The Movement of Marine-Derived Nutrients from a Salmon Spawning River to a Nursery Lake

by

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Abstract

Salmon play a key role in the redistribution of marine-derived nutrients (MDNs) in aquatic and terrestrial ecosystems. Research conducted on the movement and storage of MDNs in aquatic systems throughout the Pacific Northwest seem to vary in whether MDNs have a beneficial, neutral, or detrimental impact. Using Horsefly Bay (Quesnel Lake), the mechanism and driving factors for the delivery and dispersion of MDNs were evaluated. Higher concentrations of marine-derived nitrogen and carbon were found to enter this nursery system in the fall spawning period. However, due to the increased water discharge, it was found that the load of marine-derived nitrogen and carbon was higher during the spring freshet study period. These increases in MDNs were found to correlate with chlorophyll-a and fluorescence levels which indicate increases in productivity. Increased production can support the growth and survivorship of juvenile salmon rearing in this nursery system through bottom-up trophic transfer.

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Acronyms

AIC - akaike information criterion

^{12}C - lighter isotope (naturally occurring)

^{13}C - heavier isotope (naturally occurring)

CFC - continuous flow centrifuge

Chl-a - chlorophyll-a

CTD - Seabird water profiler (conductivity, temperature, depth)

D_{50} - median diameter particle size

DOC - dissolved organic carbon

DP - dissolved phosphorous

HFB - Horsefly Bay

HFR - Horsefly River

HSD - honest significance difference

HVFS - high volume filtration system

ISP - inorganic suspended particulate

LISST - laser in-situ scattering transmissometry

LOESS - curve fitting local polynomial regression

MDN - marine-derived nutrient

^{14}N - lighter isotope (naturally occurring)

^{15}N - heavier isotope (naturally occurring, predominantly marine-derived)

NH_4 - ammonium

NO^{-3} - nitrate

OSP - organic suspended particulate

P - phosphorous

PO_4^{-3} - orthophosphate

QRRC - Quesnel River Research Centre

SIAR - stable isotope analyzes in R

SIMMR - stable isotope mixing model in R

SPM - suspended particulate matter

TN - total nitrogen

TP - total phosphorous

UV-VIS - ultraviolet visible spectrophotometry

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Preface

This thesis is divided into four chapters. Chapter 1 provides an overview of the importance and process of the delivery and incorporation of marine-derived nutrients (MDNs) into nursery systems across the Pacific Northwest. Specifically, this chapter illustrates the biological impacts of the decomposition of salmon and the release and dispersal of nutrients into a nursery system. Results in Chapter 2 examine the timing and transportation of MDNs into a nursery lake and the driving factors behind this delivery. This chapter looks at temporal variations and the physical characteristics of MDNs entering a nursery lake. Chapter 3 analyzes the movement of particulates vertically and horizontally throughout the water column of the bay which receives discharge from the salmon-spawning river. Tracking of these particles provides data to better predict the dispersal of nutrients entering a nursery lake. Chapter 4 presents conclusions and management implications based on the results that were presented in Chapters 2 and 3.

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Chapter 1: Marine-Derived Nutrients and Salmon; A Literature Review

1.1 Introduction

The movement of suspended particulates throughout watersheds is an important hydrological, fluvial, and geomorphological process. These particulates composed of sediment and nutrients become suspended in rivers and streams and make their way from high elevations to lower elevations until they settle out into slower moving water bodies (Owens, 2005). This results in larger particles settling out faster and finer particles staying suspended longer and moving farther downstream. Nutrients and contaminants tend to bind more easily to finer particles in the water column due to their larger surface area/volume ratios (Horowitz & Elrick, 1988). These finer inorganic particles have a propensity to bind available nutrients through the process of flocculation and in turn modify the transportation of both materials through aquatic ecosystems (Choles, 2004; McConnachie & Petticrew, 2006). This process is particularly important in interior oligotrophic British Columbian lakes and rivers that are used for salmon spawning and rearing as these systems are usually nutrient limited (Naiman et al., 2002).

Each year in these ecosystems millions of Pacific salmon migrate from the sea, where they have accumulated more than 95% of their body mass, to their natal freshwater streams to spawn and die (Naiman et al., 2002). The displacement and suspension of particulate matter by spawning salmon, in rivers and streams, is an important process that supplies nursery lakes with pulses of sediment, organic/inorganic matter, and nutrients (Petticrew et al., 2011 & Reisinger, 2013).

Since the early 1990's salmon numbers observed on the west coasts, and most interior rivers and streams of British Columbia and Alaska, have been in steady decline (Stouder et al., 2012). Fewer salmon will result in smaller run sizes and subsequently less nutrient influx to streams. Gresh et al. (2000) and Naiman et al. (2002) performed a study to compare historical levels of biomass, nitrogen, and phosphorus in Pacific Northwest nursery lakes to what was present in the early 1990's and found that there was an 87%-93% reduction of biomass and nutrients delivered to these systems. This decrease in nutrients will limit the amount of nutrient and carbon sources available to organisms living in these nursery lakes (Larkin & Slaney, 1997).

At a larger scale, the decrease in any marine-derived nutrient (MDN) may inhibit many aquatic systems in sustaining salmon populations (Bilby et al., 1996). Although this assumption has rarely been tested, a better understanding of the behavior and distribution of MDNs in limnetic ecosystems will allow a more informed approach in the conservation and management of future salmon populations.

Nursery lakes are an important habitat for some species of juvenile salmon for the first one to two years of their lives before they migrate to the ocean (Naiman et al., 2002). These lakes are typically oligotrophic and primary productivity is severely nutrient-limited (Naiman et al., 2002). The transfer of MDNs into these nursery lakes increases productivity and helps drive algae, zooplankton, and fish populations in a bottom-up trophic transfer (Hyatt et al. 2004; DeVries, 2012). Although, with this increase in productivity due to MDNs, research has not demonstrated a clear link between lake productivity and salmon-spawner population size (Naiman et al., 2002; Holtgrieve & Schindler, 2011).

Table 1.1: Table showing various studies throughout Alaska and British Columbia that suggest a positive (+), negative (-), or neutral effect that MDNs have on future salmon stocks.

Study	**Study Location**	**MDN Impacts of Future Salmon Populations**
Stockner and Macisaac (1996)	BC	+
Schmidt et al. (1998)	BC	+
Finney et al. (2000)	Alaska	+
Stocker (2003)	Alaska & BC	+
Schindler et al. (2005)	Alaska	Neutral
Uchiyama et al. (2008)	Alaska	Neutral
Walters (2014)	BC	-

Results of research on the impacts that spawning salmon have on ecosystems, such as the disturbance and redistribution of stream bed sediment and the mass influx of MDNs, vary as to what effect MDNs have upon their natal systems (Table 1.1). Some studies show that the influx of MDNs help increase riverine benthic productivity as well as increase survivorship of juvenile

salmon in downstream rearing lakes (Wipfli et al., 1998; Naiman et al., 2002; Johnson et al., 2004) while others show a detrimental or neutral impact with nutrient export by smolts exceeding nutrient import from spawning salmon as well as an observed decline in riverine primary productivity (Holtgrieve & Schindler, 2011; Walters, 2014). However, these varying results may be credited to the lack of understanding of the spatial and temporal factors that affect the behavior of MDNs and therefore may be more system-specific than a general overall observation.

It is the objective of this study to determine seasonal quantitative differences in the amount of MDNs flushed into a nursery lake from a river system and the depth at which these nutrients disperse in the water column over the course of a salmon-spawning event, spring freshet, and a summer period.

1.2 Salmon Decomposition

Nutrients from salmon carcasses are utilized and incorporated into the surrounding biota by direct consumption of dead salmon tissue (Cederholm et al., 1999), the uptake of soluble nutrients by primary producers (Schindler et al., 2003), and the uptake of dissolved and particulate organic matter by micro-fauna (invertebrates) in streambed substrate (Claeson et al.,

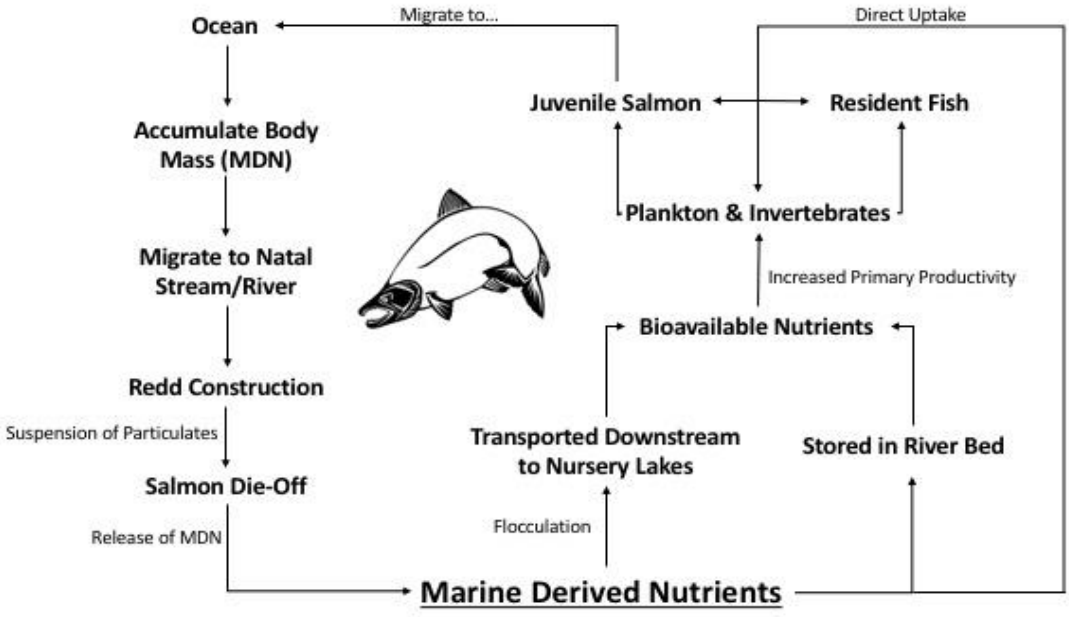


Figure 1.1: Trophic pathways influenced by anadromous salmon in freshwater systems and the energy flow within these systems.

2006)(Figure 1.1). These nutrients have been associated with the enhancement of algae and aquatic invertebrate populations near carcasses and the increase of phytoplankton and chlorophyll-a concentrations in nursery lakes (Mathisen, 1972; Schmidt et al., 1998; Schindler et al., 2003). Organic matter and nutrients released from these carcasses can be the most significant source of annual nutrient input and may be important in the growth of juvenile salmon that reside in these ecosystems (Naiman et al., 2002).

The ability to identify MDNs in these aquatic systems helps track the effects that salmon carcasses and their nutrients have on an ecosystem. Isotopic signatures of marine-derived nitrogen (^{15}N) have been used to trace MDNs throughout watersheds (Hocking & Reynolds, 2011, Albers & Petticrew, 2013). The nitrogen derived from an adult salmon has a higher level of ^{15}N than that found in freshwater aquatic and terrestrial sources, allowing for the identification of MDNs (Uchiyama et al., 2008). The percent ^{15}N in an adult Sockeye Salmon averages around 11%-12% of total N, while terrestrial sources of ^{15}N are closer to zero (Kline et al., 1993; Welchand & Parsons, 1993; Satterfield & Finney, 2002). This allows the use of the isotopic signature of ^{15}N to be used to trace MDNs pathways in freshwater ecosystems (Kline et al., 1990).

1.3 Salmon versus Non-Salmon Effects

The introduction of salmon carcasses to spawning rivers and lakes can have many effects on biota that live in these watersheds (Bilby et al., 2011). Understanding the differences in nutrient availability and nutrient uptake between salmon bearing rivers and lakes and non-salmon bearing rivers and lakes is important in understanding how salmon alter and possibly enhance these ecosystems. Bilby et al. (2011), Claeson et al. (2011), and Wipfli et al. (2011) have performed studies in which salmon carcasses were added to streams and compared to control sites where no salmon carcasses were introduced. Biofilm and macroinvertebrate abundance increased in natural streams where salmon carcasses were added, suggesting that marine-derived nutrients were enhancing stream productivity (Wipfli et al., 2011). These findings were consistent with results showing that the addition of inorganic nitrogen and phosphorous, and organic matter increased biological activity throughout trophic levels (Peterson et al., 1993; Lamberti, 1996; Stockner & MacIsaac, 1996). Bilby et al. (2011) found delta ^{15}N values in resident fish were elevated at treated sites, indicating that decomposing salmon were ingested by fish

living in these streams. In another study the introduction and presence of decomposing salmon increased ammonium and chlorophyll-a levels as well as the abundance of macroinvertebrates when compared to non-salmon streams (Claeson et al., 2011). A study on Quesnel Lake phosphorous levels shows that P levels were higher closer to the mouth of a salmon spawning river than sites located away from the river delta with higher levels occurring in the spring freshet, summer, and fall spawn, respectively (Neil, 2006). These studies show that there are differences in water chemistry and/or biotic populations when comparing salmon bearing and non-salmon bearing rivers and streams (Table 1.2) and further research and analyses should take this into consideration.

Table 1.2: Results from four studies looking at water quality and biotic differences among salmon bearing and non-salmon bearing streams and lakes. (+) denotes there was higher levels or populations in salmon bearing streams and lakes. (N) denotes there was no significant difference found in salmon bearing streams and lakes. (NA) denotes that the study did not mention parameter. Results with * were taken from same lake; however, salmon bearing was at the outflow of a salmon spawning river and non-salmon bearing was in the middle of lake away from any salmon spawning river mouths.

Study	Chl-a	TP	TN	NH^4	$\delta^{15}N$	$\delta^{13}C$	Macroinvertebrates	Resident Fish	Biofilm
Bilby et al. 2011	NA	NA	NA	NA	+	+	+	+	NA
Claeson et al. 2011	+	NA	NA	+	+	+	N	NA	NA
Wipfli et al. 2011	NA	NA	NA	NA	NA	NA	+	NA	+
Neil 2006	NA	+*	N*	NA	NA	NA	NA	NA	NA

1.4 Plankton Background

Juvenile Sockeye Salmon (*Oncorhynchus nerka)* make extensive use of freshwater lake habitat as rearing areas. These fish typically spend the first one to two years of their lives living in the limnetic zone of a lake before making their way to the ocean (Burgner, 1991; Naiman et al., 2002). While inhabiting these freshwater systems, Sockeye Salmon are predominantly planktivoruous and mainly feed on pelagic zooplankton (Burgner, 1991; Kyle et al., 1996; Koenings & Kyle, 1997). Hume et al. (2005) conducted a study on Quesnel Lake, Shuswap Lake,

and Mara Lake in British Columbia Canada that found that *Daphnia sp.* made up more than fifty percent of biomass found in the stomachs of rearing Sockeye Salmon.

Studies have been implemented to determine the relationship between MDNs and plankton communities in oligotrophic interior British Columbian and Alaskan lakes where productivity is very nutrient-limited. Higher trophic level productivity in lakes is assumed to be dependent on larger populations of plankton, as larger populations of phytoplankton means more food and faster growth-rates for Sockeye Salmon (Hyatt et al., 2011). Larger populations of zooplankton within these nursery lakes could also promote internal recycling of nutrients furthering the enhancement of both phytoplankton and fish productivity (Vanni, 1987). Sweetman (2001) found that Sockeye spawner abundance was highly correlated with the abundance of herbivorous zooplankton populations in 23 Alaskan nursery lakes. This correlation implies that with larger populations of sockeye spawners in nursery systems zooplankton communities will also increase because of the higher amounts of MDNs. This idea suggests that MDNs delivered by spawning salmon could be directly related to productivity in nursery lakes. However, Walters (2014) found that zooplankton populations do not show the same decreasing trend as female spawners have over the past 50 years which suggests that returning salmon numbers have no effect on plankton populations. Walter's findings, that the amount of MDNs being delivered to nursery systems by spawning salmon, do not have any effect on growth rates and survivorship of zooplankton in nursery lakes, suggests that the contribution MDNs have no to little significance in bottom up trophic transfer.

1.5 MDNs Effect on Water Chemistry

Many studies have looked at the effects of salmon decomposition and how MDNs affect water parameters. Concentrations of ammonium and soluble reactive phosphorus (SRP) are positively affected by the arrival of MDNs (Bilby et al., 1998; Hood et al., 2007; Wipfli et al., 2010) due to the addition of the salmon's waste products and their post-spawn decay (Hood et al., 2007; McIntyre et al., 2008). This increase in ammonium may help contribute to the increased productivity level of water bodies and could be the mechanism for more algal growth that support plankton communities. Total phosphorous (TP) and phosphate (PO_4^{-3}) also increase with the arrival of MDNs to spawning rivers/streams and nursery lakes (Bilby et al., 1998 & Hume et

al., 2005). Hume et al. 2005 supported earlier conclusions that TP measured in the spring was highly correlated with the previous year's spawner's density in Quesnel and Shuswap Lakes (Shortreed & Hume, In Prep). This may be an important relationship as this increase occurs near the beginning of the open-water season when temperatures are increasing and chlorophyll concentrations are peaking (Hume et al., 2005). The other form of this nutrient observed to increase in concentration, phosphate (PO_4^{-3}), is important in these interior, oligotrophic nursery systems because it is the most readily available form of phosphorous for uptake by primary producers such that higher concentrations of PO_4^{-3} generally coincide with algal blooms (Ministry of Environment, 1988). Increased algal growth is measured as higher levels of primary productivity which tends to result in the growth and survival rate of secondary producers. Concentrations of nitrates (NO^{-3}) and dissolved organic carbon (DOC) also increase with the addition of MDNs to freshwater systems; however, studies suggest that these aquatic parameters are not solely related to the arrival of salmon in these systems (Hood et al., 2007; Cak et al., 2008). These findings in these two papers indicate that with the arrival of salmon, concentrations of TP and PO_4^{-3} increase promoting the growth of algae and play the more significant role in aiding productivity in nursery systems.

1.6 Movement and Behavior of Marine-Derived Nutrients

The delivery of MDNs by salmon is significant to aquatic and terrestrial ecosystems (Naiman et al., 2002). Spawning salmon generate important biophysical changes to their natal streams by such actions as disturbing streambeds/ re-suspending sediment during redd construction and the introduction of MDNs to the system from the decomposition of their carcasses (DeVries, 2012). There are many variables that affect the behavior and movement of MDNs from the location where they are introduced in aquatic systems such as the order of the stream or river, magnitude of hydrologic discharge, numbers of spawning salmon, seasonal climatic changes, and floodplain connectivity (Cederholm et al., 1999; Naiman et al., 2002). The re-suspension and redistribution of MDNs and sediment by spawning salmon can alter ecosystems at all levels as the flocculation of suspended particulates affects the downstream flow of MDNs (Rex et al., 2008; Petticrew et al., 2011). Interior streams depend on the cycling of these MDNs because of their distance from marine ecosystems (Johnson et al., 1997). The

storage (Albers & Petticrew, 2012) and movement of these MDNs may be particularly important for juvenile salmon that rear in downstream nursery lakes for up to a year or more (Naiman et al., 2002).

The construction of spawning redds and the decaying of salmon carcasses, which may occur simultaneously, plays an important role in the movement and storage of nutrients in salmon-spawning streams (Wipfli & Baxter, 2010). This combination of events provides favorable biological conditions for flocculation (the formation of aggregates of organic and inorganic matter) of fine sediment (>63 μm) and organic matter originating from salmon (Rex & Petticrew, 2008; Petticrew et al., 2011). Larger flocs can have increased settling rates that enhance particle delivery to gravel beds, which increases the availability of organic matter and nutrients to benthic organisms (Wotton, 2007: Petticrew et al., 2011). This process is important to inland streams, which experience low flow during spawning events, because it increases the potential of these gravel-bed driven nutrients to be available for hyporheic nutrient recruitment and storage (Rex et al., 2014). The storage of MDNs in gravel beds, hyporheic zones, and riparian areas during the fall season's low flow allows these nutrients to be resuspended and transported farther downstream during spring's higher flows (O'Keefe & Edwards, 2002; McConnachie & Petticrew, 2005; Moore et al., 2007). Therefore, seasonal storage of MDNs may be a significant factor in primary and secondary production both locally in the stream and in downstream nursery lakes.

1.6.1 MDNs in Nursery Lakes

Sources of nutrients in many Pacific Northwest salmon-rearing lakes are limited and one study shows that the influx of MDNs by spawning salmon represents a major nutrient source to nursery lakes which may only happen once a year (Moore & Schindler, 2004). Other studies on biota in these nursery ecosystems show that substantial amounts of MDNs are retained and stored in recipient freshwater systems (Gende et al., 2002; Naiman et al., 2002). Data have suggested that because salmon spend a large amount of time in these freshwater nursery systems, the storage of MDNs from previous salmon runs, inter-annual flux, is important for the productivity of future salmon populations (Finny et al., 2000; Stockner, 2003). Although there is minimal research supporting the linkage of MDNs and future salmon populations, this relationship has become an important concern in salmon management and recovery efforts of

impacted populations in the Pacific Northwest (O'Keefe & Edwards, 2002; Compton et al. 2006; Holtgrieve & Schindler, 2011).

Physical limnology plays an important role in how nutrients move throughout the water column in lakes (Carmack et al., 1979). The stratification of lakes restricts the exchange of suspended particulates and nutrients among the hypolimnion, metalimnion, and epilimnion. The solar energy entering the lake's surface in summer months promotes stratification in most temperate lakes, while in the fall the surface water cools decreasing the density gradient which allows the entire water column to mix via wind (Wetzel, 2001). This mixing of water in the spring and fall months allows nutrients to be recycled back up to the euphotic zone from the hypolimnion promoting primary productivity (Brock et al., 2007). However, if a lake doesn't mix fully, nutrient supply to the epilimnion will be limited which reduces nutrient recycling and primary productivity (Brock et al., 2007). These physical characteristics limit MDNs from moving freely throughout the water column during times of stratification; however, allow MDNs that may have settled to the bottom of nursery lakes to be redistributed during times of mixing.

Although, there has been no substantial evidence that supports that MDNs have a direct effect on future salmon population numbers, the amount of MDNs should have a direct effect on juvenile salmon rearing in nursery lakes because of the effect it has on bottom up trophic transfer. Schindler et al. (2005) discovered that algal abundance in Alaskan nursery lakes was positively linearly correlated with sedimentary ^{15}N in sediment cores. This coupled with findings that ^{15}N is strongly correlated to the density of spawning salmon (Finney et al., 2000; Brock et al., 2006), suggests that algal abundance increases with higher spawning salmon populations. Zooplankton communities that are consumed and provide fuel for the growth of juvenile salmon are dependent on algal abundance for food (Mazumder & Edmundson, 2002). Therefore, the delivery of MDNs by spawning salmon to nursery lakes is expected to be a regulating factor in the development of juvenile salmonids.

1.6.2 Primary Productivity & Nutrient Pulses

Spawning salmon can supply a substantial nutrient subsidy to nursery lakes as they decompose and release MDNs into their natal spawning rivers that connect with these lakes (Larkin & Slaney, 1997; Gresh et al., 2000). Previous studies show that nitrogen (N) from Sockeye

Salmon can account for a 25% increase in N to Alaskan nursery lakes (Naiman et al., 2002) and 90% of total phosphorus (P) increase to coastal freshwater lakes and rivers (Schmidt et al., 1998; Naiman et al., 2002; Mitchell & Lamberti, 2005). Finney (1998) found that approximately a million Sockeye Salmon spawners brought in an estimated 64,100 $kg.year^{-1}$ of nitrogen to Karluk Lake in Alaska, while only 43,200 $kg.year^{-1}$ and 800 $kg.year^{-1}$ of nitrogen were delivered by rivers and rain, respectively. However, because the amount of MDNs depends on the number of spawners present, and this varies each year relative to the background of N and P from other non-salmon sources (Naiman, 2002), there is a significant annual and regional discrepancy regarding the effects of MDNs on primary production in nursery lakes (Wipfli et al., 1998; Scheuerell et al., 2005; Schindler et al. 2005).

Some studies have shown that MDNs, specifically marine-derived nitrogen (^{15}N), from spawning Sockeye Salmon do not get taken up quickly by the surrounding biota and instead are circulated in a dissolved form throughout nursery lake systems before stimulating primary production (Finney et al., 2000; Schindler et al., 2005; Brock et al., 2006). In a study done by Hume et al. (2005), which aimed to differentiate stream versus lake stored sources of nutrients, they found results which supported previous research (Shortreed & Hume, In Prep) that suggested that total phosphorous levels in Quesnel Lake during the spring freshet were directly correlated with the amount of salmon spawners the year previous. This would suggest that a significant amount of phosphorous is stored in the river ecosystem and not delivered to this nursery lake until the spring during high, flushing flows. This may be important because seasonal differences in a lake's physical structure can limit or influence where incoming nutrients will be available for uptake by biota living in these systems.

1.7 Plume Dispersion Effects at River Lake Interface

In many nursery lake ecosystems, river and stream discharges lead to the creation of plumes in these lakes due to differences in temperature, suspended particulate load, and/or salinity (Grimes & Kingsford, 1996). These river plumes have different water characteristics than the lake they enter; these differences can be chemical (nutrients), physical (suspended particulate, temperature), and biological (organisms, biomass) and will typically be higher in turbidity and nutrient concentrations (Morgan et al., 2005; Owens, 2005; Vanderploeg et al.,

2007; Reichert, 2009; Hodder, 2009). These differences depend greatly on location, topography, land use, geomorphology, watershed characteristics, and seasonal weather patterns (Grimes & Kingsford, 1996; Mallin et al., 2005).

River plumes will mix and disperse into lake systems differently depending on the relative properties of both water bodies (Figure 1.2). Colder and more particulate laden river water will plummet to deeper depths when entering a lake ecosystem with warmer surface

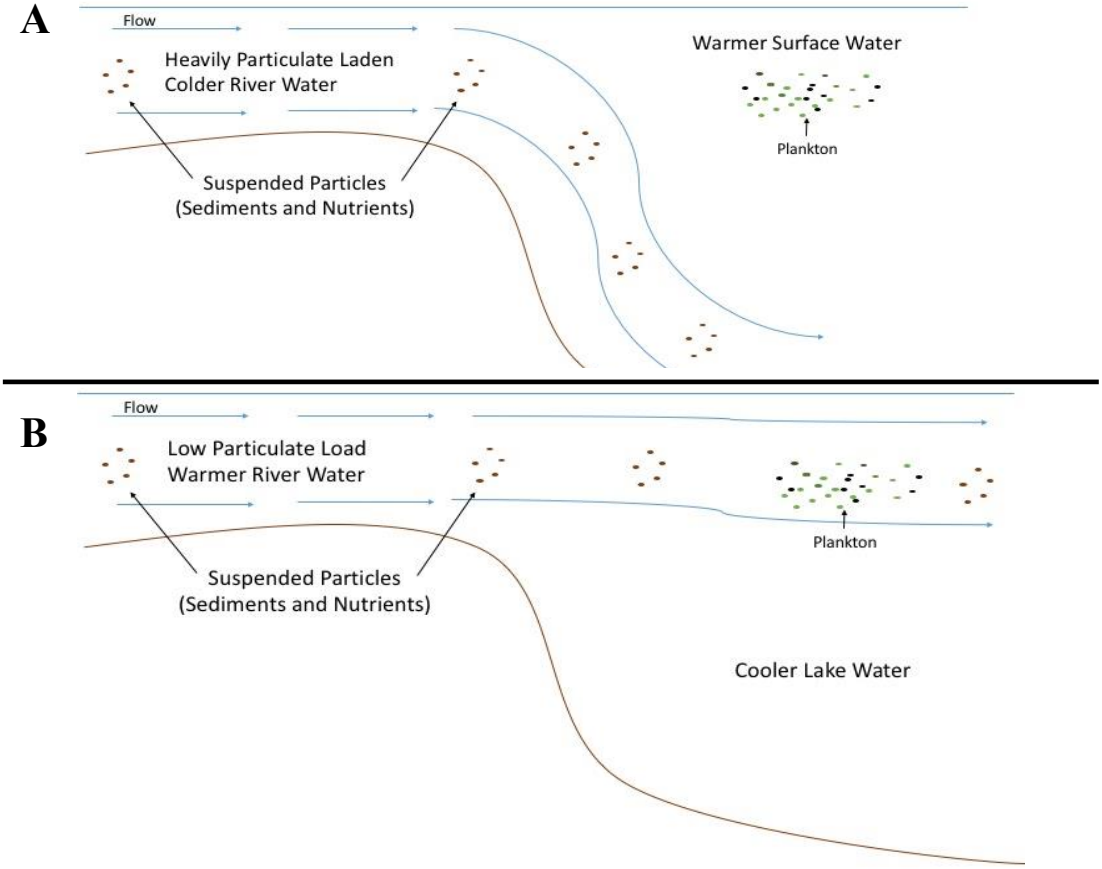


Figure 1.2: Depicts a river/lake interface ecosystem during situations when river waters are colder and more sediment-laden than lake surface waters (A) and when river waters are warmer and less sediment-laden than lake surface waters (B). Blue arrows signify flow path. (Desloges & Gilbert, 1998; Boehrer, 2008).

waters, since water around 4°C is denser than warmer water (above 4°C) and colder water (below 4°C) (Figure 1.2A). Warmer and less particulate laden river water will stay suspended in a lake system when lake waters are colder (Figure 1.2B). This process will influence where a river plume and its contents will disperse in the lakes water column. Therefore, depending on the season and

water temperatures of both salmon spawning rivers and nursery lakes, MDNs that are contained in these river plumes could be readily available for plankton that live in the warmer surface waters of a lake or could be lost to the depths and not utilized by primary producers.

