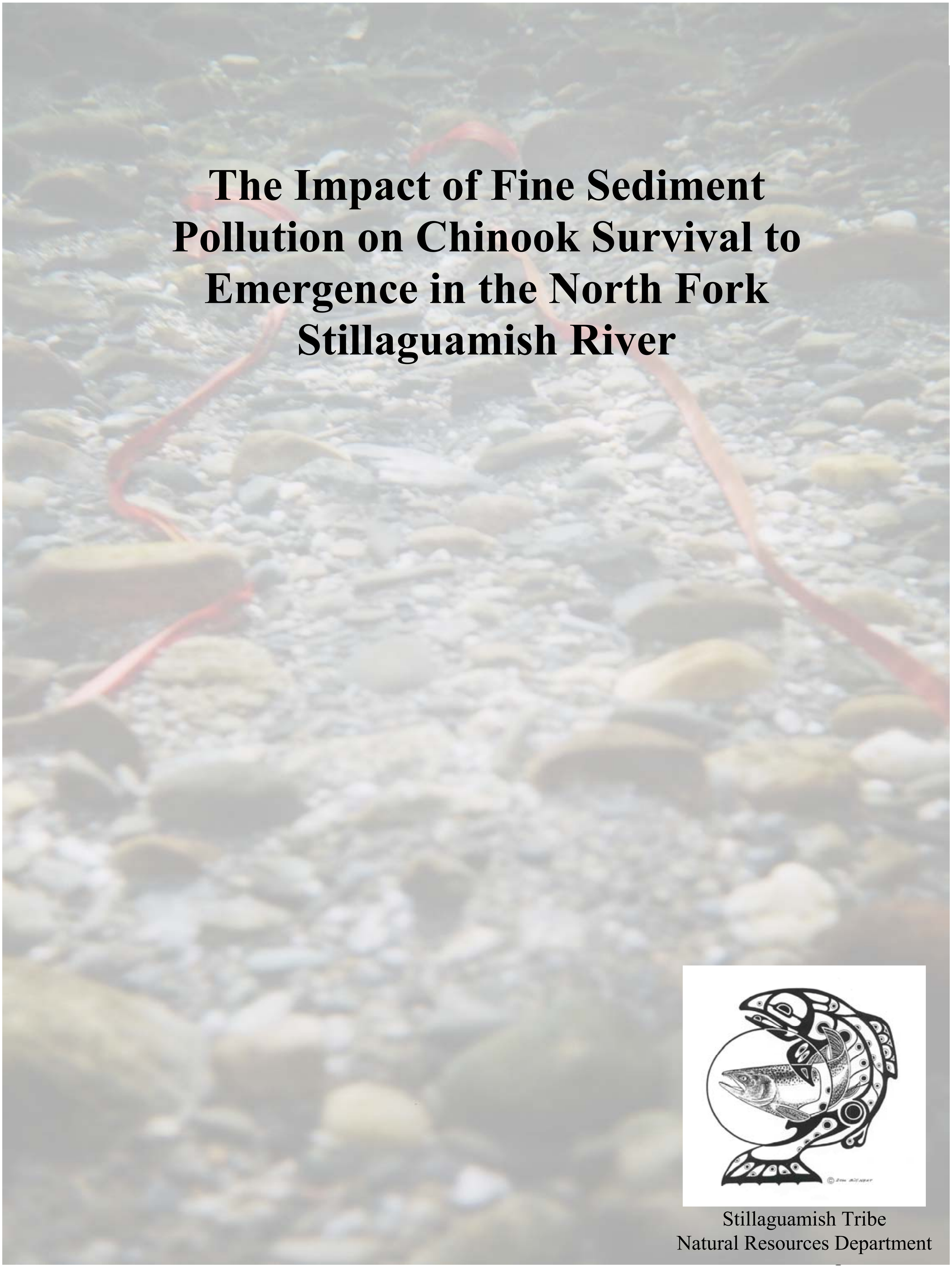

The Impact of Fine Sediment Pollution on Chinook Survival to Emergence in the North Fork Stillaguamish River

Stillaguamish Tribe
Natural Resources Department

ACKNOWLEDGEMENTS

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INTRODUCTION

Fine sediment is a natural and necessary component to river systems and is typically flushed out as new naturally occurring sediment enters in. However when fine sediment input increases beyond the systems natural limits, the system can no longer flush all the material out and sediment accretion occurs (Suttle *et al*. 2004). There are numerous potential sources of sediments that may become suspended and/or settleable upon reaching surface water. Some of which can be natural such as sediment released from ice melt and stream bank erosion. Other sources are usually a result of poor management of land use activities such as forestry, agriculture, and development. The most common sources of fine sediment pollution in the Pacific Northwest are from the following:

- Landslides resultant from forestry, including road building and maintenance (Amaranthus *et al*. 1985)
- Extensive network of improved, unimproved, and abandoned roads constructed and maintained primarily for forestry (Beschta 1978)
- Erosion of streambanks exacerbated by upstream dikes and revetments, riparian vegetation removal, and an increasing trend in the discharge of peak flow events (Kondolf and Wilcock 1996)
- Erosion from farm fields, ditches, and pastures (McCool and Roe 2005)
- Urban development (Nelson and Booth 2002)
- Resuspension of fine sediments previously deposited on streambeds (Daum and Hoenicke 1998).

There are a number of negative impacts related to fine sediment pollution. Suspended sediments cloud the water column increasing turbidity. This not only reduces aesthetics but also lessens sunlight penetration, which in turn reduces photosynthetic activity and limits primary production (McCubbin *et al*. 1990, Persaud and Jaagumagi 1995). Turbid water also absorbs heat so an increase in suspended sediment can cause an increase in water temperatures (Marcus *et al.* 1990). Suspended sediments adsorb and concentrate trace metals and other contaminants such as pathogens and can transfer them from terrestrial to aquatic environments thereby increasing their availability to aquatic life (Murty 1986). Suspended sediments can also adversely affect aquatic life such as fish by reducing feeding activity (Gregory 1990), modifying natural movements by inducing avoidance reactions (McLeay *et al*. 1984), causing physiological damage to gills (Goldes 1983) and other organs (Herbert and Merkens 1961), altering spawning habitat (Slaney *et al*. 1977), and under extremely high concentrations suspended sediments can be lethal to fish (Newcombe and MacDonald 1991).

Pacific salmon are intimately linked to rivers and streams and the landscapes they drain. The quality of the water salmon reside in heavily influences their success to propagate and sustain their populations for future generations. Fine sediment pollution has been shown to be deleterious to salmon on many levels. It has been demonstrated that fine sediments severely impact incubation success of salmonid embryos (McNeil and Ahnell 1964, Koski 1966, Hausel and Coble 1976, Reiser and White 1988, and Bennett *et al.* 2003). Female salmon effectively remove fine sediment from redd locations by the winnowing action of their tail leaving large sediments while smaller sediments get carried downstream by the current forming the tailspill. However, fine sediment eventually finds its way back into the redd by the "pulling" of water downward through the redd (Cooper 1965). Redds are constructed in such a way to create down-welling through it to bring oxygen rich water into contact with incubating eggs and to remove metabolic wastes (Kondolf 2000). This down-welling also brings with it fine sediments that are drawn into the redd even at times when high water velocities would prevent deposition on the gravel surface. Therefore, suspended sediments that would normally get carried out to the bay or get deposited in fringe, low velocity areas work their way down through the redd. These sediments oftentimes form a "crust" or a "seal" layer above the egg pocket (the actual location of egg deposition) thus sealing off the eggs for effective metabolism (Chapman 1988).

Laboratory and field researchers have attempted to relate fine sediment to incubation and emergence success. Of the studies conducted to determine the effects of fine sediment on incubating salmonids, two particle size classes have shown to correlate well with survival to emergence (STE), 6.4 mm and 0.850 mm. Particles less than 6.4 mm may allow sufficient flow through the egg pocket allowing alevins to hatch, however migration through gravel is often lessened as these fine particles sufficiently fill in interstitial spaces effectively entombing alevins (Phillips *et al*. 1975, Hawke 1978). Particles less than 0.850 mm seal off flow from reaching the eggs thus suffocating eggs before alevins hatch (Tagart 1976, 1984, Tappel and Bjornn 1983). This is believed to be due to the depletion of oxygen in the substrate from the biochemical oxygen demand and the low permeability from increased fines preventing the interchange of oxygenated surface water with intergravel water (Chapman 1988).

BACKGROUND

The Stillaguamish Watershed is located in the western Cascade Range and Puget Lowlands of Washington State (Figure 1). The Stillaguamish River drains an area of approximately 684 square miles and includes more than 975 miles of streams and rivers. The river enters Puget Sound at Stanwood, 16 miles north of Everett in northwest Snohomish County. Elevations in the watershed range from sea level to 6,854 feet on Three Fingers Mountain. The Watershed is divided into three general regions: the North Fork, South Fork and the Lower Mainstem (Figure 2).

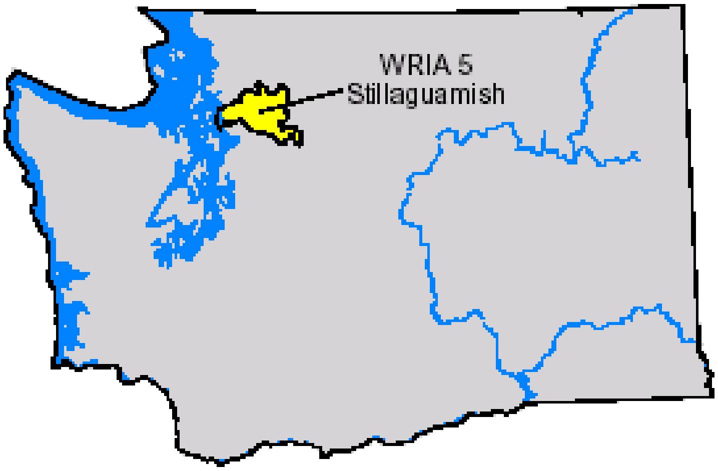

Figure 1. Stillaguamish Watershed in Washington State

Figure 2. Stillaguamish Watershed Regions

Eight species of anadromous salmonids use the Stillaguamish watershed and near shore estuaries for critical stages of their life cycle. Since 1999 three species of anadromous salmonids, Chinook salmon (*Onchorhynchus tshawytscha*), Puget Sound steelhead (*Onchorhynchus mykiss*), and bull trout (*Salvelinus confluentus*) were listed as threatened under the Endangered Species Act (ESA). Factors contributing to the decline and the current, critically low population levels of these species, especially Chinook, are noted as being high stream temperatures, poor estuary conditions, reduction in slough and side-channel juvenile rearing habitat, reduction in the diversity of instream physical habitat, and accelerated sediment delivery (Pess, *et al*. 1999, WCC 1999, Haas *et al*. 2003).

There is virtually no part of the Stillaguamish watershed that has not been impacted by land use activities. Most of the upland areas are managed for commercial timber harvest and mismanagement of these areas is believed to be one of the main causes of water quality degradation such as increased sedimentation. In the report the "Effects of Land Use on the Stillaguamish River, Washington, ~1870 to ~1990: Implications for Salmonid Habitat and Water Quality and their Restoration" Collins (1997) connects land-use activities in the Stillaguamish Watershed with degraded salmonid habitat and water quality. Collins (1997) reports that by 1942 nearly the entire anadromous zone had undergone riparian logging. Riparian logging removes trees from the channel migration zone (CMZ) and truncates the input of large woody debris (LWD) into river systems. Riparian logging also destabilizes stream banks and slopes causing landslides and introducing fine sediment into surface waters. Collins (1997) reports that nearly 75% of the landslides recorded in the North and South Forks were associated with logging activities such as clear cuts (52%) and logging roads (22%). Of the landslides inventoried the ones that contributed the largest volume of sediment were the Deforest Creek slide in Deer Creek Basin, various locations in the Upper North Fork Stillaguamish, the Hazel slide in the Higgins Ridge Basin, and Gold Basin and Canyon Creek slides in the South Fork.

Perkins and Collins (1997) conducted an analysis of aerial photos to document landslides in the Stillaguamish Watershed. Of the 1080 landslides they located, 851 delivered sediment to stream channels. 61% of these were located in the North Fork basin. Deer Creek, Upper North Fork and Higgins Ridge sub-basins were the largest contributors of sediment, followed by Boulder Ridge, Hell/Hazel, Squire Creek, and Frailey Mountain sub-basins (Table 1).

