Coupling hydrodynamic modeling and empirical measures of bed mobility to predict the risk of scour and fill of salmon redds in a large regulated river

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[1] In order to assess the risk of scour and fill of spawning redds during floods, an understanding of the relations among river discharge, bed mobility, and scour and fill depths in areas of the streambed heavily utilized by spawning salmon is needed. Our approach coupled numerical flow modeling and empirical data from the Trinity River, California, to quantify spatially explicit zones of differential bed mobility and to identify specific areas where scour and fill is deep enough to impact redd viability. Spatial patterns of bed mobility, based on model-predicted Shields stress, indicate that a zone of full mobility was limited to a central core that expanded with increasing flow strength. The likelihood and maximum depth of measured scour increased with increasing modeled Shields stress. Because redds were preferentially located in coarse substrate in shallow areas with close proximity to the stream banks, they were less likely to become mobilized or to risk deep scour during high-flow events but were more susceptible to sediment deposition.

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1. Introduction

[2] Flow releases in regulated rivers are increasingly being used to improve habitat for salmon downstream of reservoirs [e.g., *Ligon et al.*, 1995; *Kondolf and Wilcock*, 1996; *Schmidt et al.*, 2001]. Because of limited water availability and dam safety issues, the volume of water that can be released from reservoirs is often insufficient for mobilizing a significant portion of the streambed or for flushing fine sediment from the subsurface. For this reason, dam release floods may be most effective at creating habitat when combined with tributary-generated floods. However, in much of the Pacific Northwest the winter rainy season coincides with the period of time when salmonid eggs are incubating in streambed gravels. If numerous gravel nests or ‘‘redds’’ are scoured to the depth of egg burial during a flood event, egg mortality can be high and the population viability of highly valued salmonid species may be reduced. However, if fish are burying their eggs below anticipated scour depths for a given range of discharges, or if redds are constructed in areas of low bed mobility, the potential loss of incubating eggs and embryos will be low. Because many regulated rivers have a deficit of coarse sediment below the dam, mortality due to sediment deposition is often unanticipated and concern has traditionally focused on the risk of scour. Our study assesses the relative risk of both processes.

[3] In order to assess the risk of scouring spawning redds during flood events, an understanding of the relations among river discharge, bed mobility, and scour depth in areas of the streambed heavily utilized by spawning salmon is needed. Our approach combines hydrodynamic modeling and empirical data to quantify spatially explicit predictions of bed mobility and specific areas where scour is deep enough to impact redd viability. We generate values of local boundary shear stress in a reach of the Trinity River in northern California using the Flow and Sediment Transport Morphological Evolution of Channels (FaSTMECH) model [*Nelson and Smith*, 1989] within the MultiDimensional Surface Water Modeling System (MD_SWMS) preprocessor and postprocessor [*McDonald et al.*, 2005]. We calculated Shields stress from local shear stress and median particle size obtained by detailed mapping of particle size distributions. Shields stress (τ_i^*) is a commonly used mobility parameter that represents the ratio of tractive and gravitational forces acting on bed particles:

$$\tau_i^* = \tau / R D_i$$

where τ = boundary shear stress, R = submerged specific weight of sediment, and D_i = particle size of a given cumulative frequency i.

[4] In the course of measuring scour, we also measured widespread deposition or ‘‘fill’’ of new bed material. Relations between fill and embryo survival are poorly understood but several effects can be identified. Spawning

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Table 1. Characteristics of the Sheridan Bar Study Reach in the Trinity River

	Value
Channel slope	0.002
Reach length (m)	1250
Average bankfull channel width (m)	48
Reach average D_{50} grain size (mm)	47
Reach average D_{84} grain size (mm)	92

salmon bury their eggs in bed material from which substantial fractions of fines are flushed during redd construction [*Kondolf et al.*, 1993]. In contrast, bed material deposited during floods usually contains a fraction of fine sediment (mostly sand) in approximately the same proportion as the bed material load. Model results by *Wu* [2000] indicate that embryo survival is very sensitive to the composition of deposited sediment, particularly the fraction of fine sediment. In many rivers, this fraction is abundant enough (20–30%) to clog gravel interstices and substantially reduce intergravel flow that supplies oxygen to egg pockets and removes metabolic waste (see review by *Chapman* [1988]). Regardless of size composition, greater burial tends to reduce intergravel flow in the egg pocket because intergravel velocities tend to decrease with depth in the bed. Finally, young fish attempting to emerge from the gravel can be entombed beneath a capping layer of finer bed material, or only smaller fish are able to emerge [*Koski*, 1966; *Phillips et al.*, 1975]. We treat fill similarly as we do scour, by examining relations between fill and hydraulic conditions, and estimate the risk of fill for embryo mortality in the study reach.

[5] Statistical modeling of habitat preferences for Chinook salmon (*Oncorhynchus tshawytscha*) spawning were developed from surveyed redds, and hydraulic and geomorphic parameters at observed spawning redds. Predictions of preferred spawning areas were verified using an independent data set. These site preferences enabled the expansion of individual spawning locations to estimates of preferred spawning habitat throughout the reach. Preferred spawning areas were compared to ambient bed areas to determine whether fish spawn in locations of inherently higher or lower mobility, thus affecting their risk of scour and fill during floods.

2. Study Site

[6] The Trinity River in northern California is impounded by two large dams that block access to salmon in the upper 1860 km^2 of the basin. Downstream of the dams, over 250 km of main stem river are used by several anadromous salmonid species, including spring and fall run Chinook salmon (*Oncorhynchus tshawytscha*), coho salmon (*Oncorhynchus kisutch*) and steelhead trout (*Oncorhynchus mykiss*). The majority of runoff to the upper basin is exported out of the catchment and into the neighboring Sacramento River drainage for agricultural use, and flooding was virtually eliminated in the reach directly below the dam for several decades. Postdam changes in water and sediment supply have resulted in numerous adverse effects to salmon habitat [*McBain and Trush*, 1997]. In response, experimental flood releases to the lower river are being conducted as part of a larger restoration strategy.

[7] For this study, a 1.25 km reach of the Trinity River at Sheridan Bar was selected for investigation (Table 1). The morphology of the reach is a simple bar-pool sequence, with a straight rectangular glide in the upper segment, a bedrock forced pool on the apex of the bend at Sheridan Bar, and a low-gradient riffle in the lower portion of the reach (Figure 1). This reach of the river has a relatively high density of Chinook salmon spawning activity, and is second only to the reach immediately below Lewiston Dam in abundance of spawning fish (C. May, analysis of unpublished data, 2003). The study area is located approximately 50 km downstream of Lewiston Dam, which provided the opportunity to investigate tributary-generated flood events in addition to annual dam releases. The study reach is also located 2.7 km upstream of a U.S. Geological Survey stream gauge at Junction City (11526250), thus providing a continuous record of discharge.

3. Model Description and Applications

[8] Field methods were designed to parameterize and test a spatially distributed flow model that generates hydraulic parameters used to predict Shields stress and consequent bed mobility, and to measure scour and fill and its relation to bed mobility in areas used by Chinook salmon for spawning. Directly measuring local hydraulic conditions throughout the study reach during a flood is impractical. The most accurate way to generate such data is to use a distributed flow model based on first principles of river mechanics, and to verify model predictions with point measurements made during flood flows. The MultiDimensional Surface Water Modeling System (MD_SWMS) interface for the Flow and Sediment Transport Morphological Evolution of Channels (FaSTMECH) model [*Nelson and Smith*, 1989], uses water discharge and detailed channel topography and roughness measurements to compute force balances responsible for the distribution of depth, velocity, and boundary shear stress.

[9] As presented by *Nelson and Smith* [1989], the FaSTMECH model solves the full vertically and Reynolds-averaged momentum equations. The full vertically averaged equations used in the computational solution are cast in a channel-fitted curvilinear coordinate system. The model computes water surface elevation and downstream and cross-stream components of both vertically averaged velocity and bottom shear stress. Inputs to the vertically averaged model are discharge, topography, and roughness in the form of drag coefficients. A vertical structure submodel yields downstream and cross-stream components of velocity and Reynolds shear stress at discrete points in the vertical, and also yields the structure of secondary flows and modifications to the bed stress associated with secondary flows. Inputs to the vertical structure submodel are eddy viscosity structure functions and results of the vertically averaged model. The approach uses the assumptions that (1) the flow is steady (or at least does not vary appreciably over short time scales), (2) the flow is hydrostatic (vertical accelerations are neglected), and (3) the turbulence can be treated adequately by relating Reynolds stresses to shears using an isotropic eddy viscosity. Development of the model equations can be found by *Nelson and Smith* [1989], while the numerical techniques and the streamline-based vertical

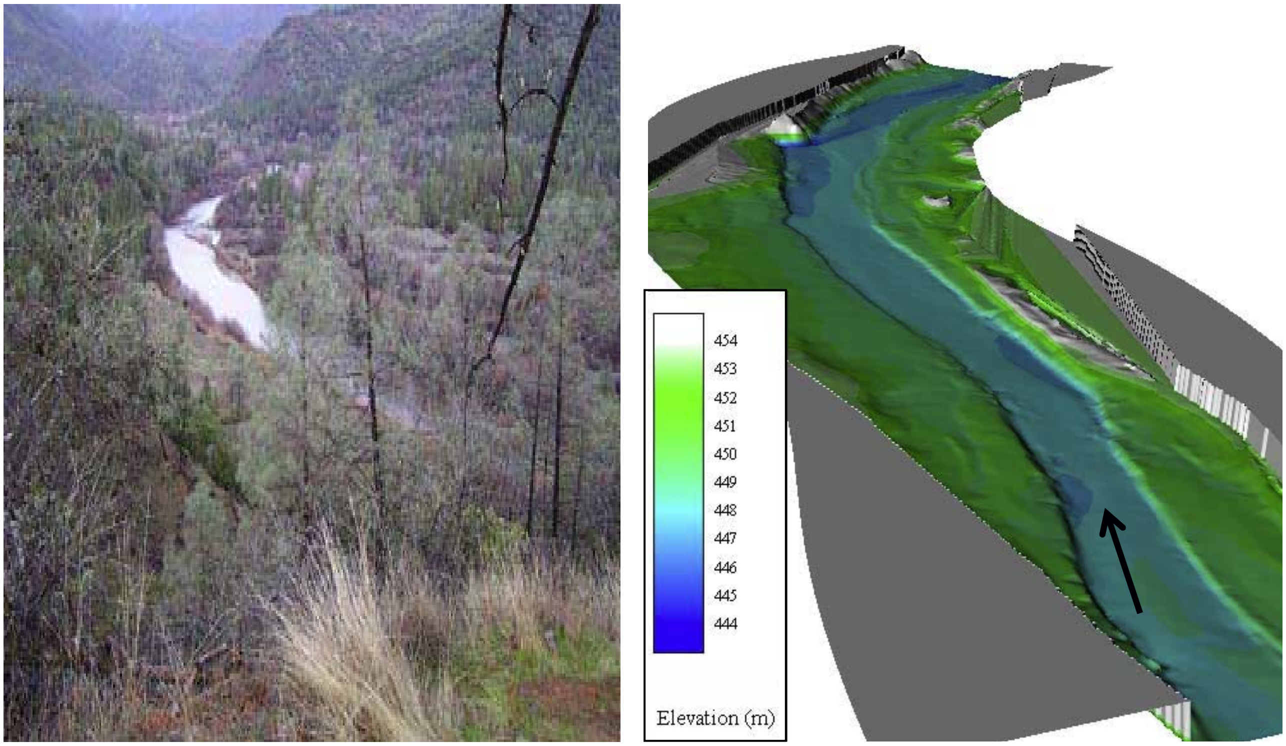

Figure 1. Photograph and topographic base map of the Sheridan Bar study reach.

