. The results from past multi-disciplinary experiments completed there, and ones continuing today, have influenced forestry policies in the province of British Columbia and around the world. The ability for multiple groups, organizations and a variety of specialized scientists to cooperate for a single mission is a strong testament to the desire to maintain our natural landscapes with more sustainable management operations.

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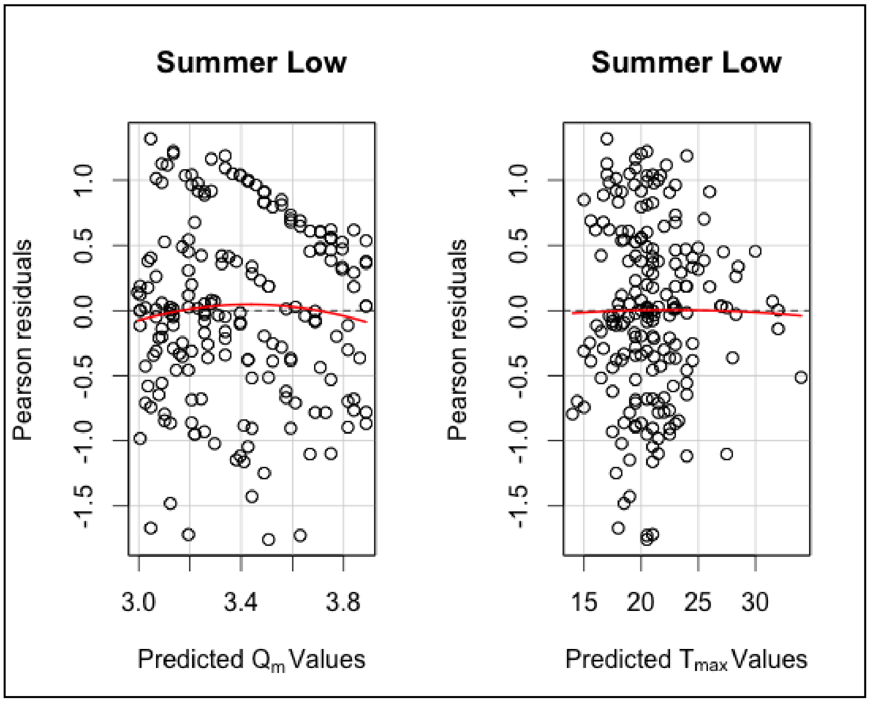
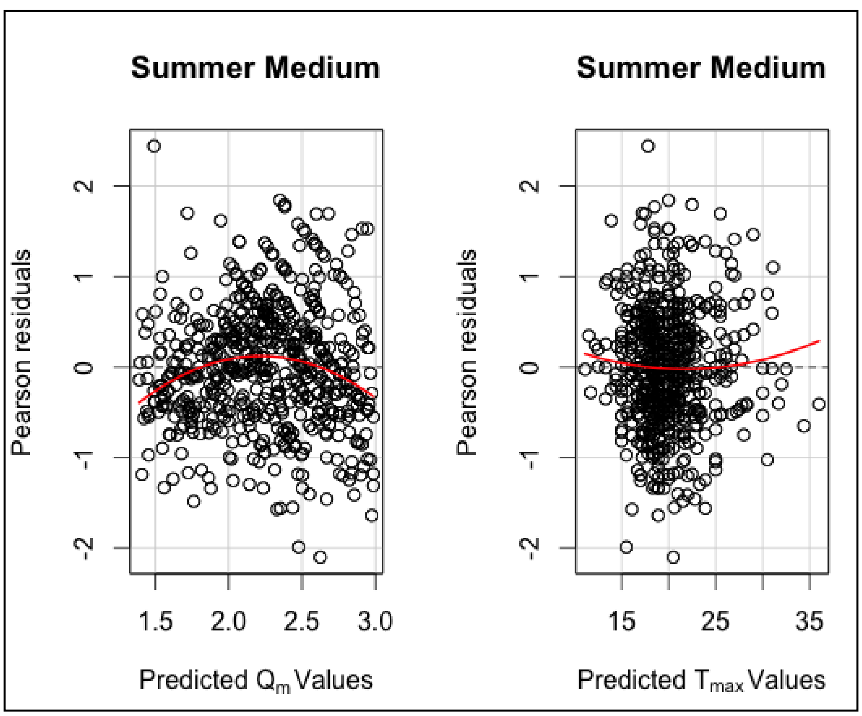
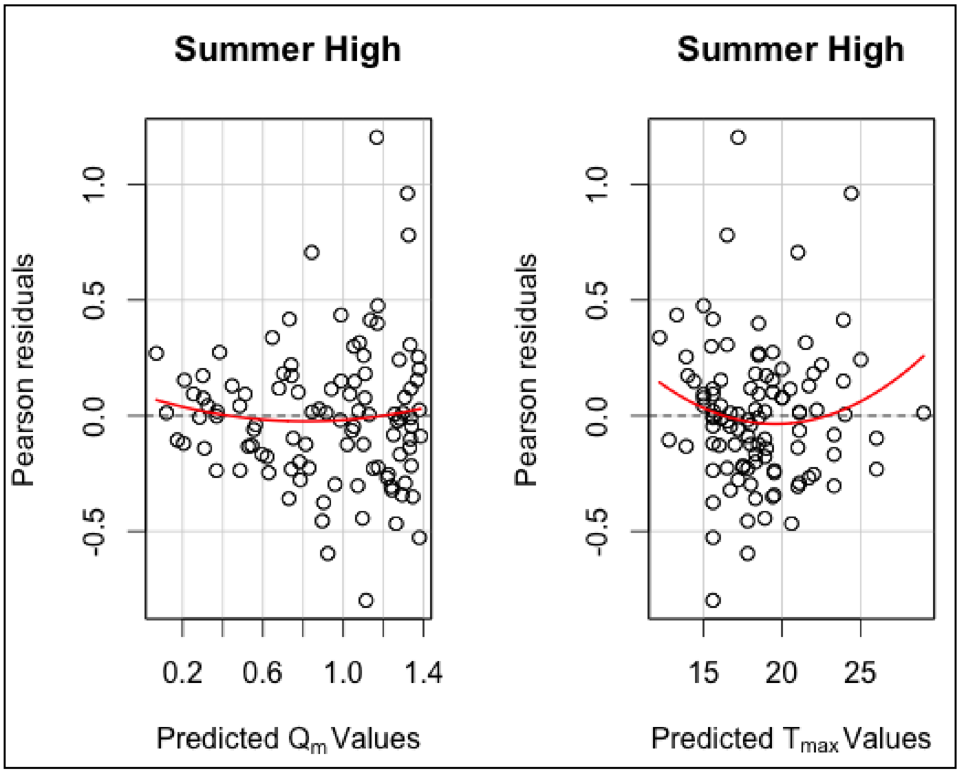
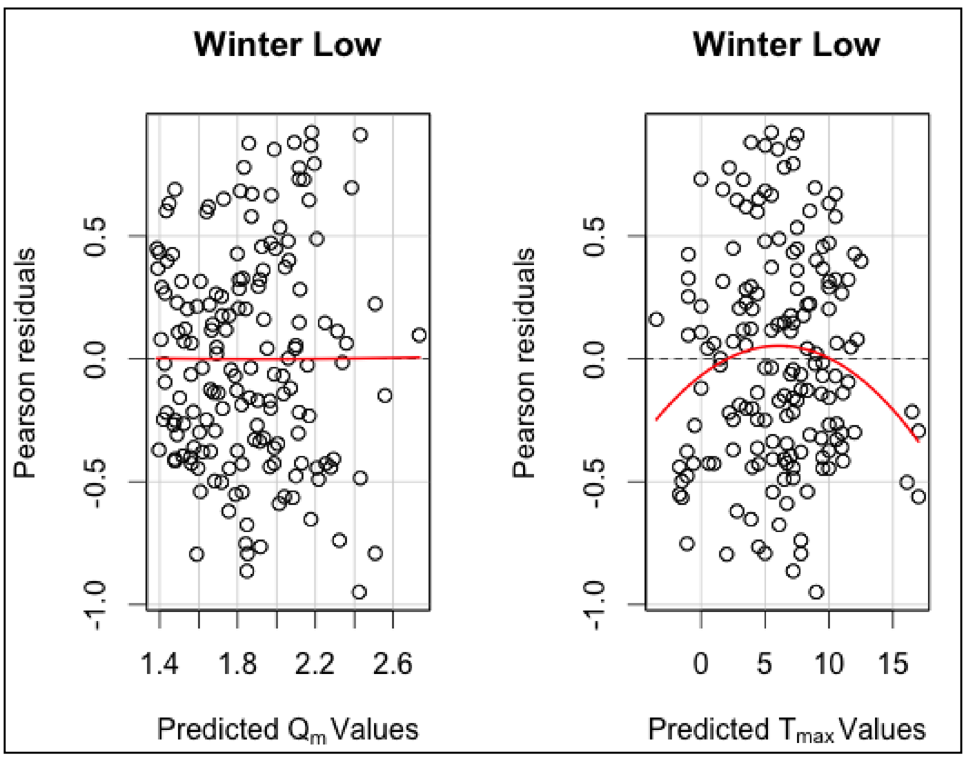
7. Appendices