Unfortunately, to date there hasn't been published research identifying the seasonal magnitude of MDNs entering nursery lake systems or the mechanisms that control the spatial and temporal variability of primary and secondary productivity to nutrient pulses. To reiterate the objective of this study is to address this lack of information by determining the seasonal quantitative differences in the amount of MDNs flushed into a nursery lake from a river system and the depth at which these nutrients disperse in the water column over the course of a salmon spawning event, spring freshet, and a summer period.

Chapter 2: Timing and Delivery of MDNs from a Spawning Salmon River to a Nursery Lake - The Horsefly River/Quesnel Lake system

2.1 Introduction

Many studies have been undertaken to try to predict the relationship between MDNs and future salmon populations (Schindler et al., 2005; Naiman et al., 2009; Holtgrieve & Schindler, 2011; DeVries, 2012). However, no real consensus has been achieved to say whether MDNs are beneficial, neutral, or detrimental to future salmon spawners. Spawning salmon returning to their natal streams from the ocean, are transporting nutrients against the usual downstream energy river gradient, supplying rivers and lakes with pulses of nutrients that are essential for many oligotrophic interior British Columbia lakes (Bilby et al., 1996). These rivers and nursery lakes where these salmon spawn and die act like sinks as both soluble and insoluble nutrients find their way into river beds and/or are deposited on the lake bottom. These nutrient pulses could be important to primary and secondary production in these nursery lakes where juvenile salmon live for the first 1-2 years of their lives.

Extensive amounts of information have been gained in studying the transportation and storage of MDNs in salmon-spawning streams (Petticrew et al., 2011; Reisinger, 2013). However, the timing of the delivery of these MDNs relative to seasonal plankton production remains understudied. The objective of this chapter is to examine the timing of delivery of MDNs from a salmon-spawning river to a nursery lake, comparing the salmon fall-spawn event versus the subsequent spring freshet.

2.2 Research Question

When salmon migrate back to their natal rivers they spawn and die, creating an influx of soluble nutrient and particulate pulses that can move downstream into nursery lakes. The magnitude and timing of the downstream delivery of MDN is the focus of this chapter. Specifically, are there differences in the amount of sediment-associated MDNs transported from the Horsefly River (HFR) system to Quesnel Lake during the fall spawn event versus the spring freshet? Differences in the amount of MDNs that enter Horsefly Bay (HFB) during these two events should identify if these nutrients are stored over winter in the spawning river or if the bulk

delivery of MDNs are associated with the fall spawn. This question will be addressed by analyzing stable isotopic ratios and nutrient levels over the course of a fall spawning event and a spring freshet.

2.3 Methods

2.3.1 Study Site

The Horsefly watershed is located in the Cariboo region in interior British Columbia. The HFR runs 131 kilometers from the Cariboo Mountains to Quesnel Lake where it empties into Horsefly Bay. The HFR represents a unique ecosystem that historically supports one of the largest Sockeye Salmon runs in the Fraser River Watershed and eventually empties into Quesnel Lake which is one of the deepest fiord lakes in the world reaching depths of 510 meters (Stockner & Shortreed, 1989; Hume et al., 1996).

Table 2.1: Salmon escapement from 2013-2016 from the Horsefly Watershed and the Horsefly River (HFR) specifically.

Salmon Escapement

Year	Horsefly River	Horsefly Watershed
2013	69,937	95,784
2014	457,553	492,011
2015	23,524	28,471
2016	619	642

2.3.1.1 Site Characteristics

A hydrometric station (08KH031) which records water level data every five minutes was installed in the HFR near the mouth (52° 26' 39'' N 121° 25' 05'' W) by the Water Survey of Canada, Environment Canada. These data were used to obtain daily river discharge rates (m^3/s). A pressure transducer data logger (Onset Hobo - model #U20-001-04) was placed 1500 meters upstream of the HFR delta to record water level data, as well as temperature from August 2014 through October 2014 and again from April 2015 through September 2015, to document the HFR water levels (Figure 2.1).

2.3.2 Study Design

Five sites (S1, S2, S3, S4, and S5) were monitored in HFB (Figure 2.1); four of the five were placed near the mouth of the HFR (S2, S3, S4, S5), and the furthest site (S1) was located across the bay to act as a reference site. Sampling was performed twice monthly from June 1, 2014 through July 31, 2014, and twice weekly from August 1st, 2014 through November 1st, 2014 to monitor salmon pre-spawn, mid-spawn, and post-spawn activity. Sampling twice weekly recommenced on April 15th, 2015 through August 1st, 2015 to evaluate the pre-freshet, mid freshet, and post freshet flush.

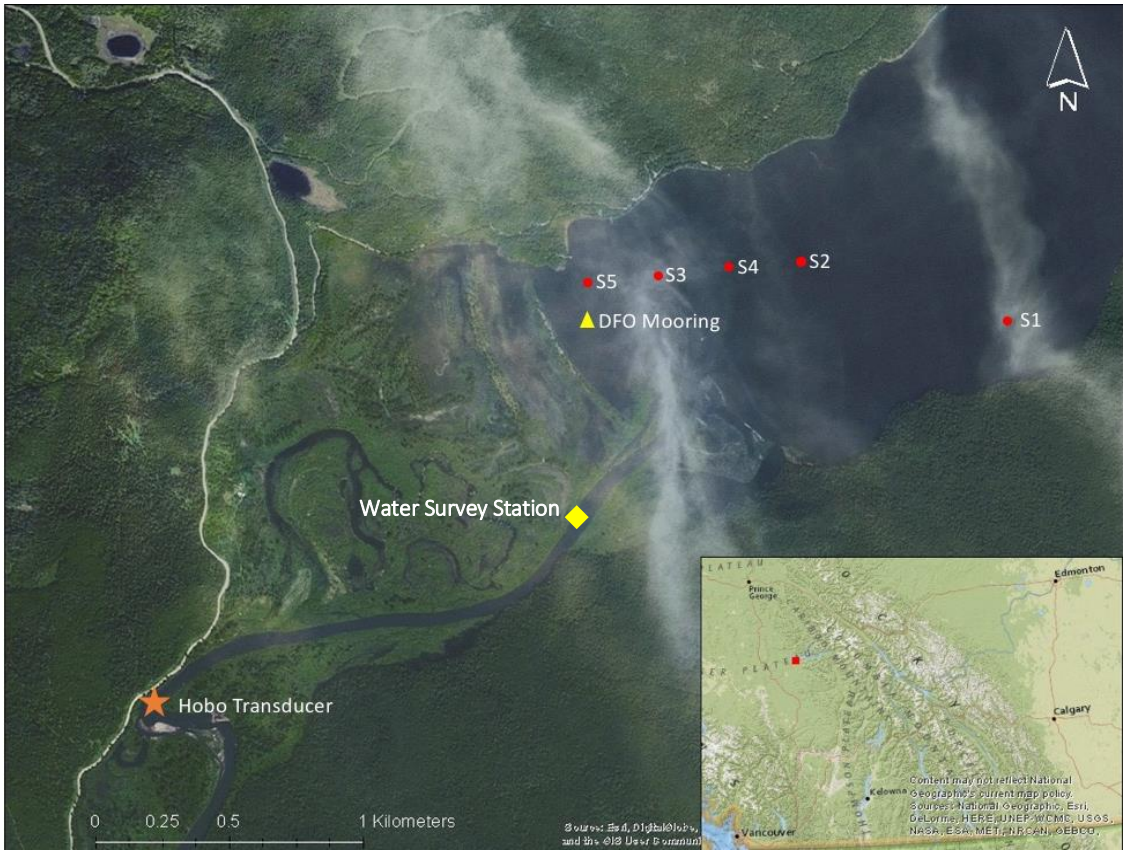


Figure 2.1: Map displaying sampling sites in HFB.

The sampling can be categorized into 3 distinct periods: 1) the spring freshet event which took place from the beginning of April through the end of 2014 & 2015; 2) the summer which took place during July and August (2014 & 2015); and 3) the fall spawn which took place from the beginning of September though the beginning of November 2014 includes both the digging of reds and the decaying of carcasses (Figure 2.2).

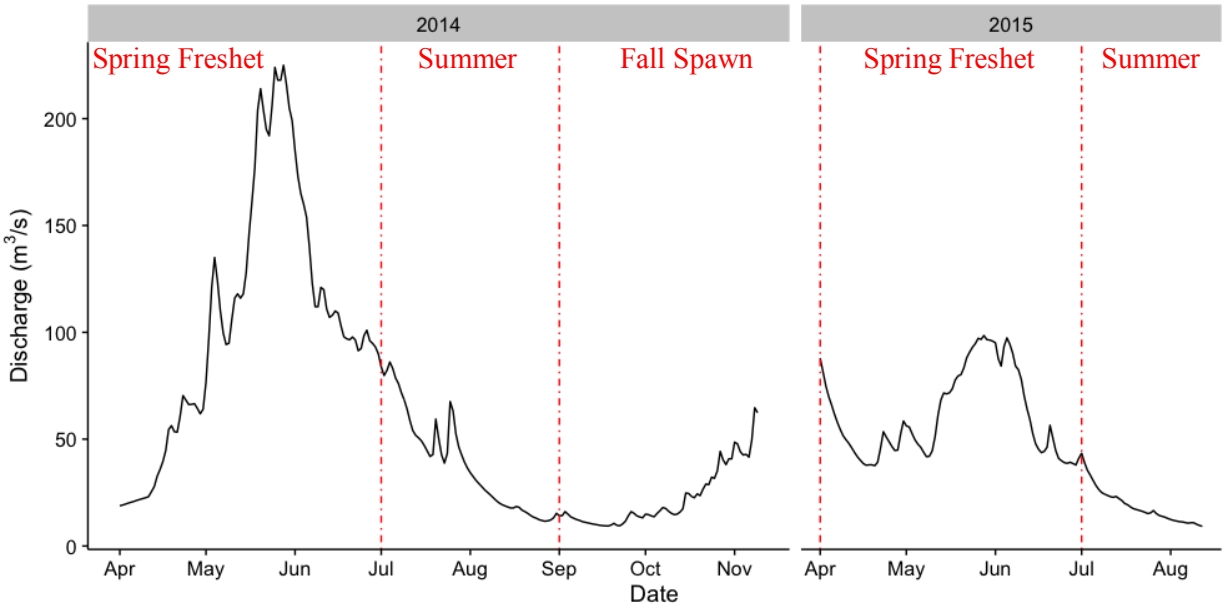


Figure 2.2: HFR hydrograph, data taken at the river delta every five minutes. Red lines designate sampling periods in 2014 and 2015 (Environment Canada).

2.3.3 Sampling Techniques (Collection & Analysis)

2.3.3.1 Isotopes

Suspended particulates used for isotopic analysis were collected from three of the five sites (S1, S3, S5) using two methods including a continuous flow centrifuge (US Centrifuge M-512) (CFC) and a high-volume filtration system (HVFS). The CFC, used between August 1st, 2014 through July 15th, 2015, uses centrifugal force to trap suspended particulates contained in water being sampled against the side of a plastic bowl which can be collected after sampling. Centrifuge times ranged from 45 minutes to 90 minutes depending on turbidity levels in the water column. The CFC was equipped with reinforced vinyl tubing and a submersible pump which was lowered to a selected depth for sampling of the water column. Sampling depth during the fall-spawn sampling period was three meters, while sampling depth during the spring-freshet sampling period was dependent on the depth of the river plume. A handheld turbidity meter (YSI: Nephelometric-Optical, 90^0 Scatter) was used to measure turbidity throughout the water column during the spring freshet to identify where the river plume was located. The submersible pump was then lowered to the depth with the highest turbidity reading. These collected CFC samples were scraped from the centrifuge bowl into 5 mL polystyrene Eppendorf tubes and stored in

storage box until arrival at the lab (~2-4 hours). Once at the lab, samples were stored at -20°C until further analysis. From July 15th, 2015 until the end of the sampling season a high-volume filtration system (HVFS) was used to collect suspended sediment. This filtration system used a submersible pump to sample water from a selected depth into a collection chamber where water was forced through a 5-micron mesh filter which trapped the suspended particles. Once the filter was clogged with suspended material, the water in the chamber and particulates attached to the filter were transferred to small buckets and left to settle for 24 hours. Supernatant was then syphoned off and the remaining material was placed into 5 mL polystyrene Eppendorf tubes and stored at -20°C.

Suspended particulate samples were put in a freeze drier and left for 48 hours and transferred into clean 50 mL polystyrene Falcon tubes. A small ball bearing was used to homogenize the samples. In between homogenizing samples, the ball bearing was washed with tap water, acetone, and deionized water to ensure the ball bearing did not transfer sample material from one tube to another. The homogenized samples then were prepared for delivery to the University of California-Davis's Isotope Lab where they were analyzed for isotope ratios of δ^{14}N- δ^{15}N and δ^{12}C- δ^{13}C.

To calculate the load of marine-derived nutrients entering HFB from the HFR, an equation was formulated (see Appendix 1) using the percent of MDNs relative to the total N in the samples collected. A δ^{15}N value is needed to complete this equation.

$$15_N\% = 100 - 100\ /(0.003676\ \left(1\ +\ \left(\frac{\delta 15_N\ ppt}{1000}\right)\right) + 1) \qquad (1)$$

$$Load\ Particulate\ 15_N = (\left(\frac{15_N\% \times Total\ N\ \mu g}{Total\ \mu g\ Sample}\right) \times \left(Suspended\ Particulate\ Matter\ \frac{\mu g}{L}\right)) \times (Flow\ Rate\ \frac{L}{S}) \qquad (2)$$

2.3.3.2 Concentration of Suspended Particulate Matter

Samples were collected to determine suspended particulate concentrations along with organic/inorganic concentrations from an influent hose that was connected to the CFC or the

HVFS. These were collected in 1.5-liter polystyrene Nalgene bottles from three sites (S1, S3, S5). Two surface grab samples were also collected at sites S2 and S4. Samples were stored at 4°C in the dark, until filtration of the samples was initiated, which generally was 1 to 3 days.

To obtain suspended sediment and organic/inorganic concentrations, a known volume of sample was filtered through a pre-ashed /pre-weighed 0.7μm Whatman glass microfiber filter (GF/F). These filters then were dried in a 60°C oven for 24 hours and then weighed to obtain total particulate mass. Filters were then placed in a muffle oven at 550°C for one hour to burn off organic matter. Filters once again were weighed to determine organic and inorganic mass. The organic particulate mass volume, $\emptyset$ (g/L^{-1}), the inorganic particulate volume density, χ (g/L^{-1}), and the total particulate mass volume ψ (g/L^{-1}) were obtained as,

$$\emptyset = (Dried\ Filter\ Weight - Ashed\ Filter\ Weight) \times \frac{1000mL/L}{mL\ Sample\ Filtered} \quad (3)$$

$$\chi = (Ashed\ Filter\ Weight - Pre\ Filter\ Weight) \times \frac{1000mL/L}{mL\ Sample\ Filtered} \quad (4)$$

and

$$\psi = (Dried\ Filter\ Weight - Pre\ Filter\ Weight) \times \frac{1000mL/L}{mL\ Sample\ Filtered} \quad (5)$$

respectively.

2.3.3.3 Chlorophyll-A

Water samples that were tested for chlorophyll-a levels were collected at a depth of three meters at four sites (S1, S2, S3, S4). Site S5 was not sampled for chlorophyll-A because of higher flows of water which would hinder phytoplankton from free floating at this site. There also would be higher concentrations of SPM at certain parts of the year which also could interfere with the amounts of chlorophyll-a analytical technique. A discrete depth water sampler (Van Dorn) was used to collect all chlorophyll-a samples and these samples were placed in 1.5-liter polystyrene Nalgene bottles. Chlorophyll-a samples were filtered through a 0.7 μm Whatman glass microfiber filter (GF/F) using a vacuum pump. After filtration took place, filters were folded, wrapped in aluminum foil, and frozen at -20°C.

To determine chlorophyll-a levels for each sample, frozen filters were unfolded, placed into 50 mL beakers, and fully submerged in a 90% acetone solution for 24 hours at -20°C in the

dark. Samples then were placed into a centrifuge and centrifuged for 15 minutes at 3000 rpm. Samples were transferred to a 1cm wavelength ultraviolet spectrometer (UV-VIS) cuvette using a micro-pipet. A Biochrom Ultraspec 2100 Pro UV-VIS was used to analyze samples at five wavelengths (750, 663, 645, 630, 664). The recorded numbers were used to calculate uncorrected values for chlorophyll-a (Equation 6). Samples were also acidified (0.1 mL of hydrochloric acid 1N) and run through a UV-VIS at wavelengths 750 and 665 approximately 90 seconds after the addition of the acid. These numbers were used to calculate the corrected pheophytin value for chlorophyll-a using Strickland and Parson's equation (1972).

$$Chla\left(\frac{\mu g}{10mL}\right) = (11.6 \times O.D._{664} - 1.31 \times O.D._{645} - 0.14 \times O.D._{630})\left(\frac{Extract\ Volume\ (mL)}{Cuvette\ Width\ (cm)}\right) \quad (6)$$

2.3.3.4 Phosphorous

Water samples were collected to analyze levels of dissolved phosphorous (DP) and total phosphorous (TP). These water samples were collected bi-weekly throughout the fall sampling season at sites S1, S3, and S5. During the spring sampling season water samples were collected weekly at sites S1 and S3 while water samples were collected twice weekly at S5. Two samples of 40 mL water for each DP and TP were collected from an influent hose that was connected to either the CFC or the HVFS. The samples for DP were filtered using a 0.45-micron filter to remove suspended particulates. Samples were frozen and kept at -20^{o}C until further analysis took place. For analysis, samples were concentrated by allowing 10 mL of well mixed, representative sub-sample to evaporate to approximately 3 mL. Digestion acids were added to top up all samples to 5 mL. An Agilent Technologies ICP-OES (model #: 5100ICPOES) was used to read levels of both DP and TP in each sample. To calculate for particulate phosphorus, DP was subtracted from TP.

2.3.3.5 Statistical Analysis

To assess differences among the parameters tested (SPM, organic/inorganic, isotope enrichment, isotope load, phosphorus) a one-way ANOVA was used assuming there was normality, equality, and independence between the samples. Although all parameters were not normally distributed when using a Shapiro-Wilks test, an ANOVA is not very sensitive to moderate deviations. Statistical studies using a variety of non-normal distributed data have shown that the

false positive rate is not affected by this assumption (Glass et al., 1972, Harwell et al., 1992, Lix et al., 1996). If significant differences were found through the one-way ANOVA, a Tukey's Honest significance difference (HSD) test was used to determine differences among sample periods. A two-way ANOVA was used to assess chlorophyll levels using sample site and study period as fixed effects. A post hoc test, Tukey's HSD, was used to find where the significant differences lie in this two-way ANOVA.

A stable isotope mixing model written in R (version 3.2.2), SIMMR (Parnell, 2016), which is an upgrade to the stable isotope analyzes (SIAR) program in R, was used to determine what proportions of samples collected were made up of which source material (salmon, terrestrial vegetation, aquatic vegetation). This package solves mixing models within a Bayesian framework. Other sources such as plankton were collected to be source material. However, since samples collected for isotope data were only used from site S5, where the flow would be too fast for plankton to stay suspended, only salmon, terrestrial vegetation, and aquatic vegetation were used. Boxplots showing proportions of sources materials in samples in each study period, and a boxplot of the proportion of salmon through the three study periods was also created within this package.

Multiple linear models were created and selected with akaike information criterion (AIC) to try to determine what river characteristics were driving the delivery of delta ^{15}N values and the load of MDNs (Table 2.2). With the delta ^{15}N values as the variable of interest; river temperature, SPM concentrations, phosphorous concentrations, discharge data, and study period variables were included in the first linear model created to be tested by an AIC (1). This linear model tested all and only first order terms. The second linear model (2) tested SPM concentrations, discharge data, and study period parameters. Phosphorus concentrations and river temperature were left out as they were not significant in the first linear model and logically should have little effect on when MDNs were delivered to HFB. The third linear model (3) tested all first and second order terms, which were included in the second linear model. The fourth linear model (4) tested interactions of all first order and second order terms that were significant in the summary output for the third linear model.

This same method and creation of linear models (1, 2, 3, 4) was applied to the second variable of interest, the load of MDNs, to create linear models (5, 6, 7, 8). Once again, all variables were used for the fifth linear model tested as the sixth, seventh, and eighth linear models included only SPM concentrations, discharge data, and study period data, as phosphorous and river temperatures were non-significant in the fifth linear model and shouldn't impact when the load of MDNs is delivered to HFB.

Table 2.2: Linear models created and selected by AIC to test which parameters drive the delivery of $\delta\ ^{15}N$ levels and the load of ^{15}N to HFB.

Model

Interest Variable	Variable Selection	Model #
$\delta\ ^{15}N$ Levels	Flow + River Temp + SPM + TP + Study Period	1
	Flow + SPM + Study Period	2
	$Flow^2 + SPM^2 + Study\ Period^2$	3
	Flow x SPM + Flow x Study Period + SPM x Study Period	4
Load of ^{15}N	Flow + River Temp + SPM + TP + Study Period	5
	Flow + SPM + Study Period	6
	$Flow^2 + SPM^2 + Study\ Period^2$	7
	Flow x SPM + Flow x Study Period + SPM x Study Period	8

2.4 Results

2.4.1 Suspended Particulate Characteristics

2.4.1.1 Total Particulate

The timing of suspended particulate matter (SPM) entering HFB from the HFR both in 2014 and 2015 reflects historical observations in that with higher flow comes higher

concentrations of SPM (McConnachie & Petticrew, 2006). There appears to be a correlation between discharge and SPM data shown in Figure 2.3. Kendall's correlation equation was used to check this relationship, yielding a correlation coefficient of 0.68.

Concentrations of SPM rise at the end of April and beginning of May 2015 to the highest recorded concentration of SPM, 12.5 mg/L, on May 28, 2015. Concentrations then decrease and remain between 5-10 mg/L until mid-July when concentrations drop to below 2 mg/L which coincides with decreasing flow rates. In late September and early October of 2014, there is a gradual increase in SPM concentrations during that year's salmon spawning event.

It was found that there was a significant difference ($p<0.000$) in-between study periods and a post-hoc test, Tukey HSD, revealed that SPM concentrations were significantly lower during the summer ($p<0.000$) and salmon spawn ($p<0.000$) periods than during the spring freshet. However, there was no significant difference in SPM concentrations between the summer and the salmon spawn with a p-value of 0.78.

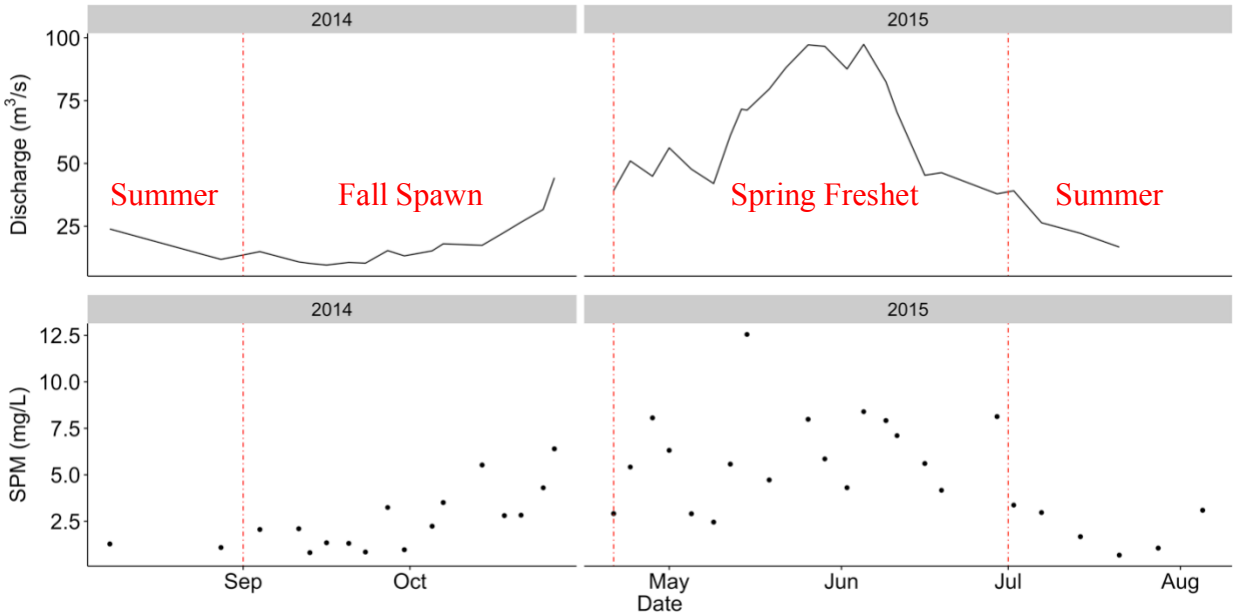


Figure 2.3: Suspended particulate matter concentrations and discharge over time at site S5. Vertical lines denote the three study periods.

2.4.1.2 Organic vs. Inorganic Particulates

The dispersal of organic and inorganic suspended particulates is greatly influenced by flow rates. Organic suspended particulate (OSP) concentrations stay below 1 mg/L in the summer study period (Figure 2.4). During the salmon spawn and die-off, there is an increase in the amount

of OSP, which more than doubles to 2.3 mg/L at the end of October 2014, but for most of this period the concentration remains more consistent around 1 mg/L. However, the spring freshet period has elevated concentrations of OSP with a mean of 1.45 mg/L, but with peaks above 2.1 mg/L and 2.2 mg/L in May and June, respectively. Also, at the end of June 2015 the concentration increases to a high of 4.3 mg/L.

When analyzing OSP concentrations, a 1-way Anova was used and a p value of <0.000 was found, which suggests that there is a significant difference in the concentrations of OSP over the three study periods. A post-hoc test, Tukey's HSD, showed that OSP concentrations were significantly lower during the summer ($p<0.000$) and salmon spawn ($p<0.01$) periods than during the spring freshet. However, there was no significant difference between the summer and salmon spawn ($p<0.23$).

Inorganic particulate concentrations (ISP) were found to have a significant difference ($p<0.000$) over the three study periods. A post-hoc test, Tukey's HSD, revealed that ISP concentrations were significantly lower during the summer ($p<0.000$) and salmon spawn ($p<0.000$) periods than during the spring freshet. However, there was no significant difference in ISP concentrations between the summer and salmon spawn periods with a p-value of 0.58.