Table 1 shows that Boulder Ridge, Squire Creek, and Grandview sub-basins peaked between 1941-1956. Perkins and Collins attribute this to early timber harvest and high levels of alpine activity. Higgins Ridge and Hell/Hazel sub-basins peaked in the 1960's and Deer Creek and the Upper North Fork peaked in the 1980's, however insufficient data was available to estimate delivery in the 1990's. Of the documented landslides, 47% of them occurred in glacial soils, 32% in bedrock, 1% in former landslide deposits, 0.6% in alluvium, and 20% in soils of unknown geology.

Perkins and Collins (1997) also noted that more than 75% of channel segments investigated indicated accretion associated with some landsliding in the stream segments upstream. This suggests that more sediment is being deposited than that which could be flushed out potentially widening channels, and filling in pools. Sediment pulses from the major landslides in the North Fork have altered salmonid spawning productivity in the North Fork especially below the Hazel Slide and Deer Creek (Pess and Benda 1994).

Table 1. Volume of sediment from landslides delivered by sub-basin and time period (taken from Perkins and Collins 1997).

Estimated Delivered volume (m^3) from landslides in photos dated:

Sub-Basin	Date not determined	Chronic Landslides	1941-56	1962-70	1972-79	1983-1989	1991-1993	Total
Boulder Ridge	0	300	32500	10,150	1,000[4]	12,950	2,100	59,000
Deer Creek[3]	181,142[1]	0	2,173[4]	167,220	68,818[4]	1,700,111[4]	N/A[1]	2,119,464
Frailey Mtn.	0	0	6,820	2,720	N/A	5,600	0	15,140
Grandview	0	0	3,400	500	N/A	0	0	3,900
Hell/Hazel[5]	27,000	0	5,800	7,400	5,200	3,270	2,200	50,870
Higgins Ridge[3]	0	0	1,600[4]	218,036	74,435	16,400	7,000	317,471
Squire Creek	0	0	24,220	1,720	N/A	0	0	25,940
Upper North Fork[2]	0	0	N/A	23,559	36,458	522,779	N/A	582,795
Total	**208,142**	**300**	**76,513**	**431,305**	**185,911**	**2,261,110**	**11,300**	**3,174,580**

1. Date not determined (Deer Creek): only 1983 and 1991, date of landslide occurrence unknown. 2. 100% delivery was assumed. 3. Volumes were not estimated for 33% of landslides. 4. Only partial coverage used. 5. The Hell/Hazel sub-basin does not include the Hazel landslide.

The sediment sources in the Upper North Fork have mainly been described to be due in large part to road building and forest management (Perkins and Collins 1997). The Upper North Fork has a road density of 3.2 miles/mile^2 ranking it 6th in road density out of the 30+ sub-basins identified in the Stillaguamish Watershed (DNR 2002). Of these roads, a total of 47.8 miles are on unstable geology and steep slopes > 30% ranking the Upper North Fork 1st in the percentage of at-risk roads (28%, DNR 2002). The high road density increases surface runoff and thus erosion pulses into the North Fork during periods of rain. High road density on unstable slopes increases the potential for creating high sediment pulses into the North Fork when roads fail.

Of the various landslides and other sources of fine sediment pollution found in the North Fork Stillaguamish Basin, only a few have been documented in reports. These are the Deer Creek/Deforest Creek slide, the Steelhead Haven/Hazel Slide, slides in Montague Creek sub-basin, and slides in the Boulder Ridge sub-basin. Of these documented sediment sources, the most notable is probably the Deforest Creek landslide in the Deer Creek sub-basin. The Deforest Creek slide has been blamed for the loss of some of the best steelhead habitat in the Puget Sound region. Eide (1990) did a 48-year sediment budget for the Deer Creek basin for a master's thesis. He found that 90% of all sediment production in the Deer Creek basin was accounted for by landslides, debris torrents, and gullying on slopes. The Deforest Creek landslide accounted for nearly 50% of all of the sediment production in the Stillaguamish Watershed between 1942-1989. Eide found that 87% of the landslides initiated between 1942-1989 failed in areas of the basin that had been logged and the number of failures was nearly proportional to the area logged.

The Steelhead Haven Landslide, also known as the Hazel Landslide, is also well known, mainly for its impacts on the North Fork Stillaguamish. Miller and Sias (2000) did an analysis of the Steelhead Haven Landslide (SHL) and determined that it has a documented history of movement since the 1950's. They attributed the failure at SHL to logging activities, but river activity at the toe of the landslide was also blamed. Logging in the basin upslope from the landslide caused an increase in groundwater infiltration that resulted in a higher water table in the post-glacial slump that the slide is located in. Landowner activity on the CMZ just upstream forced the river directly into the toe of the landslide, which further exacerbated the problem (Drury 2001). In 1967, the landslide failed and dammed the North Fork for 4 hours (Drury 2001). This forced the river into a side channel for a number of years where it was away from the toe of the slide. As time progressed, the river moved closer to the toe where it continued to erode the bank making the slide unstable. The result was a massive failure in late winter – early spring 2006 which again dammed the river for a few hours and pushed it over to the side channel.

Of the sediment sources documented in the Boulder River and Squire Creek drainage basins, two in particular, have caused the most damage to river resources. Shaw (2004) determined from aerial photos that a total of 226 mass wasting events occurred in this Watershed Assessment Unity (WAU). The two main failures found to overwhelm the estimated sediment volumes were (1) a large deep-seated failure caused or reactivated by clearcutting in lower Boulder River and (2) a large debris torrent in Squire Creek caused by seismic activity. The Boulder River deep-seated landslide continues to actively produce sediment whereas the Squire Creek debris torrent appears to have subsided.

Kennard and Pess (1994) completed a watershed assessment of the Montague basin. They found that there have been 33 shallow-rapid landslides in the basin that could be identified from aerial photos. Of these, 32 were associated with forest practices such as clearcuts and road building. They found that a deep-seated slide, termed "Big Slump" has been contributing most of the sediment into Montague Creek. They go on to suggest that accretion in Montague Creek has begun as a result of a 42% increase in sediment supply compared to its transport capacity during the period 1948 – 1965.

These documented sediment sources continue to deliver sediment to the North Fork Stillaguamish River either directly, in the case of the Steelhead Haven landslide, or indirectly via tributaries. Since 1993 the Stillaguamish Tribe has monitored these sediment sources. A summary of the Tribe's water quality data from 1993 – 2006 presented in Table 2 shows the estimated mean annual TSS delivery from each of the above-mentioned sources. (These values are not weighted for flow and so only show suspended sediment concentration, not loading.) It is interesting to note that the four highest sources of TSS are all from deep-seated landslides (Boulder, Montague, Deer, and Steelhead Haven). Deep-seated landslides are often referred to as ancient landslides because their features may have existed for hundreds of years (WA DOE 2007). Therefore, it can be quite difficult to remedy their impacts.

Table 2. Summary of documented sediment sources in the North Fork Stillaguamish River.

Source	Sub-basin	Type	Receiving Waterbody	Mean Annual TSS (mg/L)
Upper North Fork	Upper North Fork	Road Failures	North Fork	8.07
Squire Creek	Squire Creek	Debris Torrents	Squire Creek	22.41
Boulder Slide	Boulder Ridge	Deep Seated	Boulder River	44.32
Big Slump	Hell-Hazel	Deep Seated	Montague Creek	129.88
Upper Deer Creek	Deer Creek	Deep Seated	Deer Creek	111.15
Upper Grants Creek	Frailey Mountain	Shallow Rapid	Grants Creek	9.21
Steelhead Haven	Higgins Ridge	Deep Seated	North Fork	70.81*

* estimated from North Fork at Whitman Road

Our goal for conducting this study was two fold. First, we wanted to verify the previously identified fine sediment pollution sources located in the North Fork Stillaguamish watershed, document other sources that have not yet been described and determine their loading. Second, we wanted to determine impacts of fine sediment on incubating salmon eggs by measuring fine sediment intrusion in artificially created salmon redds.

METHODS

This study was completed over 3 years, 2006-07, 2007-08, and 2008-09 during typical Chinook egg incubation. (September – February).

Study Sites

We chose 14 sites in the North Fork Stillaguamish basin to measure fine sediment loading (Figure 3). Of these, 5 were located on the North Fork mainstem. The remaining 9 were located near the mouths of tributaries to the North Fork that had known or suspected sediment delivery impacts.

Fine Sediment Loading

We quantified stream discharge at all sites by one of three methods (Figure 3):

1) Data was downloaded from real time flow gages (RTFG) operated by either the USGS or WDOE.
2) Two sites, SSID 087 and 012, did not have a RTFG nor were discharge measurements taken. Therefore, discharge was calculated by multiplying the ratio of their basin area *vs*. the basin area of the USGS RTFG against the USGS RTFG flows.

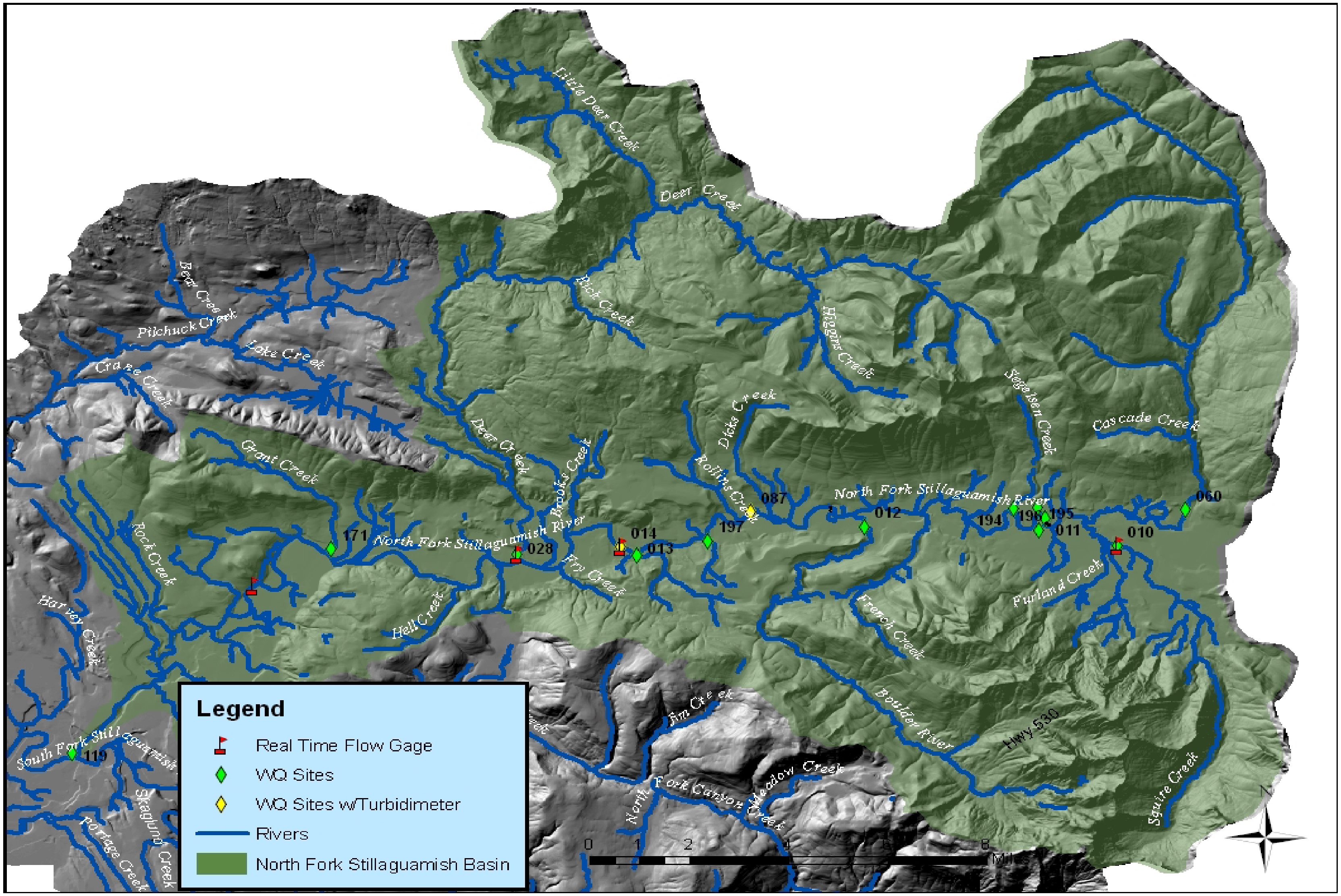

Figure 3. Map of the North Fork Stillaguamish depicting the study sites and flow gages.