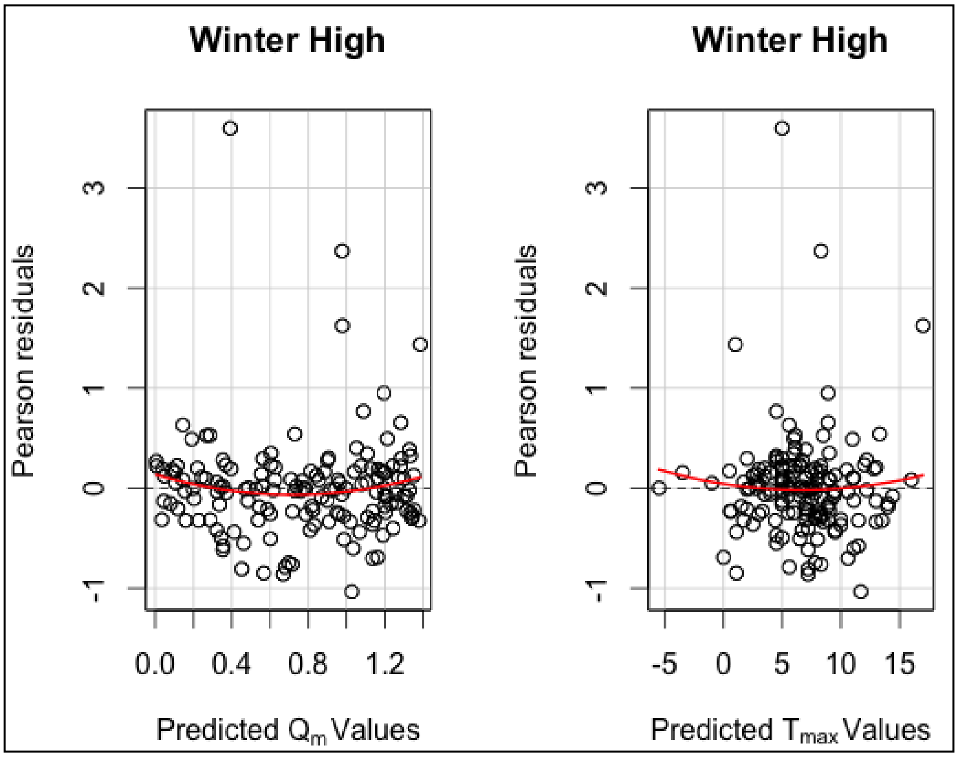
7.1 Appendix A – Residual Plots






Summer High
Summer High
Pearson residuals
Pearson residuals
-0.5
0.0
0.5
1.0
0.2
0.6
1.0
1.4
15
20
25
Predicted Q_m Values
Predicted T_{max} Values


Winter Low
Winter Low
Pearson residuals
Pearson residuals
-1.0
-0.5
0.0
0.5
1.4
1.8
2.2
2.6
0
5
10
15
Predicted Q_m Values
Predicted T_{max} Values



7.2 Appendix B – Shapiro-Wilk Normality Tests

Table 3. The W test statistics and p-values of linear model residuals using a Shapiro-Wilk normality test.