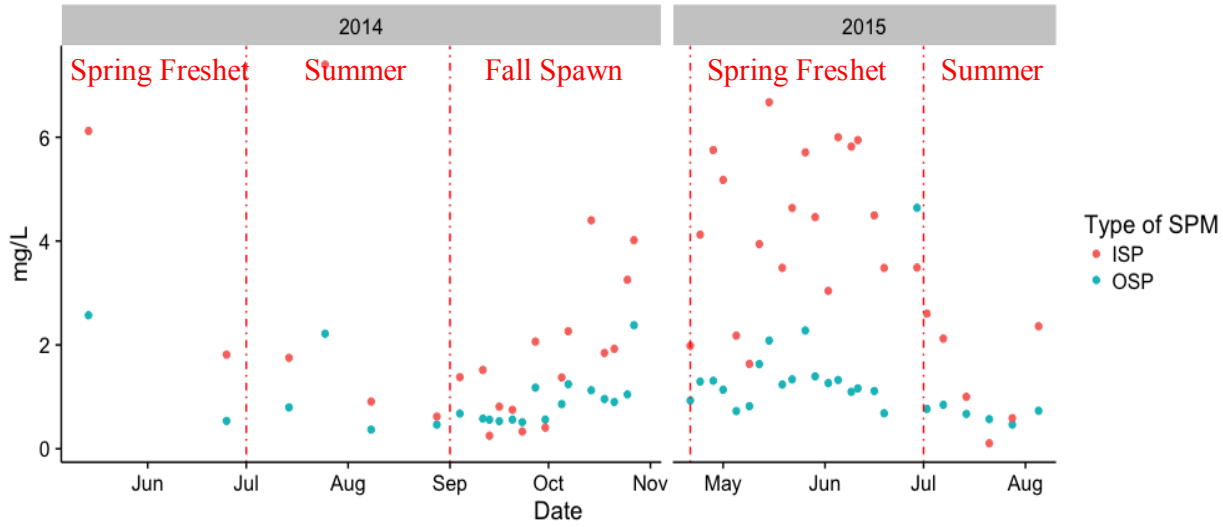


Figure 2.4: Organic and inorganic suspended particulate matter concentrations covering the three study periods at site S5.

2.4.1.3 Stable Isotopes: Nitrogen and Carbon (Enrichment)

In Figure 2.5, the delta values of $\delta^{15}N$ show a steady increase starting in early September 2014 and continued to rise until the end of that study period in middle to late October 2014. The delta values of $\delta^{13}C$ show the same increasing trend but starts later in the spawning study period. Its lowest delta values occur mid-September right as salmon begin to spawn; however, it then increases in late September and continues through the end of the study period in middle to late October 2014. Both $\delta^{15}N$ and $\delta^{13}C$ values start to drop at the beginning of November 2014. Conversely, $\delta^{15}N$ values during the spring freshet and summer stay consistent at approximately 2 ppt, which is considerably less than values observed during the fall salmon spawning period. $\delta^{13}C$ during the spring freshet and summer stays consistent between -26 ppt and -28 ppt.

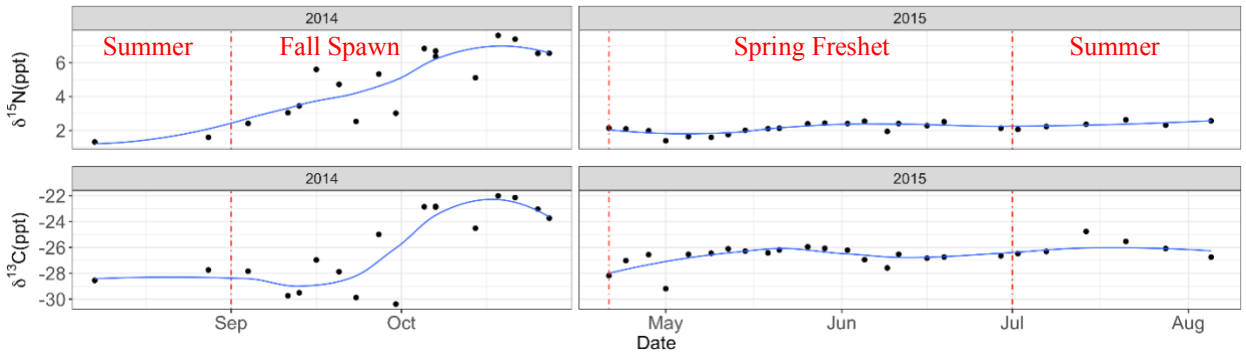


Figure 2.5: The concentration of $\delta^{15}N$ and $\delta^{13}C$ in SPM over three study periods collected at site S5. Method used to create blue lines was LOESS.

The delta values associated with nitrogen were analyzed using a one-way ANOVA in which a p-value of 6.08e-11 was found. This number shows that there was a significant difference in delta values between study periods. A post-hoc test (Tukey's HSD) found that nitrogen delta values were significantly lower during the summer ($p<0.000$) and spring freshet ($p<0.000$) periods than the salmon fall spawn. However, there was no significant difference in nitrogen delta values between the summer and spring freshet with a p-value of 0.99. The delta values associated with carbon between study periods were also analyzed using a one-way ANOVA; however, the p-value (0.125) indicates that there was no significant difference between periods.

2.4.1.4 Stable Isotopes: Nitrogen and Carbon (Mixing Model)

The three source materials (aquatic vegetation, terrestrial vegetation, and salmon) are shown in Figure 2.6 along with the isotopic values for the SPM collected seasonally. The results

show that the summer and freshet SPM samples were more heavily composed of aquatic vegetation and terrestrial vegetation than of salmon. However, fall spawn SPM samples show a trend of increasing $\delta^{15}N$ values which exceed the $\delta^{15}N$ values of both types of vegetation, indicating that they contained more source material from salmon than the other two sampling periods. These findings support section 2.4.1.3. Summer and freshet SPM also are composed of more terrestrial vegetation than aquatic vegetation. However, this evens out during the salmon spawn period.

Focusing on the spring freshet (Figure 2.7), source material that was contained in the SPM samples from salmon were low at approximately four percent, while source material that was contained in the SPM samples from aquatic and terrestrial vegetation were approximately 37% and 59% respectively. The summer period (Figure 2.7) shows similar results to what was found during the spring freshet period. SPM samples collected during this study period were composed of approximately 4% salmon, 37% aquatic vegetation, and 59% terrestrial vegetation. Although, these percentages are the same as the spring freshet period, the inter-

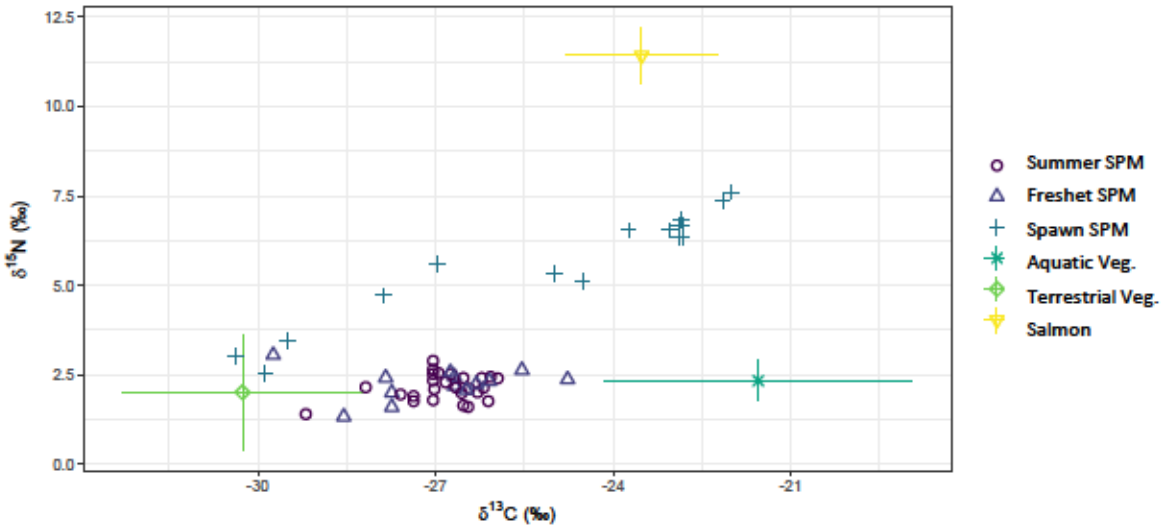


Figure 2.6: SIMMR mixing model, showing the $\delta^{15}N$ $\delta^{13}C$ values of SPM samples collected throughout the freshet, summer, and spawning sample periods at site S5.

quartile range is smaller during the spring freshet than during the summer sampling period. The salmon spawning event shows the highest proportion of salmon during the three sampling periods, with a percentage around 37 (Figure 2.7). This sampling period also shows that SPM

samples were composed of more salmon material than aquatic (~32%) or terrestrial vegetation (~31). The proportion of terrestrial vegetation in the SPM samples dropped from approximately 59% to 31% during the salmon spawn. Comparing the three study periods, the SPM samples collected are significantly comprised of more salmon during the salmon spawn period than the other two study periods. SPM samples were made up of approximately 40% salmon source during the salmon spawn, 3% during the summer, and 4% during the spring freshet.

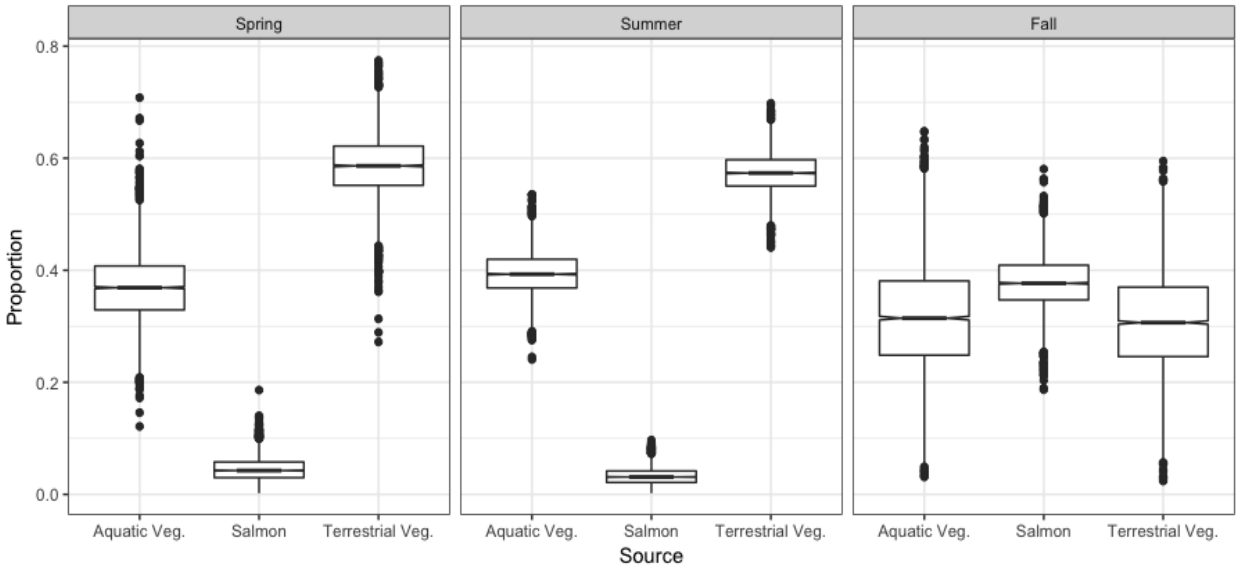


Figure 2.7: Proportion of three sources (aquatic vegetation, terrestrial vegetation, and salmon) found in SPM samples taken from site S5 during the spring freshet, summer, and fall spawn. The line in the middle of the boxes for each source signifies the median point of the data. Boxes above and below the median line represent the upper and lower quartile. At the end of the solid vertical lines are the highest and lowest data values excluding outliers which are the black dots in this plot.

2.4.1.4 Stable Isotopes: Nitrogen and Carbon (Specific Load)

The specific load of marine-derived nitrogen (^{15}N) (mg/s) is much higher during the month of May 2015 through the middle of June with the highest amount of ^{15}N collected, 8.8 mg/s, on May 15, 2015 (Figure 2.8(C)). During July 2014, the specific load of ^{15}N drops and stays below 2.5 mg/s until a slight rise to approximately 3.75 mg/s at the end of the fall spawn study period.

The specific load of ^{15}N was found to be significantly different ($p<0.0001$) over the three study periods. A post-hoc test, Tukey's HSD, revealed that ^{15}N loads were significantly lower during the summer ($p<0.001$) and salmon spawn ($p<0.001$) periods than during the spring freshet. However, there was no significant observed difference in ^{15}N loading between the

summer and salmon spawn periods with a p-value of 0.78. When observing Figures 2.3 and 2.8 (C), the specific loading of ^{15}N appears to be dependent on the flow rate of the HFR, as flow

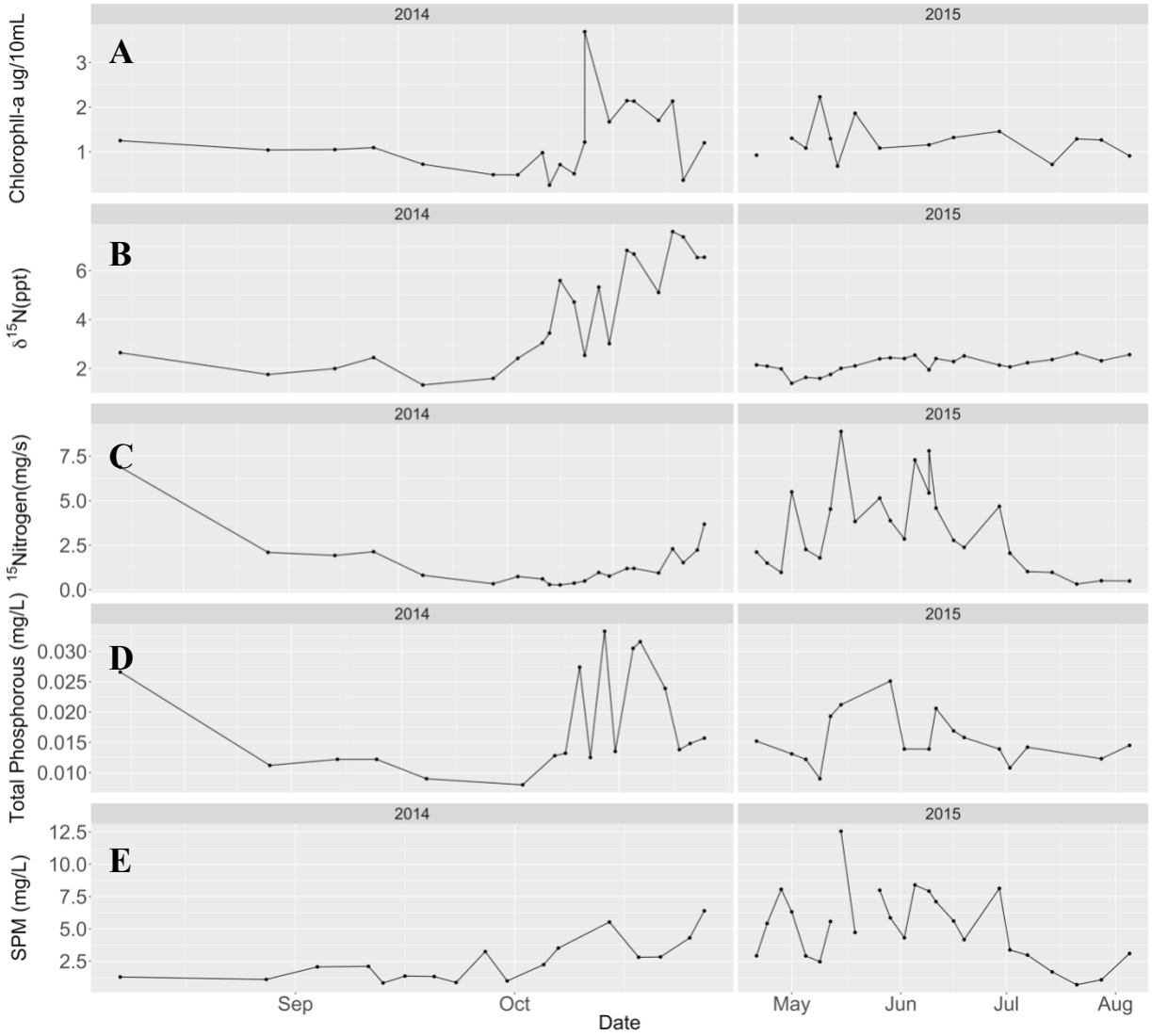


Figure 2.8: Chlorophyll-a, delta ^{15}N, ^{15}N loading, TP, and SPM data levels collected in HFB over the three study periods. All data used in this plot, except chlorophyll-a, was collected from site S5. Chlorophyll-a data used was collected from S1.

peaks during the spring freshet and falls during the summer, as do the amount of ^{15}N loads. The discharge of the HFR greatly affects the load of ^{15}N, as concentrations of marine-derived N and δ ^{15}N values are highest in the fall spawn when flows are low; however, the load of marine-derived N is highest in the spring freshet when discharge is high.

2.4.2 Water Analysis

2.4.2.1 Chlorophyll-a & Fluorescence

Figure 2.9, illustrates the changes in chlorophyll-a levels throughout the three study periods. Chlorophyll-a increases at the beginning of August 2014 at sites S2, S3, and S4 but decreases at site S1. All four sites however see a further increase in chlorophyll-a by the middle of October. Considering 2015, there is an increase in chlorophyll-a at sites S1 and S3 but a decrease at sites S2 and S4. Three sites (S2, S3, S4) also see an increase in chlorophyll-a during the middle of June, however, all sites see a drop in the beginning of July.

The interaction between the variables study period and study site was not significant for chlorophyll-a through the three study periods (Table 2.3). There also was no significant difference among study sites. However, there was a significant difference between study periods when assessing chlorophyll-a levels (p-value 0.004). Using a post hoc test, Tukey's HSD,

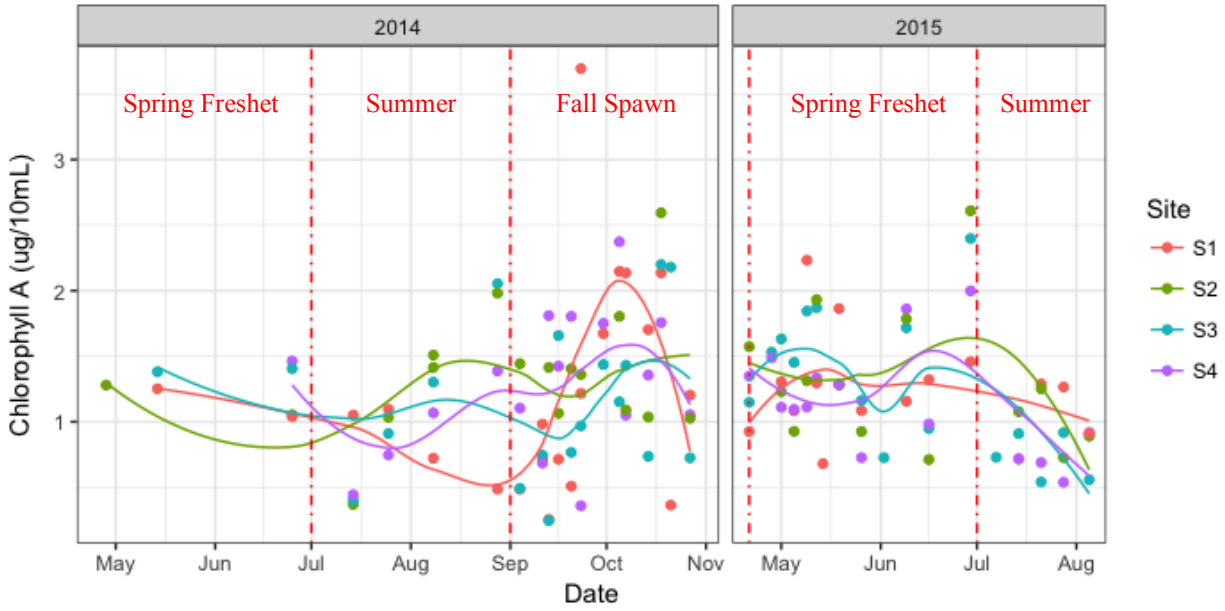


Figure 2.9: Chlorophyll-A levels at four sites throughout HFB over the three study periods. Lines were created using LOESS.

it was found that there was a significant difference between the summer and the spring freshet (p-value 0.025) periods as well as significant differences between summer and fall spawn periods (p-value 0.005). However, there was no significant difference found between the fall spawn and the spring freshet (p-value 0.85).

Fluorescence levels peak in both the 2014 fall spawn and 2015 spring freshet at sites S1, S3, and S5 (Figure 2.10). The biggest peaks at S1 and S3 occur in the 2014 fall spawn while the highest peak at S5 occurs during the 2015 spring freshet. During both summer periods, fluorescence shows to be consistent between 0.5-1 RFU. There were significant differences at site S5 (p-value 0.00736) when comparing study periods.

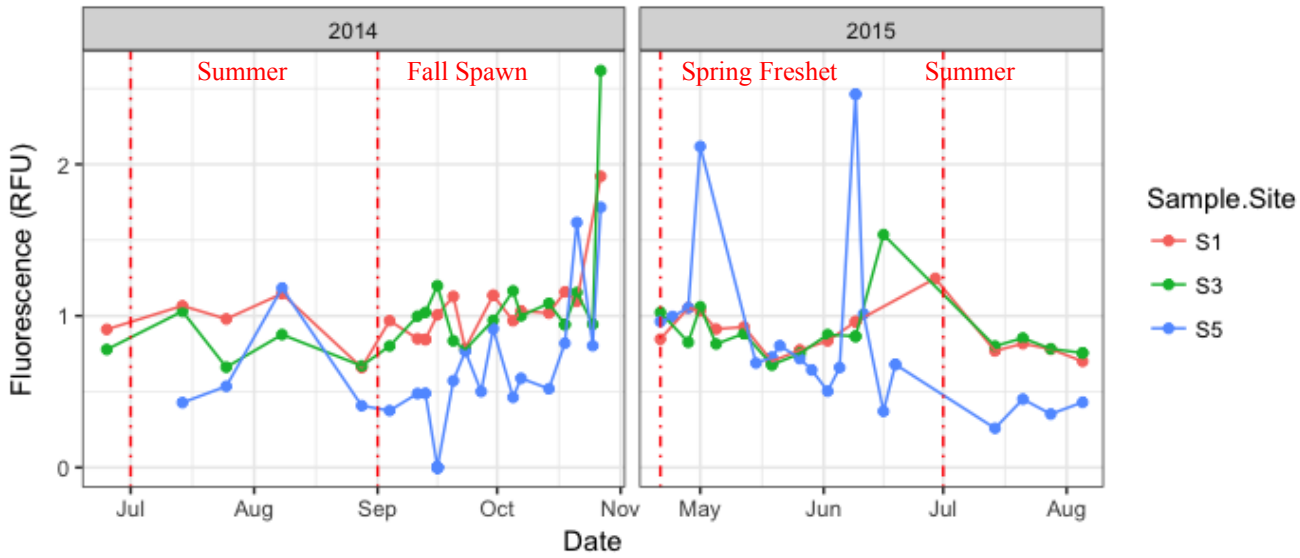


Figure 2.10: Fluorescence levels at three sites throughout HFB over the three study periods.

2.4.2.2 Phosphorus

At the start of the first study period in May 2014, total phosphorus levels were up to 0.026 mg/L while dissolved phosphorus levels were approximately half that value at 0.014 mg/L (Figure 2.11). Both total and dissolved phosphorus concentrations drop to approximately equal values (shown by the trend line) in the middle of July, begin to increase in the beginning of September, and peak at the beginning of October, with TP reaching 0.034 mg/L. After this peak both forms of phosphorus decrease and continue to decease throughout the rest of the sampling period. In 2015, there is a slight increase in dissolved phosphorus throughout the spring freshet, followed by a decrease as the summer period begins. Total phosphorus also increases during the spring freshet but has a much steeper rise at the end of May. When comparing phosphorus between the dissolved and particulate form, the data shows that throughout all study periods dissolved phosphorus was in higher concentrations than particulate bound phosphorus except on three

sampling dates: May 14, 2014, April 21, 2014, and June 29, 2015.

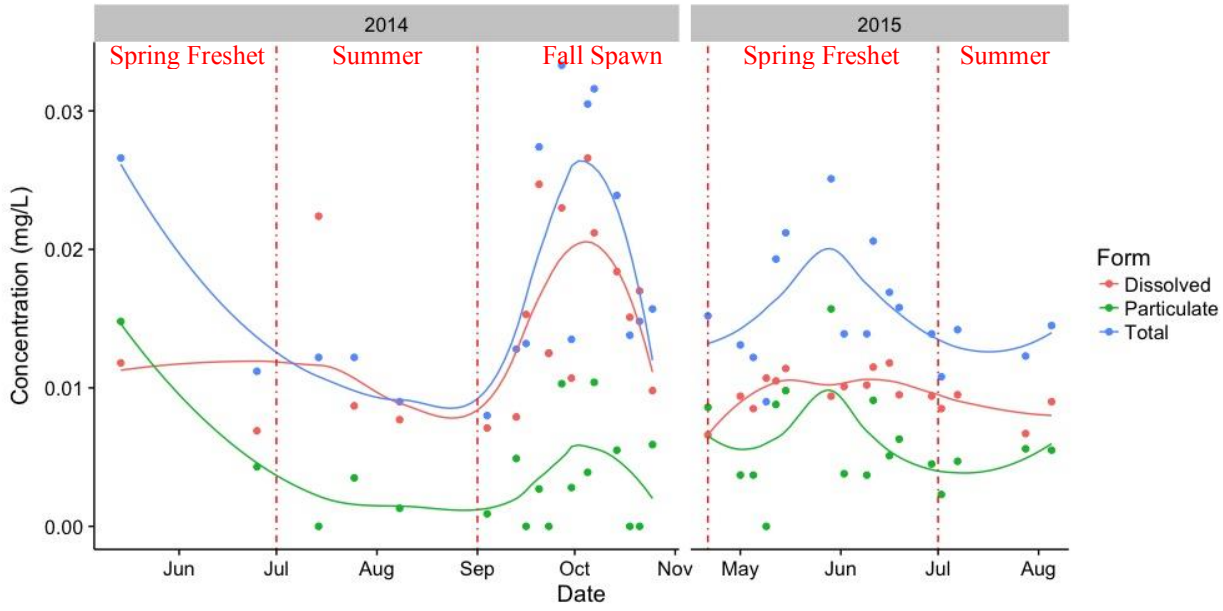


Figure 2.11: Phosphorus levels in three forms (dissolved, particulate, total) at site S5 over the three study periods. Trend lines were made using LOESS.

The interaction between study period and phosphorus form was not significant through the three study periods (Table 2.3). However, both study period and form were significant on their own. A post hoc, Tukey's HSD, test showed that there was a significant difference between the fall spawn and spring freshet (p-value 0.002) and the summer (p-value 0.0008). There was, however, no significant difference in phosphorus levels between the summer and spring freshet periods (p-value 0.789). There was a significant difference between the total form of phosphorus and the dissolved form with a p-value of 8.36e-05.

2.4.2.3 Comparison of Variables / Linear Models

In Figure 2.8, five characteristics of HFB were plotted above one another to visually assess trends over the two sampling years. Except for the specific load of ^{15}N, Chlorophyll-a, delta ^{15}N, TP, and SPM all increase and peak at the beginning of October 2014. During April, May, and June of the 2015 sampling season, there is a similar visual trend in SPM, load of ^{15}N, and TP with the highest peaks during that study period.

