A REVIEW OF TWENTY YEARS OF NUTRIENT ENRICHMENT IN THE SALMON RIVER WATERSHED, VANCOUVER ISLAND (1989-2010)

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EXECUTIVE SUMMARY

The feasibility of enriching the Salmon River watershed with nutrients was explored beginning in the summer of 1988. The first nutrient applications were conducted in 1989 above the BC Hydro diversion dam in Grilse and Norris creeks. Other sites were added over time including several in the mainstem Salmon River and two in the Memekay River through 2010. Following two decades of nutrient treatments, members of the BC Hydro Fish and Wildlife Compensation Program (FWCP) board requested a detailed review of the program, conditional to future financial support.

An investigation of the bio-physical response to varying nutrient treatments was conducted including the effect of nutrient quantity, application timing and stream flow. Biological response was characterized by increased periphyton accrual, accelerated juvenile steelhead growth, and changes in adult steelhead abundance/ distribution.

Nutrient concentrations in untreated reaches were found to follow similar seasonal patterns. Phosphorus (P) levels decreased throughout the treatment period (typically June to September) while nitrogen (N) concentrations increased. The addition of nutrients was found to increase P immediately downstream of treatment sites but decreased proportionally with distance. N decreased in reaches of increased productivity but appeared to recover at the estimated spiralling distance for most sites (5-15 km). Periphyton accrual in treated reaches (chlorophyll *a*) was found to be significantly higher compared to control sites in most years. The source of nutrients (product or application method) did not appear to influence monitoring results despite frequent changes to the program.

Nutrient quantity and earlier application timing were found to be positively correlated with the magnitude of biological response (r^2=0.42 and 0.47, respectively) while stream flow was negatively correlated (r^2=0.48). Steelhead fry were found to be significantly heavier in treated reaches (α 0.05) during eleven of twelve years. The magnitude of the response averaged 104% (1.56 g) and varied between 11% and 218%. The response was found to be similar at sites 350 m and 3.8 km downstream of the nutrient source (p=0.40) suggesting a spiralling distance of nearly 4 km in Grilse Creek.

The average age of steelhead smolts captured at the diversion dam (1989-2002) was found to be consistent with nutrient treatments on the Keogh River at 2.15 years. The length of two year old smolts was found to be highly correlated to the quantity of nutrients applied to Grilse Creek two years prior (r^2=0.84) suggesting early growth sustained as fry may be driving increased size and abundance of smolts under enriched conditions.

Periphyton accrual did not correlate with the magnitude of juvenile steelhead growth response although it was found to be strongest near the nutrient source. High nutrient loading in Grilse Creek (100 kg P or more) produced an exponential algal growth response while only a moderate response was associated with lower loading rates (15-80 kg P).

The density of steelhead fry in the Salmon River is positively correlated with the number of adults observed during March snorkel counts in an 11.5 km index reach. Both fry and

adult densities have been approaching target levels in recent years (2006-2011) and the density of adults in the upper watershed is currently at the highest level formally documented. Further investigation into bio-physical effects of nutrient enrichment is recommended by continuing monitoring in non-treatment years.

Citation:

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1.0 INTRODUCTION

The Salmon River watershed on northern Vancouver Island has been enriched annually since 1989 as a fish habitat restoration measure. The construction of the BC Hydro diversion dam in 1958 followed by the operation of the facility represents one of the largest anthropogenic influences on the watershed. Several footprint impacts associated with the dam have been identified including loss of habitat and reduced mainstem access according to the BC Hydro Strategic Plan. The feasibility of a nutrient enrichment program was first investigated in 1988 through the collection of baseline water chemistry and periphyton data (Perrin 1989). A pilot program was initiated in 1989 and 1990 through funding from the Habitat Conservation Trust Fund (now Habitat Conservation Trust Foundation; Perrin 1990, 1991). Nutrients, mainly phosphorus and nitrogen, have been continuously applied during the spring and summer growing season for twenty-two years (Carswell 1992a-1993a, Hansen 1994a, 1995, 1999a,c,e,f, 2001a, 2002a, Hansen and Wright 2003, Manley et al. 2005, Hansen and Wright 2007, Pellett 2008-2011).

A variety of monitoring techniques have been implemented including periphyton sampling, water chemistry, stream temperature and fish growth analysis. A comprehensive review of the results to date was requested by the Coastal Fish and Wildlife Compensation Program Board (FWCP), to support future enrichment proposals.

2.0 GOALS AND OBJECTIVES

Nutrient enrichment of the Salmon River watershed was intended to stimulate the growth of stream rearing salmonids as compensation for footprint impacts associated with operation of the BC Hydro diversion dam. Increased growth prior to the over-wintering period leads to greater survival and optimizes the number of smolts produced by each spawner. There is also evidence to support increased smolt size positively influences marine survival (McCubbing and Ward 2001). Enrichment has also been found to decrease the average age of smolts, effectively reducing cumulative over-winter mortality and further increasing stock productivity (Slaney et al. 2003).

The objective of nutrient enrichment activities in the Salmon Watershed has been previously stated as *"…. to maximize freshwater productivity (i.e., smolts) in order to increase the probability of sustainable escapements through periods of reduced ocean survival."* (an objective of the nutrient enrichment project funded by BC Hydro through the Bridge Coastal Restoration Program). Slaney et al. (2003) indicated that nutrient enrichment of the Salmon River had the potential to "*offset logging impacts and to accelerate colonization of steelhead in headwater reaches upstream of a diversion*".

A review of nutrient enrichment in the Salmon River watershed provides an opportunity to summarize multiple data sets. Conclusions from individual treatment years are often limited and are typically a presentation of results rather than a comprehensive analysis. The primary goal of this review is to analyze the data in a way that reflects how nutrient enrichment has influenced bio-chemical responses in the watershed. It is hoped that this will result in a conclusive unbiased summary of nutrient enrichment in a form that is useful to the FWCP Board in their evaluation of the program. Secondary benefits include the opportunity to refine future enrichment programs in order to maximize effectiveness and efficiency. It is also expected that a retrospective analysis of the Salmon River program will be transferable to development of future enrichment projects in other watersheds.

3.0 STUDY AREA

3.1 Site Locations

Nutrient enrichment of the Salmon River watershed began in headwater reaches well above the diversion dam in 1989. The upper portions of Grilse Creek including Norris Creek were enriched with a considerable quantity of nutrients to produce a top loading effect. Over time, the program expanded to include a site at lower Grilse Creek Bridge in 1990, Rock Creek (Salmon River) in 1992, and the Memekay Mainline Bridge in 1993. A tank was added to Menzies Mainline Bridge in 1996 to enrich the reach between Rock Creek and Memekay Mainline Bridge. The Memekay River was first enriched in 1997 at two sites and then scaled back to just the upper site from 1998-2009; the lower site was enriched again in 2010. A nutrient enrichment site was added at the Bigtree Mainline Bridge in 2008 and 2009 before being relocated upstream to Kay Creek in 2010. Figure 1 provides a summary of key enrichment and monitoring locations in the watershed.

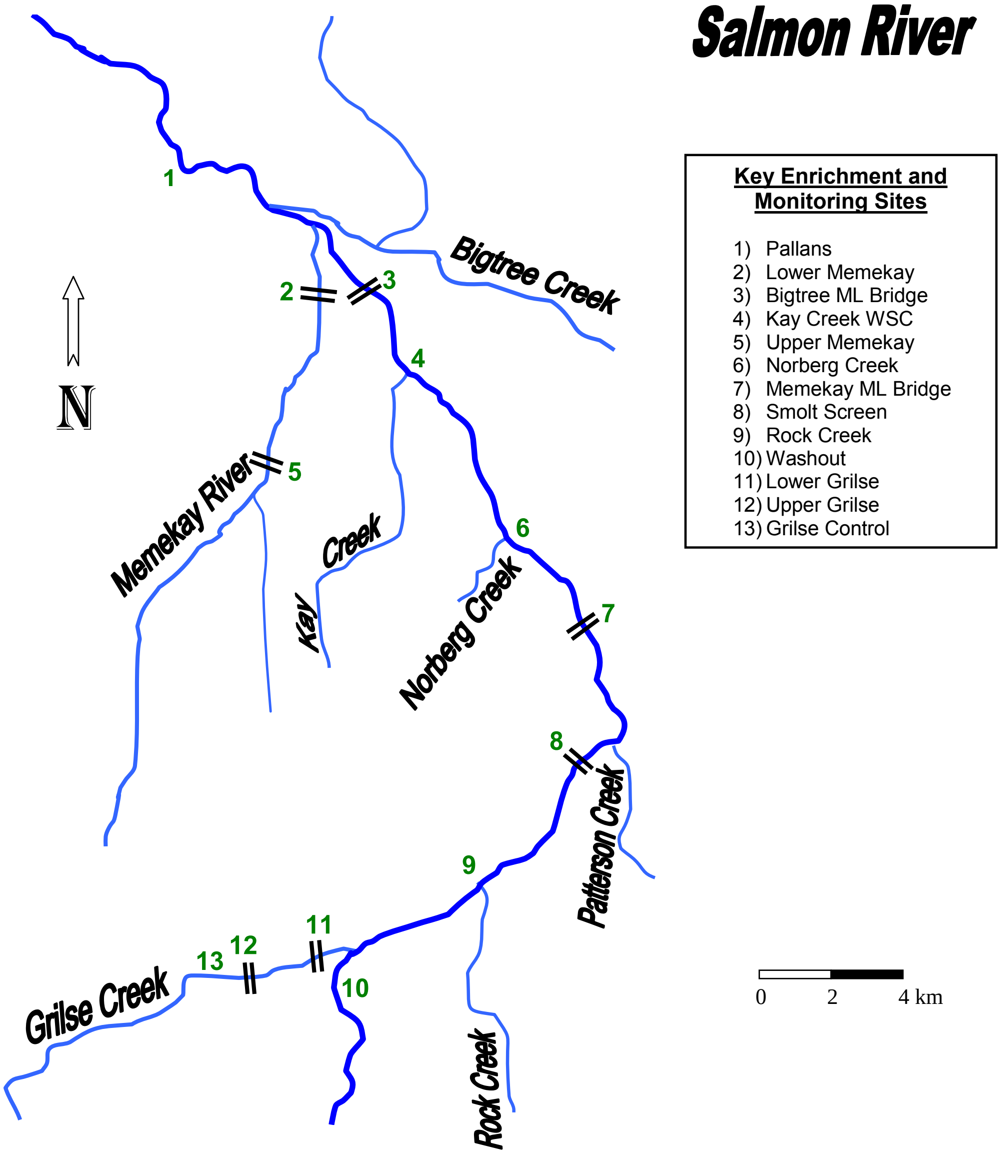

Figure 1. Overview of the Salmon River watershed from Bigtree Creek to Grilse Creek including key enrichment and monitoring locations.

4.0 MATERIALS AND METHODS

4.1 Nutrient Loading

Phosphorus has been considered the key limiting nutrient in the Salmon River watershed although feasibility work by Perrin (1989) indicates co-limitation occurs intermittently through the summer growing season. In order to increase primary productivity, loading rates for nutrient addition (1989-2007) were set at 5 *µg/L* soluble reactive phosphorus (SRP) and 20 *µg/L* dissolved inorganic nitrogen (DIN) after Perrin (1990). In 2008, a target concentration of 2.5 *µg/L* SRP was implemented after McCusker et al. (2002) in order to align with nutrient enrichment programs in other watersheds on Vancouver Island.

Treatments in the first three years included a significant application of nitrogen (N) in Grilse Creek. Treatments from 1992 to 2010 resulted in the addition of more phosphorus (P) than nitrogen. The quantity was reduced in 2008 when the product was changed to a solid slow release prill from liquid and loading rates were adjusted to 2.5 *µg/L* SRP. Significantly less nitrogen was applied in 2009 and 2010 due to a change in the slow release fertilizer formulation from 16% N to 5% N, as well as reduced SRP loading rates.

A variety of different fertilizer products have been applied over a range of growing seasons and flow conditions to different sites during all treatment years. The type and formulation of fertilizer products has changed eight times over the duration of the program. Loading rates have been recalibrated on a regular basis to compensate for changes in formulation (N-P-K ratio) and application method (liquid vs solid). Liquid drip stations result in a more accurate concentration of nutrients as loading rates are re-calibrated weekly based on stream flow and head pressure in the tanks. However, program costs associated with constant recalibration of liquid drip applications are considerably higher compared to a solid slow release nutrient application.

Individual treatment year reports were summarized and the quantity of each product was converted into equivalent weight. The weight of N and P was then calculated based on the formulation of each nutrient source in order to standardize treatment years and sites. The N-P-K ratio refers to percent P_2O_5 by weight which was first converted to P before the quantity could be calculated. Theoretical nutrient concentrations were reconstructed based on drip rate records, stream flow data and nutrient formulations. Early work by Perrin (1990) suggested a wide variation in theoretical and measured nutrient loading rates due to pulsing and rapid biological uptake so theoretical SRP concentrations or nutrient quantity were used in the analyses. Table 1 provides a summary of application timing, as well as product formulation, for all nutrient treatments to the Salmon River watershed.

4.2 Periphyton Growth Response

Algal biomass was measured by quantifying chlorophyll *a* concentrations on artificial substrates as a proxy for stream substrates. Sites were chosen based on similar depth, water velocity and sun exposure where possible (Perrin 1989). Core samples were collected bimonthly following the initial placement of artificial substrata that typically coincided with the start of enrichment. Sample plugs were taken from 1.25 cm x 19 cm x 39 cm sheets of florist's foam that were fastened to concrete blocks and stabilized in the river with cobbles. Two samples were collected each session at random using seven dram plastic vials (2.7 cm in diameter or 5.73 cm^2). Samples were then frozen and shipped on ice to Maxxam Analytics Inc. in Burnaby, BC for analysis.

Table 1. Summary of nutrient products applied to the Salmon River watershed including nutrient formulation, 1989-2010.

Application			Product			Application			Product		
Year	Start	Stop	state	blend	name	Year	Start	Stop	state	blend	name
1989	2-Jun-89	26-Aug-89	solid	34-0-0	urea	**1999**	9-Aug-99	28-Sep-99	liquid	10-34-0	ammonium polyphosphate
	2-Jun-89	26-Aug-89	solid	12-51-0	monammonium phosphate	**2000**	19-Jun-00	8-Sep-00	liquid	10-34-0	ammonium polyphosphate
1990	12-May-90	29-Jul-90	liquid	10-34-0	ammonium polyphosphate		19-Jun-00	8-Sep-00	solid	7-40-0	Vigro briquette (silver bullet)
	12-May-90	29-Jul-90	liquid	32-0-0	urea (UAN)	**2001**	5-Jul-01	24-Aug-01	liquid	10-34-0	ammonium polyphosphate
1991	18-May-91	31-Jul-91	liquid	10-34-0	ammonium polyphosphate	**2002**	18-Jun-02	19-Aug-02	liquid	10-34-0	ammonium polyphosphate
	18-May-91	31-Jul-91	liquid	32-0-0	urea (UAN)		29-Jul-02	30-Sep-02	solid	18-16-0	struvite
1992	15-May-92	28-Jul-92	liquid	10-34-0	ammonium polyphosphate	**2003**	17-Jun-03	31-Aug-03	liquid	10-34-0	ammonium polyphosphate
1993	25-May-93	8-Aug-93	liquid	10-34-0	ammonium polyphosphate		11-Jun-03	31-Aug-03	solid	6-17-0	pollock bone meal
	25-May-93	8-Aug-93	liquid	32-0-0	urea (UAN)	**2004**	8-Jun-04	17-Sep-04	liquid	10-34-0	ammonium polyphosphate
1994	19-May-94	14-Aug-94	liquid	10-34-0	ammonium polyphosphate		17-Jun-04	17-Sep-04	solid	6-17-0	pollock bone meal
	19-May-94	14-Aug-94	liquid	32-0-0	urea (UAN)	**2005**	2-Jun-05	10-Sep-05	liquid	10-34-0	ammonium polyphosphate
1995	25-May-95	19-Aug-95	liquid	10-34-0	urea (UAN)		2-Jun-05	10-Sep-05	solid	6-17-0	pollock bone meal
	25-May-95	19-Aug-95	solid	8-40-0	Vigro briquette (silver bullet)	**2006**	14-Jun-06	5-Sep-06	liquid	10-34-0	ammonium polyphosphate
1996	1-Jun-96	5-Sep-96	liquid	10-34-0	ammonium polyphosphate		29-Jun-06	6-Sep-06	solid	6-17-0	pollock bone meal
	1-Jun-96	5-Sep-96	solid	8-40-0	Vigro briquette (silver bullet)	**2007**	4-Jul-07	30-Sep-07	solid	16-40-0	Nutricote T-40
1997	12-Jun-97	6-Oct-97	liquid	10-34-0	ammonium polyphosphate	**2008**	24-Jun-08	30-Sep-08	solid	16-40-0	Nutricote T-40
	10-Jun-97	6-Oct-97	solid	7-40-0	Vigro briquette (silver bullet)	**2009**	17-Jun-09	19-Sep-09	solid	5-27-0	Crystal Green
	27-Jun-97	6-Oct-97	solid	7-40-0	Vigro briquette (silver bullet)	**2010**	30-Jun-10	25-Sep-10	solid	5-27-0	Crystal Green
1998	10-Jun-98	19-Aug-98	liquid	10-34-0	ammonium polyphosphate						
	10-Jun-98	19-Aug-98	solid	7-40-0	Vigro briquette (silver bullet)						

Chlorophyll *a* concentrations were averaged for each site by year and 95% confidence intervals applied. Data was plotted by stream to investigate differences in mean periphyton concentrations between sites each year. A comparison of mean growth at 15 day intervals was not conducted as substrates were changed halfway through the growing season thereby masking seasonal variation. In order to investigate the statistical significance of the growth response the data was then subjected to a t-test (α 0.05). Chlorophyll *a* data were paired by date of collection and mean yearly concentrations were compared in control and treated sites. The difference in sample means was considered to be statistically significant at the 95% confidence level if t-Stat > t-Critical, P value < α 0.05 (H_o = no difference in sample means).

4.3 Water Chemistry

Water samples were collected using various methods each specified in individual treatment reports. Several different labs were used including Zenon Environmental Laboratories, Maxxam Analytics, The Pacific Environmental Science Center (PESC) and Vancouver Island University (VIU). While other parameters were often tested, low level nutrient analysis was used as an indicator of enrichment effect. Minimum detection limits varied between labs but were commonly 1.0 *µg/L* for SRP and 2.0 *µg/L* for nitrate/nitrite. A small number of samples collected in 2009 and 2010 were sent to VIU for ultra-low level SRP analysis. Detection limits were 0.5 *µg/L* and samples were analyzed in triplicate to produce a 95% confidence interval. These samples were used to verify samples sent to PESC as well as to determine actual loading rates.

SRP and nitrate/nitrite concentrations were retrieved from yearly enrichment reports and summarized by control and treated sites. Three different reaches were analyzed including the mainstem Salmon River as well as Grilse Creek and the Memekay River. Two approaches were taken with the data from each reach. The first was intended to investigate concentrations between years by first averaging yearly concentrations at control and treated sites. The data was also summarized by pooling all years and investigating seasonal changes to nutrient concentrations at 15 day intervals. Finally, nitrogen and *SRP* concentrations in control reaches were plotted to reveal trends in seasonal variability upstream of nutrient treatments.

Nitrogen concentrations were often above detection limits but undetectable SRP concentrations were regularly encountered. Several samples taken across Vancouver Island in 2009 and 2010 were sent to VIU for ultra-low level analysis. Of the samples that were less than 1 *µg/L* SRP (n=29) concentrations were found to average 0.54 *µg/L* with a standard deviation of 0.23 *µg/L* (Pellett 2010, Brennan and Pellett 2011). No samples tested by VIU in any control or treated reach registered a true zero value. Therefore, rather than assigning a zero value to undetectable samples each was assigned an arbitrary reading corresponding to half of the associated detection limit (typically 0.5 *µg/L* SRP). As it was unclear if this relationship existed for undetectable nitrogen concentrations any values less than detection limits were not included in the analysis. A total of 328 nitrogen and 363 *SRP* samples were incorporated into the final analysis.

Grilse Creek

Low level nutrient monitoring was conducted at four main sites in Grilse Creek over the course of nutrient additions (1989-2010), as well as one year prior during feasibility assessments (1989). The location of the control site varied between treatment years. Norris Creek (a tributary to Grilse) was used as a control for 1989-2000 treatments and a site 3.8 km downstream in Grilse Creek for 2001-2010 treatments after nutrient additions in the upper watershed were discontinued. Treated sites also varied with three monitoring locations at 50 m, 3.8 km and 4.4 km intervals downstream of enrichment sites. The 3.8 km site monitored the downstream effect of the upper most enrichment site and later became the control in 2001. The 50 m and 4.4 km sites monitored nutrient levels downstream of the enrichment site located at the second Grilse Creek Bridge. SRP and nitrate/nitrite concentrations were consistently analyzed as fertilizer formulations typically included both nutrients.