Season	Period Comparison	Discharge Level	W (test stat)	p-value
Summer	Pre vs. Post 1	Low	0.9804	0.3064
----------	Pre vs. Post 1	Medium	0.9952	0.7768
----------	Pre vs. Post 1	High	0.9553	0.1245
----------	Pre vs. Post 2	Low	0.9902	0.5945
----------	Pre vs. Post 2	Medium	0.9924	0.1924
----------	Pre vs. Post 2	High	0.9212	0.002332
----------	Pre vs. Logging	Low	0.9654	0.1497
----------	Pre vs. Logging	Medium	0.9918	0.03312
----------	Pre vs. Logging	High	0.9461	0.004182
----------	Logging vs. Post 1	Low	0.9763	0.1237
----------	Logging vs. Post 1	Medium	0.9869	0.00455
----------	Logging vs. Post 1	High	0.9744	0.2997
----------	Logging vs. Post 2	Low	0.9936	0.8482
----------	Logging vs. Post 2	Medium	0.9878	0.002233
----------	Logging vs. Post 2	High	0.9864	0.6864
----------	Post 1 vs. Post 2	Low	0.994	0.8055

-----------	Post 1 vs. Post 2	Medium	0.9931	0.4263
-----------	Post 1 vs. Post 2	High	0.9679	0.4071
Winter	Pre vs. Post 1	Low	0.8262	2.06E-07
-----------	Pre vs. Post 1	High	0.9815	0.9849
-----------	Pre vs. Post 2	Low	0.9849	0.4402
-----------	Pre vs. Post 2	High	0.814	5.69E-09
-----------	Pre vs. Logging	Low	0.9683	0.03129
-----------	Pre vs. Logging	High	0.7636	8.48E-10
-----------	Logging vs. Post 1	Low	0.9799	0.2273
-----------	Logging vs. Post 1	High	0.6835	5.32E-11
-----------	Logging vs. Post 2	Low	0.9876	0.4498
-----------	Logging vs. Post 2	High	0.7129	7.94E-12
-----------	Post 1 vs. Post 2	Low	0.9869	0.6113
-----------	Post 1 vs. Post 2	High	0.7983	5.84E-09

7.3 Appendix C – FULL Model VIF Results

FULL MODEL $|\log(dQ/dt)| = |\log(Q_m)| * T_{max} * P$

Summer

Pre-Logging vs Post-Logging 1 – MEDIUM

Qm	Tm	P	Qm:Tm	Qm:P	Tm:P	Qme:Tm:P
70.899	70.818	1067.314	189.880	1110.029	1190.646	1284.704

Pre-Logging vs Logging LOW

Qm	Tm	P	Qm:Tm	Qm:P	Tm:P	Qm:Tm:P
111.0589	633.9565	26912.7832	473.3785	25913.2011	29890.4624	28532.7548

Pre-Logging vs Logging MEDIUM

Qm	Tm	P	Qm:Tm	Qm:P	Tm:P	Qm:Tm:P
122.4904	122.2065	1252.1269	266.0358	1542.7001	1340.8997	1636.8703

Pre-Logging vs Post-Logging 2 MEDIUM

Qm	Tm	P	Qm:Tm	Qm:P	Tm:P	Qm:Tm:P
98.50343	83.90610	1119.53724	185.93440	1330.54212	1140.05448	1329.93133

Logging vs Post-Logging 1 LOW

Qm	Tm	P	Qm:Tm	Qm:P	Tm:P	Qm:Tm:P
942.4994	2763.5658	38260.4530	3310.6260	45263.5092	37620.4959	43955.8644

