SCOUR, FILL, AND SALMON SPAWNING IN A NORTHERN CALIFORNIA COASTAL STREAM

by

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ABSTRACT

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Streambed scour and fill affecting incubation survival of salmon embryos were investigated in a Northern California coastal stream (Freshwater Creek) for coho *(Oncorhynchus kisutch*) and chinook (*Oncorhynchus tshawytscha*) species. Objectives of the study were to: (1) test a reach-scale scour and fill model (Haschenburger 1999) based on Shields stress (dimensionless shear stress), and (2) test two published hypotheses of salmon spawning adaptation to streambed scour. Testing of the model clarified some limitations, revealed potential improvements, and demonstrated sufficient potential for predicting scour at salmon spawning areas (redds) based on a small sample size (n = 9 redds) to warrant additional testing. The model appears best suited for individual floods on reaches that are straight, in equilibrium between sediment supply and transport, and have roughness elements similar to the creeks where the model was developed. Differences in model predictions and measured values were likely due to variable scour and fill patterns in Freshwater Creek that were weakly influenced by Shields stress and highly influenced by sediment supply, location within the channel network, and channel morphology (form roughness).

This study provided no evidence of salmon adaptation to streambed scour from:
(1) reduced bed mobility as a result of surface coarsening from redd construction, or
(2) selection of stable sites for spawning. Scour was often deeper at redds ($n = 16$) than the adjacent bed ($p = 0.16$), indicating that redd construction did not reduce scour but instead may have increased scour by loosening the bed and reducing imbrication. Scour at random locations and redd sites ($n = 9$) within a reach were similar ($p = 0.75$), indicating that salmon did not select low scour areas for spawning. Testing of both hypotheses is based on small sample sizes and further testing with larger sample sizes is needed. Redd sites were commonly located in areas prone to sediment storage (upstream of log jams and in pool tails) and consistently aggraded. Consequently, fill may have been a more significant source of egg mortality than scour in Freshwater Creek.

Keywords: scour, fill, active layer, bed load transport, model, prediction, spawning, redd, egg mortality, adaptation to scour, salmonids, coho, chinook

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This thesis is dedicated to the memory of Ken Kesey and Allen Ginsberg, whose lives and prose have provided a boat through a sea of permanent uncertainty.

What this country needs is sanity.
Individual sanity,
and all the rest will come true.

-Ken Kesey

Work like the sun
Shine in your heaven
See what you've done
Come down and walk

-Allen Ginsberg

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1.0 INTRODUCTION

"Everything flows, nothing stays still."

-Heraclitus

Over their life cycle, salmon and trout (salmonids) experience highest mortality rates during the incubation period in streambed gravels that can range from 2 - 8 months, depending on the species (Sandercock 1991). Salmonids build a redd by digging a depression into streambed gravels, depositing and fertilizing the eggs in the depression, and covering the eggs with gravel (Figure 1). When floods occur during incubation periods, eggs can be lost if the streambed scour depth exceeds the egg deposition depth, possibly lowering populations (Wales and Coots 1954; Seegrist and Gard 1972; Holtby and Healey 1986; Erman et al. 1988). In streams with high local concentrations of fines, scour followed by fill at redds can allow deeper infiltration of fine sediments (Lisle 1989; Platts et al. 1989, Peterson and Quinn 1996a) and reduce dissolved oxygen supply to embryos (see review by Chapman 1988) or form a seal within and over redds that prevents emergence of fry (Koski 1966; Everest et al. 1987; Scrivener and Brownlee 1989).

Recent declines in Pacific salmon populations may partially reflect human impacts on watershed conditions (Holtby and Scrivener 1989; Bisson et al. 1992). Some land-use activities that alter the sediment flux and hydrology of rivers can increase scouring of redds (Tripp and Poulin 1986; Nawa et al. 1990) or infiltration of fines into redds (Mouring 1982; Platts et al. 1989; Scrivener and Brownlee 1989). Consequently, the health of some salmon stocks may be sensitive to scour and fill impacts to redds (Haschenburger 1994; DeVries 2000). A recent reach-scale scour and fill probability model (Haschenburger 1999) is a possible candidate to predict such impacts, hereafter referred to as the Haschenburger model. The Haschenburger model predicts a right-skewed distribution of scour and fill depths to a first approximation using channel and flow characteristics. While measured scour and fill distributions have been tested for conformance with the exponential function, the specific model offered for general use has not been validated nor has it been tested at redds.

Understanding of salmonid adaptation to streambed scour would improve application of the Haschenburger or other scour and fill models at redds. For species that spawn during periods of high flows, testable hypotheses of adaptation to streambed scour include:
(1) decreased bed mobility as a result of surface coarsening from redd construction (Montgomery et al. 1996), and (2) spawning in low scour areas, such as: the top of riffles (Yee 1981), near channel margins (Stefferud 1993), hydraulically sheltered areas behind log jams and in side channels (Montgomery et al. 1999), and riffles and pool tails buffered by sediment storage (DeVries 2000). Additional hypotheses that may not be testable include depositing eggs below typical scour depths (Montgomery et al. 1996), and natural selection for larger fish that can bury their eggs deeper or selection for fish that spawn at times when scour is less likely (Steen and Quinn 1999). Within this context, the objectives of this study were to:

1) Test the accuracy of the Haschenburger model for predicting scour and fill on a northern California coastal stream.

2) Enhance the understanding of salmon adaptation to streambed scour by testing the following hypotheses:

    a) Redd construction reduces scour.

    b) Salmon select low scour areas for spawning.

The model and hypotheses testing were performed on data collected from Freshwater Creek in Humboldt County, California (Figure 2) during the 1999-2000 winter spawning season for coho (*Oncorhynchus kisutch*) and chinook (*Oncorhynchus tshawytscha*) salmon.

Because the definition of scour and fill varies between disciplines (geomorphology, fisheries, engineering), clarification of these terms is necessary. In this study, scour is the difference between the initial bed elevation and the deepest level of scour (or bed mobilization) as recorded by a scour chain, fill is the net material deposited above the deepest level of scour, and the active layer is the difference between the highest bed elevation measured at the beginning or end of the study and the lowest level of scour (i.e. the maximum bed elevation range at a point for a given period) (Figure 3), similar to the “active bed” term defined by Lisle (1989). Because scour chains were only recovered once at the end of the flood season, measurements reflect the seasonal maximum scour and net fill depths over the study period (seasonal scour and fill).

2.0 BACKGROUND

The relation between scour, fill and salmon spawning has been studied by several researchers. To provide additional context for this study, the relevant research to date and appropriate details of salmonid life history and spawning are summarized in the following section.

2.1 COHO AND CHINOOK LIFE HISTORY

Coho salmon generally mature after three or more years, including incubation periods of 1 to 2 months, rearing 1 or more years in freshwater, and a 1½ to 3 year growing period in the ocean. Mature coho return to spawn in their natal streams between November and January (California stocks) as stream temperatures decrease and rainfall and stream flow increase, allowing coho to reach smaller low gradient tributaries with ideal spawning and rearing conditions (Sandercock 1991). Coastal chinook salmon have a similar life history, but can spawn in larger streams than coho and rear in freshwater for only 6 to 8 months.

2.2 SPAWNING

Spawning begins as the female turns on her side and vigorously flexes her body and tail to dig a pit in stream gravels. The movements create a suction effect that entrains bed materials into the current, causing gravel to deposit just below the pit and form a tailspill, while fines are suspended and carried farther downstream. Cobbles too large to be moved by the female will remain in the pit as a coarse lag (Chapman 1988; Kondolf et al. 1993). Once a pit is completed, the female pushes her anal fin between the cobbles, the male swims alongside the female, and the eggs and milt are simultaneously deposited. The female then resumes digging upstream to bury the first egg pocket and create another pit. The spawning continues for several days and a single redd can contain several egg pockets (Sandercock 1991) (Figure 1).

2.3. PREVIOUS WORK

2.3.1 Previous Scour, Fill, and Spawning Studies

As part of a scour monitoring protocol for redds, Schuett-Hames et al. (1996) provided a synthesis of scour and fill processes that is summarized and slightly modified here. The depth and frequency of scour is dependent on a combination of factors, including the magnitude and duration of peak flows, the quantity and particle size of the sediment supply, and the distribution of channel nick points (bedrock, boulders, large wood) that cause localized scour and fill. Spatial and temporal changes in these factors result in complex and variable patterns of scour and fill. Bedload movement begins when the shear stress threshold for incipient motion is reached. However, shear stress does not increase uniformly with discharge over a reach due to variable channel configuration, secondary currents and turbulence caused by bed roughness or obstructions, and variation in bed particle size. For example, Lisle et al. (2000) found that spreading of flow over bar surfaces and convergence into troughs produced highly variable bedload transport rates, and hence variable scour and fill patterns. Consequently, portions of the bed begin to move at different thresholds and tend to occur in irregular pulses or waves (e.g. Paige and Hickin 2000). Bed compaction that occurs during long intervals between peak flows increases resistance to scour (e.g. Reid et al. 1985), resulting in different scour patterns over a storm season.

DeVries (2000) also provides a synthesis of scour processes, but suggests that the size and quantity of gravel and cobbles in a reach exert a much stronger influence on scour depth than flood magnitude and duration. Scour and fill was measured in western Washington streams on cross sections in relatively plane-bed, low-gradient reaches with ample spawning gravel and cobbles. Scour occurred from (1) bedload layer movement and (2) spatial and temporal imbalances in sediment transport rate, including (a) scour and fill of transient finer grained deposits downstream of partial flow obstructions, (b) scour and fill at the pool-riffle scale, where scour depth is related to distances between riffles and the size of the riffle deposit, and (c) scour and fill at the reach scale in response to variable sediment supplied to the reach. Scour depths from bedload layer movement appeared to be a function of grain size and approached a limit at approximately twice the 90th percentile of the streambed particle size distribution ($2D_{90}$). Based on the relationship between egg pocket depth and particle size (egg depth/D_{90} ratio) in published studies, DeVries (2000) suggests that salmonids may have adapted to scour by burying their eggs greater than 2 to $2.5D_{90}$. In addition, salmonids may have adapted to scour by constructing redds at locations in the channel least likely to experience scour from imbalances in sediment transport rates.

Scour and fill processes and their relation to chum salmon (*Oncorhynchus keta*) spawning habitat were studied extensively in Kennedy Creek near Olympia, Washington (Montgomery et al. 1996; Schuett-Hames et. al. 1994; Schuett-Hames et al. 2000). Scour and fill were measured in a sinuous pool-riffle reach and a relatively straight plane-bed reach. Scour monitors were installed on cross sections in all habitat types except pool bottoms, the only areas of the stream not used for spawning. Egg pocket depths were also measured in redds (see Peterson and Quinn 1996b) and "auxiliary" scour monitors were placed near egg pockets.

Scour and fill was spatially variable and approximated a right-skewed negative exponential distribution (both reaches combined). The range of scour depth and frequency distribution was significantly greater in the more complex pool-riffle reach due to lateral channel migration, flow over and around large wood jams, movement of large wood, and side channel formation. Mean scour depth was 11 centimeters (cm) (both reaches combined), while mean scour was higher in pool lateral bars (20 cm) and pool tails (16 cm) than in other habitat types (2 - 9 cm). The percentage of monitor locations that scoured to 20 cm (the mean depth to measured egg pockets) was also higher in pool lateral bars (39%) and pool tails (28%) than in other habitat types (0 - 17%). Chum salmon appeared to favor spawning in areas with high intergravel flow and dissolved oxygen levels such as pool tails. Because these areas are prone to scour at higher flows, Schuett-Hames et al. (2000) infer that scour can be a significant source of egg loss. This also implies that scour is not a factor in spawning site selection.

Using the same data set, Montgomery et al. (1996) speculated that the close correspondence between egg burial and scour depths indicates an adaptation to typical depths of scour. Based on paired pebble counts in the tailspills of redds and unspawned adjacent areas of Kennedy Creek, spawning increased the median surface particle size by 33 to 39%. Theoretical calculations indicated that the spawning-related bed modifications may reduce scour in redds by coarsening the surface and increasing friction angles. In potential contradiction, Schuett-Hames et al. (1994) reported that scour in the auxiliary egg pocket monitors was *"similar or somewhat higher than on cross-sections for the same habitat type"*, but cautioned that the comparison may not be appropriate because egg pocket monitors were typically near the thalweg, while the cross section monitors were at uniform intervals across the channel width.

In a similar study, scour and fill was measured in four chum salmon redds and adjacent bed material in Kanaka Creek near Vancouver, British Columbia (Rennie 1998; Rennie and Millar 2000). Scour monitors were installed on a grid over a low gradient riffle and recovered multiple times over a single flood season. Scour depths were spatially variable (mean = 8.5 cm) and the lack of spatial autocorrelation between scour monitors suggested a random pattern of scour. However, localized scour and fill was noted around a rootwad and near a collapsed bank. The distribution of scour depths was right skewed and resembled a negative exponential function. Maximum scour depth at the egg pockets of redds (mean = 6 cm, n = 4 redds) was not significantly different from the adjacent bed (mean = 8 cm, n = 18). Rennie (1998) concluded that redd construction may not reduce scour, however, the small sample size *"limits the generality of the results".*

Yee (1981) measured scour and fill in Prairie Creek, a low gradient gravel-bed coastal stream in old growth redwood (*Sequoia sempervirens*) forests of northern California. Scour chains were installed on a grid in spawning riffles and recovered multiple times over a two-year period. Similar patterns of scour and fill were observed over the period, where scour depths were much deeper at the bottom of the riffle (6 - 24 cm) than the head of the riffle (3 - 8 cm). Laterally, scour and fill depths were shallow near the banks and deeper near the thalweg. Based on the longitudinal pattern of riffle scour observed, Yee (1981) hypothesized that salmonids have evolved to spawn at the head of riffles (pool tails) not only for favorable intergravel flow, but also for stable gravels.

Lisle (1989) measured the infiltration of fine sediment into streambed gravel and scour and fill of spawning areas in low-gradient northern California coastal streams over a 2 - 4 year period. Gravel filled cans (to collect fine sediment) and scour chains were installed on cross sections in spawning areas of each stream. Fine sediment infiltrated down to the bottom of gravel cans during small storms, but formed a seal near the top several centimeters during larger storms. Although depth of scour and fill was highly variable, the cross sections maintained the same general shape from storm to storm even though segments of cross sections commonly scoured up to 10 cm or more during a storm. Lisle (1989) concluded that while both scour and infiltration of fines pose a threat to incubating eggs, scour and fill depths and rates of fine sediment infiltration are highly variable in space and time and this *"variability poses the greatest challenge to predictions of spawning success as a function of flow and sediment transport."*

2.3.2 Reach Scour and Fill Prediction

Based on the negative exponential distribution of tracer (i.e. marked rocks) burial depths observed in previous studies (Hassan and Church 1994), Haschenburger (1999) developed a model of scour and fill depths using the exponential probability density function:

$$f(x) = \lambda e^{-\lambda x} \qquad (1)$$

where f(x) equals proportion of the distribution at value *x*, and λ is the inverse of both the distribution mean and standard deviation. The specific model offered for general use in gravel-bed rivers (Haschenburger model) was based on Shields stress (dimensionless shear stress) using data collected over a range of flows in coastal streams on Vancouver Island, British Columbia (Haschenburger 1996) and England (Carling 1987). Data from the primary study reach on Carnation Creek, British Columbia included recovery of scour indicators (chains and monitors) from cross sections in pool, riffle, and bar areas after individual storms over a two-year period. A strong correlation between flow strength and mean depths of scour or fill provided the fundamental basis for the empirical model. The

Haschenburger model predicts a negative exponential distribution of scour and fill depths to a first approximation based on reach-average Shields stress, a parameter used to express the ratio of the tractive and gravitational forces acting on a representative bed particle:

$$\tau^{*} = \frac{\rho_{\mathrm{w}}\, R\, S}{(\rho_{\mathrm{s}} - \rho_{\mathrm{w}})\, D_{50}} \qquad (2)$$

where R is the hydraulic radius (meters), S is the slope, ρ_w is the density of water (kg/m^3), ρ_s is the density of sediment (kg/m^3), and D_{50} is the median particle size (meters).

The Haschenburger model was developed by (1) calculating the reach mean scour or fill depth for different flows, (2) plotting the inverse of the mean scour or fill depth (model parameter) against the respective Shields stress for that flow (normalized by a reference Shields stress for incipient motion), and (3) fitting a line to the plot and using functional analysis to generate equation coefficients for the exponential function, resulting in the following predictive equation applicable to gravel-bed rivers in general, for any given flow:

$$\theta = 3.33e^{-1.52\tau^{*}/\tau_{\mathrm{r}}} \qquad (3)$$

where θ is the inverse of the mean scour of fill depth referred to as the "model parameter", τ^* is Shields stress (described above), and τ_r^* is the reference Shields stress for incipient bed entrainment (0.045). For a given Shields stress, the inverse of the model parameter gives the predicted mean scour or fill depth. The distribution of scour or fill depths is then predicted by the exponential function:

$$f(x) = \theta e^{-\theta x} \qquad (4)$$

where f(x) equals the proportion of streambed scour or fill to a given depth *x* (centimeters). The Haschenburger model-predicted scour distributions are equivalent to fill distributions because the mean scour and fill depths on Carnation Creek were not statistically different (Haschenburger 1996, 1999). The model was developed primarily from individual flood events, *"although some monitored flows contained more than one discreet flood hydrograph"* (Haschenburger 1999). Although Haschenburger (1996; 1999) does not use the term active layer (the full range of bed elevation at a point for a given flow or flood season, Figure 3), the model also predicts active layer depths for individual flood events because scour and fill depths are predicted as equivalent. It should be noted that empirical and predicted scour or fill distributions (frequency histograms) presented by Haschenburger (1996, 1999) and this study are "modified relative frequencies", where the relative bin frequency is divided by the bin interval. This is appropriate for grouped data where the frequency represents the whole bin class rather than the individual measurement (Olkin et al. 1980). It should also be noted that Haschenburger (1999) compared measured distributions with the exponential function that best fit the measured distribution:

> *"In this study, theoretical exponential distributions were articulated using maximum likelihood estimators of model parameters, which were generated using a Newton-Raphson iterative procedure with grouped empirical observations. Similarity between theoretical and empirical distributions was then assessed using an Anderson-Darling statistic (A^2)…. "* (Haschenburger 1999).

Measured distributions were not compared with the distributions predicted by the Haschenburger model offered for general use in other gravel bed rivers (equations 3 and 4). Because one thesis objective was to test the Haschenburger model, I compare scour and fill distributions measured in this thesis study directly with distributions predicted by the Haschenburger model.

2.3.3 Redd Scour and Fill Prediction

Based on evidence of a scour depth limitation due to particle size, DeVries (2000) recommends a modification to the Haschenburger model when considering scour depth at redds. Assuming that approximately 90 percent of the scour depths in areas used by spawning salmonids are less than $2.5D_{90}$, the predictive equation becomes:

$$0.9 = 1 - e^{(-\theta 2.5 D_{90})}$$

resulting in:

$$\theta = \frac{\ln(10)}{2.5D_{90}} = \frac{0.92}{D_{90}}$$

The utility of this modification may be limited because it does not predict scour associated with a specific flood event, but rather predicts the maximum scour possible based on a limit to bedload layer movement observed by DeVries (2000).

Lapointe et al. (2000) developed a model to predict Atlantic salmon (*Salmo salar*) egg mortality due to scour or fill in riffles based on flood strength and substrate size. The empirical model was developed from measurements of reach-average boundary shear stress (τ) and net scour or fill during three flood events on the Sainte-Margueritte River, Quebec. The model requires (1) dividing spawning areas into low (point bar side), thalweg, and high (cut bank side) velocity subzones, and (2) measuring the reach-average boundary shear stress and median bed particle size for the riffle, that is used to develop a bed mobility ratio (shear stress/critical shear stress). Based on pre and post-flood topographic surveys of the spawning riffles, the thalweg and high velocity subzones were consistently prone to net scour while the low velocity subzone was prone to net fill. The model was developed by (1) plotting the proportion of each subzone undergoing net scour or fill to 20 and 30 cm (the range of published egg burial threshold depths for Atlantic salmon) against the mobility ratio, and (2) fitting a linear function to the plot using regression analysis. While estimates of egg mortality due to scour are quantitatively based on published egg pocket depths, little is known about the threshold effects of fill depths on egg mortality. This model appears promising because it predicts scour or fill for a given location in a subzone of the riffle, but it remains to be tested on other rivers. Because the model is based on net scour or fill, it provides minimum estimates of egg mortality and is not applicable to redds that experience similar amounts of scour and fill, where the bed elevation stays relatively constant.

2.3.4 Synthesis of Previous Studies

While a basic understanding of scour and fill processes in gravel-bed streams has evolved from previous studies, the primary factors influencing scour and fill are not consistent between studies. Some studies indicate a strong correlation between flow strength (or shear stress) and scour or fill depths (Carling 1987; Wilcock et al. 1996; Haschenburger 1996, 1999), while others have found weak correlation with shear stress (Hales 1999; DeVries 2000) and suggest that scour is controlled strongly by sediment supply and size (DeVries 2000). Where provided by studies, the distribution of scour or fill depths are generally right-skewed (negative exponential) (e.g. Montgomery et al. 1996; Haschenburger 1996, 1999; Rennie and Millar 2000), a pattern characterized by frequent small scour and fill depths and infrequent large scour and fill depths. This pattern suggests the majority of streambed remains undisturbed during a flood, while a small portion of the channel scours or fills relatively deeply (Haschenburger 1996). This may also reflect the probability of streambed exposure to different flow depths (Haschenburger 1999) and that small portions of the channel (lanes) convey major portions of the load (Lisle et al. 2000).

Scour and fill depths are spatially variable both laterally and longitudinally. Observed patterns of lateral scour and fill have been either random (Rennie and Millar 2000), or related to channel configuration, where scour depths are higher near the thalweg than the channel margins (Yee 1981). Where scour and fill are measured over long (10^3 meters) or multiple (3 or more) reaches, variable sediment flux is generally observed longitudinally, as bed elevations of different subreaches alternately aggrade, degrade, or remain stable (e.g. Hassan 1990, Matthaei et al. 1999), a process well documented in sand-bed channels (e.g. Colby 1964, Leopold et al. 1966, Andrews 1979). This pattern likely reflects variation in sediment supply (e.g. DeVries 2000); channel morphology (e.g. Schuett-Hames et al. 2000); roughness elements such as large wood (e.g. Rennie 1998; Schuett-Hames et al. 2000), boulders, bedrock bends, and bedrock outcrops (e.g. Lisle 1986); and location within the channel network and proximity to tributary junctions (e.g. Napolitano 1996, Lisle and Napolitano 1998; Benda et al. 2003; Benda et al. submitted). In contrast, scour and fill measured in relatively straight reaches (Haschenburger 1996, 1999) or specific habitats (Lisle 1989) often reveal relatively stable bed elevations. In addition to sampling design, a probable source for the differences in observed patterns between studies are the cause and scale of scour and fill measured, which are summarized here in order of increasing scale (T. Lisle, personal communication 2001):

1) Uniform entrainment (scour) of the armor layer (thickness ~D_{90}) primarily from bedload movement (e.g. Wilcock et al. 1996, DeVries 2002).

2) Scour and fill due to stage-dependent variations in shear stress, where pools scour and riffles fill at high flows, and the reverse occurs during waning stages (e.g. Keller 1971, Lisle 1979).

3) Localized scour and fill from flow over and around channel obstructions or roughness elements such as bends, large wood, boulders, and bedrock (e.g. Lisle 1986; Rennie 1998; Rennie and Millar 2000).

4) Reach-scale bedload fluxes or gravel sheets that cause net aggradation or degradation over one or a few high flow events (e.g. DeVries et al. 2002).

5) A progressive change in channel morphology, for example, resulting from channel avulsion, bank erosion, or movement of large wood (e.g. Lisle 1989; Schuett-Hames et al. 2000).

6) Large scale aggradation or degradation occurring (a) over a period of years, for example, resulting from a fundamental change in sediment or large wood supply from land management (e.g. Tripp and Poulin 1986; Platts 1989), (b) during a single large disturbance event (e.g. Griffiths 1979, Kelsey 1980, Lisle 1982; Lisle 1995), or (c) a combination of both (e.g. Madej and Ozaki 1996).

Prediction of scour and fill may be possible for small-scale events in stable channels (e.g. Haschenburger 1999), but becomes increasingly difficult to predict at larger scales because of the stochastic nature of scour and fill. To better understand and predict scour and fill, the relative influence of flow strength (or shear stress) and sediment supply and size on scour and fill depths requires further elucidation. In addition, the influence of reach location within the network and proximity to major channel nick points on scour and fill should also be considered. As research progresses, eventually prediction of scour and fill should encompass the various causes and scales of scour and fill.