Table 2.3: Results from a two-way ANOVA of spatial (study site) and temporal (study period) for chlorophyll-a levels in HFB, from a one-way ANOVA of temporal (study period) for phosphorus levels and forms in HFB, and a one-way ANOVA of temporal (study period) for fluorescence levels at site S1, S3, and S5 in HFB. The phosphorus form interaction term includes dissolved and total phosphorus.

Chlorophyll-a

Source of Variance	DF	Sum Sq.	Mean Sq.	Pr(>F)
Study Period	2	4.09	2.0467	.00465
Study Site	3	1.04	0.3471	0.41973
Study Period X Study Site	6	3.34	0.5571	0.17580
Residuals	138	50.56	0.3664	

Phosphorous

Source of Variance	DF	Sum Sq.	Mean Sq.	Pr(>F)
Study Period	2	0.0004713	0.0002357	0.000318
Form	1	0.0004557	0.0004557	8.14e-05
Study Period X Form	2	0.0000214	0.0000214	0.450113

Fluorescence	Source of Variance	DF	Sum Sq.	Mean Sq.	Pr(>F)
S1	Study Period	2	0.2666	0.13331	0.0632
	Residuals	34	1.5120	0.04447	
S3	Study Period	2	0.595	0.29741	0.0558
	Residuals	36	3.420	0.09499	
S5	Study Period	2	3.108	1.5541	0.00736
	Residuals	45	12.741	0.2831	

Using an AIC, linear models were tested to determine which linear model best predicted higher delta ^{15}N values. It was found that the model with the lowest AIC value was the linear model (Model 1) that looked at only first order terms (Table 2.4). Table 2.5, shows a summary of the linear model that had the lowest AIC value and suggests that the study period factor plays the most important role in finding what drives higher delta ^{15}N levels with a P-value of 0.0009. Linear models were also used to determine the factors that drive the load of MDNs in HFB (Table

2.4). However, three models that were tested produced AIC values that were within two AIC units. Summaries of these models also revealed little interaction between factors.

Table 2.4: Statistics results performed by an AIC on which parameters drive the delivery of $\delta^{15}N$ levels and the load of ^{15}N to HFB.

Interest Variable	Model #	K- # Parameters	AIC	R^2
$\delta\ ^{15}N$ Levels	1	6	57.99872	0.8473
	2	4	71.75135	0.7785
	3	4	77.09301	0.7851
	4	4	77.09301	0.7851
Load of ^{15}N	5	6	10.95368	0.7804
	6	4	6.34016	0.7343
	7	4	7.08423	0.7907
	8	4	7.08423	0.7907

Table 2.5: Results from a linear model function showing interactions between factors and $\delta^{15}N$ values in HFB.

Source of Variance	Std. Error	P Value
Flow	0.02014	0.426639
River Temperature	0.07609	0.859301
Suspended Particulate Matter	0.18102	0.512272
Total Phosphorus	67.03843	0.314964
Study Period	0.52869	0.000922

2.5 Discussion

The productivity of an aquatic system is influenced by nutrient availability and quantity as well as the hydrological and physical characteristics of the system (Bilby et al., 1996; Larkin & Slaney, 1997; McConnachie & Petticrew, 2006). All samples that were analyzed for MDNs were collected from the HFR's plume to ensure the ability to compare three distinct study periods and to understand the transport of sediment-associated MDNs to a nursery lake system in HFB. The spatial abundance and delivery patterns of MDNs from the HFR to HFB were mostly impacted by the presence, disturbance, and decay of spawning salmon (salmon disturbance regime; Albers, 2010) and the HFR's discharge. These two processes dominate the productivity of HFB and the timing of when MDNs are available to the biota in the bay. This conclusion is supported by increasing trends that are shown in chlorophyll-a, isotope enrichment / load, phosphorus levels, OSP, ISP, and SPM during the spring freshet and fall spawn study periods. Although some results (chlorophyll-a, SPM, OSP, ISP) were consistent with previous studies (McConnachie & Petticrew, 2006; Hume et al., 2005), there were other parameters (phosphorus, chlorophyll-a) that were not (Hume et al., 2005). These differences could be due to Quesnel Lake's unique structure being one of the deepest and largest lakes in North America and therefore system-specific.

To assess the timing of MDNs delivery to HFB, the present research was split into three study periods (spring freshet, summer, and fall spawn). The spring freshet study period was meant to capture the early spring flush of snow melt at low elevation and the later high elevation melt. The channel scouring flows can deliver material stored over winter and determining how these conditions affected the source and amount of nutrients entering HFB was an objective of this research. The summer study period was intended to determine the amount and source of nutrients entering the bay during low flow periods before the salmon arrived to spawn. The fall spawn study period was designed to evaluate the movement of nutrients into the nursery system while salmon were present in their natal stream, creating redds, spawning, and subsequently decomposing. The spring freshet was characterized by higher flow volumes, higher SPM/ISP concentrations, high ^{15}N load, higher chlorophyll-a levels, and higher phosphorus levels. The summer was shown to have the lowest flows which coincided with lower values of phosphorous, chlorophyll-a, SPM, and ^{15}N load. The fall spawn exhibited higher SPM concentrations, high

isotope enrichment of ^{15}N and ^{13}C, a higher proportion of salmon particulate, and high chlorophyll-a / phosphorus levels.

2.5.1 Suspended Particulate Characteristics / Load

The high flows that accompany the spring freshet are well documented as increasing SPM concentrations and for flushing inorganic and organic material to downstream lake systems (Owens, 2005; McConnachie & Petticrew, 2006). The present study supports these findings. During the summer and fall spawning periods, the HFR's flow ranged between five and forty-eight cubic meters per second and concentrations of SPM ranged from 1 to 6 milligrams per liter (Figure 2.3). As the flow increased during the spring freshet, from forty to ninety-five cubic meters per second, particles that had been stored in the river bed and banks were re-suspended and flushed down stream creating SPM concentrations between 2.5 and 12.5 milligrams per liter. Highest concentrations were recorded during peak flow and then started to decline as the river flow rate plateaued and subsequently decreased. The flow reached and maintained its peak rate from the middle of June through the beginning of July; however, there was an observed drop in SPM concentration during this plateau period. Although, the flow plateaued and remained relatively high, it is presumed that the supply of available SPM would have been flushed by the flows in the rising limb of the hydrograph such that the material had already been transferred down river, leaving heavier particulate, too heavy to erode, behind in the river bed and banks. The data shown in Figure 2.3 also show a strong relationship between the concentration of SPM and the river's discharge rate with a Kendall's correlation of 0.68. This suggests that there is a relationship between flow and SPM concentration; however, there is some discrepancy between peaks which could be due to sediment/nutrient source exhaustion.

The trend in ISP is consistent with what was observed in the SPM concentrations (Figure 2.4). ISP concentrations were around one milligram per liter at the beginning of first sampling period in 2014. This concentration rose as salmon started arriving and began constructing redds in the HFR, and peaked in middle to late October which coincided with fall storms and an increase in river discharge (Figure 2.2). The observed OSP mirrors this trend, but on a smaller scale. ISP and OSP started the spring freshet 2015 sampling period at around 6.8 milligrams per liter and 1.3 milligrams per liter respectively. The OSP concentrations were as high in the spring freshet as

they were during the fall spawning period. This suggests that salmon organic material could have been bound to inorganic particles creating flocs (Petticrew & Rex, 2008) that entered HFB in the fall increasing OSP concentrations. On the other hand, the observed increased OSP concentrations in the spring could be a result of higher river discharge flushing and overbank flows contributing riparian vegetation into HFB as evidenced by the results of the mixing model.

The use of ^{15}N and ^{13}C isotopes to trace MDNs elucidates food web processes at the aquatic and terrestrial levels (Rinella, 2010). This method was also used in this research to determine the enrichment levels of SPM and the amount of MDNs that entered HFB. In Figure 2.5, the delta values of marine-derived nitrogen (^{15}N) and carbon (^{13}C) are approximately 1 parts per thousand and -28.5 parts per thousand respectively at the mouth of the HFR. The delta values of ^{15}N and ^{13}C stay relatively consistent until the salmon spawning event when delta levels increase through the end of the study period. This increase could only be contributed to arrival of the salmon as ^{15}N signals are marine-derived. At the start of the 2015 spring freshet, the delta values of ^{15}N and ^{13}C are approximately 2 parts per thousand and -27 parts per thousand. These levels are consistent through the spring freshet and summer. These findings suggest that SPM that is enriched in ^{15}N and ^{13}C is delivered to HFB only during the fall salmon spawn and may not be available to be re-suspended during the following spring freshet. However, due to climate change, British Columbian winters are becoming warmer and causing melts to happen earlier in the year (Schnorbus et al., 2012). In 2015, there was a significant low-elevation snowmelt event during the middle of January that may have caused MDNs to be re-suspended in the HFR and flushed downstream into HFB (Figure 2.2). No data were collected at this time due to lack of access and therefore there is no way to confirm if MDNs were delivered into HFB at this time. The MDNs that may have been flushed with this abnormal snowmelt in January would otherwise have been flushed with the spring melt at the end of April. Therefore, the idea that the highest enrichment levels of ^{15}N and ^{13}C only happen during the fall salmon spawn cannot be assumed until this can be tested in future years.

Although, delta values of ^{15}N were highest during the fall spawn event, the load of ^{15}N was significantly higher during the spring freshet. This result was heavily influenced by the discharge rate of the HFR as the average flow of water was 30 cubic meters per second during

the fall spawn and tripled to approximately 90 cubic meters per second during the spring freshet. Consequently, SPM coming into HFB during the fall spawn contains a greater concentration of MDNs which could allow easier uptake of these nutrients as flow levels are low and plankton are able to stay suspended in these nutrient rich waters. However, a larger load of MDNs is delivered to HFB during the spring freshet but is more diluted with other suspended particulates. During this time, the water discharge rate is high, possibly making it difficult for plankton to take up these nutrients in HFB as it is more difficult for these organisms to stay suspended in faster-moving waters. These nutrients would eventually spread out or settle out of the faster moving waters for uptake, delivering MDN to surface waters outside of the plume and/or deeper depths farther out into Quesnel Lake.

Neil (2006) found that phosphorous levels were higher in HFB than levels in Quesnel Lake outside of HFB throughout the year. As the HFR empties into Quesnel Lake at HFB, these levels of phosphorus can be directly attributed to the HFR. Although, it cannot be directly related to the presence of salmon, this delivery of phosphorous is still important. His research also suggests that the spring melt produces the highest concentration of TP and the fall spawn produces the least. The findings in this research contradict Neil's, as TP concentration was highest during the fall spawning event. This could be due to differences in sampling site, as Neil sampled out in the middle of HFB and this research was conducted at the mouth of the HFR. However, the increase in phosphorous during the fall is associated with the arrival of salmon, as the increase of TP occurs when discharge is at low flow.

Most phosphorus input to HFB was in dissolved form occurring during the fall. Particulate phosphorus, like the dissolved form, also had a smaller peak during the spring freshet, suggesting that particulate phosphorus was stored in the HFR during winter months. Only four samples collected throughout the study exhibited more particulate than dissolved P. Three of these samples were collected during the spring freshet and Figure 2.11 shows dissolved and particulate phosphorus levels are much closer during this study period. This is likely due to the ability to bind to a higher concentration of suspended particulates as the increased discharge from the HFR contains more suspended particulates. Given that dissolved phosphorus is more readily available for uptake by primary producers than particulate bound phosphorus (Bricker et al., 2007),

biological uptake of this nutrient in HFB is enhanced during the fall spawn event when the higher proportion of phosphorus is in the dissolved form.

2.5.2 Isotope Mixing Model

The SIMMR mixing model in R used three source materials to represent the dominant supply of isotopic C and N in the system. Salmon were chosen because the nutrients they contribute to this nursery system are the focus of this research. Terrestrial vegetation and aquatic vegetation were also chosen as they are at the base of the food web and are composed of different levels of ^{13}C which allows the model to differentiate sample sources more efficiently. Plankton, from the open water areas of the bay were also collected and would be a good source material for a model in HFB. However, as the SPM mixturesamples were collected at site S5, which is situated at the mouth of the HFR, the open water algal source materials were not used in this model. The current speeds varied significantly at S5, where the sampling focused on river effluent such that pelagic plankton would not be represented in these samples. It would also be difficult to characterize the river plankton from these samples for use as a potential source material as the separation of plankton and suspended sediment would be difficult.

Figure 2.6 shows that SPM collected during the summer and spring freshet were dominantly comprised of aquatic and terrestrial vegetation with the majority being of terrestrial origin. The fall spawn period SPM had an increased level of ^{15}N, signifying that it is made up of more salmon source than during the other two periods. This supports the previous assumption (Section 2.51), that MDNs were entering HFB in a higher concentration during the fall spawning event than in the other two study periods. In Figure 2.7, the median terrestrial vegetation contribution is 58% of the SPM samples, and aquatic vegetation and salmon contribute 38% and 4% respectively. During the spring freshet study period, flow rates and water levels were at their highest, scouring river banks and flushing large amounts of detrital riparian vegetation from both the floodplain and gravel bed storage down river. Terrestrial plant detritus was also the dominant source in the summer period suggesting that the supply continued, it is not clear where it was coming from but it exceeded aquatic vegetation by approximately 15%. During the fall spawning event, salmon were the main contributors to the makeup of SPM contributing approximately 37% while terrestrial and aquatic vegetation contributed 31% and 32%

respectively (Figure 2.7). The various instream processes associated with the spawn are the key contributors to this change of SPM make up. With their construction of redds, the salmon are disturbing the gravel beds and removing biofilms on the surface rocks which is reflected in the increase in the proportion of aquatic plant signal in the fall spawn SPM samples. SPM samples that were collected in the fall spawn are also made up of approximately nine times as much salmon material as they were in spring freshet and summer sampling periods. This result supports the hypothesis that most salmon-derived ^{15}N (MDNs) is being delivered to HFB during the fall spawn sampling period.

2.5.3 Chlorophyll-a Concentrations & Fluorescence

Chlorophyll-a is used widely in ecological studies to show productivity levels in aquatic systems throughout the Pacific Northwest (Hume et al., 2005; Schindler et al., 2005). Most studies aim to understand the effect MDNs have on productivity and most conclude the nursery lake's productivity levels are reliant on spawner numbers (Uchiyama et al., 2008; Larkin & Slaney, 1997). Chlorophyll-a levels throughout the three study periods varied significantly by study season within HFB (p-value<0.0047), but statistical analysis showed no significant differences among sites (p-value<0.42). Claeson et al. (2011) found there to be higher chlorophyll-a levels in salmon bearing systems than in non-salmon bearing systems during the fall spawn. Findings from this study support this research, as peaks of chlorophyll-a are present across all sites during the fall spawn, which could be directly attributed to the higher concentrations of MDNs and phosphorus that were being delivered into HFB (Figures 2.9). This implies that MDNs entering HFB during the fall spawn directly increased phytoplankton populations throughout the bay. Smaller peaks of chlorophyll-a were found throughout the spring freshet period, which again could be attributed to large quantities of MDNs entering the bay during this period. Hume et al. (2005) found similar results as they saw chlorophyll-a increases during June at the peak of the freshet. However, they also found no temporal trends in chlorophyll-a levels which contradicts the results of this research. In Figure 2.8, there isn't a definitive trend at sites S2, S3, and S4. Site S1 has a wider variation in chlorophyll-a which suggests that location is critical when sampling for chlorophyll-a levels. Sites S2, S3, and S4 are situated in the flow path of the HFR while S1 is not.

Therefore, different results were found depending on location which could explain why Hume et al. (2005) came to different conclusions.

Fluorescence differed significantly when comparing study periods at site S5; however there were no significant differences among sites. In Figure 2.10, peaks are shown to occur at sites S1, S3, and S5 at the end of the spawning study period. These increases could be directly related to the presence of MDN's that are being delivered to HFB from salmon carcasses up the HFR. These peaks also correlate with peaks found in chlorophyll-a levels which suggests higher productivity in HFB during this study period. There are also similar trends between chlorophyll-a and fluorescence at the end of the 2015 spring freshet. This may be due to nutrients and particulates being flushed into HFB from the HFR during higher discharge.

2.5.4 Parameter Comparisons

Figure 2.8 allows for the visual comparison among variables measured in HFB throughout the study periods. Individual parameter observations can be found in their respective sections throughout this chapter. However, Figure 2.8 suggests that there may be correlations between chlorophyll-a values, delta ^{15}N levels, and TP during the fall spawn. The increase and correlations among these three variables is likely due to the arrival, spawning, and decomposition of salmon during this period. During the spring freshet, variables that show a common upward trend include MDN load, SPM, and TP. With higher discharge comes higher amount of SPM and nutrients that would have been stored in the river bed over the winter period.

AIC values were calculated for linear models created to identify what parameters are driving higher delta ^{15}N values and the load of MDNs in HFB. The best model created in assessing delta ^{15}N values, based on an AIC, shows that the most important parameter was study period (Table 2.5). This result indicates that the levels of delta ^{15}N values are dependent on the study period and the fall spawning period was found to contain the highest delta ^{15}N values which coincides with the arrival, spawning, and decomposition of salmon. Therefore, it can be assumed that delta ^{15}N concentrations entering HFB will always be highest during the fall spawning period. The method of comparing models was also used when determining what parameters drive the load of MDNs. However, as the three linear models that were created only varied in AIC values by less than two units, it is concluded that there are no differences in the models that were

produced (Stoica & Selen, 2004). This indicates that the data is insufficient to support selecting a single model.

2.6 Implications

The predominant delivery of MDNs to HFB took place during the spring freshet and the fall spawning periods. The pulses of MDNs in each study period possessed different characteristics which affected both the availability and utilization of these nutrients. The spring freshet was found to deliver the larger load of MDNs but in a more diluted and heavily sediment-laden flush. With more particulates available to bind to and higher concentrations of OSP, phosphorus levels in particulate form increased and in a few sampling days were higher than the dissolved form. With the increase in particulate phosphorus, the amount of phosphorus readily available for uptake by organisms in HFB could have been more limited than if it had been in a dissolved state. This suggests that MDNs entering HFB during the spring freshet are flushed and carried out into deeper parts of Quesnel Lake.

The fall spawning study period was found to provide a more concentrated / enriched delivery of MDN and a higher amount of dissolved phosphorus to HFB. Chlorophyll-a levels were found to increase during this flush of MDNs and dissolved phosphorus. Hume et al. (2005) found that Daphnia populations within Quesnel Lake peaked during late September and early October, coinciding with this flush of MDNs and subsequent increase of chlorophyll-a. This suggests that Daphnia populations, which make up 99% of juvenile salmonids diet (Hume et al., 2005) in Quesnel Lake are utilizing the fall flush of MDNs which results in higher chlorophyll-a levels. These findings support the hypothesis that future populations of salmonids are dependent on the fall flush and delivery of MDNs to nursery lake systems.

Chapter 3: The Movement and Dispersal of a River Plume and its Contents in a Nursery Lake – Quesnel Lake

3.1 Introduction

The delivery of suspended particulates from streams and rivers into downstream lake systems is an important ecological process which aids in organic matter cycling and the delivery of nutrients. These particulates containing inorganic and organic sediments as well as marine-derived nutrients (MDNs) and possible contaminants become suspended in rivers and streams and make their way to receiving lake systems where they eventually settle out (Owens, 2005). Being able to track and determine where suspended particulates travel and settle is important for the management of waterways as it influences many ecological processes. Larger or heavier particles settle out of the water column faster near river mouths, while finer or less dense particles stay suspended longer, which allows them to move out into deeper areas of lakes. Finer particles have the ability to adsorb nutrients and contaminants due to their larger surface areas (Horowitz & Elrick, 1988). These finer inorganic particles can combine with MDN through the process of flocculation and in turn modify the transportation of both materials through aquatic ecosystems (Choles, 2004; McConnachie & Petticrew, 2006; Hodder, 2009). As well, the displacement and suspension of particulate matter by spawning salmon, in rivers and streams, is an important process that supplies nursery systems with pulses of sediment (organic/inorganic material), and nutrients (Petticrew et al., 2011; Reisinger, 2013). These processes, in interior oligotrophic British Columbian nursery lakes, is thought to be especially important for maintenance of salmon spawning and rearing habitats (Petticrew et al., 2011).

The objective of this study is to assess seasonal changes in the movement, composition, and distribution of suspended particulates and their associated MDNs emptying into Horsefly Bay (HFB) from the Horsefly River (HFR) on Quesnel Lake in British Columbia. In excess of 457,000 spawning salmon returned to the Quesnel system in the fall of 2014, compared to 69,000 the year before. Sampling in the fall 2014 spawn and die-off period during this peak year of Sockeye returns allowed us to asses a potentially strong fall MDN signal and as well the 2015 freshet was expected to provide a significant contribution to the lake if river channel storage was an

important process. Capturing these two events was intended to represent the "peak" spawn endmembers for evaluation of the process and effects of suspended particulates and their associated MDNs moving through the watershed. Understanding how these sediments and nutrients disburse into nursery systems is important for the future management of juvenile salmon as, depending on their pathway and fate, these particulates may play a significant role in their growth and development.

3.1.2 Research Question

Determining the depth at which sediment associated MDNs are delivered to HFB is important in assessing if these nutrients are available for use by biota. If MDNs are delivered to and stay suspended in the photic zone, lake surface water that receives light, they remain available for primary and secondary production in nursery ecosystems. However, if the density difference of the river water relative to the lake water forces MDNs to plunge to deeper aphotic regions of the lake, the attenuated sunlight may restrict uptake by biota limiting primary production but could potentially be available for benthic invertebrates in the deeper portions of the bay and lake (secondary production). The specific question addressed in chapter 3 is:

- Is there a difference in the movement and distribution of MDNs in the water column of Horsefly Bay among the spring freshet, summer, and spawning event periods?

3.2 Methods

3.2.1 Site Characteristics

Water quality parameters were sampled from HFB on Quesnel Lake, British Columbia. A more detailed description of the study site and its characteristics can be found in section 2.2. Water temperature, conductivity, and water current patterns in HFB were monitored by a mooring deployed by the Department of Fisheries and Oceans where the HFR empties into Horsefly Bay in approximately 20 meters of water (Figure 2.1). This mooring was deployed in the spring and recorded data through the fall each year. A more detailed description of this mooring and its instrumentation can be found in section 3.2.3.1.

3.2.2 Study Design

Sample site locations were created by generating 50 points throughout Horsefly Bay with an equal distance of 50 meters in-between each point (ArcMap 10). These sites ranged in distance from the mouth of the HFR to the bay's connection with Quesnel Lake. The techniques and methods used in this research limited the number of locations that could be sampled in a reasonable time. Therefore, 28 out of the 50 points were selected to encompass and represent the different regions of HFB (Figure 3.1). This grid of sample locations as well as sites S1, S3, and S5 (Section 2.3.2) were used in this study.

Figure 3.1: Map showing CTD sampling stations in HFB.

3.2.3 Sampling Techniques (Collection and Analysis)

3.2.3.1 Observations of Water Column Parameters

Water column profile properties including depth, turbidity, transmissivity, and temperature were collected by a water profiling instrument (Seabird SB19 Plus) (CTD) which also had some additional sensors attached to this unit. The CTD uses a 100x gain cable to amplify signals in low turbidity settings. A five point transect was initially used to track the plume moving through HFB. However, it was determined that a larger grid would need to be implemented to better illustrate the movement of the HFR plume. A 28-point grid was added to this research project near the end of the fall spawn in 2014; therefore, the CTD grid was used only once during the 2014 spawning event. During 2015, however, sampling was performed weekly from April 15th, 2015 through August 8th.

This instrument was turned on, lowered into the water until submerged, and held at the surface for one minute to allow the pump to purge standing water and air from the system. The CTD was then lowered through the water column at 0.5-meters per second until within one meter of the lake bottom. Data from the descending cast were used for analyses.

3.2.3.2 Observations of Water Column Parameters from the LISST

Suspended sediment concentrations, particle size profiles, and optical water properties in the water column were determined using an in-situ laser diffraction (Sequoia Scientific - laser in-situ scattering transmissometry -100x) (LISST). Laser diffraction is advantageous because the size distribution of a large population of particles can be obtained from the pattern of scattered light. This allows the LISST to record the particle-size distribution at discrete depths in the water column as well as calculate a volume concentration of particles at any given depth. This instrument was also used to calculate transmission data or the amount of light that passes through a specific water volume, which aids in determining how turbid the water is at certain depths. The LISST was lowered into the water until submerged, and held at the surface for one minute to allow the instrument to warm up. At sites S1, S3, and S5 the LISST was lowered to a pre-determined depth and retrieved in five-meter increments stopping one minute at each depth. This was performed twice weekly from September 1st, 2014 through November 1st, 2014 and recommenced April 15, 2015 until the LISST malfunctioned on July 15th, 2015.

3.2.3.3 Mooring Observations of Water Column Parameters

For continuous monitoring of water properties in HFB a subsurface mooring was deployed at the mouth of the HFR in approximately 20 meters of water. This mooring had sensors that recorded water temperature, conductivity, water current movements, and depth (Figure 3.2). A RBR TDR-2050 recorder that measured temperature and pressure every 20 seconds was placed alongside a RBR CT recorder that measured conductivity and temperature at a depth of five meters every 40 seconds. A Teldyne RD Workhorse Sentinel 1.2 MHz Acoustic Doppler Current Profiler (ADCP) was anchored at the bottom of the mooring and recorded horizontal water current speeds and direction every 1m from the bottom to approximately 4m below the surface every 1 to 18 minutes. A RBR TR-1050 was attached to the ADCP to also measure temperature at the bottom of the mooring every 20 seconds. The mooring was deployed in mid to late April every year and retrieved at the same time the following year.

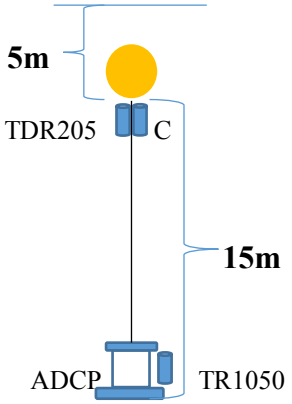


Figure 3.2: Diagram of DFO mooring setup.

3.2.4 Analysis of Results

Unlike in Chapter 2, there was no statistical analyses run on Chapter 3 data to determine significant differences because the aim of this chapter was primarily to track the river plume in the lake as a function of time and depth. Four variables (temperature, transmissivity, sediment concentration, and D_{50}) were plotted using ggplot (ggplot2) in R (version 3.3.2) to show the movement of the HFR plume through HFB.

Spatial analysis was performed on the data from the twenty-eight point CTD grid using linear interpolation. Data points that were chosen throughout HFB were unevenly spaced and therefore the "maximum point technique" (spatial analyst tool) in ArcMap was used to interpolate in-between points. The river plume's movement through HFB has a directional bias because it flows from the mouth of the HFR out into Quesnel Lake, in a general east to west direction. Therefore, the general direction of the plume is known which better suits the

interpolation option of "kriging" because it assumes that the distance or direction between sample points reflects a spatial correlation that can be used to explain the variation in the surface.

To assess CTD casts performed to characterize the vertical profile of HFB at various points throughout the bay, a R code was created to generate a 3-dimensional plot that could be assessed. The R code (version 0.6-2) used a package called akima, that uses bicubic spline interpolation to generate values for spaces in-between points. Bicubic spline interpolation is an extension of cubic interpolation and used to plot data points on a 2-dimensional grid. This interpolation method is preferred in this situation over bilinear interpolation of nearest-neighbor interpolation as it generates a smoother interpolation product (Johnston et al., 2003).