Memekay River

Nutrient concentrations were monitored at two locations in the Memekay River from 2001 to 2010. The control site was located approximately 50 m upstream of the middle bridge crossing while nutrients were applied a similar distance downstream. The treatment monitoring site was located 7.2 km downstream from the nutrient source through 2009. In 2010, a second site was enriched 100 m upstream of the treatment monitoring location. The data from 2001-2009 provide insight relative to the effects of nutrient enrichment at approximately twice the suggested spiralling distance while the 2010 data describe a ‘full-mix’ effect.

Salmon River

Water chemistry was monitored at one control site and four treated sites within the mainstem Salmon River from 1996-2010. Treated sites to 2006 were located between 5.2 km and 23.5 km downstream of nutrient additions. In 2007, monitoring sites were re-located relative to enrichment sites in order to investigate full-mix effects. Nutrient concentrations were plotted to investigate differences in mean concentrations at yearly and 15 day intervals. Site names were referenced to the distance downstream of the closest nutrient source (T-km) or indicate a control sample (C). The concentrations at three full-mix sites (T-0.05 km) from the 2007-2010 period were averaged to avoid redundancy.

4.4 Fish Growth Response

Steelhead Fry

Small numbers of juvenile steelhead were captured during the first three years of enrichment (Perrin 1990, 1991, 1992). Perrin (1990) commented that the only way to conduct a proper in-stream assessment was to monitor several years of treatment followed by continued monitoring when no nutrients were added. Treatments from 1992 through 1997 did not involve monitoring fish growth response. Starting in 1998, a significant number of steelhead fry were captured in control and treated reaches near the end of the growing season allowing comparison of relative growth. This data set provides the fundamental basis for effectiveness monitoring beyond algal growth and water chemistry.

Juvenile surveys targeting steelhead fry in late summer/early fall have been regularly conducted as both a stock assessment tool and as a method of monitoring nutrient enrichment. Each captured fish was measured and weighed before release providing a data set for growth analysis.

If less than 30 fish were captured at each site, spot electrofishing was used to boost sample size and reduce confidence intervals associated with mean weights. Many of the sites corresponded with enrichment sampling or application locations, including three in Grilse Creek. Two of the three sites were downstream of nutrient applications while one was located in the upstream control reach. As both fry and parr (i.e. yearling and older juveniles) were captured by electrofishing, differentiation between the two had to be clear in order to not include larger parr in the growth analysis. Hooton et al. (1987) suggested a mean one year old parr size of 86 mm for the Salmon River under background nutrient concentrations, and as high as 127 mm in the Cowichan River where favourable rearing conditions produce larger juveniles. As elevated nutrient levels were expected to increase steelhead growth in the Salmon River, the division between fry/parr was set at 95 mm for treated sites and 86 mm for control sites.

Several assumptions were made before analyzing the data. The first was that no immigration/emigration occurred with respect to control and treated sites. The second assumption was that fry density did not influence growth when looking at paired samples for a given year. The third assumption was that stream temperature was similar at control and treated sites which can affect emergence time and summer growth. Finally, it was assumed that a measurable fry growth response indicated parr growth was also enhanced in that particular year. We assumed that an improved juvenile growth response positively influenced over-winter survival, decreased average smolt age and increased the number of smolts produced per spawner.

The relative fry growth response was calculated by subtracting the mean treated weight from the mean control weight. This response was then compared to a variety of factors that were theorized to influence fry growth including stream flow, nutrient quantity, application timing/duration, and periphyton growth response. Mean daily stream flows were retrieved from the Water Survey of Canada (WSC) archived hydrometric database (http://www.ec.gc.ca/rhc-wsc) for the Salmon River above diversion (station 08HD015). Flows were used as a proxy for Grilse Creek as monitoring data suggests there is a linear relationship between flow in Grilse Creek and the WSC station downstream (Figure 2).

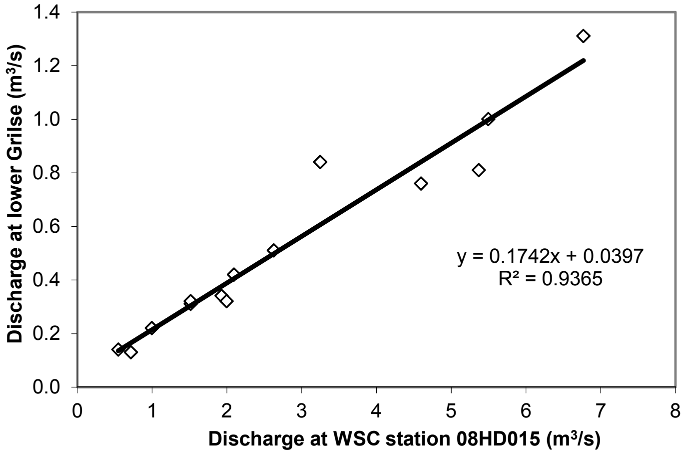

Figure 2. Relationship between flow measured at lower Grilse Creek and that reported at WSC station 08HD015, Salmon River above diversion.

Steelhead Smolts

Water diverted out of the mainstem Salmon River by BC Hydro was screened during the spring salmonid smolt migration period over the course of nutrient treatments. A subsample of the migrants was collected annually in order to enumerate, measure, age, and assess their condition as they passed the facility (Carswell 1990-1993, Hansen 1994-2002). Secondary objectives included monitoring the screen as modifications were completed to increase fish bypass efficiency. Data from 1989 through 2002 were compiled in order to determine mean steelhead smolt age as well as the distribution of age classes in sub samples. Fish captured at the diversion were exposed to nutrient treatments in Grilse Creek, Norris Creek, and the mainstem Salmon River (Rock Creek and Jessie Creek sites).

4.5 Steelhead Population Trends

Beginning in 1998, juvenile steelhead densities at ten sites in the Salmon River watershed have been monitored. Also, adult snorkel survey data has been collected over much of the same time yielding two methods of tracking steelhead stock abundance trends. The data collected for the Salmon River provides an indication of overall stock health in relation to conservation standards set by provincial fisheries staff, as well as an indication of population trends over a decadal time scale.

Ten representative electrofishing sites were chosen in 1998 by Steelhead Recovery Plan staff (BC Conservation Foundation) to assess steelhead abundance in the watershed. The majority of steelhead fry were captured using standard closed site electrofishing techniques. Approximately 100 m^2 of suitable habitat was netted off at each site and a two pass removal technique was implemented to calculate fry density (deLeeuw 1989). Flow transects were conducted in each site and compared against Habitat Suitability Index curves (HSI, derived by provincial fisheries staff) to “correct” fish density based on depth/velocity (DV) differences between sites. Fry densities are expressed as geometric means and DV corrected.

Snorkel surveys in key index reaches of the Salmon River were sporadically conducted prior to 1999 by provincial fisheries staff to enumerate adult winter steelhead. Staff from the BC Conservation Foundation conducted regular surveys from 1999 through 2011. Surveyors targeted a key 11.5 km index reach from Kay Creek to Pallans in mid-March each year. Stream conditions were low and clear at the time of the surveys although varying conditions were thought to impact observer efficiency (effective visibility ranged from 4-8 m, mean 6.5 m). Beginning in 2008 several additional upper reaches were surveyed providing additional information on upper river steelhead distribution and run timing.

4.6 Other Vancouver Island Stream Enrichment Projects

Keogh River

The Keogh River on northern Vancouver Island has a long term (1976-present) research station that is able to track steelhead stock-recruitment through an intensive smolt and adult monitoring program. It has been continuously monitored during two enrichment cycles (1983-87 and 1998-2007), as well as control years before, between and following enrichment. It is an ideal monitoring location with the ability to track population response under various nutrient treatment regimes. Without the Keogh research station it is difficult to arrive at conclusions regarding population level responses to treatments in other watersheds.

Harris Creek

A similar nutrient enrichment program to the Salmon River has been implemented on tributaries of the San Juan River on south western Vancouver Island since 2001. Nutrient enrichment of upper Harris Creek (above a semi-selective barrier) has been monitored through water quality testing and juvenile assessments. Several different blends of solid slow release fertilizer have been applied to one site near the anadromous barrier leaving a 1.0 km control reach and a 2.7 km treated section. In 2008, the reach was left untreated while water chemistry and steelhead fry growth were monitored at each site.

5.0 RESULTS

5.1 Nutrient Loading

The following provides a brief history of the Salmon River nutrient enrichment program with respect to treatment locations, fertilizer products and application rates. It is important to understand that the program evolved from an applied research focus in its earliest years to an operation level within a decade or so. During this and subsequent periods the geographic scope of treatments expanded in the watershed and products changed due to availability and cost considerations. Moreover, P-loading rates were frequently adjusted (in-season) in response to product performance and water chemistry monitoring results (Figure 3).

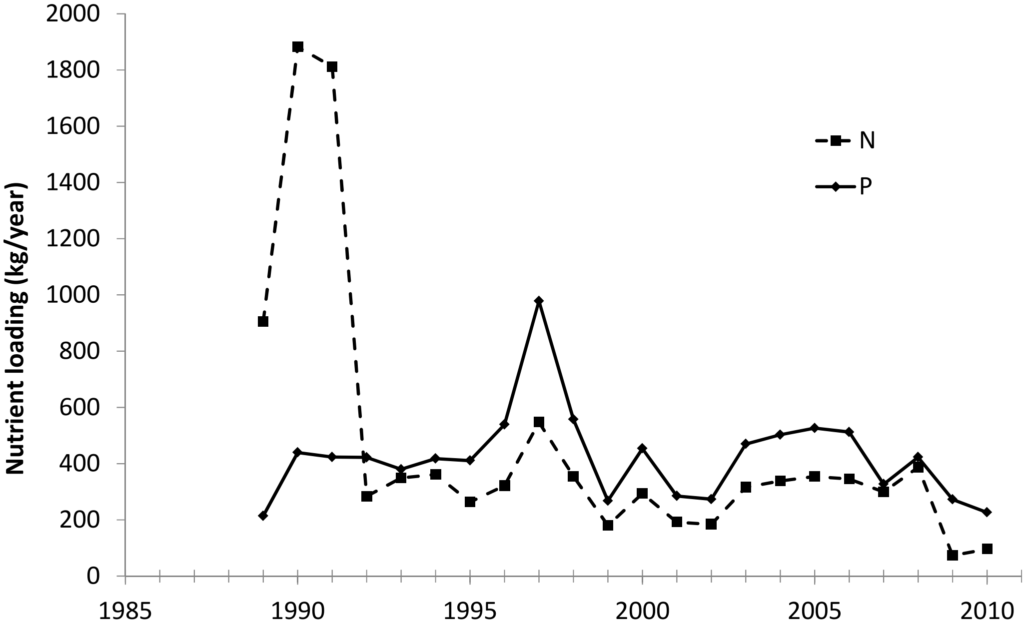

Figure 3. Summary of nitrogen and phosphorus loading across all sites in the Salmon River watershed, 1989-2010.

The first treatment in 1989 targeted a 10 km reach of Grilse Creek. Nutrients were added at two sites in order to achieve theoretical concentrations of 5 *µg/L* P and 20 *µg/L* N. In reality, the upper site (Norris Creek, a tributary of Grilse Creek) was “top loaded” to ensure nutrient concentrations were near target levels once diluted in Grilse Creek. It is also the only area of the Salmon River watershed to have received nutrient applications throughout the full duration of the program (twenty consecutive years). Nitrogen additions peaked in 1990 when top loading of Norris Creek was conducted although nutrient additions to Norris Creek stopped in 2000. When application techniques changed in 1992 much less nitrogen was added to Grilse Creek. Phosphorus loading has been more consistent over time although a reduction in the number of treatment sites occurred in 2001 and a shift in fertilizer products (2007) reduced overall loading rates (Figures 4 and 5).

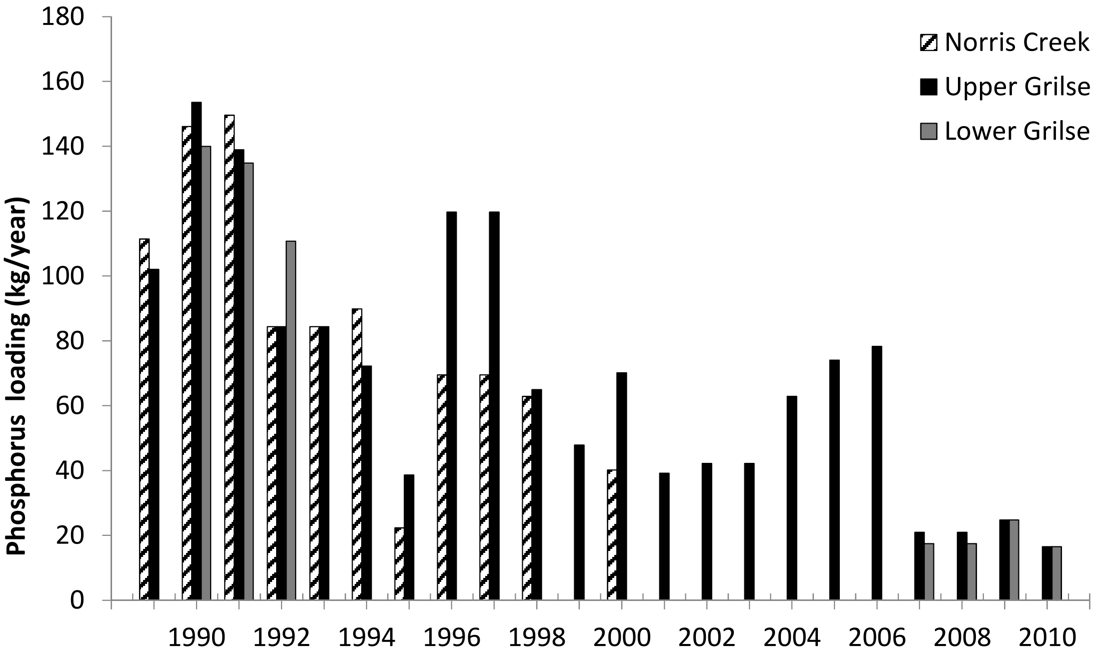

Figure 4. Summary of phosphorus loading by site in Grilse Creek, 1989-2010.

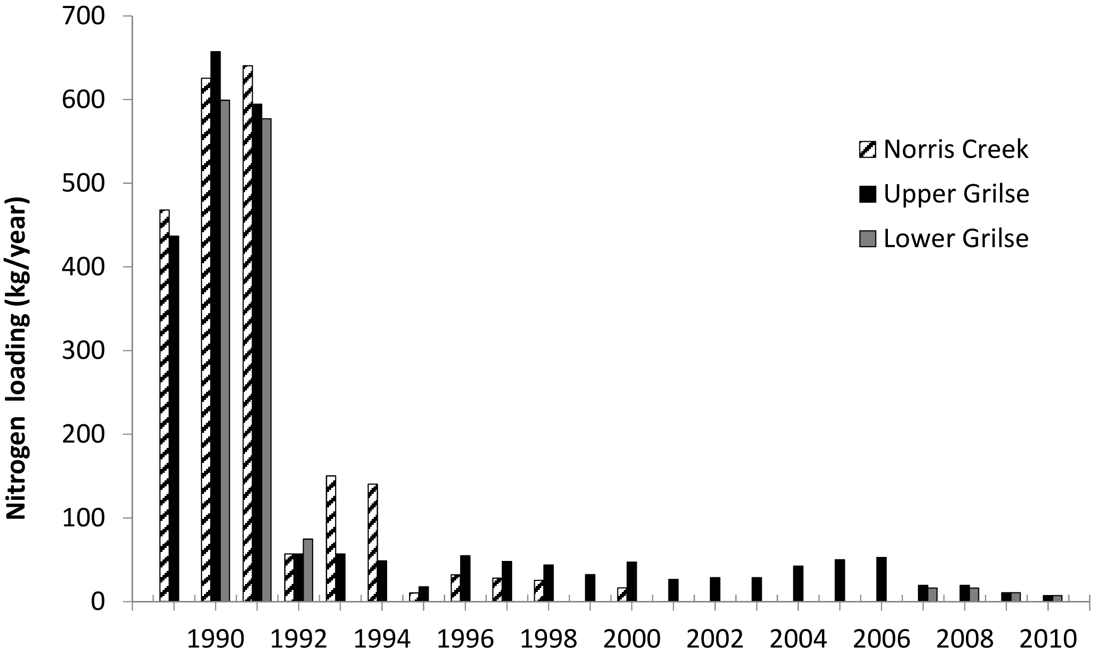

Figure 5. Summary of nitrogen loading by site in Grilse Creek, 1989-2010.

Following a shift in fertilizer blend in 1992 to liquid 10-34-0, the first mainstem Salmon River site was added at Rock Creek which continued through 2010 (Figures 6 and 7). A second mainstem site was added at the Memekay Mainline Bridge in 1993 and a third site at the Menzies Mainline Bridge in 1995. Trials with organic pollock bone meal were conducted in the Upper Salmon River near Jessie Creek from 2004-2007. Also in 2007, a large scale shift in fertilizer product was conducted with 16-40-0 solid slow release fertilizer replacing liquid drip tanks in an attempt to reduce program costs. In 2009 and 2010, Crystal Green (5-27-0) replaced T40 (16-40-0) as a more cost effective alternative. The Bigtree Mainline Bridge was enriched in 2008 and 2009 in order to provide nutrients to a section of the river heavily utilized by winter steelhead. This site was shifted upstream to Kay Creek in 2010 to provide nutrient rich water to the newly constructed Bigtree side-channel project.

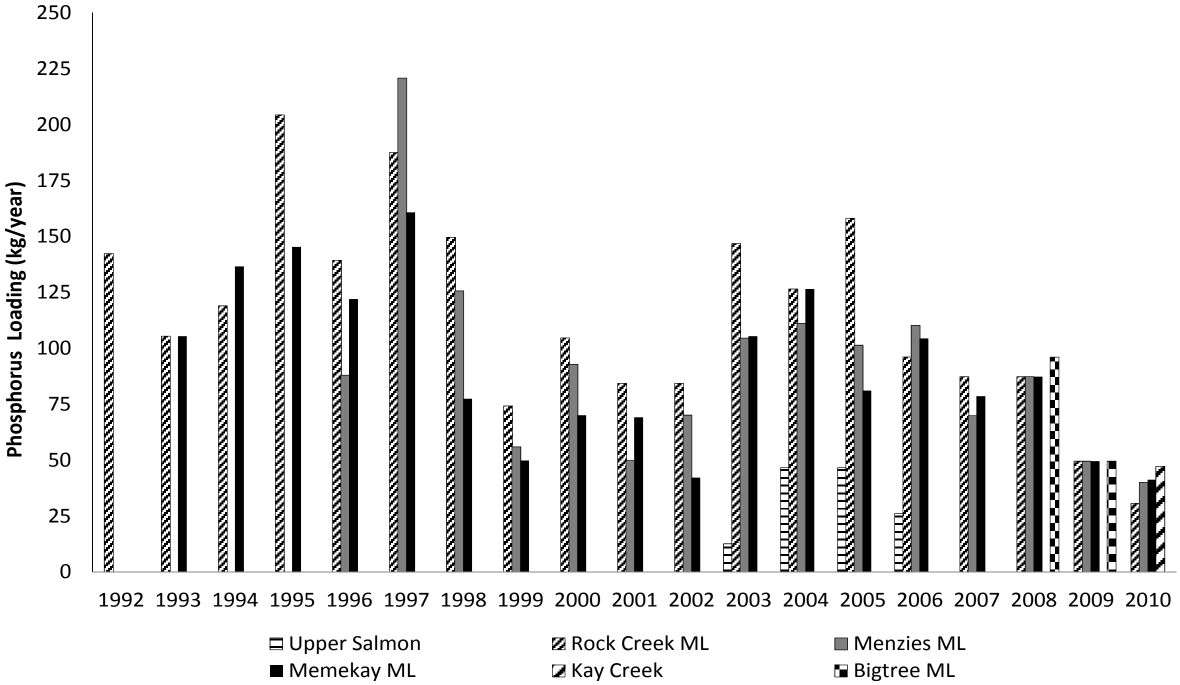

Figure 6. Summary of phosphorus loading by site in the Salmon River mainstem, 1991-2010.