Existing research of scour and fill processes in relation to salmonid spawning is sparse. As mentioned previously, current hypotheses of adaptation to streambed scour for salmon that spawn during high flows include: decreased bed mobility as a result of surface coarsening from redd construction (Montgomery et al. 1996), spawning in low scour areas (Yee 1981; Stefferud 1993; Montgomery et al. 1999; DeVries 2000), depositing eggs below typical scour depths (Montgomery et al. 1996), and natural selection for larger fish that can bury their eggs deeper or selection for fish that spawn at times when scour is less likely (Steen and Quinn 1999). Some of these hypotheses may not be testable, for example, the deposition of eggs below typical scour depths hypothesis cannot be quantitatively assessed because measurement of egg pocket depth would disturb the bed and influence scour depth (DeVries 2000). The hypothesis that redd construction reduces scour (Montgomery et al. 1996) has received some limited testing by Rennie and Millar (2000), where they found no difference between scour in redds and the adjacent bed (n = 4 redds). In addition, there appears to be conflicting interpretation of the data reported by Montgomery et al. (1996), where Schuett-Hames et al. (1994) indicates that scour near egg pockets was *"similar or somewhat higher than on cross-sections for the same habitat type"*, suggesting that redd construction does not reduce scour. I could find no published data concerning spawning in low scour areas. However, the following limited indirect observations suggest that some salmonids and grayling may not select low scour areas for spawning. Schuett-Hames et al. (2000) observed that chum salmon favor pool tails that are prone to scour at higher flows, indicating chum salmon actually select high rather than low scour areas for spawning. Of spawning habitat available (assumed to be all of the channel encountered by spawners), Sempeski and Gaudin (1995) found that grayling (*Thymallus thymallus*) selected sites with highest shear stress (and presumably high scour). Finally, some salmonids limited to habitat in step-pool channels can only spawn in high scour areas where gravel accumulates (e.g. Kondolf et al. 1991).

The existing scour and fill models potentially applicable to redds have some limitations and require validation. The Haschenburger model based on Shields stress appears limited to prediction of scour or fill at redds that experience equal amounts of scour and fill. Conversely, the model developed by Lapointe et al. (2000) based on boundary shear stress is limited to redds that undergo net scour or net fill. The approach developed by DeVries (2000) is based on a limit to scour depth by grain size ($2D_{90}$) and does not allow prediction of scour for a given flood magnitude. Development of a model flexible to predict scour and fill at redds for variable channel conditions (aggrading, degrading, equilibrium) would be more useful for watershed managers. In addition, better understanding of salmon adaptation to scour and fill could improve application of such models.

3.0 STUDY AREA AND METHODS

3.1 STUDY AREA

This study was performed on two reaches of Freshwater Creek, a coastal stream that drains a 66 km^2 basin into Humboldt Bay just south of Arcata, California (Figure 2). The upper portion of the basin is predominantly second growth redwood timberland, while the lower basin consists of mixed residential and agricultural land use where the vegetation may have been historically dominated by redwood, but is now mostly red alder (*Alnus rubra*) and willow (*Salix lasiandra*). Annual precipitation is high (150-200 cm) and falls primarily between October and April. The 840 - 900 m study reaches are 4th order gravel-bed streams that are moderately confined, low gradient (0.007 - 0.011), and contain a combination of plane-bed, pool-riffle, and forced pool-riffle channel morphology (see Montgomery and Buffington 1997). Most of the lower reach is underlain by poorly consolidated Tertiary sandstones and mudstones (Wildcat Group) with some adjacent Quaternary terrace deposits, while the upper reach is underlain by more competent Jurassic and Cretaceous interbedded sandstones and shales (Yager Formation and Central Belt of the Franciscan Complex) (Knudsen 1993) and also contains intermittent adjacent Quaternary terraces. The most characteristic differences between the reaches are (1) the higher amount of competent bedrock, boulders, and large wood in the upper reach, resulting in more forced pool-riffle channel morphology, and (2) the higher proportion of riparian deciduous trees in the lower reach (Figure 4), and

(3) the wider valley width of the lower reach (Figure 5). Table 1 summarizes the physical characteristics of the study reaches.

3.2 MEASUREMENT OF REACH SCOUR AND FILL AND SHIELDS STRESS PARAMETERS

To test the accuracy of the Haschenburger model, scour, fill, and active layer depths were measured for comparison with those predicted by the model from reach-average Shields stress (calculated from reach-average values of water depth [hydraulic radius], slope, and median particle size). The measured and model-predicted distributions were compared using a Cramér–Von Mises goodness-of-fit test (W^2 test statistic, Spinelli and Stephens 1997), where the W^2 significance level is considered the probability of similarity (p-value) (e.g. Haschenburger 1999; Spinelli 2001). This is the same test used in the dissertation work by Haschenburger (1996).

3.2.1 Reach Scour and Fill Sampling Design

Scour and fill were measured at random locations in both reaches. Scour chains were installed on two cross sections randomly located within every 100-meter section of the reach. On each cross section, chains were installed at 1.5-meter intervals across the active width. This sampling design ensures that cross sections are randomly located but spread somewhat uniformly over the whole reach. The design differs from previous studies where scour chains or monitors were installed on a grid over a short reach (e.g. Rennie and Millar 2000, Yee 1981), on cross sections in straight reaches with limited complexity (e.g. Haschenburger 1996; 1999), or in specific habitats (e.g. Lisle 1989;

DeVries 2000; Schuett-Hames et al. 2000). To observe patterns of scour and fill based on channel geomorphic units (e.g. Schuett-Hames et al. 2000), the area of each scour chain was identified at low flow as: (1) *bars* that were long-term storage areas of gravel or larger substrate, (2) *pools* that had a scoured pool head, definitive tailout, flat unbroken water surface, and a residual depth greater than 0.5 m, (3) *riffles* that had a dominant particle size of gravel or larger, turbulent broken water surface, and shallow water depths, or (4) *plan-bed* areas that had a relatively flat planform channel bed, homogeneous substrate, unbroken water surface, and residual depths less than 0.5 m.

Upper Reach

On the 900-meter upper reach, two of the 18 initial cross sections were located in bedrock or boulder sites where chains could not be installed. Because boulder and bedrock areas cannot scour nor can salmon spawn at such locations, zero scour or fill values from these two cross sections were not included in the reach scour calculations. Of the 98 chains installed on 16 cross sections in the upper reach (Figure 5A), 88 chains were recovered. Minimum scour depths were inferred at three locations in a pool where chains scoured out entirely and minimum fill depths were inferred at three locations where fill depth precluded recovery (total n = 91 chain locations).

Lower Reach

On the lower reach, 25 cross sections were initially placed over a distance of 1,000 meters. Five cross sections that were located in bedrock or boulder sites were not included in the reach scour or fill calculations. Five cross sections at the bottom of the reach contained extensive fill that prevented chain recovery. Because scour and fill depths could not be measured at the majority of these five lower cross sections, they were excluded from the study and the reach was shortened to 840 meters. On the 15 cross sections with usable chain data in the lower reach (Figure 5B), 60 of the 67 chains installed were recovered (total n = 60 chain locations).

3.2.2 Measurement of Scour and Fill

Because scour and fill were measured at numerous locations, chains (Leopold et al. 1964; Laronne et al. 1994) were selected over sliding bead/wiffle ball scour monitors (Tripp and Poulin 1986; Nawa and Frissell 1993) and scour cores for ease of installation. Chains yield similar results to monitors (Haschenburger 1996; 1999) and cores of painted gravel (Hales 1999). Scour chains were constructed using a duckbill anchoring device (Figure 6) and brass link chain with a small magnet on the end to aid relocation with a magnetic locator. Chains were installed by creating a vertical pilot hole with a sledge hammer and a small-diameter (~2.5 cm) drive rod. Upon careful removal of the drive rod, a smaller-diameter (~2.0 cm) probe with the scour chain attached was tapped into the base of the hole to seat the anchor. The insertion probe was removed and an upward pull on the chain rotated the duckbill into a horizontal position creating an anchor (Figure 6). Recovery of scour chains is time intensive and loosens the bed, potentially affecting subsequent measurements. Consequently chains were only recovered once, at the end of the flood season. Maximum scour depth was determined by the difference between the pre- and post-flood horizontal chain length, net fill was measured as the vertical distance above the elbow in the chain to the post-flood bed surface, and the active layer was the maximum bed elevation range measured by the chain (Figure 3). Because scour chains were only recovered at the end of the flood season, scour and fill measurements reflect maximum scour and net fill depths over the study period (seasonal scour and fill).

3.2.3 Measurement of Reach-Average Shields Stress

Reach-average Shields stress parameters (mean water depth, slope, median particle size) for the peak flood were measured to predict scour and fill depths using the Haschenburger model. Stream discharge was continuously recorded at a gauging station at the bottom of the lower reach (Salmon Forever 2001). Cross sections and water surface slopes were surveyed at the end of the flood season with an auto level and stadia rod using standard techniques (e.g. Harrelson et al. 1994). Flood marks (leaf litter) were used as indicators of peak stage and the mean water depth (hydraulic radius) was determined at cross sections with adjacent flood marks using WinXSPro (U.S. Forest Service 1997). To check the reliability of the flood marks, discharge at the cross sections was independently estimated using WinXSPro. Flood marks that gave discharge estimates 45 percent or more higher than the measured discharge were excluded from the reach-average water depth calculation (see Appendix A for details). Low flow water surface slopes were used as a surrogate for peak discharge water surface slopes. Low and peak flow water surface slopes were similar (within 15%) on the lower reach (O'Connor et al. 2001), and were assumed to be similar for the upper reach. Median grain size was determined from surface pebble counts (Wolman 1954) performed at each cross section and combined to estimate a reach average. At least 100 particles were measured at each cross section. Because smaller particle sizes are mobilized more readily at low shear stresses (Wilcock et al. 1996), particle sizes less than 8 millimeters were excluded (discarded) from the median particle size analysis (see also Haschenburger 1996; DeVries 2000) (upper reach n = 1,587 particles, lower reach n = 1,389 particles).

3.3 MEASUREMENT OF SCOUR AND FILL AT REDDS

To determine if redd construction affects scour, the depth of scour at redds was compared with scour adjacent to redds. Because coho salmon are a threatened species in California, chains could not be installed directly in the redd. Consequently, scour chains were installed on each side of a redd, midway along the redd tailspill where the bed elevation is near that of the surrounding substrate (Figure 1). These chain locations avoid damage to embryos and presumably measure scour depths equal to those of the bracketed redd (e.g. Harvey and Lisle 1999). This presumption is based on observations of planar scour and fill at redds in this study and other northern California coastal streams (Lisle 1989), where the redd forms (pit and tailspill) were smoothed out or obliterated by bankfull flows, leaving no visible resistant pedestal nor a scoured hole. The chain locations also measure scour and fill depths relative to the original streambed surface, a more reliable datum than the disturbed redd material (DeVries 1997; Steen and Quinn 1999; Rennie and Millar 2000; DeVries 2000). Two additional chains were installed in control areas that were 1 to 2 meters away from the redd and contained similar substrate, water depth, and velocity as the redd. Hydraulics at these control locations are presumably equal to the redd but are not influenced by the coarsening of the redd surface. Plan maps of the channel at each redd were prepared to roughly document the hydraulics of the redd and chain locations.

Scour chains were installed at a total of 16 redds. Nine of the redds were within the upper reach and seven redds were located above and below the upper reach. To determine if salmon spawn in low scour areas, scour depths at the random locations in the upper reach were compared with scour depths at the nine redds within the upper reach (control and redd locations; see rationale in results). This comparison assumes that the spawning habitat was the entire channel encountered by spawners, an approach used by others to determine habitat preference (e.g. Sempeski and Gaudin 1995). Because embryos are potentially susceptible to mechanical shock mortality during the initial two weeks of incubation (Jensen and Alderdice 1983; 1989; Dwyer et al. 1993), scour chains were installed at least two weeks after a redd was completed. Permission to install scour chains adjacent to redds was obtained from the Humboldt State University Institutional Animal Care and Use Committee (Appendix B) and the National Marine Fisheries Service (D. Logan, personal communication 1999). Only three redds were observed within the lower reach. Unfortunately, peak discharge occurred within two weeks of redd completion and it was not possible to measure scour at these locations.

4.0 RESULTS AND DISCUSSION

> *"You can only write what you see."*
>
> *-Woody Guthrie*

4.1 STUDY FLOWS AND SPAWNING ACTIVITY

The largest flow recorded during the study was 25.9 cubic meters per second (m^3/s) on January 11, 2000, followed by flows of similar magnitude on January 14 (25.2 m^3/s) and February 14 (23.2 m^3/s) (Figure 7). Flood marks from the flows were above bankfull indicators (i.e. break in bank slope, base of perennial vegetation). The estimated recurrence intervals for these flows are 1.2 to 1.3 years (Appendix C), within the estimated range for regional bankfull flows (Rosgen and Kurtz 2000). The high flows coincided with the 1 - 2 month incubation period for chinook and coho embryos. Two periods of spawning were observed in the upper reach: an initial wave of chinook and coho spawning prior to the January 11 flood, followed by a second pulse of coho spawning in mid January to early February. Movement of substrate and large wood was apparent in all three events. The most noticeable changes in streambed morphology and large wood jams occurred during the last peak flow event (February 14), suggesting the initial January flows loosened streambed material while the subsequent February flow moved more material (e.g. Reid et al. 1985).

4.2 MODEL TESTING AND REACH SCOUR AND FILL PATTERNS

The first objective of this study was to test the Haschenburger model for predicting scour and fill on Freshwater Creek. While Haschenburger (1999) found that measured scour and fill distributions were fitted by the exponential function, the Haschenburger model (equations 3 and 4) has not been tested (see section 2.3.2).

4.2.1 Upper Reach Scour and Fill - Results

The distribution of scour or fill depths measured in the upper reach ($n = 91$) was right-skewed and approximated a negative exponential form, while the distribution of active layer depths was more symmetric but slightly right-skewed (Figure 8). Haschenburger model predictions of scour or fill depths were calculated using reach-average values for water surface slope, median grain size, and mean water depth for the peak flow (Table 2), and the predicted and measured distributions of scour, fill, and active layer depths were compared using a Cramér–Von Mises goodness-of-fit test (W^2 test statistic, Spinelli and Stephens 1997). The model-predicted distribution was similar to the measured distribution of scour depths ($p > 0.25$, $W^2 = 0.046$, $\mu = 10.6$), but provided a poor fit of the measured distributions of fill ($p < 0.005$, $W^2 = 0.32$, $\mu = 10.2$) and active layer depths ($p < 0.001$, $W^2 = 1.65$, $\mu = 14.7$) (Figure 8). The model underestimated the proportion of stream bed experiencing little or no fill (< 8 cm) and overestimated the proportion of stream bed filling deeply (> 8 cm) (Figure 8). The model-predicted mean depths (9.8 cm for scour, fill, and active layer) were very similar to the measured mean scour (10.6 cm) and fill (10.2 cm) depths, but under predicted the measured mean active layer (14.7 cm) by 50 percent.

Measured scour and fill depths were variable across the width and length of the upper reach (Appendices D and E). By averaging the net elevation change recorded at each chain, the average change in streambed elevation was calculated for each cross section (Appendix E). In Figure 9, the average streambed elevation change is plotted against reach distance to observe net scour or fill patterns over the reach. In the upper reach, approximately half of the cross sections experienced small amounts of net fill (+1.8 to +8.3 cm) and half showed net scour (-0.1 to -6.4 cm), with an overall reach average bed elevation change of +0.9 cm (Figure 9A). Aggradation at six of the eight cross sections near the top of the upper reach may be due to local sediment supply from a small southern tributary at the top of the reach (Figures 2 and 5), or may be material moving down along the mainstem into the upper reach. Within the upper and lower reaches, significant local sediment supply from bank erosion or streamside landslides was not apparent.

The distribution of channel geomorphic units within the upper reach was variable, with the majority of the randomly sampled bankfull channel (two random cross sections located within every 100-meter subreach) consisting of bars (49%), followed by riffles (21%), pools (19%), and plane-bed areas (11%) (Figure 10A). The range of scour and fill depths experienced in the different geomorphic units was also variable, where mean scour or fill depths were deepest in pools (scour = 20 cm, fill = 14 cm), followed by riffles (scour = 12 cm, fill = 11 cm), bars (scour = 8 cm, fill = 10 cm), and plane-bed areas (scour = 8 cm, fill = 7 cm) (Figure 10B).

4.2.2 Lower Reach Scour and Fill - Results

The distribution of measured scour depths in the lower reach (n = 60) was right skewed (negative exponential), while the distribution of fill and active layer depths were more symmetric and crudely approximated a normal distribution (Figure 8). The model-predicted distributions were different than the measured distributions of scour ($p < 0.001$, $W^2 = 1.0$, $\mu = 6.0$) , fill ($p < 0.001$, $W^2 = 6.6$, $\mu = 13.3$), and active layer depths ($p < 0.001$, $W^2 = 8.6$, $\mu = 14.3$) (Figure 8). The model underestimated the proportion of stream bed experiencing little or no activity (< 8 cm) and overestimated the proportion of stream bed scouring or filling deeply (> 8 cm) (Figure 8). The model-predicted mean depth (5.3 cm for scour, fill, and active layer) was similar to the measured mean scour depth (6.0 cm), but under predicted the measured mean fill depth (13.3 cm) and mean active layer depth (14.3 cm) by over 50 percent. As indicated by the large difference between measured mean scour and fill depths, sediment supply to the lower reach was greater than sediment transport out of the reach, resulting in net fill at 13 of the 15 cross sections (average +7.2 cm, range -3.7 to +18.6 cm) (Figure 9B).

In contrast to the bar-dominated upper reach, the distribution of channel geomorphic units in the lower reach consisted primarily of riffles (42%), followed by plane-bed areas

(34%), and bars (11%) (Figure 10A). Pools were conspicuously absent from the random sample of channel locations (two random cross sections located within every 100 meter subreach). The range of scour or fill depths in each of the channel geomorphic units was fairly uniform, where average scour or fill depths in bars (scour = 5.7 cm, fill = 15.0 cm) was similar to riffles (scour = 5.8 cm, fill = 10.6 cm) and plane-bed areas (scour = 6.4 cm, fill = 15.4 cm) (Figure 10C). Appendices D and E show the measured scour and fill depths in the lower reach.

4.2.3 Scour and Fill Patterns - Discussion

Evaluation of the different scour and fill patterns in the two reaches of Freshwater Creek may clarify model limitations and reveal potential improvements for predicting scour and fill. The measured scour or fill depths in the upper reach and scour depths in the lower reach were right skewed and approximated a negative exponential distribution (Figure 8). This right-skewed distribution is consistent with other studies (Montgomery et al. 1996; Haschenburger 1999; Rennie and Millar 2000) and supports inferences that the majority of streambed remains undisturbed during a flood, while a small portion of the channel scours or fills relatively deeply (Haschenburger 1996), and that small portions of the channel convey major portions of the load (Lisle et al. 2000). The distribution of fill depths in the lower reach was more symmetric and approximated a normal distribution (Figure 8B), in part, resulting from the consistent aggradation that was fairly uniform across the width of the reach (Appendices D and E) and increased downstream (Figure

9B) with proximity to the major channel bend and tributary junction at the bottom of the reach (Figure 5B).

The distributions of active layer depths in both reaches were more symmetric than exponential in shape (Figure 8C). Also, despite differences in scour and fill distributions in the lower reach (t-test, lower reach $p < 0.0001$; upper reach $p = 0.87$) and major differences in scour and fill between reaches (scour, $p = 0.002$; fill, $p = 0.01$), the active layer distributions were fairly similar between reaches ($p = 0.79$), indicating the active layer may be more predictable than discreet distributions of scour and fill in streams with fluctuating bed elevations.

Differences in scour and fill patterns in the upper and lower reaches are partially due to channel morphology (e.g. Schuett-Hames et al. 2000). The bar-dominated upper reach with large wood had more channel form roughness in comparison to the uniform riffle- and plane-bed-dominated channel of the lower reach (Figures 10A and 11). Consequently, the complex upper reach experienced more spreading of flow over and around obstructions (bedrock, boulders, large wood) creating a wider range and magnitude of scour and fill, while the simpler lower reach experienced fairly uniform scour and fill depths (Figures 8, 10B, and 10C).

The most notable difference in the two reaches was the aggradation in the lower reach, where the mean fill depth (13.3 cm) was over twice the mean scour depth (6.0 cm). In the lower reach, net fill increased downstream as the gradient decreased (Figure 8B) with proximity to a major channel bend (approximately 180°) and the Graham Gulch tributary junction at the bottom of the reach (Figures 2, and 5B). The bend and possibly high sediment supply from Graham Gulch appear to create a backwater effect causing sediment deposition. Although a recent fan is not apparent at the Graham Gulch junction, O'Connor et al. (2001) observed increased sediment production in Graham Gulch following the January 1997 flood, where eroded material from of a remnant landslide dam deposit and a remobilized earthflow moved downstream as hyperconcentrated flow, aggrading the channel in many places, with 0.3 to 0.9 meters of aggradation near the lower portion of the tributary. Continued sediment impacts to the lower portion of Graham Gulch were projected to continue for up to a decade. Various morphological nick points can create a backwater effect and cause sediment to deposit behind them, including channel bends (Lisle 1986; Matthaei et al. 1999), canyon walls, and tributary alluvial fans and debris fans (Small 1973; Melis et al. 1994; Knighton 1998; Benda et al. 2003; Benda et al. in press). Due to major discontinuities in both discharge and sediment supply and the presence of fans (Knighton 1998), tributary junctions are also areas higher scour and fill (Napolitano 1996; Lisle and Napolitano 1998). The channel also widens significantly at the 180° bend, a typical channel response to an accumulating sediment wedge behind a channel nick point (e.g. Small 1973; Knighton 1998; Benda et al. 2003). Watershed-scale simulation models and field evidence suggest that persistence of sediment perturbations (i.e. aggradation) depends on location in the channel network and proximity to channel nick points, primarily tributary junctions (Benda and Dunne 1997; Benda et al. submitted).

In addition to the major bend and the tributary junction, aggradation of the lower reach appears to be influenced by sediment supply from areas above the reach. O'Connor et al. (2001) estimated sediment supply (bank erosion and stream side landslides) to the lower reach was significantly higher than sediment supply to the upper reach. This may be due to differences in underlying geology, where the area supplying sediment to the lower reach is predominantly underlain by more erosive unconsolidated mudstones (Wildcat Group), while the area supplying sediment to the upper reach is underlain by more competent sandstones and shales (Franciscan Complex-Central Belt and Yager Formation). Differences in recent and historic land management, including historic stream cleaning of wood, may also affect the sediment supply and transport in the two reaches. For example, Landsat images (U.C. Berkeley 2002) show significant recent land disturbance (1994 – 1998) to areas draining to the lower reach, but minimal recent land disturbance to areas draining to the upper reach.

4.2.4 Model Limitations, Applications, and Improvements - Discussion

Although the model-predicted and measured distributions of scour, fill, and the active layer were often statistically different, the predicted mean scour and fill depths were within 8 to 12 and 4 to 60 percent of the measured values, respectively. Based on application to Freshwater Creek, the model provides a reasonable approximation of mean scour and fill depths for a given flow, but often gives unreliable predictions of scour, fill, and active layer depth distributions. Fundamental differences between predicted and measured distributions were due to variable patterns of scour and fill in Freshwater Creek (Figures 8, 9, and 10) that were weakly influenced by Shields Stress (e.g. Hales 1999; DeVries 2000) and highly influenced by (1) location within the channel network, specifically proximity to major channel bends (e.g. Lisle 1986; Matthaei et al. 1999) and tributary junctions (Napolitano 1996; Lisle and Napolitano 1998; Benda et al. 2003), (2) sediment supply (e.g. Devries 2000), and (3) channel morphology (form roughness) (e.g. Schuett-Hames et al. 2000). The dominance of sediment supply on scour and fill processes likely increases with scale (see summary of scales of scour and fill in section 2.3.4). Consequently, scour and fill models based on shear stress may only be relevant to small-scale scour and fill, such as individual small floods. More specific sources for the differences between the predicted and measured distributions are summarized below, some that may provide the basis for improved modeling of scour and fill.

1) **Untested Model.** Haschenburger (1999) found that measured scour and fill distributions were similar to the exponential function that best fit the measured data using maximum likelihood estimators (A^2 significance level [p-value] mean = 0.55, n = 73 flood events on different streams and reaches; see Tables 2 and 3 in Haschenburger 1999), however, measured distributions were not compared with distributions predicted by the Haschenburger model (equations 3 and 4) offered for general use on other gravel-bed streams. Consequently, the validity of the Haschenburger model in predicting the scour and fill distributions from which it was developed remains unknown. To test the accuracy of the Haschenburger

model, measured distributions from Freshwater Creek were compared with those predicted by the model.

2) **Sediment Flux.** Because the Haschenburger model was developed from streams with relatively stable bed elevations, mean scour and fill depths were statistically similar, and hence the model predicts equivalent scour and fill depths. Both reaches of Freshwater Creek show imbalances in sediment supply and transport. Scour and fill is balanced over the length of the upper reach, but shows local imbalances within the reach (Figure 9A). The lower reach shows a net imbalance in sediment supply and transport and is aggrading at nearly all cross sections (Figure 9B). This confirms a previous limitation of the model recognized by Haschenburger (1999), where *"scour distributions that incorporate localized net change related to significant adjustments of bed morphology were not fitted by the exponential function…"* and ultimately, *"It must be recognized that fluctuations in sediment transfers, either short term or long term, are not directly incorporated into estimates nor are specific calibrations for particular site characteristics."* Rennie (1998) also found poor exponential fits (using the measured mean scour depth and equation 4) for distributions of scour depths on a British Columbia coastal stream, where scour and fill were often not equivalent. Modeling reaches undergoing net scour or fill would require a mass balance approach (i.e. sediment budget), integrating affects of both sediment supply and transport on scour and fill, as well as considering the reach location within the network and proximity to major channel nick points such as tributary junctions (e.g. Benda et al. submitted).