3) Discharge was measured as described by Pleus (1999) using a Swoffer® Model 2100 flow meter to measure velocity and depth at regular intervals along a stream transect. USGS Style A staff gages were installed to develop stage discharge relationships. The discharge for the streams was then correlated against the four RTFGs, and the RTFG that correlated best (highest r^2 value) was used to calculate discharge for that stream during the monitoring period. Discharge was determined by calculating the basin area of the stream as a percentage of the total basin area from the highest correlate RTFG and applying this ratio to RTFG discharge.

Grab samples were collected from each site roughly once a month from September – February. Samples were collected in 1-liter poly bottles with the use of a sampling rod within 1 foot from the surface. When flows were high (> 2000 cfs at USGS gage) two grab samples were collected from the North Fork Mainstem sites and larger tributaries (Deer, Boulder, and Squire Creeks), one within 1 foot from the bottom and the other within 1 foot from the surface and the average TSS calculated to better estimate concentrations at higher flows (Collins 1997). Samples were placed in an ice chest and taken back to the laboratory where they were stored in a refrigerator for future analysis. TSS was then determined in the laboratory as described by the Stillaguamish Tribe's EPA approved Standard Operating Procedures (TSS SOP-STILL-LP-2, Appendix A). Also, two turbidity probes (OBS 3+, D&A Instruments) with associated dataloggers (CR1000, Campbell Scientific, Inc.) were located at two of the sites (Figure 3) as part of another study, and the data downloaded and used to aid in suspended sediment loading calculations and turbidity-TSS correlations.

Estimates for suspended sediment loading were calculated using a regression model (Thomann and Mueller 1987). Daily loads were calculated for the days when samples were collected and plotted on a logarithmic grid against their corresponding stream discharge measurements using Microsoft Excel. A power equation trendline (Equation 1) was plotted and was used to estimate daily load for the days that concentration was not measured. Suspended sediment loading was then calculated for typical Chinook incubation period (September – February).

$$c = aQ^b \qquad \textit{Equation 1}$$

where,
c = daily concentration or load
Q = mean daily flow
a = the slope and
b = the y-intercept

Cohn *et al.* (1992) recommends a sample size of 75 samples to be collected over two years when using regression models in order to collect data over a range of different flows. They further suggest that 25 samples be collected each following year to verify that the regression relationship does not change. However, Cohn's recommendations were beyond the resources available to complete this study as sample sizes ranged from 2

- 8 during each monitoring period (September - February). It is therefore assumed that our estimates may not be as accurate. For comparative purposes between sites and with other studies (Nelson *et al.* 1995) this method appears to be adequate.

Artificial Redds

Artificial redds were created during typical Chinook spawning in the North Fork Stillaguamish of late August – mid October (WCC 1999). Locations for redds were dependent on a number of variables. First, redds were placed in typical spawning habitat upstream and downstream of known sources of fine sediment to the North Fork. Second, redds were placed in North Fork Stillaguamish EDT (Ecosystem Diagnosis and Treatment) reaches (SIRC 2005) in order to update assumptions on Chinook egg incubation success for the EDT model. Third, redds were placed in riffles where Chinook salmon have been known to spawn or were spawning. In 2006-07 and 2007-08 redds were constructed at 6 sites, in 2008-09 redds were constructed at 7 sites. Three redds were constructed at each site for a total of 18 redds during 2006 – 07 and 2007 –08 and 21 redds during 2008-09. Site locations differed each year (Figure 4). We moved the TFH site approximately 400 meters downstream for the third year of the study because we were denied accessibility to the previous location.

Solid walled, 2.5 liter, PVC buckets were used to monitor sediment intrusion rates in each redd (Figure 5). Lisle and Eads (1991) found that using solid walled buckets precluded the ability to capture sediment transported by intergravel flow. However, they found that solid-walled buckets are better suited to retaining intruded sediments during removal through the water column compared to a porous-walled bucket or Whitlock-Vibert (WV) egg boxes.

Figure 5. Solid walled, 2.5 liter, PVC bucket were used to monitor sediment intrusion in redds (6 per redd).

The buckets were filled with a clean mixture of gravels from 19mm – 64 mm (DeVries *et al*. 2001) excavated from the constructed redd by use of a hand shovel, and sieved through brass Tyler® sieves to ensure that fine particles (< 6.3 mm) were not included (Figure 6). Six buckets were buried in each redd to a bottom depth of 30 cm below the original streambed surface elevation. The depth of installation was standardized with the use of a constructed PVC pipe device (DeVries *et al.* 2001, Figure 7). This depth was within the range of typical egg deposition for Chinook salmon (DeVries 1997). Six buckets per redd were used in order to resemble a typical Chinook redd which may have between 4 – 6 egg pockets, the small area in a redd that actually contains embryos or alevins (Chapman 1988). Buckets were placed in an excavated redd and buried with a layer of clean cobbles and gravels (Figure 8).

Figure 6. Excavation of a redd with the use of a shovel.

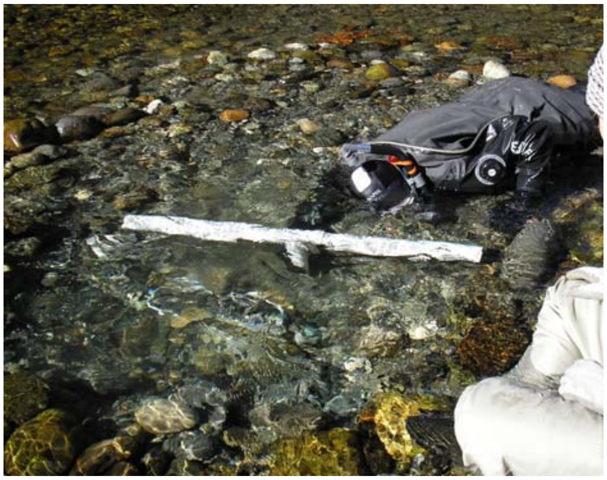

Figure 7. T-shaped PVC device used to ensure bucket placement at depth of 30cm.

Figure 8. A redd with 6 buckets and a layer of clean gravel being hand placed over the top of the buckets.

Several steps were taken to ensure artificial redds could be relocated. Each redd was geo-located with the use of a Trimble® GeoExplorer 3 GPS unit. Maps were hand drawn depicting relative location of each redd and associated characteristics of each site. At each constructed redd we recorded compass bearings and tape measure distances to three predetermined benchmarks (e.g., large trees on the bank with a headpin nailed in) and to one another. Also a schematic was drawn of each redd indicating the relative location of each bucket within the redd.

Retrieval of buckets in 2006-07 differed than the following two years. In 2006-07 all of the buckets from a given redd were retrieved on collection dates as described by DeVries *et al.* (2001). In order to better describe spawning areas, two buckets from each redd were retrieved on collection dates the following two years. The dates of collection are described in Table 3. Redds were carefully hand excavated until the top of a bucket was exposed. Gravels were removed from around the brim of the bucket and a plastic shower cap was placed over the top. A rubber band was then placed around the shower cap to hold the contents of the bucket (Figure 9). The bucket was then completely excavated from the stream and placed in a sealable plastic bag and transported to the laboratory where they were placed in a freezer for future analysis.

Prior to analysis, buckets were removed from the freezer and allowed to thaw in large aluminum trays. After thaw, the contents of each bucket were poured out into the tray and the bucket was thoroughly rinsed with distilled water to wash out any sediment particles into the tray. The samples were then dried to 60° C for a minimum of 48 hours in a Memmert® UNE 600 oven, sieved through a series of brass Tyler® sieves (45.3mm, 25.0mm, 19.0mm, 6.3mm, 4.75mm, 4.00mm, 2.00mm, 1.40mm, 0.850mm, 0.600mm, 0.355mm, and bottom pan) and weighed to the nearest 0.1 gram using an Ohaus Navigator balance. The percentages of fine sediment intrusion by the last retrieval would be indicative of redd conditions at the time of Chinook emergence.

Table 3. Dates of installation and retrieval of artificial redds during all three years of the study

2006

	WHT	SEG	BTP	TFH	RCK	SKA	OSO	CRO
Date Installed	10/5/06	10/11/06	9/8/06	9/15/06	9/20/06	9/28/06		
Date of Last Retrieval	1/18/07	1/18/07	1/19/07	N/A	N/A	1/19/07		
Days in River	105	99	133	N/A	N/A	113		

2007

	WHT	SEG	BTP	TFH	RCK	SKA	OSO	CRO
Date Installed			9/10/07	9/17/07	9/18/07	9/7/07	9/28/07	10/16/07
Date of Last Retrieval			1/31/08	12/10/07	1/31/08	2/1/08	2/4/08	2/1/08
Days in River			143	84	135	147	129	108

2008

	WHT	SEG	BTP	TFH	RCK	SKA	OSO	CRO
Date Installed		10/14/08	10/2/08	10/3/08	9/24/08	9/19/08	10/2/08	9/19/08
Date of Last Retrieval		2/19/09	2/19/09	2/19/09	2/20/09	2/20/09	3/13/09	N/A
Days in River		128	140	139	149	154	162	N/A

Figure 9. A bucket being removed from a redd with a plastic shower cap over the top.

Intrusion weights were determined for particles < 6.3 mm. Survival of incubating eggs to emergence (STE) criteria indicate that high quality incubation conditions are associated with intruded fines < 0.850 mm ≤ 5% by weight, and fines < 6.4 mm ≤ 20% by weight (DeVries *et al.* 2001). It was determined that the difference between our use of a 6.3 mm threshold was not much different than a threshold of 6.4 mm. The percent of intruded fines < 6.3 mm and < 0.850 mm were compared to STE criteria reported in the literature (Tappel and Bjornn 1983, and Reiser and White 1988).

RESULTS AND DISCUSSION

Fine Sediment Loading

Suspended sediment loading increased from the upstream through the downstream sites on the North Fork Stillaguamish throughout all three years (Figure 10). Overall, suspended sediment (SS) loading was estimated to be lowest during the first year (2006 – 07) at all North Fork sites followed by the second year (2007 – 08) and the third year (2008 – 09) with the highest SS loading (Figure 10). The North Fork at Whitman Bridge was the only site that was lower in year two than in year one. Average flow during the sampling dates was highest during year three (4,112 cfs) and lowest during year one (2,097 cfs). The average flow during year two was 3,842 cfs. A higher average flow during sampling dates would likely result in higher loading estimates since SS is usually higher during higher flows. Also, the third year hydrograph resulted in record flows for the North Fork Stillaguamish, which resulted in higher loading than the previous two years (Figure 11a – c).

