Patterns of Gravel Scour and Fill after Spawning by Chum Salmon in a Western Washington Stream

DAVE E. SCHUETT-HAMES
Northwest Indian Fisheries Commission,
6730 Martin Way East, Olympia, Washington 98506, USA

N. PHIL PETERSON
Simpson Timber Company,
Post Office Box 460, Shelton, Washington 98584, USA

ROBERT CONRAD
Northwest Indian Fisheries Commission,
6730 Martin Way East, Olympia, Washington 98506, USA

THOMAS P. QUINN*
University of Washington, School of Fisheries,
Box 355020, Seattle, Washington 98195, USA

Abstract.—The patterns of gravel scour and fill during the incubation period of chum salmon Oncorhynchus keta were studied in Kennedy Creek, a low-gradient alluvial channel draining into southern Puget Sound, Washington. In 1991–1992, scour occurred during two storms having estimated return intervals of 1.4 years and less than 1 year. Scour to median egg pocket depth (0.2 m) occurred at 20% of the monitored locations during the greater event and at 1.3% during the lesser event. Differences in depth of scour were observed between the two study reaches and among habitat units (rifles, lower rifles, glides, pool tailouts, and pool lateral bars) within reaches. Average depth of scour in a relatively simple, straight, and narrow reach of the creek was 0.075 m, whereas average scour was nearly twice as deep (0.140 m) at a more complex, sinuous, and wide reach. Scour to median egg pocket depth occurred at 28% of the monitors in the complex section compared with only 9% in the simpler section. Average scour depth and the percentage of monitors scoured to median egg pocket depth were greater in pool-associated habitats (pool lateral bars and pool tailouts) than in riffle-associated habitats (rifles, lower rifles, and glides). Chum salmon often used sites such as pool tailouts that would be suitable under moderate flow conditions but that would be prone to scour under higher flow events. The relatively widespread scour to egg pocket depths that we observed during a bank-full event indicates that scour can be a significant source of egg-to-fry mortality for salmonids spawning in low-gradient pool–riffle channels.

Female salmonids select and compete for spawning sites from the range of habitats available in their natal stream. The sites used by the population reflect a combination of preferences for physical attributes (Smith 1973; Beland et al. 1982; Parsons and Hubert 1988; Knapp and Vreedenburg 1996; Fukushima and Smoker 1998) and competition. The females bury their eggs within streambed substrates where the embryos complete development before emerging into the free-flowing stream several months later. Many salmonid species in coastal regions of the Pacific Northwest spawn in fall; the embryos develop in the streambed through the winter storm cycle, when heavy precipitation causes frequent freshets. Occasionally, the discharge reaches a sufficient stage to mobilize the streambed, placing embryos at risk of being shocked, crushed, or displaced (McNeil 1966).

The scour of substrate particles is a fluvial process associated with transport of bedload material and adjustment of channel morphology. Burial of eggs under the gravel is probably an adaptation to this dynamic incubation environment. By burying their eggs in the streambed, salmonids reduce the probability that scour will reach them (see review by DeVries 1997). The digging action of the female coarsens the surface of the bed (Kondolf et al. 1993), which may increase the threshold discharge required to initiate scour (Montgomery et
al. 1996) and reduce the proportion of fine particles in the egg pocket (Peterson and Quinn 1996a).

Scour of eggs and developing alevins can be a significant cause of mortality to salmonids. McNeil (1966) recorded numerous instances of egg loss due to gravel movement in spawning areas of pink salmon *Oncorhynchus gorbuscha* and chum salmon *O. keta* in southeast Alaska. Mortality regularly exceeded 50% and reached 90% in one instance. Tripp and Poulin (1986) documented scour in 12 salmon streams in the Queen Charlotte Islands of British Columbia. Mean scour depth ranged 5–31 cm among streams, and estimated mortality from scour to egg pocket depth ranged 0–70% for coho salmon *O. kisutch*, 2–80% for chum salmon, and 4–90% for pink salmon. Scour depth was greatest in stream reaches responding to mass wasting related sediment input and channel disturbance. Frissell et al. (1996) documented scour in the spawning microhabitats of 11 coastal southwest Oregon streams over a period of several years where the recurrence interval of the peak flows ranged from less than 2 to 5 years. The average percentage of sites scoured to 15 cm ranged from 0% to 30%. Scour was more frequent in reaches of streams highly disturbed by sediment input from mass wasting associated with forest roads and timber harvest. In one instance, 75% of the redds of chinook salmon *O. tshawytscha* were either scoured or deeply buried during a relatively small peak flow (R. K. Nawa, C. A. Frissell, Flathead Lake Biological Station, University of Montana, and W. J. Liss, Department of Fish and Wildlife, Oregon State University, personal communication).