3) **Channel Form Roughness.** The model was developed from scour and fill data collected from cross sections on relatively straight subreaches with some bars in Carnation Creek (Vancouver) and flat areas in Great Eggleshope Beck (England) (Haschenburger 1999) that likely reflect primarily mobilization depths during bedload transport and excludes more variable local scour and fill from flow around bends and obstructions such as bedrock, boulders, or large wood (e.g.

Rennie 1998; Rennie and Millar 2000; Schuett-Hames et al. 2000; DeVries et al. 2002). Cross sections on Freshwater Creek were randomly selected and reflect both scour and fill from flow around obstructions as well as bed mobilization depths during bedload transport. Others have found higher variation of scour and fill depths in more complex reaches (e.g. Schuett-Hames et al. 2000) and in Freshwater Creek there was higher variation in scour and fill depths in the more complex bar-dominated upper reach than the simpler plane-bed dominated lower reach (Figures 8, 10B, 10C). The model is based on Shields stress that includes force exerted on bed particles as well as "channel form roughness" elements such as banks, bars, bends, bedrock outcrops, large boulders, large wood, and riparian vegetation (e.g. Lisle 1989, Railsback and Harvey 2001), which can be a large component of the overall flow resistance (e.g. large wood, Manga and Kirchner 2000).

There are likely significant differences in channel form roughness between Freshwater Creek and Carnation Creek (British Columbia), the primary stream used to develop the Haschenburger model, and is likely another major source for the differences in the measured and predicted scour and fill distributions. Consequently, the model may only be applicable to sites with similar form roughness as Carnation Creek. Parker and Peterson (1980) developed an equation to partition Shields stress applied to the bed (Shields grain stress τ_G^*) and form roughness, that was primarily from bars in their study reaches. At the time this thesis was completed, the data were not yet available to quantify form roughness in Carnation Creek (J. Haschenburger, personal communication 2002). In Freshwater Creek, the estimated reach-average Shields grain stress was 0.044 in the upper reach and 0.049 in the lower reach, approximately half of the estimated overall Shields stress (Table 1). Form roughness in the upper reach appeared to be primarily from large wood, bars, channel bends, and some boulders and bedrock, causing flow to move around and over obstructions resulting in more variable scour and fill depths. Conversely, form roughness in the lower reach was primarily from an encroaching riparian thicket of deciduous trees and berry bushes that created roughness near the channel margins reducing flow velocity but did not cause variation in scour and fill depths. Consequently, to apply a scour and fill model between different channels, some characterization of roughness elements that cause flow to move over and around obstructions may be necessary. While it is likely beyond the ability and resources of most watershed managers, further partitioning of shear stress between bed particles, bed forms, large wood, and other elements (banks, bends, boulders, bedrock, and riparian vegetation) (e.g. Einstein and Banks 1950) or between the margins and middle of the channel (e.g. Benson and Dalrymple 1967) will likely improve prediction of scour and fill. A simpler approach might include a form roughness factor in Shields stress specifically for channel obstructions, for example, using the volumetric ratio of obstructions (large wood, boulders, bedrock outcrops) within the bankfull channel to the overall bankfull channel, or calculating a "scour multiplier" used by engineers (see Galay et al. 1987).

4) **Scale of Scour and Fill.** The model was developed primarily for scour and fill at a *scale* of individual flood events and may not be applicable to scour and fill over multiple events (J. Haschenburger, personal communication 2001) (see scales of scour and fill summary in section 2.3.4). Although Haschenburger (1996) found that seasonal scour and fill measured in the Queen Charlotte Islands, British Columbia were similar to the best fit exponential function, it was further qualified that the exponential function may best describe seasonal scour and fill distributions (i.e. for a series of floods) where there is a large peak event and preceding or subsequent floods are comparatively small (Haschenburger 1999). However, Haschenburger (1999) did not compare measured *seasonal scour and fill* with predictions by the Haschenburger model (equations 3 and 4). It was not possible to recover chain data after each individual storm in Freshwater Creek, consequently the chain data were only recovered at the end of a storm season that included three peak events of similar magnitude (Figure 7). The model

predictions are based on the largest peak event, but the seasonal scour and fill measured in Freshwater Creek cumulatively reflect the initial peak flood and two subsequent flood events of similar magnitude. Regardless, the model would have performed poorly on Freshwater Creek for individual events since bed elevations were not stable. For example, Rennie (1998) also found poor exponential fits to scour for an individual bankfull flood on a British Columbia coastal stream with fluctuating bed elevations. DeVries (2000) suggests that exponential distributions do not fit scour data for a series of floods (as particle motion becomes more frequent), possibly because the particle distance traveled approaches the spacing between bars and riffles, where particles are stored as flows recede, resulting in a non-random pattern.

5) **Local Variation of Shields Stress.** The model is based on reach-average values of Shields stress that do not reflect the high variation of local Shields stress over a reach. In a comprehensive review of bedload transport in alluvial channels, Carson and Griffiths (1987) admonished that spatial variability over the bed caused by irregularities in channel geometry are common in gravel-bed streams and limit the utility of a mean hydraulic state, and suggest integrating shear stress over a cross section provides a better estimate of the fraction of channel involved in bedload transport (or scour and fill). In a comparison of sediment mobility at local and reach scales in gravel-bed rivers of northern California and Colorado, Lisle et al. (2000) found large scale variations in Shields stress over the length and width of a reach, indicating high discontinuities in bedload transport. Channel topography reflected variations in local Shields stress and divergence of flow, where flow spread and slowed over bar surfaces and converged and accelerated into troughs. This results in variable transport rates (and scour), where small portions of the bed convey major portions of the load. Practicably obtained reach-average values of boundary shear stress (using mean water depth, slope, median particle size) differed widely from the mean local values derived from a three dimensional flow model, tending to under predict the mean of local

transport rates. As a result, predictions of bedload transport (and scour and fill) based on mean hydraulic variables can be highly inaccurate. The authors concluded that, *"...local imbalances appear to drive stage dependent scour and fill and channel evolution"*, a similar conclusion reached by DeVries (2000). Consequently, the model may introduce uncertainties by using reach-average values of Shields stress. Unfortunately, measurement of local shear stress is not practical for most watershed managers and a model based on such measurements would likely receive little use.

6) **Uncertainty at High Shields Stress.** There is higher uncertainty in the model predictions at large shear stresses (Haschenburger 1999). The Shields stress during peak events on both Freshwater Creek reaches ($\tau_* = 0.08$ to 0.10) were similar to the maximum values used to develop the model ($\tau_* = 0.11$) (Haschenburger 1999), where uncertainty in the model is highest.

Model Application

Based on the discussion points above, the current form of the Haschenburger model appears most suitable for reaches that are: (1) in equilibrium between sediment supply and transport, (2) straight and reflect scour and fill primarily from bedload mobilization depth, and (3) have roughness elements similar to Carnation Creek (See Figure 3.2 in Haschenburger 1996 or Figure 1 in Haschenburger and Church 1998). The model may be best suited for coarse applications, such as predicting bedload transport when used in conjunction with tracer gravel studies (e.g. Haschenburger and Church 1998). The model may also be useful at finer scales such as predicting scour at salmon redds (see results and discussion later), but requires additional testing.

Improvements In Predicting Scour and Fill

To create a scour and fill model applicable to a wider range of channel conditions, future scour and fill studies should include data to calibrate for site specific conditions, including the effects of sediment supply and transport, location within the channel network, and form roughness (channel obstructions that cause spreading of flow). For example, to incorporate sediment supply and transport into scour and fill predictions, the net mass sediment balance of a reach (aggrading, degrading, equilibrium) could be estimated by measuring sediment transport at the top and bottom of a reach (T. Lisle, personal communication 2003). This may, in part, also incorporate influences of reach location within the network, for example, reaches behind a tributary fan or bedrock bend may aggrade. The scour and fill data collected from that reach could then be used to develop predictions for similar reaches. To incorporate channel obstructions that cause spreading of flow and variation in scour and fill, a form roughness factor might be included in Shields stress, for example, calculating the volumetric ratio of channel obstructions (large wood, boulders, bedrock outcrops) within the bankfull channel to the overall bankfull channel, or calculating a “scour multiplier” used by engineers (see Galay et al. 1987). The scour and fill data collected from that reach could then be used to develop predictions for similar reaches. As scour and fill data are collected from channels over a range of form roughness, the effects of obstructed flow on scour and fill may become more apparent and predictable. In addition, to better estimate the fraction of channel involved in scour and fill, shear stress should be integrated over a cross section rather than using mean values (e.g. Carson and Griffiths 1987).

Finally, a model based on the cumulative distribution of scour and fill may provide more precision because all empirical data are represented and limitations from averaging data into bins are circumvented. Using cumulative distributions would require high resolution measurement of scour and fill using scour chains or sliding bead monitors (e.g. Nawa and Frissell 1993), where resolution is on the order of 1 – 2.5 cm. The resolution error for scour chains results from interpreting the rounded 90° inflection point that defines the depth of scour (Figure 3). The main disadvantage of using scour chains is the time required to relocate buried chains, and if measuring scour and fill for individual floods, chain recovery loosens the bed, potentially affecting subsequent measurements. Chain recovery time may be reduced significantly by attaching brightly colored floating chord to the end of the chain (see Matthaei et al. 1999).

4.3 SALMON ADAPTATION TO SCOUR HYPOTHESES TESTING

The other major objective of the study was to improve understanding of salmon adaptation to streambed scour by testing the hypotheses that (1) redd construction reduces scour, and (2) salmon select low scour areas for spawning.

4.3.1 Scour and Redd Construction - Results and Discussion

To determine if redd construction affects scour, the depth of scour at 16 redds was compared with scour adjacent to redds (control locations) using a paired t-test. Scour depths at redds were on average 2.3 cm deeper than the adjacent bed (control locations) ($\sigma = 6.2$ cm), but they were not significantly different (paired t-test, $p = 0.16$, $df = 15$) at the 0.05 significance level (Tables 3 and 4, Figure 12A). Plan maps of the redd and control scour chain locations are provided in Appendix F. Appendix G contains a summary of all scour chain measurements at redd and control locations.

Contrary to theoretical calculations by Montgomery et al. (1996), redd construction in Freshwater Creek did not appear to decrease the depth of scour, but possibly increases scour depth by loosening the bed and reducing imbrication. Results from this study (n = 16 redds) are consistent with a previous study by Rennie and Millar (2000) that found no significant difference between scour in redds and the adjacent bed (n = 4 redds).

The generality of these results are limited by the sample size. Although a power analysis of sample size is most useful prior to a study, a post analysis provides some insight into the probability of detecting a difference and guidance for future studies. Given the sample size (n = 16) and variation of scour observed at redds ($\sigma = 5.4$ cm), there was a 20 percent probability of detecting a 2.5 cm difference in scour between redd and adjacent bed locations at a significance level of 0.05. A 2.5 cm interval is the estimated maximum error in measuring scour and fill depths using chains. For variation in scour depths similar to those observed in Freshwater Creek, a study would require sampling 47 to 156 redds to have a 50 to 95 percent probability of detecting a 2.5 cm difference in scour.

When the general pattern of scour at redds and estimated egg pocket depths are considered, a different hypothesis of salmon adaptation appears viable. Using the average female body lengths of 63 cm (coho) and 83 cm (chinook) for Freshwater Creek (Humboldt Fish Action Council, unpublished data 2001) and the relation between female body size and egg burial depth for coho (egg depth = -10.44 + 0.411 * body length, van den Berghe and Gross 1984; Steen and Quinn 1999), the estimated average depths to the top of egg pockets in Freshwater Creek are 15 cm (coho) and 23 cm (chinook), which are similar to values proposed by DeVries (1997) for use in scour studies. Although the majority of redds sampled were not positively identified by species (either chinook or coho), the vast majority of adult fish observed in the upper reach were coho. Because scour depths at redds rarely exceeded the estimated 15 cm (coho) average depth to the top of egg pockets (2 of 16 redds [12%], Figure 12B), scour during the bankfull flows did not appear to be a significant source of mortality in Freshwater Creek. However, the majority of redds experienced scour depths near typical egg pocket depths for coho salmon (Table 4, Figure 12B). This close correspondence between scour depths at redds and estimated egg burial depths supports a previous hypothesis that salmon (species spawning during high flows) have adapted to scour by laying their eggs below typical (annual) scour depths (Montgomery et al. 1996; 1999). However, this hypothesis cannot be quantitatively tested, because measurement of egg pocket depth would disturb the bed and influence scour depth (DeVries 2000).

4.3.2 Scour and Redd Site Selection - Results and Discussion

To determine if salmon spawn in low scour areas, scour at random locations in the upper reach was compared with scour at the 9 redd locations within the upper reach using a t-test. Because there was not a statistical difference between scour at redd and adjacent bed locations (Table 3), reach scour was compared to scour at redd and adjacent bed locations combined to provide a more robust test. This comparison assumes that available spawning habitat included all areas of the channel encountered by spawners (e.g. Sempeski and Gaudin 1995). There was not a statistical difference between scour depths at reach and redd locations (t-test, $p = 0.75$, $df = 116$) (Table 3, Figure 13). There were two periods of spawning on the upper reach (see section 4.1) and redds created during the second phase of spawning (redds #7 - 9, Table 4) were not subjected to the higher peak flows in January 2000 (Figure 7). Inclusion of these redds in the t-test is conservative because, if they were subjected to lower scour depths, it would favor a finding that salmon select low scour areas. But again, the January flows appeared to loosen the bed while the February 14 flow moved more material (e.g. Reid et al. 1985), hence if the February 14 flow produced the deepest scour depths, all 9 redds (#1-9) in the upper reach experienced the same “treatment”.

This result suggests that salmon do not select low scour areas for spawning in Freshwater Creek and is consistent with indirect observations of spawning areas by (1) Schuett-Hames et al. (2000), who observed that chum salmon favor pool tails that are prone to scour at higher flows, and (2) Sempeski and Gaudin (1995) who found that grayling selected sites with highest shear stress. The results are in contrast to a previous hypothesis that salmon select low scour areas as an adaptation to streambed scour (Yee 1981; Montgomery et al. 1999; DeVries 2000), but do not exclude the possibility that salmon select low scour areas in other rivers. For example, salmonids have been observed to spawn in side channels of braided rivers that certainly experience lower scour depths than the mainstem channels (P. DeVries, personal communication 2002).

The usefulness of these results is also limited by the sample size. Given the number of redds sampled ($n = 9$) and variation of reach scour observed ($\sigma = 12.5$ cm), there was a 12 percent probability of detecting a 5 cm difference in scour between redd and reach locations at a significance level of 0.05. A 5 cm difference was selected because (1) it seems a reasonable difference in depth to detect over a long reach (900 m), and (2) it is twice the estimated maximum error in measuring scour and fill depths using chains. With the given variation in scour observed, a study would require sampling 49 to 164 redds to have a 50 to 95 percent probability of detecting a 5 cm difference in scour.

4.4 ADDITIONAL OBSERVATIONS

While not a specific objective of this study, additional analysis of the data yielded two noteworthy observations, including the fill patterns at redds and Haschenburger model predictions at redds.

4.4.1 Fill Patterns And Salmon Spawning

Because there is little published data on fill depths at redd locations, it is worthwhile to examine the patterns of fill at redds in Freshwater Creek. At individual redds, fill depths were on average 6 cm greater than scour depths (paired t-test, $p = 0.04$, df = 15) (Tables 3 and 4, Figure 12B). At the reach scale, fill depths at redds within the upper reach were on average 4.6 cm greater than fill depths at random locations in the upper reach (Figure 13), although they were not significantly different (t-test, $p = 0.12$, $df = 61$) at the 0.05 significance level (Table 3).

Both of the above comparisons suggest that spawning sites in Freshwater Creek were prone to aggradation. Redds within the upper reach were located in long subreaches (100+ m) of both aggradation and degradation (Figure 9A). The majority of redds were located upstream of channel-spanning wood jams and in pool tails (Table 4, Figures 12 and 14). Both are areas of sediment storage prone to fill when material is moving through a reach. While scour exceeded 15 cm in only 12 percent of the redds, fill and the active layer exceeded 15 cm in 44 percent of the redds. Consequently, fill, and scour followed by fill (active layer) may have been a more significant source of egg mortality than scour, through infiltration of fines (e.g. Platts et al. 1989), increased infiltration of fines following scour (e.g. Lisle 1989, Peterson and Quinn 1996a), or physical entombment if the fill thickness cannot be penetrated by emerging fry (e.g. Koski 1966; Everest et al. 1987; Scrivener and Brownlee 1989). The latter process may be significant in Freshwater Creek, as the average fill thickness at redds was 16 cm (range 5 – 33 cm) (Table 3). I have found little published data on mortality thresholds for physical entombment (e.g. Bams 1969 as cited in Crisp 1993; Crisp 1993), and results of this and another study (DeVries 2000) indicate it may deserve further research.

4.4.2 Model Application to Redds - Results and Discussion

Because there are relatively few scour and fill models applicable to redds and data to test predictions were available from this study, it is also worthwhile to note the accuracy of the Haschenburger model at redd locations (e.g. O'Connor et al. 2001; Railsback and Harvey 2001). Applying the model to scour at redds appears appropriate in Freshwater Creek because (1) the Haschenburger model provided reasonable estimates of mean scour and fill depths and (2) salmon selected spawning locations similar to the reach average scour.

If egg mortality is assumed to occur when scour exceeds the estimated 15 cm depth to the top of coho egg pockets (based on female body length, see section 4.3.1), the model prediction (using equations 3 and 4) that 20 percent of the bed is scoured to depths greater than 15 cm in the upper reach (where spawning occurred) is similar to that measured at redds, where scour was deeper than 15 cm in 2 of 9 redds (22 percent) (redds #1 – 9, Table 4, Figure 12B). Based on the very limited testing in Freshwater Creek, the Haschenburger model appears sufficiently promising for predicting scour-related mortality at salmon redds (e.g. O'Connor et al. 2001; Railsback and Harvey 2001) where reach scour is representative of redd scour (i.e. salmon not selecting low or high scour areas for spawning) to warrant additional testing.

Due to the pattern of aggradation at redd sites, the model predictions of fill and active layer at redd sites were not as reliable, but still promising. Although threshold values for fill- and active layer-related mortality at redds have not been developed, if mortality is assumed to occur at an arbitrary fill or active layer threshold of 15 cm, the model predicts that 20 percent of the redds experience fill of 15 cm or more, while measured fill and active layer depths were 15 cm or greater in 33 percent of the redds (3 of 9 redds) (redds #1 – 9, Table 3, Figure 12B). Because of increased infiltration of fines following scour may be the highest source of egg mortality (e.g. Lisle 1989, Peterson and Quinn 1996a), prediction of the active layer (including the proportions of scour to fill) at redds may be most useful to watershed managers, but may still require knowledge of the discreet scour and fill depths. Further, ascertaining the type of material deposited may be necessary to evaluate all fill impacts at redds, where silt and finer fractions tend to infiltrate redds and fill them from the bottom up, while sand tends to from a bridge at the top of the redds (e.g. Lisle and Lewis 1992).

Because the model testing at redd locations in Freshwater Creek is very limited (based on 9 redds) and additional testing is necessary, caution should be used when applying the model at redd locations. Watershed managers seriously concerned with scour and fill as a source of mortality at redds may consider monitoring a portion of representative redd sites with scour chains or monitors to directly assess impacts (see Schuett-Hames et al. 1999) and possibly collect additional data (Shields stress, form roughness, sediment transport) to further test and improve the model.

5.0 SUMMARY AND CONCLUSIONS

"What have we learned that we can use?"

-William James

The initial objective of this study was to test the Haschenburger model on Freshwater Creek. The model provided a reasonable approximation of mean scour or fill depths (within 4 to 60 percent) for a given flow on Freshwater Creek, however, predicted distributions of scour, fill, or active layer depths were not reliable. Similar to previous studies, the distributions of scour or fill in Freshwater Creek were often right-skewed (negative exponential) distributions, supporting inferences that the majority of streambed remains undisturbed during a flood, while a small portion of the channel scours or fills relatively deeply (Haschenburger 1996) and that small portions of the channel convey major portions of the load (Lisle et al. 2000). However, the distribution of fill depths in the lower reach were more symmetric due to the fairly consistent aggradation experienced over the reach that increased with proximity to the major channel bend and tributary junction at the bottom of the reach. Differences in scour and fill patterns in the upper and lower reaches are probably highly influenced by channel morphology, where the simpler riffle- and plane-bed-dominated lower reach experienced fairly uniform scour and fill, while the more variable bar-dominated upper reach with large wood exhibited a wider range and magnitude of scour and fill depths.

Based on these observations, differences between model-predicted and measured values were likely due to variable patterns of scour and fill in Freshwater Creek that were weakly influenced by Shields stress (e.g. Hales 1999; DeVries 2000) and highly influenced by (1) sediment supply (e.g. DeVries 2000), (2) location within the channel network (e.g. Benda and Dunne 1997; Benda et al. submitted) and proximity to major channel nick points, such as tributary junctions and channel bends (e.g. Lisle 1986; Napolitano 1996; Matthaei 1999; Benda et al. 2003), and (3) channel morphology (form roughness) (e.g. Schuett-Hames et al. 1999). The dominance of sediment supply on scour and fill processes likely increases with storm and flood size (i.e. scale of scour and fill). Consequently, scour and fill models based on shear stress may only be relevant to small-scale scour and fill, such as individual small floods.

Based on application to Freshwater Creek, the Haschenburger model appears best suited for individual flood events on reaches that are straight, in equilibrium between sediment supply and transport, and have roughness elements similar to Carnation Creek, where the model was developed. Further, since the model appears to predict reasonable estimates of mean scour and fill depths, it may be applicable to redds where salmon are not selecting low or high scour areas (i.e. scour at redds is similar to reach-average scour), however, additional testing of the model is needed.

Because scour and fill can be driven by imbalances in sediment transport (Lisle et al. 2000; DeVries 2000), rough estimates of sediment supply and transport may improve scour and fill models and allow their application to a wider range of channel conditions. The net mass sediment balance of a reach (aggrading, degrading, equilibrium) could be estimated by measuring sediment transport at the top and bottom of a reach (T. Lisle, personal communication 2003). This approach may also incorporate influences of reach location within the network, for example, reaches behind a tributary fan or a bedrock bend may aggrade. The scour and fill data collected from that reach could then be used to develop predictions for similar reaches. Because variation in scour and fill from obstruction of flow may be driven by channel form roughness (bed forms, large wood, channel bends, bedrock outcrops, boulders), to apply a scour and fill model between different channels, some characterization of roughness elements that spread flow may be necessary. Researchers may attempt further partitioning of shear stress between bed roughness elements (e.g. Einstein and Banks 1950) or between portions of the channel (e.g. Benson and Dalrymple 1967) to improve prediction of scour and fill, or a simpler approach might include creating a form roughness factor, for example, using the volumetric ratio of roughness elements that obstruct and spread flow (large wood, boulders, bedrock outcrops) within the bankfull channel to the bankfull channel. Alternatively, a “scour multiplier” used by engineers (see Galay et al. 1987) could be applied. The scour and fill data collected from that reach could then be used to develop predictions for similar reaches, and as a data set over a range of different channels evolves, the effects of obstructed and spreading of flow on scour and fill may become more apparent and predictable.

Additionally, a model based on the cumulative distribution could improve precision because all empirical data are represented and limitations from averaging data into bins are circumvented. This would require high resolution measurement of scour and fill using scour chains or sliding bead monitors (e.g. Nawa and Frissell 1993).

Another objective of the study was to enhance understanding of salmon adaptation to scour by testing the hypotheses that (1) redd construction reduces scour, and (2) salmon select low scour areas for spawning. Scour was often deeper at redds ($n = 16$) than the adjacent bed ($p = 0.16$), suggesting that redd construction did not reduce scour, but may have increased scour by loosening the bed and reducing imbrication. While the result is in contrast to theoretical calculations by Montgomery et al. (1996) that indicate redd construction decreases the depth of scour, the close correspondence between scour depths at redds and estimated egg burial depths supports a different hypothesis by Montgomery et al. (1996; 1999) that salmon have adapted to scour by laying their eggs below typical scour depths. However, this later hypothesis cannot be quantitatively assessed, because measurement of egg pocket depth would disturb the bed and influence scour depth (DeVries 2000).

In contrast to a previous hypothesis that salmon may select low scour areas (Yee 1981; Montgomery et. al 1999; DeVries 2000), scour depths at redds ($n = 9$) and random locations within the reach were similar ($p = 0.75$), suggesting that salmon did not select low scour areas for spawning. This result indicates that model predictions of reach-average scour were representative of redd locations. This may also apply to other low gradient channels where the majority of the bed is mobile, but would require further validation. Testing of both hypotheses is based on small sample sizes and further testing with larger sample sizes is needed.

A noteworthy observation of this study was the consistent aggradation of redd sites in Freshwater Creek. Redds were often located in areas of sediment storage, including upstream of channel-spanning log jams and in pool tails. While most studies have focused on scour as a significant source of egg mortality (e.g. Wales and Coots 1954; Seegrist and Gard 1972; Holtby and Healey 1986; Erman et al. 1988), fill may have similar or greater impacts (e.g. Koski 1966; Everest et al. 1987; Platts et al. 1989; Scrivener and Brownlee 1989). While much research has focused on the effects of fine sediment (silt and clay) infiltration into redds (see review by Chapman 1988), there is little data on fill thickness thresholds for physical entombment from coarser fractions (sand) that form a seal near the bed surface (e.g. Bams 1969 as cited in Crisp 1993; Crisp 1993) and additional research is needed, a similar conclusion reached by DeVries (2000). Matthaei et al. (1999) identified a parallel need for research of fill impacts on invertebrates as a result of their study on a gravel-bed river in New Zealand.