3.3 Results

Many studies have focused on the relationship between riverine sediment storage and resuspension/transportation of particles as a means of evaluating whether, and for what time period, nutrients are delivered and retained by stream beds. A retention and storage period exceeding hours or days would retard the delivery of MDNs to a downstream nursery lake (McConnachie & Petticrew, 2006; Rex & Petticrew, 2006; Rex et al., 2014) and enhance uptake of MDN by riverine organisms. Other research has studied physical dynamics of nursery lakes including water thermal structures and mixing parameters (Carmack et al., 1978) which influence the trophic structure and diets of organisms that live within these nursery lakes (Hume et al., 2005). However, there are few studies that demonstrate the linkage between physical limnology and nutrient flow. This study attempts to bridge this gap to determine if the lake and river's water variable density structure, at different times of the year, regulates the distribution and therefore the availability of these nutrients. Evaluating the spatial pattern of MDNs delivery with various combinations of temperature/density differences between the river and lake should indicate if and when MDNs are available for both primary and secondary production in the photic zone or are involved in pelagic and/or benthic productivity.

3.3.1 Water Properties

3.3.1.1 Temperature & Thermal Structure

Water temperature values in the HFR, measured near the river mouth by the Hobo are compared to the surface water temperatures measured in HFB on the mooring over the period

of this study in Figure 3.3. Throughout the spring freshet, the HFR temperatures were 1.3°C higher than temperatures in HFB. The summer water temperatures were 1.5°C above the surface temperatures in HFB. However, at the beginning of August 2015, the river temperature decreases faster than in the bay. Due to this decrease, which was observed during both the 2014 and 2015 spawning periods, the measured river temperatures were an average of 1.3°C and 3.2°C below the surface waters in the bay in 2014 and 2015, respectively. This seasonal cooling pattern in the river does not hold for the whole period of study but shows some fluctuations. For example, there is a noticeable increase in temperature during the 2014 fall spawning period (mid-August) in both the HFR and HFB and another in HFB at the end of October.

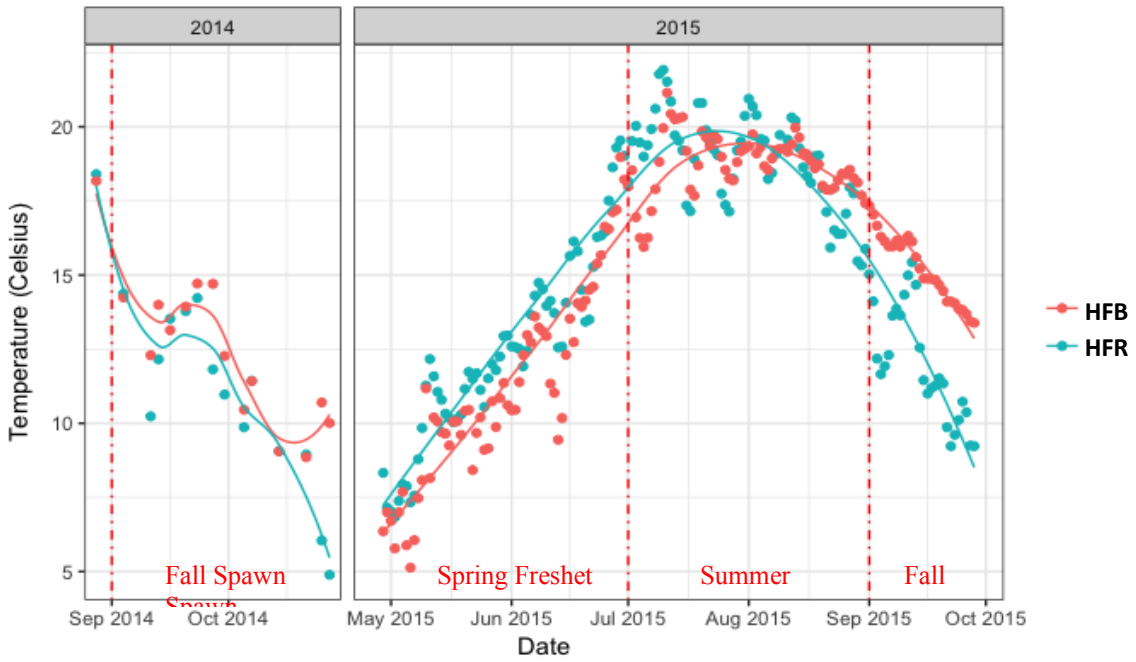


Figure 3.3: Temperature values of the HFR and the surface water of HFB throughout the period of record (2014 fall spawning period, 2015 spring freshet, summer, and fall spawning periods). Method used to create trend lines in R was LOESS. River water temperature was collected using the Hobo while HFB temperatures were collected using the DFO mooring.

The thermal structure of HFB can be seen in Figure 3.4 which shows temperature profiles at site S3 which is approximately 150 m from the river mouth in 15 m of water depth. During the spring months of May and June the thermocline, a denser layer of water that can act to inhibit particles from settling to deeper depths, is situated in the warmer photic waters above 8 meters in depth. During July and August, the thermocline is deeper at around 10 to 12 meters and during the months of September and October it is even deeper at approximately 13 to 15 meters.

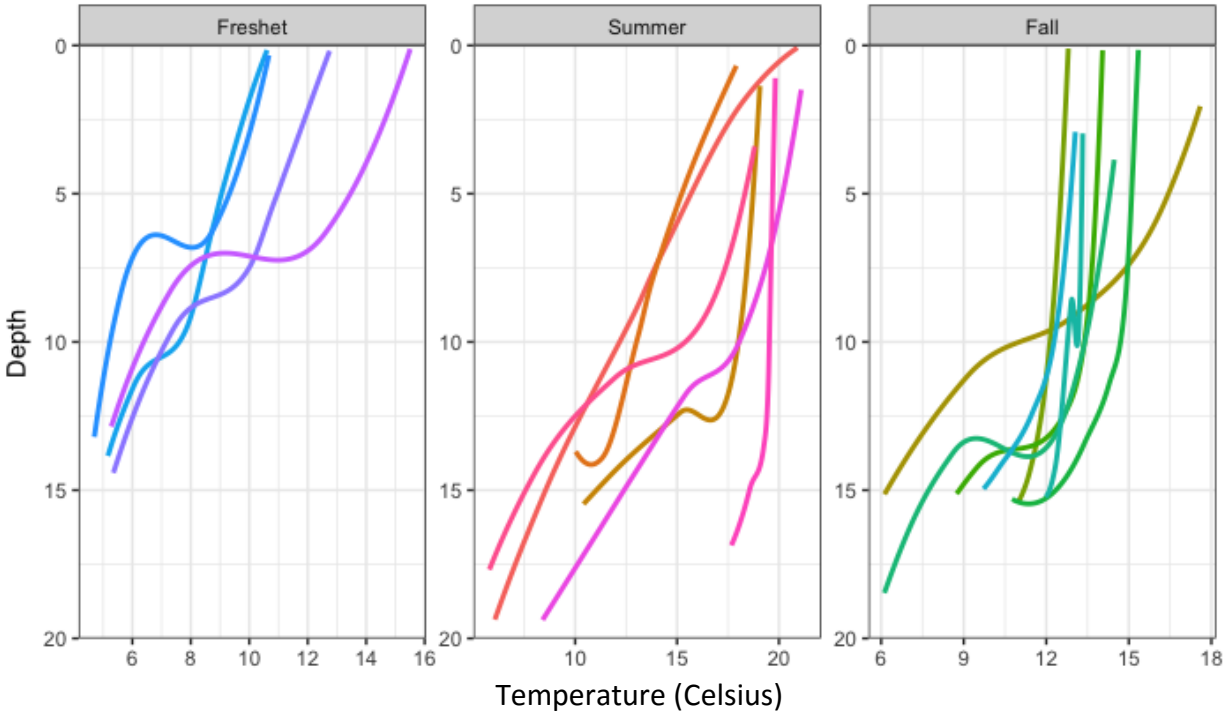


Figure 3.4: Temperature profiles at site S3 throughout the three study periods. Data obtained using the CTD. Lines created with LOESS.

3.3.1.2 Turbidity & Transmission of Light

To assess where the HFR plume travels once it enters HFB, Celsius LISST data was used to estimate SPM concentrations at various depths at site S3, which is in 15 meters of water and near the mouth of the HFR. In Figure 3.5, SPM concentrations at the beginning of the summer sampling period (mid-July 2014) tended to be highest at the surface (49 μg/L). However, surface concentrations dropped at the end of the summer at which time the highest concentrations, approximately 20 μg/L and 16 μg/L, were found at 10 and 15-meter depths, respectively. During the middle of September, SPM concentrations at all depths decreased to near zero, while at the

end of October, SPM concentrations at the depths of 5, 10, and 15 meters all increased again. During the 2015 spring freshet, SPM concentrations were similar through the beginning and middle of May at all depths. However, at the end of May, SPM concentrations increased at the surface and at the five-meter depth. There were similar trends in SPM concentrations in both the 2014 and 2015 summer sampling periods. Concentrations at the 10 and 15-meter depths started to increase as the surface and five-meter depth concentrations decreased towards the end of the summer.

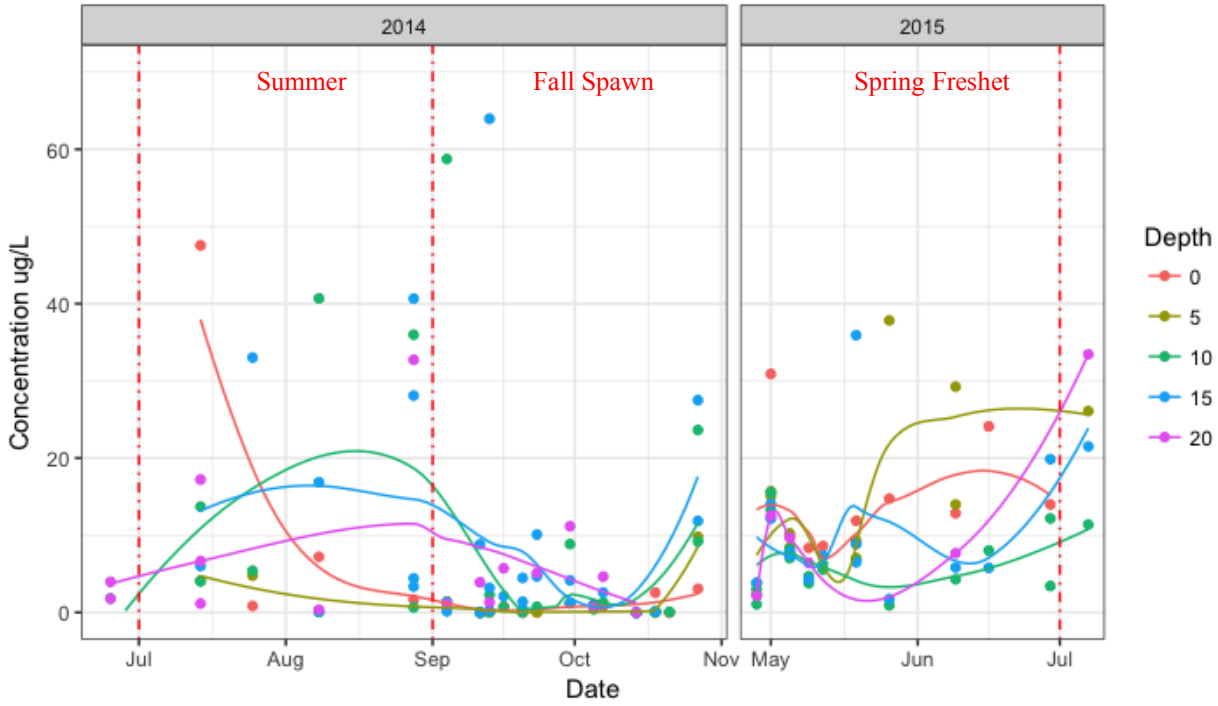


Figure 3.5: Site S3 SPM concentrations at five depths over the three study periods (2014-2015). Data was collected by using a LISST and the plotting method in R used to create trend lines was LOESS.

Percent transmission values throughout the 2014 summer and salmon spawning periods tended to stay consistent, ranging between 80 and 100 percent transmission (Figure 3.6). There are points that dropped to as low as 60 percent transmission at depths of 10 and 15-meters during the beginning and middle of September, respectively. The 2015 spring freshet sampling period had larger and sharper decreases in transmission over time than the summer and salmon spawning periods in 2014. At the end of May, there was a drop-in transmission at the surface and at five-meters depth. However, the surface transmittance percentage leveled off at

approximately 80 percent as the five-meter transmission continued to drop to approximately 22 percent at the beginning of July. During the middle of June, transmission at the ten-meters depth dropped and continued to drop to approximately 48 percent in the beginning of July.

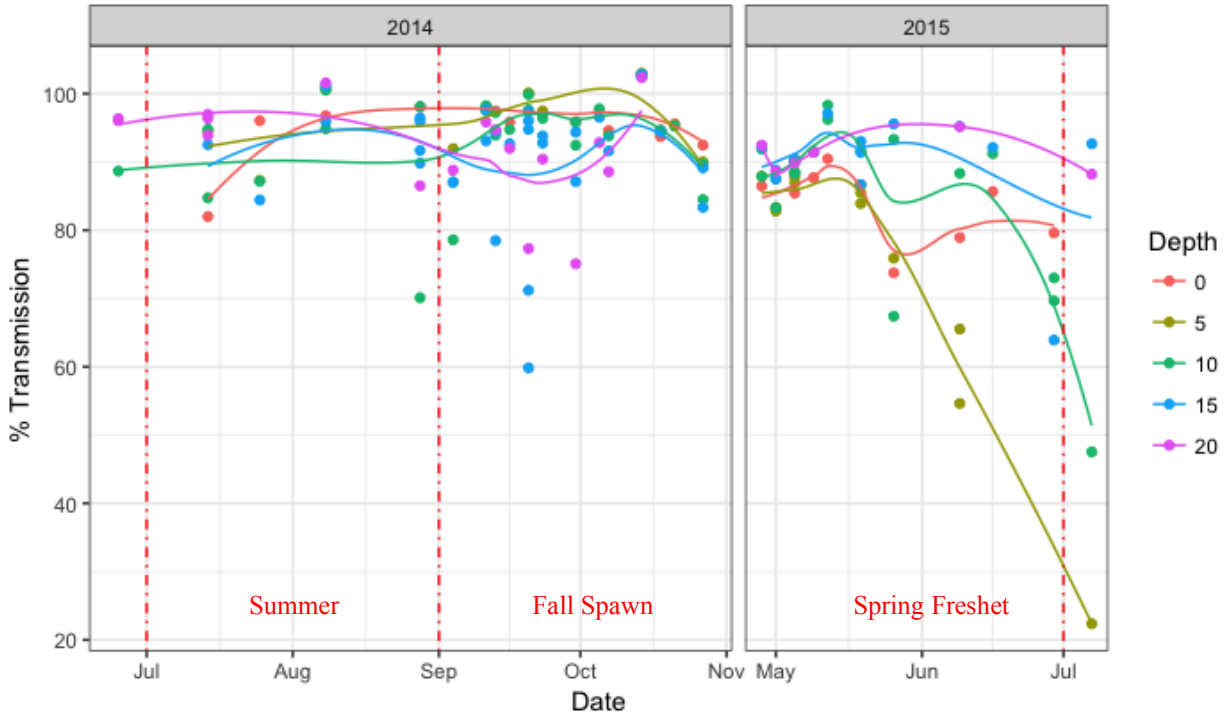


Figure 3.6: Site S3 percent transmission levels at four depths over the three study periods. Data was collecting by using a LISST and the plotting method in R used to create trend lines was LOESS.

3.3.1.3 D_{50}

The D_{50} or median diameter of the particle-size distribution at site S3 throughout the three study periods is shown in Figure 3.7. The D_{50} during the 2014 summer study period started off with the largest median particle-size distribution, approximately 340, 280, and 280 microns, being at the surface, 10-meters deep, and at 15-meters deep respectively. The surface D_{50} decreased as the salmon spawning study period began; dropping from approximately 280 microns to 20 microns. Although, the D_{50} at the five-meter depth started off the summer study period at around 280 microns, it dropped to approximately 5 microns and did not increase again until mid-October, when it peaked at approximately 250 microns. At the ten-meter depth we see a constant slope which continued into the fall spawning study period. Although there are outliers, one being in the middle of July and one at the beginning of the fall spawn study period.

In the 2015 spring freshet sampling period, the D_{50} at the surface of HFB started at approximately 95 microns and increased to approximately 245 microns where it remained consistent throughout the rest of the 2015 study periods. D_{50} at the five and 10 meter depths appear to have the same trend in which they have peaks at the beginning and end of May and a decrease in the beginning of July. The D_{50} at the 15-meter depth also decreased once the fall spawning study period began due to two sampling dates in the beginning of September where the D_{50} was below 100 microns. However, after these two sampling days, D_{50} at the 15-meter depth exhibited a median particle size of approximately 260 microns through into the beginning of October. The D_{50} at the 15-meter depth trend stays consistent around 240 microns; however, there are outliers at approximately 75 and 340 microns during the end of June and beginning of July respectively.

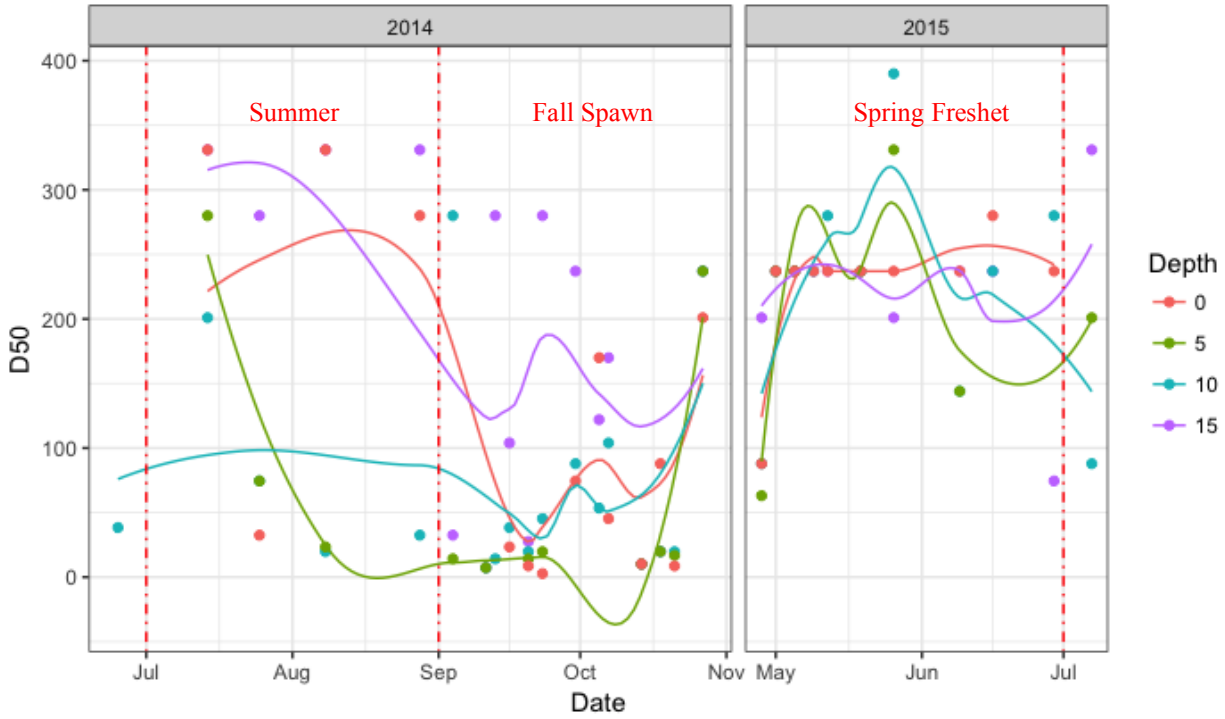


Figure 3.7: Site S3 D_{50} levels at various depths over the three study periods. Data was collecting by using a LISST and the plotting method in R used to create trend lines was LOESS.

3.3.2 Movement of the Plume

3.3.2.1 Overhead View of Turbidity

River water carrying suspended sediment enters HFB with a turbidity of approximately 3 NTU and hugs the northern shoreline until it enters Quesnel Lake with a turbidity of

approximately 2.5 NTU (Figure 3.8, A). Although the highest turbidity water stays along the north shore of HFB, the HFR plume does affect and increase the turbidity across the whole bay until it disperses into Quesnel Lake. The waters with the highest turbidity remain along the north shore of HFB as they enter Quesnel Lake.

On May 29, 2015 NTU levels of the water entering HFB from the HFR reached upwards of 9.8 in the HFR delta (Figure 3.8, B). This plume moved through the bay in a similar fashion to the plume observed on April 24 (Figure 3.8, A). The highest turbidity once again was found at the river delta and hugged the northern shoreline as it moved through HFB and entered Quesnel Lake. This plume also increased turbidity levels across the entire bay. Unlike, the plume on April 24, the plume on May 29th carried more turbid waters out into Quesnel Lake, spanning the full extent of the HFB as it entered Quesnel Lake.

The HFR Plume on June 19, 2015 entered HFB at approximately 6 NTU and exhibited a more direct path into the lake (Figure 3.8, C). The most turbid water was located at site b which is shown on Figure 3.8 (C), even though sites a and c are closer to the mouth of the HFR. As the plume moves out farther into HFB the route looks to be more localized, as it doesn't span the whole bay, and moves from the northern shore across the bay to the southeastern shore as it makes its way out into Quesnel Lake.

On July 2, 2015, the HFR plume enters HFB with a turbidity of 3.1 NTU and travels along the northern shore until it enters Quesnel Lake (Figure 3.9, A). After spreading along the north shore, it spreads southward and eastward. As the plume spreads towards Quesnel Lake it flows and exists on the northern shore.

In Figure 3.9 (B), the highest turbidity in HFB is approximately 2.8 NTU and is found at the mouth of the HFR on July 24, 2015. Compared to previous sample dates, this turbidity level is low. The HFR plume enters HFB and turns south until it hits the southern shore. In this case, the turbid waters do not make it out into Quesnel Lake and end up diminishing as they move towards the southern shoreline.

On August 7, 2015 (Figure 3.9, C), turbidity values in HFB are also found to be low with the highest turbidity reading being approximately 2.8 NTU around the mouth of the HFR. As the plume enters HFB it spreads out across the bay and uniformly dissipates as it moves towards

Quesnel Lake. At the mouth of the bay, turbidity levels are approximately 1 NTU and the HFR plume looks to be non-existent.

In Figure 3.10 (A) from October 7, 2015, turbidity levels across HFB are less than 1 NTU. Although the figure suggests differences in turbidity from the mouth of the HFR out into Quesnel Lake, the differences are very small, indicating that the HFR plume is non-existent.

On October 20, 2015 (Figure 3.10, B), the highest turbidity level recorded in HFB was approximately 4 NTU. Point b in Figure 3.15, shows where the highest turbidity was observed in HFB, even though points a and c, which are closer to the mouth of the HFR show lower NTU levels. Turbidity levels dropped as the HFR plume moved farther out into HFB and the plume was not detected where HFB empties into Quesnel Lake.

When assessing the HFR plume's movement and characteristics throughout the three study periods, turbidity levels were highest during the spring freshet and lowest during the summer and the salmon-spawning event. There was an increase in turbidity near the mouth of the HFR at the end of the salmon spawning event. This increase was approximately 4 NTU higher than three weeks earlier. The HFR plume was found travel and enter Quesnel Lake via the northern shore of HFB.

When the spring freshet is ending and the summer is starting, the HFR plume appears to be more focused and not as dispersed. During this time period, the HFR plume also changes direction and is found along the southern shoreline.

3.3.2.2 Turbidity's Vertical Profile and Distance from Delta

Figure 3.11 shows the evolution of the plume as it expands through the HFR delta and HFB at four different time periods during 2015. On April 24 turbidity levels reached levels of approximately 4 NTU in the top ten meters of the water column and extended approximately 700 meters into HFB (Figure 3.11, A). Turbidity levels decreased as the HFR plume exited HFB and was approximately 3 NTU at the location where the plume entered Quesnel Lake. levels decreased away from the river delta and were observed to be 5 NTU where the plume exited HFB. Again, most of the particulate matter was contained within the top 10-15 meters of the water column. However, as the plume moved eastward and exited the bay, the more turbid waters are found higher in the water column and are contained within the top five meters.

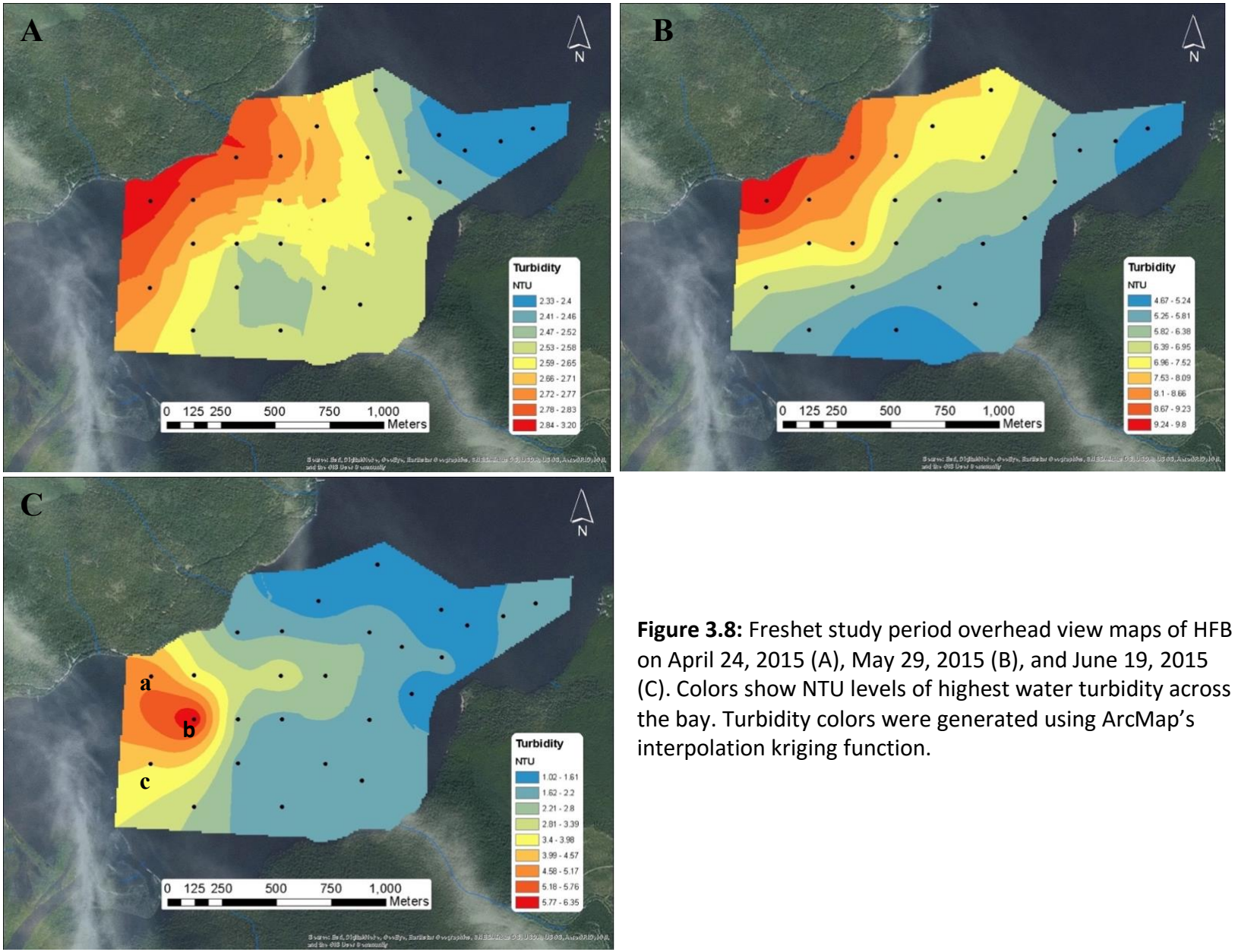


Figure 3.8: Freshet study period overhead view maps of HFB on April 24, 2015 (A), May 29, 2015 (B), and June 19, 2015 (C). Colors show NTU levels of highest water turbidity across the bay. Turbidity colors were generated using ArcMap's interpolation kriging function.