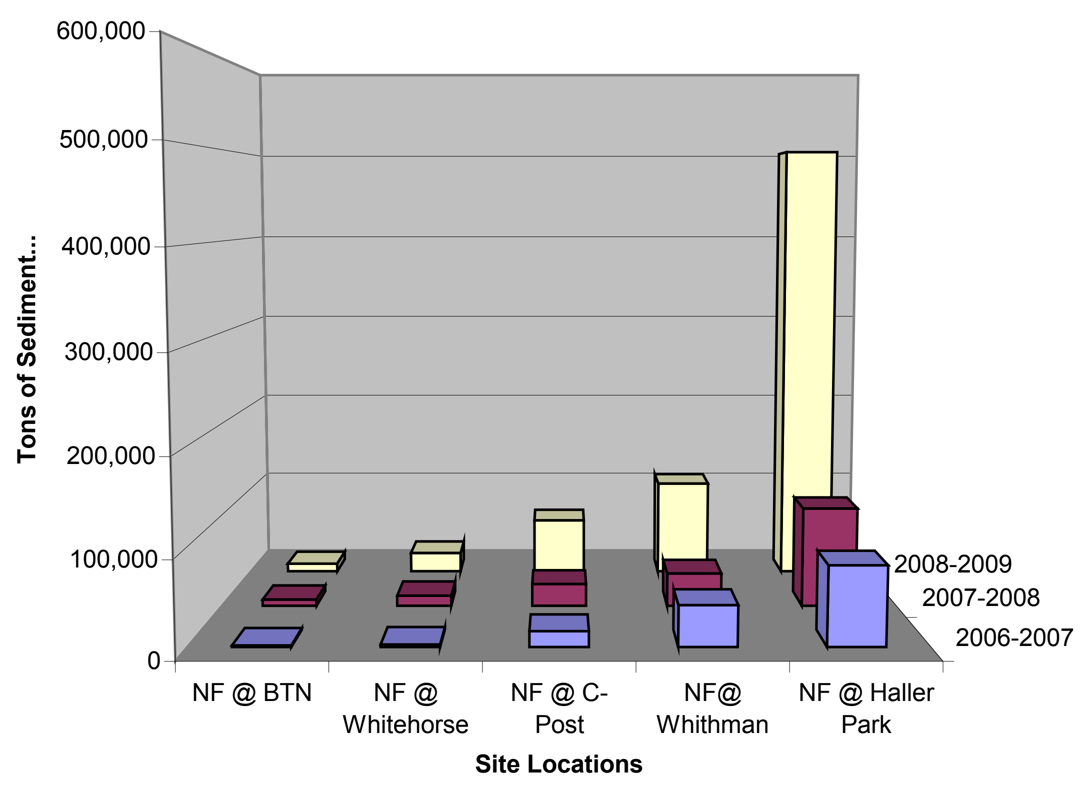

Figure 10. Suspended sediment loading at North Fork Stillaguamish sites during the three years of the study.

The biggest relative increase is suspended sediment loading occurred between Whitehorse and C-Post Bridges and then between Whitman Bridge and Haller Park. Two large tributaries enter into the North Fork within these two segments, Boulder River and Deer Creek respectively, both of which are large tributaries that contribute significant amounts of flow and sediment to the North Fork Stillaguamish (Figure 12). Most of the smaller tributaries contributed very little SS load to the North Fork Stillaguamish, the only exception to this was Montague Creek. The basin area of Montague Creek is roughly one fifth of the basin area of Boulder River and yet it was estimated that Montague contributed more SS load than Boulder. Montague has chronic suspended sediment yields even during summer months and has the highest SS concentration of all sites monitored by the Tribe since 1998 (Table 2).

Based on this review, Deer Creek, Montague Creek, and Boulder River are the three largest individual sources of SS to the North Fork Stillaguamish. However, all the SS load estimated at the North Fork @ Haller Park site cannot be accounted for from the sites measured in this study. Six percent of the SS load estimated at Haller Park was not accounted for from the tributaries measured in this study for the first year. For the second and third years the unaccounted SS load at Haller Park was much higher at 30 and 42 % respectively. We speculate that bank erosion, resuspension of sediments in the stream channel and SS from tributaries not measured in this study would account for this. Other studies have estimated that bank erosion can be from 20% - 90% of the total suspended sediment yield (Nelson and Booth 2002, Rosgen 1973, 1976). If proven true for the North Fork Stillaguamish, then it seems likely that net sediment deposition would occur instead of a net export. This could have significant lethal impact on incubating Chinook salmon eggs.

Artificial Redd Study

Redds constructed during the first year of the study were retrieved by excavating all the buckets from a given redd at one time. This was done in order to limit our influence on the surrounding buckets had we only removed a couple of the buckets per retrieval. After completing the first year of study it became apparent that two buckets could be removed from a given redd with little to no disruption to the other buckets in the redd. For the second and third year of the study two buckets per redd were removed each retrieval. This allowed us to characterize the surrounding spawning area more completely as the redds were scattered throughout the entire riffle where Chinook were naturally spawning. Nevertheless, although the first year redds were retrieved differently and may not necessarily portray the spawning grounds with as much vigor as the following two years, they were treated the same for the purposes of this study.

First Year (2006 – 2007)

All sites had one redd retrieved during the 1st retrieval time period (26 October – 30 October 2006). The RCK redd recovered at the 1st retrieval had been disturbed by spawning chum salmon (*Onchorhynchus keta*). One bucket was excavated and the rest of

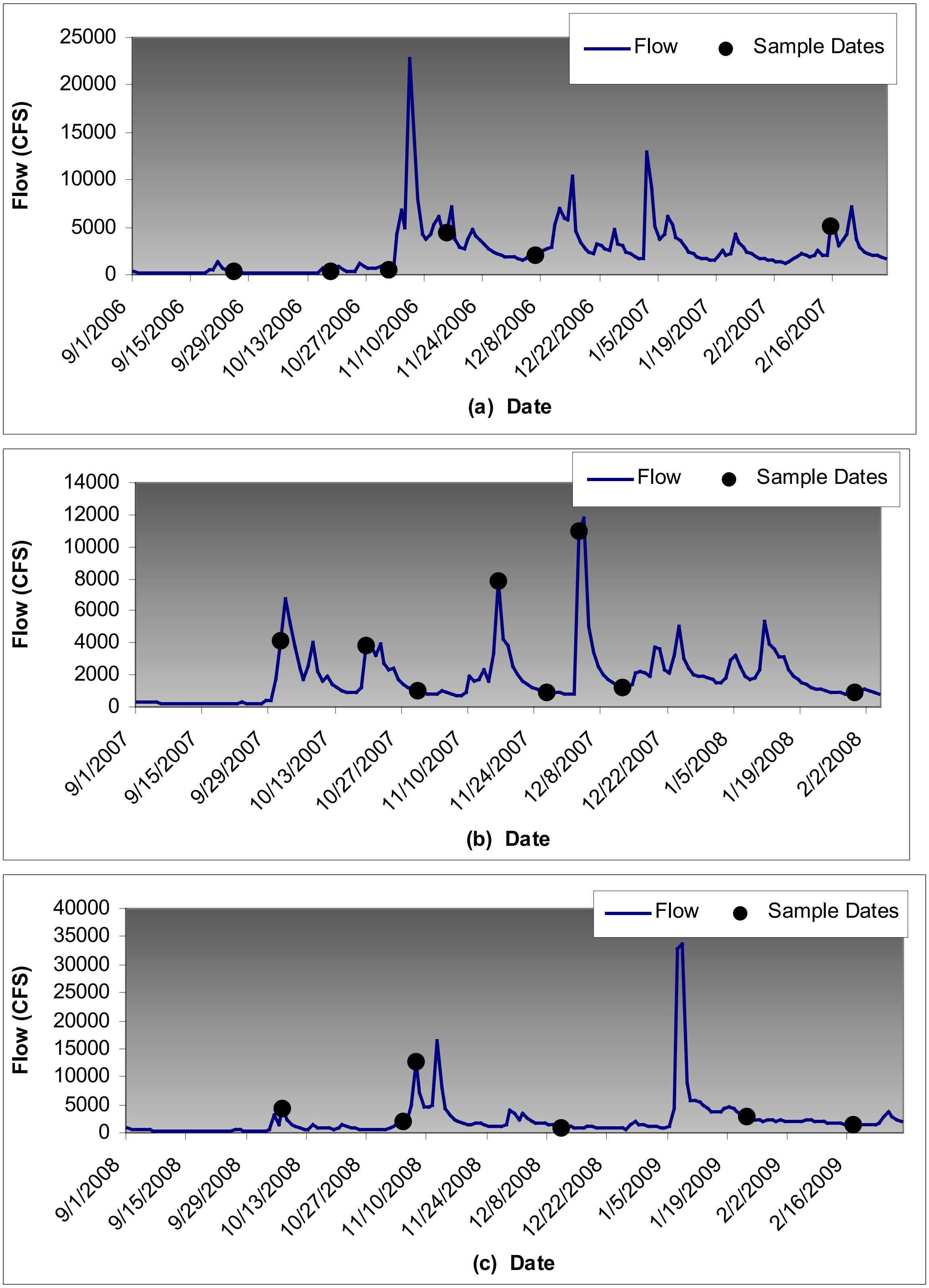

Figure 11. Hydrographs of the North Fork Stillaguamish River during the first (a), second (b) and third (c) years of the study. Black dots are the dates of SS sampling.

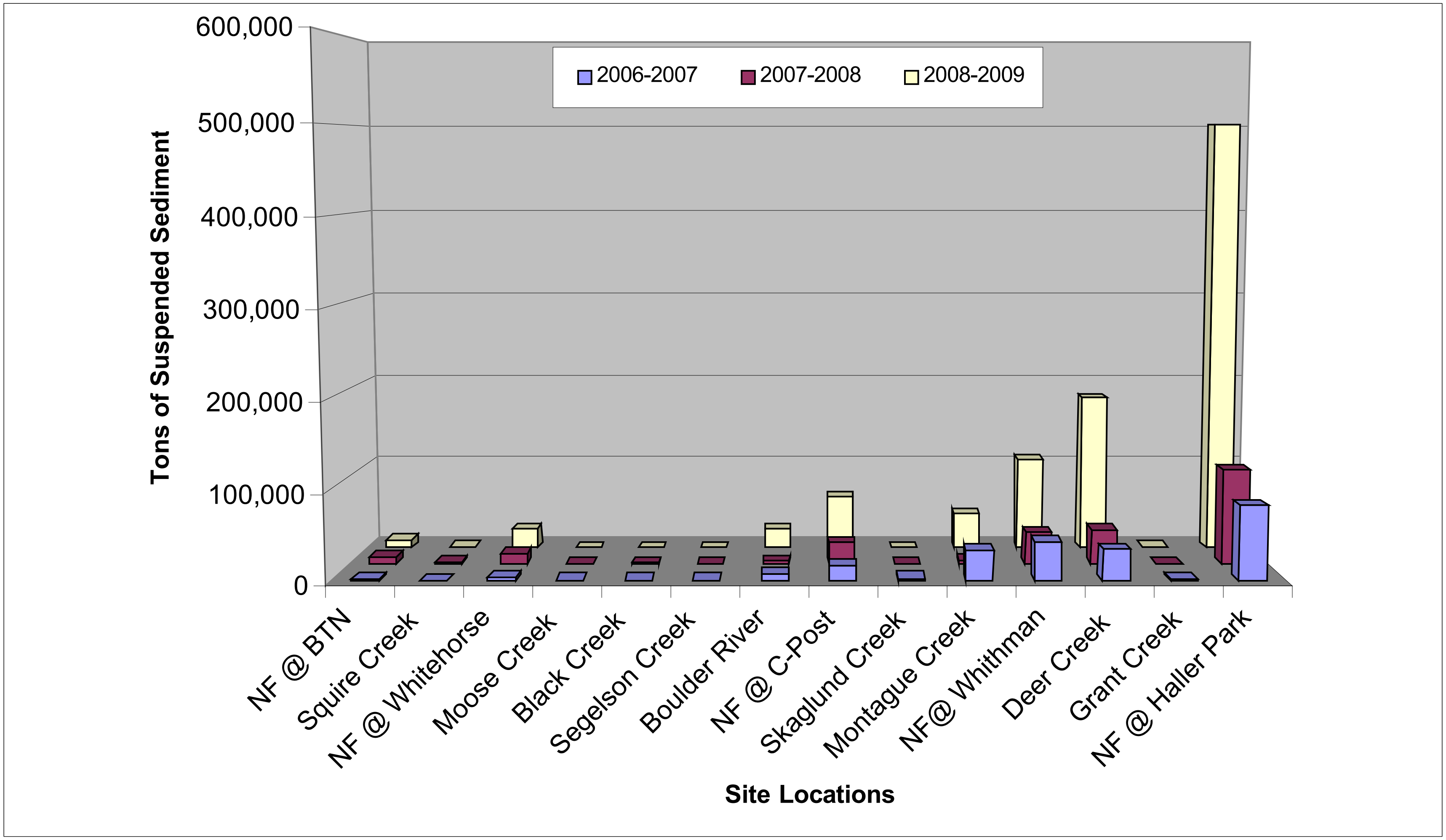

Figure 12. Suspended sediment loading estimates at all sample sites during all three years of the study. Locations are in order from upstream to downstream, left to right respectively.

the buckets were covered with 7 – 13.5 cm of fine gravel from the tailspill of the chum redd. Therefore, the sediment that infiltrated into this redd was largely a result of biologic activity instead of hydrologic. Four of the six sites had undisturbed redds that were recovered on the 18th or 19th of January (WHT, SEG, BTP and SKA). Redds at the other two sites, TFH and RCK, were scoured out by the time of the 2nd retrieval. A third attempt to retrieve redds in early February occurred, but no redds could be located at any of the sites. It was assumed that the redds that could not be retrieved were either scoured out or buried to deeply by sediment to be located and were therefore considered to be complete losses. This is supported by the fact that all redds were subjected to at least one bedload transport event (Figure 13). Of the 18 artificially created redds (3 redds/site X 6 sites), 9 (50%) were considered complete losses.