> "*This then is my story. I have reread it. It has bits of marrow sticking to it,*
> *and blood, and beautiful bright green flies.*"
>
> *-Vladimir Nabokov*

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Table 1. Physical characteristics and scour and fill sampling measurements of study reaches.

Variable	**Upper Reach**	**Lower Reach**
Reach length (m)	900	840
Drainage area (km^2)	22.5	34.1
Mean Slope	0.011	0.007
Mean Width (m)	13	12
Surface D_{50} (mm)	33/45[a]	44/49[a]
Surface D_{90} (mm)	138	110
Shields Stress (τ_*)	0.14/0.10[a]	0.14/0.08[a]
Grain Shields Stress (τ_{G*})	0.044	0.049
No. cross sections	15	15
No. chains recovered/installed	88/98	60/67

Note:

a Values to the left of the slash include all particles, values to right exclude particles < 8 mm for Haschenburger model predictions.

Table 2. Summary of model constants, inputs, outputs (predictions), and measured values (for comparison).

Variables	Units	Upper Reach	Lower Reach
Model Constants			
Density of water: ρ_w	kg/m^3	1000	1000
Density of sediment: ρ_s	kg/m^3	2800[a]	2800
Reference shields stress: τ_{r*}	--[b]	0.045[c]	0.045
Model Inputs			
Slope: S	%	1.1	0.7
Median surface sediment size: D_{50}	m	0.045	0.049
Hydraulic radius: R	m	0.76	1.07
Model Outputs			
Shields Stress: $\tau_* = (RS\rho_w)/(\rho_s - \rho_w)D_{50}$	--	0.10	0.08
Model parameter: $\theta = 3.33e^{-1.52\tau*/\tau r*}$	--	0.102	0.189
Predicted mean scour/fill depth: $1/\theta$	cm	9.8	5.3
Measured Values			
Mean scour depth	cm	10.6	6.0
Mean fill depth	cm	10.2	13.3
Mean active layer depth	cm	14.7	14.3

Note:

[a] Typical value for metasedimentary and metamorphic rocks, which comprise the majority of the that substrate in the upper and lower study reaches.

[b] No units/dimensionless.

[c] Reference shields stress value for incipient motion used by Haschenburger (1999).

Table 3. Summary of statistical hypotheses testing results.

Null Hypothesis (and Statistical Test)	**Parameter**	**n**	**Mean (cm)**	**σ (cm)**	**Probability of Similarity (P-value)[a]**
Redd construction does not affect scour (paired t-test)	redd scour	16	10.0	5.4	0.16
	control scour	16	7.8	6.1	
	difference	16	2.3	6.2	
Scour is not a factor in redd site selection (t-test)	reach scour	91	10.6	12.5	0.75
	control scour	34	11.1	5.9	
Redds are not prone to aggradation (paired t-test)	redd scour	16	10.0	5.4	0.04
	redd fill	16	16.0	8.0	
	difference	16	6.0	10.7	
Redds are not prone to aggradation (t-test)	reach fill	93	10.2	8.3	0.12
	control fill	9	13.6	5.5	

Note:

[a] Paired and unpaired two-tailed t-tests were used assuming unequal and unknown variances.

Table 4. Scour and fill depths at redds and adjacent bed (control). Values shown are an average of two chains, except where only one redd or control chain was recovered. Redds numbered 1-9 were within the upper reach; redds numbered 10-16 were above or below the upper reach.

Redd No.	Species[a]	Unit	Date Installed	Distance on Reach (m)	Ave Redd Scour (cm)	Ave Control Scour (cm)	Ave Redd Fill (cm)	Ave Control Fill (cm)
1	coho	pool tail	1/5/00	281	13	17	27	22
2	chinook	pool tail	1/5/00	393	13	4	15	12
3	unknown	pool tail	1/5/00	229	8	16	10	22
4	unknown	pool tail	1/6/00	396	16[b]	11	26	11
5	unknown	riffle	1/6/00	683	12	17	5	10
6	unknown	riffle	1/6/00	737	12	4	12	5
7	unknown	pool tail	2/6/00	228	17[b]	16	15	11
8	unknown	pool tail	2/6/00	280	10	12	13	15
9	unknown	pool tail	2/6/00	396	12	6	12	14
10	unknown	pool tail[c]	2/6/00	--	0	0	23	22
11	coho	pool tail[c]	2/6/00	--	0	0	33	30
12	coho	pool tail[c]	2/8/00	--	14	5	9	12
13	coho	pool tail[c]	2/8/00	--	5	5	13	11
14	unknown	pool tail	2/8/00	--	13	0	24	24
15	unknown	pool tail	2/10/00	--	12	5	8	10
16	coho	pool tail	2/10/00	--	2	7	11	15

Notes:

a Although the majority of redds sampled were not positively identified by species (either chinook or coho), the vast majority of fish observed in the upper reach were coho.

b Scour depth exceeded 15 cm estimated average depth to top of coho egg pocket using the relation between coho female body size and egg burial depth (van den Berghe and Gross 1984). Data on average female body size for Freshwater Creek provided by Humboldt Fish Action Council (unpublished data, 2001).

c Unit is within a wedge of sediment behind a channel-spanning log jam.

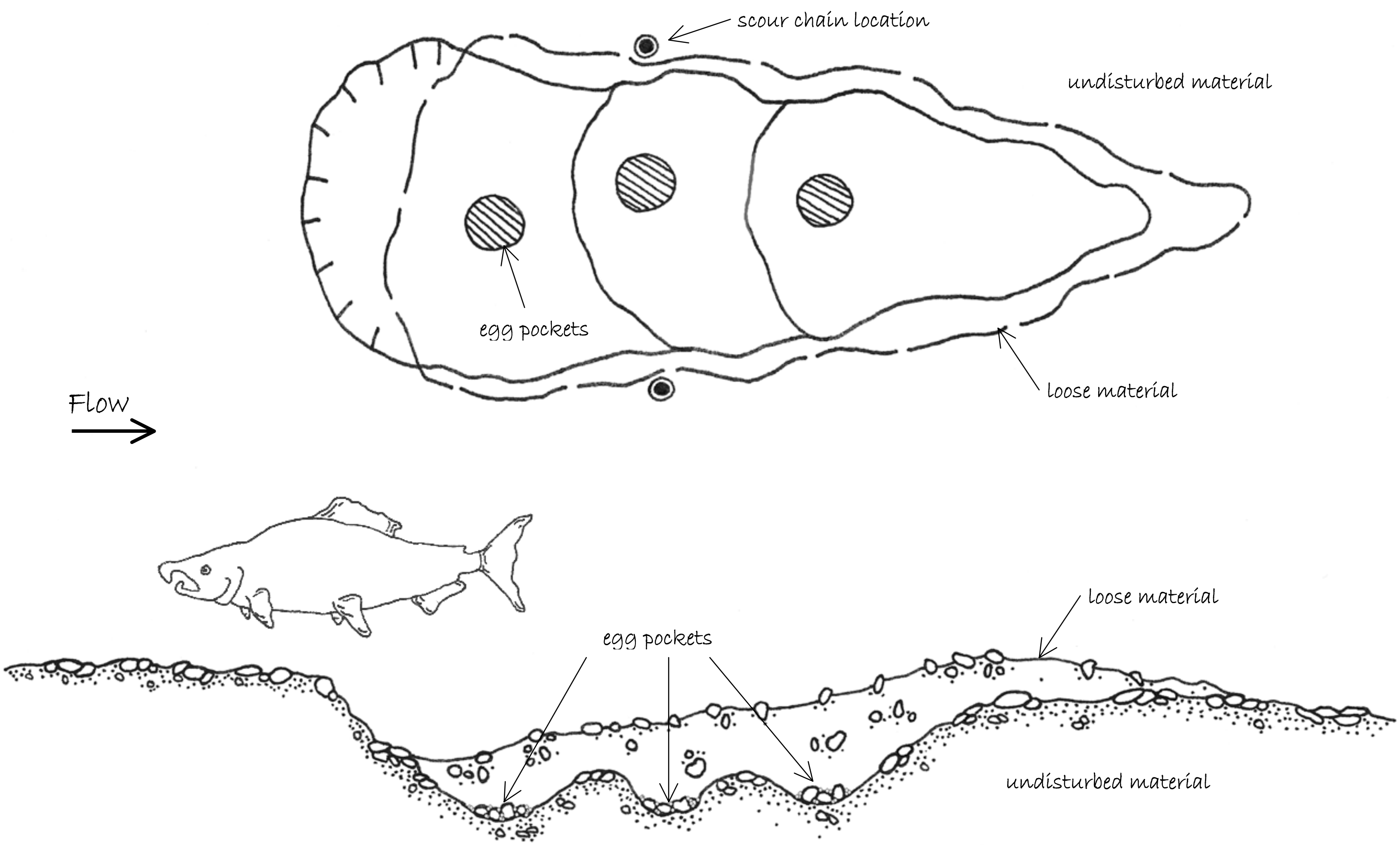


Figure 1. Diagram of typical salmon redd showing plan view (top) and cross sectional view (bottom). Adapted from Chapman (1988) and Rennie and Millar (2000).

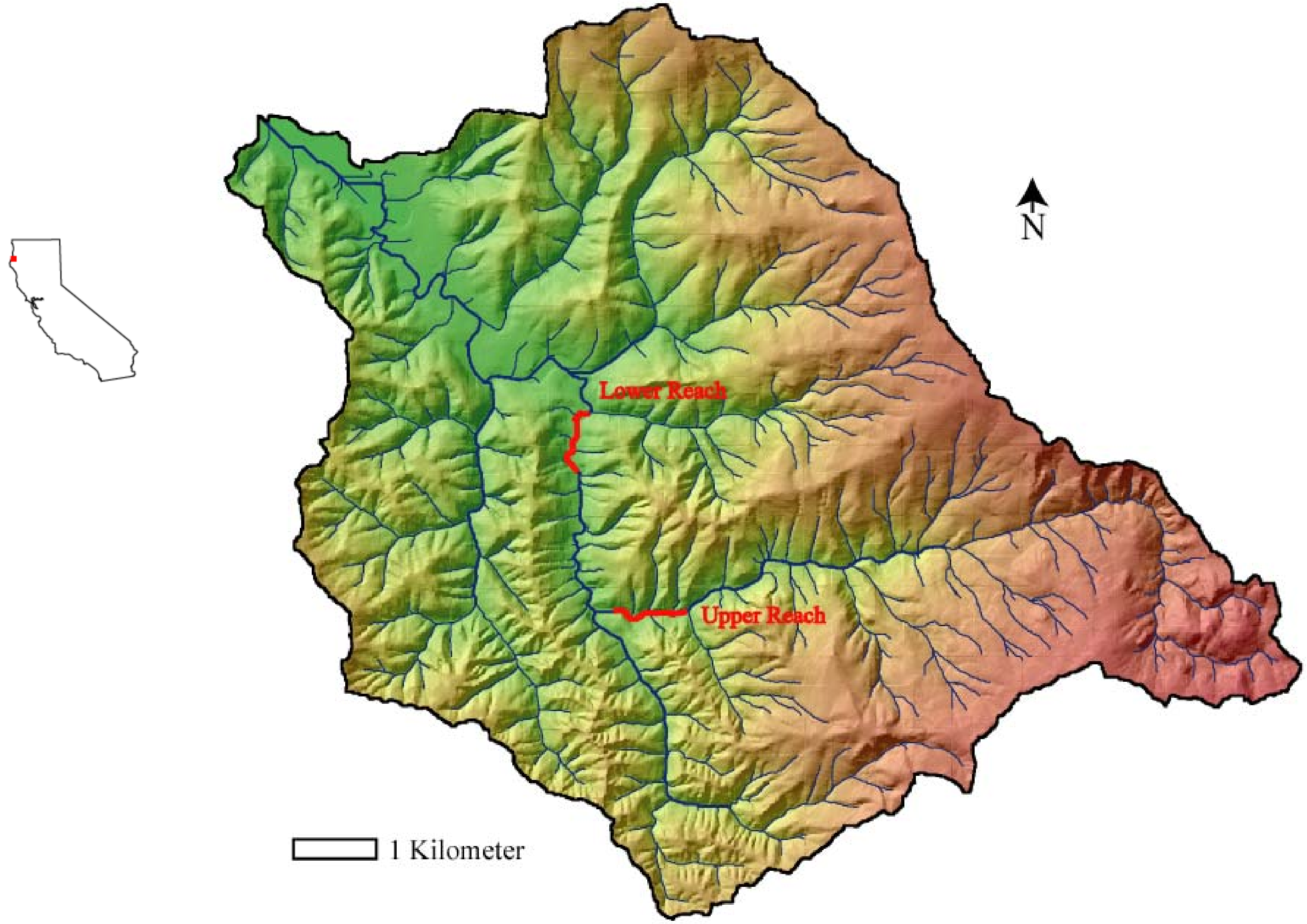


Figure 2. Freshwater Creek watershed and study reach locations, Humboldt County, California.

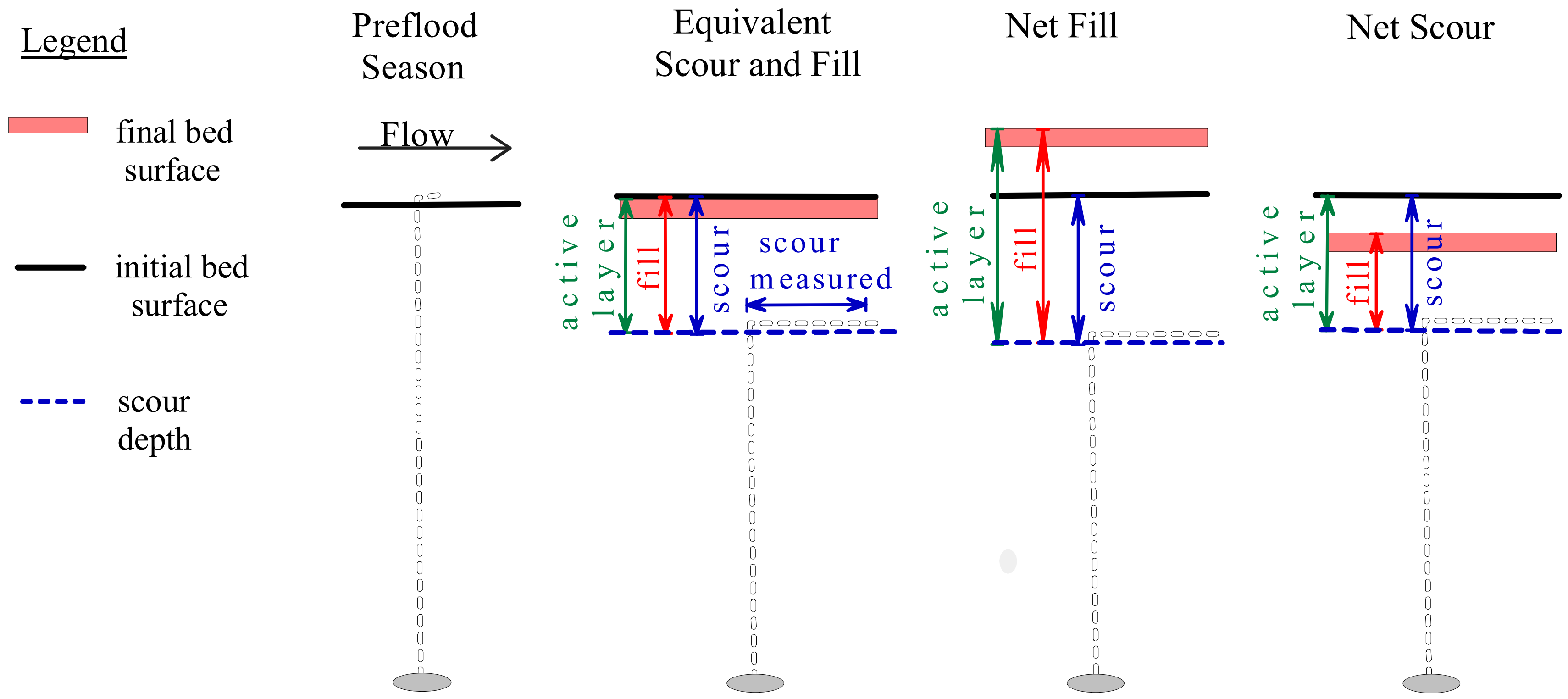
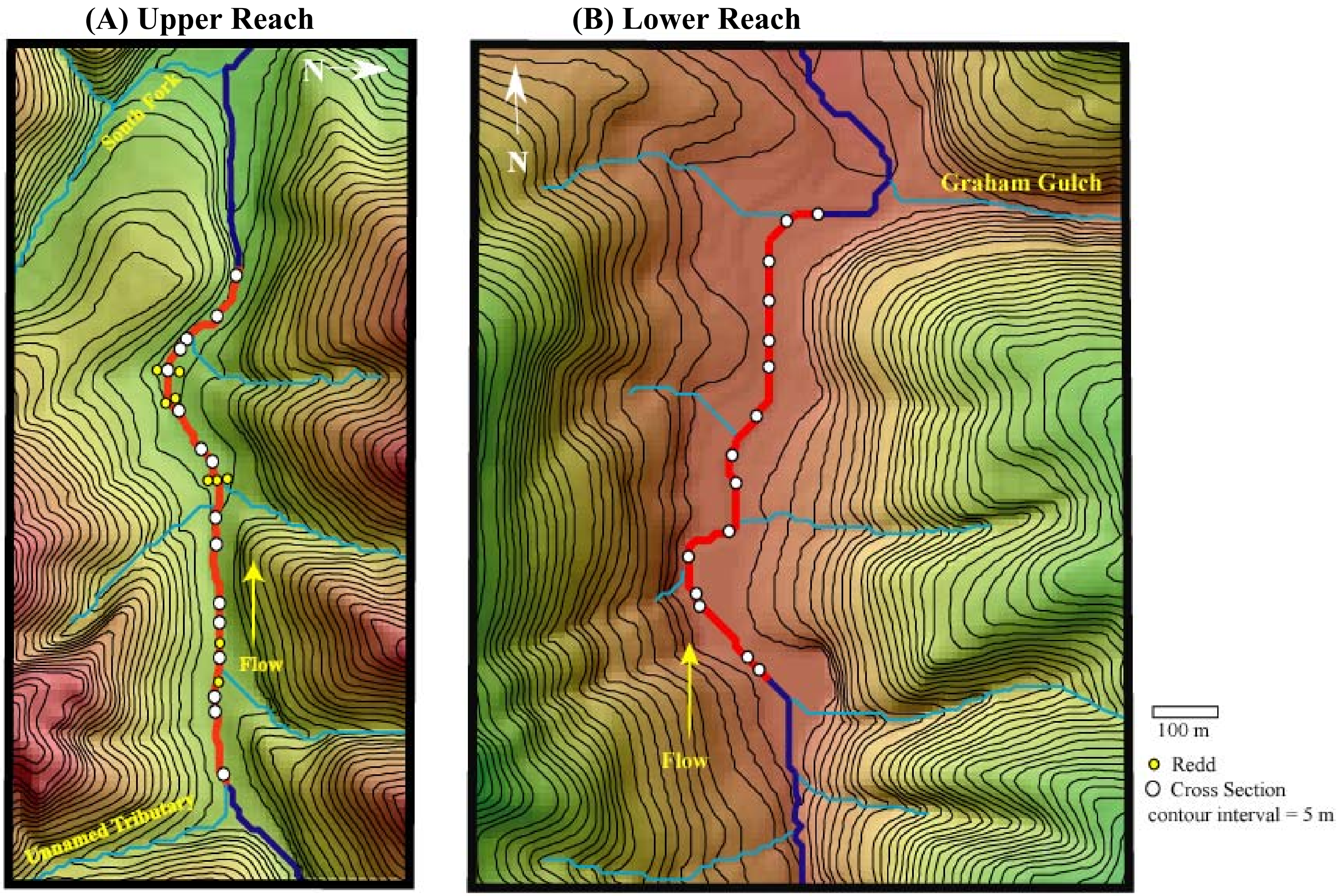


Figure 3. Streambed cross section showing how scour, fill, and the active layer are measured using scour chains under different conditions.

(A) Upper Reach

(B) Lower Reach

Figure 4. Representative photographs of the (A) bar-dominated upper and (B) riffle- and plane bed-dominated lower reach.


(A) Upper Reach

(B) Lower Reach

Figure 5. Topographic maps of the (A) upper and (B) lower reach showing approximate cross section and redd locations.

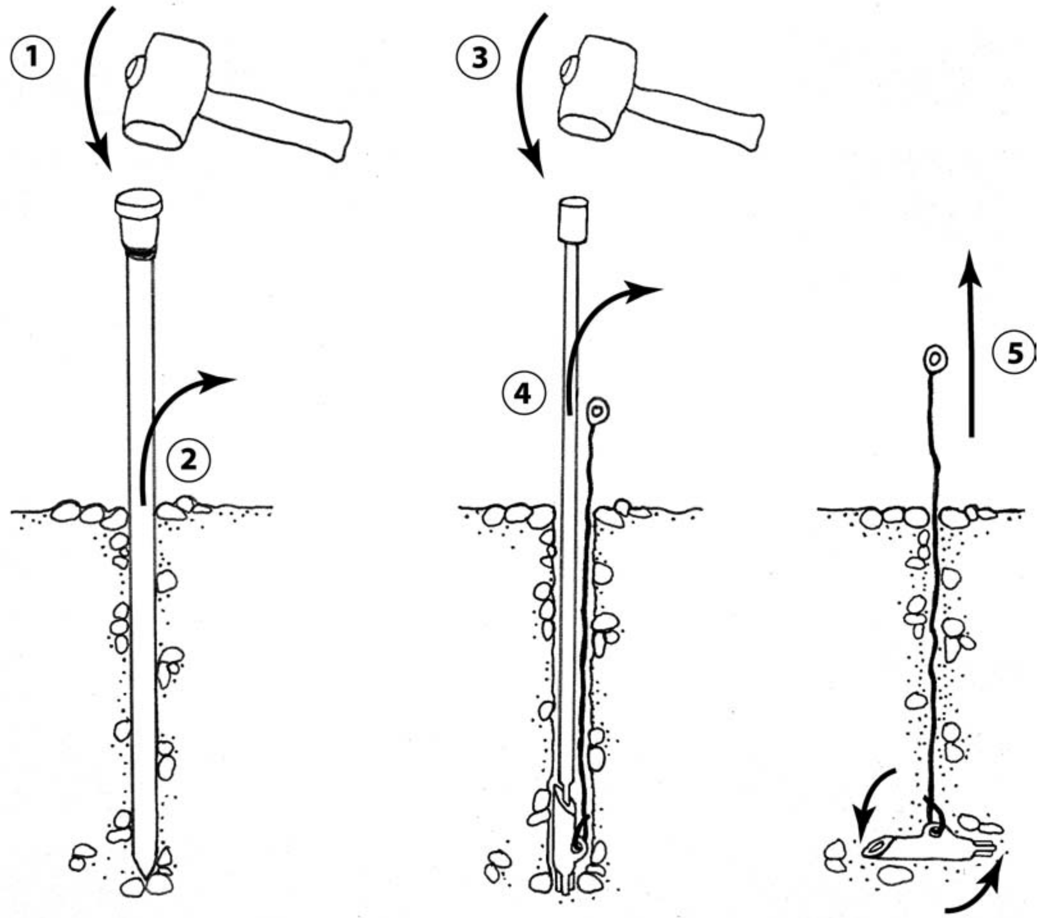


Figure 6. Streambed cross section showing scour chain installation steps: (1) create pilot hole with sledge hammer and drive rod, (2) remove drive rod, (3) insert smaller probe with scour chain attached and tap to bottom with hammer, (4) remove smaller probe, and (5) pull chain upward to rotate duckbill into a horizontal position, creating an anchor.