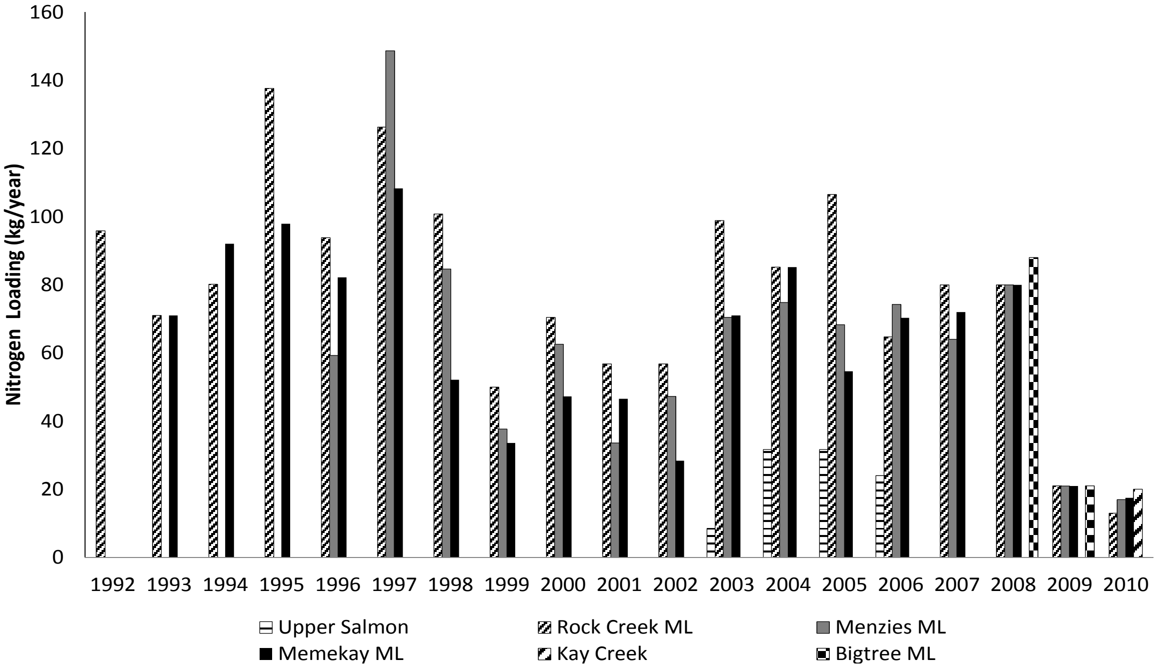

Figure 7. Summary of nitrogen loading by site in the Salmon River mainstem, 1991-2010.

Watershed enrichment expanded to two sites in the Memekay River and one in Cooper Creek (Memekay R. tributary) in 1997. Cooper Creek was enriched in 1998 and 2000 while the lower Memekay did not receive a second nutrient application until 2010 (Figures 8 and 9). Loading rates in the Memekay watershed were not as variable compared to other systems, although a lower quantity of nutrients were loaded from 2007 to 2010 following a shift to a solid slow release product.

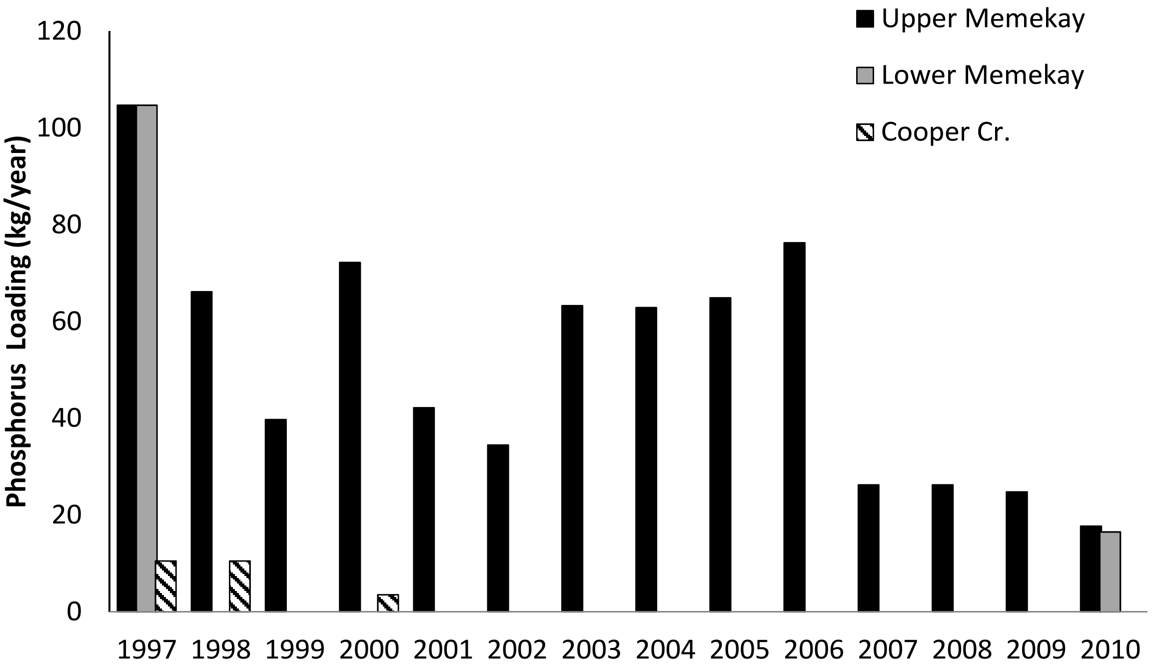

Figure 8. Summary of phosphorus loading by site in the Memekay River, 1997-2010.

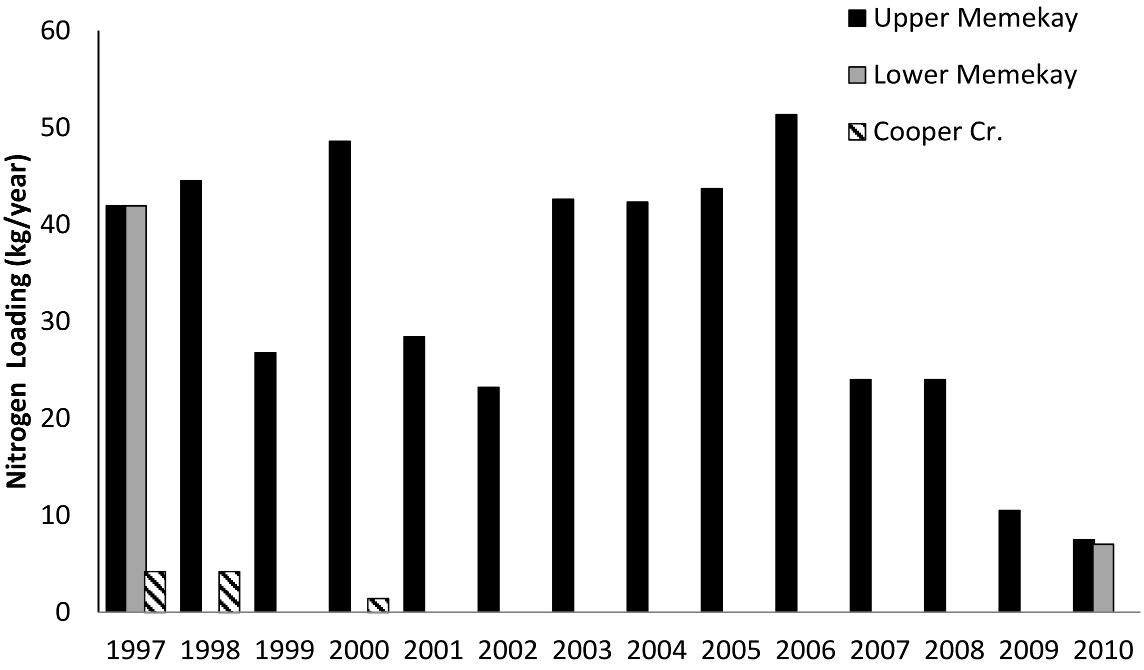

Figure 9. Summary of nitrogen loading by site in the Memekay River, 1997-2010.

Application methods, loading rates, and nutrient products have varied throughout the duration of Salmon River treatments. The advantage of loading nutrients by using liquid fertilizer was that loading rates were re-calibrated as flows changed and as head pressure in the drip tank was reduced. Solid slow release fertilizer was applied once at the start of the growing season and application rates were based on pre-season flow forecasts and were generally more conservative. A comparison of theoretical and actual (measured) SRP concentrations in Grilse Creek was constructed using flow data from WSC station 08HD015 (Salmon River above diversion) and the actual quantity of P added over the growing season (excluding Norris Creek (1989-98, 2000) and lower Grilse (1990-92, 2007-10)). The theoretical SRP concentration was found to be higher than the desired concentration of 2.5-5.0 *µg/L* in most years and often was near 10 *µg/L*. Treatments from 2007-2010 using slow release solid products were re-calibrated to a lower concentration of 2.5 *µg/L* (Figure 10). Measured SRP values at the treated site 4.4 km downstream were found to be much less than theoretical concentrations while the difference was found to be smaller when water sampling was conducted closer to the nutrient source in 2007-10 (Figure 11).

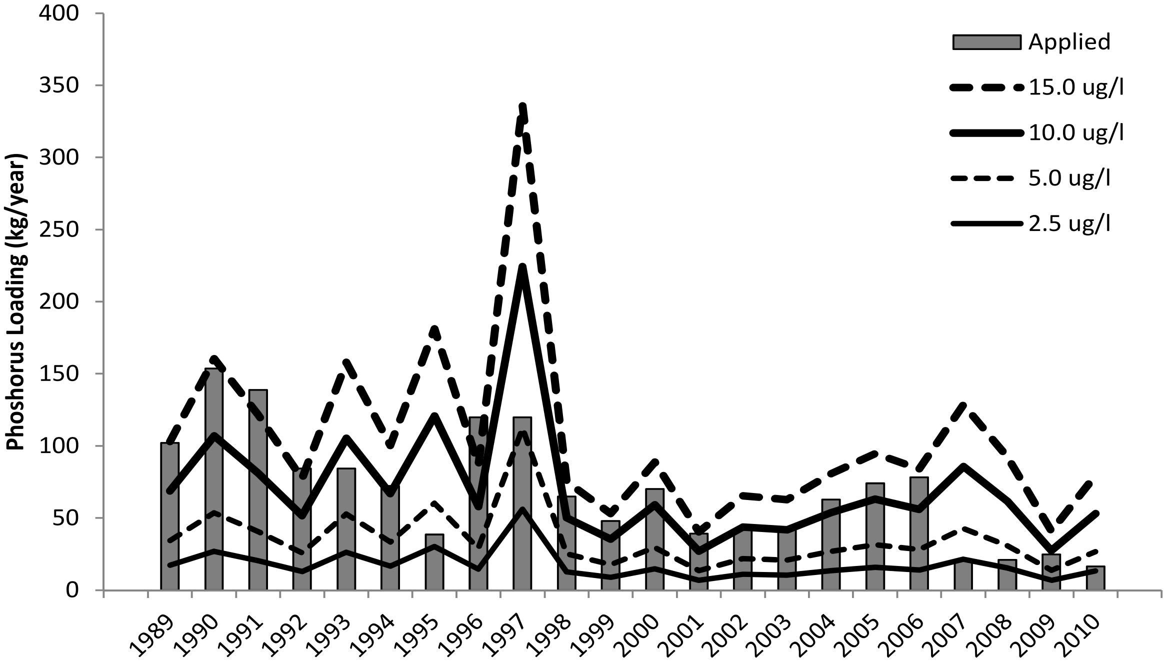

Figure 10. Quantity of phosphorus applied in Grilse Creek compared to theoretical loading rates based on retrospective flow analysis for yearly treatment periods.

Ultra low level nutrient analysis was conducted at several sites on Grilse Creek in 2009 and 2010. The Applied Environmental Research Laboratory (AERL) at Vancouver Island University (VIU) was able to calculate 95% confidence intervals on *SRP* samples while operating at detection levels of approximately 0.5 *µg/L*. Theoretical concentrations (based on a 90 day release) were found to be similar to measured concentrations immediately downstream under average summer flows (4.3-5.9 vs 6.2-6.4 *µg/L* P) but less during very low flows (23.4 vs 10.7 *µg/L* P). Much of this can be explained by the characteristics of Crystal Green, a solid, slow release fertilizer, which exhibits a velocity dependent release rate. Low flows result in lower velocities and a slower release of nutrients at treated sites.

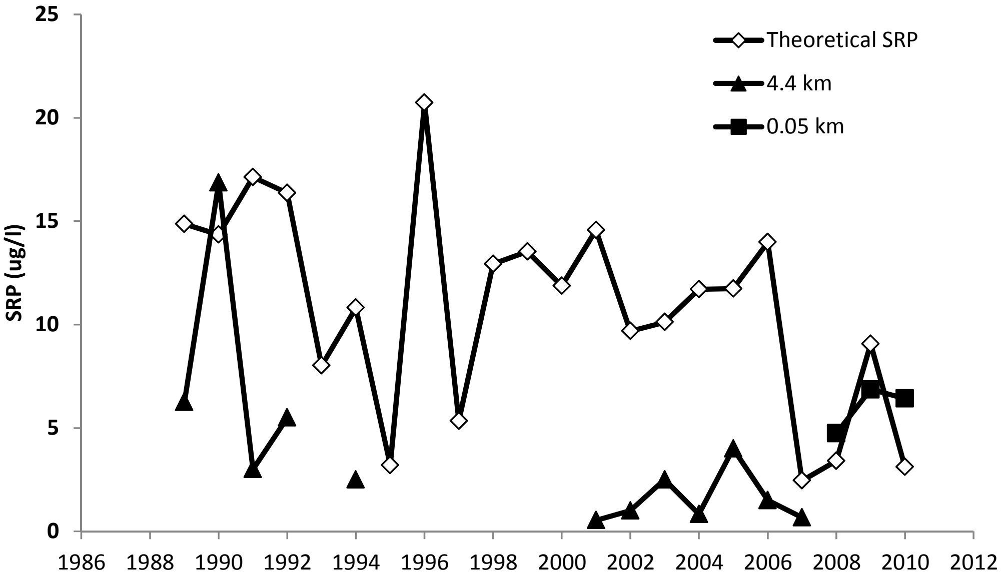

Figure 11. Theoretical SRP concentrations in Grilse Creek based on discharge records and loading rates compared to actual measured values 0.05 km and 4.4 km downstream.

5.2 Periphyton Growth Response

Grilse Creek

Chlorophyll *a* biomass was found to be consistently higher on average in treatment sites compared to the upstream control. Concentrations were highest at the site closest to the nutrient source although concentrations 3.5 km downstream were found to be comparable under high nutrient loading rates (Figure 12). The statistical significance of results was investigated by conducting a t-test. Chlorophyll *a* biomass was found to be significantly higher at the 95% confidence level at sites closest to nutrients (T or T-1) in seven of ten years (Table 2). Years 1989, 2006 and 2007 all showed a weak response although the low number of samples in 1989 (n=2) likely contributed to a large confidence interval despite a large difference in means (9.7 vs 0.6 ug/cm^2).

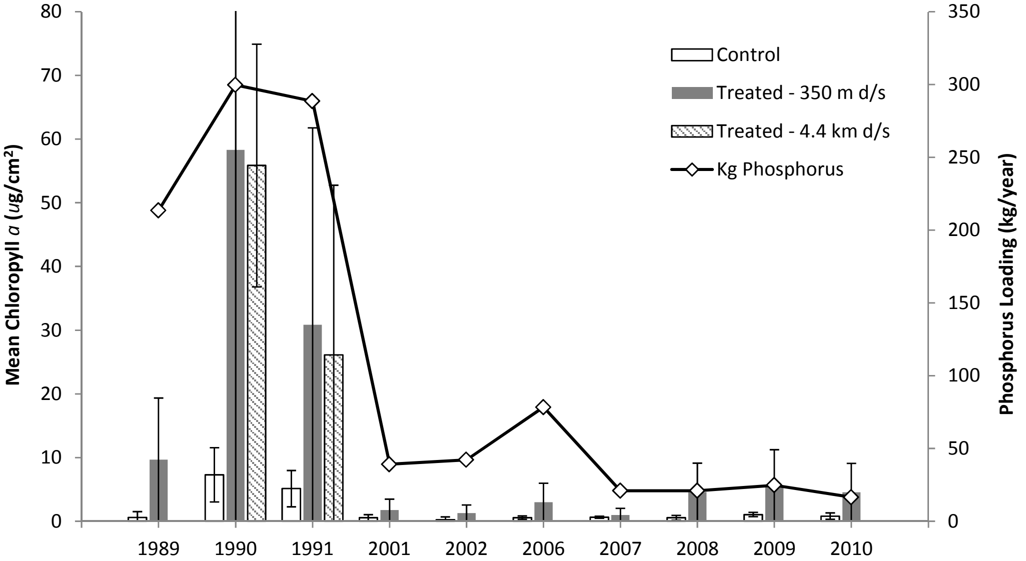

Figure 12. Mean chlorophyll *a* concentrations on artificial substrates placed in Grilse Creek (95% CI) in reference to phosphorus loading rates.

Table 2. Summary of t-test output (α 0.05) to investigate differences in chlorophyll *a* concentrations between control and treated sites in Grilse Creek, 1989-2010.

t-Test: Paired Two Sample for Means												
	1989		1991			1990			2001		2002	
	T	*C*	T 1	T 2	C	T 1	T 2	C	T	C	T	C
Mean	9.665	0.585	30.875	26.125	5.125	58.28571	55.85714	7.285714	1.74	0.5575	1.266667	0.233333
Variance	53.76845	0.45125	694.0536	1474.982	16.98214	985.5714	661.8095	32.90476	0.884733	0.223825	0.063333	0.163333
Observations	2	2	8	8	8	7	7	7	4	4	3	3
Pearson Correlation	1		0.737045	0.790596		-0.03755	-0.48645		0.348839		0.114708	
Hypothesized Mean Difference	0		0	0		0	0		0		0	
df	1		7	7		6	6		3		2	
t Stat	1.927813		3.102747	1.685596		4.200291	4.438476		2.64731		3.969143	
P(T<=t) one-tail	0.152315		0.008628	0.06787		0.002842	0.002192		0.038586		0.029004	
t Critical one-tail	6.313752		1.894579	1.894579		1.94318	1.94318		2.353363		2.919986	
P(T<=t) two-tail	0.304631		0.017256	0.13574		0.005684	0.004383		0.077171		0.058007	
t Critical two-tail	12.7062		2.364624	2.364624		2.446912	2.446912		3.182446		4.302653	

	2006		2007		2008		2009		2010	
	T	*C*	*T*	*C*	*T*	*C*	*T*	*C*	*T*	*C*
Mean	2.988	0.56	1.005	0.62	4.566	0.542	5.6175	1.0375	4.546667	0.81
Variance	5.92552	0.10935	0.80645	0.0128	10.55553	0.18452	5.033892	0.122092	4.320133	0.1983
Observations	5	5	2	2	5	5	4	4	3	3
Pearson Correlation	-0.40313		-1		0.946211		-0.29905		-0.0323	
Hypothesized Mean Difference	0		0		0		0		0	
df	4		1		4		3		2	
t Stat	2.100002		0.538462		3.161752		3.862241		3.024796	
P(T<=t) one-tail	0.051827		0.342774		0.017063		0.015343		0.04706	
t Critical one-tail	2.131847		6.313752		2.131847		2.353363		2.919986	
P(T<=t) two-tail	0.103653		0.685547		0.034127		0.030687		0.09412	
t Critical two-tail	2.776445		12.7062		2.776445		3.182446		4.302653	

Memekay River

Periphyton growth response was monitored in the Memekay River over seven years from 2001 to 2010 (Figure 13). Chlorophyll *a* biomass at the treated site located 7.3 km downstream of the nutrient source was found to be highest in years when nutrient loading was high (2006), or when stream flows were low (2008, Figure 13). A large response was also observed when nutrients were added in close proximity to the monitoring site (within 150 m as in 2010). Algal biomass was found to be statistically stronger at the 95% confidence level in three of seven years (Table 3). Concentrations in the 7.3 km treated site during 2001 and 2006 were found to be significantly higher while in 2010 the difference was also significant 150 m downstream of the second enrichment site.

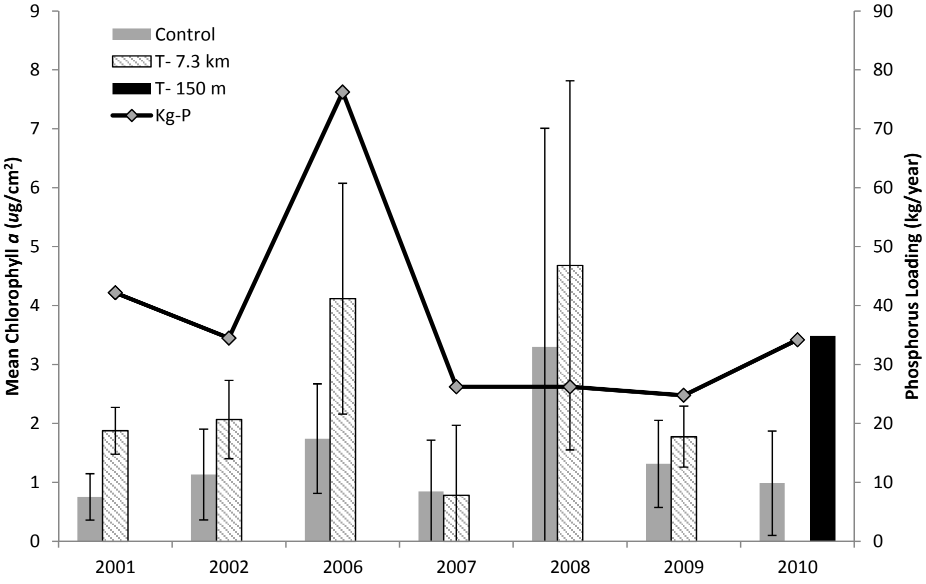

Figure 13. Mean chlorophyll *a* concentrations on artificial substrates placed in the Memekay River (95% CI) in reference to phosphorus loading rates.