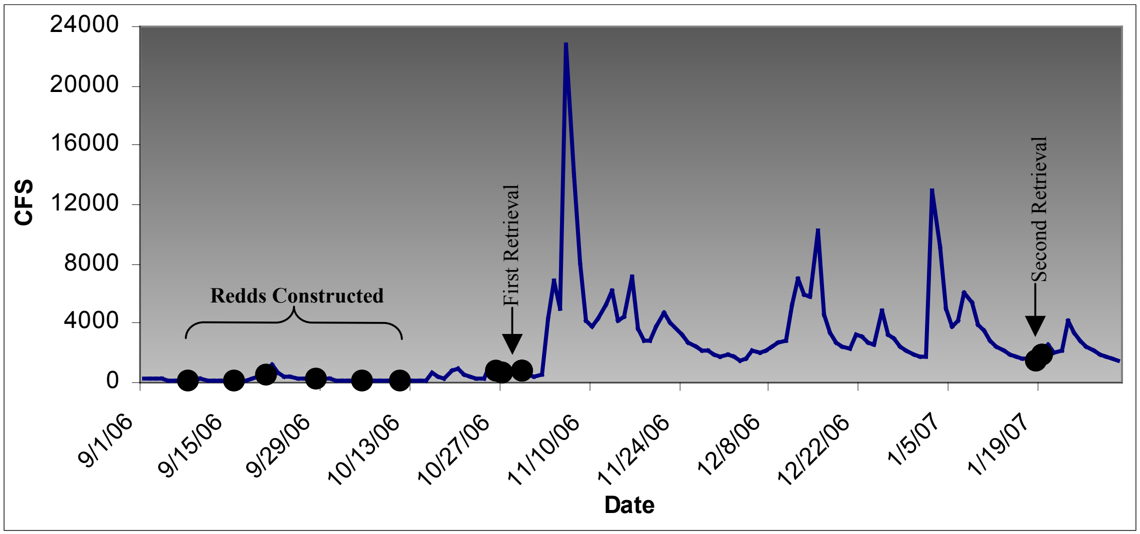

Figure 13. Hydrograph of the North Fork Stillaguamish during the first year of the study. Black dots indicate dates of artificial redd construction and retrieval.

The percentage of fine sediment < 6.3 mm that intruded into artificial redds by the time of the 1st retrieval ranged from 21 % at the RCK site to 1.8 % at the SEG site (Figure 14). As mentioned above, one of the buckets from the RCK redd was excavated by spawning chum salmon. Since the remaining 5 buckets from the RCK redd were buried by the tailspill of a chum redd, the amount of intruded fines was considerably higher than the other redds (Figure 14). The redd at TFH had the next highest concentration of intruded fines < 6.3 mm (11.5%) followed by BTP (11.3%), SKA (10.7%), WHT (3.2%) and SEG (1.8%) (Figure 14). These results closely follow the dates of installation indicating that the longer the buckets were incubated, the greater the percentage of intruded fines < 6.3 mm. The results for sediments < 0.850 mm differed slightly. The RCK site showed the highest concentration of this size class (8.3%), followed by the SKA site with 6.0% being of particles < 0.850 mm (Figure 14). The WHT and SEG sites had the lowest concentration of intruded sediments < 0.850mm (Figure 14). These results indicate that the sources of fine sediment < 0.850 above the SKA site is more consistent than the other sites. The Hazel Landslide, located just upstream of the SKA site, has been know to consistently send a plume of turbid water into the North Fork Stillaguamish (Drury 2001).

The concentration of fine sediment < 6.3 mm that intruded into artificial redds by the time of the last retrieval ranged from 8.2% at the SEG site to 29.2% at the BTP site (Figure 14). Sediments < 0.850 mm ranged from 3.8% to 9.2% at the SEG and BTP sites respectively (Figure 14). The BTP site had the higher concentration of intruded fines despite not being located downstream of any major SS source. DeVries *et al.* (2001) stated that > 15 – 20 percent fines < 6.4 mm or > 5 – 10 percent of fines < 0.85 mm can be detrimental to salmonid survival by influencing emergence or incubation success respectively. The BTP, SKA, and WHT sites all had concentrations of fine sediments within those thresholds (Figure 14).

Second Year (2007 – 2008)

Buckets were successfully retrieved from 16 of the 18 constructed redds. All sites had buckets retrieved between 01 – 06 November 2006. Buckets were again retrieved between 29 November and 11 December 2006, however two redds at the TFH site were scoured out by that time. The third redd at TFH had the top 2 cm of the remaining four buckets exposed above the streambed elevation so they were removed as the representative samples from that site. We retrieved buckets from all sites except TFH (all buckets were already retrieved or scoured out) a third time between 31 January and 04 February 2008. Flows during the second year of the study were lower than the first year (Figure 15). This made for minimal scouring of redds as only 2 of the 18 constructed redds (11%) were considered a complete loss due to scour.

The percentage of fine sediment < 6.3 mm that intruded into artificial redds by the first retrieval ranged from 11.9 % at the RCK and SKA sites to 20.7% at the CRO site (Figure 16). Unlike the first year, the second year fine sediment concentrations did not follow the dates of installation as the redds at the CRO site were incubated the shortest amount of time and yet had the highest concentrations of both size classes of fine sediment. Percentages of fine sediment < 0.850 mm ranged from 4.1 % at the BTP site to 14.7% at the CRO site. Most sites exhibited an increase in both fine sediment size classes by the time of the second retrieval. The SKA and OSO sites showed slight decreases in either both size classes (SKA) or only in the < 6.3mm size class (OSO). Most sites exhibited increases again by the time of the third retrieval. The OSO and RCK sites showed decreases in either both particle size classes (OSO) or in the < 6.3mm size class (Figure 16).

The CRO site consistently had the highest concentration of fines < 0.850mm. This site is located downstream of Deer Creek which was the single largest contributor of SS load to the North Fork throughout this study (Figure 12). Of the other sites, RCK was the second highest in fines < 0.850 mm at 8.4 %. The other sites had less than 6% of fines < 0.850 mm.

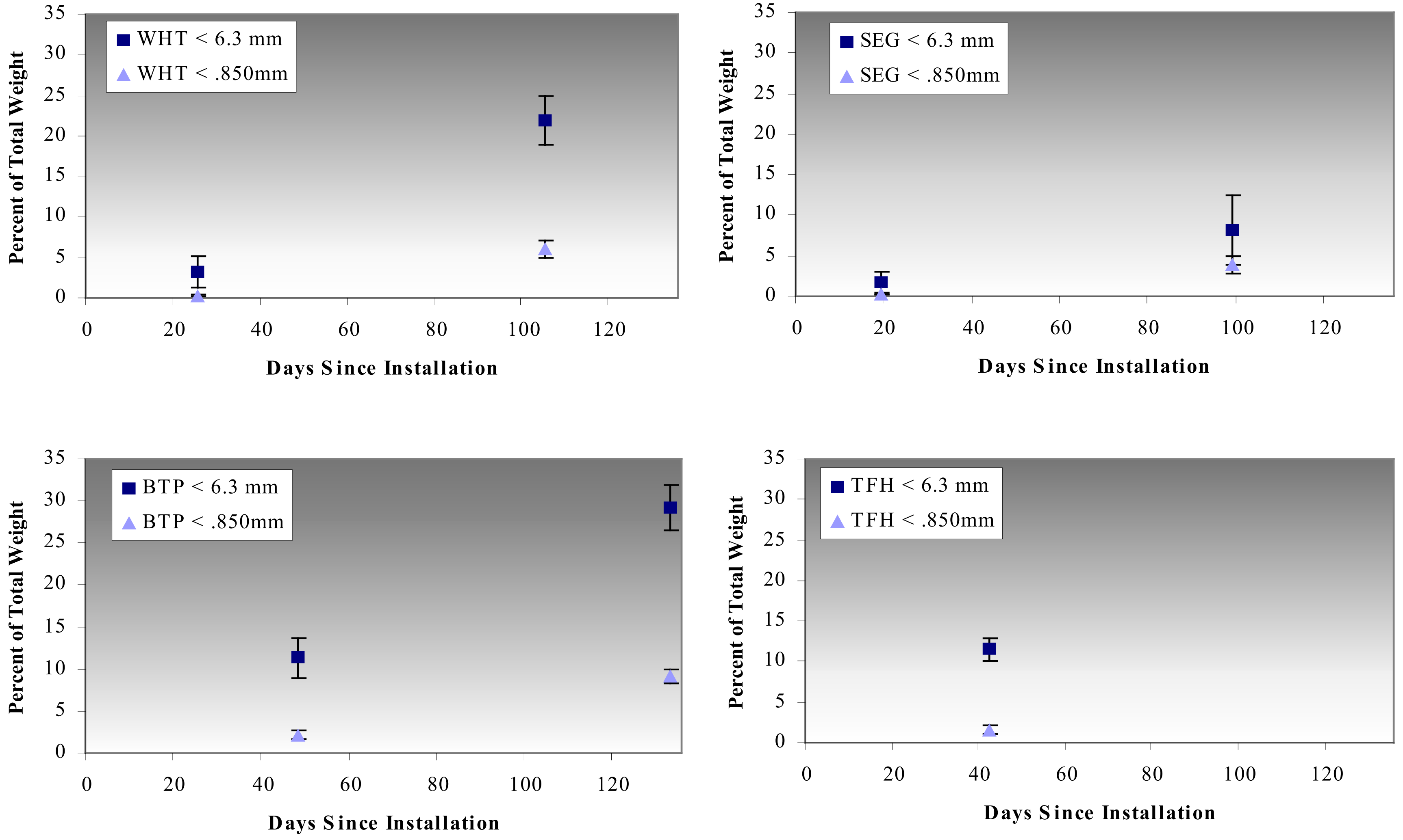

Figure 14. Mean concentration of intruded fines < 6.3 and <0.850 mm ± SD for each site at each retrieval for year one redds.

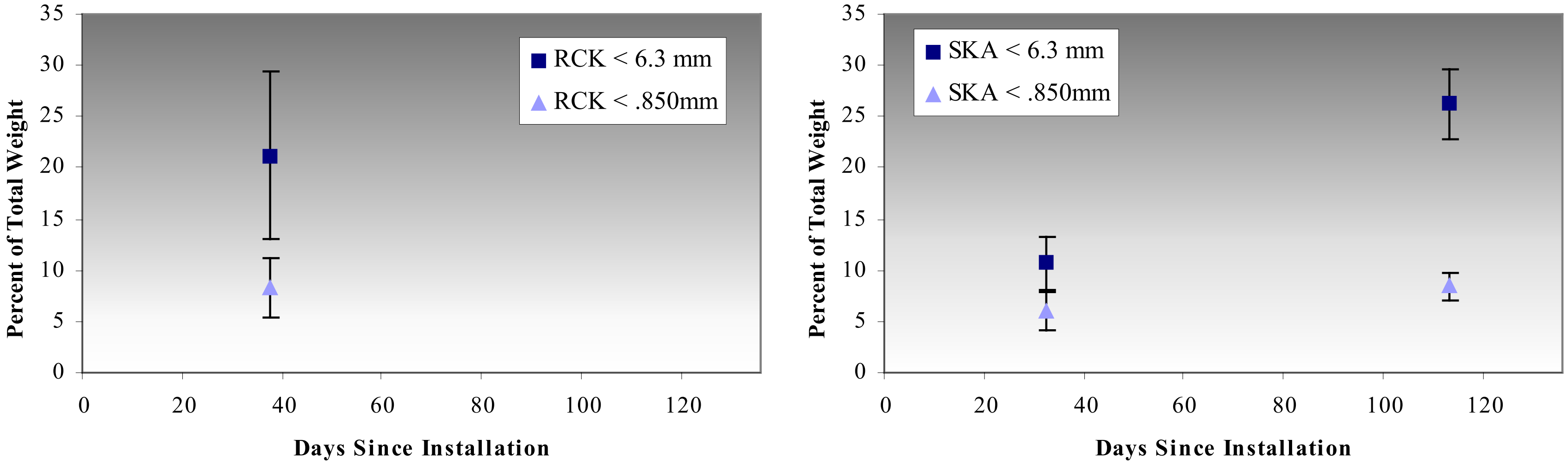

Figure 14 cont. Mean concentration of intruded fines < 6.3 and <0.850 mm ± SD for each site at each retrieval for year one redds.