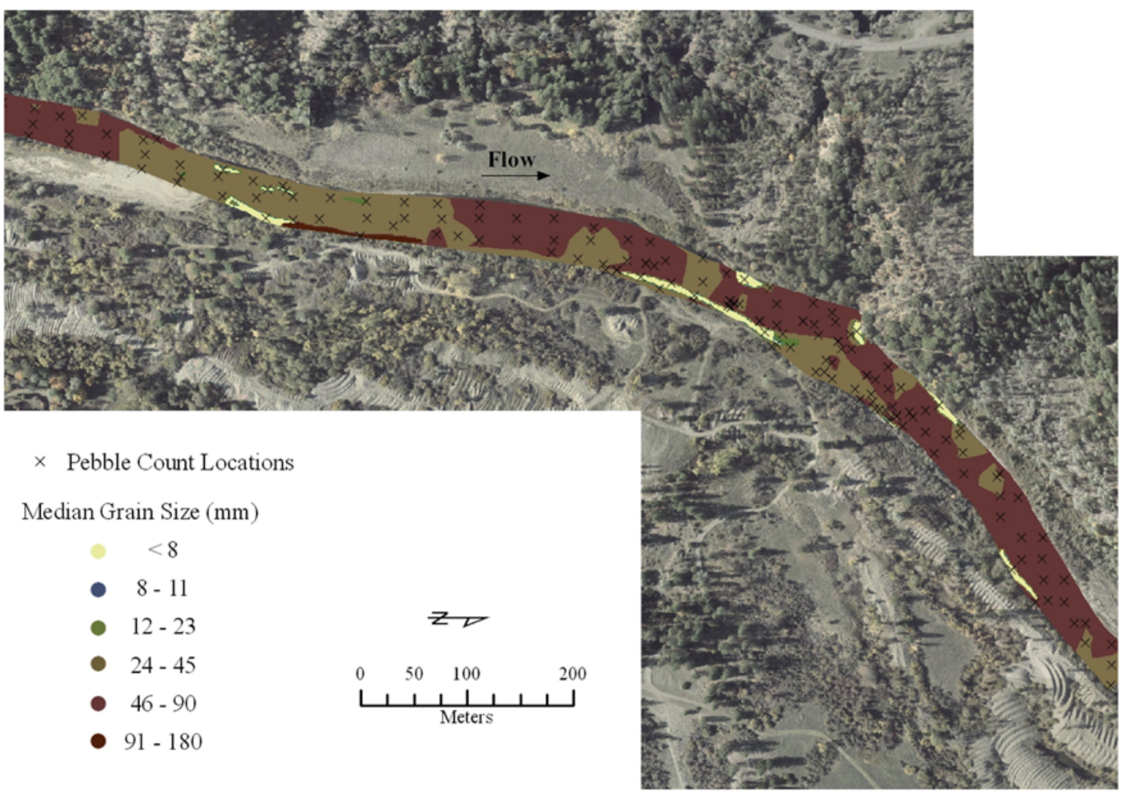

Figure 2. Interpolated grid of the median grain size throughout the study reach. Site map indicates the location of grain size measurements and discrete patches of fine sediment (<8 mm).

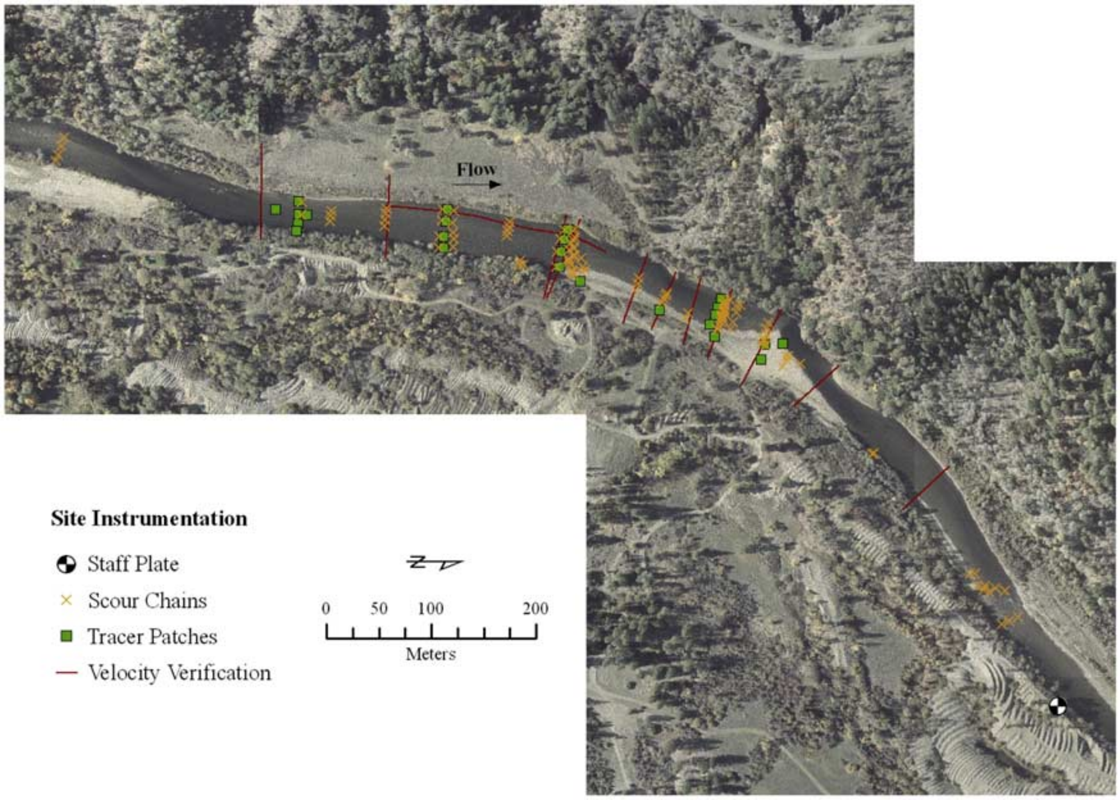

Figure 3. Site instrumentation of the Sheridan Bar study reach.

structure submodel are discussed by *Nelson and McDonald* [1996].

[10] The total boundary shear stress (τb) throughout the model domain is calculated as a combination of the skin friction (*sf*) and form drag (*fd*) components of the shear stress as

$$\tau_b = \tau_{sf} + \tau_{fd}$$

Because application of the FaSTMECH model was used within a stream reach with a relatively simple morphology, boundary shear stress for this study was assumed to be dominated by skin friction. Form drag was considered negligible and was not included in the calculations.

[11] Because determination of the total bed shear stress depends on the local velocity within and above the boundary layer, a quasi-3-D velocity field is generated using a logarithmic relationship for the boundary layer. The boundary layer velocity calculations are described by *McLean et al.* [1999]. A number of detailed laboratory and field experiments have been conducted to compare the total bed shear stresses predicted by the FaSTMECH model to observed values [*Nelson and Smith*, 1989; *Nelson et al.*, 1993; *McLean et al.*, 1999]. In addition, the model has a long track record of accurately predicting local flow conditions in a variety of rivers [*Andrews and Nelson*, 1989; *Lisle et al.*, 2000; *Conaway and Moran*, 2004; *Barton et al.*, 2005].

3.1. Model Inputs

[12] We created a topographic base map for the 1250 m study reach with a combination of bathymetric mapping from depth sounding and high-resolution global positioning system (GPS) in deep water areas, and total station surveys in shallow or dry areas (Figure 1). The topography of areas outside the bankfull channel was extracted from digital orthophoto quads. A 1 m resolution topographic map was used as input to FaSTMECH. Assessment of scour and fill depths and repeated surveys of established cross sections indicated that limited topographic change occurred between high-flow events, thus the original base map was used throughout the study period.

[13] High-resolution grain size mapping was conducted on the bed and bars via wading, snorkeling and scuba diving. A sampling grid with 20 m spacing was overlain on the study reach in GIS, and sample points were located in the field with GPS coordinates (Figure 2). At each point a 4 m^2 iron frame was used to delineate the sampling area. Within each sampling area a minimum of 100 particles were sampled at an equal interval of 20 cm. Particle size was measured by passing each grain through a square-holed template. In addition to sampling areas on the systematic grid, supplemental sample sites were added to capture abrupt changes in grain size. Particle size distributions were measured at a total of 93 sampling areas throughout the reach. Grain size metrics (D_{16} representing the fine fraction of bed material as the lower 16th percentile of the distribution of measured grains, D_{50} the median grain size, and D_{84} representing the coarsest fraction as the upper 84th percentile of the cumulative frequency distribution) were assigned to the centerpoint of each sampling area, and used to develop a map of streambed particle size using linear interpolation. This method of interpolation was used because bed material changed gradually throughout the reach

Table 2. Summary of High-Flow Events Observed During the Study Period[a]

Sampling Date	Measured Discharge (cm^3/s)	Event Peak Discharge[b] (cm^3/s)	Event Type	Average Shields Stress in Low-Flow Channel at Measured Discharge	Average Shields Stress in Low-Flow Channel at Event Peak	Number of Scour Chains	Average Scour Depth (cm)
17 Feb 2004	391	422	tributary flood	0.059	0.063	72	7.1
24 May 2004	162	180	dam release	0.041	0.040	72	3.3
12 May 2005	201	242	dam release	0.044	0.050	66	5.2
30 Dec 2005	351	473	tributary flood	0.057	0.061	58	12.9
31 May 2006	223	281	dam release	0.047	ND[c]	ND[d]	ND

[a]The study period is water year 2004–2006.
[b]Peak flow was estimated from Junction City stream gauge, 15 min data.
[c]ND means no data.
[d]Streamflow was too high to reset scour chains between tributary flood and dam release in 2006.

and boundaries between grain size patches were commonly indistinct.

[14] Nine distinct patches of fine sediment (<8 mm) were present in the study reach. These patches were mapped separately, and distinct patch boundaries were overlain on the interpolated map of grain size used as input for the model. Outside of these patches, fine sediment was limited to interstitial spaces between coarse grains and was composed primarily of coarse sand. Observations of the bed surface and core sampling indicated that most fine sediment was trapped within the subarmor layer of the bed and that the bed was well armored, indicative of a river with a low supply of coarse sediment [*Dietrich et al.*, 1989]. Because pebble counts cannot effectively sample fine bed material, particularly in large rivers and in high-velocity areas [*Church et al.*, 1987; *Wilcock et al.*, 1995], grain size distributions input into the model excluded particles <8 mm. Being unable to effectively sample fine bed material in the surface layer did result in a minor biasing of grain size distributions input to the model. This bias affects our results by slightly overestimating bed stability.

[15] Vegetation patches on bar surfaces and along the channel banks were mapped using total station surveys and digital orthophoto quads. Vegetation was delineated into homogeneous polygons on the basis of species and age class. The effect of vegetation on localized and downstream water velocities was incorporated into FaSTMECH by increasing the drag coefficient in the vegetated patches. Baseline hydraulic roughness values for the patches were derived from *Freeman et al.* [2002], who developed relationships on the basis of the stiffness of partially submerged plants and shrubs but did not specifically address vegetation height. Modifications to vegetation patch drag coefficients were made during our study to calibrate FaSTMECH to observed velocities near vegetation patches.

3.2. Model Calibration and Validation

[16] We used measurements of velocity, discharge, and water surface elevation over a range of flow levels to calibrate and validate FaSTMECH. Data were collected using a narrow band acoustic Doppler profiler (ADP) and positioned in real time using a real time kinematic (RTK) global positioning system. For each high-flow event, discharge was measured at the upstream end of the reach, water surface elevation was measured throughout the reach, and velocity profiles were measured along established cross sections. Measurements were collected as close to the peak streamflow as possible; however, storm generated peak flows were difficult to anticipate and were not of sufficient duration for measurement. Excessive debris and nighttime conditions also made measurements infeasible during some peak flows. The nearby Junction City stream gauge record was used to identify the timing and magnitude of peak discharges.

[17] Model runs were calibrated for the measured discharge on sampling dates, and extrapolated values were used to model peak discharges. Model parameters specified by the user in FaSTMECH include discharge, water surface elevation at the downstream boundary, grain size, vegetation roughness, and lateral eddy viscosity. Calibrated runs had measured discharge and water surface elevation throughout the reach. Spatially varying drag was computed for each run using the measured grain size and model-predicted depth, calibrated to water surface elevations measured along the midchannel. Drag coefficients within a vegetated polygon were constant for all flows, but varied between polygons according to species and age class. Lateral eddy viscosity varied from 0.035 in low-flow runs to 0.08 m^2/s in high-flow runs. The lateral eddy viscosity was selected to obtain model convergence, then adjusted slightly to improve correspondence between model predictions and measured water surface elevation. For model runs without corresponding water surface elevation data, a separate 1-D model Hydraulic Design Package for Channels (USACE SAM) [*Thomas and Copeland*, 2002] was used to estimate the water surface elevation at the downstream boundary. Lateral eddy viscosity was applied from the closest model run with calibration data.