Logging vs Post-Logging 1 MEDIUM

Qm	Tm	P	Qm:Tm	Qm:P	Tm:P	Qm:Tm:P
48.50840	46.14674	979.38251	111.80573	911.21611	1088.13421	1039.11345

Logging vs Post-Logging 1 HIGH

Qm	Tm	P	Qm:Tm	Qm:P	Tm:P	Qm:Tm:P
106.63796	15.79913	409.67210	125.52866	414.70749	455.69421	465.39758

Logging vs Post-Logging 2 LOW

Qm	Tm	P	Qm:Tm	Qm:P	Tm:P	Qm:Tm:P
1564.485	6014.272	42925.198	10294.648	52039.472	51236.734	63717.344

Logging vs Post-Logging 2 MED

Qm	Tm	P	Qm:Tm	Qm:P	Tm:P	Qm:Tm:P
59.04932	52.17458	1001.00505	111.73833	1082.43413	1005.53322	1078.48261

Winter

Pre-Logging vs Post-Logging 1 LOW

Qm	Tm	P	Qm:Tm	Qm:P	Tm:P	Qm:Tm:P
5.924	230.0319	128.0639	200.174	120.432	359.355	308.610

Pre-Logging vs Post-Logging 2 LOW

Qm	Tm	P	Qm:Tm	Qm:P	Tm:P	Qm:Tm:P
10.52616	227.26329	144.84047	277.70883	164.13838	375.07257	457.28022

Pre-Logging vs Logging LOW

Qm	Tm	P	Qm:Tm	Qm:P	Tm:P	Qm:Tm:P
9.482334	246.567591	260.038753	262.315168	288.03581	556.241031	602.372525

Logging vs Post-Logging 2 HIGH

Qm	Tm	P	Qm:Tm	Qm:P	Tm:P	Qm:Tm:P
13.00545	21.46418	31.09494	26.50309	28.79800	39.06798	35.81650

7.4 Appendix D – Coefficient Estimates (Simple Model)

Table 4. The simple model intercept and log(Q_m) coefficient estimates. The gray column indicates coefficients where extreme low-flow data is included in the regression.

Season	Period	Discharge Level	Dependent Variable	b_0 Intercept	b_1 $\lvert\log(Q_m)\rvert$	b_0 Intercept	b_1 $\lvert\log(Q_m)\rvert$
Summer	Pre-Logging	Low	|log(dQ/dt)|	0.6356804	1.5641538	1.28213	1.378929
-----------	Pre-Logging	Medium	-----------	1.100859	1.839675	-----------	-----------
-----------	Pre-Logging	High	-----------	-0.28643	2.3234	-----------	-----------
-----------	Logging	Low	-----------	-1.9003	2.56671	-1.90033	2.5667
-----------	Logging	Medium	-----------	-0.25825	2.2694	-----------	-----------
-----------	Logging	High	-----------	-0.09023	1.96925	-----------	-----------
-----------	Post-Logging 1	Low	-----------	1.595655	1.2130	2.84022	0.83740
-----------	Post-Logging 1	Medium	-----------	0.3081784	1.7615	-----------	-----------
-----------	Post-Logging 1	High	-----------	-0.01256	2.095797	-----------	-----------
-----------	Post-Logging 2	Low	-----------	0.53390	1.59421	3.91146	0.60812
-----------	Post-Logging 2	Medium	-----------	0.418238	1.700284	-----------	-----------
-----------	Post-Logging 2	High	-----------	-0.04554	1.94557	-----------	-----------
Winter	Pre-Logging	Low	|log(dQ/dt)|	-1.62	3.216438	-----------	-----------
-----------	Pre-Logging	High	-----------	-0.0863	2.198623	-----------	-----------
-----------	Logging	Low	-----------	-0.248	2.35121	-----------	-----------
-----------	Logging	High	-----------	0.299	2.043610	-----------	-----------
-----------	Post-Logging 1	Low	-----------	1.4431	1.340731	-----------	-----------
-----------	Post-Logging 1	High	-----------	2.93E-01	2.1087	-----------	-----------
-----------	Post-Logging 2	Low	-----------	0.154991	2.10427	-----------	-----------
-----------	Post-Logging 2	High	-----------	9.06E-02	2.17378	-----------	-----------