Table 3. Summary of t-test output (α 0.05) to investigate differences in chlorophyll *a* concentrations between control and treated sites in the Memekay River, 2001-2010.

t-Test: Paired Two Sample for Means	2001		2002		2006		2007		2008		2009		2010	
	T	*C*	T	C	T	C	*T*	*C*	*T*	*C*	*T*	*C*	*T*	*C*
Mean	1.876667	0.753333	2.066667	1.133333	4.118	1.742	0.785	0.845	4.682	3.304	1.7775	1.315	3.49	0.986667
Variance	0.124133	0.120233	0.343333	0.463333	4.98112	1.11807	0.73205	0.39605	12.76597	17.85453	0.279492	0.5681	2.5159	0.612133
Observations	3	3	3	3	5	5	2	2	5	5	4	4	3	3
Pearson Correlation	0.867386		0.455481		0.821353		1		0.558627		0.219715		0.77865	
Hypothesized Mean Difference	0		0		0		0		0		0		0	
df	2		2		4		1		4		3		2	
t Stat	10.80372		2.427908		3.563753		-0.375		0.830877		1.127972		3.965671	
P(T<=t) one-tail	0.004229		0.067951		0.011753		0.3858		0.22638		0.170697		0.02905	
t Critical one-tail	2.919986		2.919986		2.131847		6.313752		2.131847		2.353363		2.919986	
P(T<=t) two-tail	0.008459		0.135901		0.023507		0.771599		0.452761		0.341394		0.0581	
t Critical two-tail	4.302653		4.302653		2.776445		12.7062		2.776445		3.182446		4.302653	

Salmon River

Periphyton growth response in the mainstem Salmon River was periodically monitored in seven seasons from 1997 to 2010 (Figure 14). Treated sites were located well below nutrient addition locations from 1997-2006 and showed a minimal response to treatments. The full mix site (T-FULL) in 2006 was designed to test the full effect of nutrients within 150 m of the nutrient source and showed a large increase in chlorophyll *a* concentrations. Treatment monitoring sites from 2007-2010 were relocated from several kilometers to tens of meters below nutrient inputs to test the full mix effect and indicated a positive algal growth response. The Bigtree Mainline Bridge site (T-BTML) tested the full effect in 2008 and 2009 nutrient additions, and a downstream effect in 2010 when the enrichment site was moved upstream 3.5 km (Kay Creek). Algal biomass in 2010 was found to be less than in 2009 although it was comparable to the smolt screen site (T-SS, also known as the Menzies Mainline Bridge).

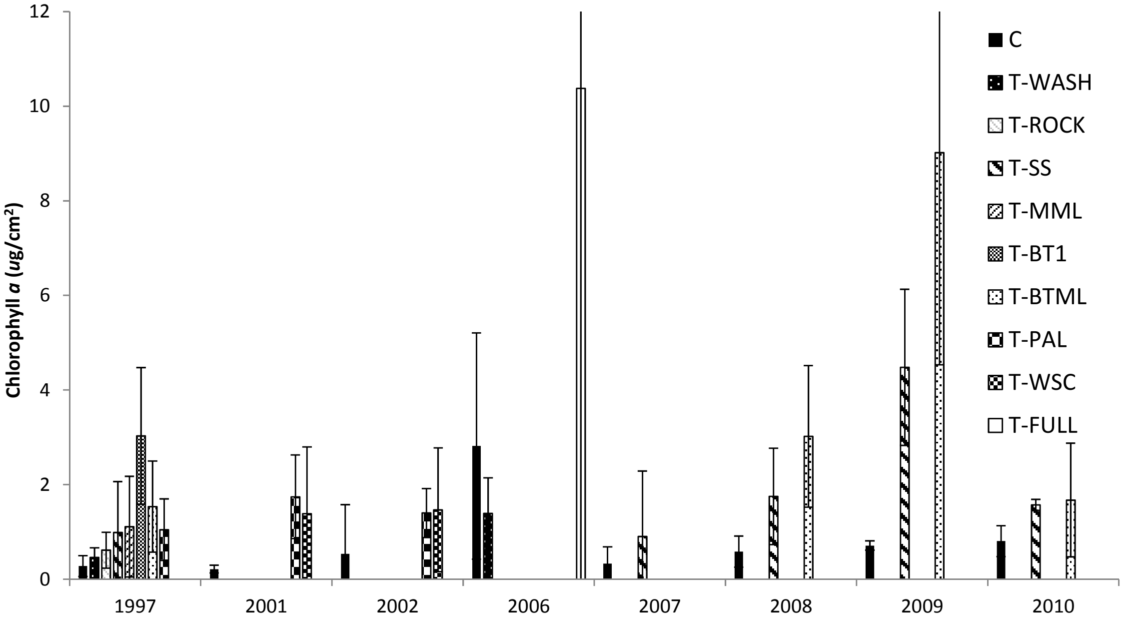

Figure 14. Mean chlorophyll *a* concentrations on artificial substrates placed in the Salmon River mainstem (95% CI). (C-Control,T-Treated, WASH-Washout, ROCK- Rock Cr, SS- Smolt Screen, MML-Memekay Mainline Bridge, BT1- Bigtree 1, BTML- Bigtree Mainline Bridge, PAL- Pallans, WSC- Water Survey of Canada Station at Kay Creek, FULL- Full mix)

A t-test for paired two sample means was conducted for mainstem periphyton monitoring sites (Table 4). Of the 20 treated sites evaluated only 11 were found to have statistically higher biomass compared to controls. In general, the largest responses were observed at sites closest to the nutrient source. Higher biomass was consistently observed downstream of enrichment sites although the difference compared to control sites was not always significant. Biomass at Bigtree Mainline Bridge (T-BTML) was statistically higher in 2008 and 2009 when the enrichment site was located 100 m upstream. In 2010 the enrichment site was moved upstream 3.5 km and no statistical difference in growth was detected.

Table 4. Summary of t-test output (α 0.05) to investigate differences in chlorophyll *a* concentrations between control and treated sites in the Salmon River mainstem, 1997-2010.

t-Test: Paired Two Sample for Means														
	1997								2001			2002		
	T-WASH	*T-ROCK*	T-SS	T-MML	T-BT1	T-BTML	T-PAL	C	T-PAL	T-WSC	C	T-WSC	T-PAL	C
Mean	0.465	0.615	0.986	1.112	3.0325	1.536	1.0475	0.28	1.7425	1.3875	0.215	1.466667	1.4	0.533333
Variance	0.041233	0.1497	1.51653	1.47227	2.170958	1.20743	0.441758	0.06315	0.814092	2.061225	0.0067	1.333333	0.21	0.853333
Observations	4	4	5	5	4	5	4	5	4	4	4	3	3	3
Pearson Correlation	-0.39377	0.868171	0.427107	0.758651	-0.25184	0.322762	0.201263		-0.98595	-0.26365		1	0.755929	
Hypothesized Mean Difference	0	0	0	0	0	0	0		0	0		0	0	
df	3	3	4	4	3	4	3		3	3		2	2	
t Stat	0.681073	3.64848	1.376488	1.796201	3.550503	2.687186	2.152942		3.107614	1.606808		7	2.307127	
P(T<=t) one-tail	0.272343	0.017765	0.120349	0.073443	0.019039	0.027409	0.060187		0.02649	0.103227		0.009902	0.073713	
t Critical one-tail	2.353363	2.353363	2.131847	2.131847	2.353363	2.131847	2.353363		2.353363	2.353363		2.919986	2.919986	
P(T<=t) two-tail	0.544685	0.03553	0.240698	0.146886	0.038077	0.054818	0.120373		0.05298	0.206453		0.019804	0.147426	
t Critical two-tail	3.182446	3.182446	2.776445	2.776445	3.182446	2.776445	3.182446		3.182446	3.182446		4.302653	4.302653	

	2006			2007			2008			2009			2010		
	T-WASH	T-FULL	C		T-SS	C	T-BTML	T-SS	C	T-BTML	T-SS	C	T-BTML	T-SS	C
Mean	1.39	15.515	2.8175		0.905	0.33	3.02	1.752	0.584	9.015	4.48	0.7125	1.673333	1.57	0.806667
Variance	0.5922	112.1382	5.954092		0.99405	0.0648	2.90695	1.35067	0.14148	20.90757	2.836267	0.009958	1.130133	0.0109	0.083333
Observations	4	4	4		2	2	5	5	5	4	4	4	3	3	3
Pearson Correlation	0.273942	0.51971			1		0.946036	0.779816		-0.93591	-0.70451		-0.46706	-0.9954	
Hypothesized Mean Difference	0	0			0		0	0		0	0		0	0	
df	3	3			1		4	4		3	3		2	2	
t Stat	-1.21544	2.6587			1.095238		4.021061	2.901257		3.558717	4.291358		1.225597	3.366555	
P(T<=t) one-tail	0.155561	0.038212			0.235541		0.007925	0.022031		0.018927	0.011632		0.172543	0.039022	
t Critical one-tail	2.353363	2.353363			6.313752		2.131847	2.131847		2.353363	2.353363		2.919986	2.919986	
P(T<=t) two-tail	0.311122	0.076423			0.471083		0.01585	0.044062		0.037855	0.023264		0.345086	0.078043	
t Critical two-tail	3.182446	3.182446			12.7062		2.776445	2.776445		3.182446	3.182446		4.302653	4.302653	

The magnitude of algal growth response was found to be strongly correlated with the quantity of phosphorus added upstream in Grilse Creek. The relationship suggests that adding a large quantity of nutrients will produce large periphyton biomass response up to 300 kg of P (Figure 15). Only three years of data were analyzed in which phosphorus loading rates were in excess of 100 kg so additional data may be required to strengthen the "top end" of the relationship.

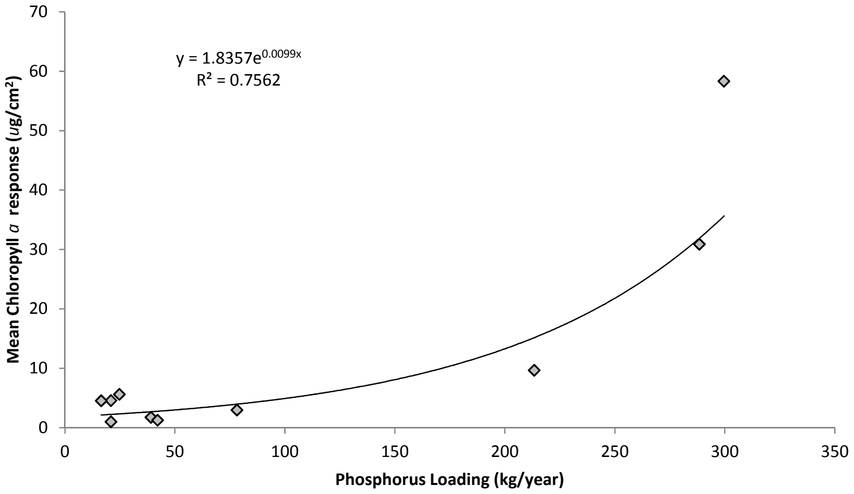

Figure 15. Phosphorus loading at the upper nutrient enrichment site plotted against chlorophyll *a* concentrations measured in the treated site 350 m downstream (1989-2010 data).

5.3 Water Chemistry

Grilse Creek

Measured nutrient concentrations varied in control and treated sites between years. Larger quantities of nutrients were added in early treatment years (1989-91) resulting in significant increases in SRP concentrations at sites 3.8 km to 4.4 km downstream (Figure 16). The differences between concentrations at control and treated sites were largest when looking at water samples closest to the nutrient source. The 50 m treated site routinely produced measurements significantly higher than the control while the 3.8 km and 4.4 km sites were marginally higher on occasion, and often very similar to the control. A similar response in nitrogen concentrations was also documented in treatment years when a significant quantity of N was applied (Figure 17).

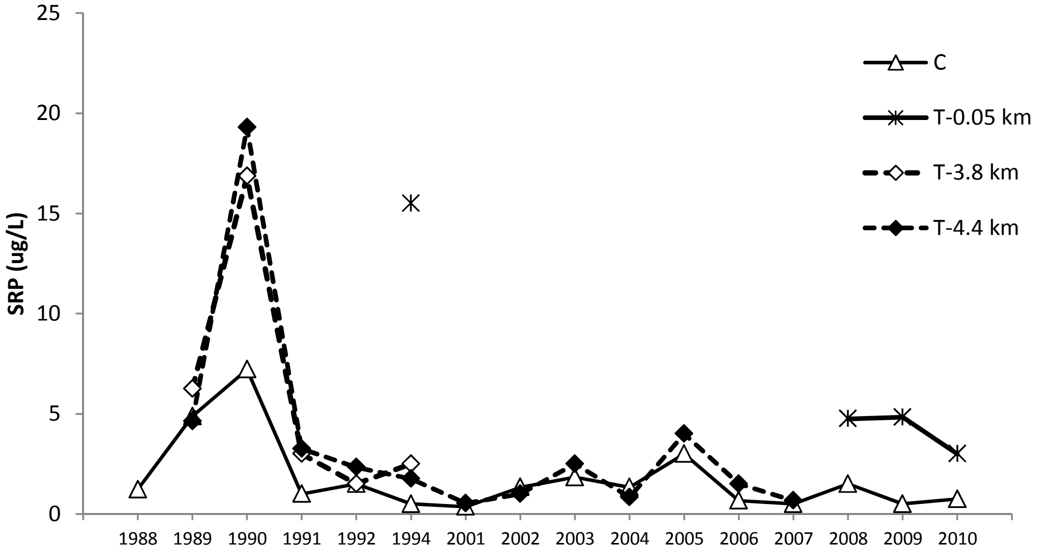

Figure 16. Mean measured SRP concentrations at 50 m, 3.8 km, and 4.4 km intervals downstream of the upper nutrient site in Grilse Creek in reference to control values, 1988-2010.

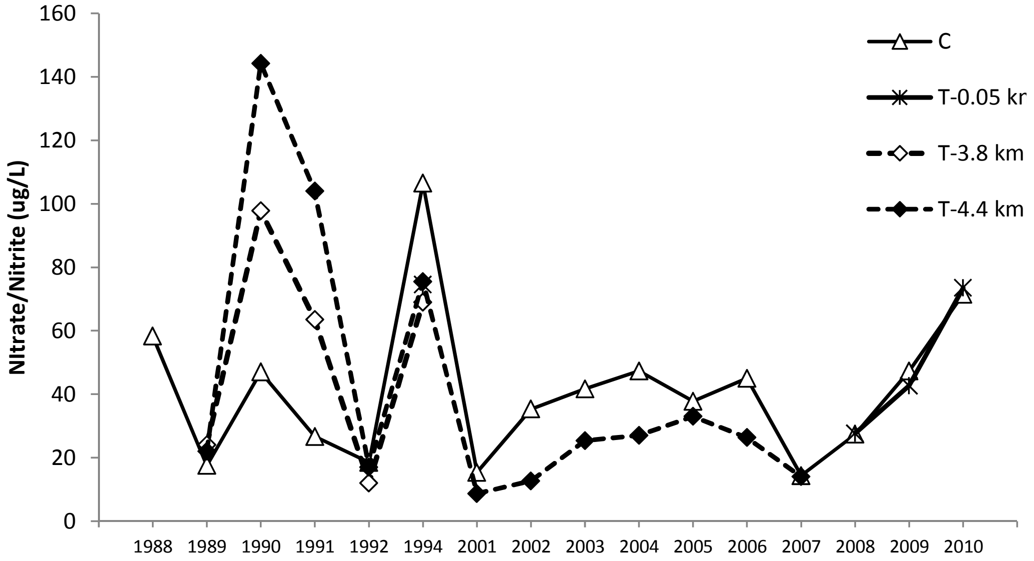

Figure 17. Mean measured nitrate/nitrite concentrations at 50 m, 3.8 km, and 4.4 km intervals downstream of the upper nutrient site in Grilse Creek in reference to control values, 1988-2010.

Nitrogen concentrations in treated sites were higher than the control during significant N loading in 1989-91, and were found to be lower than the control site in years of low N loading (2001-2010). Reduction of nitrogen in treated sites was only evident at sites which were 3.8 – 4.4 km from the nutrient source (2001-2007), and not significantly different 50 m below (2008-2010).

Seasonal variations in nutrient concentrations were also investigated. Nitrogen concentrations in control sites were found to increase throughout the duration of the season and peak during September 1-15 (Figure 18). SRP concentrations followed an inverse pattern and peaked June 1-15 before consistently decreasing throughout the summer (Figure 19). Concentrations of both nutrients followed a similar pattern at treated sites with peak concentrations measured in mid-July. Concentrations at 3.8 km and 4.4 km sites were found to be lower than those measured in the control after August 1 while the 50 m site registered similar nitrogen and higher SRP values during the same period. In general, the duration of elevated nutrient concentrations in treated sites coincided with the timing of nutrient application. However, concentrations in August appeared to be reduced at all treated sites even though nutrient addition continued into September in most years.

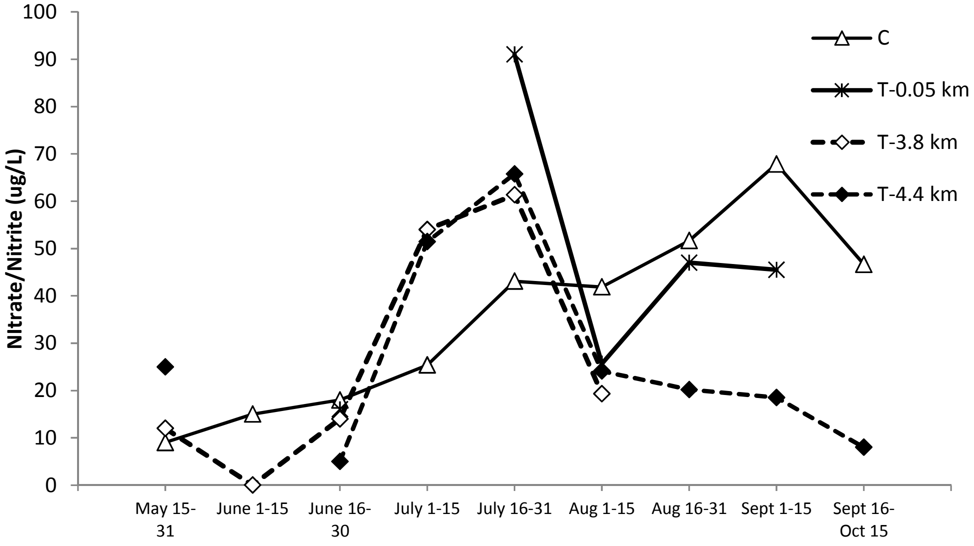

Figure 18. Seasonal nitrate/nitrite concentrations averaged at one control and three treated sites in Grilse Creek, 1988-2010.

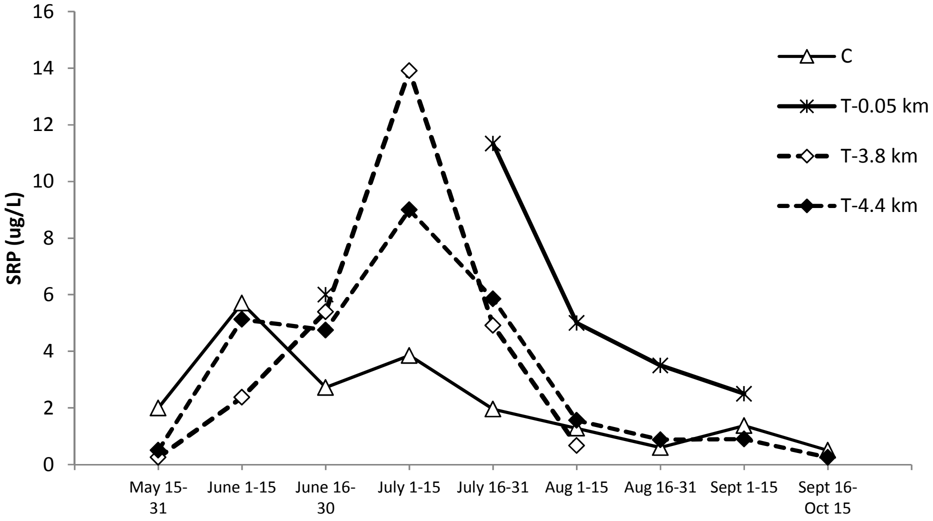

Figure 19. Seasonal SRP concentrations averaged at one control and three treated sites in Grilse Creek, 1988-2010.

Memekay River

Nutrient concentrations were found to be very similar between sites from 2001 to 2009 suggesting a limited measurable downstream effect at 7.2 km. SRP concentrations measured 50 m downstream of the lower nutrient enrichment site in 2010 were elevated (4.0 *µg/L* vs 0.5 *µg/L*) and near target loading rates (Figure 20). A spike in SRP concentrations was noted in 2005 at both sites which was also documented in Grilse Creek. Little variation was noted in nitrate/nitrite concentrations between any of the sites although above average levels were noted in 2010 (Figure 21).