4. Field Methods

4.1. Hydraulic Measurements

[18] Discharge and velocity were measured using a boat mounted ADP positioned in real time using RTK GPS. An ADP is a profiling instrument that simultaneously measures water velocities in multiple depth bins. A Sontek narrow band instrument (3 MHz) was used with a measurement frequency of 20 pings per second and bin size of 15 cm. The

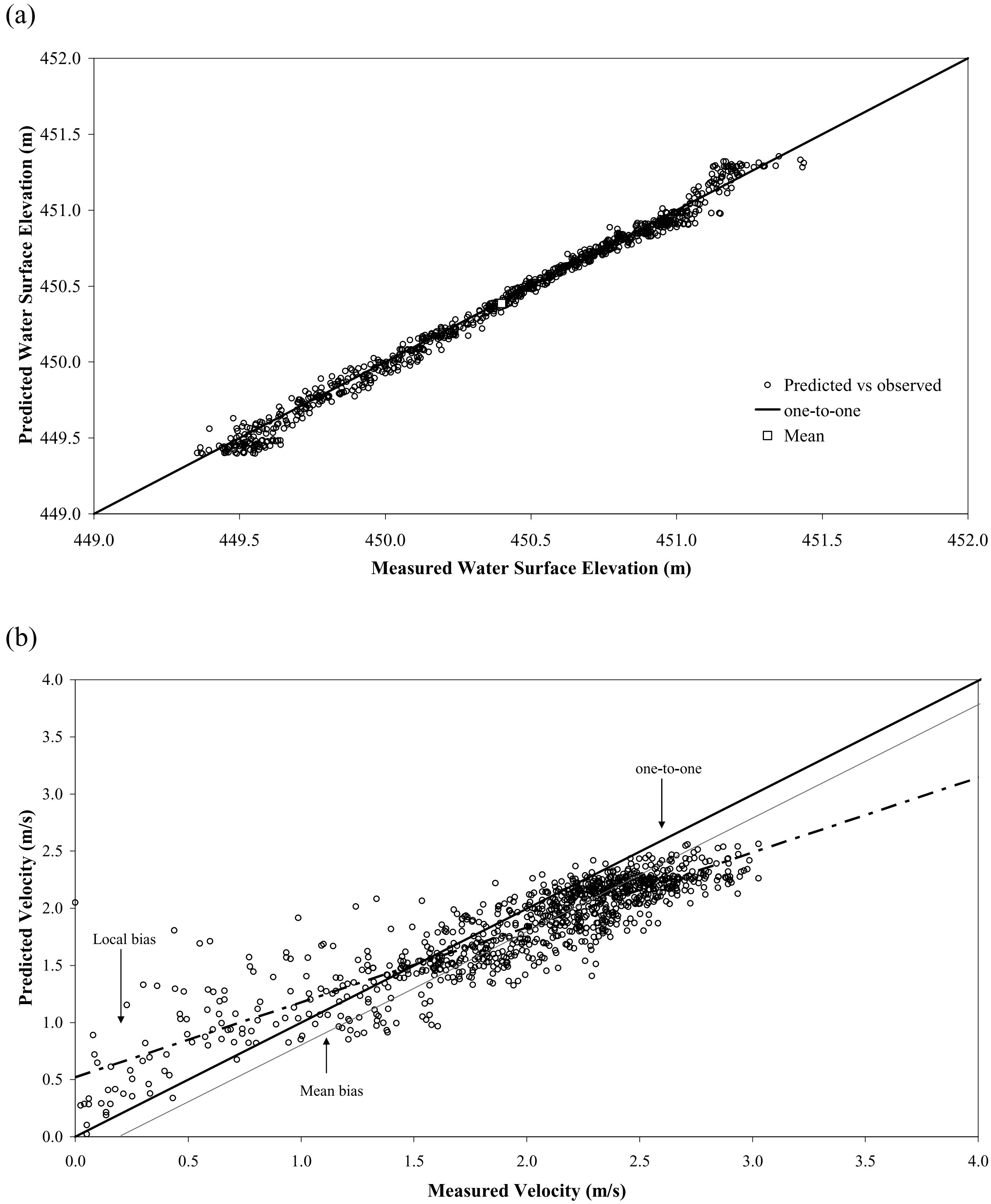

Figure 4. Model verification from the 2005 dam release, discharge of 201 cm^3/s. (a) Measured versus predicted water surface elevation and (b) observed versus predicted depth-averaged velocity for all ADP verification points.

Table 3. Calibrated Model Performance for Dam Release Events[a]

		Velocity Verification						Water Surface Elevation	
Water Year	Measured Discharge (cm^3/s)	Stationary Boat Velocity Profiles[b]	Moving Boat Transects[b]	Average Model Bias (m/s)	Standard Deviation	Average Percent Difference	Correlation Coefficient r	Number of Measured Points	Correlation Coefficient r
2004	162	4	86	−0.09	0.23	−5.5	0.96	356	0.99
2005	201	0	916	−0.17	0.29	−2.0	0.87	862	0.99
2006	223	31	278	−0.05	0.31	−8.7	0.88	209	0.99

[a]Measured velocity was compared to predicted velocity for model validation; water surface elevation was used for model calibration.
[b]Number of sample points.

instrument mounting depth was 30 cm and blanking distance was 20 cm. Pings were averaged in real time over user-specified intervals, also referred to as ''ensembles,'' and rated with a data quality index in the manufacturer's software. The averaging interval was increased as the bed became more mobile, with an averaging interval of 5 s used for flows <200 cm^3/s and 10 s for flows >200 cm^3/s. Data were collected until a minimum of 2400 pings met the data quality specifications (minimum 120 s).

[19] Depth-averaged velocity was estimated from a stationary boat. An assessment of the error associated with these ADP measurements indicates that measurement precision averaged 7.2% of the depth-averaged velocity, determined by the coefficient of variation for ensembles of 31 stationary profiles measured during the 2006 dam release. The standard deviation of these ADP measurements ranged from 0.02 to 0.34 m/s, with an average of 0.14 m/s.

[20] An alternate method of velocity measurement applied the same instrumentation setup and protocols that are typically used to collect discharge measurements with the ADP. For this approach, the boat traveled slowly across a transect at speeds <0.43 m/s, averaging measurements at the same user-specified intervals as velocity profile measurements. Each data point was rated by the Sontek software with a data quality index. Data points that did not meet the data quality specifications were excluded. Transects were measured a minimum of two times, and generally more than three times to exclude potential outliers. This method of velocity measurement is less accurate than standard velocity profiling because velocities are averaged over a larger area. The important advantage of the transect method, and the reason it was included in the study design, is that data of reasonable quality can be rapidly collected over a broader area to provide more comprehensive spatial coverage for model verification. Both methods are adversely affected by vegetation because it creates poor depth readings.

[21] During dam release events, moving boat transects were used to gain insight into the spatial pattern of velocity throughout the reach. Velocity data were not collected during tributary floods because of rapid changes in discharge during the time frame required for measurement. Depth-averaged velocity extracted from the moving boat transects were compared to depth-averaged velocity profile measurements at four transects during the 2006 dam release to assess the loss of precision associated with transect measurements. The comparison is not perfect because the moving boat measurements do not pass directly over the location of stationary velocity profile measurements and the spatial scales of the measurements differ. Depth-averaged velocity measurements were extracted from transects that were within a 2.3 m radius (half the measurement interval) of velocity profiles. The mean difference between methods is 0.04 m/s (standard deviation 0.11 m/s), with a range of −0.12 to 0.27 m/s, resulting in an average error of 1.8%.

[22] Bottom tracking with an ADP can be an additional source of error in velocity measurements. When the streambed is mobile, bottom tracking can produce a systematically lower bias in water velocity measurements [*Rennie et al.*, 2002; *Mueller and Wagner*, 2007]. To avoid this bias we used a high-resolution GPS, Trimble 4700 base station accompanied by a Trimble 4800 rover, as the position reference to allow accurate measurement of water velocity. Bottom tracking was only used as a depth reference, which is unaffected by bed mobility. Calibration of the ADP internal compass was performed prior to each measurement.

[23] Water surface elevation throughout the reach was also measured with high-resolution GPS. The rover was mounted on the boat at the water surface. Measurements were collected midchannel as the boat drifted downstream with the current. Two to three passes were conducted at each discharge. The motor was not engaged to minimize disturbance to the water surface. Occasionally there was poor midchannel GPS coverage in one section of the reach, in this case a person wading along the shoreline used the GPS rover to collect water surface elevation data. Large eddies and side channels were avoided.

4.2. Bed Mobility and Scour

[24] To test model predictions of differential bed mobility we conducted a tracer rock experiment during the 2005 dam release. A total of 336 painted rocks were placed in 21 1 m^2 patches immediately prior to the dam release (Figure 3). Each patch contained 16 tracer rocks with an intermediate diameter of 64 mm. Tracer stones were carefully placed by removing a grain of similar shape and size from the bed and placing a tracer stone in the remaining void space. Patches were located in areas with a broad range of model-generated Shields stress values. Immediately after the dam release, painted rock patches were relocated with total station surveys. The entire surface layer within the patch was overturned to find any tracer rocks that may have been buried. Scour chains adjacent to the patch were also used to indicate potential burial depths. All painted rocks found

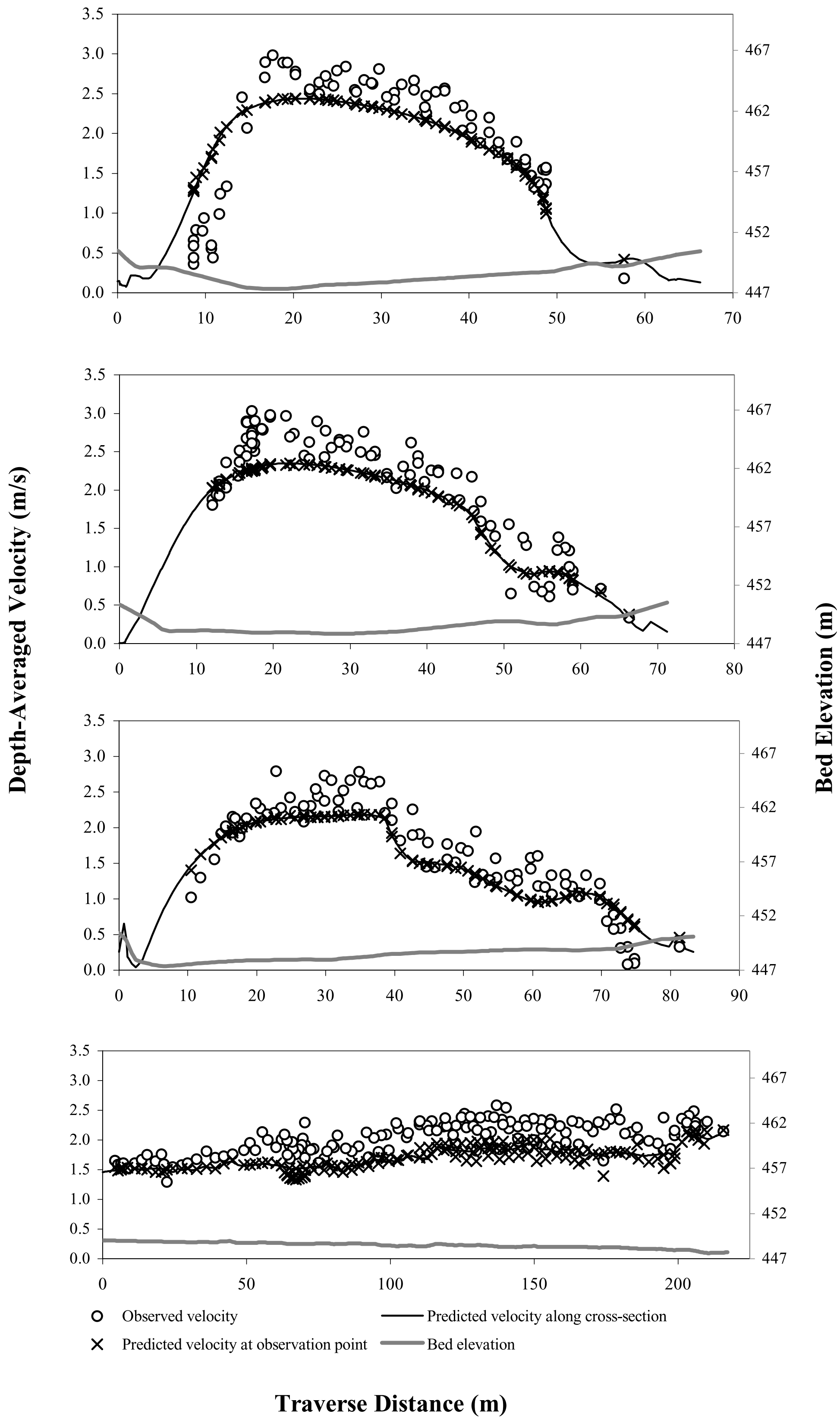

Figure 5. Comparisons between observed and predicted depth-average velocity. The first three plots show cross-section measurements, while the last plot shows a longitudinal section along the channel margin (see Figure 3 for location). Measurements were limited along the ends of cross sections because of boat access into shallow areas with overhanging vegetation.