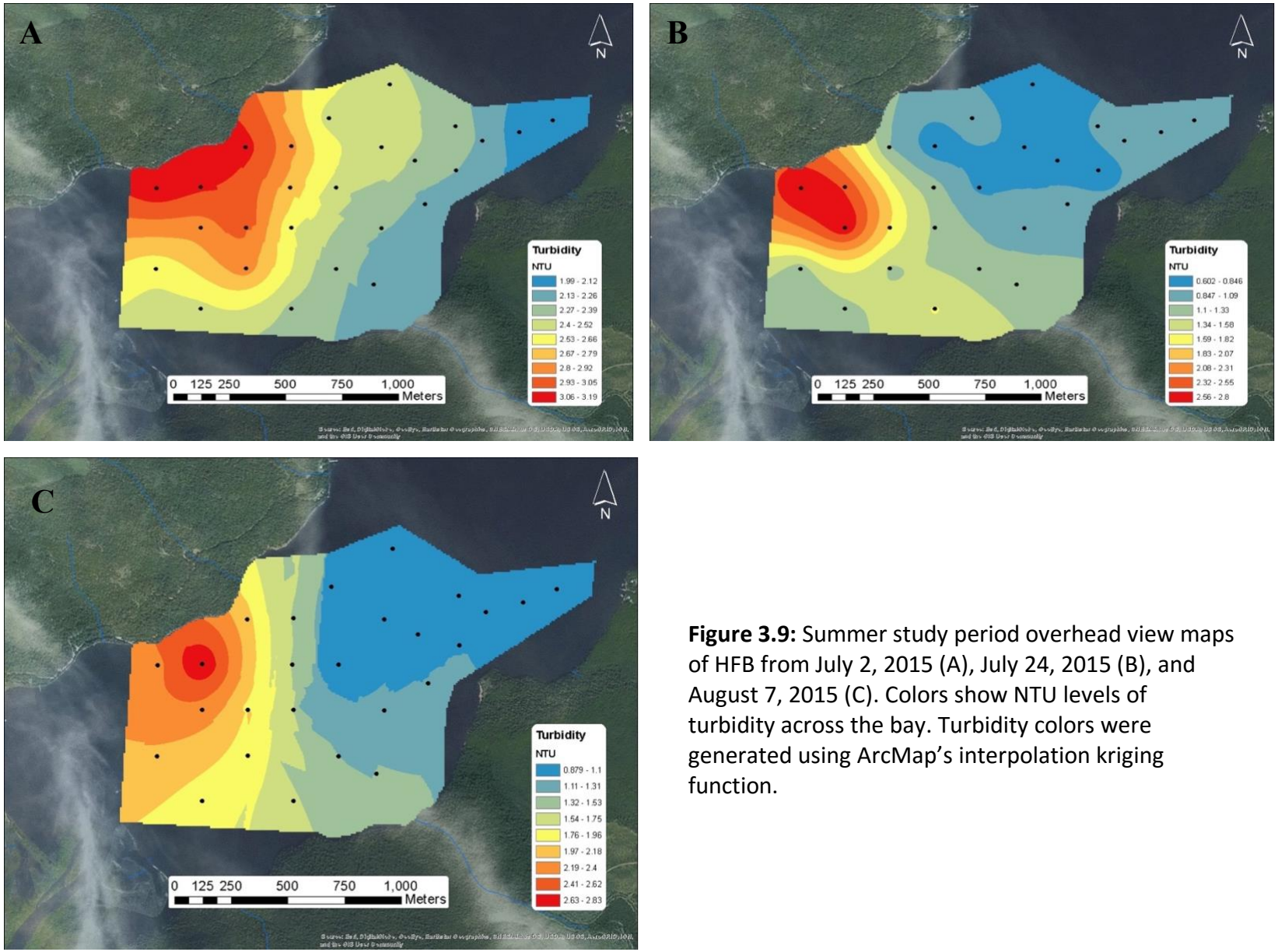
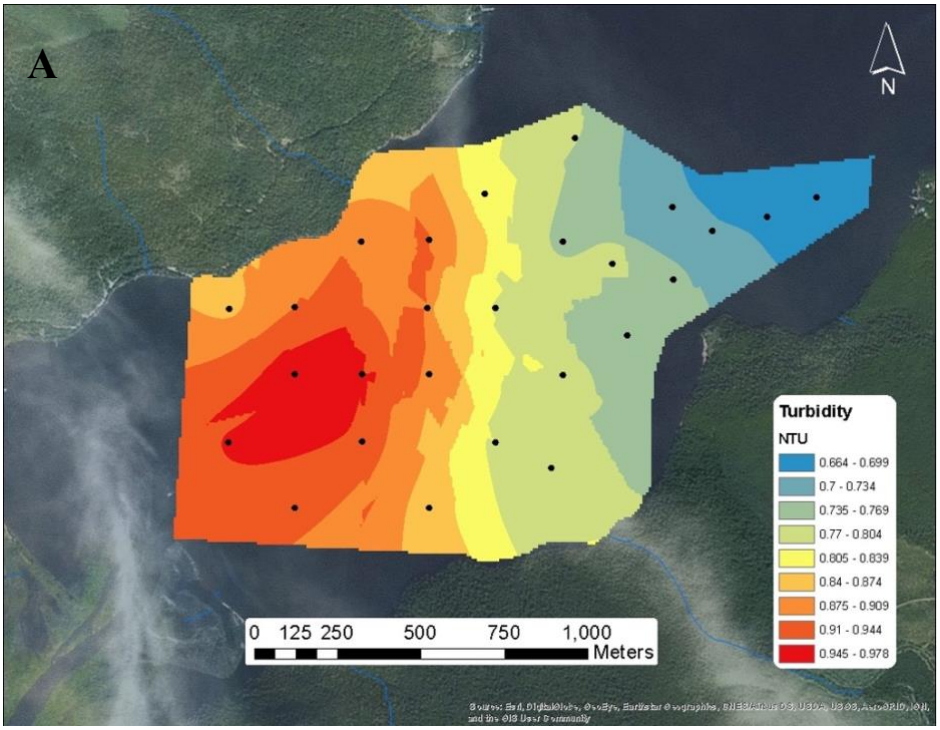


Figure 3.9: Summer study period overhead view maps of HFB from July 2, 2015 (A), July 24, 2015 (B), and August 7, 2015 (C). Colors show NTU levels of turbidity across the bay. Turbidity colors were generated using ArcMap's interpolation kriging function.



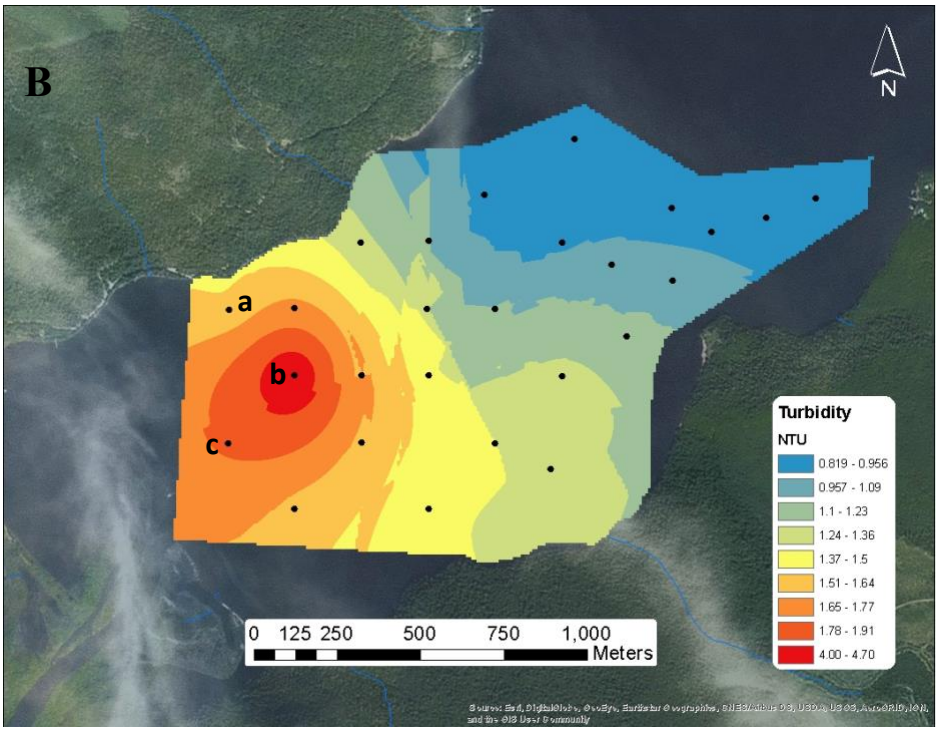


Figure 3.10: Fall spawn study period overhead view map of HFB from October 7, 2015 (A), and October 20, 2015 (B). Colors show NTU levels of turbidity across the bay. Turbidity colors were generated using ArcMap's interpolation kriging function.

On June 19, the observed turbidity levels were lower than at the end of May (Figure 3.11, C). The HFR plume entered HFB with a turbidity level of approximately 4 NTU and was contained to the top five meters of the water column. The turbidity of the plume on this sampling day decreased to approximately 2 NTU once it had traveled 1000 meters from the delta.

The data from July 2, showed a similar trend to that of June 19 (Figure 3.11, D). Once again, the turbidity levels of the water entering the bay were approximately 4 NTU and the turbid waters remained within the top five meters of the water column. However, during this sampling period the HFR plume did not dissipate once it had traveled 1000 meters from the HFR delta but continued traveling east and exited HFB with a NTU level of approximately 4.

On July 24 (Figure 3.12) there was increased turbidity near the HFR delta, with levels reaching nearly 2 NTU (Figure 3.12, A). As the plume traveled farther from the delta, the turbidity gradually decreased and the vertical extent of the plume also decreased.

On August 7, the turbidity in the HFB was found at deeper depths than previously observed (Figure 3.12, B). The HFR plume entered HFB with turbidity levels of approximately 2 NTU. The turbidity level increased with depth as the plume moved eastward and reached 6 NTU at a depth of 27 meters, approximately 300 meters from the HFR delta. At a distance of 600 meters the turbidity levels remained constant while the depth of the center of the plume increased to a depth of almost 90 meters. The plume was not detectable beyond this point.

On October 7, 2014, there is no evidence of the HFR plume and the measured turbidity levels are relatively constant throughout the bay (Figure 3.12, C). However, on October 20 an increase in turbidity levels at deeper depths in HFB was detected (Figure 3.12, D). The observations from this day show that turbidity levels reached approximately 4 NTU at a depth of 40 meters, which then spread throughout the water column as the plume moved farther away from the HFR delta. This plume started around 400 meters from the delta and traveled about 150 meters. As this plume traveled eastward, both its turbidity level and the depth of maximum turbidity increased. Once the plume had traveled approximately 550 meters, the depth of this plume spanned between 25 and 80 meters; even though, the turbidity level of the plume had decreased to approximately 2 NTU. There was another increase in turbidity at 1100 meters from the HFR delta with a turbidity

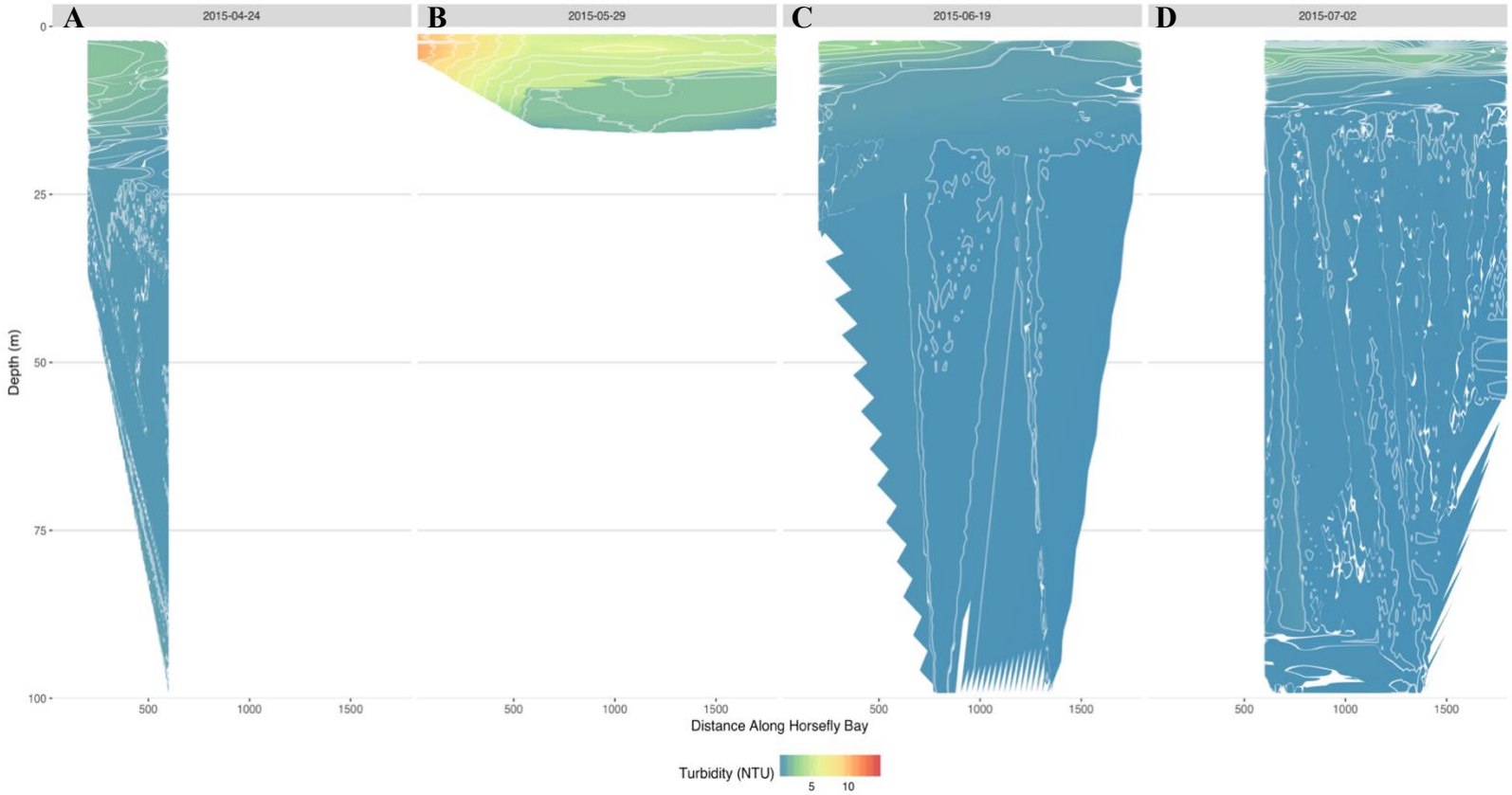


Figure 3.11: Interpolated vertical profile plot of the HFR plume (turbidity) as it enters at the mouth of the HFR and exits at the end of HFB. These plots represent data taken from April 24, 2015 through July 2, 2015. Graph was created in R using ggplot and data was interpolated using bicubic spline interpolation. White contour lines denote changes in turbidity.

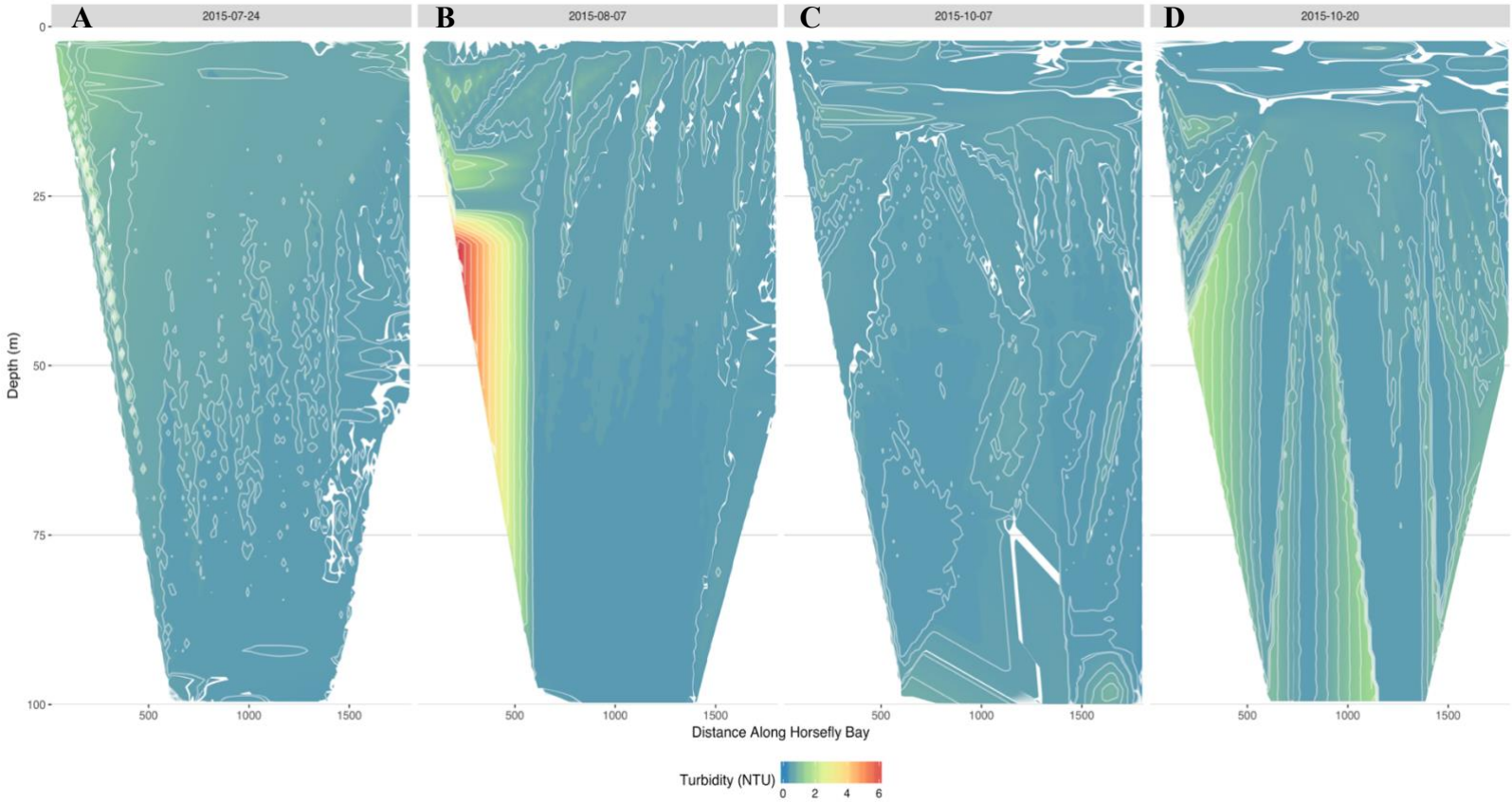


Figure 3.12: Interpolated vertical profile plot of the HFR plume (turbidity) as it enters at the mouth of the HFR and exits at the end of HFB. These plots represent data taken from July 24, 2015 through October 20, 2015. Graph was created in R using ggplot and data was interpolated using bicubic spline interpolation. White contour lines denote changes in turbidity.

level of approximately 3 NTU. This increase in turbidity covered the whole water column 30 meters in depth to the bottom at 100 meters.

3.4 Discussion

The movement and dispersal of river water and its contents entering a large body of water such as a lake are affected by the physical characteristics of both the river and lake waters (Carmack et al., 1979). The sampling stations used during this research were spread throughout HFB to ensure the ability to compare the movements of the HFR plume across a spring freshet, a summer, and a salmon spawning period. The movement patterns of the HFR plume are driven by differing temperatures and turbidities, which modify densities in the HFR and HFB and the HFR's flow. Trends in D_{50}, concentration, and the spatial mapping suggest that the movement of the HFR Plume and its contents differ depending on time of year, which could affect where MDNs may be available to organisms living in this nursery system. Although some results obtained from this research were consistent with previous studies performed (Carmack et al., 1979; Reichert, 2009), there were some that were not (Carmack et al., 1979). As stated in the previous chapter, these research findings could be system-specific.

3.4.1 Characteristics of Horsefly Bay

Temperature is one of the main factors when trying to predict how a river's water and contents will interact with that of a lake (Hilton et al., 1986). At temperatures above ~4^{o}C the colder a water body is, the denser it is. Therefore, colder river water will enter and stay below warmer lake water allowing the contents of the river water to settle to the bottom of the lake (Wetzel, 2001). On the other hand, if the river's water is warmer than that of the lake's water, then the river water and its contents, if the suspended material does not modify the density differences significantly, will stay suspended in the lake's water column. In Figure 3.4, the HFR water temperature is warmer than that of HFB during the spring freshet and most of the summer study periods (May-beginning of August). Therefore, river water and its contents that are entering HFB from the HFR would most likely stay suspended higher in the water column assuming the SPM concentration is minimal. The contents of the HFR, which could contain MDNs would be more readily available for uptake by plankton living in these warmer surface waters (Baines & Pace, 1994). Evidence to corroborate this is seen in the results of chlorophyll-a and

fluorescence measurements, which both exhibit peaks at the end of the spring freshet. In the beginning of August, the HFR water temperature dropped and became colder than HFB's water temperature. The river water would become denser than that of HFB's water, and upon entering the bay its contents would stay below the thermocline promoting settling to the bottom of the bay or further offshore in Quesnel Lake. These findings are consistent with what was found with suspended particulates entering Quesnel Lake from the Mount Polley Mine spill staying suspended below the thermocline and spreading out over deeper depths of the lake (Petticrew et al., 2015).

Water heavily laden with suspended particulates will also affect where river water and its contents will go once they enter a lake system. Assuming equivalent temperatures, waters that are less laden with particulates are less dense than water that contains more suspended particulates. At the end of the summer and throughout the salmon spawn period, the most turbid waters are located at around the 10 to 15 meter depths, while the river water is colder than that of lake surface water. Water and particulate contents during this study period were entering HFB below the thermocline and staying suspended in the hypolimnion until settling out on the bottom of HFB, as the thermocline was located at approximately 15 meters in depth. During the spring freshet, the most turbid waters are found to be at the surface and at the 5-meter depth. This is due to warmer river water entering a cooler HFB. Even when the freshet exhibits the highest SPM concentrations for the study period, the amount of particulates does not result in a denser plunging plume (Figure 3.3). Water that enters HFB from HFR during this study period is remaining suspended in the surface epilimnetic water because of the depth of the thermocline.

Another way to look at a waterbody's particle concentration, is by recording transmission or light attenuation data. Transmission is the measurement of how much light can pass through a certain volume of water. The more turbid a waterway, the less light transmission there is. In Figure 3.6, transmission data trends are similar to what was seen in the turbidity data in the previous section. Lower levels of transmission are observed at deeper depths, around 10-15 meters, during the end of the summer and throughout the salmon spawning period. However, during the spring freshet the upper 5 m of water tend to have lower transmission, meaning they contain higher amounts of suspended particulates than water at the 10 or 15-meter depth. These

results indicate that when the HFR plume and its particles enter HFB from August through the end of October, they enter below the thermocline which restricts mixing into the epilimnion and enhances settling through the hypolimnion. On the other hand, evidence here indicates when the HFR plume enters HFB from April through July, it enters above the thermocline and remains suspended in the warmer surface waters.

Analyzing the size of the particulates coming out of the HFR and whether they stay suspended in the water column are important in understanding the movement of the particulates that are transported via the HFR. Suspended particulates entering HFB were largest during the spring freshet and the beginning of the summer at all depths. There is a decrease in the suspended particulate median size at the end of summer and throughout the salmon spawning period. This suggests that with higher flow periods, larger particles can be transported down river and out into HFB. In the spring freshet, larger particles tend to be suspended between the 5 and 10-meter range. However, at the start of June we see a drop in D_{50} at the 5 to 10-meter range and a slight increase in D_{50} at the surface which contains the highest D_{50} until the start of the summer period. The increase in D_{50} in surface waters could be due to a rise in chlorophyll-a levels as we see an increase during the 2014 spawning period and during June 2015 (Figure 2.8). These small plankton communities would affect D_{50} levels at shallower depths of the water column as the thermocline would trap these smaller organisms in the photic surface waters. Two studies previously looking at suspended particulate median size in O'Ne-eil Creek and the HFR (McConnachie & Petticrew, 2006; Albers & Petticrew, 2012) found that larger-sized particles were found to be suspended in the river during spawning and post-spawning events. Most likely bioturbation caused by spawning salmon had re-suspended larger particles that may had been trapped in the river beds. However, results found in this study show that larger particles suspended in HFB are found to be present in the spring freshet with lower median-sized particles being found during the spawning event. This suggests that although larger particles are re-suspended by bioturbation, they never make their way to HFB and are only transported by the higher flow event of the spring freshet. This assumption is supported by Liu et al. (2011) who found particle size and load in suspended and bed sediment to be highly dependent on discharge.

3.4.2 The Dispersal of the Horsefly River Plume

Assessing the dispersal of the HFR plume into HFB is most easily observed through spatial and temporal mapping of turbidity. Such analysis shows that the HFR plume brings the most turbid waters into HFB during the spring freshet period with turbidity levels reaching approximately 11 NTU. There is a slight increase in turbidity during the salmon spawn period, which is most likely due to bioturbation and redd construction (Naiman et al., 2002; Moore et al., 2007; Albers, 2010) as well as a late October storm event (Figure 2.2). These results support findings that were documented in chapter 2. One common trend that is shown in these maps and is consistent with previous research studies (Carmack et al., 1979; Saetre & Ljoen, 1972; Hilton et al., 1986), is the movement of the HFR plume seems to be affected by the Coriolis effect. Seven out of the eight days sampled, the HFR plume makes its way into HFB and turns right towards the southernmost shoreline. May 29th, 2015 is the only sampling date that the plume appears to exit HFB along the northern shoreline. This date also exhibits the highest turbidity levels observed during this research period and supports the findings of Saetre & Ljoen (1971) who state that the Coriolis force has less effect on plumes with higher velocities and higher water densities.

The HFR plume stays suspended during the spring freshet and beginning of summer and drops to lower depths at the end of the summer and throughout the salmon spawning period. Turbidity again was shown to be highest during the spring freshet and lowest during the summer and salmon spawning periods. In the months of April, May, June, and the beginning of July, the HFR plume stays in the upper 10 m of the lake, and the densest water is at a depth of 10 to 15 meters (Figure 3.17). This dense water layer is likely the reason that the HFR plume and its contents are staying suspended above the 10 m depth. In the months of August, September and October, there is little evidence on certain sampling days that a plume exists in HFB. However, when there are higher turbidity levels during this time period, those areas of high turbidity exist below the 20 to 25-meter depth. This suggests that if a HFR plume enters HFB during this period that it and its contents will enter below the thermocline and would not be able to rise in the water column through warmer surface waters. These findings and assumptions are consistent with Petticrew et al. (2015), where the water column thermal structure restricted high turbid waters from mixing with epilimnetic waters.

3.4.3 Implications

The movement and dispersal of the HFR plume to HFB is dependent on the time of year, which affects the relative differences in temperature of the two "water systems". Warmer river waters during the spring freshet allows river water and its contents to stay suspended in the warmer surface lake water, while the colder river water in the fall spawn period plunges down below the surface lake water and is trapped beneath the thermocline. These different processes could directly affect how sediment-associated nutrients, that are carried in this HFR plume, are utilized and taken up by biota living in HFB. Nutrients that are suspended in the warmer surface waters are more readily utilized by plankton populations living in these waters, and will aid in enhanced primary and secondary production. Nutrients that enter below the thermocline are less available for uptake by plankton communities, limiting primary production and may only be available to secondary production. In Figures 2.8 and 2.9, there are peaks in both chlorophyll-a and fluorescence at the end of both the 2014 fall spawn and the 2015 spring freshet. This could indicate that MDNs are available and being utilized during these study periods and increasing productivity. This implies that particulates entering HFB during the fall season are still entering above the thermocline but at deeper depths seen in the freshet and summer periods.