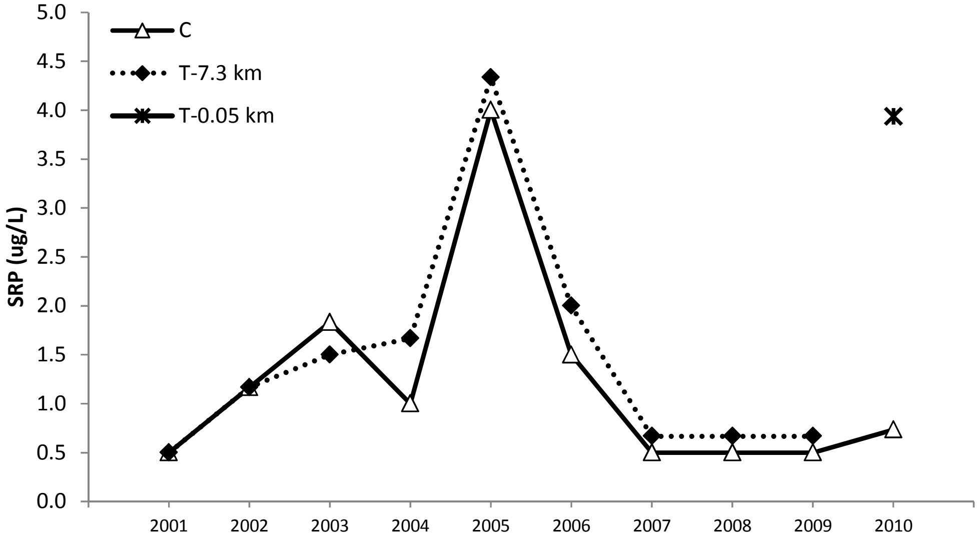

Figure 20. Mean measured SRP concentrations at 50 m and 7.2 km intervals downstream of the upper nutrient site in Memekay River in reference to control values, 2001-2010.

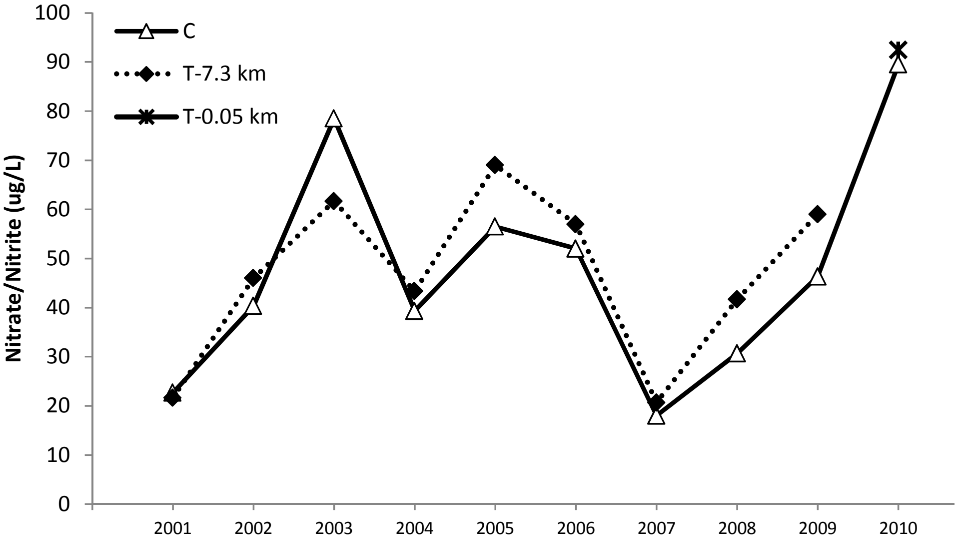

Figure 21. Mean measured nitrate/nitrite concentrations at 50 m and 7.2 km intervals downstream of the upper nutrient site in Memekay River in reference to control values, 2001-2010.

Seasonal variations in nutrient concentrations were slightly different in Memekay River compared to Grilse Creek. SRP levels at the control site followed a similar decreasing trend throughout the treatment period (Figure 22). Concentrations at the 7.3 km treated site did not appear to be significantly different. However, significantly higher SRP concentrations were noted in 2010 when sampling was conducted 50 m downstream of the enrichment site. Nitrogen levels peaked August 16-31 and decreased through September at all sites (Figure 23).

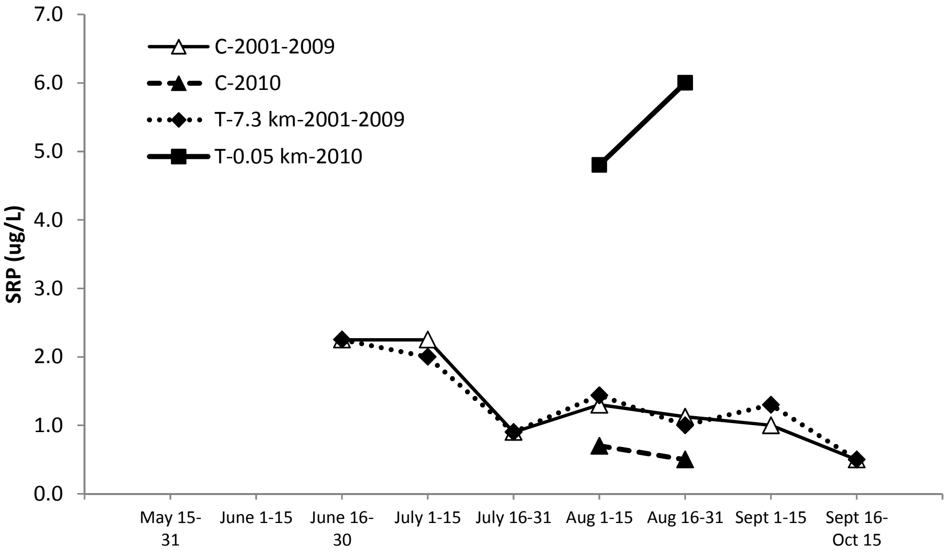

Figure 22. Seasonal SRP concentrations averaged at one control and two treated sites in the Memekay River, 2001-2010.

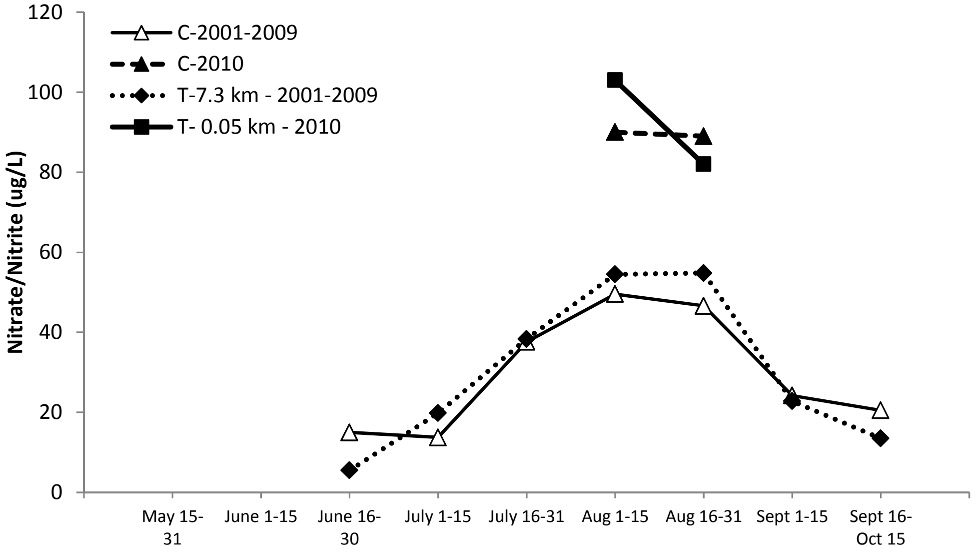

Figure 23. Seasonal nitrate/nitrite concentrations averaged at one control and two treated sites in the Memekay River, 2001-2010.

Salmon River

Nutrient concentrations have been measured at several different locations on the Salmon River mainstem since 1995. SRP concentrations in treated sites were variable but generally higher when sampling was conducted closer to the nutrient source (T-0.05 km, 2007-2010; Figure 24). Elevated phosphorus levels were measured up to 23.5 km downstream of nutrient enrichment locations although the presence of pink salmon adults in this reach may have confounded results. Mainstem nitrogen concentrations appeared to be influenced by nutrient enrichment from 1995-2006. Elevated levels were regularly documented in treated sites up to 23.5 km downstream when liquid fertilizer was applied (Figure 25). In 2007, a shift to solid slow release fertilizer reduced concentrations at downstream sites. Year 2007 also had the lowest average nitrogen concentration at the control site over the period of record, while SRP concentrations were similarly low.

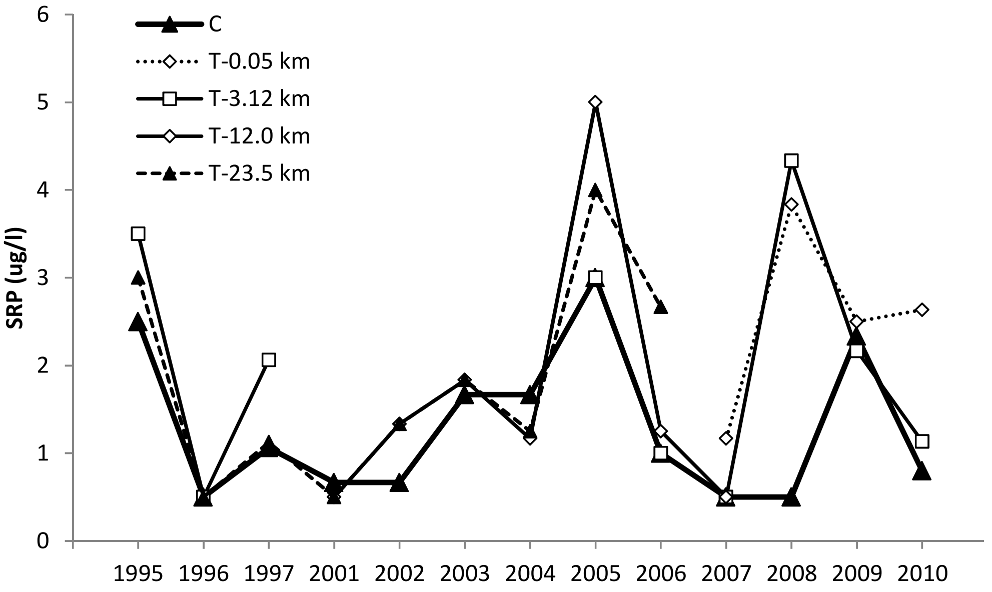

Figure 24. Mean measured SRP concentrations at 50 m, 3.12 km, 12.0 km and 23.5 km intervals downstream nutrient enrichment sites on the Salmon River in reference to control values, 1995-2010.

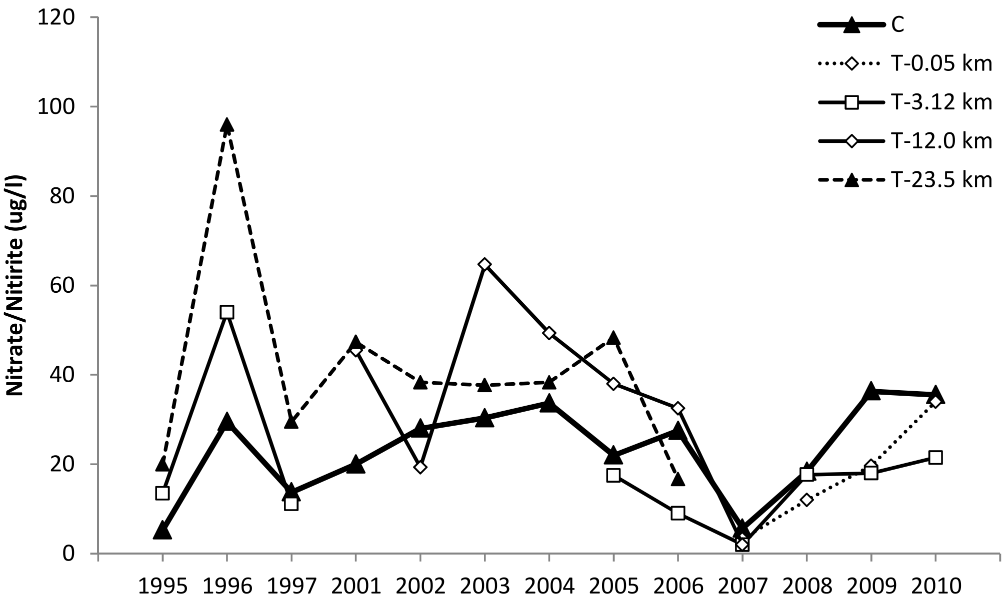

Figure 25. Mean measured nitrate/nitrite concentrations at 50 m, 3.12 km, 12.0 km and 23.5 km intervals downstream nutrient enrichment sites on the Salmon River in reference to control values, 1995-2010.

Seasonal variations in Salmon River nutrient concentrations were similar in mainstem sites as compared to Grilse Creek and Memekay River samples. At the control site, SRP concentrations were found to decrease throughout the season while nitrogen concentrations increased (Figures 26 and 27). SRP concentrations at treated sites were usually maintained throughout the treatment period before falling off in September. Concentrations were found to be slightly higher than average at the T-0.05 km site and near target loading rates of 2.5 *µg/L*. Nitrogen concentrations at treated sites were similar to the control site and increased throughout the season although the highest values were consistently recorded in the control reach.

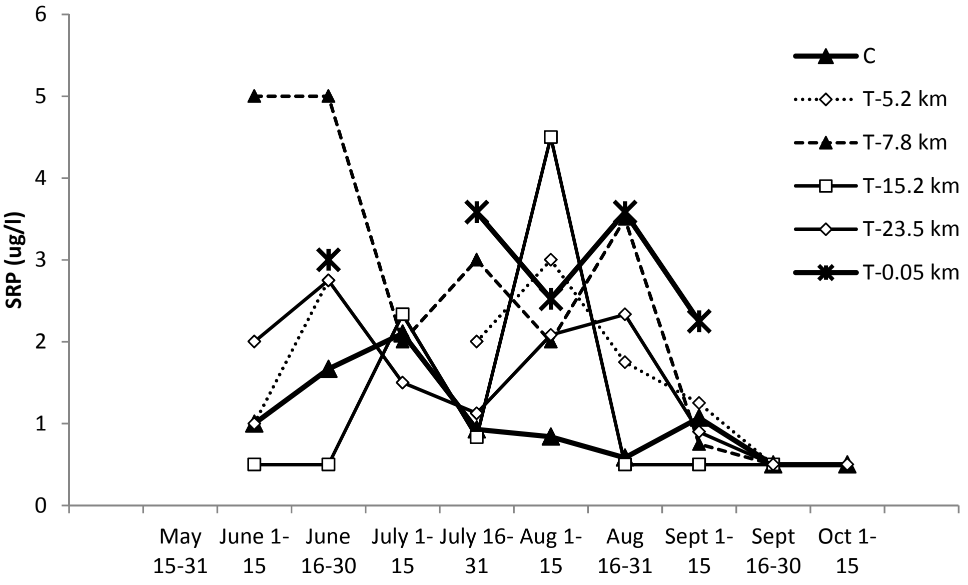

Figure 26. Seasonal SRP concentrations averaged at one control and four treated sites in the Salmon River, 1996-2010.

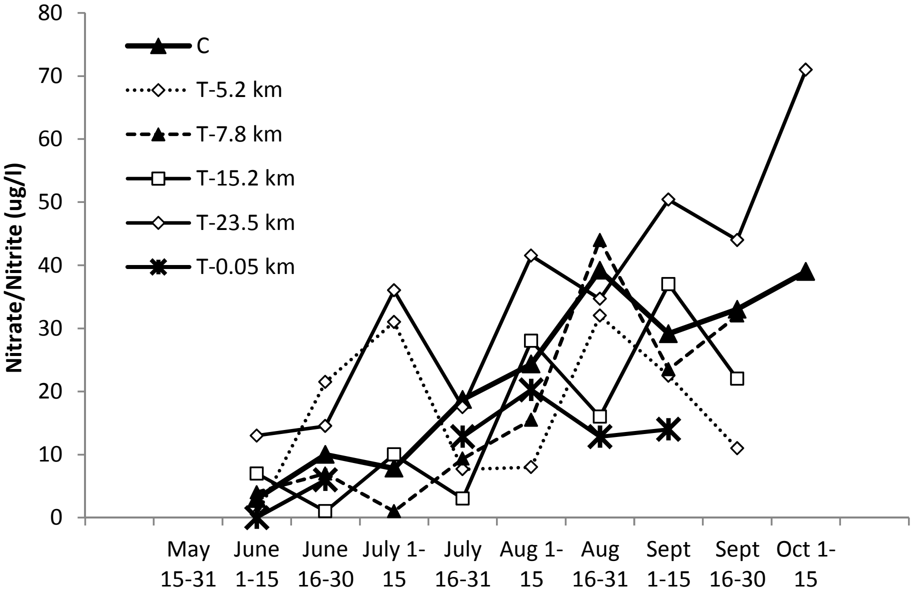

Figure 27. Seasonal nitrate/nitrite concentrations averaged at one control and four treated sites in the Salmon River, 1996-2010.

5.4 Fish Growth Response

Steelhead Fry

The average increase in fry growth over 12 years was 104% when comparing mean weights of fry in control and treated reaches. The response varied from a high of 218% in 2004 to a low of 11% in 2010 (Figure 28). The absolute increase in fry weight averaged 1.56 g with a range of 0.24 g (2010) to 2.92 g (2004). Below average responses were documented in 1999 and 2007-2010, while strong responses were observed in 2000 and 2002-2006. Less than 3% of fry were found to be greater than 80 mm in treated sites and none in the control suggesting a strong separation between fry and parr was present.

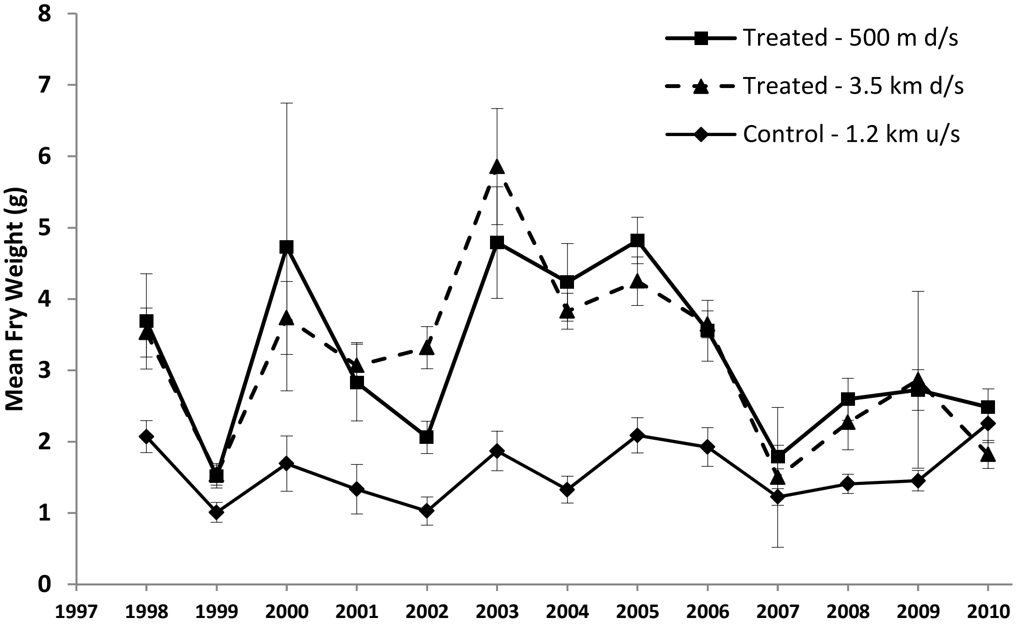

Figure 28. Mean weight of steelhead fry captured in two treated sites in Grilse Creek in reference to a control site 1.2 km upstream of the nutrient source (95% C.I.), 1998-2010.

A t-test revealed that there was a significant difference in mean weights at control and treated sites in 11 out of 12 years. In 2010, mean weights at control and treated sites were not deemed to be statistically different at the 95% confidence level. The statistical significance of the mean weights between all three sites (paired by year, α 0.05) was found to be statistically different 500 m downstream of the enrichment site (p=0.00005) and 3.5 km downstream (p=0.001; Table 5). The two treated reaches were also compared and were found to be not statistically different (p=0.40) suggesting that growth was similar at each site and significantly different from the control area (Table 6).