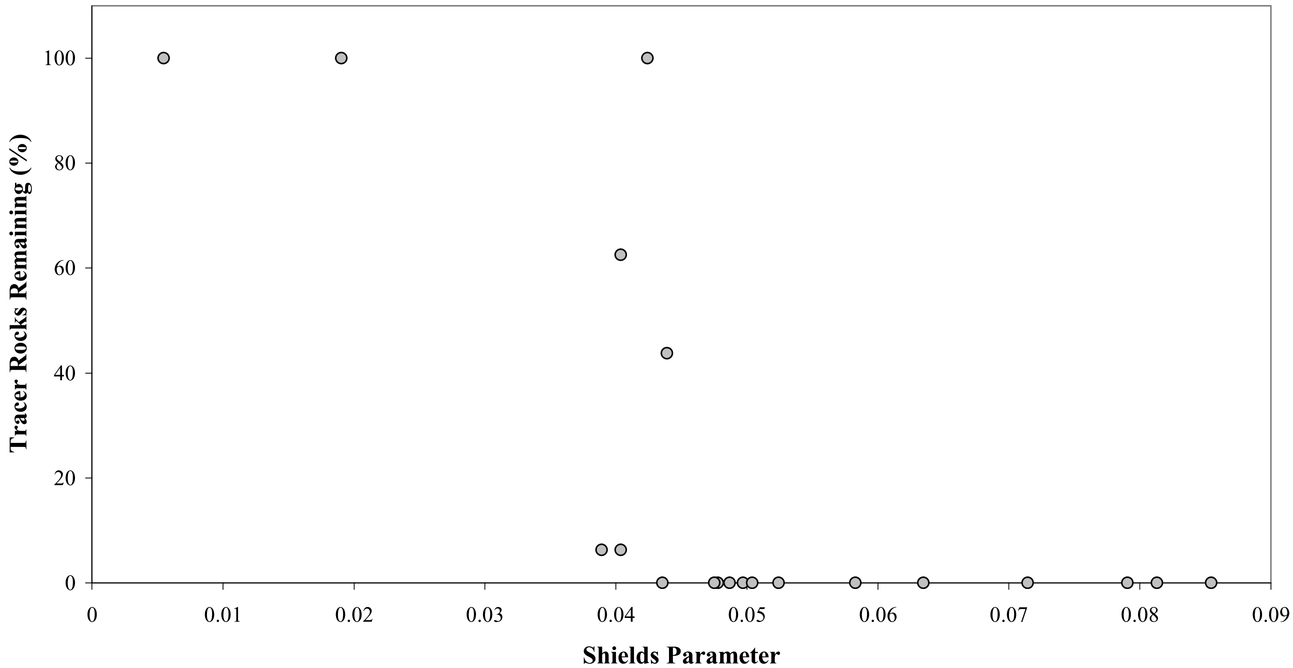

Figure 6. Result of tracer rock experiment conducted during the 2005 dam release. Shields stress values are based on the peak flow model run of 242 cm^3/s.

within a patch were used to calculate the proportion of remaining rocks.

[25] Depths of scour and fill were measured with an array of scour chains throughout the reach. Scour chains were inserted to a minimum depth of 1 m, and a metal bracket marked where the chain exited the bed surface. Chains were placed on cross sections and along the channel margins (Figure 3). The location and bed elevation at each scour chain was determined with total station surveying, and chains were remeasured between high-flow events. One exception occurred in 2006, when flows were not low enough prior to the dam release to reset scour chains following a large tributary-generated flood. Thus, scour measurements in 2006 recorded scour that occurred during multiple events.

[26] One potential source of error in scour chain measurements is the effect of spawning fish. Scour chains in 2004 were installed after the spawning season and thus were not affected. Prior to the dam release in 2004 and 2005, scour chains were checked and reset if necessary. Only data in 2006 could be affected by spawning disturbance because chains were not monitored throughout the water year. However, the number of spawning fish was were very low that year and <30 redds were observed in the study reach so the potential for disturbance was minimal.

4.3. Spawning Site Selection

[27] To locate redds and infer site selection preferences for spawning fish, we mapped redds and developed a low-flow run of FaSTMECH. Biweekly mapping of Chinook salmon redds was conducted in the fall and winter of 2003 and 2005. The location of each redd was recorded with a total station survey point. To account for the large size of salmon redds, hydraulics were averaged within a 3 m circular buffer around each surveyed redd.

[28] Site selection preferences of spawning Chinook salmon were quantified with output from FaSTMECH on the basis of discharge measured during the peak of the spawning season. Base flow in the study reach is generated by dam release flows, which are held at a consistent discharge of 8.5 cm^3/s, and winter base flow from tributaries downstream of the dam. The majority of precipitation during the spawning season falls as snow in high-elevation mountains. A discharge of 14.7 cm^3/s was measured during the peak of the spawning season in 2003 and was used as the reference discharge for spawning-related analyses. This discharge also approximates the average winter base flow during 2003 at the Junction City gauge.

[29] Redd location data collected in 2003 was used to develop a logistic regression equation to predict site selection preferences, and data collected in 2005 was used to verify the predictions. Parameters considered in development of the logistic regression model were grain size (D_{50} and D_{84}), distance to the stream bank (m), water depth (m), water velocity (m/s), and shear stress (Pa). Also considered was a parameter that represented the longitudinal position within the reach, measured as distance from the upstream boundary (m). This parameter was included to explicitly incorporate spatial structure into the statistical model. If spatial structure is important for spawning site selection, the inclusion of the parameter would be expected to significantly increase the amount of variation explained by the model [*Knapp and Preisler*, 1999].

5. Results and Discussion

[30] Two tributary-generated flood events and three dam releases, which ranged from 180 to 473 cm^3/s in peak discharge, occurred during the study period (Table 2). Both tributary-generated floods exceeded the postdam bankfull

a.)

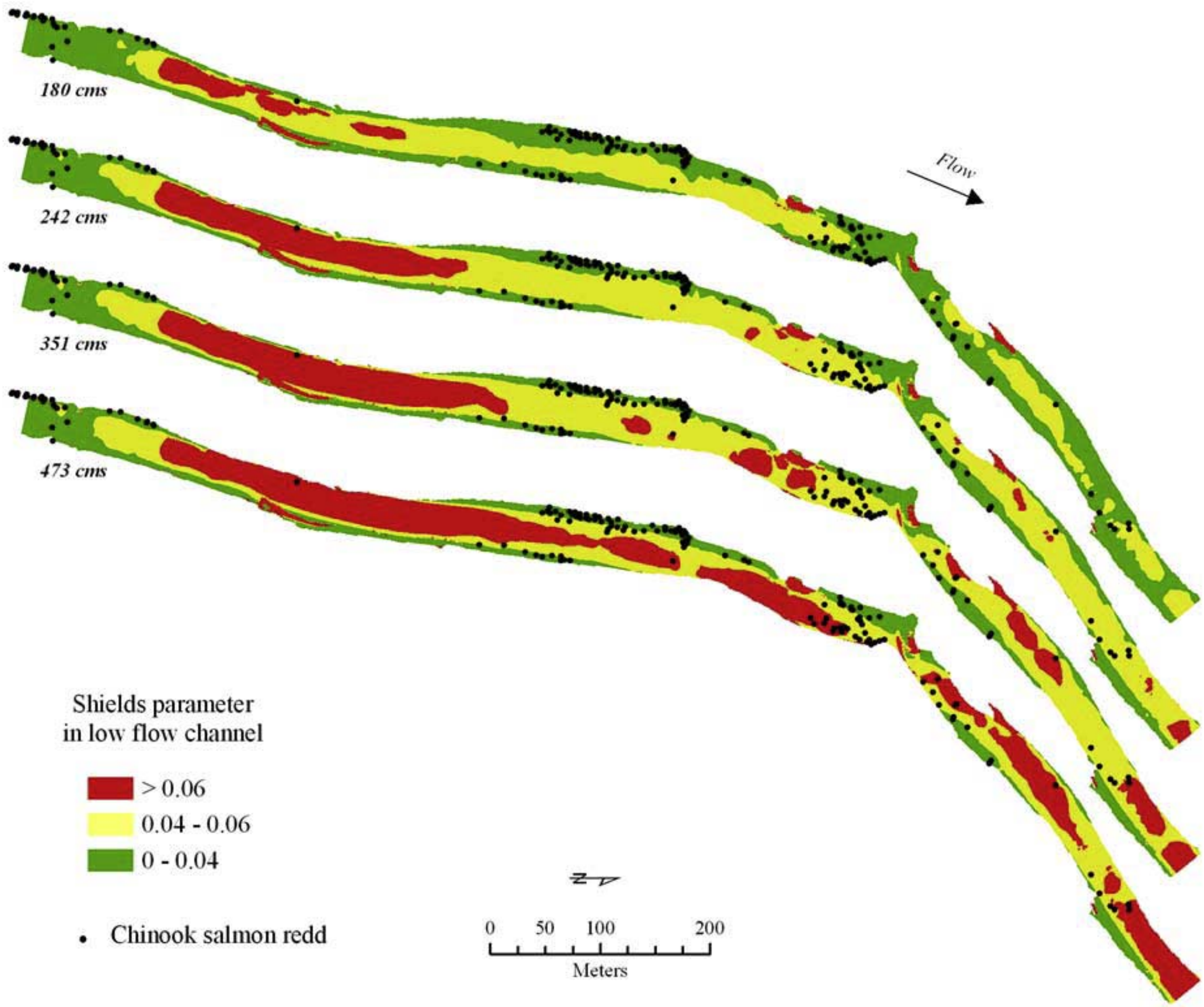

Figure 7. (a) Spatial patterns of Shields stress over a range of discharges and (b) corresponding cumulative frequency distributions. Dashed vertical lines highlight Shields values of 0.04 and 0.06. Data are limited to the low-flow channel to establish comparable areas.

discharge (218 cm^3/s) estimated by *McBain and Trush* [1997] and the maximum potential dam release of 311 cm^3/s. During the initial year of the study, 133 Chinook salmon redds were observed in the study reach. However, subsequent spawning seasons had especially small year classes of spawning fish, with only 20–30 redds observed in the study reach.

5.1. Model Performance

[31] Water surface elevations for all high-flow events were adequately predicted by the model with no mean or local bias (Figure 4a), and correlation coefficients (r) between observed and predicted values exceeded 0.9 (Table 3). The mean bias is the average difference between observed and predicted measurements. The local bias displays the deviation from a one-to-one relationship between observed and predicted measurements [*Gomez and Church*, 1989]. Depth-averaged velocity was slightly underpredicted and had an apparent local bias (Figure 4b). The model tended to overpredict velocity in slow-water areas and underpredict velocity in fast water areas. These results, i.e., good correspondence in water surface elevation and a slight systematic bias in velocity predictions, were consistent among model runs at all discharges.

[32] Model performance was evaluated for each measured discharge. To illustrate the accuracy of the calibrated model for routing flow through the study reach, model-predicted velocities are compared to depth-averaged velocity measured during the 2005 dam release (201 cm^3/s) in Figure 5. Spatial locations for this comparison include three of the most intensively instrumented cross sections and a longitudinal transect adjacent to the channel bank where abundant spawning was observed. These and comparisons at other transects indicate that the model performs well at predicting the local hydraulics and capturing the spatial pattern of velocity variation throughout the study reach. Values of the correlation coefficient (r), which measures the tendency of predicted and observed values to vary together linearly,

(b.)

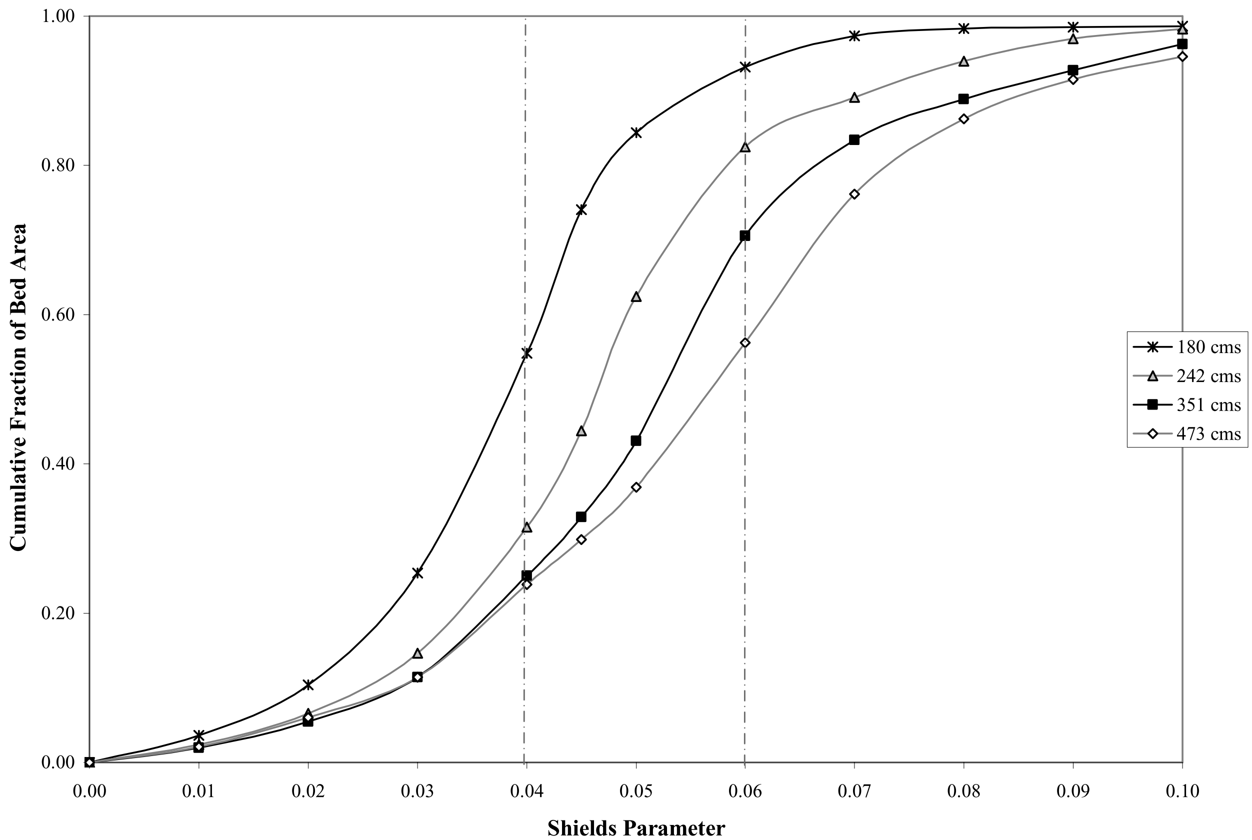

Figure 7. (continued)

ranged from 0.87 to 0.96 across all flow events (Table 3). The average difference in observed versus predicted velocities ranged from −2.0 to −8.7% (Table 3), which is within the same magnitude of error associated with measurement precision.