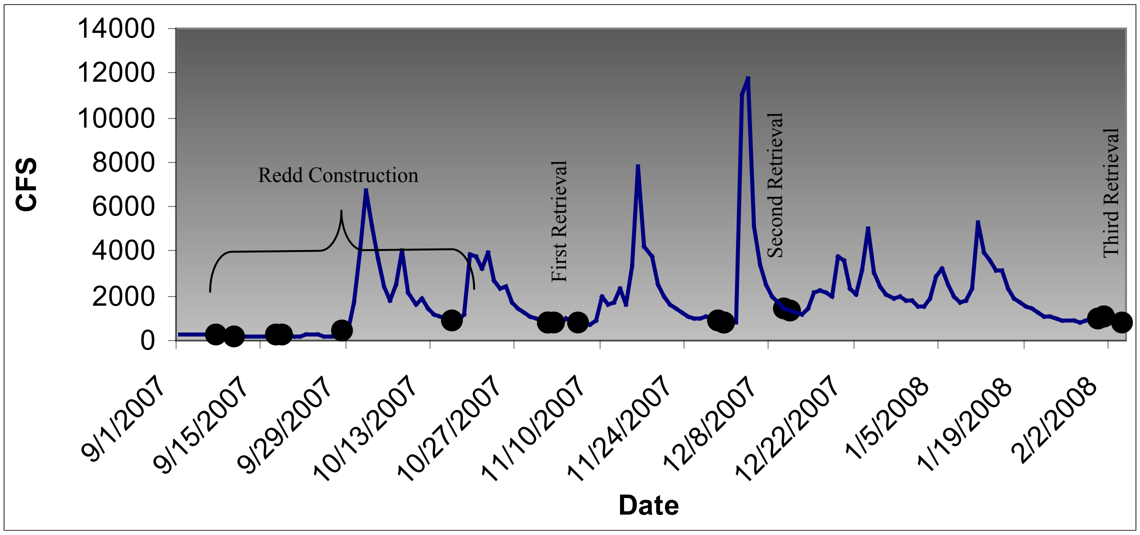

Figure 15. Hydrograph of the North Fork Stillaguamish during the second year of the study. Black dots indicate dates of artificial redd construction and retrieval.

Third Year (2008 – 2009)

Buckets were successfully retrieved from 13 of the 21 artificially created redds. Buckets were retrieved from 5 of the 7 sites between the dates of 18 and 19 November 2008. The flows at the SKA and CRO sites were too high and powerful to allow for safe retrieval during this time period. A second attempt to recover redds occurred during the dates of 19 and 20 February 2009. During these dates, buckets from the SEG, BTP, TFH, RCK, and SKA sites were successfully retrieved. All of these sites except SEG and RCK had redds scoured out by this second attempt. Buckets from OSO were recovered on 13 March 2009. All the redds at CRO were likely scoured out by the record high flood observed on the North Fork on 08 January 2009 (Figure 17) since redds could not be located during the recovery attempts in February or March. Eight of the 21 (38%) constructed redds were considered complete losses likely due to scour.

The buckets retrieved during the first period had a range of intruded fine sediments < 6.3 mm from 14.8 % at the RCK site to 24.3 % at the SEG site (Figure 18). Fines < 0.850 mm ranged from 7.2 % at the BTP site to 11.8 % at the SEG site (Figure 18). These results were typically higher than the previous first two years (except for CRO results in the second year). The buckets from the last retrieval had a range of intruded fine sediments < 6.3 mm from 17.9 % at the RCK site to 26.4 %at the SEG site. The range for fines < 0.850 mm ranged from 7.8 % at the BTP site to 14.2 % at the SEG site (Figure 18).

The SEG site consistently had the highest percentages of both size classes of fine sediment during the third year of the study. This is a complete reversal from the first year of the study when the SEG site had the lowest. The SS load estimated from upstream of the SEG site is represented in Figure 12 as the NF at Whitehorse (Moose and Black Creeks are above as well, however their SS loads are quite low). It is possible that

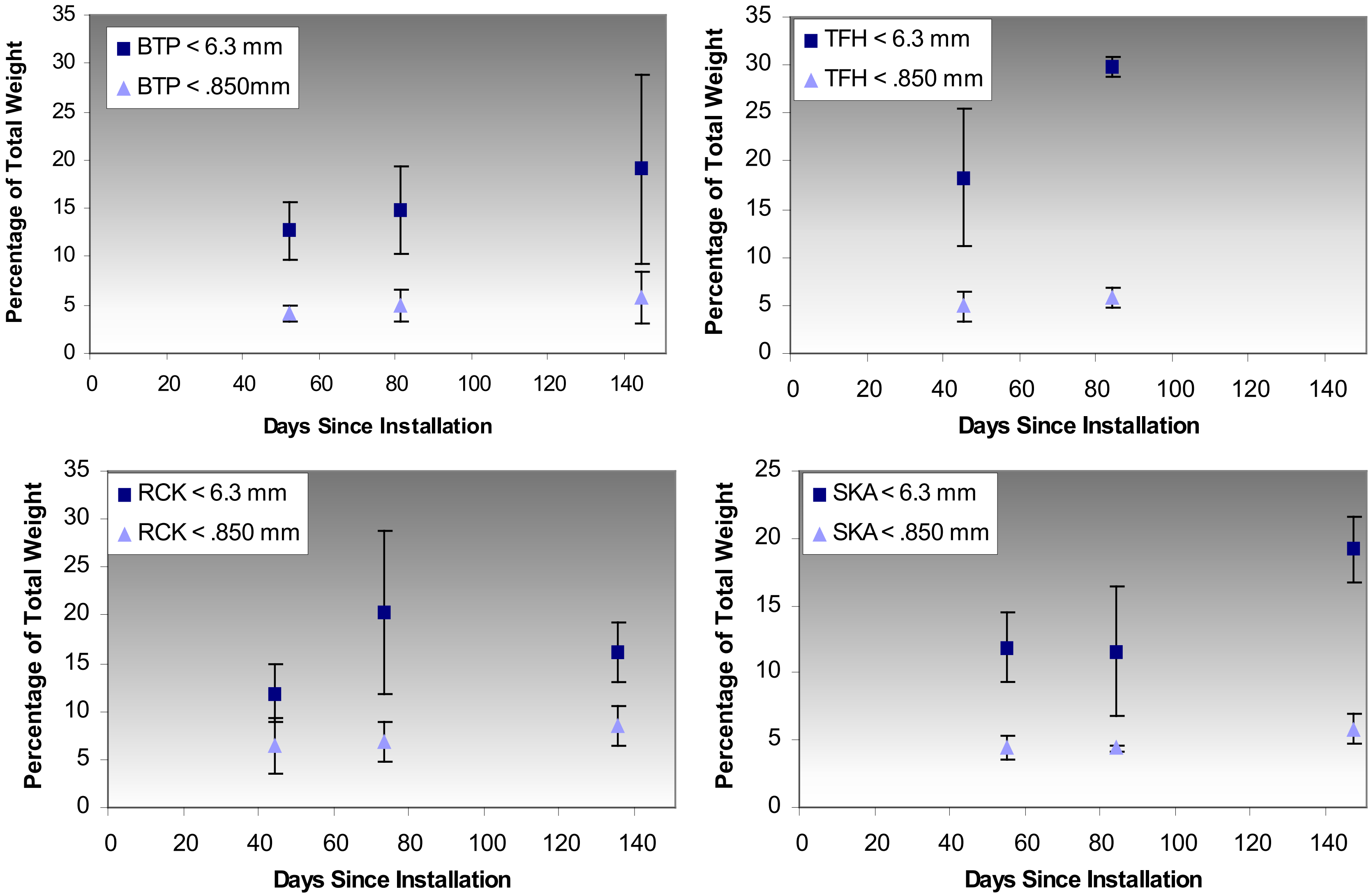

Figure 16. Mean concentration of intruded fines < 6.3 and <0.850 mm ± SD for each site at each retrieval for year two redds.

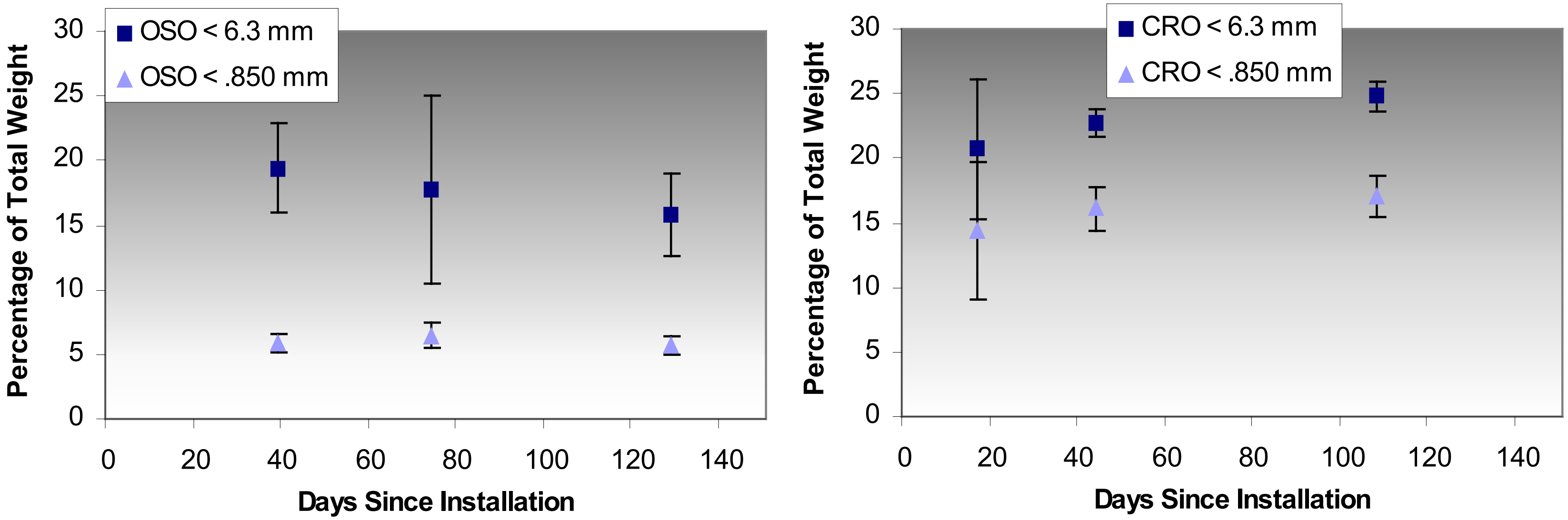

Figure 16 cont. Mean concentration of intruded fines < 6.3 and <0.850 mm ± SD for each site at each retrieval for year two redds.