This study indicates that the direction of the plume is affected by the Coriolis force, such that suspended particulates that are transported by the plume can be deposited on the southern-most banks of HFB and not into the deeper parts of Horsefly Bay or Quesnel Lake. The deposition of these suspended particulates in shallow waters will expose themto subsequent re-suspension processes of wind-generated waves or higher river flows associated with the spring freshet. These processes can thenincrease the distribution of nutrients that werenot previously utilized allowing these nutrients to be delivered into deeper lake regions.

Linking the information in this chapter, with evidence presented in chapter 2 of this thesis can help determine where nutrients are being delivered, and when they are available to biota living in HFB. These findings support the idea that future populations of salmonids are dependent on the fall flush and delivery of MDNs to nursery lake systems.

Chapter 4: Conclusions and Management Implications

4.1 Conclusions

This thesis demonstrates how seasonal and temporal differences in discharge and water properties affect timing of the movement and the range dispersal of marine-derived nutrients (MDNs) from a salmon spawning river to a nursery lake. Moreover, this thesis supplements existing literature which explores and aims to determine whether MDNs are beneficial, neutral, or detrimental to juvenile salmonid rearing habitat. The results presented in Chapter 2 and 3 show that MDNs do enter Horsefly Bay (HFB) during both the spring freshet, during which nutrients remain suspended, as well as the fall spawning period, during which nutrients fall to deeper depths. These natural and behavioral observations provide further insight into the movement of MDNs through freshwater systems and aid in determining the degree to which they contribute to lake productivity.

The findings in Chapter 2 support past literature, which states that MDNs have a positive effect on chlorophyll-a, phosphorous, fluorescence, total nitrogen, and total carbon levels that could potentially stimulate nursery lake productivity-- helping drive algae, zooplankton, and fish populations in a bottom-up trophic transfer (Hyatt et al., 2004; DeVries, 2012). While these findings outline benefits to the productivity of HFB, it's important to consider this research does not specifically address whether lake productivity has an effect on salmon-spawner populations. However, as productivity is positively linked to the increase of bottom-up trophic transfer, one may conclude that growth and survival of juvenile salmon willbenefit from the delivery of MDNs.

Understanding the underlying mechanisms of a biological process is important in assessing how particular processes can affect organisms. Both the discharge rates and presence of salmon (spawn and decay) played critical roles in regulating MDN load and MDN concentration, respectively. The productivity of HFB benefited from the increased load of MDNs delivered during the spring freshet and the high concentrations of MDNs entering in the fall spawn, as shown by increased chlorophyll-a and fluorescence levels during these two study periods. Although it was identified that nutrients entering HFB during the fall spawning period enter below the thermocline and settle to the bottom based on differences in river and lake

water temperatures, there was still an increase in productivity during this period. The D_{50} distribution throughout the water column during the fall spawning period identifies smaller particles suspended higher in the water column, around the five-meter mark, while larger particles are found in deeper water, around 15 meters. This shows that larger particles entering HFB are entering below the thermocline and dropping to deeper depths as is shown in Figure 3.12, whereas lighter particles are entering above the thermocline and staying suspended--aiding in productivity as can be seen in Figures 2.9 and 2.10. These findings indicate that MDNs entering HFB in the fall spawning period are spanning across the entire water column and could be aiding in both primary and secondary production. This also implies that MDNs are available to support the survival of benthic lake invertebrates, as shown by Wiplfli et al. (2011) and Bilby et al. (2011) in rivers and streams supplied with salmon carcasses.

Overall, the spring freshet and fall spawning periods are equally important in the delivery of MDNs to nursery systems. The spring freshet delivered an increased but diluted load of MDNs to HFB, fueling chlorophyll-a, phosphorous, and fluorescence levels and, in turn, increased productivity. The fall spawn delivered a more concentrated load of MDNs to HFB, supplying both the epilimnion and hypolimnion with nutrients that could be used in the growth of algae, plankton populations, and benthic communities.

4.2 Future Management Implications

The results summarized throughout this thesis could help researchers better understand the timing and movement of MDNs entering HFB from the HFR. In Chapter 2, data shows that the load of marine-derived N is driven by higher discharge due to the spring melt. With climates changing across Central British Columbia, it's important to question how earlier spring melts may affect the timing and load of MDNs that are traditionally delivered to HFB in the months of April, May, and June. In Figure 4.1, early melting periods are evident in 2015 and 2017. These melts start as early as January and greatly affect the discharge during previously normal freshet time periods. Colder weather could potentially impact the utilization of MDNs in primary production, limiting the uptake by plankton as growth rates and populations decrease during winter months (Weslawski et al., 1991). MDNs entering HFB at this time could settle on the bottom and become re-suspended in later, high-flow periods or be lost entirely to productivity. The results found in

this thesis, combined with further research into winter MDNs delivery and movement, may help in understanding how earlier melts might affect productivity and juvenile salmon growth rates in nursery systems.

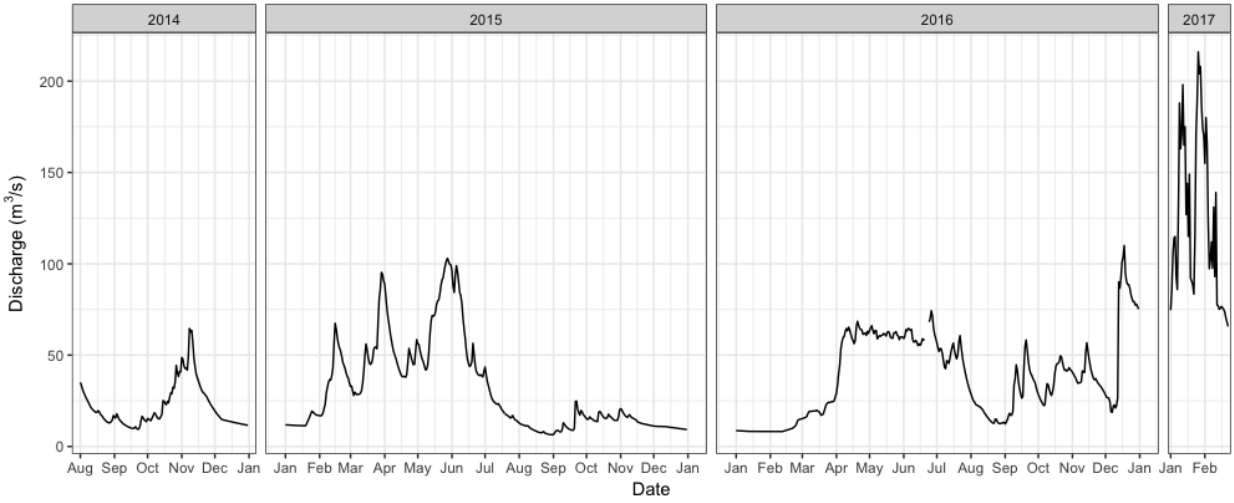


Figure 4.1: 2014 through 2017 hydrograph data taken from Environment Canada - station number 08KH031 in Horsefly River above Quesnel Lake.

Within the last few years, salmon return numbers have been lower than expected (Cone, 2017). If returns continue to decrease, the amount of MDNs being delivered to these nursery systems will also decrease, limiting productivity (Bilby et al., 1996). Past studies have shown the benefits of artificially fertilizing rivers and streams with salmon carcasses to increase productivity throughout the system (Bilby et al., 2011; Claeson et al., 2011; Wipfli et al., 2011). Results from Chapters 2 and 3 demonstrate both timing and delivery tendencies and mechanisms; these results may help in determining when and where artificial fertilization can be implemented-- for example, in systems where low salmon return numbers are limiting primary and secondary production. Although a few published studies project that the increase of imported nutrients to nursery systems is detrimental to future female spawner populations (Holtgrieve & Schindler, 2011; Walters, 2014), there has been no data collected to support these predictions. However, alternative studies show that salmon carcasses, and the nutrient input they provide to nursery systems, are beneficial and of ecological value (Johnson et al., 2004; Wipfli et al., 2010). The research conducted for this thesis, supports the idea that MDNs do enhance productivity in this nursery system and in turn should increase the survivorship of salmon living in this nursery lake.

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Appendix 1: Marine-Derived Nitrogen Load Equation

Delta ^{15}N=3.45 & Amount of N (μg) =152.58 (These numbers were provided by UC-Davis Isotope Laboratory).

$$\delta 15_N = 1000 \times \left(\frac{R\ Sample - R\ Standard}{R\ Standard}\right) \quad (1)$$

UC-Davis Air Standard vs Sample= 99.6337% ^{14}N and 0.3663% ^{15}N

$$\frac{0.3663\%}{99.6337\%} = 0.003676 \quad (2)$$

Equation

$$3.45 = 1000 \times \left(\frac{R\ Sample - 0.003676}{0.003676}\right) \quad (3)$$

Divide both sides by 1000 to remove 1000 on right side of =

$$0.00345 = \frac{R\ Sample - 0.003676}{0.003676} \quad (4)$$

Multiply both sides by 0.003676 to remove 0.003676 in denominator

$$0.00001268 = R\ Sample - 0.003676 \quad (5)$$

Add 0.003676 to both sides to remove 0.003676 to isolate R Sample

$$0.00368868 = R\ Sample$$

$R\ Standard = \frac{15_N}{14_N}$ so $\frac{15_N}{14_N}$ would equal the sample.

Overall equation

$$R\ Sample = 0.003676\left(1 + \left(\frac{\delta 15_N}{1000}\right)\right)$$

To find ^{15}N%

$$\frac{15_N}{14_N} = 0.00368868$$

Multiply through by ^{14}N to get ^{15}N alone

$$15_N = 0.00368868(14_N)$$

Assuming ^{14}N μg + ^{15}N μg would equal my total N so…

$$100\%\ N = 0.00368868(14_N) + 14_N$$

Solve this equation

$$100\%\ N = 14_N(0.00368868 + 1)$$

Divide both sides by (0.00368868 + 1) to get ^{14}N alone

$$14_N = 99.6324876\%$$

Which means

$$15_N = 0.3675124\%$$

Overall equation

$$15_N\% = 100 - \frac{100}{R\ Sample + 1}$$

Take the % and multiply by concentration of N to find the amount of ^{15}N in μg.

Appendix 2: R Script for Data Processing

September 4, 2017

Chapter 2

Packages Used

```
library(dplyr)
library(simmr)
library(tibble)
library(tidyr)
library(viridis)
library(ggplot2)
library(Stack)
library(PerformanceAnalytics)
library(lubridate)
```

R-code used to analyze marine-derived nitrogen and carbon using simmer mixing models.These Scripts were taken from Parnell and Inger (2016) and edited and added to by Jacob Duros and Samuel Albers on August 23, 2017.

Vegetation and salmon delta N/C values at site S5

```
mix = matrix(c(-27.04, -27.04, -27.04, -27.04, -27.04, -27.37, -27.37, -27.74
, -26.68, -26.68, -28.55, -27.74, -27.84,
               -29.74, -29.5, -26.97, -27.88, -29.88, -25, -30.38, -22.86, -2
2.83, -22.88, -22.83, -22.88, -24.52, -22.01,
               -22.15, -23.04, -23.74, -28.18, -27.02, -26.56, -29.19, -26.53
, -26.45, -26.11, -26.29, -26.43, -26.19, -25.95, -26.07,
               -26.22, -26.95, -27.59, -26.53, -26.83, -26.74, -26.65, -26.48
, -26.31, -24.77, -25.54, -26.09, -26.75, 2.52, 2.89,
               2.65, 1.79, 2.34, 1.9, 1.76, 2, 2.45, 2.18, 1.33, 1.6, 2.42, 3
.05, 3.45, 5.6, 4.72, 2.54, 5.33, 3.02, 6.83, 6.68, 6.68,
               6.36, 6.36, 5.11, 7.6, 7.38, 6.54, 6.55, 2.15, 2.1, 1.99, 1.4,
1.64, 1.6, 1.76, 2.01, 2.11, 2.14, 2.4, 2.44, 2.41, 2.55,
               1.95, 2.41, 2.29, 2.52, 2.14, 2.07, 2.24, 2.37, 2.63, 2.32, 2.
57), ncol=2, nrow=55)
```

Naming columns and sources

```
colnames(mix) = c('d13C','d15N')
s_names = c("Aquatic Veg.", "Terrestrial Veg.","Salmon")
```

Entering means and standard deviations calculated from data

```
s_means = matrix(c(-21.55, -30.26, -23.52, 2.33, 2.01, 11.43), ncol=2, nrow=3
)
s_sds = matrix(c(2.59, 2.02, 1.27, 0.57, 1.6, 0.76), ncol=2, nrow=3)
```

Grouping into Study Periods (Summer=1, Spring Freshet=2, Fall Spawn=3)

```
grp = as.integer(c(1, 1, 1, 1, 1, 1, 1, 2, 2, 2, 2, 2, 2, 2, 3, 3, 3, 3, 3, 3
, 3, 3, 3, 3, 3, 3, 3, 3,
                   3, 3, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1
, 1, 2, 2, 2, 2, 2, 2))

simmr_groups = simmr_load(mixtures=mix,
                          source_names=s_names,
                          source_means=s_means,
                          source_sds=s_sds,
                          group=grp)
```

Plotting Mixing Model Output

```
plot(simmr_groups,group=1:3,xlab=expression(paste(delta^13, "C (\u2030)",sep=
"")),
     ylab=expression(paste(delta^15, "N (\u2030)",sep="")),
     title='',mix_name='SPM')
```

Running Simmr's statisical analysis

```
simmr_groups_out = simmr_mcmc(simmr_groups)

##
## Running for group 1
##
## Compiling model graph
##    Resolving undeclared variables
##    Allocating nodes
## Graph information:
##    Observed stochastic nodes: 52
##    Unobserved stochastic nodes: 5
##    Total graph size: 210
##
## Initializing model
##
##
## Running for group 2
##
## Compiling model graph
##    Resolving undeclared variables
##    Allocating nodes
## Graph information:
##    Observed stochastic nodes: 26
##    Unobserved stochastic nodes: 5
##    Total graph size: 158
##
## Initializing model
##
##
```

```
## Running for group 3
##
## Compiling model graph
##    Resolving undeclared variables
##    Allocating nodes
## Graph information:
##    Observed stochastic nodes: 32
##    Unobserved stochastic nodes: 5
##    Total graph size: 170
##
## Initializing model
```

Viewing statistics generated

```
summary(simmr_groups_out,type=c('quantiles','statistics'),group=c(1:3))
```

```
##
## Summary for group 1
##                   2.5%   25%   50%   75% 97.5%
## Aquatic Veg.     0.320 0.369 0.394 0.419 0.471
## Terrestrial Veg. 0.504 0.551 0.574 0.596 0.639
## Salmon           0.009 0.022 0.031 0.041 0.063
## sd_d13C          0.011 0.118 0.256 0.428 0.869
## sd_d15N          0.006 0.068 0.144 0.253 0.529
##                   mean    sd
## Aquatic Veg.     0.394 0.038
## Terrestrial Veg. 0.573 0.034
## Salmon           0.032 0.014
## sd_d13C          0.301 0.234
## sd_d15N          0.176 0.141
##
## Summary for group 2
##                   2.5%   25%   50%   75% 97.5%
## Aquatic Veg.     0.245 0.330 0.369 0.409 0.495
## Terrestrial Veg. 0.471 0.549 0.584 0.621 0.691
## Salmon           0.012 0.030 0.043 0.059 0.095
## sd_d13C          0.020 0.253 0.535 0.922 1.893
## sd_d15N          0.010 0.108 0.235 0.400 0.880
##                   mean    sd
## Aquatic Veg.     0.370 0.062
## Terrestrial Veg. 0.584 0.056
## Salmon           0.046 0.022
## sd_d13C          0.646 0.509
## sd_d15N          0.286 0.233
##
## Summary for group 3
##                   2.5%   25%   50%   75% 97.5%
## Aquatic Veg.     0.123 0.252 0.318 0.381 0.513
## Terrestrial Veg. 0.127 0.247 0.306 0.367 0.489
## Salmon           0.285 0.346 0.375 0.406 0.472
```

```
## sd_d13C          1.917 2.497 2.881 3.361 4.520
## sd_d15N          0.952 1.286 1.499 1.770 2.404
##                   mean    sd
## Aquatic Veg.     0.317 0.098
## Terrestrial Veg. 0.307 0.091
## Salmon           0.376 0.047
## sd_d13C          2.976 0.686
## sd_d15N          1.553 0.384
```

Arranging data into data frame.

```
str(simmr_groups_out)
```

```
## List of 2
##  $ input :List of 12
##   ..$ mixtures           : num [1:55, 1:2] -27 -27 -27 -27 -27 ...
##   .. ..- attr(*, "dimnames")=List of 2
##   .. .. ..$ : NULL
##   .. .. ..$ : chr [1:2] "d13C" "d15N"
##   ..$ source_names       : chr [1:3] "Aquatic Veg." "Terrestrial Veg." "Sa
lmon"
##   ..$ source_means       : num [1:3, 1:2] -21.55 -30.26 -23.52 2.33 2.01 .
..
##   ..$ source_sds         : num [1:3, 1:2] 2.59 2.02 1.27 0.57 1.6 0.76
##   ..$ correction_means   : num [1:3, 1:2] 0 0 0 0 0 0
##   ..$ correction_sds     : num [1:3, 1:2] 0 0 0 0 0 0
##   ..$ concentration_means: num [1:3, 1:2] 1 1 1 1 1 1
##   ..$ group              : int [1:55] 1 1 1 1 1 1 1 2 2 2 ...
##   ..$ n_obs              : int 55
##   ..$ n_tracers          : int 2
##   ..$ n_sources          : int 3
##   ..$ n_groups           : int 3
##   ..- attr(*, "class")= chr "simmr_input"
##  $ output:List of 3
##   ..$ :List of 4
##   .. ..$ : mcmc [1:1000, 1:5] 0.389 0.401 0.423 0.432 0.415 ...
##   .. .. ..- attr(*, "dimnames")=List of 2
##   .. .. .. ..$ : NULL
##   .. .. .. ..$ : chr [1:5] "Aquatic Veg." "Terrestrial Veg." "Salmon" "sd_
d13C" ...
##   .. .. ..- attr(*, "mcpar")= num [1:3] 1010 11000 10
##   .. ..$ : mcmc [1:1000, 1:5] 0.447 0.342 0.415 0.406 0.371 ...
##   .. .. ..- attr(*, "dimnames")=List of 2
##   .. .. .. ..$ : NULL
##   .. .. .. ..$ : chr [1:5] "Aquatic Veg." "Terrestrial Veg." "Salmon" "sd_
d13C" ...
##   .. .. ..- attr(*, "mcpar")= num [1:3] 1010 11000 10
##   .. ..$ : mcmc [1:1000, 1:5] 0.363 0.362 0.385 0.398 0.431 ...
##   .. .. ..- attr(*, "dimnames")=List of 2
##   .. .. .. ..$ : NULL
```

```
##   .. .. .. ..$ : chr [1:5] "Aquatic Veg." "Terrestrial Veg." "Salmon" "sd_
d13C" ...
##   .. .. ..- attr(*, "mcpar")= num [1:3] 1010 11000 10
##   .. ..$ : mcmc [1:1000, 1:5] 0.406 0.337 0.367 0.426 0.375 ...
##   .. .. ..- attr(*, "dimnames")=List of 2
##   .. .. .. ..$ : NULL
##   .. .. .. ..$ : chr [1:5] "Aquatic Veg." "Terrestrial Veg." "Salmon" "sd_
d13C" ...
##   .. .. ..- attr(*, "mcpar")= num [1:3] 1010 11000 10
##   .. ..- attr(*, "class")= chr "mcmc.list"
##   ..$ :List of 4
##   .. ..$ : mcmc [1:1000, 1:5] 0.448 0.502 0.277 0.365 0.308 ...
##   .. .. ..- attr(*, "dimnames")=List of 2
##   .. .. .. ..$ : NULL
##   .. .. .. ..$ : chr [1:5] "Aquatic Veg." "Terrestrial Veg." "Salmon" "sd_
d13C" ...
##   .. .. ..- attr(*, "mcpar")= num [1:3] 1010 11000 10
##   .. ..$ : mcmc [1:1000, 1:5] 0.425 0.387 0.282 0.341 0.396 ...
##   .. .. ..- attr(*, "dimnames")=List of 2
##   .. .. .. ..$ : NULL
##   .. .. .. ..$ : chr [1:5] "Aquatic Veg." "Terrestrial Veg." "Salmon" "sd_
d13C" ...
##   .. .. ..- attr(*, "mcpar")= num [1:3] 1010 11000 10
##   .. ..$ : mcmc [1:1000, 1:5] 0.393 0.288 0.278 0.375 0.282 ...
##   .. .. ..- attr(*, "dimnames")=List of 2
##   .. .. .. ..$ : NULL
##   .. .. .. ..$ : chr [1:5] "Aquatic Veg." "Terrestrial Veg." "Salmon" "sd_
d13C" ...
##   .. .. ..- attr(*, "mcpar")= num [1:3] 1010 11000 10
##   .. ..$ : mcmc [1:1000, 1:5] 0.312 0.406 0.337 0.316 0.373 ...
##   .. .. ..- attr(*, "dimnames")=List of 2
##   .. .. .. ..$ : NULL
##   .. .. .. ..$ : chr [1:5] "Aquatic Veg." "Terrestrial Veg." "Salmon" "sd_
d13C" ...
##   .. .. ..- attr(*, "mcpar")= num [1:3] 1010 11000 10
##   .. ..- attr(*, "class")= chr "mcmc.list"
##   ..$ :List of 4
##   .. ..$ : mcmc [1:1000, 1:5] 0.291 0.473 0.232 0.171 0.317 ...
##   .. .. ..- attr(*, "dimnames")=List of 2
##   .. .. .. ..$ : NULL
##   .. .. .. ..$ : chr [1:5] "Aquatic Veg." "Terrestrial Veg." "Salmon" "sd_
d13C" ...
##   .. .. ..- attr(*, "mcpar")= num [1:3] 1010 11000 10
##   .. ..$ : mcmc [1:1000, 1:5] 0.393 0.376 0.468 0.44 0.443 ...
##   .. .. ..- attr(*, "dimnames")=List of 2
##   .. .. .. ..$ : NULL
##   .. .. .. ..$ : chr [1:5] "Aquatic Veg." "Terrestrial Veg." "Salmon" "sd_
d13C" ...
##   .. .. ..- attr(*, "mcpar")= num [1:3] 1010 11000 10
##   .. ..$ : mcmc [1:1000, 1:5] 0.292 0.326 0.237 0.345 0.204 ...
```

```
##   .. .. ..- attr(*, "dimnames")=List of 2
##   .. .. .. ..$ : NULL
##   .. .. .. ..$ : chr [1:5] "Aquatic Veg." "Terrestrial Veg." "Salmon" "sd_
d13C" ...
##   .. .. ..- attr(*, "mcpar")= num [1:3] 1010 11000 10
##   .. ..$ : mcmc [1:1000, 1:5] 0.35 0.336 0.249 0.189 0.351 ...
##   .. .. ..- attr(*, "dimnames")=List of 2
##   .. .. .. ..$ : NULL
##   .. .. .. ..$ : chr [1:5] "Aquatic Veg." "Terrestrial Veg." "Salmon" "sd_
d13C" ...
##   .. .. ..- attr(*, "mcpar")= num [1:3] 1010 11000 10
##   .. ..- attr(*, "class")= chr "mcmc.list"
##  - attr(*, "class")= chr "simmr_output"

out_all_1 = as_tibble(do.call(rbind, simmr_groups_out$output[[1]][,1:simmr_gr
oups_out$input$n_sources]))
out_all_1$Season = "Summer"
out_all_2 = as_tibble(do.call(rbind, simmr_groups_out$output[[2]][,1:simmr_gr
oups_out$input$n_sources]))
out_all_2$Season = "Spring"
out_all_3 = as_tibble(do.call(rbind, simmr_groups_out$output[[3]][,1:simmr_gr
oups_out$input$n_sources]))
out_all_3$Season = "Fall"

out_all = rbind(rbind(out_all_1, out_all_2), out_all_3)

df = gather(out_all, Source, Proportion, -Season)
df$Season_f=factor(df$Season, levels=c("Spring","Summer","Fall"))
```

Ploting Boxplots

```
ggplot(df, aes(x = Source, y = Proportion)) +
  geom_boxplot(notch = TRUE) +
  #coord_flip() +
  #scale_colour_viridis(discrete = TRUE)+
  theme_bw()+
  facet_grid( . ~ Season_f)
```

Using SPM data to see if there are significant differences between study periods. All scripts were written by Jacob Duros on August 23, 2017.

Inputting and Organizing Data

```
SPM <- read.csv("~/Desktop/Thesis Stuff/ISP.csv")
SPM<-stack(SPM)
names(SPM)<-c("SPM","Period")
```

Performing a 1-way ANOVA

```
SPM1<-aov(SPM~Period,data=SPM)
summary(SPM1)
```

```
##             Df Sum Sq Mean Sq F value   Pr(>F)
## Period       2  127.6   63.80   31.03 1.07e-09 ***
## Residuals   54  111.0    2.06
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

Performing a Tukey's HSD to determine significant differences among study periods.

```
tk1<-TukeyHSD(SPM1)
tk1

##   Tukey multiple comparisons of means
##     95% family-wise confidence level
##
## Fit: aov(formula = SPM ~ Period, data = SPM)
##
## $Period
##                       diff       lwr        upr     p adj
## Spawn-Freshet  -2.9173306 -4.038444 -1.7962169 0.0000002
## Summer-Freshet -3.3797887 -4.500902 -2.2586750 0.0000000
## Summer-Spawn   -0.4624581 -1.583572  0.6586556 0.5837308
```

Using organic and inorganic SPM data to see if there are significant differences between study periods. All scripts were written by Jacob Duros on August 23, 2017.

Inputting Data

```
ISPS <- read.csv("~/Desktop/Thesis Stuff/ISP.csv")
OSPS <- read.csv("~/Desktop/Thesis Stuff/OSP.csv")
```

Organzing Inorganic SPM Data

```
ISP<-stack(ISPS)
names(ISP)<-c("IPM","Period")
```

Performing a 1-way ANOVA

```
ISP1<-aov(IPM~Period,data=ISP)
summary(ISP1)

##             Df Sum Sq Mean Sq F value   Pr(>F)
## Period       2  127.6   63.80   31.03 1.07e-09 ***
## Residuals   54  111.0    2.06
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

Performing a Tukey's HSD to determine significant differences among study periods.

```
tk2<-TukeyHSD(ISP1)
tk2
```

```
##   Tukey multiple comparisons of means
##     95% family-wise confidence level
##
## Fit: aov(formula = IPM ~ Period, data = ISP)
##
## $Period
##                       diff       lwr        upr     p adj
## Spawn-Freshet  -2.9173306 -4.038444 -1.7962169 0.0000002
## Summer-Freshet -3.3797887 -4.500902 -2.2586750 0.0000000
## Summer-Spawn   -0.4624581 -1.583572  0.6586556 0.5837308
```

Organzing organic SPM Data

```
OSP<-stack(OSPS)
names(OSP)<-c("OPM","Period")
```

Performing a 1-way ANOVA

```
OSP1<-aov(OPM~Period,data=OSP)
summary(OSP1)
```

```
##             Df Sum Sq Mean Sq F value   Pr(>F)
## Period       2  6.877   3.439   10.86 0.000109 ***
## Residuals   54 17.097   0.317
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

Performing a Tukey's HSD to determine significant differences among study periods.