[33] One unanticipated model result, which is contrary to the expectation of increasing Shields stress with increasing discharge, is that the reach-averaged Shields stress (0.063) for the 2004 tributary flood (peak of 422 cm^3/s) is slightly higher than that of the 2005 tributary flood (reach-averaged Shields of 0.061) that had a higher peak discharge (473 cm^3/s) (Table 2). Both of these flows were tributary-generated floods and had limited verification data. Most of the difference between Shields values is at the downstream end of the reach, where minimal spawning activity occurs. This difference could be due to the water surface elevation estimate at the downstream boundary or expansion of flow into vegetated channel margins where roughness was high. Bedrock protruding into the channel midway through the reach may also influence the reach-averaged Shields stress by causing a backwater effect at higher flows.

5.2. Bed Mobility

[34] Degrees of bed mobility range continuously between states when all particles are stable to those when all are entrained. A bed is ''partially mobile'' when some surface grains of a given size class remain immobile over the duration of a transport event and ''fully mobile'' when all particles are entrained during the event [*Wilcock and McArdell*, 1993, 1997]. As flow strength increases a streambed typically becomes more mobile over an increasing proportion of the channel [*Wilcock*, 1997; *Haschenburger*, 1999]; and full mobility across the entire bed can be achieved as discharge approaches bankfull [*Haschenburger and Wilcock*, 2003]. Understanding the portion of the bed that is entrained and the flow required for full mobility is important for understanding where areas of deep scour may occur and where fine sediment may flush from the subsurface.

[35] For the purposes of mapping mobility fields in a river bed with mixed particle sizes, we parameterize Shields stress (τ^*_{50}) by the median particle size of the bed surface ($D_i = D_{50}$). Values of Shields stress corresponding to partial and full mobility in mixed-size gravel beds measured in field observations and laboratory experiments are highly variable [*Buffington and Montgomery*, 1997; *Wilcock and McArdell*, 1993]. Commonly used values for critical Shields stress for entrainment range from 0.03 to 0.045, which is within the range of the values compiled by *Buffington and Montgomery* [1997] for gravel beds. Laboratory studies indicate that full mobility typically occurs at values of boundary shear stress equal to approximately twice that of incipient motion [*Wilcock and McArdell*, 1993].

[36] Results of our tracer rock experiment indicate that stable portions of the streambed occurred at Shields values <0.04 (Figure 6). Partial mobility occurred in a tightly

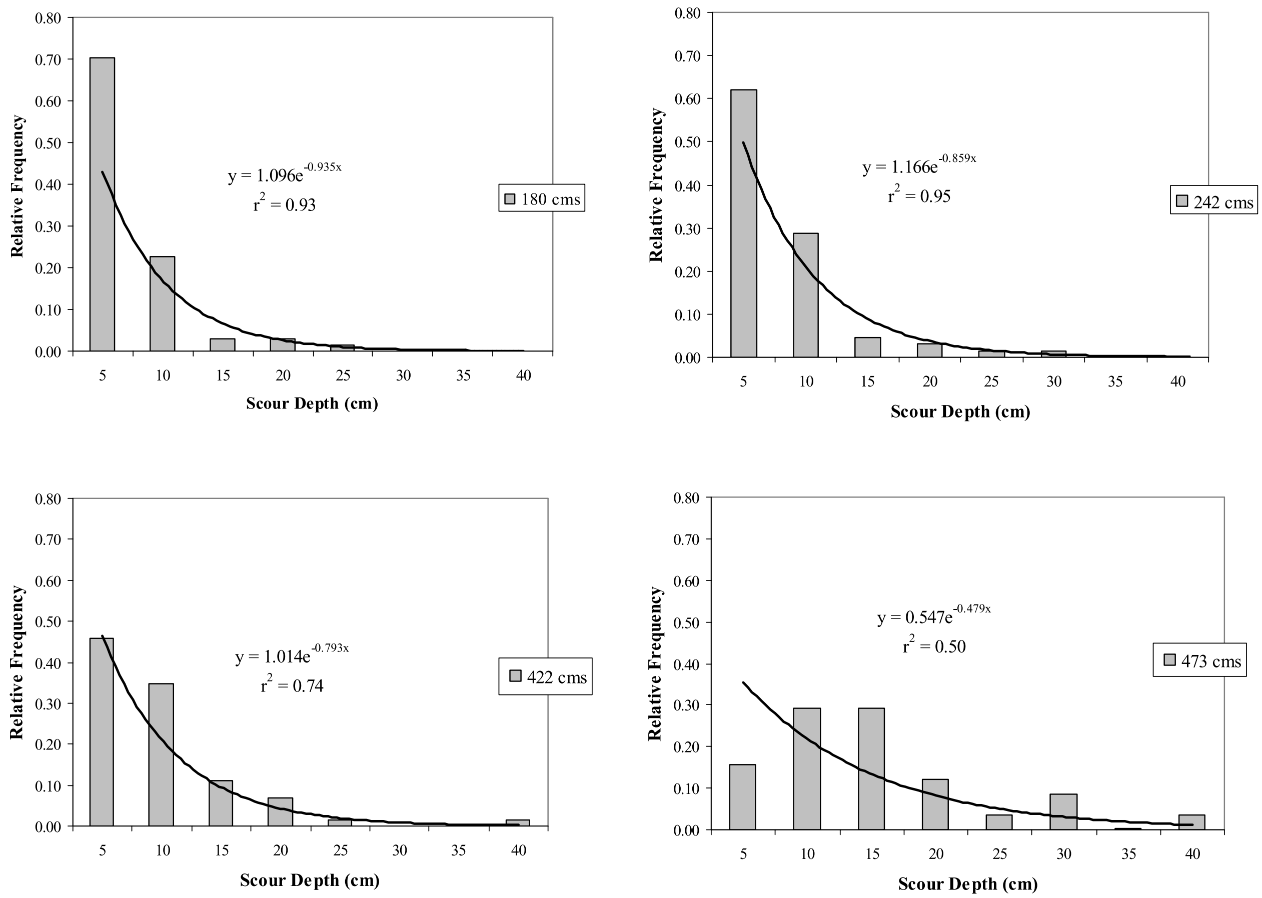

Figure 8. Distributions of scour depth for four high-flow events that occurred within the study period. The potential for redd scour occurs when scour depth exceeds 23 cm [*Evenson*, 2001].

confined range of Shields values between ~0.04 to 0.045, and full mobility occurred where Shields stress exceeds 0.045. However, tracer studies may result in artificially enhanced mobility. Although tracer stones were carefully placed in the streambed, and not left laying on the bed, tracer rocks may still have been more mobile than shear-worked bed particles that tend to imbricate and occupy stable pockets. However, our results indicate that the model is consistently predicting zones of differential bed mobility. Scour chain data indicate that areas of zero scour frequently occurred (20% of 90 scour chain measurements) at Shields values between 0.045 and 0.06. At Shields values >0.06, only 3 of 61 scour chain measurements recorded zero scour. To refine our mobility mapping in light of results from the tracer experiments and scour chains, we divided the partial mobility field into Shields values of 0.04 to 0.06, and full mobility into Shields values that exceed 0.06. These threshold values of Shields stress are consistent with those used by *Lisle et al.* [2000] to map mobility fields in six channels in California and Colorado.

[37] Model-predicted zones of full mobility were limited to a central core that typically followed the thalweg and expanded with increasing flow strength (Figures 7). At a discharge that substantially overtopped the channel banks (351 cm^3/s), 25% of the bed was stable ($\tau^*_{50} < 0.04$), 46% was estimated to be in a state of partial mobility ($0.04 < \tau^*_{50} < 0.06$), and 29% was fully mobile ($\tau^*_{50} > 0.06$). At the highest discharge observed during the study period (473 cm^3/s), the percentage of the bed that remained stable was similar (24%), while areas of partial mobility were reduced (32%) in favor of fully mobile areas (44%). Data used in this comparison was limited to the low-flow channel (reference discharge of 14.7 cm^3/s) to establish comparable areas. These results indicate that even relatively large flood events are unlikely to completely mobilize the armor layer, cause deep scour, or flush fine sediment from a substantial portion of the bed. This is particularly evident for dam releases, which have relatively low flow strengths. For example, during the 2004 dam release (180 cm^3/s) full mobility was limited to 7% of the low-flow channel ($\tau^*_{50} > 0.06$).

[38] Sediment supply plays an important role in bed mobility and channel dynamics [*Dietrich et al.*, 1989]. Sediment-rich channels have greater areas of full mobility; sediment-poor channels have greater areas of partial transport; and both supply regimes have significant areas that are essentially immobile [*Lisle et al.*, 2000]. Limited bed mobility observed in the Trinity River suggests a sediment-poor channel, consistent with other regulated rivers.

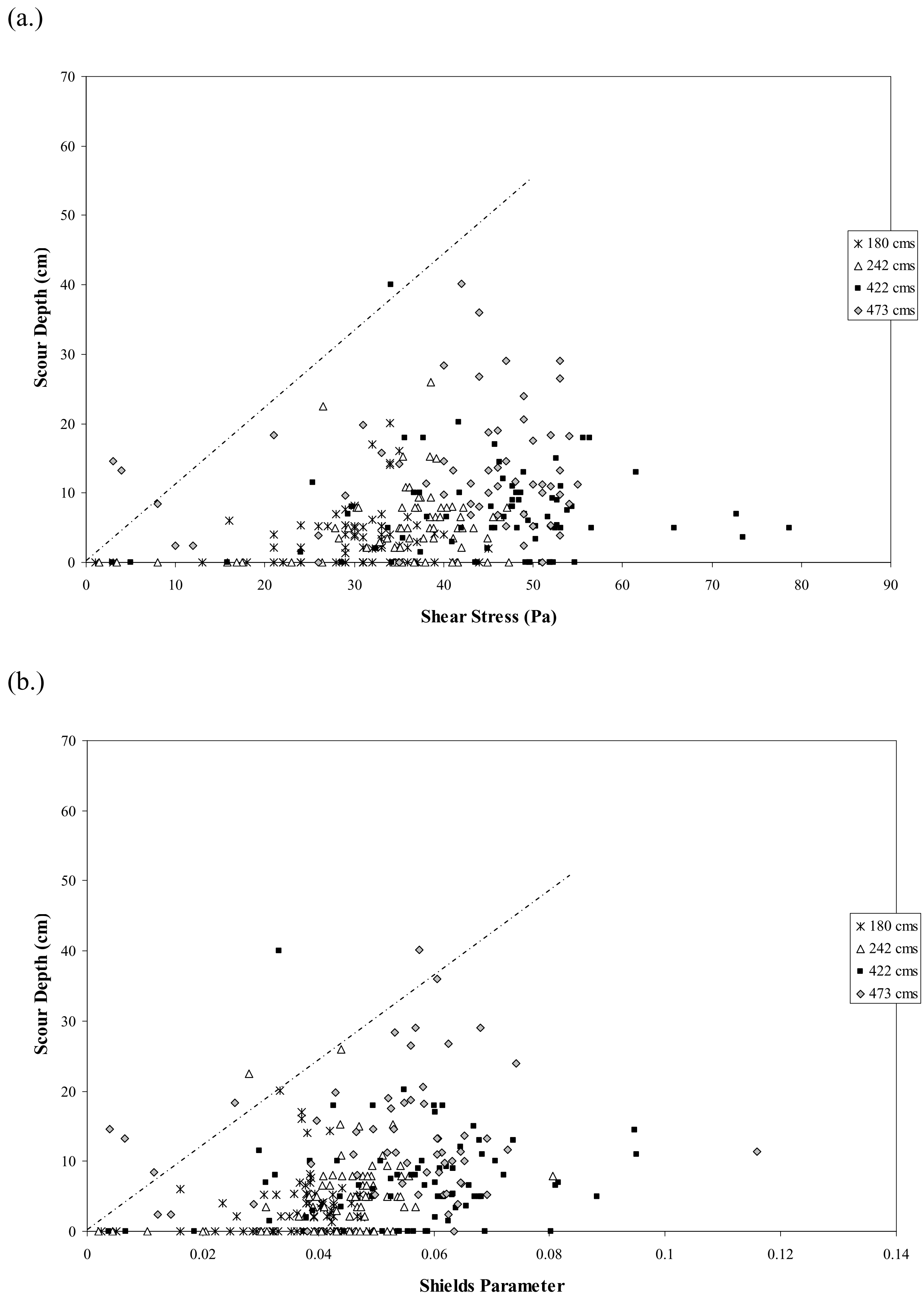

Figure 9. Scour depth relative to model-predicted (a) shear stress and (b) Shields stress. Dashed line represents the “scour potential line.”