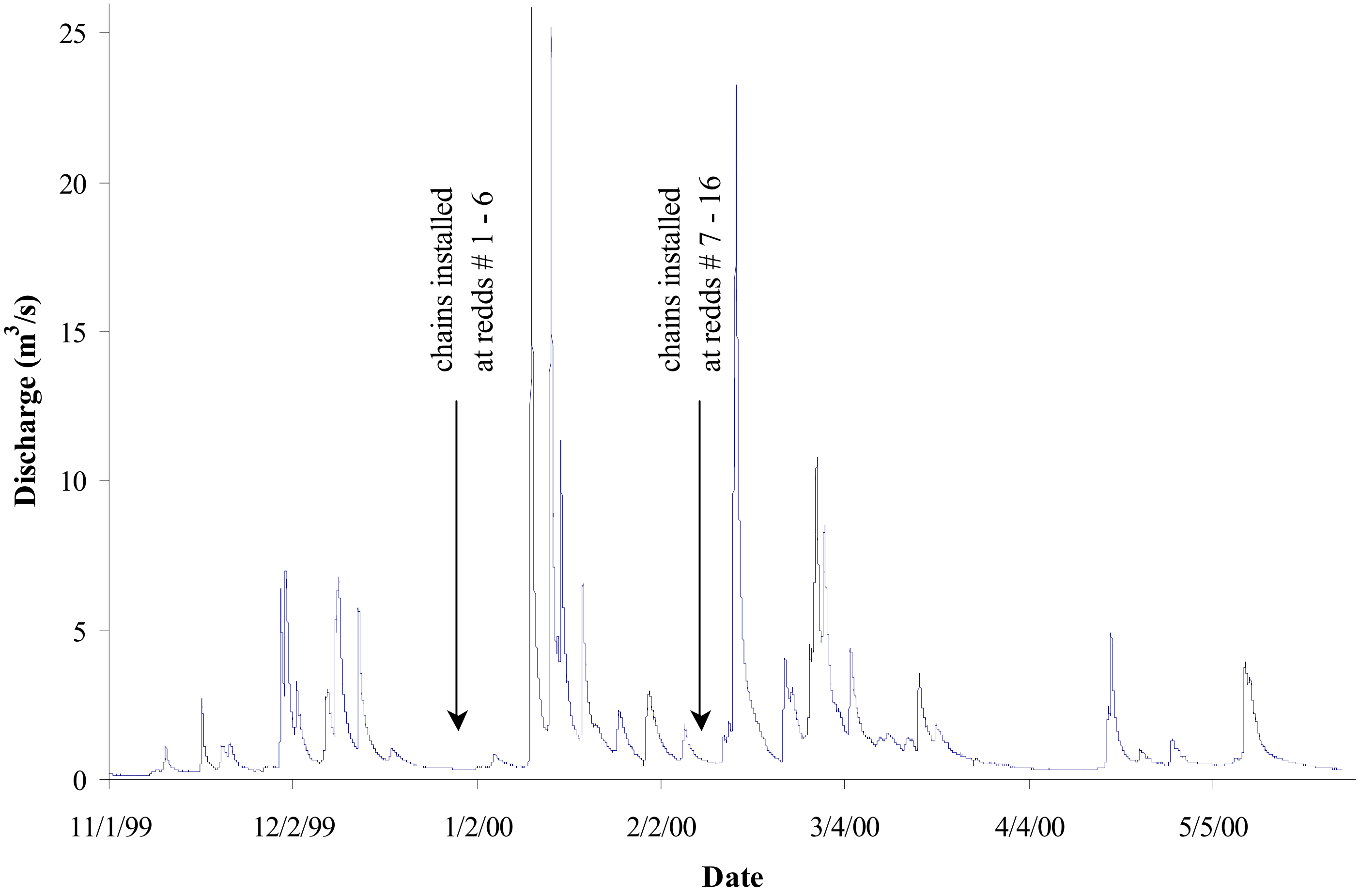


Figure 7. Discharge in Freshwater Creek from November 1, 1999 to May 30, 2000, recorded at the Salmon Forever (2001) gauge at the bottom of the lower reach.

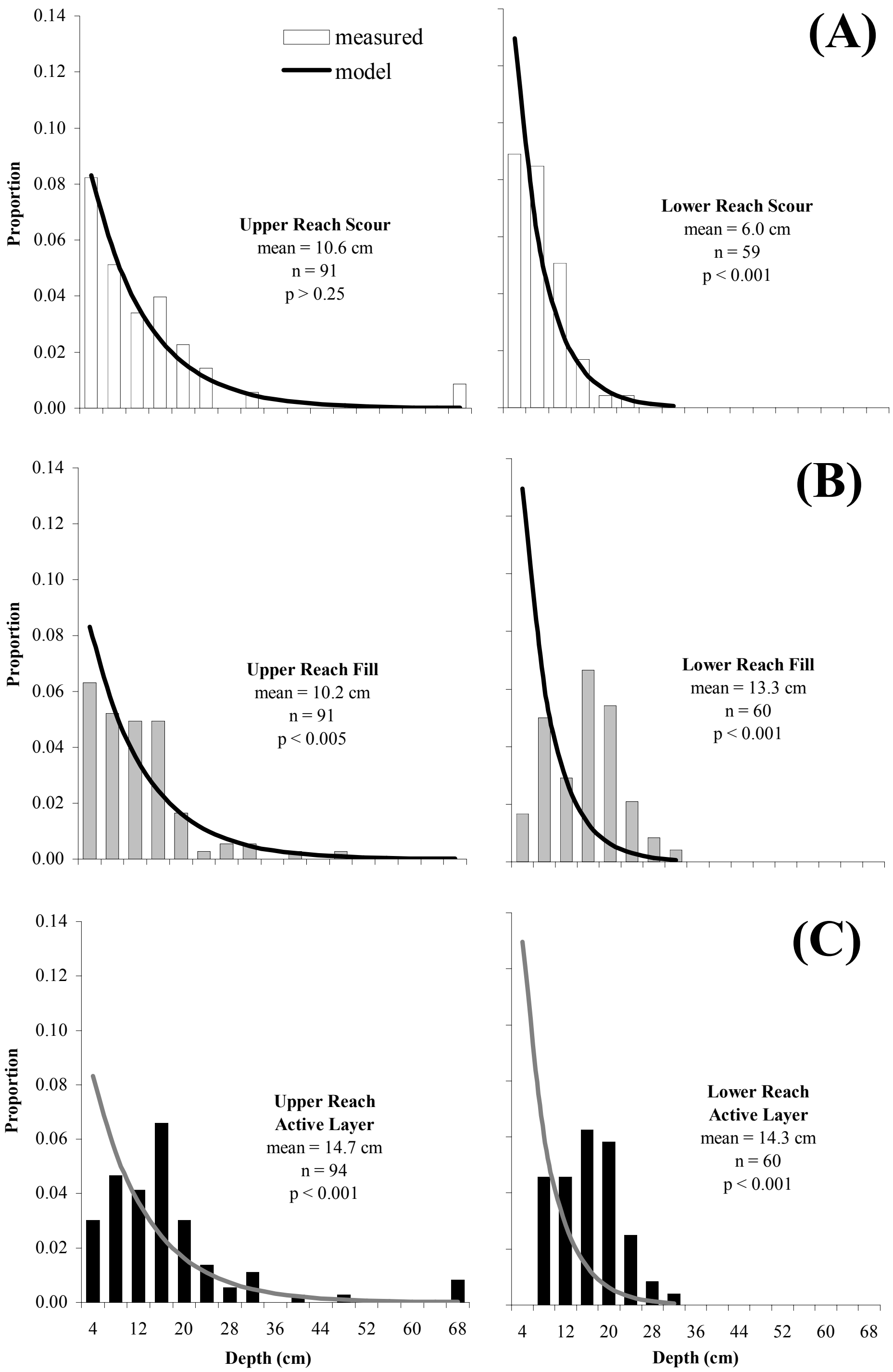
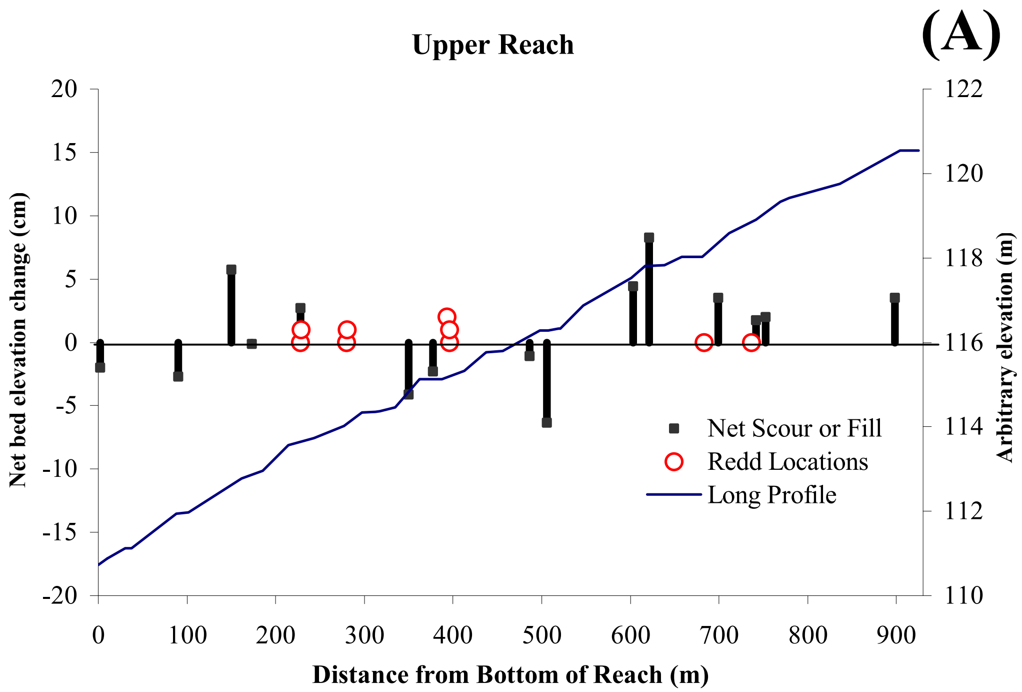


Figure 8. Modified relative frequency histograms of measured and predicted (A) scour, (B) fill, and (C) active layer depths for the upper and lower reach. Measured values are in bins, model predictions are shown by line. Histograms are modified by dividing the relative frequency of each bin by the bin interval (Olkin et al. 1980). P-value is the probability of similarity between measured and model predicted distributions.



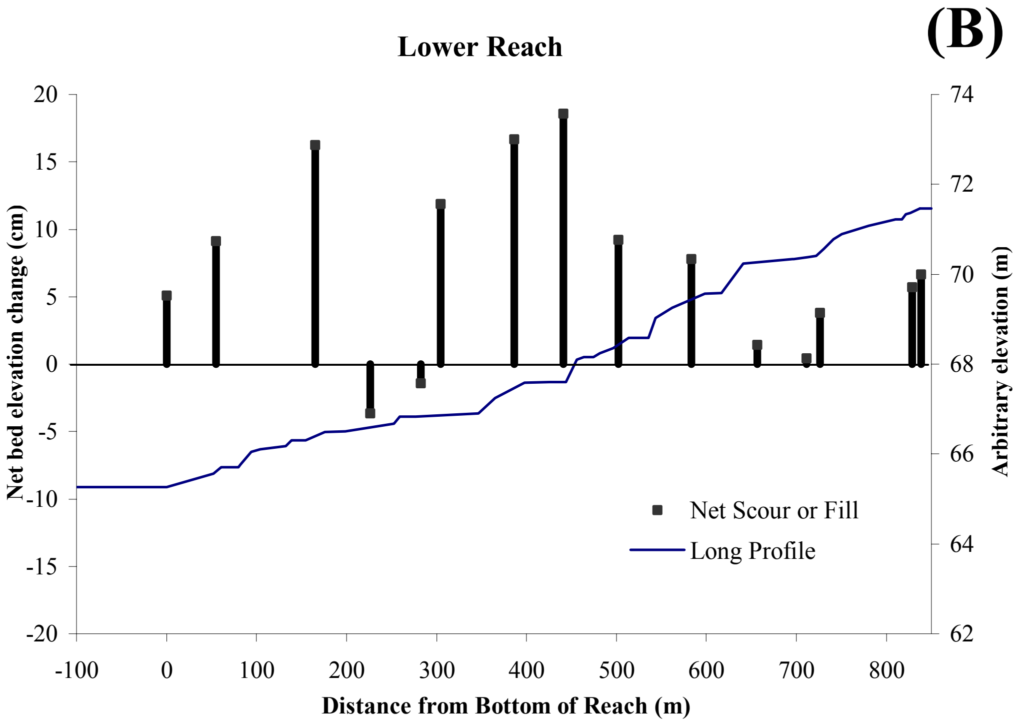


Figure 9. Average streambed elevation change at each cross section (left y-axis) and low flow water surface profile (right y-axis) for the (A) upper and (B) lower reach. Bed elevation change is based on an average of six and four scour chains per cross section on the upper and lower reaches, respectively.

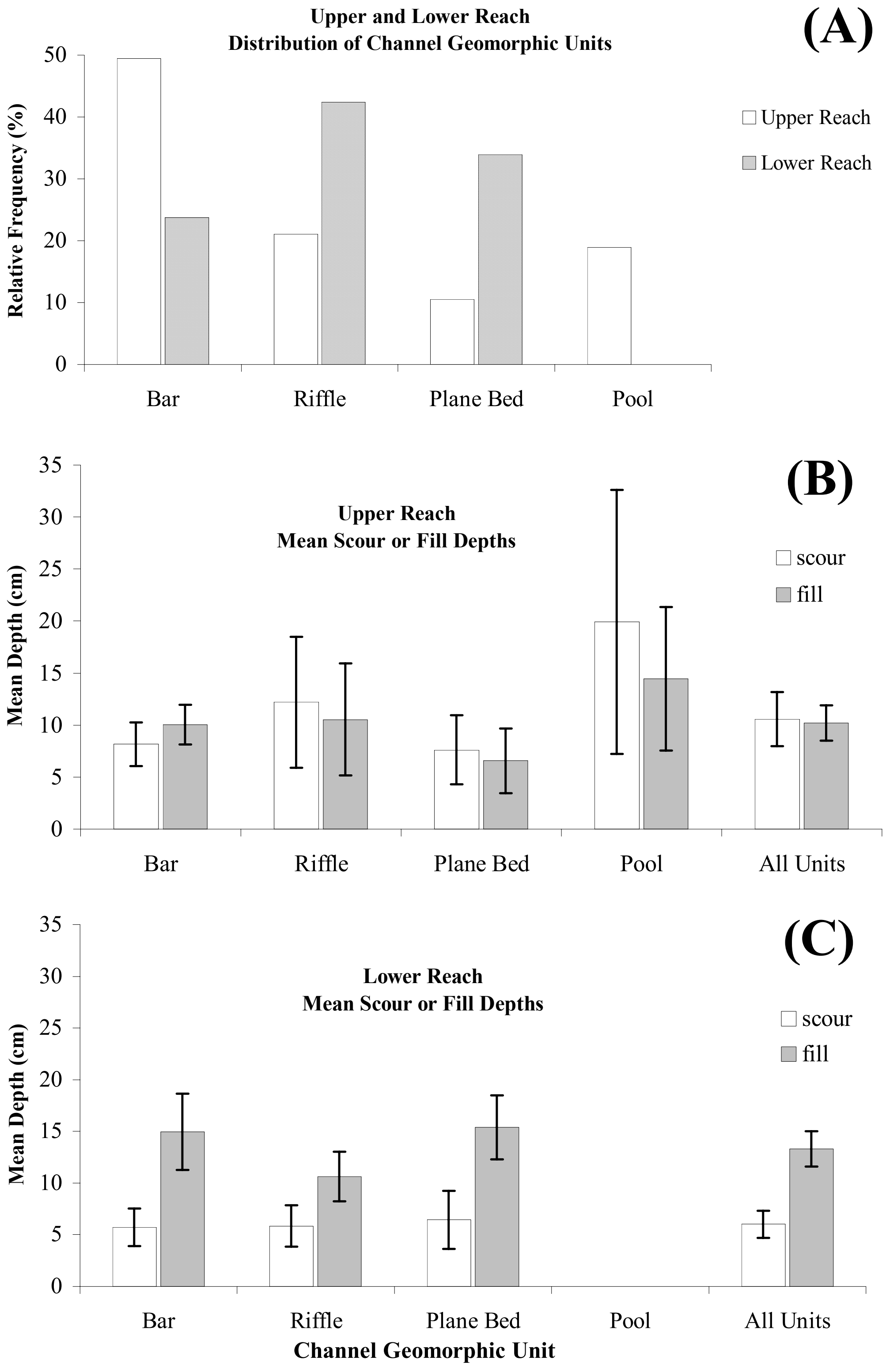


Figure 10. Distribution of (A) channel geomorphic units in both reaches and mean scour or fill depths (and 95% confidence interval) within each unit on the (B) upper reach and (C) lower reach.

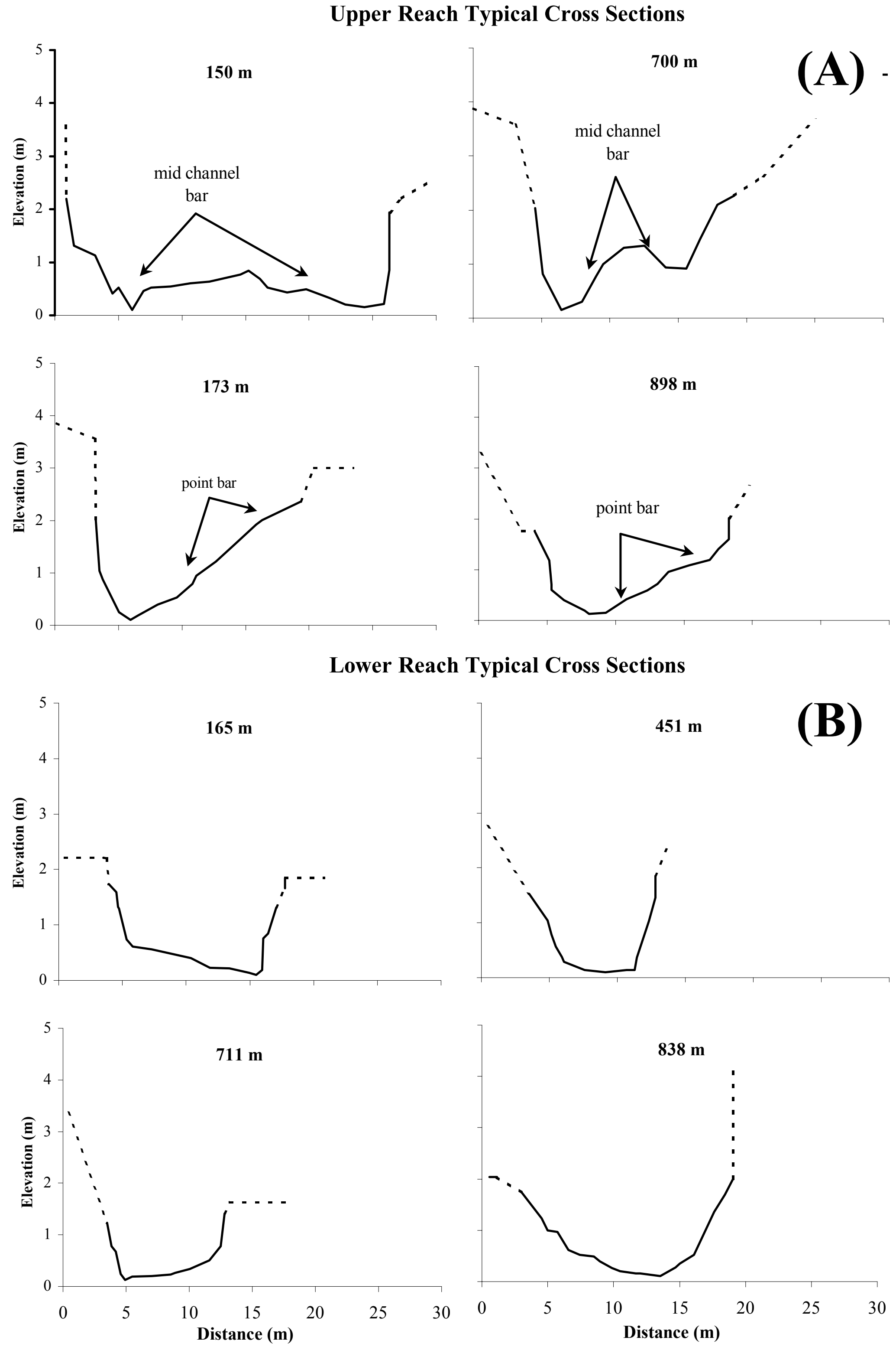
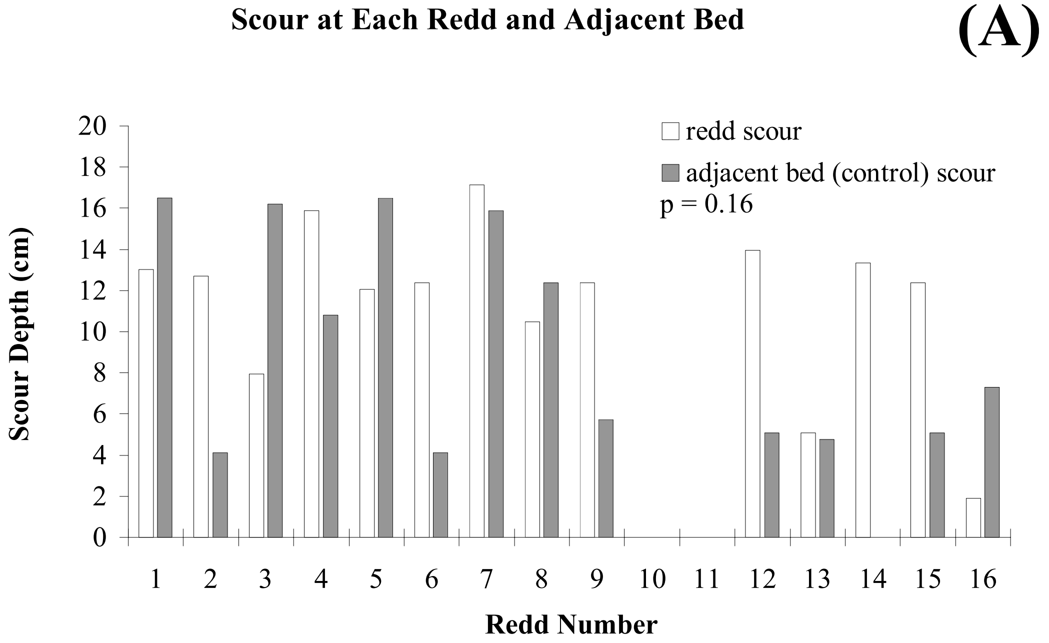


Figure 11. Typical cross sections of the (A) bar-dominated upper reach and (B) riffle- and plane bed-dominated lower reach. Title on each cross section denotes its distance from the bottom of the reach.



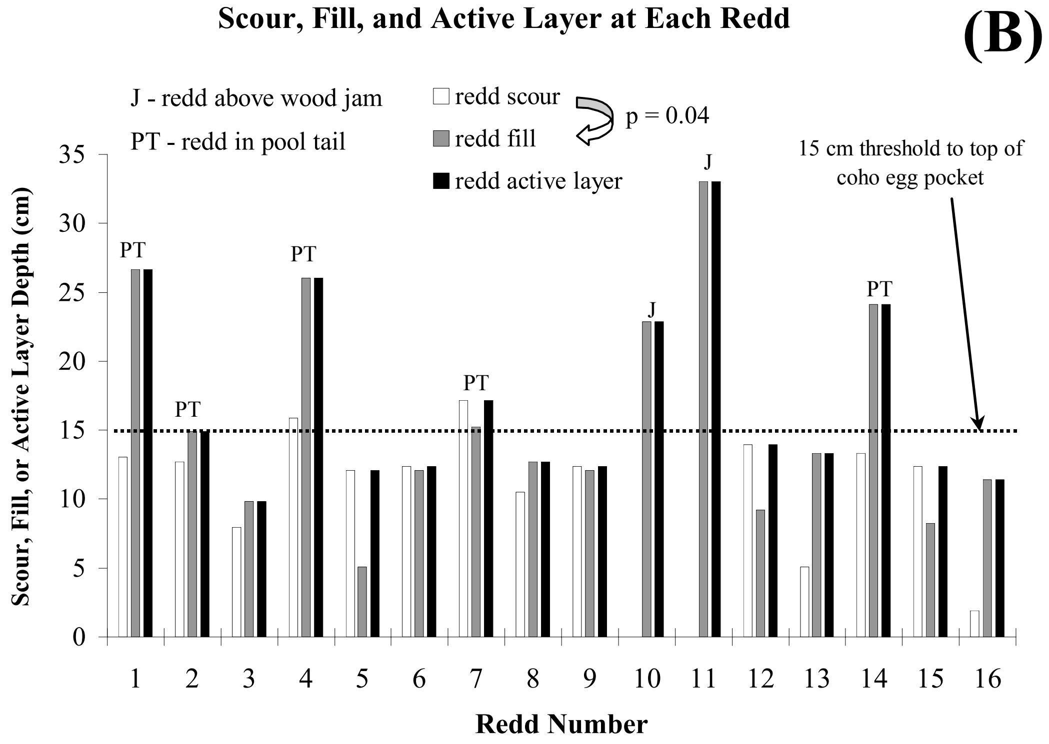


Figure 12. (A) Scour depths at each redd and adjacent bed (control) locations and (B) scour, fill, and active layer depths at each redd. Redds numbered 1 - 9 were within the upper reach; redds numbered 10 - 16 were above or below the upper reach.