7.5 Appendix E – ANOVA Tests

Summer

Pre-Logging vs Post-Logging 1

Medium

```
Analysis of Variance Table

Model 1: y ~ Qmean * P
Model 2: y ~ Qmean
  Res.Df    RSS Df Sum of Sq      F    Pr(>F)
1    196 100.55
2    198 142.34 -2   -41.791 40.73 1.613e-15 ***
---
Call:
lm(formula = y ~ Qmean)

Residuals:
     Min       1Q   Median       3Q      Max
-2.34860 -0.55893  0.02459  0.62177  1.82919

Coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept)   1.3381     0.3409   3.926 0.000119 ***
Qmean         1.5668     0.1535  10.209  < 2e-16 ***
---
Residual standard error: 0.8479 on 198 degrees of freedom
Multiple R-squared: 0.3449,   Adjusted R-squared: 0.3415
F-statistic: 104.2 on 1 and 198 DF,  p-value: < 2.2e-16
```

Pre-Logging vs Post-Logging 2

Medium

```
Analysis of Variance Table

Model 1: y ~ Qmean * P
Model 2: y ~ Qmean
  Res.Df    RSS Df Sum of Sq      F    Pr(>F)
1    260 103.24
2    262 164.98 -2    -61.74 77.746 < 2.2e-16 ***
---
Call:
lm(formula = y ~ Qmean)

Residuals:
     Min       1Q   Median       3Q      Max
-1.78151 -0.56702 -0.05287  0.62415  1.96863

Coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept)   1.3276     0.2740   4.845 2.17e-06 ***
Qmean         1.5005     0.1219  12.314  < 2e-16 ***
---
Residual standard error: 0.7935 on 262 degrees of freedom
Multiple R-squared: 0.3666,   Adjusted R-squared: 0.3642
F-statistic: 151.6 on 1 and 262 DF,  p-value: < 2.2e-16
```

Pre-Logging vs Logging

Low

```
Analysis of Variance Table

Model 1: y ~ Qmean * P
Model 2: y ~ Qmean
  Res.Df    RSS Df Sum of Sq      F  Pr(>F)
1     46 13.521
2     48 16.373 -2   -2.8521 4.8514 0.01225 *
---
Call:
lm(formula = y ~ Qmean)

Residuals:
    Min      1Q  Median      3Q     Max
-1.3439 -0.3372 -0.1700  0.4555  0.9287

Coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept)   3.6022     1.0914   3.301  0.00183 **
Qmean         0.7747     0.3307   2.342  0.02337 *
---
Residual standard error: 0.584 on 48 degrees of freedom
Multiple R-squared: 0.1026,   Adjusted R-squared: 0.08387
F-statistic: 5.486 on 1 and 48 DF,  p-value: 0.02337
```

Pre-Logging vs Logging

Medium

```
Analysis of Variance Table

Model 1: y ~ Qmean * P
Model 2: y ~ Qmean
  Res.Df    RSS Df Sum of Sq      F    Pr(>F)
1    376 173.43
2    378 190.08 -2    -16.65 18.048 3.277e-08 ***
---
Call:
lm(formula = y ~ Qmean)

Residuals:
    Min      1Q  Median      3Q     Max
-1.6765 -0.5088 -0.0458  0.5034  2.3761

Coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept)  0.38255    0.22068   1.734   0.0838 .
Qmean        2.04807    0.09765  20.973   <2e-16 ***
---
Residual standard error: 0.7091 on 378 degrees of freedom
Multiple R-squared: 0.5378,   Adjusted R-squared: 0.5366
F-statistic: 439.8 on 1 and 378 DF,  p-value: < 2.2e-16
```