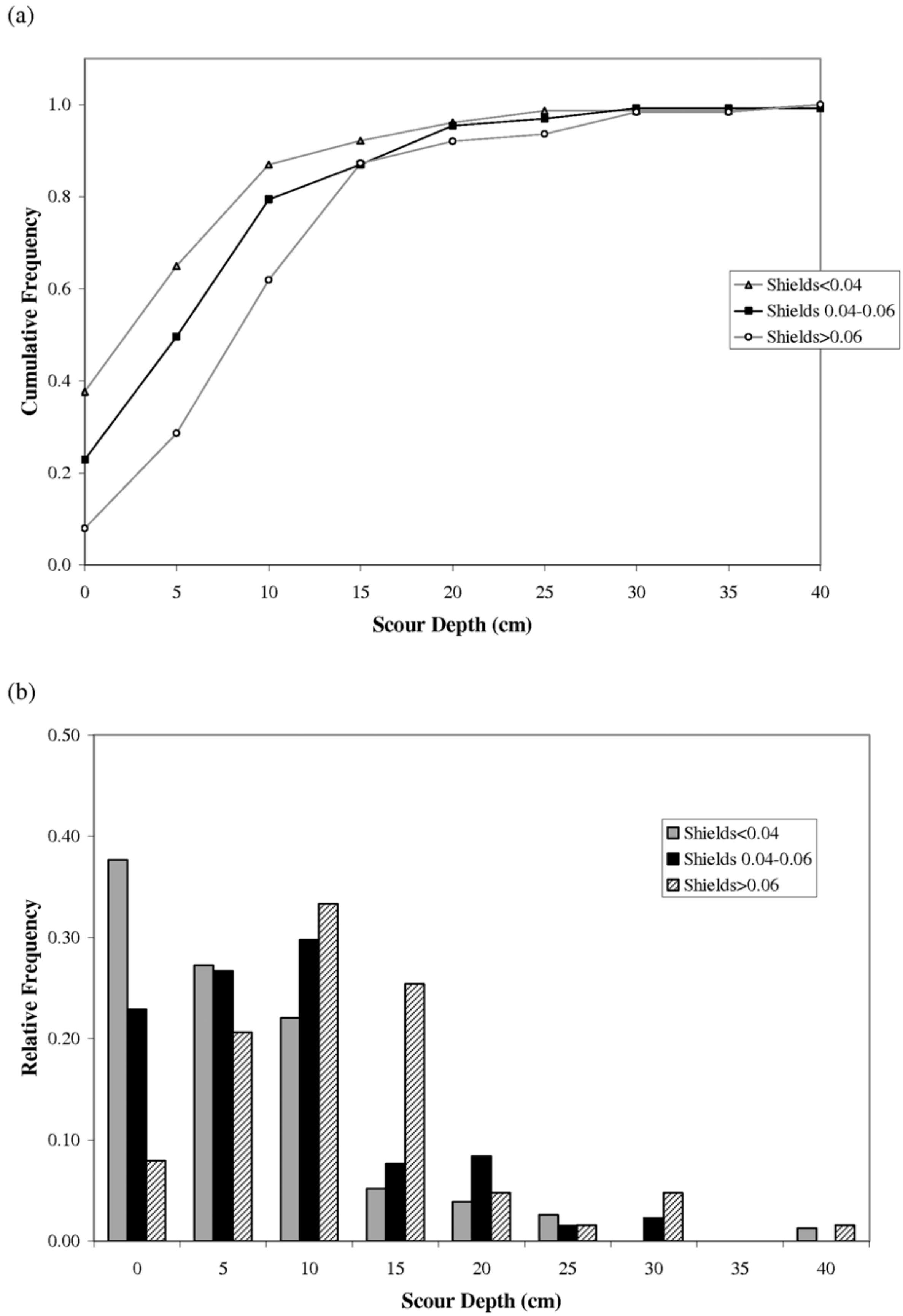

Figure 10. (a) Cumulative frequency distributions of scour depths for a range of Shields values and (b) corresponding relative frequency distributions.

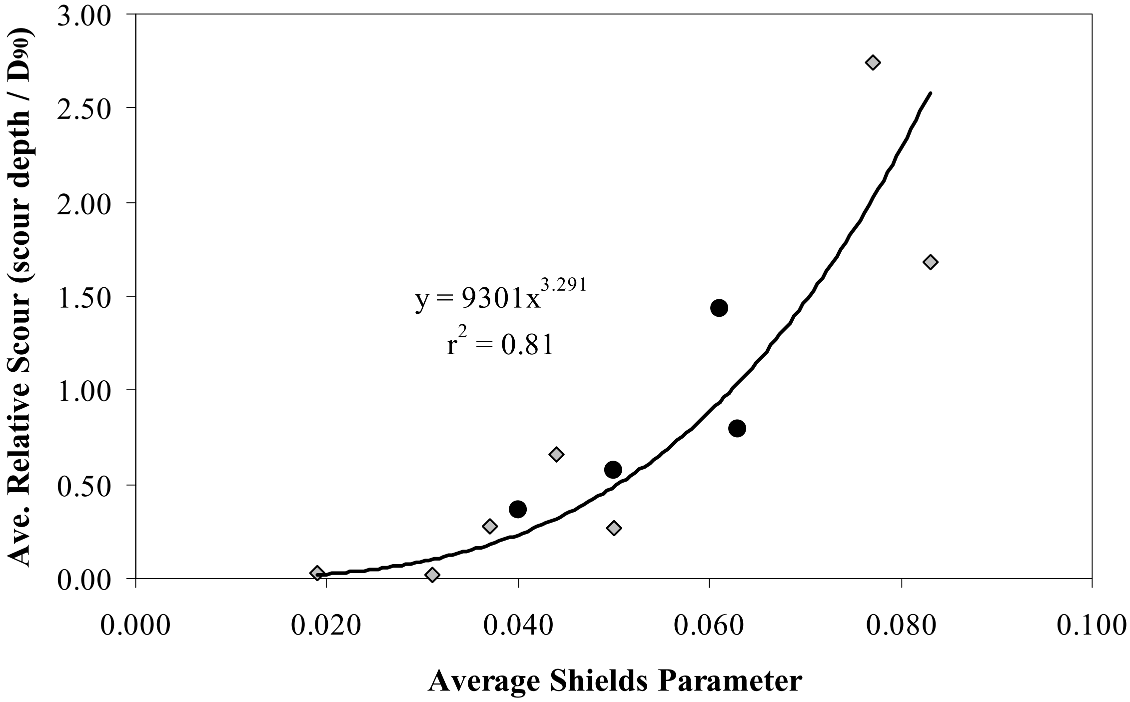

Figure 11. Reach average scour depths relative to reach average Shields stress from a compilation of studies on the Trinity River. Black circles represent data from this study; gray diamonds represent values reported by *Hales* [1999].

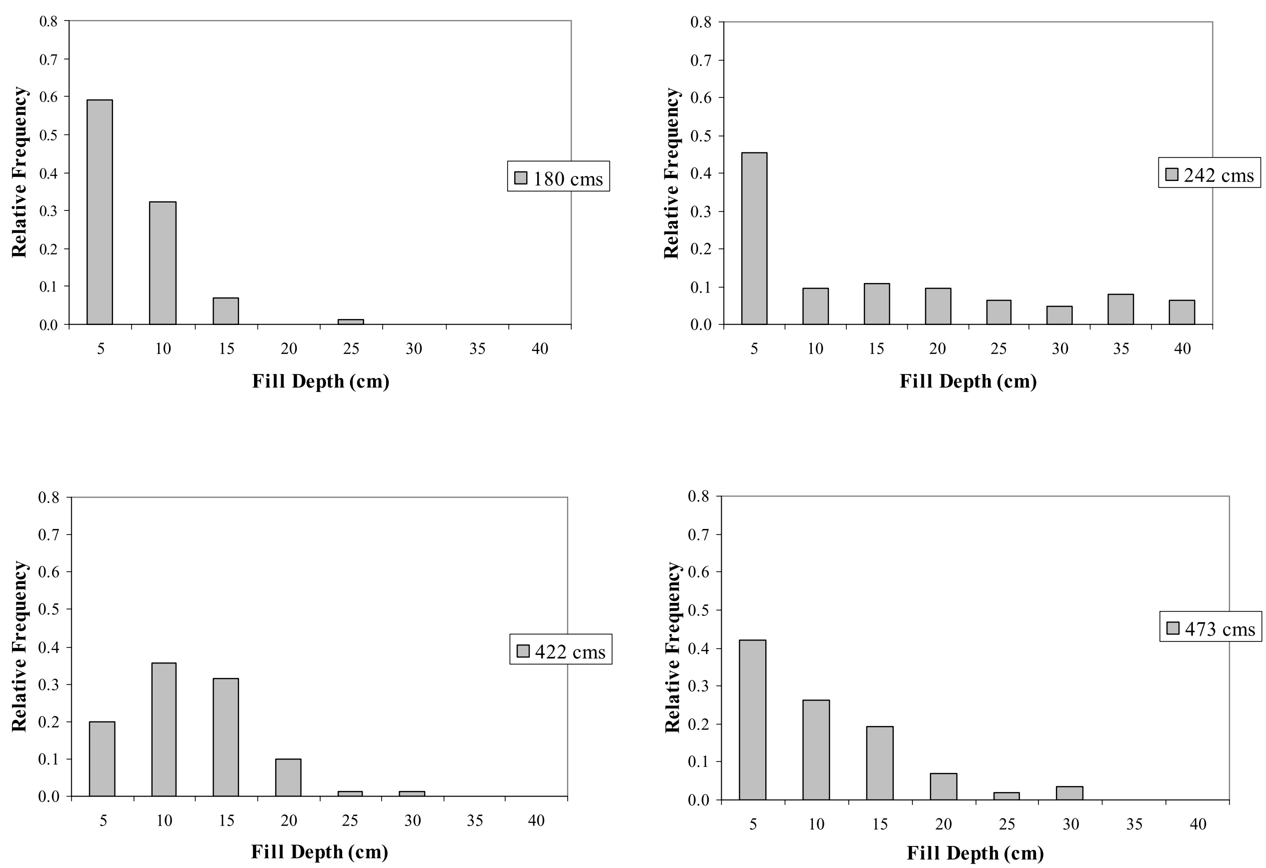

Figure 12. Distributions of fill depth for four high-flow events that occurred within the study period.

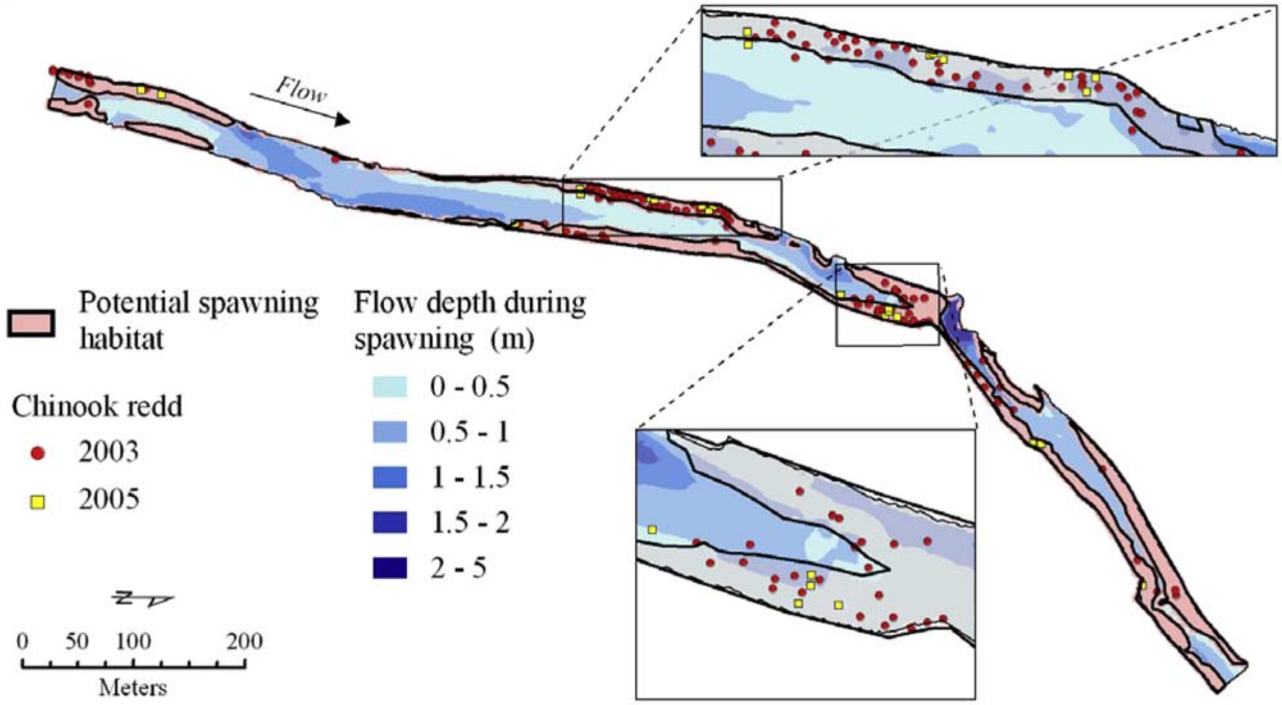

Figure 13. Map of spawning redds surveyed at Sheridan Bar. Pink areas represent locations predicted to be preferred spawning habitat for Chinook salmon on the basis of statistical analysis using a reference discharge of 14.7 cm^3/s during the peak of the spawning season. Enlarged boxes highlight high-density spawning areas.