Table 5. Output from statistical analysis (t-test, α 0.05) of steelhead fry weights from control and treated sites between years in Grilse Creek, 1998-2010.

t-Test: Two-Sample Assuming Unequal Variances

	1998		1999		2000		2001		2002		2003		2004	
	T	*C*	*T*	*C*	*T*	*C*	*T*	*C*	*T*	*C*	*T*	*C*	*T*	*C*
Mean	3.684783	2.070909	1.511111	1.007143	4.728571	1.692308	2.827273	1.333333	2.06	1.027273	4.790909	1.868571	4.234286	1.326667
Variance	5.307541	0.718027	0.061111	0.069945	7.422381	0.510769	1.659221	0.378788	0.201143	0.110182	1.752909	0.704571	2.706437	0.276506
Observations	46	55	9	14	7	13	22	12	15	11	11	35	35	30
Hypothesized Mean Difference	0		0		0		0		0		0		0	
df	55		18		6		32		24		13		42	
t Stat	4.503244		4.642119		2.895451		4.567431		6.747394		6.897872		9.883709	
P(T<=t) one-tail	1.76E-05		0.000101		0.013749		3.48E-05		2.8E-07		5.44E-06		7.95E-13	
t Critical one-tail	1.673034		1.734064		1.94318		1.693889		1.710882		1.770933		1.681952	
P(T<=t) two-tail	3.53E-05		0.000203		0.027497		6.95E-05		5.59E-07		1.09E-05		1.59E-12	
t Critical two-tail	2.004045		2.100922		2.446912		2.036933		2.063899		2.160369		2.018082	

	2005		2006		2007		2008		2009		2010	
	T	*C*	*T*	*C*	*T*	*C*	*T*	*C*	*T*	*C*	*T*	*C*
Mean	4.82069	2.0875	3.555556	1.925	1.786486	1.225	2.594	1.408511	2.725	1.451852	2.482353	2.253488
Variance	0.797414	0.631378	1.700254	0.688214	0.26509	0.155872	1.123841	0.224274	1.008723	0.286317	0.863082	0.809214
Observations	29	40	36	36	37	44	50	47	48	54	51	43
Hypothesized Mean Difference	0		0		0		0		0		0	
df	56		59		67		69		70		90	
t Stat	13.13768		6.330341		5.426283		7.181672		7.847996		1.210566	
P(T<=t) one-tail	4.77E-19		1.82E-08		4.27E-07		3.11E-10		1.74E-11		0.114616	
t Critical one-tail	1.672522		1.671093		1.667916		1.667239		1.666914		1.661961	
P(T<=t) two-tail	9.54E-19		3.64E-08		8.55E-07		6.23E-10		3.48E-11		0.229231	
t Critical two-tail	2.003241		2.000995		1.996008		1.994945		1.994437		1.986675	

Table 6. Output from statistical analysis (t-test, α 0.05) of mean steelhead fry weights between control and treated sites, Grilse Creek, 1998-2010.

t-Test: Paired Two Sample for Means

	500 m d/s	*3.5 km d/s*	*Control*
Mean	3.215462871	3.17171848	1.590581
Variance	1.35991666	1.473948333	0.174678
Observations	13	13	13
Pearson Correlation	0.585187846	0.380038463	
Hypothesized Mean Difference	0	0	
df	12	12	
t Stat	5.966468541	5.072796127	
P(T<=t) one-tail	3.27274E-05	0.000136958	
t Critical one-tail	1.782287556	1.782287556	
P(T<=t) two-tail	6.54549E-05	0.000273916	
t Critical two-tail	2.17881283	2.17881283	

t-Test: Paired Two Sample for Means

	500 m d/s	*3.5 km d/s*
Mean	3.215462871	3.17171848
Variance	1.35991666	1.473948333
Observations	13	13
Pearson Correlation	0.856483469	
Hypothesized Mean Difference	0	
df	12	
t Stat	0.246721202	
P(T<=t) one-tail	0.404647072	
t Critical one-tail	1.782287556	
P(T<=t) two-tail	0.809294143	
t Critical two-tail	2.17881283	

A moderately strong correlation was observed between the quantity of phosphorus added and the magnitude of the fry growth response in Grilse Creek (r^2= 0.45; Figure 29). Applications of 60-80 kg P were found to produce the best response while those of less than 30 kg P achieved a weaker response. In 2003, only 42 kg of P was added yet the largest growth response on record was achieved. In 2010, the least amount was added (16.5 kg) which produced the only non-significant fry growth response in 13 years. If data from 1999 are excluded from the analysis due to the dramatically late start time (August 9), the correlation coefficient increased to 0.51.

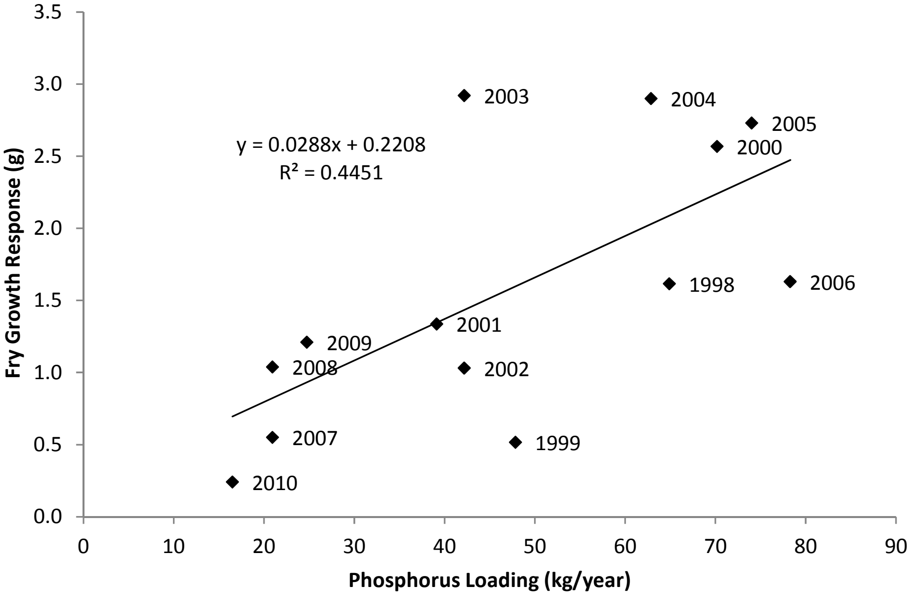

Figure 29. Regression analysis to investigate the effect of phosphorus loading on the growth of steelhead fry in Grilse Creek, 1998, 2000-2010.

Mean flows of 1-2 m^3/s in lower Grilse Creek appear to provide optimal enrichment conditions (Figure 30). Average flows of 2.5 m^3/s or greater appeared to limit growth with the poorest responses associated with the highest mean flows (2007, 2008, 1999). In 2000, fry growth response exceeded 2.5 g when the mean flow was 1.58 m^3/s. In other years when flow averaged near 1.5 m^3/s fry growth response was found to be variable, suggesting other factors were limiting growth. If data from 2010 are excluded from the analysis (lowest nutrient loading year) the correlation coefficient increased from 0.48 to 0.70.

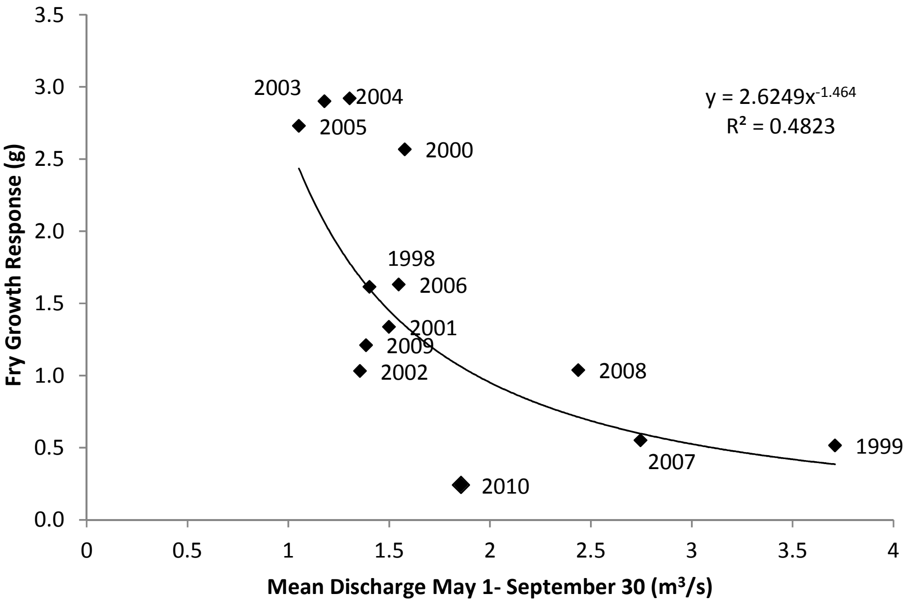

Figure 30. Regression analysis to investigate the effect of mean discharge (May 1- September 30) on the growth of steelhead fry in treated reaches of Grilse Creek, 1998-2010.

In years when nutrients were applied on or before June 25 (Julian day 176) mean fry growth responses were greater than 1 gram while applications after July 1 produced poor responses (Figure 31). The correlation between application date and fry growth (r^2=0.42) was found to be similar to the correlation with flow and nutrient loading (r^2=0.48 and 0.47, respectively). If 2010 data are excluded due to low nutrient loading the relationship is strengthened significantly with the correlation coefficient increasing to 0.58.

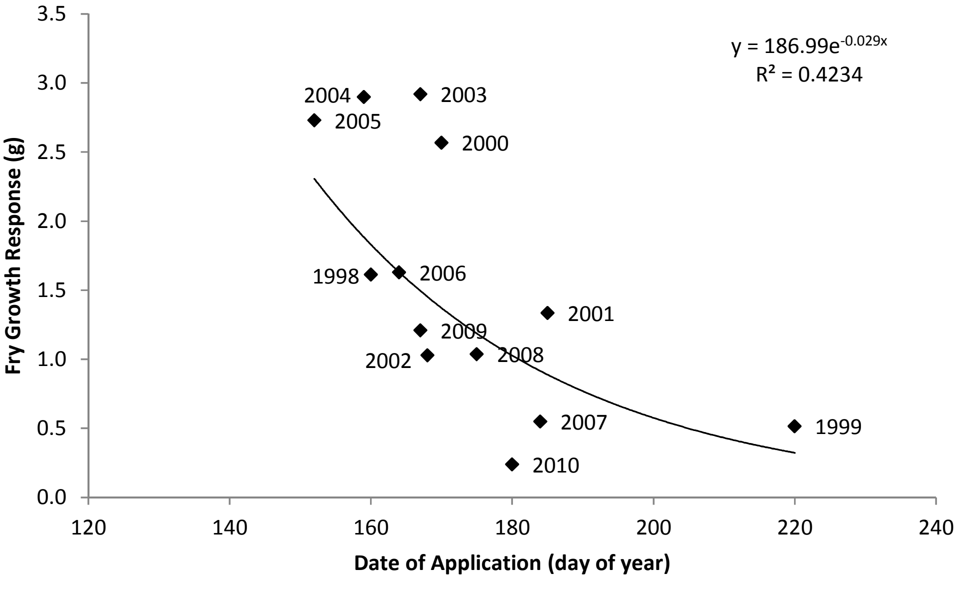

Figure 31. Regression analysis to investigate the effect of application timing on the growth of steelhead fry in treated reaches of Grilse Creek, 1998-2010.

The duration of the application did not correlate with the strength of the fry growth response (r^2=0.09; Figure 32). Removing outlying years when other factors were suspected to limit fry growth did not strengthen the relationship (1999, 2010). Applications lasting more than 50 days were found to be capable of producing satisfactory results with peak growth response achieved after 70 days, although results were variable.

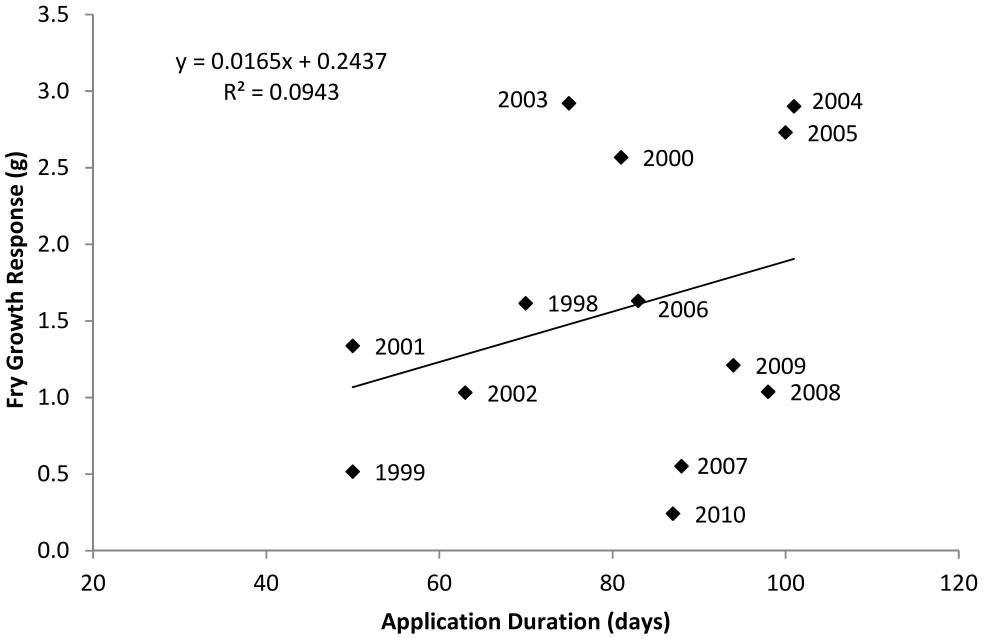

Figure 32. Regression analysis to investigate the effect of application duration on the growth of steelhead fry in treated reaches of Grilse Creek, 1998-2010.

When the algal biomass was plotted against fry growth response no correlation was evident (Figure 33). It appears that an algal standing crop / biomass of 5.0 µg/cm^2 (chlorophyll *a)* or less does not correlate with the fry growth response. For example, the algal growth response in 2010 was the second highest in six years of data yet fry growth ranked last. The fry growth response during the six years of data analysis was generally moderate to low (0.24-1.33 g) compared to maximum values for the period of treatment (2.92 g). It is possible that a clear growth response could exist when chlorophyll *a* concentrations enter the range of 10-15 ug/cm^2 as reported by Perrin (1990).

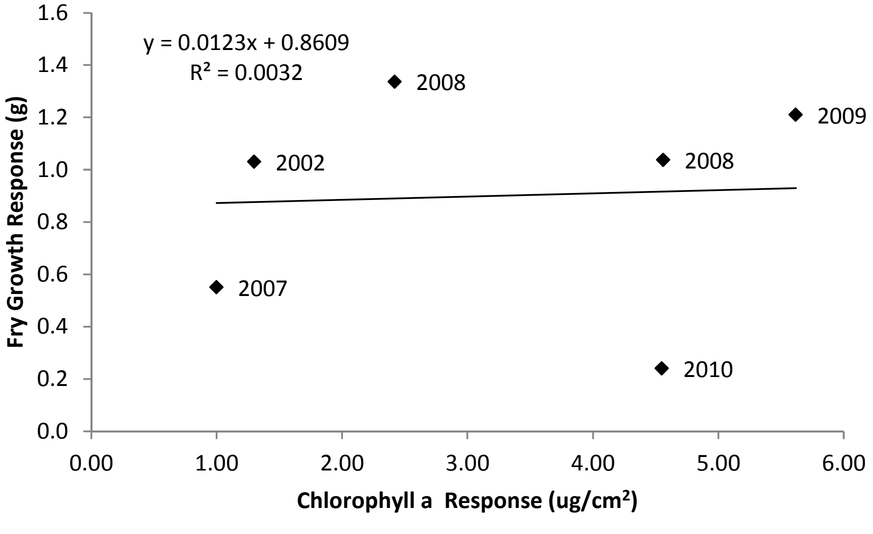

Figure 33. Regression analysis to investigate the effect of mean chlorophyll *a* biomass on the growth of steelhead fry in treated reaches of Grilse Creek, 2001-2002 and 2007-2010.

Steelhead Smolts

The mean age of steelhead smolts captured at the smolt screen on the Salmon River diversion canal has changed little since 1989. The majority of smolts sampled were two-year-olds comprising between 73% and 92% of the fish sampled. Three-year-olds made up the bulk of the remainder while one and four-year-old smolts were scarce (Figure 34). The mean smolt age was found to range between 2.07 and 2.25 years although there was a wide confidence interval in years with a low sample size (Figure 35).

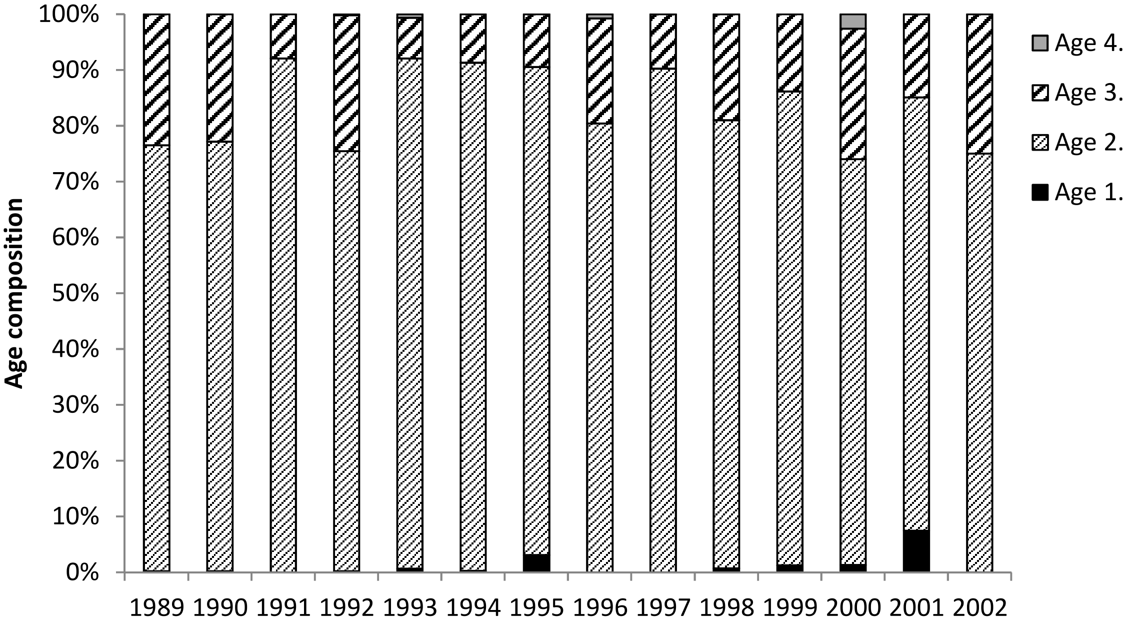

Figure 34. Age composition of steelhead smolts captured at the fish screen on the Salmon River diversion canal, 1989-2002.

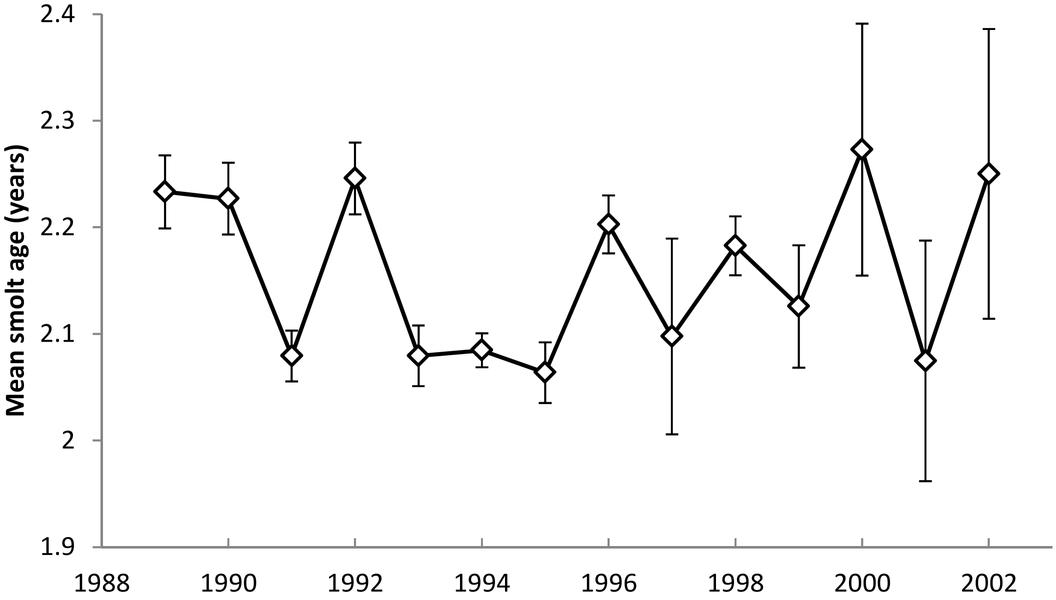

Figure 35. Mean age of steelhead smolts captured at the fish screen on the Salmon River diversion canal (95% C.I.), 1989-2002.

These observations are consistent with the Keogh River where two-year-old smolts dominate the population in enriched years and 3 year olds in non-enriched years (McCubbing et al. 2011; McCubbing and Ward 2002). However, in 1989 two-year old smolts dominated the sample group even though they were not affected by enrichment which began later that spring. In contrast, McCubbing et al. (2011) reported a mean Keogh smolt age of 3.19 years for the non-enriched 2010 migrants, with two-year-olds comprising only 9.5% of the population.

The mean length of steelhead smolts captured at the diversion has also been monitored since 1989 (Figure 36). The largest one year smolts were recorded in 1993 at 134 mm although the sample size was very low (n=3). Two-year-old smolts were largest from 1990-1994 (162 mm) compared to the long term average of 154 mm. There was a notable shift in the proportion of three-year-old to two-year-old smolts in 1997 as well as an absence of one-year-old smolts. Poor growing conditions in the summer of 1996 may have been a contributing factor.