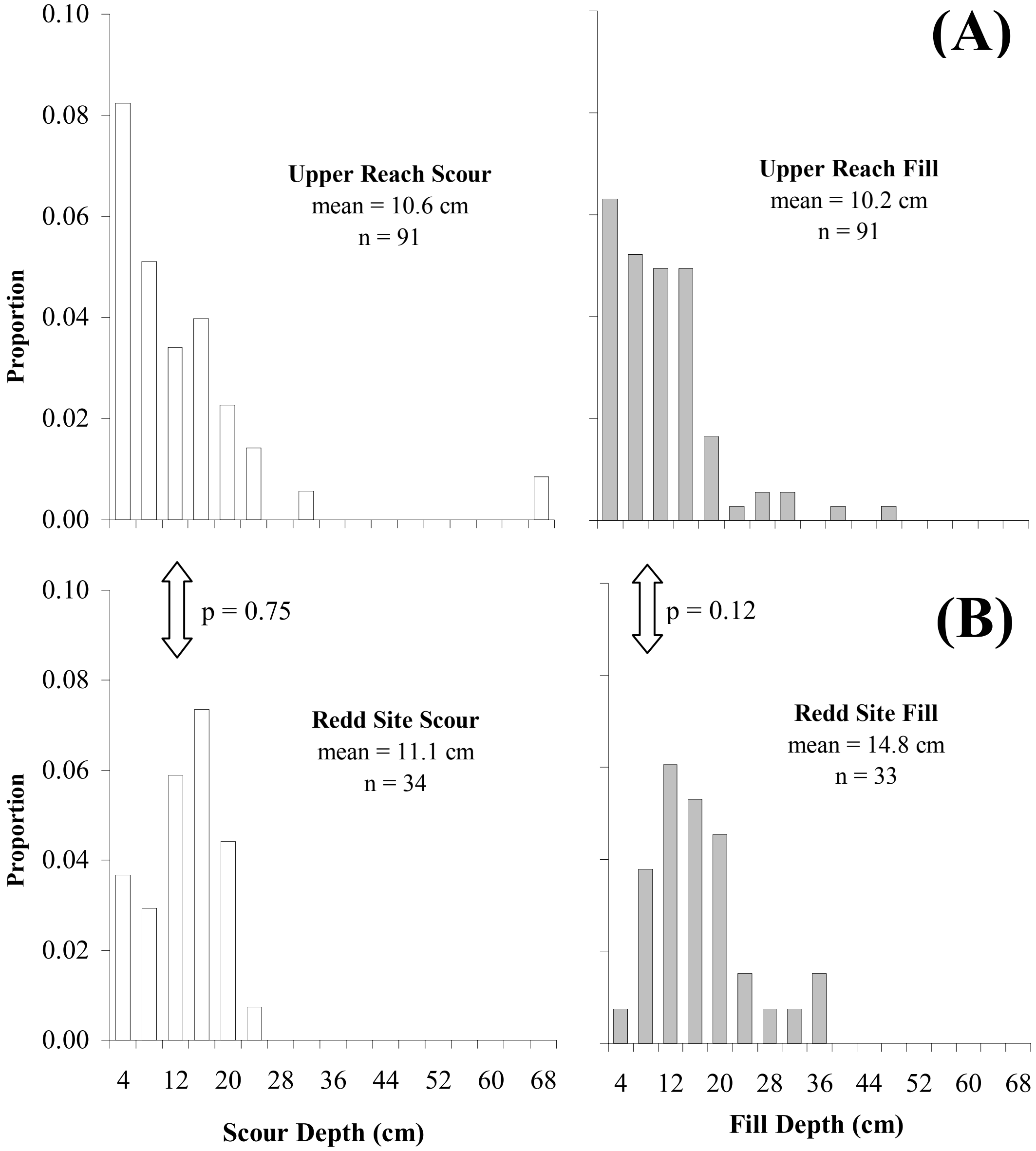


Figure 13. Modified relative frequency histograms of scour or fill depths for the (A) upper reach and (B) redd sites (9 redds, 33 to 34 chains at redd and control locations) within the upper reach. Histograms are modified by dividing the relative frequency of each bin by the bin interval (Olkin et al. 1980). P-value is the probability of similarity between distributions.

Figure 14. Example of Freshwater Creek spawning area prone to aggradation from sediment storage behind channel-spanning log jam.

Appendix A. Evaluation of cross section flood stage data.

Cross Section Location[a] (m)	Stage Flood Mark (m)	Estimated Mean Water Depth[b] (m)	Estimated Discharge[b] (m^3/s)	Measured Discharge[c] (m^3/s)	Difference[d] (%)
Upper Reach					
-20	1.56	1.10	35.8	17.0	111
603	1.32	0.73[e]	17.7	17.0	4
621	2.78	1.25	52.6	17.0	210
742	2.29	1.43	85.8	17.0	405
752	1.19	0.76[e]	14.7	17.0	13
Lower Reach					
55	1.64	1.04[e]	27.0	25.9	4
165	2.26	1.19	58.5	25.9	126
227	2.01	1.37	62.4	25.9	141
270	1.62	1.04[e]	22.4	25.9	14
283	1.68	1.10	40.7	25.9	57
387	2.48	1.68	68.5	25.9	165
451	2.17	1.34	38.4	25.9	48
583	2.12	1.31	48.5	25.9	87
726	1.71	1.13[e]	27.3	25.9	5

Notes:

[a] Cross section location in meters from bottom of the reach.

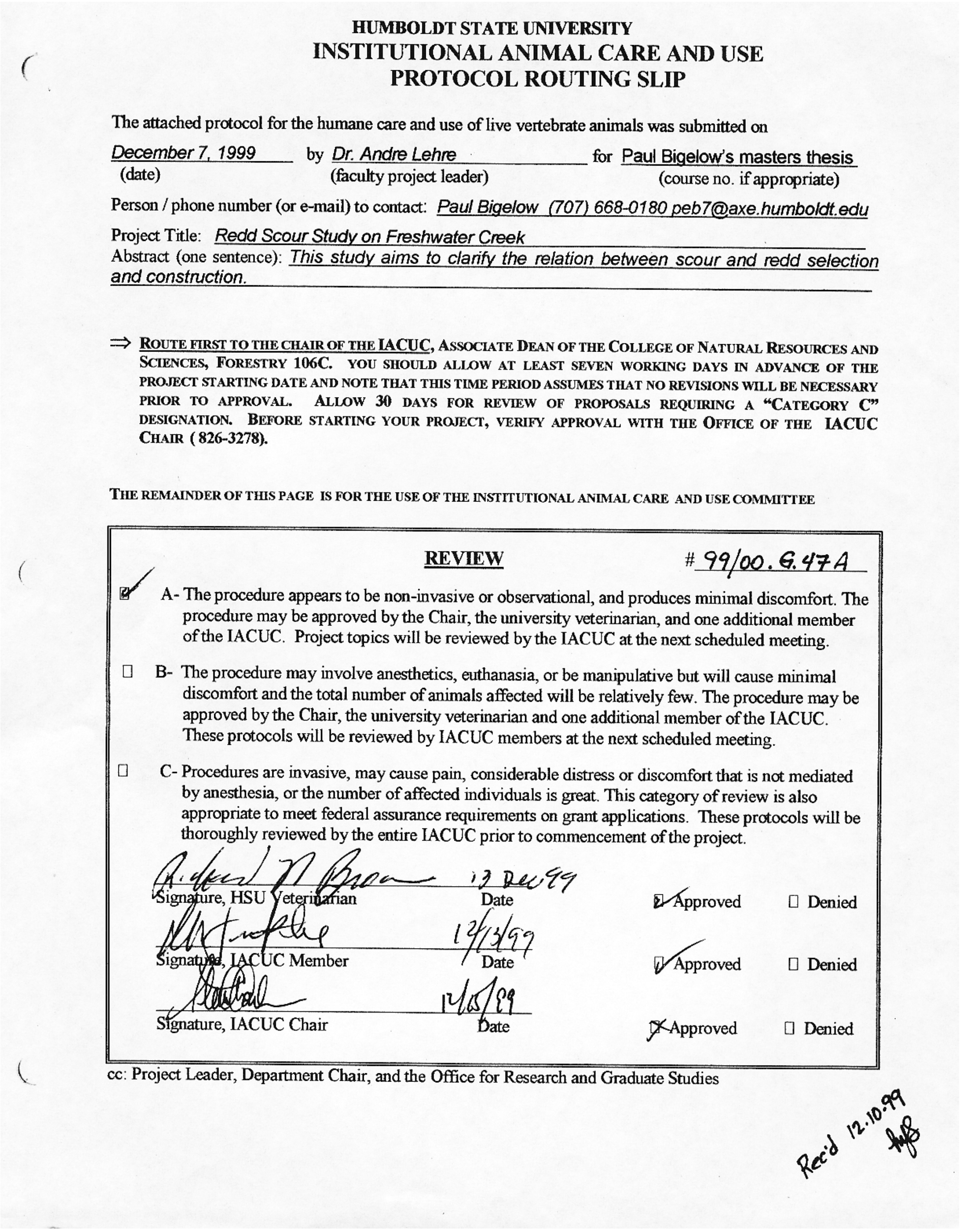
[b] Estimated with WinXSPro (U.S. Forest Service 1997) using surveyed cross section data, stage flood mark (leaf litter), and reach-average water slope derived from survey. Roughness at each cross section was estimated using Jarret's equation within the WinXSPro program.

[c] Discharge on lower reach was measured at a gage operated by Salmon Forever (2001); discharge on upper reach was estimated by prorating the lower reach discharge by drainage area.

[d] Difference between estimated and measured discharge.

[e] Mean water depth (hydraulic radius) value used in reach average calculation. Flood marks that gave discharge estimates 40 percent higher than the measured discharge were excluded from the reach-average water depth calculation.

Appendix B. Humboldt State University Institutional Animal Care and Use Committee protocol approval.



HUMBOLDT STATE UNIVERSITY
INSTITUTIONAL ANIMAL CARE AND USE
PROTOCOL ROUTING SLIP

The attached protocol for the humane care and use of live vertebrate animals was submitted on

December 7, 1999 (date) by *Dr. Andre Lehre* (faculty project leader) for Paul Bigelow's masters thesis (course no. if appropriate)

Person / phone number (or e-mail) to contact: *Paul Bigelow (707) 668-0180 peb7@axe.humboldt.edu*

Project Title: *Redd Scour Study on Freshwater Creek*

Abstract (one sentence): *This study aims to clarify the relation between scour and redd selection and construction.*

⇒ **ROUTE FIRST TO THE CHAIR OF THE IACUC, ASSOCIATE DEAN OF THE COLLEGE OF NATURAL RESOURCES AND SCIENCES, FORESTRY 106C. YOU SHOULD ALLOW AT LEAST SEVEN WORKING DAYS IN ADVANCE OF THE PROJECT STARTING DATE AND NOTE THAT THIS TIME PERIOD ASSUMES THAT NO REVISIONS WILL BE NECESSARY PRIOR TO APPROVAL. ALLOW 30 DAYS FOR REVIEW OF PROPOSALS REQUIRING A "CATEGORY C" DESIGNATION. BEFORE STARTING YOUR PROJECT, VERIFY APPROVAL WITH THE OFFICE OF THE IACUC CHAIR (826-3278).**

THE REMAINDER OF THIS PAGE IS FOR THE USE OF THE INSTITUTIONAL ANIMAL CARE AND USE COMMITTEE

REVIEW # 99/00.G.47A

☑ A- The procedure appears to be non-invasive or observational, and produces minimal discomfort. The procedure may be approved by the Chair, the university veterinarian, and one additional member of the IACUC. Project topics will be reviewed by the IACUC at the next scheduled meeting.

☐ B- The procedure may involve anesthetics, euthanasia, or be manipulative but will cause minimal discomfort and the total number of animals affected will be relatively few. The procedure may be approved by the Chair, the university veterinarian and one additional member of the IACUC. These protocols will be reviewed by IACUC members at the next scheduled meeting.

☐ C- Procedures are invasive, may cause pain, considerable distress or discomfort that is not mediated by anesthesia, or the number of affected individuals is great. This category of review is also appropriate to meet federal assurance requirements on grant applications. These protocols will be thoroughly reviewed by the entire IACUC prior to commencement of the project.

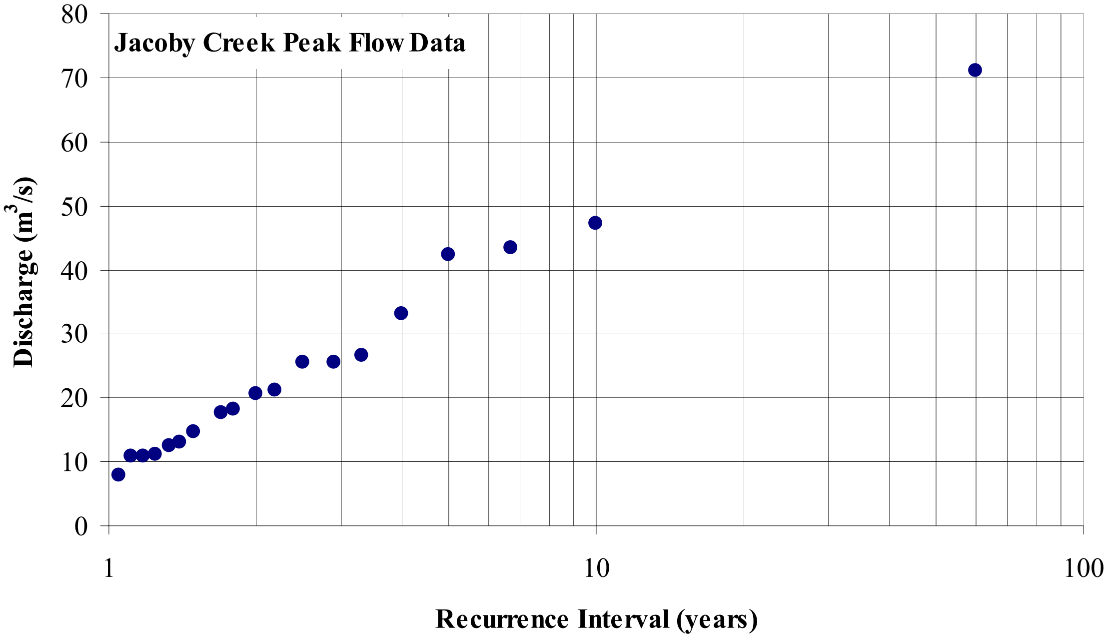
Signature, HSU Veterinarian	13 Dec 99 Date	☑ Approved	☐ Denied
Signature, IACUC Member	12/13/99 Date	☑ Approved	☐ Denied
Signature, IACUC Chair	12/10/99 Date	☒ Approved	☐ Denied

cc: Project Leader, Department Chair, and the Office for Research and Graduate Studies

Rec'd 12.10.99

Appendix C. Estimated flood recurrence intervals for Freshwater Creek based on prorating peak discharges of nearby Jacoby Creek.

Water Year	Jacoby Creek Peak Discharge[b] (m^3/s)	Freshwater Creek Prorated[c] Peak Discharge (m^3/s)	Rank	Recurrence Interval (years)
1972	71.1	154.2	1	25 - 100
1955	47.3	102.6	2	10
1965	43.3	94.0	3	6.7
1956	42.2	91.6	4	5.0
1974	33.1	71.9	5	4.0
1971	26.5	57.5	6	3.3
1964	25.5	55.3	7	2.9
1970	25.4	55.1	8	2.5
1959	21.2	46.0	9	2.2
1958	20.6	44.8	10	2.0
1960	18.2	39.6	11	1.8
1969	17.7	38.5	12	1.7
1957	14.6	31.7	13	1.5
1966	13.1	28.5	14	1.4
1963	12.6	27.4	15	1.33
1962	11.0	23.9	16	1.25
1967	10.8	23.4	17	1.18
1968	10.8	23.4	18	1.11
1961	7.8	17.0	19	1.05



Appendix C. (Continued) Estimated flood recurrence intervals for Freshwater Creek based on prorating peak discharges of nearby Jacoby Creek.

Date	**Freshwater Creek Peak Discharge[d] (m^3/s)**	**Estimated Recurrence Interval (years)**
January 11, 2000	25.9	1.3
January 14, 2000	25.2	1.3
February 14, 2000	23.2	1.1

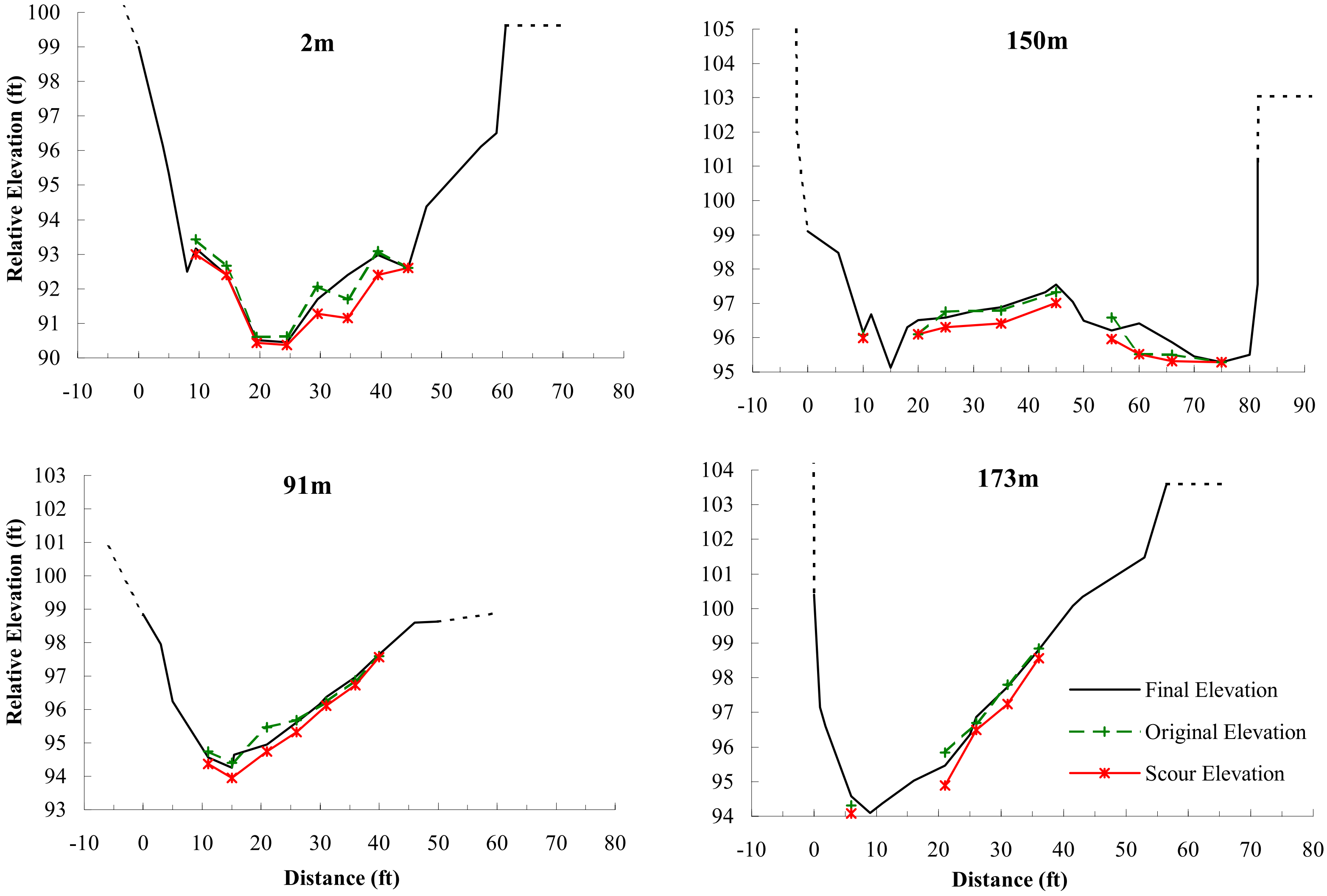
Notes:

a Jacoby Creek is a basin immediately north of Freshwater Creek.

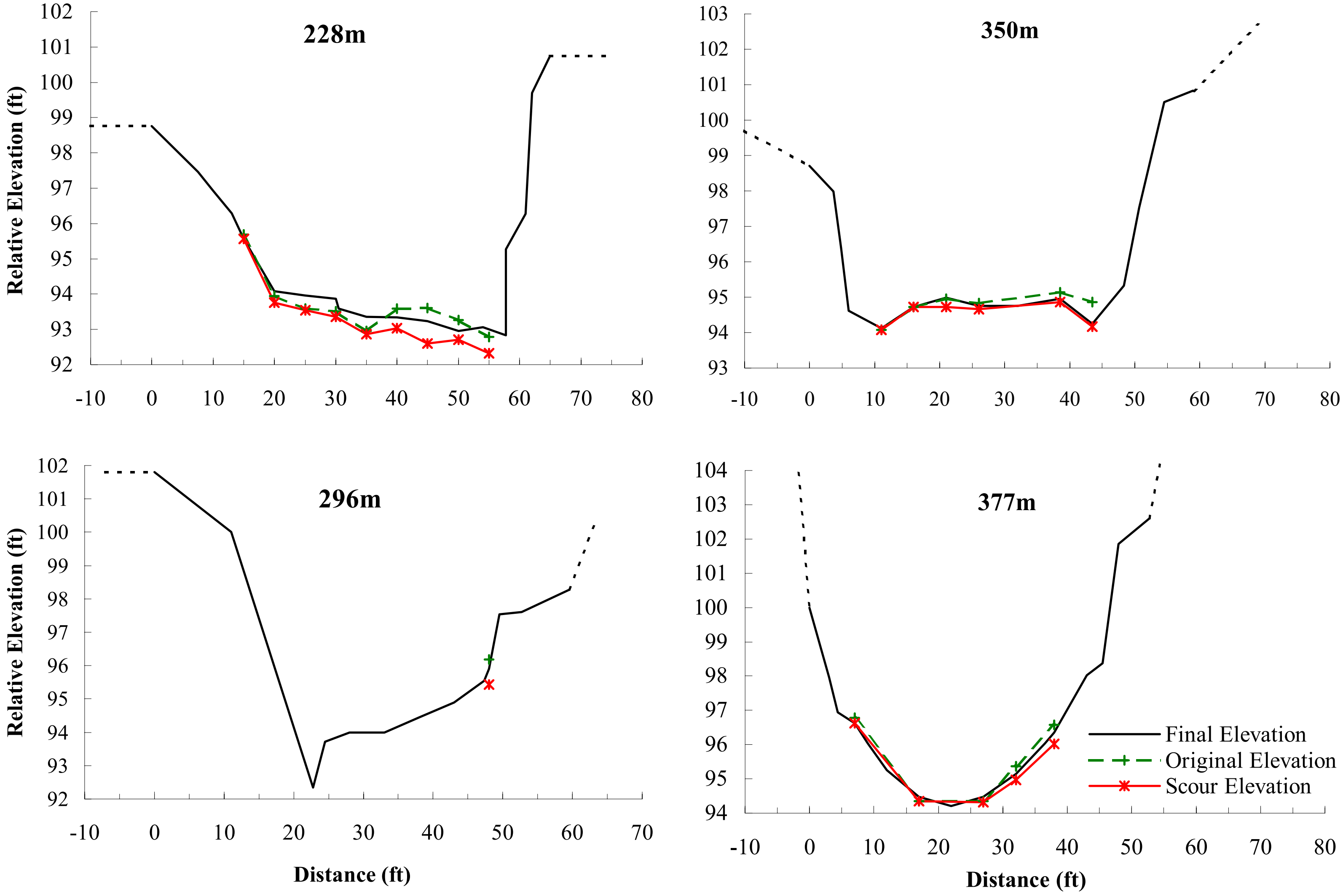
b source: U.S. Geological Survey, available at www.usgs.gov.

c prorated by gage drainage area ratio (2.17) of Freshwater Creek (34.1 km2) to Jacoby Creek (15.7 km2).

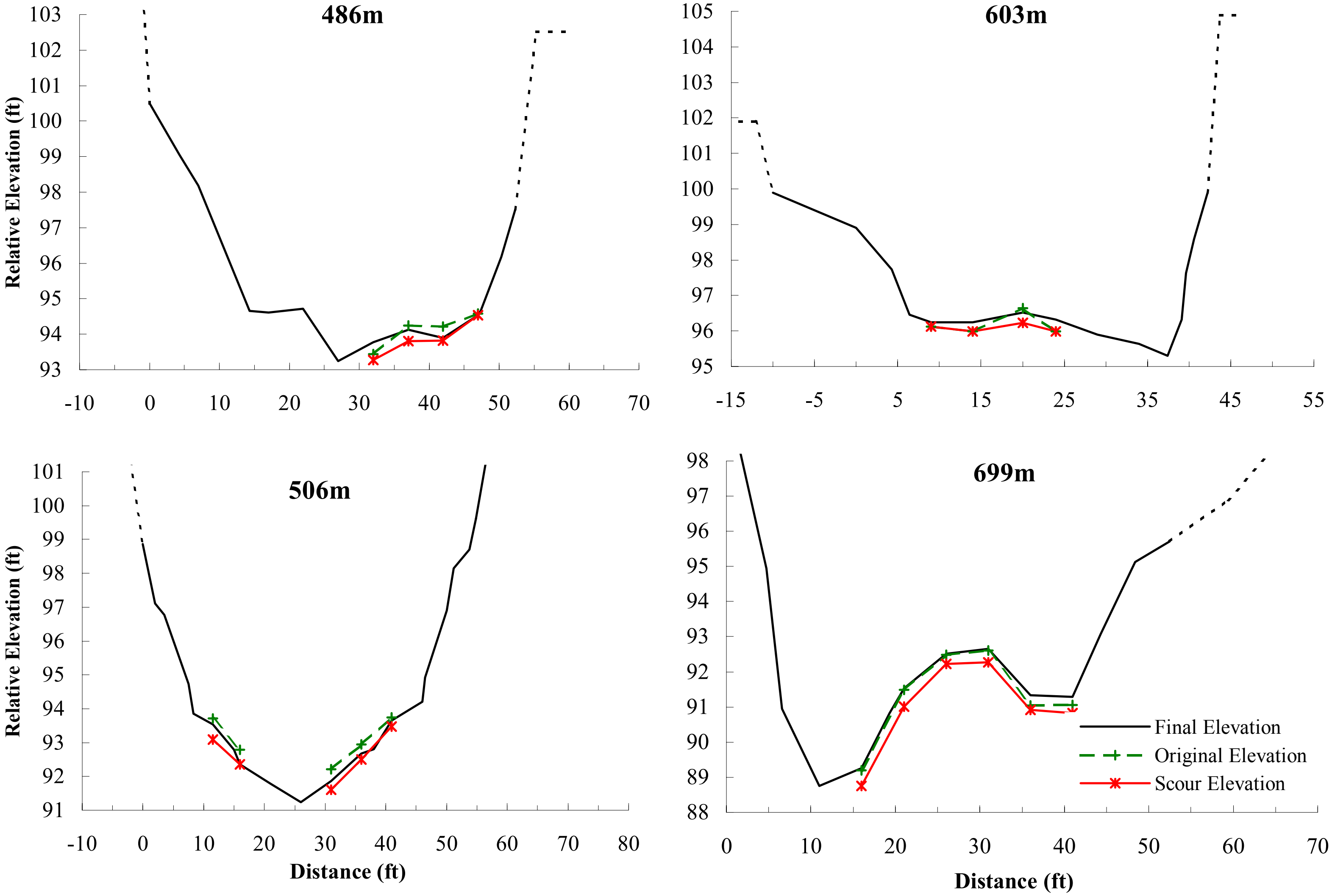
d source: Salmon Forever (2001).