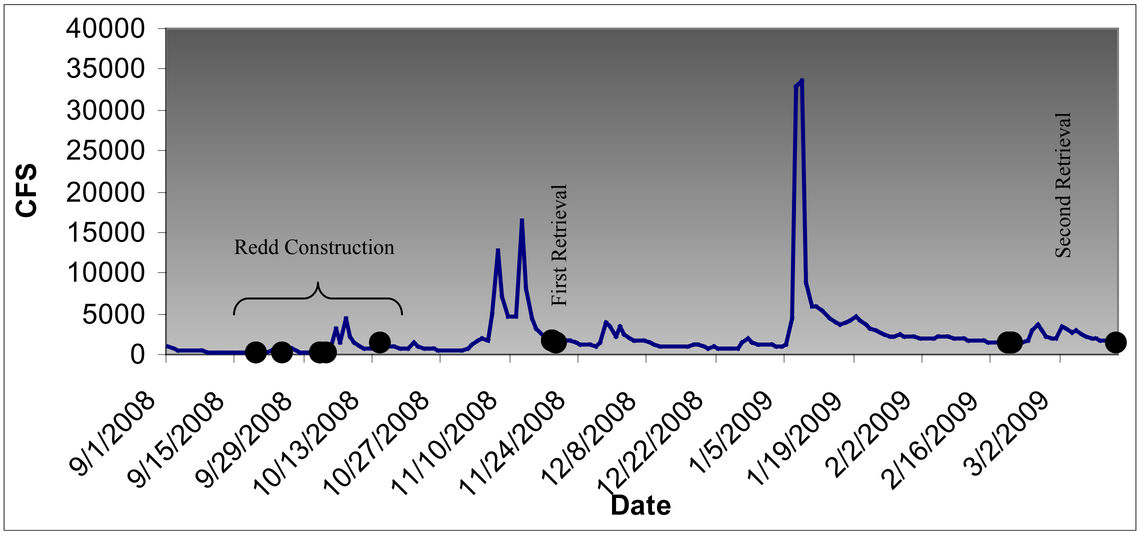

Figure 17. Hydrograph of the North Fork Stillaguamish during the third year of the study. Black dots indicate dates of artificial redd construction and retrieval.

the order of magnitude higher SS load observed at the NF at Whitehorse in the 3rd year versus the 1st year would help explain this increase observed in the redds.

The last retrieval of redds would be indicative of the condition of naturally occurring redds in the North Fork Stillaguamish near the time of salmon emergence. Table 4 summarizes this data for all three years of the study. NMFS (1996) publicized standards to be used in the evaluation of projects for the effects that the project may have on the viability of salmon listed under the ESA. These standards, termed the Matrix of Pathways and Indicators, were developed for fine sediment amongst others and were for sediments less than 6.3 mm (standard < 20%) and for sediments less than 0.85mm (standard < 12%). Based on these criteria, a number of sites during this study violate one or both of these standards (Table 4). The most common violation occurred with the 6.3 mm size class indicating that alevin entombment is a more likely cause of mortality in the North Fork Stillaguamish than suffocation.

DeVries *et al*. (2001) states that the consensus in the literature (Stowell *et* al. 1983, Chapman and McLeod 1987, and Reiser and White 1988) is a bit more stringent than that proposed by NMFS. DeVries *et al*. (2001) places the standards at > 5% and > 15% for fines < 0.85 mm and < 6.3 mm respectively as being detrimental to salmonid survival. Under this standard, nearly all sites throughout all years exhibit conditions based solely on fine sediment intrusion that are detrimental to incubating Chinook. The only site that showed to have minimal impact on developing Chinook embryos was the SEG site during the first year (Table 4). Using these standards instead of NMFS, it becomes apparent that a combination of both entombment and suffocation occur on the North Fork Stillaguamish.

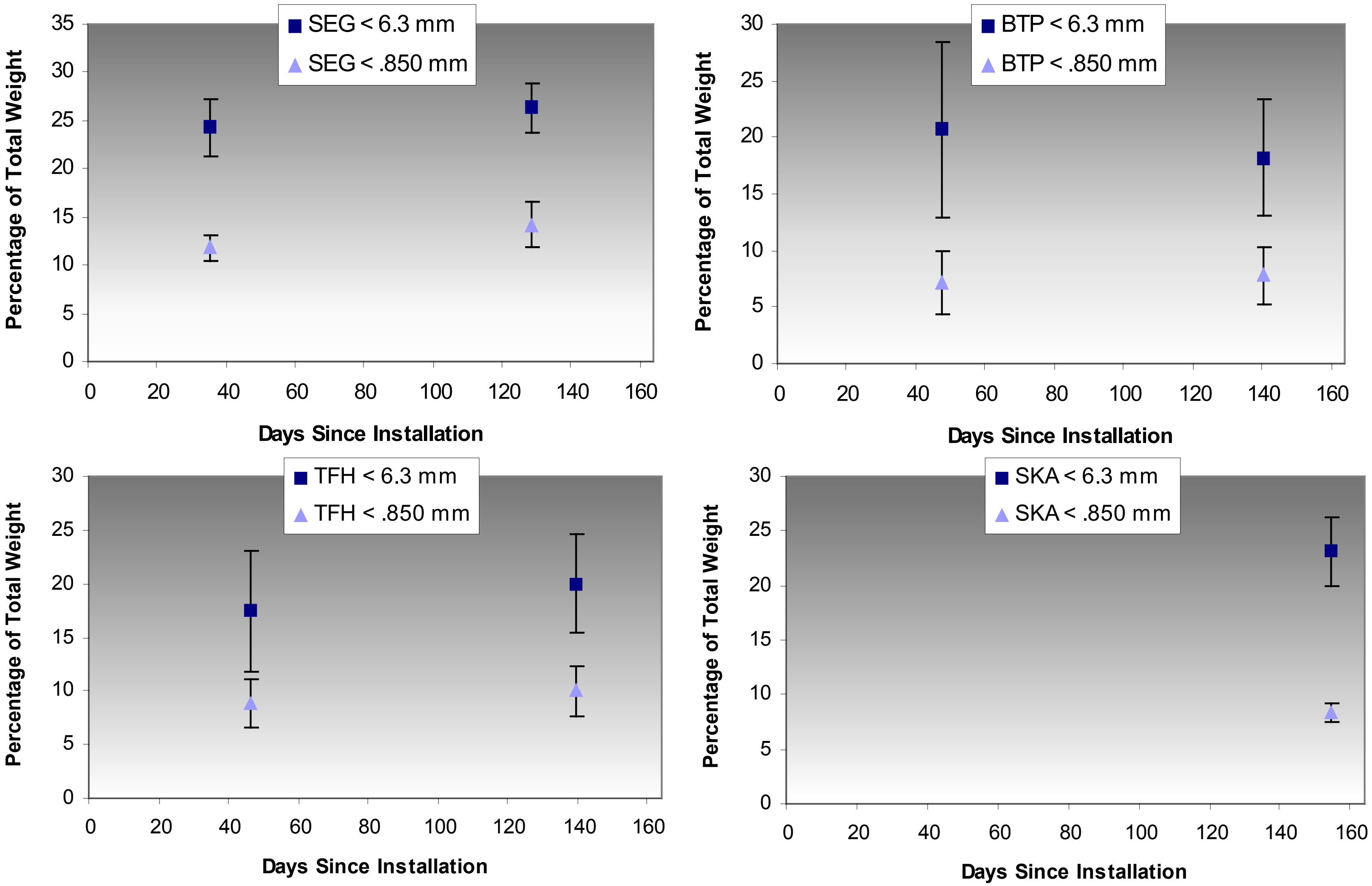

Figure 18. Mean concentration of intruded fines < 6.3 and <0.850 mm ± SD for each site at each retrieval for year three redds

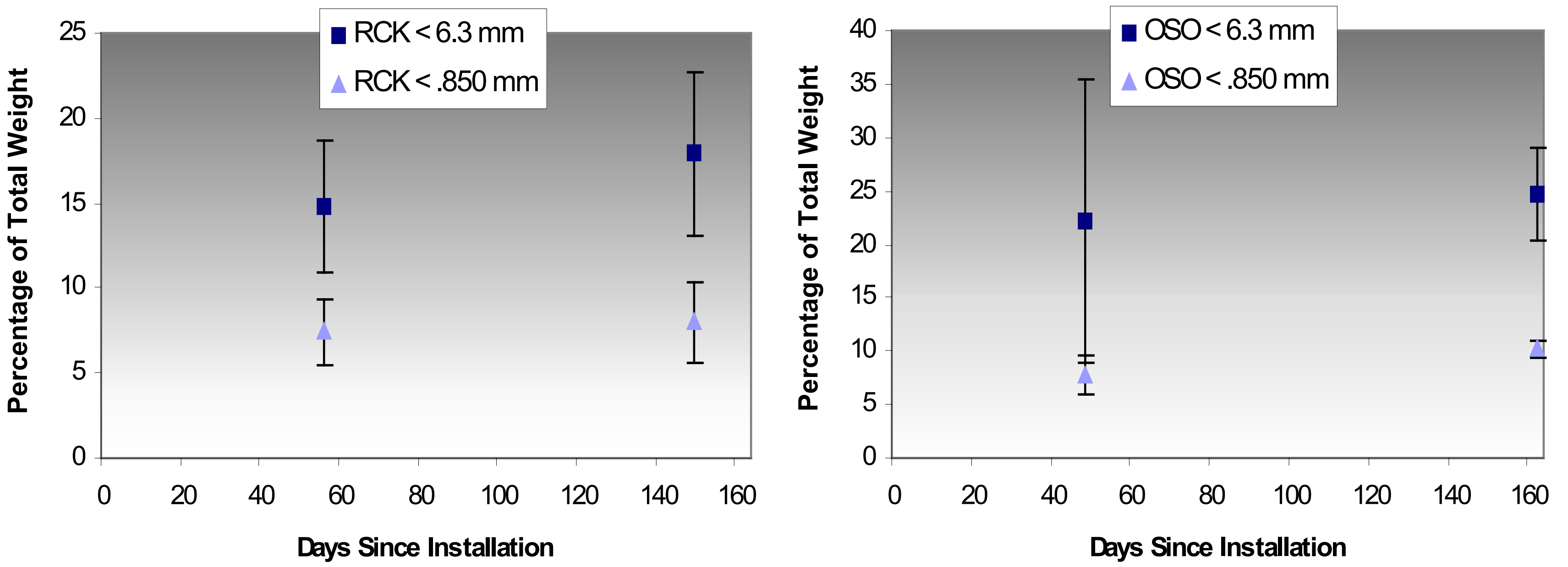

Figure 18 cont. Mean concentration of intruded fines < 6.3 and <0.850 mm ± SD for each site at each retrieval for year three redds

Table 4. Percentage of intruded fine sediments in artificial redds at all sites throughout the duration of the study.

		First Year	Second Year	Third Year
WHT	< 6.3 mm	21.9	*N/A*	*N/A*
	< 0.850 mm	6.0		
SEG	< 6.3 mm	8.2	*N/A*	26.4
	< 0.850 mm	3.8		14.2
BTP	< 6.3 mm	29.2	19.1	18.2
	< 0.850 mm	9.2	5.8	7.8
TFH	< 6.3 mm	*Scoured*	*Scoured*	20.0
	< 0.850 mm			10.0
RCK	< 6.3 mm	*Scoured*	16.1	17.9
	< 0.850 mm		8.4	8.0
SKA	< 6.3 mm	26.2	19.2	23.1
	< 0.850 mm	8.5	5.8	8.4
OSO	< 6.3 mm	*N/A*	15.8	24.7
	< 0.850 mm		5.6	10.2
CRO	< 6.3 mm	*N/A*	24.8	*Scoured*
	< 0.850 mm		17.0	

Other studies that have estimated STE (survival to emergence) have either developed correlation equations or provided figures in which STE could be estimated from the concentration of intruded fine sediment into Chinook salmon redds. Bennett *et al.* (2003) conducted laboratory tests to estimate Chinook salmon embryo survival under varying gravel mixtures. Their analysis developed a second order regression equation that was significant ($p < 0.001$) in relating substrate composition to emergence success. Their equation that related percent survival of Chinook embryos to emergence to the concentration of particles < 6.4 and 0.85 was:

$$\text{Emergence Success} = 46.643 + 1.194(S_{0.85}) - 0.111(S_{6.4})(S_{0.85}) \qquad \text{Equation 2}$$

Where $S_{6.4}$ and $S_{0.85}$ are the concentration of sediments smaller than 6.4 mm and 0.85 mm respectively. Equation 2 was applied to the results of this study to estimate STE in the North Fork Stillaguamish in 2006 – 2007. It was determined that the difference between the 6.4 mm threshold used by Bennett *et al.* (2003) was not significantly different than our use of the 6.3 mm threshold.