5.3. Scour Depths

[39] A previous study by *Evenson* [2001] measured egg pocket depths in Chinook salmon redds on the Trinity River using freeze core sampling. She documented an average depth of 23 cm to the top of the egg pocket, and an average depth of 30 cm to the bottom of the egg pocket. Our results from a total of 268 scour chain measurements indicate that scour was not widespread and was rarely deep enough to affect egg pockets over the range of flows that occurred during the study (Figure 8). Similar to previous studies [*Haschenburger*, 1999; *Bigelow*, 2005; *Powell et al.*, 2005], an exponential distribution was a good fit to scour depth data observed at lower flow strengths. A negative exponential distribution indicates that most of streambed experiences little or no scour, while a few areas experience deep scour. However, as flow strength increased more of the bed became fully mobile, and an exponential distribution was not a good fit to the data. Distributions of scour depth in 2006, which included a large tributary-generated flood event and dam release, exhibited a shift in the distribution that was more symmetric, approximating a normal or lognormal distribution (p = 0.14, Shapiro-Wilk normality test). *Powell et al.* [2005] also reported that distributions become less right skewed as flow strength increases, which reflects the increasing frequency and depth of scour at progressively higher flows. This might be expected because areas of no scour are diminished as more of the bed is mobilized.

[40] One could expect shear stress and/or Shields stress to be good predictors of scour depth because they are well correlated with entrainment. Our study was designed to test this assertion. No direct correlation between measured scour depths and model-predicted values of shear stress (Figure 9a) or Shields parameter (Figure 9b) were observed, although an upper limit of scour depth increased with both parameters. Verification of model results lends a high degree of confidence in the model-generated hydraulic values so we do not consider the lack of correlation to be associated with modeling error. On the basis of these results we infer that Shields stress is a necessary but incomplete requirement for predicting scour, and that scour predictions require a probabilistic approach instead of simple correlations. Modeling the local divergence in bed load transport rate may improve scour predictions. Other factors may also contribute to the high degree of variation in the relation between Shields stress and scour depth. For example, our approach could not account for hydrograph fluctuations, flow duration, the rate of change in discharge, temporal variations in bed strength, or fine-scale topographic and grain size variations, which can affect the total depth of scour achieved during an event [e.g., *Balachandar and Kells*, 1997; *Konrad et al.*, 2002].

[41] Although our results indicate a lack of direct correlation between Shields stress and scour, there are distinct probability distributions of scour for given ranges of Shields stress (Figure 10). This, as well as previous studies [e.g., *Haschenburger*, 1999], indicate the stochastic nature of scour. Under conditions of partial mobility there is only a likelihood that particles will be mobilized. Our data indicate that as Shields stress increased, there was a decreasing number of scour chains that recorded no activity (Figure 9). This indicates an increasing probability of scour with increasing Shields stress (Figure 10), and is supported by a statistically significant shift in the distribution of scour depths for Shields categories of <0.04, 0.04–0.06, and

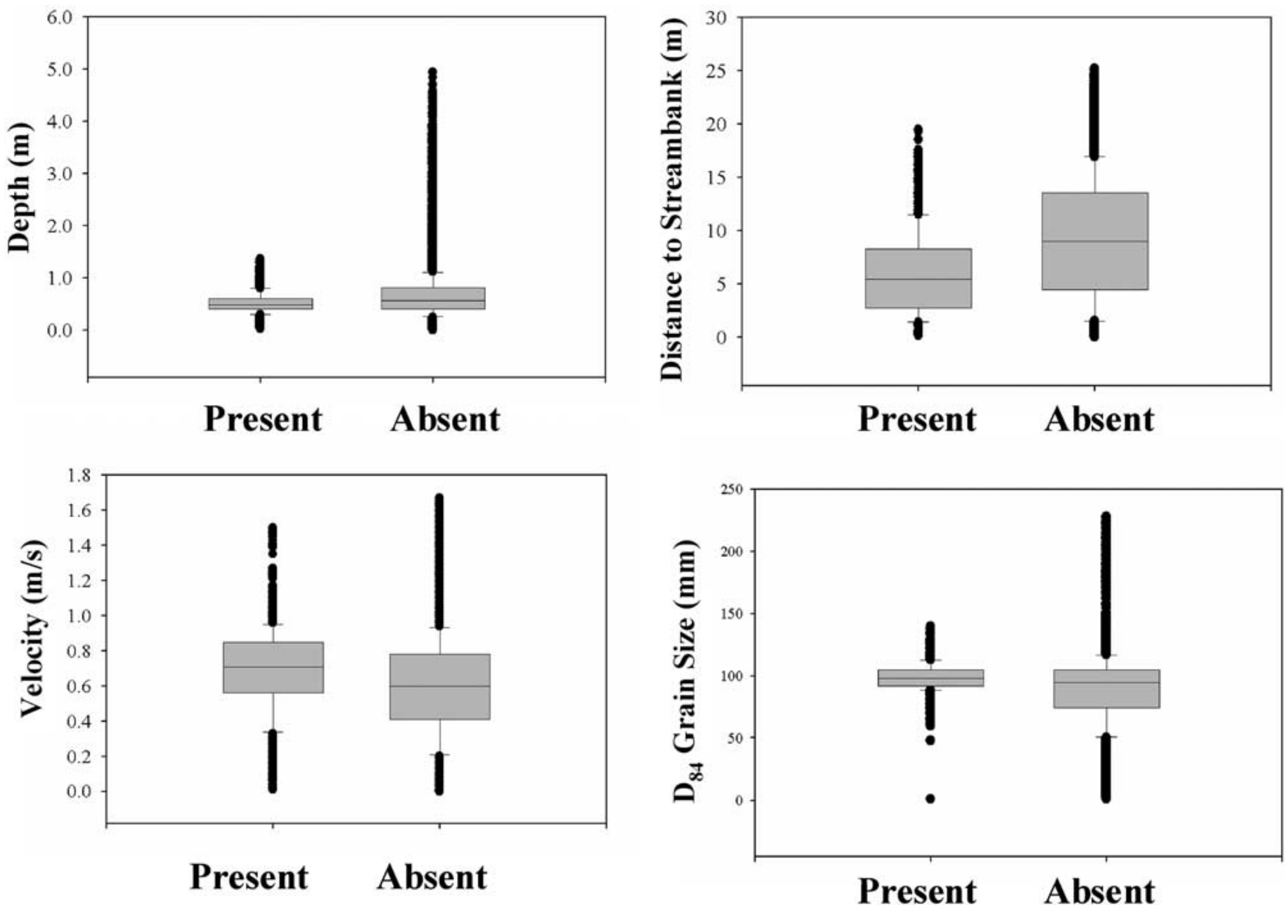

Figure 14. Box plots of depth, velocity, grain size, and proximity to nearest stream bank relative to the presence or absence of spawning redds. Centerline of the box-and-whisker plot represents the median of the distribution; lower and upper edges of the box represent the 25th and 75th percentiles, respectively. Outlier points reside outside the 10th and 90th percentiles.

>0.06 ($p < 0.008$, Kolmogorov-Smirnov test). The maximum depth of scour also increased with increasing Shields stress, suggesting an upper limit to the envelope of potential scour. Statistical comparisons of scour depths based on Shields categories indicate that the distributions shifted toward a greater extent and maximum depth of scour with each successive category ($p < 0.0001$ one-way ANOVA). For $\tau^*_{50} < 0.06$ the shape of the scour depth distribution was exponential. For $\tau^*_{50} > 0.06$ the shape of the distribution shifted and approached normal.

[42] A relationship between reach-averaged Shields stress and reach-averaged scour was developed from a compilation of studies on the Trinity River (Figure 11; modified from *Hales*, 1999). To make comparisons among reaches, this approach quantifies scour depth relative to the surface layer thickness, approximated by the D_{90} grain size. A strong correlation between reach-averaged values was observed (correlation coefficient, $r = 0.90$); which provides additional evidence for a consistent tendency for increasing scour depths with increasing Shields stress.

5.4. Fill

[43] In mobile sediment-rich rivers, deposition may pose a broader risk to egg survival than scour. However, this risk is rarely considered in regulated rivers because of reduced sediment supply. Scour is a convergent process and more localized, while deposition is a dispersive process and more widespread. Similar to results by *Bigelow* [2005] and *Powell et al.* [2005], fill depths in our study did not conform to the exponential model, and show a more uniform distribution (Figure 12). Median total fill depth was 76 mm, which is approximately equal to one D_{84} grain layer. Median net fill depth was 22 mm.

5.5. Spawning Site Selection Preferences

[44] Site selection by spawning Chinook salmon can affect the risk of redd scour and fill by locating redds in areas of the bed that may be more or less likely to be mobilized. Site selection preferences for Chinook were quantified with output from FaSTMECH using a reference discharge of 14.7 cm^3/s and logistic regression analysis. Significant parameters included depth (m), velocity (m/s), D_{84} grain size (m), and distance to bank (m):

$$\text{Logit} = -0.10 + (1.90 * \text{depth}) + (-3.12 * \text{velocity}) + (-4.77 * D_{84}) + (0.19 * \text{bank distance})$$

Longitudinal position within the reach was not a significant parameter, indicating that spatial structure within the reach

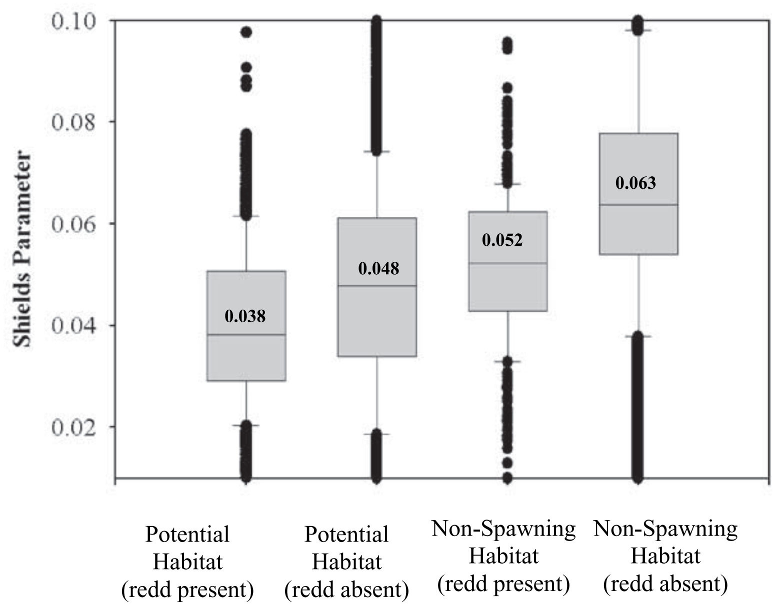

Figure 15. Location of spawning redds relative to model-predicted Shields stress from a subsequent tributary-generated flood event in 2004 (422 cm^3/s). Potential habitat is delineated from statistical analysis of depth, velocity, grain size, and proximity to stream bank (see text for details). Occupied habitat indicates a redd was present prior to the flood event. Centerline of the box-and-whisker plot represents the median of the distribution (labeled value); lower and upper edges of the box represent the 25th and 75th percentiles, respectively. Outlier points reside outside the 10th and 90th percentiles.

was unsubstantial. From the logistic regression equation, and a logit probability threshold of 0.5, preferred spawning areas were predicted and spatially identified (Figure 13). Of the 133 Chinook salmon redds surveyed during the winter of 2003, 82% occurred in areas predicted to be preferred spawning habitat. To independently test our predictions, we surveyed Chinook salmon redds during the peak of the spawning season in 2005. Of the 20 redds surveyed during this low return year, 90% occurred in areas predicted to be preferred spawning habitat. The remaining 10% of redds occurred within 6 m of predicted habitat.

[45] Our results indicate that Chinook salmon are preferentially using relatively shallow, high-velocity areas with coarse substrate and in close proximity to stream banks. Thus, spawning fish are utilizing a narrow range of habitats relative to what is available throughout the river channel (Figure 14). These site preferences correspond to areas of the streambed that are least likely to become mobilized or at risk of deep scour during high-flow events on the basis of predicted Shields stress values from a large tributary-generated flood event (422 cm^3/s) that occurred while the eggs and embryos were residing in the subsurface. Shields values were significantly lower in areas predicted to be potential spawning habitat compared to ambient bed areas (Figure 15, $p < 0.001$, one-way ANOVA). Scour and fill depths measured during the tributary flood (Figure 16) also indicate that scour depths were shallower in areas predicted to be potential spawning habitat ($p = 0.002$, two-sample t test), while fill depths were not significantly different ($p = 0.3$, two-sample t test).