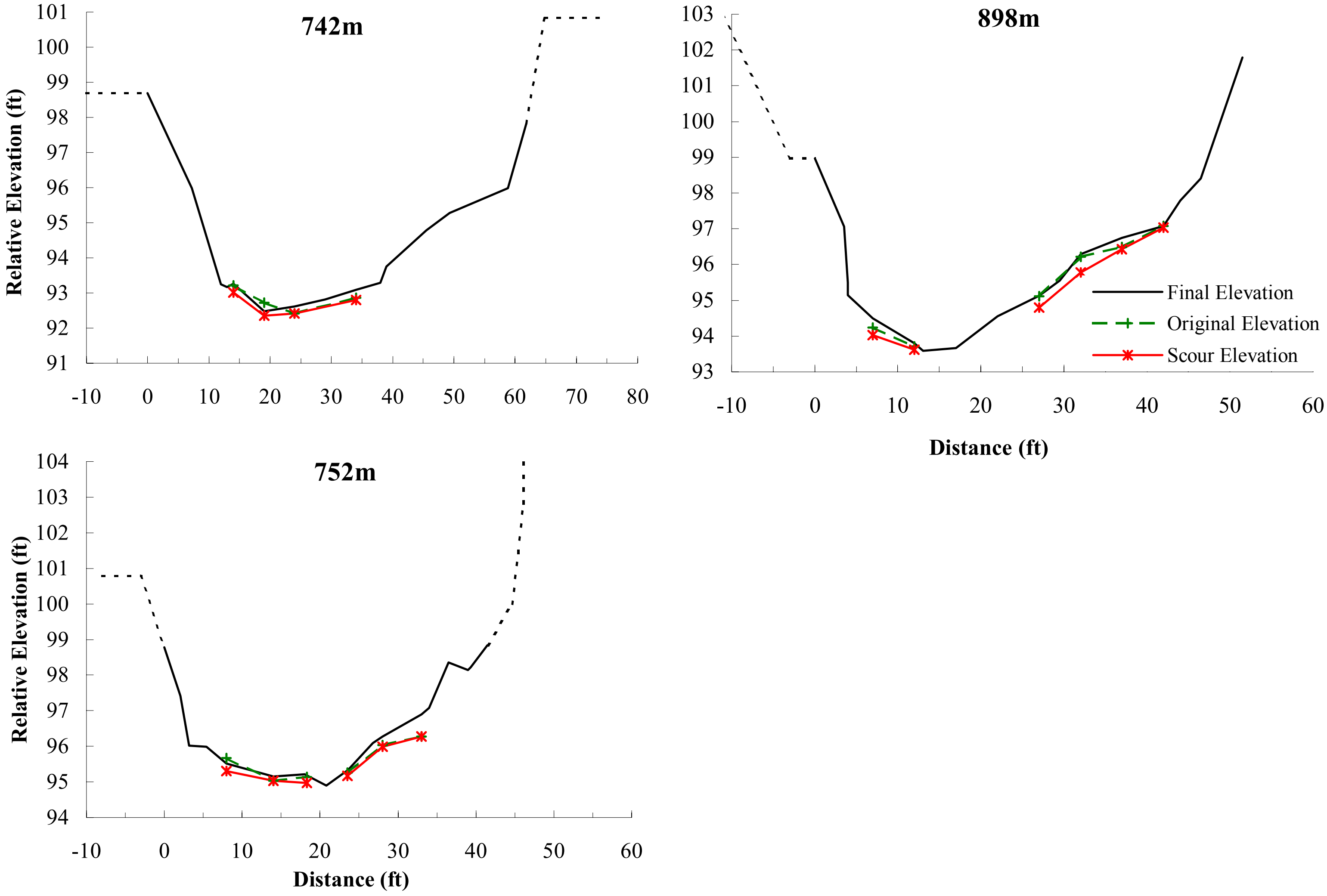
Appendix D. Cross sections – upper reach at 2, 91, 150, and 173 meters from bottom of reach.



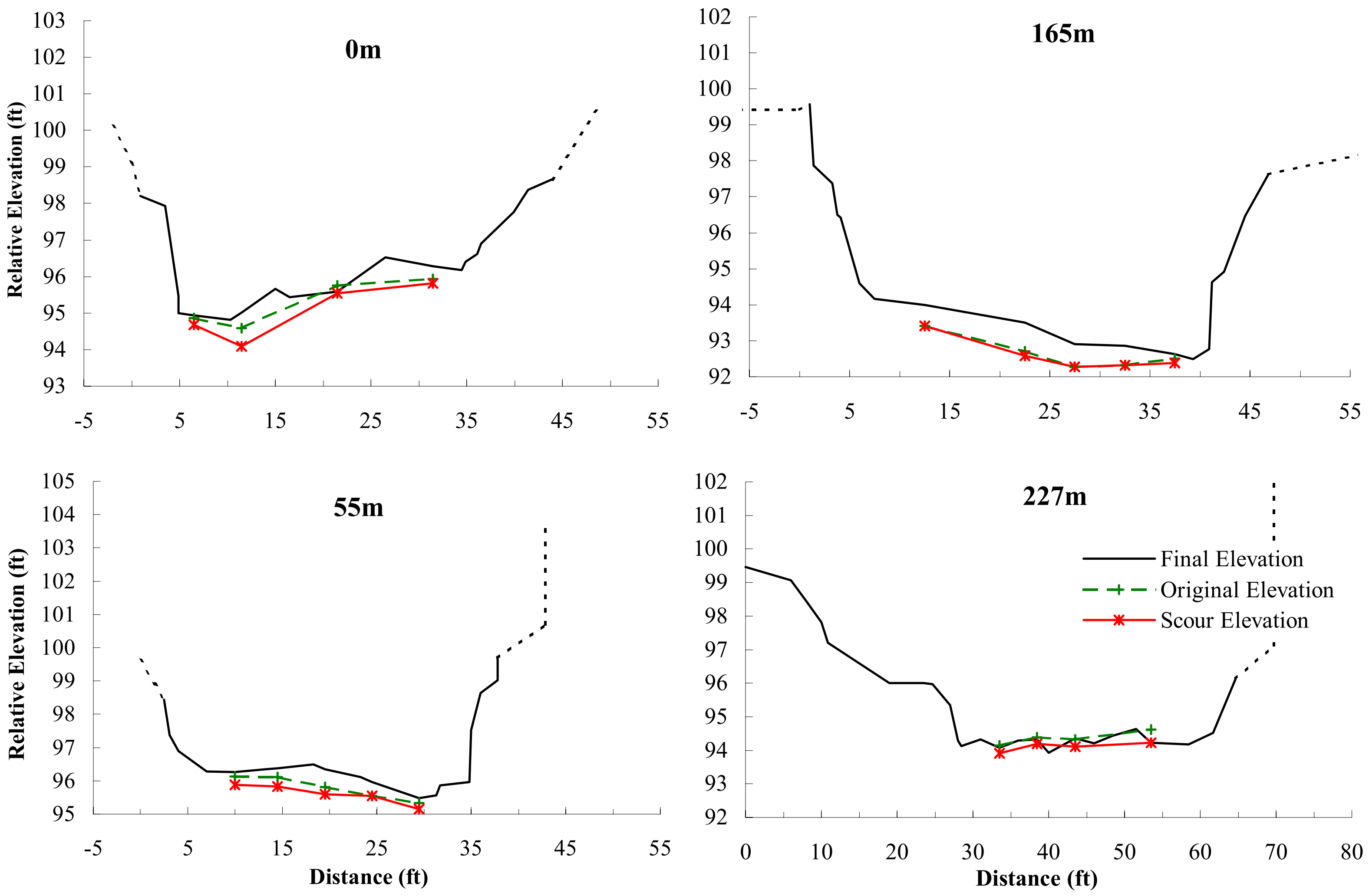
Appendix D. (Continued) Cross sections – upper reach at 228, 296, 350, and 377 meters from bottom of reach.



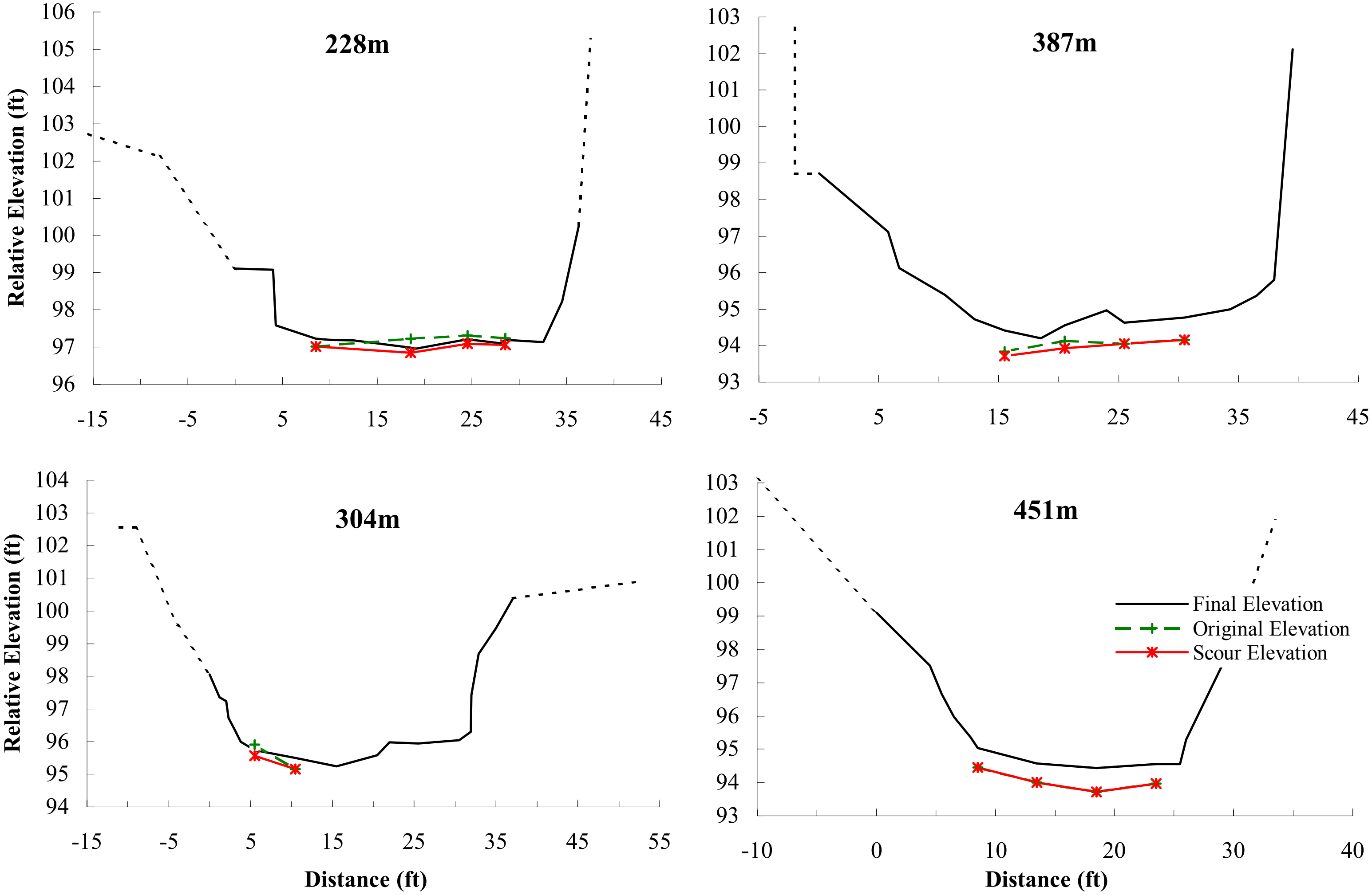
Appendix D. (Continued) Cross sections – upper reach at 486, 506, 603, and 699 meters from bottom of reach. Cross section at 621 meters could not be surveyed due to presence of poison oak along banks.



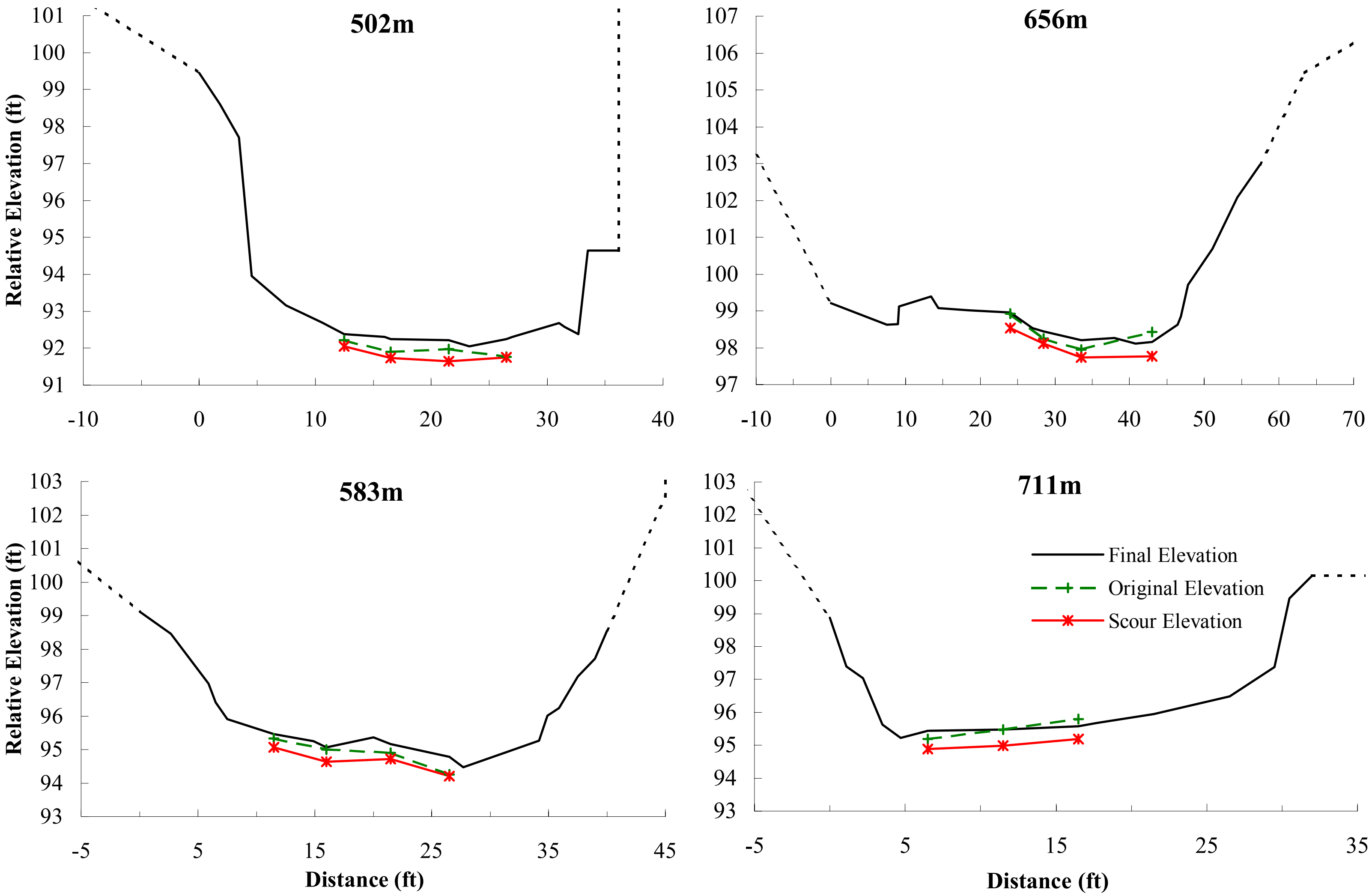
Appendix D. (Continued) Cross sections – upper reach at 742, 752, and 898 meters from bottom of reach.



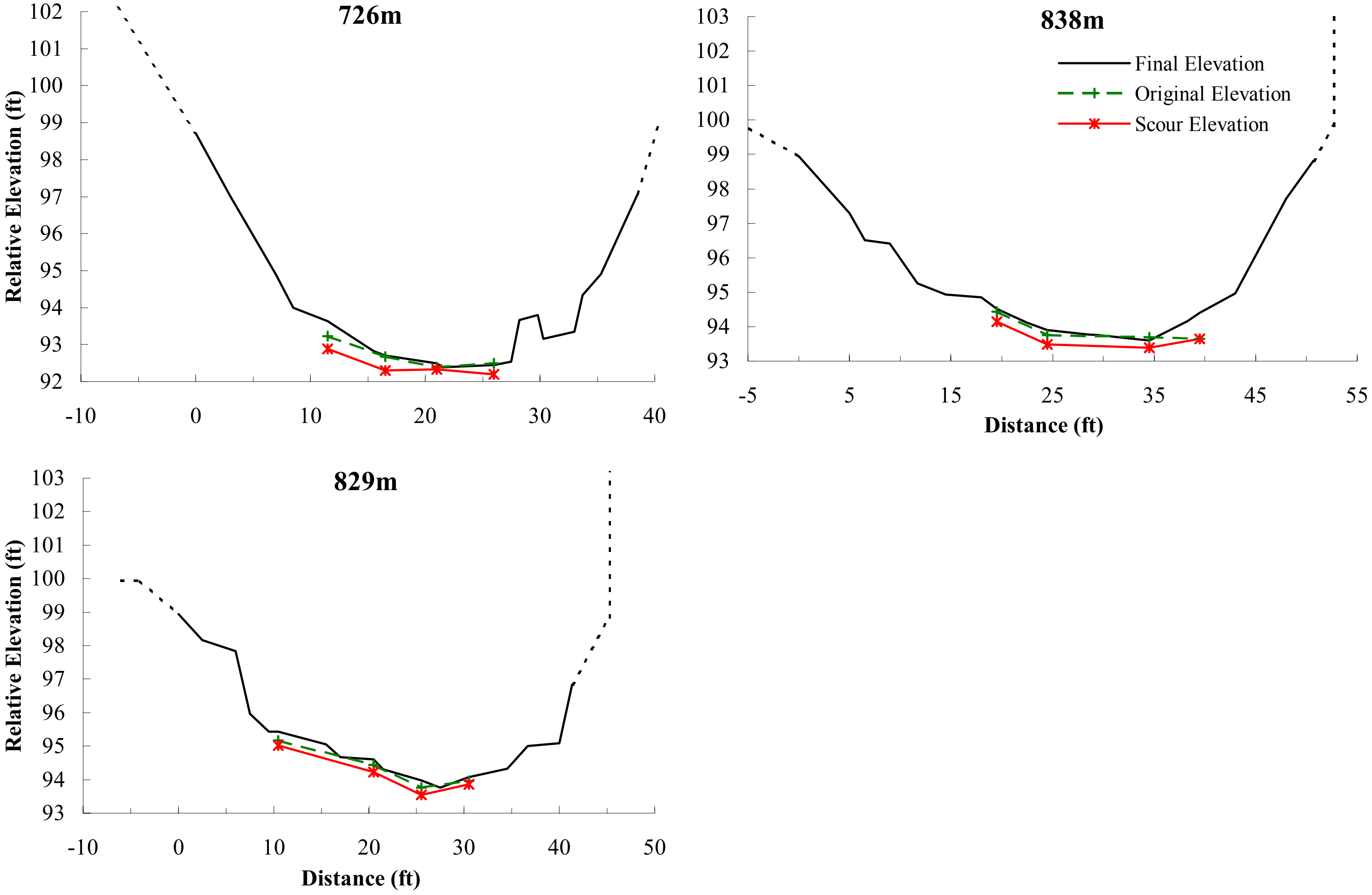
Appendix D. (Continued) Cross sections – lower reach at 0, 55, 165, and 227 meters from bottom of reach.



Appendix D. (Continued) Cross sections – lower reach at 283, 304, 387, and 451 meters from bottom of reach.



Appendix D. (Continued) Cross sections – lower reach at 502, 583, 656, and 711 meters from bottom of reach.



Appendix D. (Continued) Cross sections - Lower reach at 726, 829, and 838 meters from bottom of reach.

Appendix E. Scour and fill measurements – upper reach.

XS Location[a] (m)	Station (m)	Channel Geomorph Unit	Scour (cm)	Fill (cm)	Active Layer (cm)	Net Change (cm)	XS Net Change (cm)	Notes
2	2.9	bar	13.3	5.1	13.3	-8.3	-2.0	
	4.4	bar	7.6	0.0	7.6	-7.6		
	5.9	plane bed	5.1	2.5	5.1	-2.5		
	7.5	plane bed	7.6	2.5	7.6	-5.1		
	9.0	bar	23.5	12.7	23.5	-10.8		
	10.5	bar	16.5	38.1	38.1	21.6		
	12.0	bar	21.0	17.8	21.0	-3.2		
	13.6	bar	0.0	0.0	0.0	0.0		
91	3.4	plane bed	11.4	5.7	11.4	-5.7	-2.7	
	4.6	plane bed	14.0	9.5	14.0	-4.4		
	6.4	plane bed	22.2	6.4	22.2	-15.9		
	7.9	plane bed	10.8	8.9	10.8	-1.9		
	9.4	bar	3.2	7.6	7.6	4.4		
	11.0	bar	4.4	7.6	7.6	3.2		
	12.2	bar	1.3	2.5	2.5	1.3		
150	3.0	bar	3.2	5.1	5.1	1.9	5.7	
	6.1	bar	0.0	12.7	12.7	12.7		
	7.6	bar	14.0	8.9	14.0	-5.1		
	10.7	bar	11.4	14.0	14.0	2.5		
	13.7	bar	9.5	16.5	16.5	7.0		
	16.8	bar	19.1	7.6	19.1	-11.4		
	18.3	pool	0.0	27.3	27.3	27.3		
	20.1	pool	5.7	16.5	16.5	10.8		
	22.9							cohesive bed, no chain
173	1.8	pool	7.0	15.2	15.2	8.3	-0.1	
	3.4	pool		30.5				over 1' of fill, no chain recovery
	4.9	pool		30.5				over 1' of fill, no chain recovery
	6.4	bar	29.2	17.8	29.2	-11.4		
	7.9	bar	6.4	11.4	11.4	5.1		
	9.4	bar	17.1	15.2	17.1	-1.9		
	11.0	bar	8.3	7.6	8.3	-0.6		
228	4.6	bar	3.8	0.0	3.8	-3.8	2.7	
	6.1	bar	5.7	10.2	10.2	4.4		
	7.6	bar	1.3	12.7	12.7	11.4		
	9.1	bar	4.4	15.2	15.2	10.8		
	10.7	bar	3.2	15.2	15.2	12.1		
	12.2	riffle	17.1	10.2	17.1	-7.0		
	13.7	riffle	30.5	22.9	30.5	-7.6		
	15.2	riffle	17.1	15.9	17.1	-1.3		
	16.8	riffle	14.0	19.1	19.1	5.1		
296	8.5	pool	64.1					chain scoured out completely
	10.1	pool	66.7					chain scoured out completely
	11.6	pool	66.7					chain scoured out completely
	13.1	pool		45.7				over 1.5' of fill, no chain recovery
	14.6	pool	22.9	3.8	22.9	-19.1		
350	3.4	plane bed	0.0	1.3	1.3	1.3	-4.1	
	4.9	plane bed	0.0	0.0	0.0	0.0		
	6.4	plane bed	7.0	7.6	7.6	0.6		
	7.9	plane bed	5.1	2.5	5.1	-2.5		
	9.8							bedrock, no chain installation
	11.7	plane bed	8.3	2.5	8.3	-5.7		
	13.3	plane bed	21.0	2.5	21.0	-18.4		

Appendix E. (Continued) Scour and fill measurements – upper reach.