```
tk3<-TukeyHSD(OSP1)
tk3
```

```
##   Tukey multiple comparisons of means
##     95% family-wise confidence level
##
## Fit: aov(formula = OPM ~ Period, data = OSP)
##
## $Period
##                       diff        lwr         upr     p adj
## Spawn-Freshet  -0.5354107 -0.9753675 -0.09545379 0.0134250
## Summer-Freshet -0.8403784 -1.2803353 -0.40042152 0.0000752
## Summer-Spawn   -0.3049677 -0.7449246  0.13498915 0.2257706
```

Using Isotope data to see if there are significant differences between study periods. All scripts were written by Jacob Duros on August 23, 2017.

Inputting Data

```
Stable.Isotope <- read.csv("~/Desktop/Thesis Stuff/Stable Isotope.csv")
Stable.Isotope$Date<-mdy(Stable.Isotope$Date)
```

Organize data for Nitrogen

```
IsoN <- Stable.Isotope %>%
  filter(Site=="S5") %>%
  select(d15N, Group) %>%
  rename(`Period`=Group)
```

Performing a 1-way ANOVA

```
NI<-aov(d15N~Period,data=IsoN)
summary(NI)
```

```
##             Df Sum Sq Mean Sq F value   Pr(>F)
## Period       2 112.63   56.32   43.37 6.08e-11 ***
## Residuals   42  54.54    1.30
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

Performing a Tukey's HSD to determine significant differences among study periods.

```
tk4<-TukeyHSD(NI)
tk4
```

```
##   Tukey multiple comparisons of means
##     95% family-wise confidence level
##
## Fit: aov(formula = d15N ~ Period, data = IsoN)
##
## $Period
##                        diff       lwr       upr     p adj
## Spawn-Freshet   3.23976608  2.329184  4.150348 0.0000000
## Summer-Freshet  0.03546053 -1.131326  1.202247 0.9969990
## Summer-Spawn   -3.20430556 -4.380656 -2.027955 0.0000002
```

Organize data for Carbon

```
IsoC <- Stable.Isotope %>%
  filter(Site=="S5") %>%
  select(d13C, Group) %>%
  rename(`Period`=Group)
```

Performing a 1-way ANOVA

```
CI<-aov(d13C~Period,data=IsoC)
summary(CI)
```

```
##             Df Sum Sq Mean Sq F value Pr(>F)
## Period       2  18.78   9.391    2.19  0.125
## Residuals   42 180.15   4.289
```

Performing a Tukey's HSD to determine significant differences among study periods.

```
tk5<-TukeyHSD(CI)
tk5
```

```
##   Tukey multiple comparisons of means
##     95% family-wise confidence level
##
## Fit: aov(formula = d13C ~ Period, data = IsoC)
##
## $Period
##                       diff       lwr       upr     p adj
## Spawn-Freshet   1.3771053 -0.277873 3.0320835 0.1194931
## Summer-Freshet  0.2333553 -1.887273 2.3539836 0.9614030
## Summer-Spawn   -1.1437500 -3.281761 0.9942609 0.4032868
```

Using isotope loading data to see if there are significant differences between study periods. All scripts were written by Jacob Duros on August 23, 2017.

Import data file

```
IsoAnova <- read.csv("~/Desktop/Thesis Stuff/IsoAnova.csv")
```

Organize nitrogen 15 loading data

```
ISO<-stack(IsoAnova)
names(ISO)<-c("N","Period")
```

Performing a 1-way ANOVA

```
ISO1<-aov(N~Period,data=ISO)
summary(ISO1)
```

```
##             Df Sum Sq Mean Sq F value   Pr(>F)
## Period       2  85.07   42.54   13.46 2.89e-05 ***
## Residuals   43 135.91    3.16
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
## 11 observations deleted due to missingness
```

Performing a Tukey's HSD to determine significant differences among study periods.

```
tk6<-TukeyHSD(ISO1)
tk6
```

```
##   Tukey multiple comparisons of means
##     95% family-wise confidence level
##
## Fit: aov(formula = N ~ Period, data = ISO)
##
## $Period
##                     diff       lwr        upr     p adj
## Spawn-Freshet  -2.943265 -4.433864 -1.4526663 0.0000582
## Summer-Freshet -2.483722 -4.075041 -0.8924034 0.0013294
## Summer-Spawn    0.459543 -1.211891  2.1309775 0.7835296
```

Using isotope loading data and discharge data to see if there is a correlation betweent he two variables. All scripts were written by Jacob Duros on August 23, 2017.

Organzing data

```
isoload<-read.csv("~/Desktop/Thesis Stuff/isoload.csv")
coriso <- isoload %>%
  select(Flow,N15)
```

Using Kendall's Correlation method

```
cor(coriso, use="complete.obs", method="kendall")

##           Flow       N15
## Flow 1.0000000 0.6805221
## N15  0.6805221 1.0000000

chart.Correlation(coriso)
```

Using chlorophyll-a data to see if there are differences between study periods and study sites. All scripts were written by Jacob Duros on August 23, 2017.

Importing data

```
Chlorophyll <- read.csv("~/Documents/Graduate Research/Lab Data/Chlorophyll.csv")
HFB <- read.csv("~/Desktop/Thesis Stuff/HFB.csv")
```

Organizing and formatting data

```
Chlorophyll$Date<-mdy(Chlorophyll$Date)
HFB$Date<-mdy(HFB$Date)
CHL <- Chlorophyll %>%
  full_join(HFB, by=c("Date","Site")) %>%
  select(Date,Site,Chlorophyll.x, Study.Period)%>%
  dplyr::rename("Chlorophyll"=Chlorophyll.x) %>%
  filter(Site %in% c("S1", "S2","S3","S4"))
```

Using fluorescence data to see if there are differences between study periods and study sites. All scripts were written by Jacob Duros on August 23, 2017.

Importing data

```
Fluorescence <- read.csv("~/Desktop/Fluorescence.csv")
```

Organizing and formatting data

```
Fluorescence$Date<-mdy(Fluorescence$Date)

  #S5
FLU5 <- Fluorescence %>%
  filter(Site %in% c("S5"))
```

```
  #S3
FLU3 <- Fluorescence %>%
  filter(Site %in% c("S3"))
  #S1
FLU1 <- Fluorescence %>%
  filter(Site %in% c("S1"))
```

S5 Performing a 1-way ANOVA

```
FLUANOVA5<-aov(lm(fluorescence ~ Period, FLU5))
summary(FLUANOVA5)

##             Df Sum Sq Mean Sq F value  Pr(>F)
## Period       2  3.108  1.5541   5.489 0.00736 **
## Residuals   45 12.741  0.2831
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

S5 Performing a Tukey's HSD to determine significant differences among study periods.

```
TukeyHSD(FLUANOVA5)

##   Tukey multiple comparisons of means
##     95% family-wise confidence level
##
## Fit: aov(formula = lm(fluorescence ~ Period, FLU5))
##
## $Period
##                       diff        lwr        upr     p adj
## Freshet-Fall    0.53136697  0.1215039 0.94123001 0.0081799
## Summer-Fall     0.02246989 -0.5099578 0.55489760 0.9942496
## Summer-Freshet -0.50889708 -1.0568734 0.03907923 0.0735650
```

S3 Performing a 1-way ANOVA

```
FLUANOVA3<-aov(lm(fluorescence ~ Period, FLU3))
summary(FLUANOVA3)

##             Df Sum Sq Mean Sq F value Pr(>F)
## Period       2  0.595 0.29741   3.131 0.0558 .
## Residuals   36  3.420 0.09499
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

S3 Performing a Tukey's HSD to determine significant differences among study periods.

```
TukeyHSD(FLUANOVA3)

##   Tukey multiple comparisons of means
##     95% family-wise confidence level
##
## Fit: aov(formula = lm(fluorescence ~ Period, FLU3))
```

```
##
## $Period
##                       diff        lwr        upr     p adj
## Freshet-Fall   -0.2125573 -0.4876402 0.06252550 0.1565530
## Summer-Fall    -0.2985613 -0.6161996 0.01907696 0.0689931
## Summer-Freshet -0.0860040 -0.4036423 0.23163430 0.7869023
```

S1 Performing a 1-way ANOVA

```
FLUANOVA1<-aov(lm(fluorescence ~ Period, FLU1))
summary(FLUANOVA1)

##             Df Sum Sq Mean Sq F value Pr(>F)
## Period       2 0.2666 0.13331   2.998 0.0632 .
## Residuals   34 1.5120 0.04447
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

S1 Performing a Tukey's HSD to determine significant differences among study periods.

```
TukeyHSD(FLUANOVA1)

##   Tukey multiple comparisons of means
##     95% family-wise confidence level
##
## Fit: aov(formula = lm(fluorescence ~ Period, FLU1))
##
## $Period
##                        diff        lwr        upr     p adj
## Freshet-Fall   -0.15681081 -0.3488377 0.03521605 0.1273443
## Summer-Fall    -0.19454117 -0.4207689 0.03168661 0.1033620
## Summer-Freshet -0.03773036 -0.2667512 0.19129046 0.9143121
```

Using phosphorus data to see if there are differences between study periods. All scripts were written by Jacob Duros on August 23, 2017.

Importing data

```
PLevels <- read.csv("~/Documents/Graduate Research/Thesis/PLevels.csv")
P_Work <- read.csv("~/Documents/Graduate Research/Thesis/P Work.csv")
```

Organizing and formatting data

```
P_Work$Date<-mdy(P_Work$Date)
Phos <- P_Work %>%
  full_join(PLevels, by=c("ID")) %>%
  select(-ID)%>%
  filter(Site=="S5")
```

Data frame was exported into excel to add DP data column

```
write.csv(Phos, file="Phos.csv")
```

File imported back into R

```
PhosP <- read.csv("~/Desktop/Thesis Stuff/PhosP.csv")
```

Organizing and formatting data

```
PhosP$Date<-mdy(PhosP$Date)
Phos1 <- PhosP %>%
  gather(variable, value, -Date)

Phos1<-Phos1 %>%
  filter(variable=="Total")
```

Performing a 1-way ANOVA

```
PAOV <- read.csv("~/Desktop/Thesis Stuff/PAOV.csv")
PhosANOVA<-aov(lm(Concentration ~ Period * Form, PAOV))
summary(PhosANOVA)
```

```
##             Df    Sum Sq   Mean Sq F value   Pr(>F)
## Period       2 0.0004713 0.0002357   8.886 0.000318 ***
## Form         1 0.0004557 0.0004557  17.183 8.14e-05 ***
## Period:Form  2 0.0000427 0.0000214   0.806 0.450113
## Residuals   83 0.0022011 0.0000265
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

Performing a Tukey's HSD to determine significant differences among study periods.

```
TukeyHSD(PhosANOVA)
```

```
##   Tukey multiple comparisons of means
##     95% family-wise confidence level
##
## Fit: aov(formula = lm(Concentration ~ Period * Form, PAOV))
##
## $Period
##                          diff          lwr          upr     p adj
## Spawn-Freshet   0.0044447619  0.001387006  0.007502518 0.0023724
## Summer-Freshet -0.0008952381 -0.004152309  0.002361833 0.7895239
## Summer-Spawn   -0.0053400000 -0.008705669 -0.001974331 0.0008338
##
## $Form
##                         diff         lwr         upr    p adj
## total-dissovled 0.004566646 0.002371678 0.006761614 8.36e-05
##
## $`Period:Form`
##                                              diff           lwr         upr
## Spawn:dissovled-Freshet:dissovled   0.0054095238  0.0004240619 0.010394986
## Summer:dissovled-Freshet:dissovled  0.0001452381 -0.0050383983 0.005328875
## Freshet:total-Freshet:dissovled     0.0063452381  0.0011616017 0.011528875
## Spawn:total-Freshet:dissovled       0.0087809524  0.0035973160 0.013964589
```

```
## Summer:total-Freshet:dissovled      0.0037395238 -0.0020327294 0.009511777
## Summer:dissovled-Spawn:dissovled   -0.0052642857 -0.0107623624 0.000233791
## Freshet:total-Spawn:dissovled       0.0009357143 -0.0045623624 0.006433791
## Spawn:total-Spawn:dissovled         0.0033714286 -0.0021266481 0.008869505
## Summer:total-Spawn:dissovled       -0.0016700000 -0.0077262090 0.004386209
## Freshet:total-Summer:dissovled      0.0062000000  0.0005216108 0.011878389
## Spawn:total-Summer:dissovled        0.0086357143  0.0029573251 0.014314103
## Summer:total-Summer:dissovled       0.0035942857 -0.0026260780 0.009814649
## Spawn:total-Freshet:total           0.0024357143 -0.0032426749 0.008114103
## Summer:total-Freshet:total         -0.0026057143 -0.0088260780 0.003614649
## Summer:total-Spawn:total           -0.0050414286 -0.0112617923 0.001178935
##                                          p adj
## Spawn:dissovled-Freshet:dissovled  0.0254926
## Summer:dissovled-Freshet:dissovled 0.9999995
## Freshet:total-Freshet:dissovled    0.0075875
## Spawn:total-Freshet:dissovled      0.0000571
## Summer:total-Freshet:dissovled     0.4155433
## Summer:dissovled-Spawn:dissovled   0.0685494
## Freshet:total-Spawn:dissovled      0.9961739
## Spawn:total-Spawn:dissovled        0.4784423
## Summer:total-Spawn:dissovled       0.9659459
## Freshet:total-Summer:dissovled     0.0241000
## Spawn:total-Summer:dissovled       0.0003903
## Summer:total-Summer:dissovled      0.5450094
## Spawn:total-Freshet:total          0.8100450
## Summer:total-Freshet:total         0.8248692
## Summer:total-Spawn:total           0.1809817
```

Performing a correlation using phosphorus, chlorophyll-a, discharge, isotope, and river temperature data to see if there are trends among variables. This data was also used to perform the AIC statistical analysis below to see what variables drive the delivery of delta 15N and the load of 15N. All scripts were written by Jacob Duros on August 23, 2017.

Importing data sets that haven't already been imported

```
Hobo_Complete <- read.csv("~/Documents/Graduate Research/Hobo/Hobo Complete.csv")
#Discharge
HFR.Daily.Flow<-read.csv("~/Documents/untitled folder/untitled folder 3/Water Flow Data/HFR Daily Flow.csv")
Thesis.data<-read.csv("~/Desktop/Thesis Stuff/Thesis Data.csv")

Hobo_Complete$Date<-mdy(Hobo_Complete$Date)
HFR.Daily.Flow$Date<-mdy(HFR.Daily.Flow$Date)
Thesis.data$Date<-mdy(Thesis.data$Date)
```

Organizing and pulling all data into same dataframe

```
FD<-HFR.Daily.Flow%>%
  select(Date,Mean)%>%
```

```
  full_join(Hobo_Complete, by=c("Date")) %>%
  full_join(Stable.Isotope, by=c("Date"))%>%
  full_join(Thesis.data, by=c("Date"))%>%
  select(Date, Mean, RiverTemp,d15N,SPM.mg.L,N.Amount..ug.)%>%
  full_join(Phos1, by=c("Date"))%>%
  full_join(CHL, by=c("Date"))%>%
  distinct(Date, .keep_all = TRUE)%>%
  select(-Date,-Chlorophyll)%>%
  rename("Flow"=Mean,"SPM"=SPM.mg.L,"NLoad"=N.Amount..ug.)
```

Creating linear models to see what drives the delivery of delta 15N to HFB.

1st linear model includes variables: Discharge, River Temp, SPM, TP, and Study Period. 1st order terms only.

```
lm1<-lm(FD$d15N~FD$Flow+FD$RiverTemp+FD$SPM+FD$TP+FD$Study.Period)
summary(lm1)

##
## Call:
## lm(formula = FD$d15N ~ FD$Flow + FD$RiverTemp + FD$SPM + FD$TP +
##     FD$Study.Period)
##
## Residuals:
##      Min       1Q   Median       3Q      Max
## -1.76512 -0.23015 -0.00297  0.38294  1.18630
##
## Coefficients:
##                       Estimate Std. Error t value Pr(>|t|)
## (Intercept)           -0.37431    1.31105  -0.286  0.77976
## FD$Flow                0.03234    0.01510   2.142  0.05175 .
## FD$RiverTemp          -0.04320    0.05734  -0.753  0.46468
## FD$SPM                 0.03807    0.06547   0.581  0.57088
## FD$TP                 23.07878   29.07055   0.794  0.44151
## FD$Study.PeriodSpawn   2.32161    0.76561   3.032  0.00962 **
## FD$Study.PeriodSummer  2.23920    1.01357   2.209  0.04572 *
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Residual standard error: 0.7668 on 13 degrees of freedom
##   (343 observations deleted due to missingness)
## Multiple R-squared:  0.566,  Adjusted R-squared:  0.3657
## F-statistic: 2.826 on 6 and 13 DF,  p-value: 0.05497
```

2nd linear model includes variables: Discharge, SPM, and Study Period. 1st order terms only.

```
lm2<-lm(FD$d15N~FD$Flow+FD$SPM+FD$Study.Period)
summary(lm2)

##
## Call:
```

```
## lm(formula = FD$d15N ~ FD$Flow + FD$SPM + FD$Study.Period)
##
## Residuals:
##      Min       1Q   Median       3Q      Max
## -1.76584 -0.31446  0.06707  0.41460  1.08260
##
## Coefficients:
##                         Estimate Std. Error t value Pr(>|t|)
## (Intercept)           -0.092860   0.579138  -0.160 0.873901
## FD$Flow                0.024062   0.008633   2.787 0.010008 *
## FD$SPM                 0.014761   0.010186   1.449 0.159718
## FD$Study.PeriodSpawn   2.164635   0.471438   4.592 0.000107 ***
## FD$Study.PeriodSummer  1.668899   0.507773   3.287 0.003002 **
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Residual standard error: 0.6547 on 25 degrees of freedom
##   (333 observations deleted due to missingness)
## Multiple R-squared:  0.4908, Adjusted R-squared:  0.4093
## F-statistic: 6.024 on 4 and 25 DF,  p-value: 0.001548
```

3rd linear model includes variables: Discharge, SPM, and Study Period. 1st and 2nd order terms are used.

```
lm3<-lm(FD$d15N~(FD$Flow+FD$SPM+FD$Study.Period)^2)
summary(lm3)

##
## Call:
## lm(formula = FD$d15N ~ (FD$Flow + FD$SPM + FD$Study.Period)^2)
##
## Residuals:
##      Min       1Q   Median       3Q      Max
## -1.75745 -0.40912  0.06429  0.40796  1.06129
##
## Coefficients:
##                                  Estimate Std. Error t value Pr(>|t|)
## (Intercept)                      0.240941   1.696565   0.142    0.888
## FD$Flow                          0.016118   0.037439   0.431    0.671
## FD$SPM                          -0.060180   0.338559  -0.178    0.861
## FD$Study.PeriodSpawn             1.801568   1.686708   1.068    0.298
## FD$Study.PeriodSummer            2.643794   2.077979   1.272    0.218
## FD$Flow:FD$SPM                   0.001918   0.008574   0.224    0.825
## FD$Flow:FD$Study.PeriodSpawn     0.010856   0.036204   0.300    0.767
## FD$Flow:FD$Study.PeriodSummer   -0.081255   0.101828  -0.798    0.434
## FD$SPM:FD$Study.PeriodSpawn      0.038245   0.258042   0.148    0.884
## FD$SPM:FD$Study.PeriodSummer     0.364011   0.634177   0.574    0.572
##
## Residual standard error: 0.7125 on 20 degrees of freedom
##   (333 observations deleted due to missingness)
```

```
## Multiple R-squared:  0.5175, Adjusted R-squared:  0.3004
## F-statistic: 2.384 on 9 and 20 DF,  p-value: 0.05074
```

4th linear model includes variables: Discharge, SPM, which are interacting with Study Period which was the only significant term in the 3rd model.

```
lm4<-lm(FD$d15N~(FD$Flow*FD$Study.Period)+(FD$SPM*FD$Study.Period))#first ord
er with interaction between signifcant from above
summary(lm4)

##
## Call:
## lm(formula = FD$d15N ~ (FD$Flow * FD$Study.Period) + (FD$SPM *
##     FD$Study.Period))
##
## Residuals:
##      Min       1Q   Median       3Q      Max
## -1.75966 -0.39337  0.02412  0.40694  1.05627
##
## Coefficients:
##                                Estimate Std. Error t value Pr(>|t|)
## (Intercept)                   -0.104752   0.684539  -0.153   0.8798
## FD$Flow                        0.024152   0.010351   2.333   0.0297 *
## FD$Study.PeriodSpawn           2.128367   0.824086   2.583   0.0174 *
## FD$Study.PeriodSummer          2.950071   1.527524   1.931   0.0671 .
## FD$SPM                         0.015522   0.011074   1.402   0.1756
## FD$Flow:FD$Study.PeriodSpawn   0.004849   0.023727   0.204   0.8400
## FD$Flow:FD$Study.PeriodSummer -0.087914   0.095152  -0.924   0.3660
## FD$Study.PeriodSpawn:FD$SPM   -0.017744   0.061468  -0.289   0.7757
## FD$Study.PeriodSummer:FD$SPM   0.339249   0.610157   0.556   0.5841
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Residual standard error: 0.6962 on 21 degrees of freedom
##   (333 observations deleted due to missingness)
## Multiple R-squared:  0.5163, Adjusted R-squared:  0.332
## F-statistic: 2.802 on 8 and 21 DF,  p-value: 0.02785
```

Performing an AIC on linear models 1, 2, 3, & 4.

```
AIC(lm1,lm2,lm3,lm4)

##     df      AIC
## lm1  8 53.51926
## lm2  6 66.25595
## lm3 11 74.63790
## lm4 10 72.71289
```

Creating linear models to see what drives the delivery of the load of 15N to HFB.

5th linear model includes variables: Discharge, River Temp, SPM, TP, and Study Period. 1st order terms only.

```
lm5<-lm(FD$NLoad~FD$Flow+FD$RiverTemp+FD$SPM+FD$TP+FD$Study.Period)
summary(lm5)

##
## Call:
## lm(formula = FD$NLoad ~ FD$Flow + FD$RiverTemp + FD$SPM + FD$TP +
##     FD$Study.Period)
##
## Residuals:
##      Min       1Q   Median       3Q      Max
## -130.839  -64.389    4.416   27.570  230.098
##
## Coefficients:
##                         Estimate Std. Error t value Pr(>|t|)
## (Intercept)              394.168    167.603   2.352   0.0351 *
## FD$Flow                   -4.211      1.930  -2.181   0.0481 *
## FD$RiverTemp               2.594      7.331   0.354   0.7291
## FD$SPM                    -1.139      8.370  -0.136   0.8938
## FD$TP                    726.663   3716.341   0.196   0.8480
## FD$Study.PeriodSpawn     -78.445     97.875  -0.801   0.4373
## FD$Study.PeriodSummer -232.485    129.574  -1.794   0.0961 .
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Residual standard error: 98.02 on 13 degrees of freedom
##   (343 observations deleted due to missingness)
## Multiple R-squared:  0.4822, Adjusted R-squared:  0.2432
## F-statistic: 2.018 on 6 and 13 DF,  p-value: 0.1359
```

6th linear model includes variables: Discharge, SPM, and Study Period. 1st order terms only.

```
lm6<-lm(FD$NLoad~FD$Flow+FD$SPM+FD$Study.Period)
summary(lm6)

##
## Call:
## lm(formula = FD$NLoad ~ FD$Flow + FD$SPM + FD$Study.Period)
##
## Residuals:
##      Min       1Q   Median       3Q      Max
## -167.518  -60.850    5.248   35.821  240.319
##
## Coefficients:
##                         Estimate Std. Error t value Pr(>|t|)
## (Intercept)              400.9295   100.4172   3.993 0.000505 ***
## FD$Flow                   -3.6205     1.4969  -2.419 0.023191 *
## FD$SPM                    -0.5429     1.7662  -0.307 0.761084
## FD$Study.PeriodSpawn     -60.0858    81.7431  -0.735 0.469145
```

```
## FD$Study.PeriodSummer -60.7687    88.0433  -0.690 0.496418
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Residual standard error: 113.5 on 25 degrees of freedom
##   (333 observations deleted due to missingness)
## Multiple R-squared:  0.3073, Adjusted R-squared:  0.1964
## F-statistic: 2.772 on 4 and 25 DF,  p-value: 0.0492
```

7th linear model includes variables: Discharge, SPM, and Study Period. 1st and 2nd order terms are used.

```
lm7<-lm(FD$NLoad~(FD$Flow+FD$SPM+FD$Study.Period)^2)#all 1st and 2nd order te
rms
summary(lm7)

##
## Call:
## lm(formula = FD$NLoad ~ (FD$Flow + FD$SPM + FD$Study.Period)^2)
##
## Residuals:
##      Min       1Q   Median       3Q      Max
## -227.986  -45.666   -7.244   36.211  241.226
##
## Coefficients:
##                               Estimate Std. Error t value Pr(>|t|)
## (Intercept)                  288.9964   287.7664   1.004    0.327
## FD$Flow                       -1.0805     6.3504  -0.170    0.867
## FD$SPM                        21.9452    57.4254   0.382    0.706
## FD$Study.PeriodSpawn          20.2377   286.0945   0.071    0.944
## FD$Study.PeriodSummer        183.4968   352.4609   0.521    0.608
## FD$Flow:FD$SPM                -0.5698     1.4542  -0.392    0.699
## FD$Flow:FD$Study.PeriodSpawn  -0.9348     6.1408  -0.152    0.881
## FD$Flow:FD$Study.PeriodSummer -3.3715    17.2717  -0.195    0.847
## FD$SPM:FD$Study.PeriodSpawn  -12.6004    43.7684  -0.288    0.776
## FD$SPM:FD$Study.PeriodSummer -87.5118   107.5673  -0.814    0.425
##
## Residual standard error: 120.9 on 20 degrees of freedom
##   (333 observations deleted due to missingness)
## Multiple R-squared:  0.3719, Adjusted R-squared:  0.08925
## F-statistic: 1.316 on 9 and 20 DF,  p-value: 0.2895
```

8th linear model includes variables: Discharge, SPM, which are interacting with Study Period.

```
lm8<-lm(FD$NLoad~(FD$Flow*FD$SPM)+(FD$Flow*FD$Study.Period)+(FD$SPM*FD$Study.
Period))#first order with interaction between signifcant from above

summary(lm8)

##
## Call:
```

```
## lm(formula = FD$NLoad ~ (FD$Flow * FD$SPM) + (FD$Flow * FD$Study.Period) +
##     (FD$SPM * FD$Study.Period))
##
## Residuals:
##      Min       1Q   Median       3Q      Max
## -227.986  -45.666   -7.244   36.211  241.226
##
## Coefficients:
##                                Estimate Std. Error t value Pr(>|t|)
## (Intercept)                    288.9964   287.7664   1.004    0.327
## FD$Flow                         -1.0805     6.3504  -0.170    0.867
## FD$SPM                          21.9452    57.4254   0.382    0.706
## FD$Study.PeriodSpawn            20.2377   286.0945   0.071    0.944
## FD$Study.PeriodSummer          183.4968   352.4609   0.521    0.608
## FD$Flow:FD$SPM                  -0.5698     1.4542  -0.392    0.699
## FD$Flow:FD$Study.PeriodSpawn    -0.9348     6.1408  -0.152    0.881
## FD$Flow:FD$Study.PeriodSummer   -3.3715    17.2717  -0.195    0.847
## FD$SPM:FD$Study.PeriodSpawn    -12.6004    43.7684  -0.288    0.776
## FD$SPM:FD$Study.PeriodSummer   -87.5118   107.5673  -0.814    0.425
##
## Residual standard error: 120.9 on 20 degrees of freedom
##   (333 observations deleted due to missingness)
## Multiple R-squared:  0.3719, Adjusted R-squared:  0.08925
## F-statistic: 1.316 on 9 and 20 DF,  p-value: 0.2895
```

Performing an AIC on linear models 5, 6, 7, & 8.

```
AIC(lm5,lm6,lm7,lm8)
```

```
##     df      AIC
## lm5  8 247.5500
## lm6  6 375.5889
## lm7 11 382.6505
## lm8 11 382.6505
```