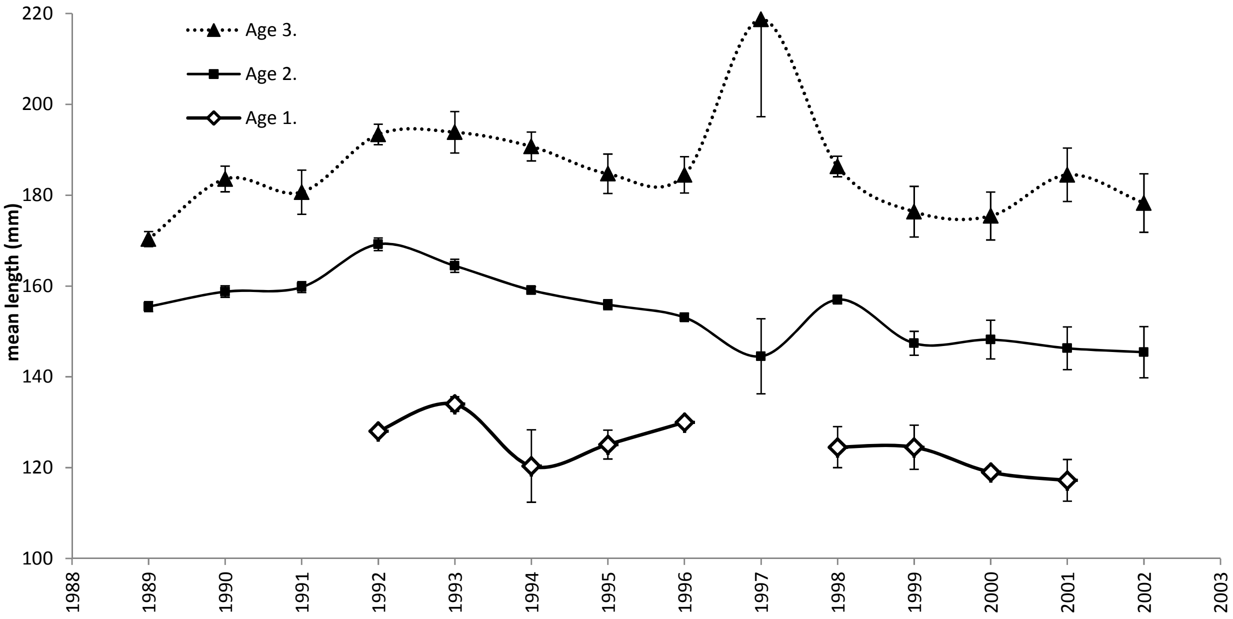

Figure 36. Summary of mean length of steelhead smolts captured at the Salmon River diversion fish screen, 1988-2003.

When the influence of nutrients on the size of smolts was investigated a strong correlation was evident (Figure 37). The quantity of nutrients that were applied to Grilse and Norris creeks was strongly correlated to the mean length of two-year-old smolts sampled at the diversion dam two years later (r^2=0.84). When 1999 smolts are removed from the analysis the correlation coefficient increases to 0.89. High flows in the summer of 1997 (3rd highest in 20 years) may be responsible for the below expected growth observed in 1999 smolts. This relationship provides evidence that increased growth of steelhead fry is responsible for larger smolts.

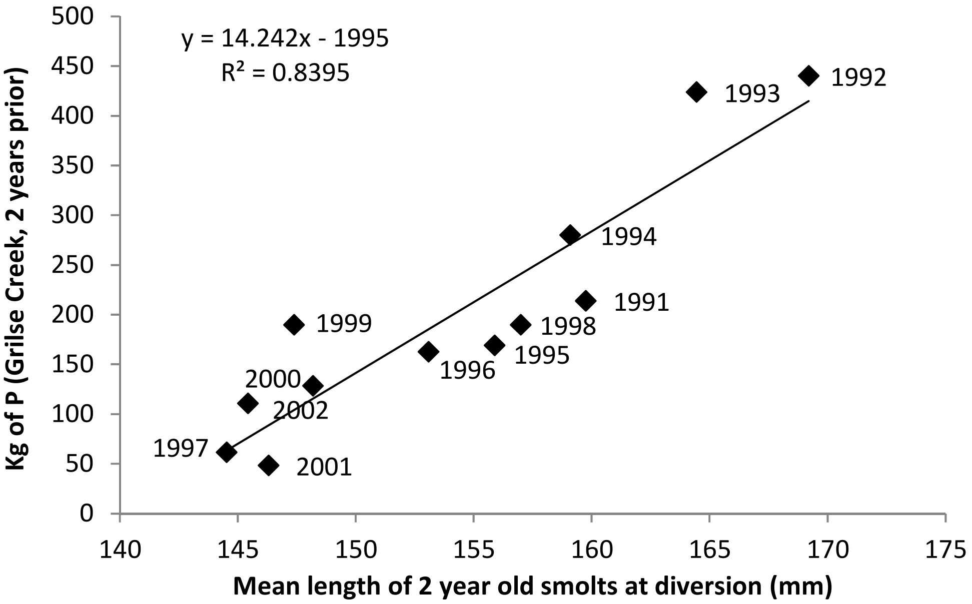

Figure 37. Mean length of two year old steelhead smolts sampled at the diversion dam plotted against the quantity of phosphorus added to Grilse Creek two years prior, 1991-2002.

5.5 Steelhead Population Trends

Electrofishing Data

A summary of thirteen years of electrofishing data was compiled to reveal year-to-year differences in mean fry density across ten sites in the watershed. A density of 60 fry/unit (162 g/100 m^2) has been previously identified as a target at which available fry habitat can be considered fully seeded (Lill 2002). Target fry densities were achieved in only three of the last thirteen years although all three occurrences were after 2005 (Figure 38).

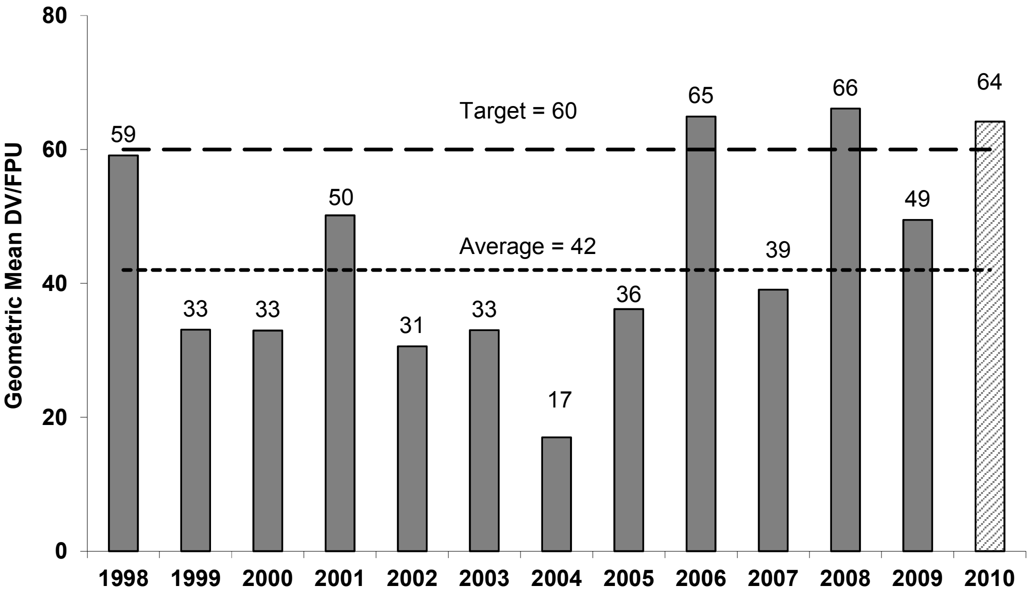

Figure 38. Geometric mean depth/velocity adjusted steelhead fry densities at ten sites in the Salmon River watershed in reference to target abundance, 1998-2010.

Fry densities with respect to the diversion dam were also examined, as an equal number of sampling sites were located in each strata. A comparison of upstream and downstream mean densities suggests a considerable amount of variation between years (Figure 39). Years 1998 to 2006 and 2010 densities were similar but from 2007-2009 they were much higher in downstream reaches. Much of this discrepancy is due to varying inter-annual adult passage conditions at the diversion dam, often related to flow. Recently (2010 and 2011) specific actions have been taken at the dam to provide periods of unrestricted access during key steelhead migration times.

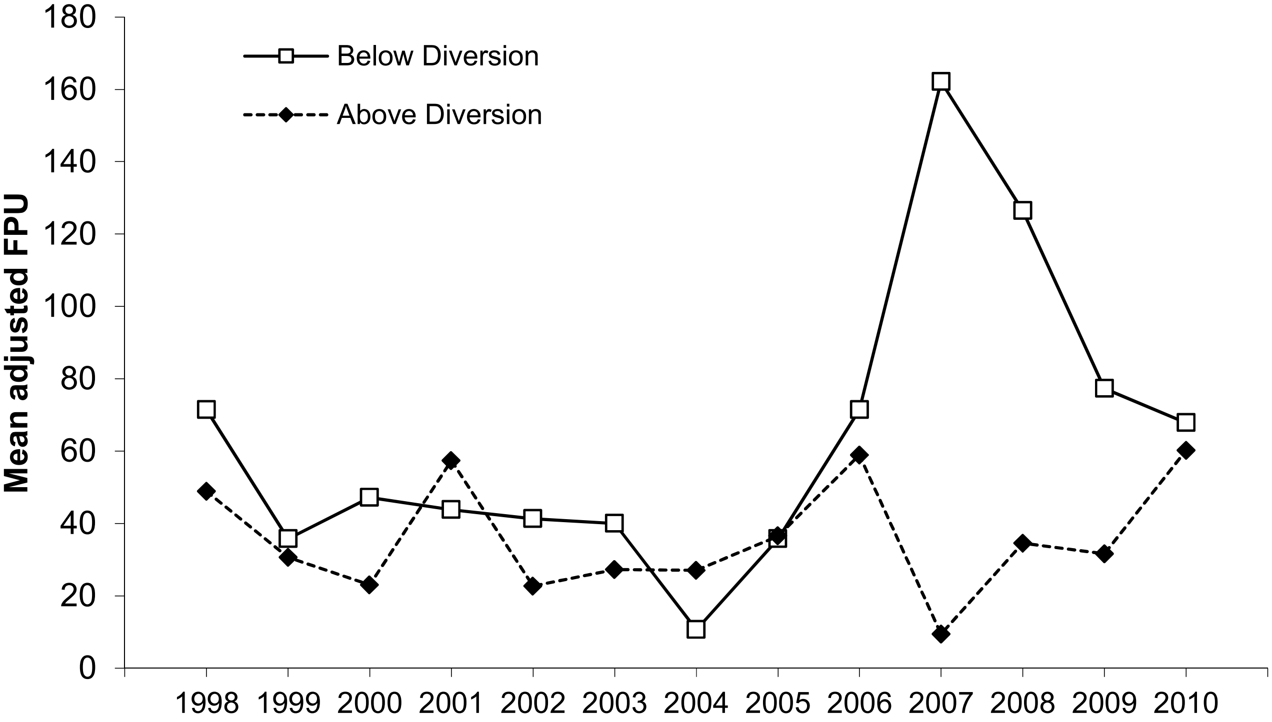

Figure 39. Mean unadjusted steelhead fry densities at sites above and below the diversion dam on the Salmon River, 1998-2010.

Snorkel Survey Data

Snorkel survey results from 1982 to 2011 reveal a high degree of variation in adult steelhead counts between years, with a high of 255 in 1988 to a low of 33 in 2004 (Figure 40). Recent counts beginning in 2006 have been relatively strong. The 5.7 km reach immediately below the diversion dam has been swum periodically since 1999 and consistently since 2008. Adult densities in this reach have been much higher since 2008 (Figure 41). Although moderate numbers of adults were observed in the lower index in 1999 and 2002, relatively few were observed upstream. In the last four years proportionally more fish have been observed in upstream reaches suggesting a higher total escapement to the watershed, as well as providing evidence of increased colonization of upstream habitats.

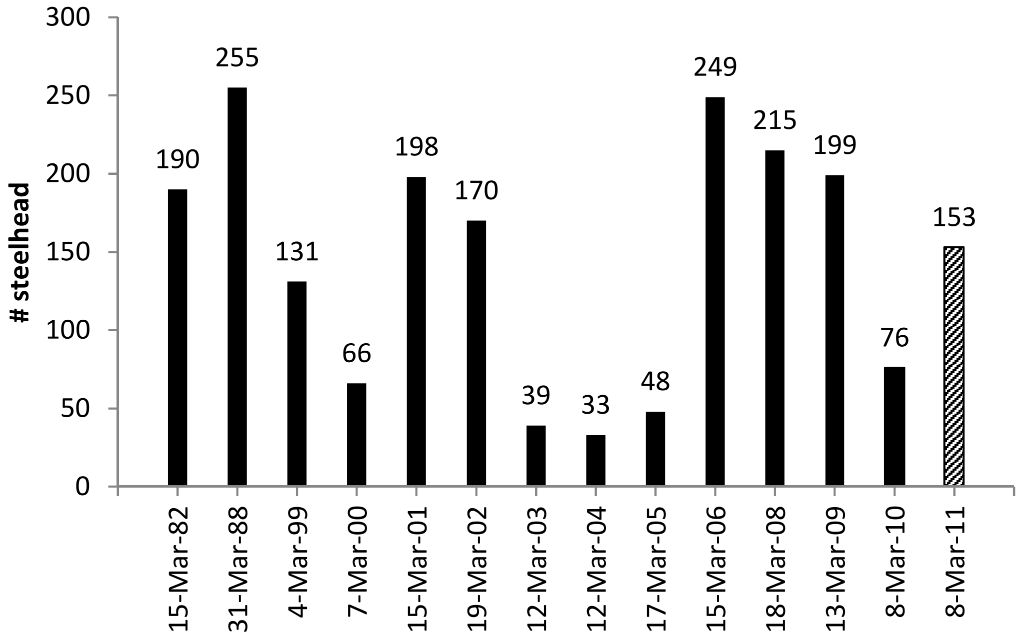

Figure 40. March winter steelhead snorkel counts from Kay Creek to Pallan's (11.5 km), 1982-2011.

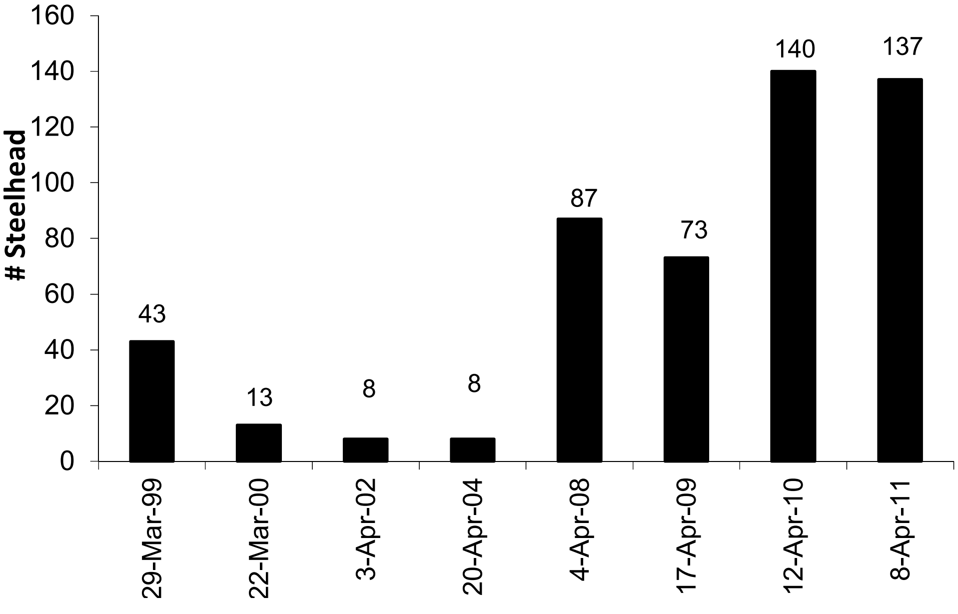

Figure 41. Summary of winter steelhead snorkel counts from the diversion dam to the Memekay Mainline Bridge (5.7 km), 1999-2011.

A lag time of 3-6 years exists between nutrient application and adult returns from enriched juvenile rearing years. For example, if nutrients were not applied to the Salmon River in summer 2012 then the first "non-enriched" adult returns would be expected six years later (spring 2018; Table 7). Adult returns in spring 2016 and 2017 would be influenced by significantly lower levels of freshwater enrichment (32.8% and 5.6% respectively).

Under the most likely smolt and adult age structure it would take six consecutive years of cessation to remove any residual effect of enrichment on adult returns. If the adult population was found to decrease in response to a six-year pause in the enrichment program it would take a further six years to bolster the return if the program was immediately reinstated (plus a possible one year delay with funding cycles).

Table 7. Summary of theoretical smolt and adult responses to the onset or cessation of nutrient enrichment on the Salmon River.

Year	Treatment	Smolt response				Adult response				Total Adult
		Age 1.	*Age 2.*	*Age 3.*	*Age 4.*	*Age .1*	*Age .2*	*Age .3*	*Age .4*	Response
1	yes	100%	100%	100%	100%	100%	100%	100%	100%	100.0%
2	yes	100%	100%	100%	100%	100%	100%	100%	100%	100.0%
3	no	100%	100%	100%	100%	100%	100%	100%	100%	100.0%
4	no	0%	50%	66%	75%	100%	100%	100%	100%	100.0%
5	no	0%	0%	33%	50%	52%	100%	100%	100%	98.2%
6	no	0%	0%	0%	25%	6%	52%	100%	100%	75.9%
7	no	0%	0%	0%	0%	0%	6%	52%	100%	32.8%
8	no	0%	0%	0%	0%	0%	0%	6%	52%	5.6%
9	yes	0%	0%	0%	0%	0%	0%	0%	6%	0.3%
10	Yes	100%	50%	33%	25%	0%	0%	0%	0%	0.0%
11	yes	100%	100%	66%	50%	48%	0%	0%	0%	1.8%
12	Yes	100%	100%	100%	75%	94%	48%	0%	0%	24.0%
13	yes	100%	100%	100%	100%	100%	94%	48%	0%	67.0%
14	yes	100%	100%	100%	100%	100%	100%	94%	48%	94.3%
15	no	100%	100%	100%	100%	100%	100%	100%	94%	99.6%
16	no	0%	50%	66%	75%	100%	100%	100%	100%	100.0%

Salmon Adults - ocean age

Age 1	Age 2	Age 3	Age 4
3.7%	43.0%	47.8%	5.5%

Salmon Smolts - FW age, enriched

Age 1	Age 2	Age 3	Age 4
1.1%	82.3%	16.4%	0.3%

* Smolt response refers to the proportion of the summer growing season(s) of that year's age class (freshwater) that were subject to enriched rearing conditions prior to emigration. Adult response refers to the percentage of each returning age class (saltwater age) that were subject to enriched freshwater conditions. Adult response was weighted based on smolt age composition data collected from monitoring at the diversion fish screen. Total adult response refers to the sum of returning age classes weighted based on age composition data from Hooton et al. (1987).

A precautionary approach would include a cessation for three consecutive years followed by reinstatement of the program in year four. If returns in years four through six are found to be impacted negatively, the program would already be underway and could be continued further. If the adult population is found to be stable the decision to take a longer absence from enrichment can be made with increased confidence. Additionally, three years of monitoring data under non-enriched conditions can be collected to compare against past treatments

5.6 Vancouver Island Stream Enrichment

Keogh River

Monitoring of juvenile steelhead during two enrichment cycles on the Keogh River has indicated a marked response in fry, parr and smolts. Steelhead fry were found to be 50% to 200% larger, on average in treated reaches, compared to control conditions (McCubbing and Ward 2001; Slaney et al. 2003).

Smolt size and age composition were found to change significantly during years of nutrient enrichment on the Keogh River. Two-year-old smolts were found to be 10 mm longer when subject to nutrient enrichment (McCubbing et al. 2011). Smolt age shifted from predominantly three-year-olds to two-year-olds under enriched conditions. One-year-old smolts were found to be nearly absent in control years while four-year-old smolts comprised up to 30% of the migrants. Conversely, a marked increase in one year old smolts and an absence of four year old smolts was noted under treated conditions.

When compared to smolts sampled in the upper Salmon River (1989 - 2002), two-year-old “enriched smolts” on the Keogh River were larger in average size (167 mm vs 158 mm). When the two years following maximum nutrient inputs to Grilse Creek were compared, mean lengths for the Salmon and Keogh smolts were consistent (167 mm, 1992 and 1993). Smolts on the Keogh were found to average 154 mm under non-enriched conditions (McCubbing et al. 2011). Slaney and Ward (2003) suggested smolt age was negatively correlated with fry growth and that changes in smolt size were not always apparent despite a shift in smolt age.