XS Location (m)	Station (m)	Channel Geomorph Unit	Scour (cm)	Fill (cm)	Active Layer (cm)	Net Change (cm)	XS Net Change (cm)	Notes
377	2.1	bar	5.1	0.0	5.1	-5.1	-2.3	
	3.7							1' to clay bed, no chain
	5.2	pool	0.0	3.8	3.8	3.8		
	6.7							water too deep for chain recovery
	8.2	pool	1.3	5.1	5.1	3.8		
	9.8	pool	12.1	5.1	12.1	-7.0		
	11.6	pool	17.1	10.2	17.1	-7.0		
486	2.1						-1.1	bedrock/boulders, no chain
	3.7							bedrock/boulders, no chain
	5.2							bedrock/boulders, no chain
	6.7							bedrock/boulders, no chain
	8.2							bedrock/boulders, no chain
	9.8	riffle	5.1	15.2	15.2	10.2		
	11.3	riffle	13.3	9.5	13.3	-3.8		
	12.8	riffle	12.1	2.5	12.1	-9.5		
	14.3	riffle	1.3	0.0	1.3	-1.3		
506	3.5	pool	19.1	0.0	19.1	-19.1	-6.4	
	4.9	pool	13.3	2.5	13.3	-10.8		
	6.4							1' to bedrock, no chain
	7.9							bedrock, no chain installation
	9.4	bar	18.4	10.2	18.4	-8.3		
	11.0	bar	13.3	12.7	13.3	-0.6		
	12.5	bar	8.3	15.2	15.2	7.0		
603	2.7	bar	0.0	3.8	3.8	3.8	4.4	
	4.3	bar	0.0	7.6	7.6	7.6		
	6.1	bar	12.7	8.9	12.7	-3.8		
	7.3	bar	0.0	10.2	10.2	10.2		
	8.8							1' to bedrock, no chain
	10.4							1' to bedrock, no chain
621	2.1	bar	14.6	10.2	14.6	-4.4	8.3	
	3.7	bar	5.1	5.7	5.7	0.6		
	5.2	plane bed	2.5	25.4	25.4	22.9		
	6.7	plane bed	3.8	17.8	17.8	14.0		
	8.2							water too deep for chain recovery
	9.8							cohesive bed, no chain
	11.3							cohesive bed, no chain
699	3.4	pool					3.5	wood, chain installation not possible
	4.9	pool	13.3	15.2	15.2	1.9		
	6.4	bar	14.6	15.9	15.9	1.3		
	7.9	bar	8.3	8.9	8.9	0.6		
	9.4	bar	10.2	11.4	11.4	1.3		
	11.0	bar	3.8	12.7	12.7	8.9		
	12.5	bar	7.0	14.0	14.0	7.0		
742	4.3	bar	6.4	7.6	7.6	1.3	1.7	
	5.8	riffle	11.4	3.8	11.4	-7.6		
	7.3	riffle	0.0	6.4	6.4	6.4		
	8.8							boulders, no chain installation
	10.4	bar	1.9	8.9	8.9	7.0		
	11.9							boulders, no chain installation
	12.5							boulders, no chain installation

Appendix E. (Continued) Scour and fill measurements – upper reach.

XS Location (m)	Station (m)	Channel Geomorph Unit	Scour (cm)	Fill (cm)	Active Layer (cm)	Net Change (cm)	XS Net Change (cm)	Notes
752	2.4	plane bed	10.8	6.4	10.8	-4.4	2.0	
	4.3	plane bed	0.0	3.8	3.8	3.8		
	5.6	plane bed	5.1	7.6	7.6	2.5		
	7.2	plane bed	2.5	5.1	5.1	2.5		
	8.5	bar	1.3	8.9	8.9	7.6		
	10.1	bar	0.0	0.0	0.0	0.0		
898	2.1	pool	6.4	14.0	14.0	7.6	3.5	
	3.7	pool	3.2	5.7	5.7	2.5		
	5.2							boulders, no chain installation
	6.7							water too deep for chain recovery
	8.2	bar	9.5	10.2	10.2	0.6		
	9.8	bar	13.3	15.9	15.9	2.5		
	11.3	bar	1.9	9.5	9.5	7.6		
	12.8	bar	1.3	1.3	1.3	0.0		
Reach Average:			10.6	10.2	12.2	0.6	0.9	

Note:

a Cross section (XS) location is the distance in meters from the bottom of the reach.

Appendix E. (Continued) Scour and fill measurements – lower reach.

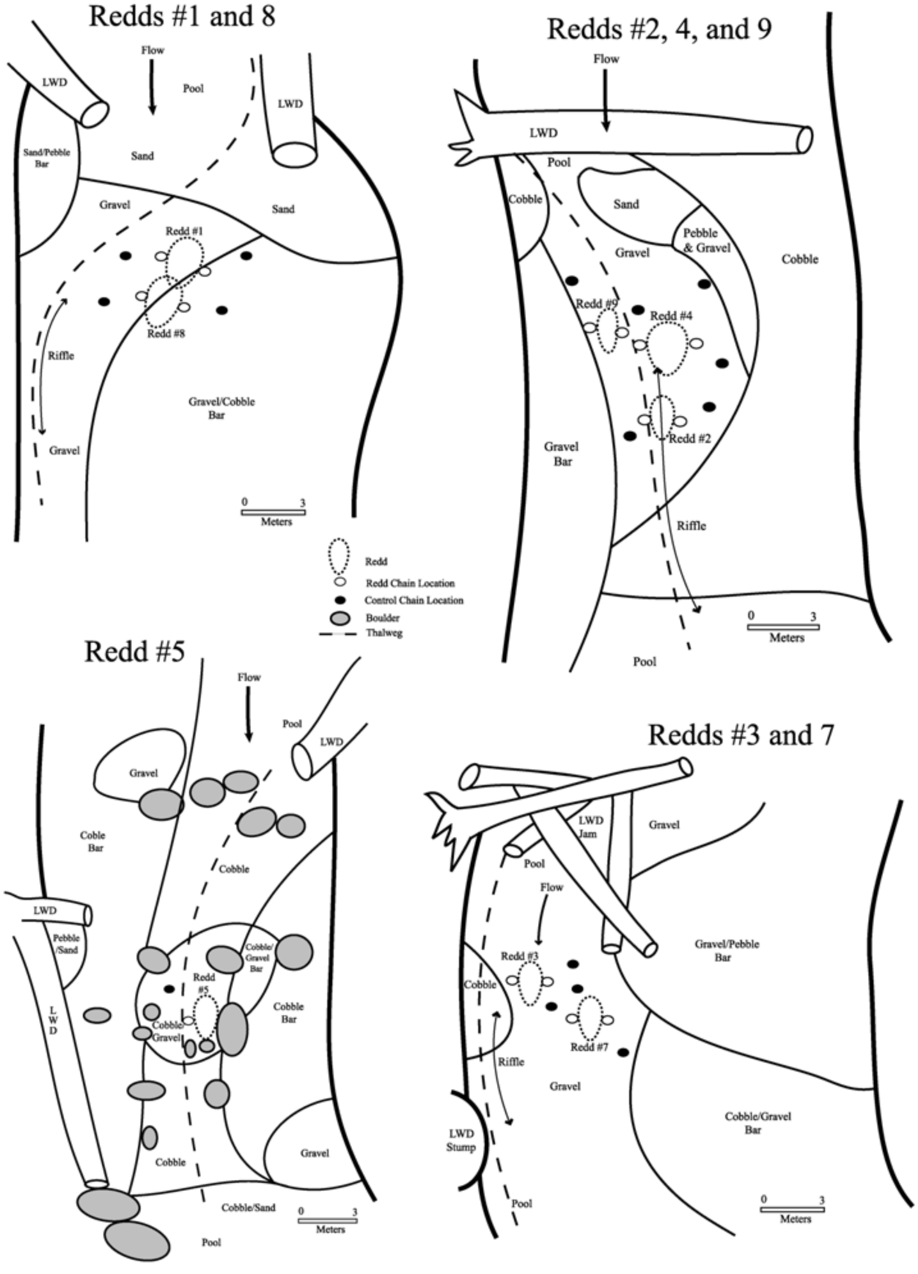
XS Location[a] (m)	Station (m)	Channel Geomorph Unit	Scour (cm)	Fill (cm)	Active Layer (cm)	Net Change (cm)	XS Net Change (cm)	Notes
0	2.0	plane bed	5.7	7.6	7.6	1.9	5.1	
	3.5	plane bed	15.2	27.9	27.9	12.7		
	5.0	bar						over 1’ fill, no chain recovery
	6.6	bar	6.4	1.3	6.4	-5.1		
	8.1							alder, no chain installation
	9.6	bar	3.8	14.6	14.6	10.8		
55	3.0	bar	7.6	11.4	11.4	3.8	9.1	
	4.4	bar	8.3	16.5	16.5	8.3		
	5.9	bar	6.4	22.9	22.9	16.5		
	7.5	riffle	0.0	12.7	12.7	12.7		
	9.0	riffle	5.7	10.2	10.2	4.4		
165	2.3						16.3	cohesive bed, no chain installation
	3.8	bar	0.0	17.8	17.8	17.8		
	5.3							wood, no chain installation
	6.9	bar	3.8	27.9	27.9	24.1		
	8.4	riffle	0.0	19.1	19.1	19.1		
	9.9	riffle	0.0	16.5	16.5	16.5		
	11.4	riffle	3.8	7.6	7.6	3.8		
227	7.2	bar					-3.7	couldn't discern bend in chain
	8.7	riffle						wood, no chain installation
	10.2	riffle	7.0	5.1	7.0	-1.9		
	11.7	riffle	6.4	4.4	6.4	-1.9		
	13.3	riffle	6.4	7.6	7.6	1.3		
	14.8							boulders, no chain installation
	16.3	riffle	12.1	0.0	12.1	-12.1		
	17.8							cohesive bed, no chain installation
283	2.6	riffle	0.0	6.4	6.4	6.4	-1.4	
	4.1							bedrock, no chain installation
	5.6	riffle	11.4	3.8	11.4	-7.6		
	7.5	riffle	7.0	3.8	7.0	-3.2		
	8.7	riffle	5.7	4.4	5.7	-1.3		
	10.2							
304	1.7	plane bed	10.2	5.1	10.2	-5.1	11.9	
	3.2	plane bed	0.0	10.2	10.2	10.2		
	4.7	plane bed		30.5	30.5	30.5		over 1’ fill, no chain recovery
	6.2							wood, no chain installation
	7.8	plane bed						no magnet, could not relocate chain
	9.3							bedrock, no chain installation
387	3.2						16.7	bedrock, no chain installation
	4.7	riffle	3.8	21.6	21.6	17.8		
	6.2	riffle	6.4	19.1	19.1	12.7		
	7.8	riffle	0.0	17.8	17.8	17.8		
	9.3	riffle	0.0	18.4	18.4	18.4		
	10.8							bedrock, no chain installation
451	2.6	plane bed	0.0	17.8	17.8	17.8	18.6	
	4.1	plane bed	0.0	17.1	17.1	17.1		
	5.6	plane bed	0.0	21.6	21.6	21.6		
	7.2	plane bed	0.0	17.8	17.8	17.8		
502	3.8	plane bed	5.1	10.2	10.2	5.1	9.2	
	5.0	plane bed	5.1	15.2	15.2	10.2		
	6.6	plane bed	10.2	17.1	17.1	7.0		
	8.1	plane bed	0.6	15.2	15.2	14.6		
	9.6							cohesive bed, no chain installation

Appendix E. (Continued) Scour and fill measurements – lower reach.

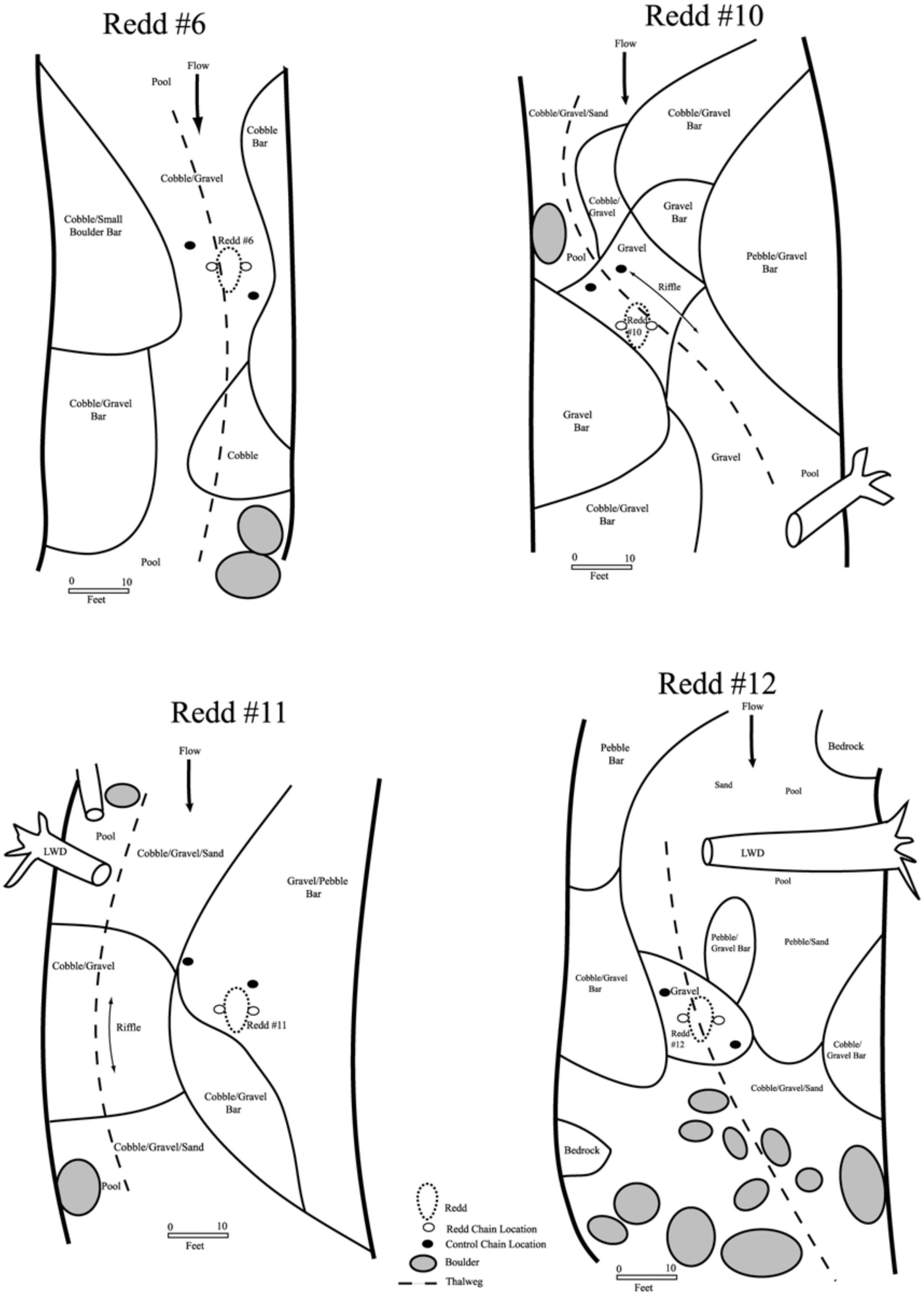
XS Location[a] (m)	Station (m)	Channel Geomorph Unit	Scour (cm)	Fill (cm)	Active Layer (cm)	Net Change (cm)	XS Net Change (cm)	Notes
583	3.5	bar	7.6	12.1	12.1	4.4	7.8	
	4.9	bar	10.8	12.7	12.7	1.9		
	6.6	bar	5.7	14.0	14.0	8.3		
	8.1	plane bed	1.3	17.8	17.8	16.5		
	9.6							cohesive bed, no chain installation
656	7.3	riffle	12.1	12.7	12.7	0.6	1.4	
	8.7	riffle	4.4	10.2	10.2	5.7		
	10.2	riffle	6.4	14.0	14.0	7.6		
	11.6							bedrock, no chain installation
	13.1	riffle	20.3	12.1	20.3	-8.3		
711	2.0	plane bed	9.5	17.1	17.1	7.6	0.4	
	3.5	plane bed	15.2	15.2	15.2	0.0		
	5.0	plane bed	18.4	12.1	18.4	-6.4		
	6.6							bedrock, no chain installation
	8.1							chain broke upon recovery
726	3.5	plane bed	10.2	22.9	22.9	12.7	3.8	
	5.0	plane bed	11.4	12.1	12.1	0.6		
	6.4	plane bed	1.9	5.1	5.1	3.2		
	7.9	plane bed	8.9	7.6	8.9	-1.3		
	9.6							wood, no chain installation
829	3.2	bar	4.4	12.7	12.7	8.3	5.7	
	4.7							chain broke upon retrieval
	6.2	bar	6.4	11.4	11.4	5.1		
	7.8	riffle	6.4	12.7	12.7	6.4		
	9.3	riffle	3.2	6.4	6.4	3.2		
	10.8							bedrock, no chain installation
838	4.4						6.7	no magnet, could not relocate chain
	5.9	bar	8.9	11.4	11.4	2.5		
	7.5	riffle	8.3	12.7	12.7	4.4		
	9.0							no magnet, could not relocate chain
	10.5	riffle	9.5	6.4	9.5	-3.2		
	12.0	bar	0.0	22.9	22.9	22.9		
Reach Average:			6.0	13.3	14.3	7.4	7.2	

Note:

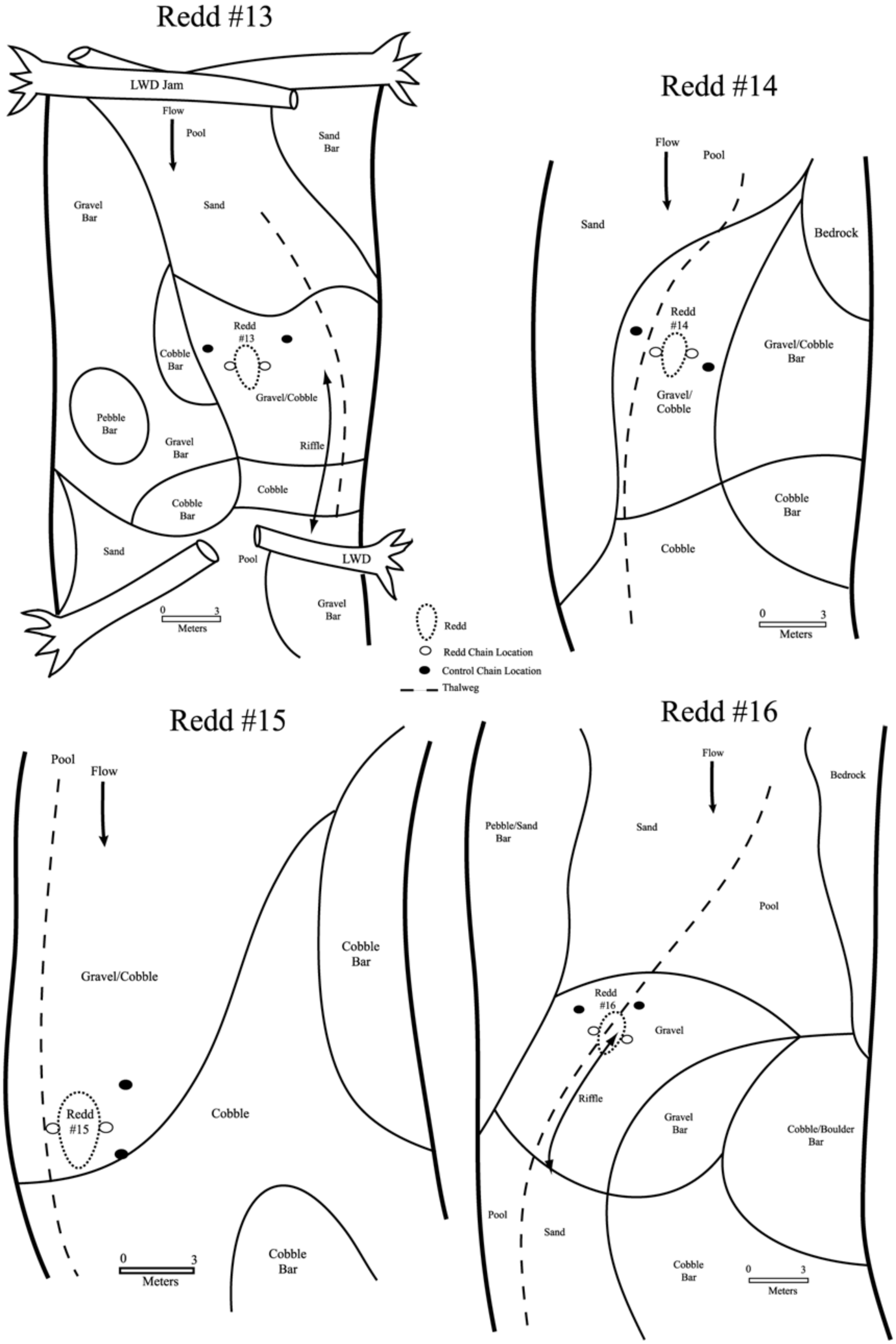
[a] Cross section (XS) location is the distance in meters from the bottom of the reach.



Appendix F. Redd plan maps: redds #1, 2, 3, 4, 5, 7, 8, and 9. All redds shown are within the upper reach.



Appendix F. (Continued) Redd plan maps: redds #6, 10, 11, and 12. Redd #6 is within the upper reach.



Redd #13

Redd #14

Redd #15

Redd #16

Appendix F. (Continued) Redd Plan maps: redds #13, 14, 15, and 16.

Appendix G. Redd scour and fill measurements.

Redd No.	Species	Unit	Installed	Location on Reach[a] (m)	Chain Location	Scour (cm)	Fill (cm)	Ave Redd Scour (cm)	Ave Control Scour (cm)	Ave Redd Fill (cm)	Ave Control Fill (cm)
1	coho	pool tailout	1/5/00	281	redd LB[b]	7.6	17.8	13.0	16.5	26.7	22.2
					redd RB	18.4	35.6				
					control LB[c]	13.3	11.4				
					control RB	19.7	33.0				
2	chinook	pool tailout	1/5/00	393	redd LB	18.4	15.9	12.7	4.1	14.9	12.4
					redd RB	7.0	14.0				
					control LB	8.3	14.6				
					control RB	0.0	10.2				
3	unknown	pool tailout	1/5/00	229	redd LB	11.4	9.5	7.9	16.2	9.8	21.6
					redd RB	4.4	10.2				
					control	12.7	19.1				
					control	19.7	24.1				
4	unknown	pool tailout	1/6/00	396	redd LB	15.9	21.6	15.9	10.8	26.0	11.4
					redd RB	--[d]	30.5				
					control	--	--				
					control	10.8	11.4				
5	unknown	riffle	1/6/00	683	redd RB	12.1	5.1	12.1	16.5	5.1	10.2
					control RB	16.5	10.2				
6	unknown	riffle	1/6/00	737	redd LB	14.0	11.4	12.4	4.1	12.1	4.8
					redd RB	10.8	12.7				
					control LB	3.2	6.4				
					control RB	5.1	3.2				
7	unknown	pool tailout	2/6/00	228	redd LB	12.7	16.5	17.1	15.9	15.2	11.4
					redd RB	21.6	14.0				
					control LB	18.4	5.1				
					control RB	13.3	17.8				
8	unknown	pool tailout	2/6/00	280	redd LB	8.3	10.2	10.5	12.4	12.7	14.6
					redd RB	12.7	15.2				
					control LB	9.5	12.7				
					control RB	15.2	16.5				
9	unknown	pool tailout	2/6/00	396	redd LB	10.2	16.5	12.4	5.7	12.1	14.0
					redd RB	14.6	7.6				
					control	8.3	20.3				
					control	3.2	7.6				
10	unknown	pool tailout	2/6/00		redd LB	0.0	15.2	0.0	0.0	22.9	21.6
					redd RB	--	30.5				
					control	0.0	12.7				
					control	--	30.5				
11	coho	pool tailout	2/6/00		redd LB	0.0	33.0	0.0	0.0	33.0	29.8
					redd RB	0.0	33.0				
					control	0.0	38.1				
					control	0.0	21.6				

Appendix G. (Continued) Redd scour and fill measurements.

Redd No.	Species	Unit	Installed	Location on Reach[a] (m)	Chain Location	Scour (cm)	Fill (cm)	Ave Redd Scour (cm)	Ave Control Scour (cm)	Ave Redd Fill (cm)	Ave Control Fill (cm)
12	coho	pool tailout	2/8/00		redd LB	13.3	12.1	14.0	5.1	9.2	12.4
					redd RB	14.6	6.4				
					control	8.3	14.6				
					control	1.9	10.2				
13	coho	pool tailout	2/8/00		redd LB	1.9	10.2	5.1	4.8	13.3	11.4
					redd RB	8.3	16.5				
					control	4.4	10.2				
					control	5.1	12.7				
14	unknown	pool tailout	2/8/00		redd LB	13.3	17.8	13.3	0.0	24.1	24.1
					redd RB	--	30.5				
					control	0.0	17.8				
					control	--	30.5				
15	unknown	pool tailout	2/10/00		redd LB	14.0	6.4	12.4	5.1	8.3	10.2
					redd RB	10.8	10.2				
					control	1.3	8.9				
					control	8.9	11.4				
16	coho	pool tailout	2/10/00		redd LB	3.8	12.7	1.9	7.3	11.4	14.6
					redd RB	0.0	10.2				
					control	10.8	15.2				
					control	3.8	14.0				

Notes:

a	Location for redds # 1 - 9 is distance from bottom of the upper reach, redds # 10 - 16 were above or below the upper reach.
b	Left bank facing downstream.
c	Right bank facing downstream.
d	No chain recovery