Reiser and White (1988) conducted a laboratory study as well and tested Chinook STE in 16 different mixtures of two distinct size classes of fine sediment, < 0.84 mm and 0.84 – 4.6 mm, mixed in with typical Chinook spawning gravel, 12.8 – 76.2mm. After incubating 100 eggs in Whitlock-Vibert egg boxes they assessed mortality and generated figures depicting the percent survival of embryos under the different fine sediment mixtures. They did not provide any correlation equations, but estimates of STE were derived from their figures for this study. In this study, the sieve smaller than the 6.3 mm sieve was 4.75 mm, which was similar to the 4.6 mm threshold used in Reiser and White

(1988). Again, it was determined that this difference was largely insignificant and as such their estimates were translated to the results of this study.

Estimates for survival to emergence (STE) of Chinook salmon in the North Fork Stillaguamish were calculated using *Equation 2* and the estimates derived from Reiser and White (1988) (Table 5). These estimates are bases solely on the impact of fine sediment intrusion and do not include results from redd scour. STE varied from site to site each year. Sites downstream of major SS sources (TFH, downstream of Boulder River; SKA, downstream of Steelhead Haven Landslide; and CRO, downstream of Deer Creek) had slightly worse survival than their immediate upstream counterparts for each year (BTP, RCK, and OSO respectively).

Table 5. Estimated percent survival to emergence of Chinook salmon during the three years of the study.

		First Year	Second Year	Third Year
WHT	Reiser & White	33.0	*N/A*	*N/A*
	Bennett *et al.*	39.1		
	Mean	*36.1*		
SEG	Reiser & White	56.5	*N/A*	19.5
	Bennett *et al.*	47.7		22.0
	Mean	*52.1*		*20.8*
BTP	Reiser & White	20.0	40.5	36.0
	Bennett *et al.*	27.7	41.2	40.2
	Mean	*23.9*	*40.9*	*38.1*
TFH	Reiser & White	***Scoured***	***Scoured***	27.5
	Bennett *et al.*			36.4
	Mean			*32.0*
RCK	Reiser & White	***Scoured***	35.8	35.3
	Bennett *et al.*		41.6	40.3
	Mean		*38.7*	*37.8*
SKA	Reiser & White	25.5	40.5	29.8
	Bennett *et al.*	32.2	41.2	35.1
	Mean	*28.9*	*40.9*	*32.5*
OSO	Reiser & White	*N/A*	45.0	22.0
	Bennett *et al.*		43.5	30.9
	Mean		*44.3*	*26.5*
CRO	Reiser & White	*N/A*	20.0	***Scoured***
	Bennett *et al.*		20.1	
	Mean		*20.1*	

DeVries *et al.* (2001) did a similar study on the North Fork Stillaguamish in 1998 – 2000. Instead of using solid walled buckets they used perforated Whitlock-Vibert egg boxes that had 3.5 x 13 mm openings all over the box. Their results showed 13 % of fine sediments < 6.4 mm and 5.5 % of fine sediments < 0.85 mm intruded into their artificially created redds in the 1998 – 99 season. Their results for the 1999 – 2000 season were similar at 14 and 7 % of < 6.4 and < 0.85 mm respectively. In 1998 – 99 their redds were located less than a river mile upstream of the RCK site. In 1999 – 2000 their redds were located less than a river mile downstream of the TFH site. Their results revealed lower percentages of intruded fines than this study (Table 4) and as a result their estimations for STE were higher than this study. STE estimates for the DeVries *et al.* (2001) study would have been between 42 and 48% using the estimates from the Bennett *et al.* (2003) and Reiser and White (1988) studies. These are better STE estimates than what was measured for this study.

We used the results of this study to estimate survival to migrant for naturally spawning Chinook in the North Fork Stillaguamish. Because this study was not specifically designed for this purpose, caution should be exercised in reviewing these estimates. Table 6 summarizes all of the calculations and assumptions used in this estimate. To calculate this, the percentage of artificially created redds that were scoured out was applied to redd census data collected by the Tribe and WDFW for the 3 years of the study. This redd data was collected on the North Fork Mainstem from river mile 0.0 to river mile 30.0. The Tribe collects North Fork Stillaguamish broodstock every year as part of the Tribe's wild stock supplementation program. The average fecundity of the females collected for this program was then multiplied by the number of naturally occurring redds in the North Fork that were assumed to survive scour. This value assumes one female per redd and that each female all of her eggs are fertilized and deposited in the given redd. The average STE from each year of the study was then applied to the estimate of intact eggs resulting in a total number of fry that would be expected to emerge from the North Fork Mainstem. Griffith (2005) estimates that Chinook juveniles experience about 1% mortality per river mile during freshwater outmigration. Chinook spawn throughout the North Fork, however the greatest density of spawners was concentrated between river miles 20.5 and 30 (average distance = 25.25 river miles). The North Fork enters the Mainstem Stillaguamish at river mile 18 and the Stillaguamish Tribe's smolt trap is located on the Mainstem at river mile 6 resulting in 12 more river miles that smolts must traverse to the trap, or a total of 37.25 river miles. We therefore, applied a blanket mortality of 37.25% to the number of emergent fry to calculate our estimate of Chinook migrants past the smolt trap.

There are obviously strong assumptions being made in this calculation. For one, the assumption that our artificially created redds function the same as naturally occurring redds has yet to be seen. To show this, more study of natural redds would need to occur which would be fatal for incubating embryos. It also is not certain that the percentage of artificially created redds scoured out could be translated to naturally occurring redds. We made every attempt to place our redds in areas that we thought Chinook would spawn, however, we also made every effort to not disturb ESA listed Chinook and also wanted to be sure to place redds in locations where we could recover them. Other assumptions include the actual deposition of eggs a female Chinook places in the redd and of those, the percentage that are fertilized. We assumed that all eggs were deposited and fertilized which is likely not the case. Another assumption stems around the use of solid walled buckets to measure fine sediment intrusion into redds.

Table 6. Estimation of Egg to Migrant Survival for North Fork Chinook during the 3 years of the study (2006, 2007, and 2008).

	First Year	**Second Year**	**Third Year**
Redds Constructed	18	18	21
Redds Scoured	9	2	8
% Survival of Redds	50%	89%	62%
Natural Redds	299	189	418
Estimate of Nat. Redds Survival	150	168	259
Average Female Fecundity	5751	5401	4730
Estimate of Intact eggs	859,775	908,502	1,225,827
Average STE	35.2%	36.9%	31.3%
Emergent Chinook Fry	302,641	335,237	383,684
Est. % migrant mortality	37.25%	37.25%	37.25%
Est. Chinook Outmigration	189,907	210,361	240,762
Outmigration reported in Smolt Trap Report	319,692*	186,115**	92,871***

*Griffith (2009a); ** Griffith (2009b); Griffith (2010)

Despite these assumptions, however, our estimations of egg to migrant survival are still within the realm of possibility. The smolt trap outmigrant estimates in Table 6 are basin wide (includes North Fork above river mile 30, North Fork tributaries, South Fork Stillaguamish, South Fork tributaries, Mainstem Stillaguamish and Mainstem tributaries that Chinook spawn in). The 95% confidence intervals (CI) for Chinook during the first year of this study are between 262,209 and 377,175 smolts (Griffith 2009) and the CI for the second year of this study are between 148,593 and 216,350 smolts (Griffith unpublished). Data for the third year of this study are not available yet.

Solid walled buckets have their advantages and its disadvantages. Solid walled buckets, like the ones used in this study, are relatively inexpensive (~ $3.00/bucket) and small in size (h = 16.51 cm, d = 15.24 cm) and therefore several can be placed in one redd to simulate typical Chinook egg deposition (Chapman 1988). Solid walled buckets also are less susceptible to lose infiltrated sediments upon removal, whereas water bearing infiltrated sediment can flow out of porous walled containers as they are removed from the streambed (Lisle and Eads 1991). This risk was further lessened in this study by covering the buckets with a plastic shower cap prior to removal from the streambed. Solid walled buckets, however, exclude sediment transported from intergravel flow. They therefore are most effective at measuring sand particles (0.062 – 2 mm) that are not transported laterally by weak intergravel flow (Lisle and Eads 1991) but rather enter the streambed under the force of gravity.

CONCLUSIONS AND RECOMMENDATIONS

From 2006 – 2009 the Stillaguamish Tribe monitored suspended sediment at 14 locations in the North Fork Stillaguamish. The monitoring was designed to provide information on suspended sediment loading into the North Fork Stillaguamish and to relate fine sediment pollution to Chinook salmon survival to emergence. This study has shown that suspended sediment continues to be a problem for water quality and salmon management in the North Fork Stillaguamish. If this study were to continue in future years we recommend that more resources would be required in order to derive more accurate suspended sediment loading estimates and to adequately characterize mercury pollution. In addition, we would recommend an expansion of the artificial redd study to characterize redd conditions throughout the North Fork Chinook spawning range.

From this study we reach the following conclusions and recommendations:

Conclusions

1. Montague, Skaglund and Deer Creeks have the highest mean TSS concentrations of the monitored sites in this study.
2. Deer and Montague Creeks are the two highest suspended sediment-loading sources to the North Fork out of the 14 sites monitored in this study, followed by Boulder River.
3. The role of bank erosion in contributing to suspended sediment observed in the North Fork Stillaguamish Mainstem is unknown.
4. Fine sediment intrusion into Chinook redds varies from site to site and on a year-to-year basis.
5. Redds were scoured out each year of the study through a range of peak flows indicating that flow conditions each year will likely scour out naturally occurring redds.
6. Biological activity, such as salmon spawning, as well as hydrological activity can impact incubating salmon eggs.
7. Average Chinook STE in the North Fork Stillaguamish above Deer Creek for the 2006 brood year was roughly 35% for redds that were not scoured out from high river flows. Average STE in the North Fork in 2007 was roughly 37% and for 2008 was 31%.
8. The methods employed in this study provide a rough estimate of STE and survival to migrant of juvenile Chinook well within the confidence intervals of smolt trapping reports.

Recommendations

1. **Suspended sediment sources from Deer, Montague, Skaglund, and Boulder River should be further investigated to determine feasibility of mending or minimizing their fine sediment contribution to the North Fork Stillaguamish.** These sources were the largest contributors of suspended sediment in this study. These sites should be reviewed to determine ways to minimize their impacts on suspended sediment loading, and potential deleterious impacts on incubating salmon.
2. **Develop a sediment budget for the North Fork Stillaguamish basin to gain a better understanding of movement of both fine (< 2.0 mm) and coarser (> 2.0 mm) bedload material.** Development of a full-blown sediment budget should further enable identification of other sediment sources in the North Fork Stillaguamish. Results from this study indicate that bank erosion and/or resuspension of stream bed sediment may be significant sources of fine sediment pollution in the North Fork and a sediment budget would be able to describe their contributions as well as the contributions of other known sources like the ones identified in this more accurately.
3. **Expansion of the artificial redd study to include intergravel oxygen measurements and actual placement of fertilized Chinook eggs.** One of the impacts of fine sediment intrusion into salmon redds is the creation of a seal over the eggs which limits oxygenated water from reaching the eggs for respiration (Chapman 1988). Current Washington State regulations state that dissolved oxygen in the stream water column should not be lower than 8.0 mg/L in streams with salmon spawning, rearing, and/or migration. However, actual levels in the redd pocket could possibly reach to lethal levels if oxygen rich water cannot penetrate a fine sediment seal over the eggs. By measuring intergravel oxygen levels, further clarity could be achieved on fine sediment impacts to incubating salmon. Also, relying on published results from laboratory experiments to determine STE do not necessarily provide the best estimates to determine STE in real world scenarios (Chapman 1988). Therefore, a field experiment in which a know quantity of fertilized eggs obtained from the Stillaguamish Tribal Hatchery deposited in artificially created redds could possibly provide a more accurate estimate of STE in the North Fork Stillaguamish under different fine sediment conditions.
4. **A study to determine if solid walled buckets trap significantly different percentages of fine sediment than adjacent gravel beds should be conducted.** The ability of solid walled buckets to collect intruded fines similarly to naturally occurring redd sites is uncertain. It is possible that fine sediment that intrudes into solid walled buckets is significantly different than the percentage of fine sediment that intrudes into naturally created redds. Therefore, further investigation on the differences in fine sediment entrainment between solid walled buckets and the surrounding redd gravels should be looked into (Garrett and Bennett 1996, for example).

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