Steelhead smolt yield was also able to be quantified under varying treatment and control conditions on the Keogh. Prior to the Watershed Restoration Program (WRP), which included installation of large woody debris (LWD) structures and nutrient treatments, annual steelhead smolt yield averaged 1,341 (1994-1998). Under nutrient enriched conditions (1999-2006), smolt yield increased 91% to an average of 2,568 fish. When nutrient treatments were terminated but LWD structures remained (2007-2010), smolt production returned to 1,495 fish on average (McCubbing et al. 2011). Slaney and Ward (2003) indicated the adult steelhead return increased by 50% as a result of nutrient enrichment.

Harris Creek

Mean weights of steelhead fry collected from control and treated reaches in Harris Creek followed a similar pattern to those in Grilse Creek (Figures 28 and 42). The mean growth response in Harris Creek averaged 1.40 g once data from 2008 were excluded (no treatment). This compared similarly to 1.56 g observed in Grilse Creek. Maximum fry weight in treated sites was also similar with steelhead exceeding 4.0 g in each system during highly effective treatments.

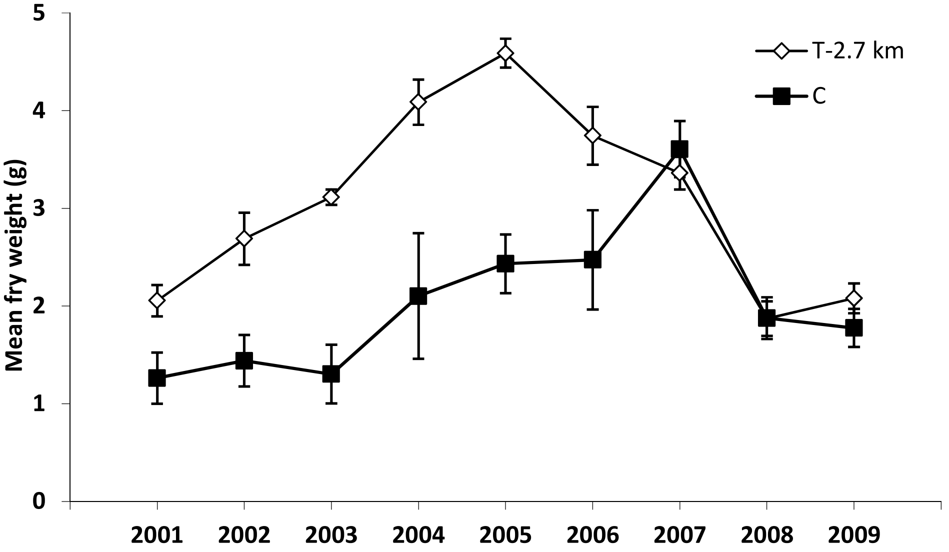

Figure 42. Mean steelhead fry weights in response to nutrient enrichment of Harris Creek in the San Juan River Watershed (Vancouver Island), 2001-2006, 2008-2009.

A t-test was conducted (two samples assuming unequal variances) to further investigate the statistical significance of the fry growth response. Treatments from 2001 to 2006 resulted in a statistically significant growth response 2.7 km downstream of the enrichment site (Table 8). From 2007 to 2009 there was no statistically significant difference in mean weights at the 95% confidence level (p=0.48). In 2007, the mean weight of steelhead fry in the control reach was unusually high and thought to be a result of immigration/emigration between the two reaches during high water prior to sampling. No nutrients were added in 2008 and the mean weights at each site were almost identical (within 0.006 g) and the largest p value in the data set was calculated at 0.48. In 2009, Crystal Green was applied as a source of nutrients although it was equivalent to less than half of the P applied in 2005. The difference in mean growth was small (0.3 g) but was found to be statistically significant.

Table 8. Output from statistical analysis (t-test, α 0.05) of steelhead fry weights from control and treated sites between years in Harris Creek, 2001-2010.

t-Test: Two-Sample Assuming Unequal Variances

	2001		2002		2003		2004		2005	
	T	*C*	*T*	*C*	*T*	*C*	*T*	*C*	*T*	*C*
Mean	2.055172	1.262069	2.688889	1.438095	3.114815	1.302747	4.0875	2.101724	4.588679	2.432456
Variance	0.521133	0.19601	0.489487	0.77705	0.639772	0.299495	1.7185	0.806839	1.245254	0.646636
Observations	29	29	27	42	27	182	16	58	53	114
Hypothesized Mean Difference	0		0		0		0		0	
df	46		64		30		19		78	
t Stat	5.04343		6.535295		11.38319		5.701235		12.62535	
P(T<=t) one-tail	3.8E-06		6.04E-09		1.03E-12		8.51E-06		7.68E-21	
t Critical one-tail	1.67866		1.669013		1.697261		1.729133		1.664625	
P(T<=t) two-tail	7.6E-06		1.21E-08		2.06E-12		1.7E-05		1.54E-20	
t Critical two-tail	2.012896		1.99773		2.042272		2.093024		1.990847	

	2006		2007		2008		2009	
	T	*C*	*T*	*C*	*T*	*C*	*T*	*C*
Mean	3.742857	2.472222	3.360674	3.604756	1.870588	1.876364	2.078462	1.774699
Variance	2.838606	0.820921	1.917186	0.602917	0.607318	0.445912	0.575779	0.711669
Observations	42	36	89	82	51	55	65	83
Hypothesized Mean Difference	0		0		0		0	
df	65		141		99		143	
t Stat	4.226321		-1.43592		-0.04082		2.300674	
P(T<=t) one-tail	3.79E-05		0.076619		0.48376		0.011428	
t Critical one-tail	1.668636		1.655732		1.660391		1.655579	
P(T<=t) two-tail	7.57E-05		0.153239		0.96752		0.022856	
t Critical two-tail	1.997138		1.976931		1.984217		1.976692	

6.0 DISCUSSION

Monitoring twenty years of nutrient enrichment in the Salmon River watershed has produced several valuable data sets from which to examine efficacy. Other streams such as the Keogh River and Harris Creek provide additional support for conclusions drawn from work conducted on the Salmon. Research from the Keogh River station also suggests gains in stock productivity are possible during years of nutrient treatments and that a rapid reversal to control conditions occurs once enrichment ends. Fry growth response in Grilse and Harris creeks was consistent with the Keogh River under enriched conditions while the mean age of smolts from the upper Salmon River was also consistent with Keogh results.

Recent stock assessment data suggest the wild steelhead population in the Salmon River is increasing and that upstream habitats are being colonized at a greater rate than previously documented. It remains unclear if ocean survival has changed recently for smolts emigrating from the Salmon River. Current monitoring results from Keogh River suggest no significant change has occurred with survival calculated at 3.1% for smolts entering the ocean in 2007 (McCubbing 2011).

While enrichment was found to have a significant biological response in the majority of treatment years, several different aspects of the program were analyzed to identify mechanisms that are limiting a biological response. A summary of the findings, including recommendations for future nutrient enrichment, are presented below.

Timing

After analysis of 13 years of data it is apparent that application timing has a significant effect on the growth response of steelhead fry. The largest gains were made in years when the addition of nutrients began before July 1, and preferably before June 25. Stream flow typically governs application timing and also has the ability to dilute nutrient concentrations throughout the treatment period. Analysis of flow data suggested that if the mean discharge for the May 1-Sept 30 period exceeded 10 m^3/s at the Salmon River diversion dam (or 1.8 m^3/s in Grilse Creek), then the mean growth response by fry was significantly reduced. Given that application timing is related to stream flow, the negative correlation between stream flow and fry growth (r^2=0.70) may also be influenced by earlier applications in low-flow years.

Loading Rates

Early applications (1989-91) involved top loading headwater reaches at rates that exceeded downstream target concentrations. Both N and P were added to ensure that N limitation did not occur under high P loading. Later, blends of N and P were applied in liquid form although the ratio was much different and the loading rate was drastically reduced. Target concentrations of 5 *µg/L* SRP and 20 *µg/L* N (as nitrate-nitrite) were suggested for early treatments and scaled back to 2.5-5 *µg/L* SRP for later treatments. Water chemistry monitoring revealed SRP concentrations of 5 *µg/L* were rarely met in treated reaches and were often at undetectable levels (<1 *µg/L*). Perrin (1990) suggested the discrepancy between theoretical and actual concentrations was due to rapid uptake by algae. Monitoring of early treatments on Grilse Creek under high nutrient loading produced SRP concentrations exceeding 70 *µg/L* in some samples.

The biomass response by algae (chlorophyll *a* levels) was found to be strongly correlated to the quantity of P added (r^2=0.76) and reached a maximum under high loading rates. However, there was little correlation with fry growth due largely to the fact that low algal biomass (5.0 ug/cm^2 chlorophyll *a*) was found to produce some of the largest growth responses in fry. Fry growth was found to have a moderate correlation with the quantity of P added (r^2=0.58) although moderate quantities of P (40 kg) were capable of producing strong growth. Optimal fry growth (1.5 - 3.0 g more than control group) was achieved when 60-80 kg of P were added to Grilse Creek. Similarly, the length of two-year-old steelhead smolts was found to be correlated to the quantity of nutrients added two year's prior (r^2=0.64) and produce optimal growth with the addition of 80 kg or more P.

Summer base flow over the typical course of treatments (June 15 to September 15) averaged 3.27 m^3/s at the BC Hydro diversion (2000-2010 data). Given the strong correlation between flows in lower Grilse Creek and diversion (r^2=0.94), a calibration curve was used to calculate the mean base flow at 0.61 m^3/s. If P was applied evenly over 90 days at an average stream flow of 0.61 m^3/s the theoretical loading rate would be 12.7 *µg/L* SRP at 60 kg, 14.8 *µg/L* at 70 kg and 16.9 *µg/L* at 80 kg. Water quality criteria for nutrients have been set by the BC Ministry of Environment-Environmental Protection Division (MoE-EP). 10 *µg/L* P has been set as a guideline for drinking water as well as recreation in lakes and 5-15 *µg/L* for aquatic life in lakes (Nordin 1985). No guidelines have been proposed for streams for nutrient concentrations. It has been suggested that 10 *µg/L* P for streams should be a maximum concentration for nutrient enrichment and has rarely been exceeded during treatments. More clarity may be required if loading rates are intended to exceed 10 *µg/L* during future treatments. There is now increased evidence that top loading produces measurable biological response at significant downstream distances while nutrient concentrations are rapidly depleted at much shorter distance.

The Keogh River has been closely monitored under enriched and natural productivity levels. Johnston et al. (1990) and McCubbing et al. (2011) both concluded the addition of N and P resulted in increased growth of steelhead and coho juveniles. Loading rates during enriched years were set at 10-15 *µg/L* SRP and 30-100 *µg/L* N which are consistent with the quantity of P added to Grilse Creek which produced the largest growth response in steelhead fry. However, this loading rate is higher than the 5 *µg/L* P and 20 *µg/L* N suggested by Perrin (1990), and also higher than the 2.5 *µg/L* SRP recommended by McCusker et al. (2002). Ashley and Stockner (2003) recommended a loading rate of 3-5 *µg/L* SRP for stream enrichment and suggested levels greater than 10 *µg/L* were capable of producing excessive algal growth.

The risk associated with adding large quantities of P is that N can become limiting if background levels drop below 20 *µg/L* or if N:P ratios (DIN:TDP) are less than 10:1 (Ashley and Stockner, 2003). Some evidence of P loading driving down N concentrations has been anecdotally documented as a mid-treatment "die-off". This is further documented by lower nitrogen concentrations in Grilse Creek beginning in mid-July and at treated sites within 5 km of the nutrient source. At sites greater than 7 km downstream in tributaries, and 10 km downstream in the mainstem, N concentrations appear similar to the control site.

Monitoring

The majority of nutrient treatments have been monitored in a similar way by documenting periphyton growth, water chemistry and steelhead fry growth. Field sampling provides insight into specific variables but is generally only as good as the quality of methods and analysis employed. For example, water chemistry analysis performed in different years by different labs produced results with varying detection limits. Earlier samples were field filtered while later samples were unfiltered and sent directly to the lab for analysis. Often, detection levels were near target loading rates and rapid nutrient uptake often resulted in undetectable nutrient concentrations in treated reaches. Periphyton monitoring was also subject to similar inconsistencies although minimum detection levels were rarely above sample concentrations.

A positive response in both low level nutrient concentrations and periphyton growth was observed in most treatment reaches across all years. A positive growth response by steelhead fry was also documented in most years however it was difficult to correlate the data sets. It is recommended that fry sampling be continued as a key metric for effectiveness monitoring of future treatments as this provides a direct linkage between nutrient addition and fish growth. Water sampling is critical to determine if target loading rates are being met and should be conducted at a full mix site (immediately downstream of the nutrient source), as well as at intervals downstream (1, 2, 5, 10 km) to investigate the nutrient spiralling distance. Periphyton monitoring effectively documents the response of the algal community to nutrient treatments and should be conducted coincidentally with water sampling.

Monitoring data collected on Grilse Creek indicated that growth response by fry to enrichment was significant at two treated sites even though the sites were separated by 3.5 km. In years when a low growth response was observed at the site closest to the nutrient source, growth at the downstream site was often comparable to the control. This provides support for the top loading effect whereby fry growth benefits from appropriately designed enrichment projects are realized at significant downstream distances. These observations underline the importance of nutrients in headwater reaches for driving stream productivity throughout a watershed. The effective distance separating enrichment sites has been suggested to range from 6.0 km in smaller systems such as the Keogh River (Ashley and Stockner 2003) to 10 km or more in larger rivers (McCusker et al. 2002). In Grilse Creek, the minimum effective distance has been shown to be 3.8 km. These findings should be taken into consideration during the design of future enrichment protocols.

Smolt age composition data from the fish screen at the BC Hydro diversion dam was useful in documenting trends over time. Data suggest that steelhead smolts emigrating from the upper Salmon River are predominantly two-year-olds under enriched conditions. Although this is consistent with results from the Keogh River, it is unclear if this is different from control conditions on the Salmon due to a lack of data from pre-treatment years.

Periphyton biomass, water chemistry, and fish growth response have been documented annually by comparing control and treated sites but there has not been any year in which background productivity levels have been monitored (i.e. no nutrient addition). Comparison of a full suite of monitoring data during a year in which no nutrients are added would provide a new set of data from which to evaluate the effectiveness of nutrient treatments (similar to Keogh River experiments).

7.0 RECOMMENDATIONS

Although the review was useful in determining the effect of nutrient addition under varying environmental conditions, monitoring of background stream productivity at the watershed level has not been conducted. Preliminary findings/conclusions could be better supported through the collection of monitoring data during years where no treatments are conducted. This will aid in evaluating the success of past treatments and provide a better understanding of limiting factors in the watershed. As it is currently unknown what effect nutrient treatments have had on supporting increased stock productivity (i.e. recent increases in the adult population) it is recommended that cessation of nutrient treatments be approached cautiously.

Although ocean survival has a large role in regulating the number of steelhead adults there is no evidence from the Keogh River study to suggest a large shift in survival has occurred despite increased returns on the Salmon. Therefore, monitoring several consecutive years (2-4) of background productivity followed by several more years of nutrient addition is recommended. Monitoring should include: 1) algal biomass, 2) steelhead fry size, 3) steelhead smolt size and age, and 4) adult steelhead abundance and distribution. In addition, water samples will be analyzed for low level nutrient concentrations throughout the summer. The analysis of juvenile size at age will provide early indications of any reduction in freshwater productivity. Adult returns from enriched or un-enriched smolt years will be delayed due to the ocean phase of the steelhead life cycle. If returns are found to be negatively impacted by the pause in nutrient addition further losses will have been offset by a reinstatement of the program prior to the evaluation of results.

After data from background productivity monitoring is examined in combination with the results presented in this review, effects of nutrient addition will be better understood and a more informed decision regarding its future application in restoring fish habitat on the Salmon River can be made.

8.0 ACKNOWLEDGEMENTS

Funding for nutrient enrichment of the Salmon River watershed was provided by the Habitat Conservation Trust Foundation and the Steelhead Society of BC - Campbell River Chapter from 1989-1996. BC Hydro first contributed to the project from 1997 to 2009 in conjunction with several partners including Forest Renewal BC (FRBC), Forest Investment Account (FIA), Living Rivers – Georgia Basin/Vancouver Island and the Campbell River Salmon Foundation. Chris Perrin of Limnotek Research and Development Inc. conducted the feasibility and first three years of nutrient applications while The British Columbia Conservation Foundation provided project administration beginning in 1992. Loreta Hansen conducted nutrient applications under the guidance of Ken Ashley and Craig Wightman from 1992 to 2006. Fisheries staff from the A-Tlegay Fisheries Society assisted with nutrient applications and BC Conservation Foundation staff (Nanaimo) conducted applications and monitoring from 2007 to 2010. Editing of the draft was conducted by Craig Wightman while financial support to complete the review was received from the Fish and Wildlife Compensation Program (FWCP, BC Hydro) and Living Rivers-Georgia Basin Vancouver Island. Dr. Richard Nordin completed a critical review of the document in accordance with the terms of reference identified by the FWCP board. His commentary and insight on the topic were much appreciated.

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APPENDIX I - FINANCIAL STATEMENT

Project # 10.CBR.04

Financial Statement Form

	BUDGET		ACTUAL	
INCOME	FWCP	Other	FWCP	Other
Total Income by Source	8,405.10	2,200.00	8405.1	3,000.00
Grand Total Income (BCRP + other)	10,605.10		11,405.10	
EXPENSES *Project Personnel*				
Wages - BCCF	7,000.00	0.00	7,613.85	1,524.98
Consultant Fees - Review	0.00	3,450.00	0.00	500.00
Training/Safety				
Per Diem				
Materials and Equipment				
Travel Expenses - Ferry	150.00	0.00	0.00	0.00
Vehicle Lease	200.00	0.00	0.00	0.00
Fuel	200.00	0.00	0.00	0.00
Per Diem	91.00	0.00	0.00	0.00
Administration				
Office Supplies				
Photocopies and printing				
Postage				
BCCF admin @ 10%	764.10	0.00	791.25	202.50
Total Expenses	8,405.10	3,450.00	8,405.10	2,227.48
Grand Total Expenses (FWCP+other)	11,855.10		10,632.58	
BALANCE (Grand Total Income - Grand Total Expenses)	0.00		772.52	

APPENDIX II - PERFORMANCE MEASURES

Performance Measures - Target Outcomes								**Project # 10.CBR.04**				
Project Type	**Primary Habitat Benefit Targeted of Project (m^2)**	**Primary Target Species**	**Habitat (m^2)**									
			Estuarine	In-Stream Habitat - Mainstream	In-Stream Habitat - Tributary	Riparian	Reservoir Shoreline Complexes	Riverine	Lowland Deciduous	Lowland Coniferous	Upland	Wetland
Impact Mitigation												
Fish passage technologies	Area of habitat made available to target species											
Drawdown zone revegetation / stabilization	Area turned into productive habitat											
Wildlife migration improvement	Area of habitat made available to target species											
Prevention of drowning of nests, nestlings	Area of wetland habitat created outside expected flood level (1:10 year)											
Habitat Conservation												
Habitat conserved – general	Functional habitat conserved/replaced through acquisition and mgmt											
	Functional habitat conserved by other measures (e.g. riprapping)											
Designated rare/special habitat	Rare/special habitat protected											
Maintain or Restore Habitat forming process												
Artificial gravel recruitment	Area of stream habitat improved by gravel plcmt											
Artificial wood debris recruitment	Area of stream habitat improved by LWD plcmt											
Small-scale complexing in existing habitats	Area increase in functional habitat through complexing											
Prescribed burns or other upland habitat enhancement for wildlife	Functional area of habitat improved											
Habitat Development												
New habitat created	Functional area created											

APPENDIX III – INDEPENDENT REVIEW

25 August 2011

Kevin Pellett
Fisheries Biologist
BC Conservation Foundation
Nanaimo, B.C.

Kevin
As per your request I have done a review of your draft report "A Review of Twenty Years of Nutrient Enrichment in the Salmon River Watershed, Vancouver Island (1989-2010)". Overall I think the report is excellent and you have done a commendable job of compiling and interpreting some difficult and varied sets of data to provide an overall view of what the program has accomplished and what the results are.

I have made a number of comments and notes in the text using the MS Word edit function. Most are minor corrections and comments that I hope will improve the report. Most of my comments center on the use of terms (like growth, accrual etc) but it is important in conveying the information in the report that the language and technical terms be as clear as possible – otherwise there are misunderstandings in communicating the information.

One overall suggestion that I have not made in the text is that the report would become considerably more readable if the figures and tables were placed into the body of the text adjacent to where they are being discussed. I realize the format that you have used is the traditional one where figures and tables are placed in the back (there was a reason for that in the pre-computer days) but with present word processing, placement of tables and figures in more useful proximity to the discussion of the data is easily done and adds considerably to the understanding and utility of both the narrative and the data.

I agree with your conclusion that it may be useful to discontinue the fertilization program but continue to monitor the status of the fish populations for a period to provide additional insight into the factors controlling the steelhead numbers. In the light of other factors like ocean survival (potentially having an overriding effect) continuing fertilization may not provide additional significant scientific information?

If you have any questions about my comments please contact me.

My best regards on a job well done

Rick Nordin PhD

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