Logging vs Post-Logging 1

Low

```
Analysis of Variance Table

Model 1: y ~ Qmean * P
Model 2: y ~ Qmean
  Res.Df    RSS Df Sum of Sq      F   Pr(>F)
1     80 40.175
2     82 49.364 -2   -9.1897 9.1498 0.000264 ***
```

```
---
Call:
lm(formula = y ~ Qmean)

Residuals:
     Min       1Q   Median       3Q      Max 
-1.80364 -0.59476  0.01979  0.74740  1.15409 

Coefficients:
            Estimate Std. Error t value Pr(>|t|)    
(Intercept)   4.1118     1.1341   3.626 0.000499 ***
Qmean         0.5351     0.3415   1.567 0.120951    
---
Residual standard error: 0.7759 on 82 degrees of freedom
Multiple R-squared: 0.02908,  Adjusted R-squared: 0.01724 
F-statistic: 2.456 on 1 and 82 DF,  p-value: 0.121
```

Logging vs Post-Logging 1

Medium

```
Analysis of Variance Table

Model 1: y ~ Qmean * P
Model 2: y ~ Qmean
  Res.Df    RSS Df Sum of Sq      F    Pr(>F)    
1    324 161.42                                  
2    326 184.38 -2   -22.962 23.045 4.391e-10 ***
---

Call:
lm(formula = y ~ Qmean)

Residuals:
     Min       1Q   Median       3Q      Max 
-2.40908 -0.45502 -0.05679  0.46849  2.69964 

Coefficients:
            Estimate Std. Error t value Pr(>|t|)    
(Intercept) -0.04158    0.24114  -0.172    0.863    
Qmean        2.11563    0.10417  20.310   <2e-16 ***
---
Residual standard error: 0.7521 on 326 degrees of freedom
Multiple R-squared: 0.5586,   Adjusted R-squared: 0.5572 
F-statistic: 412.5 on 1 and 326 DF,  p-value: < 2.2e-16
```

Logging vs Post-Logging 2

Low

```
Analysis of Variance Table

Model 1: y ~ Qmean * P
Model 2: y ~ Qmean
  Res.Df    RSS Df Sum of Sq      F    Pr(>F)    
1    119 45.708                                  
2    121 52.969 -2   -7.2617 9.4529 0.0001548 ***
---
Call:
lm(formula = y ~ Qmean)

Residuals:
     Min       1Q   Median       3Q      Max 
-1.94270 -0.40241  0.02167  0.41775  1.22065 

Coefficients:
            Estimate Std. Error t value Pr(>|t|)   
(Intercept)   2.2107     0.7627   2.898  0.00445 **
```

```
Qmean         1.1409     0.2260   5.048 1.59e-06 ***
---
Residual standard error: 0.6616 on 121 degrees of freedom
Multiple R-squared: 0.174,    Adjusted R-squared: 0.1671
F-statistic: 25.48 on 1 and 121 DF,  p-value: 1.593e-06
```

Logging vs Post-Logging 2

Medium

```
Analysis of Variance Table

Model 1: y ~ Qmean * P
Model 2: y ~ Qmean
  Res.Df    RSS Df Sum of Sq      F    Pr(>F)
1    388 164.10
2    390 203.94 -2   -39.832 47.089 < 2.2e-16 ***
---

Call:
lm(formula = y ~ Qmean)

Residuals:
     Min       1Q   Median       3Q      Max
-1.92259 -0.45322 -0.07069  0.41757  2.71056

Coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept)  0.08884    0.21042   0.422    0.673
Qmean        2.02073    0.09078  22.259   <2e-16 ***
---
Residual standard error: 0.7231 on 390 degrees of freedom
Multiple R-squared: 0.5596,   Adjusted R-squared: 0.5584
F-statistic: 495.5 on 1 and 390 DF,  p-value: < 2.2e-16
```