[46] Because redds are being constructed in areas of inherently lower mobility, they have a lower risk of scour than the surrounding bed area. Similar to studies by *Lapointe et al.* [2000] and *Montgomery et al.* [1996], our results suggest that extremely large flood events will be necessary to mobilize and deeply scour areas of the streambed that are preferentially used for spawning. Specifically, *Lapointe et al.* [2000] quantified the reach-scale probability of redd scour during flood events that affected Atlantic salmon habitat. These authors found that the average probability of redd scour, defined as net scour >30 cm in selected riffles, ranged from as little as 5% during annual floods to only 20% for an extreme, multicentury recurrence flood. Similarly, a study by *Montgomery et al.* [1996] compared scour depths to egg pocket depths in western Washington and found that only a small portion of the channel scoured deeply enough to affect buried eggs during a nearly bankfull flood event. The tradeoff for spawning in relatively stable portions of the bed is that flushing of fine sediment from the subsurface occurs very infrequently and gravel permeability may limit embryo survival.

[47] An ancillary consideration when assessing the risk of redd scour is the streambed disturbance caused by redd construction, which has the potential to affect bed mobility and scour. On the basis of theoretical calculations, *Montgomery et al.* [1996] concluded that spawning-related bed surface coarsening, sorting, and form drag reduce grain mobility and lessen the risk of redd scour. However, *Montgomery et al.* [1996] also hypothesized that spawning-related bed loosening may partially counteract reduced grain mobility caused by the aforementioned factors. *Rennie and Millar*

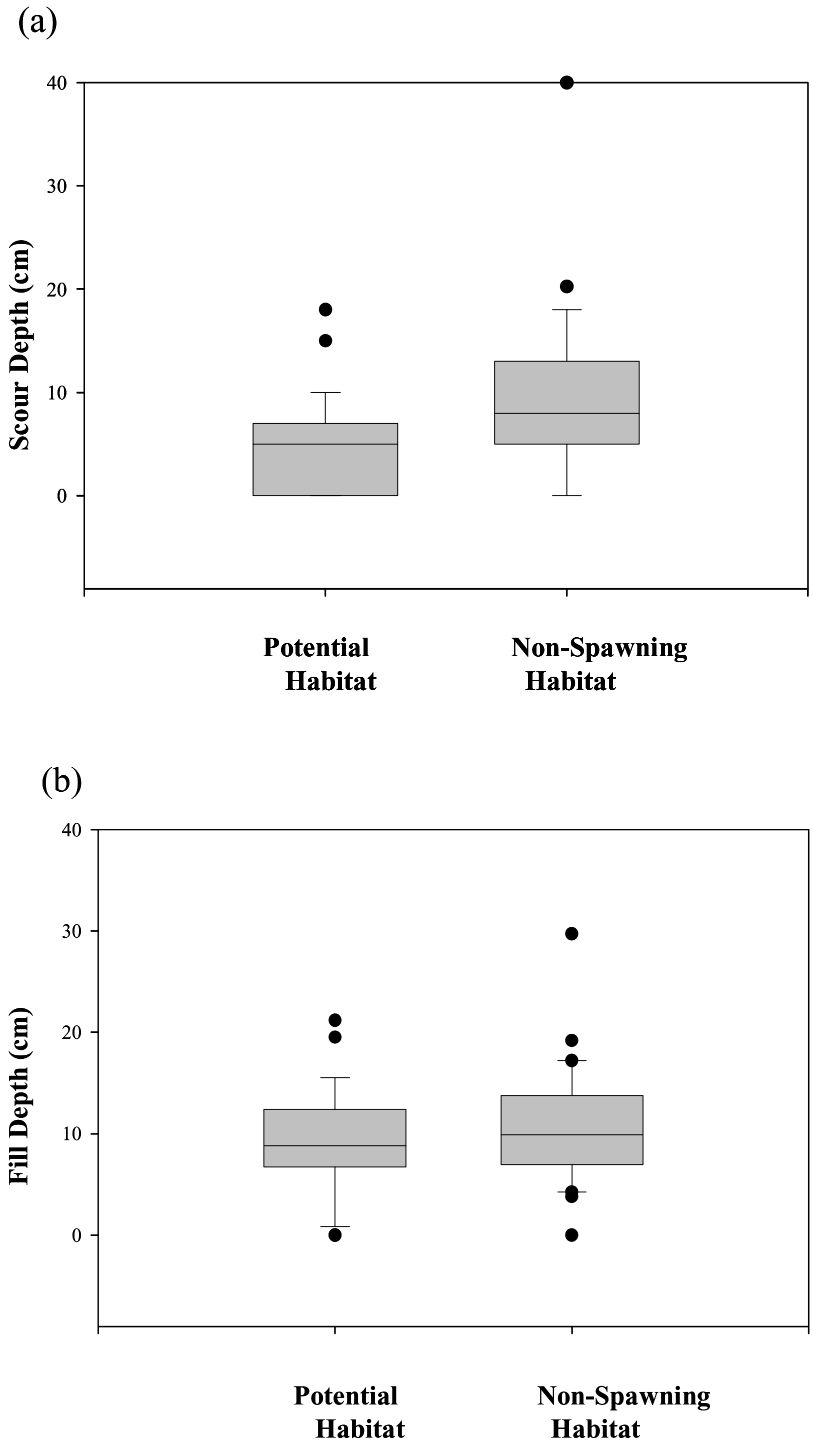

Figure 16. (a) Scour and (b) fill depths attributed to the 2004 tributary-generated flood event (422 cm^3/s) relative to areas of predicted spawning habitat.

[2000] found no difference between scour depths in egg pockets versus the adjacent bed.

6. Risk Assessment

[48] We propose that the best method for predicting scour depths is a probabilistic approach based on observed distributions of scour and the upper limit of potential scour predicted from spatially explicit modeling of Shields stress (Figure 9b, referred to hereafter as the "scour potential line"). The first requirement for scour is mobility of the bed surface. Our results demonstrate that bed mobilization can be accurately predicted with hydrodynamic modeling. In areas identified as potential spawning habitat, the envelope of potential scour and the probability distributions of scour depths for different Shields categories (Figure 10a) can be used to characterize the risk of redd scour (Table 4). For Shields stress <0.04 there is a "very low risk" of redd scour

Table 4. Categorizing the Risk of Redd Scour and Fill on the Basis of Modeled Shields Stress and the Distribution of Scour Depths Observed at Sheridan Bar

Shields Stress Category	Mobility Class	Scour Potential Line	Probability of Scour >23 cm[a] (%)	Probability of Scour >30 cm[b] (%)	Probability of Net Fill >23 cm (%)
<0.04	stable	greater than egg pocket depth	<2	<1	8
0.04 – 0.06	partial mobility	encompasses egg pocket	3	<1	12
>0.06	full mobility	greater than egg pocket depth	8	2	2

[a]Average depth to the top of the egg pocket documented by *Evenson* [2001].
[b]Average depth to the bottom of the egg pocket documented by *Evenson* [2001].

because the bed is relatively stable and the scour potential line does not exceed the average depth to top of egg pocket (23 cm) (Figure 9). For Shields values between 0.04 and 0.06 the bed is most likely to be in a state of partial mobility and there remains a "low risk" of redd scour. Within this range of Shields values the envelope of potential scour encompasses the entire depth of the egg pocket (23 to 30 cm); however, the scour potential line represents the tail of a skewed distribution. On the basis of the distribution of scour depths for categories of Shields stress (Figure 10), the probability of scour >23 cm where Shields stress is between 0.04 and 0.06 is only 3%. For Shields stress >0.06 the streambed is considered fully mobile and there is a "moderate risk" of redd scour. Scour potential exceeds the egg pocket depth; however, the probability of scour >23 cm is still very low (8%). We propose that this strategy for assessing the risk of redd scour is transferable to other portions of the Trinity River on the basis of the strong relationship between reach average scour depths and reach average Shields stress measured in multiple reaches of the river (Figure 11).

[49] To assess the risk of sediment deposition, we used the same approach used for scour. But unlike scour, the critical depth of fill that impacts fish survival is unknown. As a first approximation, we assume that net fill that doubles the initial depth of egg burial (23 cm) would impact emergence success. This thickness is nearly equal to that (25 cm) used by *Phillips et al.* [1975] in a laboratory experiment to test the ability of coho salmon (*Oncorhynchus kisutch*) and steelhead trout (*Oncorhynchus mykiss*) to emerge from a layer of gravel with varying fractions of sand (1–3 mm). Approximately one half of the fry survived to emerge when sand composed 30% of the bed, which is typical of bed material in many gravel bed rivers. The probability of net fill >23 cm was highest (12%, Table 4) in partially mobile areas ($0.04 < \tau_{50}^{*} < 0.06$). This relatively high likelihood of fill exceeds the risk posed by scour for all Shields categories. In contrast to the increased risk of scour in fully mobile areas ($\tau_{50}^{*} > 0.06$), the risk of fill was lowest in this portion of the bed.

[50] Because fish are spawning in areas of the streambed that are inherently less mobile and prone to deposition, redds may be more susceptible to the adverse effects of both coarse and fine sediment deposition than ambient bed areas. Fine sedimentation reduces oxygen delivery to eggs and embryos, and reduces the ability of juvenile fish to emerge through gravel pores. Salmon can improve spawning gravel quality by altering bed texture and increasing permeability during the act of redd construction [*Kondolf et al.*, 1993]. Thus redd construction will locally remove some fine sediment from incubation habitat; however, redeposition of fine sediment will compromise egg and embryo survival. Furthermore, flushing flows designed to release fine sediment from the streambed [*Wilcock et al.*, 1995; *Kondolf and Wilcock*, 1996] may not benefit preferred spawning habitat because they correspond to areas that will require exceptionally high flows to be mobilized. This suggests that identifying potential spawning habitat is especially important when establishing monitoring strategies that assess the storage of fine sediment in the substrate because spawning habitat may have substantially different characteristics than ambient bed areas.

7. Conclusions

[51] Substrate entrainment and transport during high-flow events is necessary to maintain the long-term productivity of riverine habitat. However, flood disturbance can also pose a risk to salmonid eggs and embryos residing in subsurface incubation habitat. In order to assess the risk of scour and fill in spawning areas during natural and dam release floods, our study developed an understanding of the relations among river discharge, bed mobility, and scour and fill depths in areas of the streambed heavily utilized by spawning salmon. By coupling numerical flow modeling and empirical data, we quantified spatially explicit zones of differential bed mobility and identified specific areas where scour and fill is deep enough to impact redd viability. Spatial patterns of bed mobility, based on model-predicted Shields stress, indicate that a zone of full mobility was limited to a central core that expanded with increasing flow strength. The likelihood and maximum depth of measured scour increased with increasing modeled Shields stress. However, our data also revealed that redds were preferentially located in shallow, high-velocity areas with relatively coarse substrate and in close proximity to stream banks. These site selection preferences correspond to areas of the streambed that were least likely to become mobilized or risk deep scour during high-flow events.

[52] Statistical modeling of site selection preferences of spawning Chinook salmon provided a means of predicting potential spawning habitat throughout the study reach. Identifying potential spawning habitat is important for predicting where fish will lay their eggs, and past studies have successfully developed statistical models of habitat preferences for salmonids [*Knapp and Preisler*, 1999]. By quantifying the risk of scour for zones of differential

mobility, and comparing the spatial overlap with spawning habitat, we identified that fish are laying eggs in areas that are least likely to be mobilized or at risk of deep scour during high-flow events. These results indicate that salmon are well adapted for reproductive success in flood-prone systems and that excessive mortality due to redd scour is unlikely, even during major flood events. Although salmon cannot "know" what portions of the streambed will be stable at high flows, they can select spawning areas on the basis of the tangible features of depth, velocity, substrate size, and distance to the stream bank. Natural selection will also enhance the preference for spawning in areas where survival is greater. Because eggs and embryos experience less mortality in stable areas of the bed, progeny will imprint and return to their natal sites and thus enhance site selection preferences that intensify survival.

[53] The most unexpected outcome of our study was that sediment deposition may pose a greater risk to egg and embryo survival than scour because scour is typically concentrated in a small portion of the channel, whereas fill is more uniformly distributed across the bed. Even though the Trinity River has a deficit of coarse sediment below the dam, the risk of fill that doubled the initial egg burial depth was greater than the risk of scour during high-flow events. Fill can reduce intergravel flow to incubating embryos and entomb young fish attempting to emerge from the gravel. However, reliable assessments of the risk of fill for salmonid embryos must await better relations between fill depth and the fraction of eggs that survive to emerge from the streambed.

[54] Limited scour and persistent deposition of sediment on the bed of the Trinity River may pose a problem for long-term fish production. Many of the tributary catchments downstream of the reservoir on the Trinity River are composed of decomposed granitic soils, which are experiencing accelerated erosion due to land use practices [*Wilcock et al.*, 1996]. Thus, sediment supplied downstream of the dam contains a large fraction of fine sediment that can be deposited in spawning areas. Although salmon have evolved successful adaptations for surviving floods, they may be poorly adapted to the impacts of increased sedimentation.

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