Winter

Pre-Logging vs Post-Logging 1

Low

```
Analysis of Variance Table

Model 1: y ~ Qmean * P
Model 2: y ~ Qmean
  Res.Df    RSS Df Sum of Sq      F    Pr(>F)
1     57 11.253
2     59 15.803 -2   -4.5497 11.523 6.272e-05 ***
---
Call:
lm(formula = y ~ Qmean)

Residuals:
     Min       1Q   Median       3Q      Max
-1.03842 -0.38120 -0.06555  0.29976  1.06296

Coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept)  -0.1504     0.4652  -0.323    0.748
Qmean         2.3412     0.2588   9.048 9.52e-13 ***
---
Residual standard error: 0.5175 on 59 degrees of freedom
Multiple R-squared: 0.5811,   Adjusted R-squared: 0.574
F-statistic: 81.86 on 1 and 59 DF,  p-value: 9.517e-13
```

Pre-Logging vs Post-Logging 1

High

```
Analysis of Variance Table

Model 1: y ~ Qmean * P
Model 2: y ~ Qmean
  Res.Df    RSS Df Sum of Sq      F  Pr(>F)
1     63 13.969
2     65 15.569 -2   -1.6001 3.6082 0.03284 *
---
Call:
lm(formula = y ~ Qmean)

Residuals:
     Min       1Q   Median       3Q      Max
-0.91928 -0.25544  0.03581  0.19693  2.30808

Coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept)  0.04059    0.11937    0.34    0.735
Qmean        2.21243    0.14043   15.76   <2e-16 ***
---
Residual standard error: 0.4894 on 65 degrees of freedom
Multiple R-squared: 0.7925,   Adjusted R-squared: 0.7893
F-statistic: 248.2 on 1 and 65 DF,  p-value: < 2.2e-16
```

Pre-Logging vs Post-Logging 2

Low

```
Analysis of Variance Table

Model 1: y ~ Qmean * P
Model 2: y ~ Qmean
  Res.Df    RSS Df Sum of Sq      F   Pr(>F)
1     79 18.768
2     81 21.962 -2    -3.194 6.7223 0.002013 **
---
Call:
lm(formula = y ~ Qmean)

Residuals:
     Min       1Q   Median       3Q      Max
-1.38063 -0.31796 -0.04818  0.34044  1.10244

Coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept)  -0.1884     0.3698   -0.51    0.612
Qmean         2.3405     0.1953   11.98   <2e-16 ***
---
Residual standard error: 0.5207 on 81 degrees of freedom
Multiple R-squared: 0.6394,   Adjusted R-squared: 0.6349
F-statistic: 143.6 on 1 and 81 DF,  p-value: < 2.2e-16
```

Pre-Logging vs Logging

Low

```
Analysis of Variance Table

Model 1: y ~ Qmean * P
Model 2: y ~ Qmean
```

```
  Res.Df    RSS Df Sum of Sq      F  Pr(>F)
1     83 19.138
2     85 21.115 -2   -1.9771 4.2874 0.01691 *
---

Call:
lm(formula = y ~ Qmean)

Residuals:
    Min      1Q  Median      3Q     Max
-0.9038 -0.3722 -0.1053  0.3884  1.0115

Coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept)  -0.5768     0.3691  -1.563    0.122
Qmean         2.5696     0.1970  13.046   <2e-16 ***
---
Residual standard error: 0.4984 on 85 degrees of freedom
Multiple R-squared: 0.6669,   Adjusted R-squared: 0.663
F-statistic: 170.2 on 1 and 85 DF,  p-value: < 2.2e-16
```

Logging vs Post-Logging 1

Low

```
Analysis of Variance Table

Model 1: y ~ Qmean * P
Model 2: y ~ Qmean
  Res.Df    RSS Df Sum of Sq      F  Pr(>F)
1     78 14.217
2     80 15.820 -2   -1.6034 4.3984 0.01549 *
---

Call:
lm(formula = y ~ Qmean)

Residuals:
     Min       1Q   Median       3Q      Max
-0.86968 -0.28090 -0.08049  0.28776  1.05839

Coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept)   0.2296     0.3169   0.725    0.471
Qmean         2.0778     0.1711  12.146   <2e-16 ***
---
Residual standard error: 0.4447 on 80 degrees of freedom
Multiple R-squared: 0.6484,   Adjusted R-squared: 0.644
F-statistic: 147.5 on 1 and 80 DF,  p-value: < 2.2e-16
```