Depth of scour is generally believed to be controlled by magnitude and duration of stream discharge and streambed texture; however, factors such as woody debris loading, sediment availability, channel morphology, and the sorting of gravel by spawning fish may also influence patterns of scour and fill (Lisle 1989; Montgomery et al. 1996). In this paper we examine how scour processes affect the reproductive success of large, fall-spawning salmonids by testing the hypotheses that depth of scour varies with (1) magnitude of peak discharge, (2) habitat type, and (3) reach-scale channel morphology. This study was part of a series of coordinated investigations of the incubation environment of salmonids, using chum salmon in Kennedy Creek, Washington, as the model system. Other studies documented egg burial depth, changes in the egg pocket architecture (Peterson and Quinn 1996a), and intragravel dissolved oxygen levels during the incubation period (Peterson and Quinn 1996b). Data from these studies were used to examine the effect of substrate sorting and coarsening resulting from redd construction on the probability of scouring to egg pocket depth (Montgomery et al. 1996).

**Methods**

Kennedy Creek is a third-order drainage that originates on the north slope of the Black Hills and flows about 16 km into Totten Inlet in southern Puget Sound, about 16 km northwest of Olympia, Washington. Elevation in the 5,300-ha watershed ranges from sea level to 721 m. The uplands consist of moderately steep hillslopes underlain by marine volcanics of the Crescent Formation. Recessional outwash materials deposited during episodic continental glaciation forms the valley floor. The forest that covers most of the watershed was harvested earlier in the century and now consists of second-growth stands of Douglas-fir *Pseudotsuga menziesii* in well-drained sites and red alder *Alnus rubra* in wetter sites. Harvest of second-growth timber is occurring, and the basin has a dense (3.6 km²) system of forest roads. The climate is maritime with wet, mild winters and cool, relatively dry summers. Annual precipitation averages 147 cm, mostly as rain from October through April. The mean annual discharge, 1.7 m³/s, responds to precipitation. Monthly mean flows range from 0.1 m³/s in August to 4.8 m³/s in January. The mean annual peak flow (the arithmetic mean of all the annual maximum discharges) is approximately 22.9 m³/s (Williams et al. 1985).

The study was conducted between river kilometers 1 and 2 (from the mouth of the creek), where the alluvial, gravel-bedded channel has a low gradient (<1%) and a pool–riffle morphology, using the classification system of Montgomery and Buffington (1993). The creek is slightly incised into the noncohesive, erodible glaciofluvial deposits of the valley floor. In 1991–1992 approximately 5,000 chum salmon/km spawned throughout the creek below a waterfall that blocks migration by anadromous salmon.

Two reaches with contrasting morphological characteristics typical of chum salmon spawning habitat in Kennedy Creek were selected to study scour. At reach A the stream was relatively straight and narrow and, compared with reach B, had a simpler habitat, smaller gravel bar deposits, and fewer pieces of woody debris. Reach B was in a large, wide meander bend and had a complex habitat, abundant woody debris, extensive gravel bar
deposits, and barren eroding banks (Table 1). Five types of potential spawning habitat were identified in both reaches during the spawning period: (1) riffles had the fastest water velocities, shallow depths, and turbulent water surfaces; (2) lower riffles were situated immediately upstream from pools at the end of the riffles; (3) glides were deeper, slower, and less turbulent than riffles; (4) pool tailouts were the shallow areas at the downstream end of pools; and (5) pool lateral bars were submerged bars adjacent to pools. We did not place scour monitors in pool bottoms or in other habitats not used for spawning.

A cross section was established at each of the five habitat types within both study reaches to examine depth of scour and fill in particular channel bed forms. After the salmon had finished spawning in early December 1991, 76 scour monitors, similar to those used by Tripp and Poulin (1986) and Nawa and Frissell (1993), were inserted along the cross sections at 2-m intervals, and the streambed was surveyed for relative elevation. These monitors consisted of 10 perforated plastic balls, 4 cm in diameter, strung on a braided-wire cable and buried vertically below the surface of the gravel so that the top of the uppermost ball was at the surface of the gravel. As gravel is scoured down, the balls that become exposed to the stream’s flow are carried to the end of the cable, which extends from the gravel into the creek. After each peak discharge event, scour was determined by counting the number of balls floating on the end of the cable. Accuracy was estimated at ±2 cm, except in cases where monitors scoured during the first peak flow event were subsequently buried by fill. Because the monitors could not be reset, gravel deposited after the first event and scoured during the second event (i.e., material overlying the top ball after the first event) could not be documented. Thus, total scour at some locations during the second event was underestimated, but scouring to egg pocket depth was accurately measured in these cases.

Monitors lost entirely were assumed to have scoured to the depth of the bottom of the monitor (60 cm). These data were also used by Montgomer et al. (1996) to test hypotheses regarding the effects of digging by salmon on surface particle size distribution and depth of scour.

Monitors were inspected regularly, and scour appeared to occur on two events during the season. Net scour or fill was documented by resurveying the cross sections after each event and comparing that with previous elevations. Peak flows were recorded using a crest gauge installed by the U.S. Geological Survey (USGS). Stage heights were converted to discharge values using a rating curve prepared by the USGS. To estimate the recurrence interval of peak flows, a flood frequency curve was constructed using USGS annual maximum peak-flow data from 1961 to 1979 (Williams et al. 1985).

The data were analyzed to determine if there were significant differences in depth of scour among habitat types, study sites, and peak discharge events. Two nonparametric tests, the Mann–Whitney test and the Kolmogorov–Smirnov test (Conover 1980), were used because the data were not normally distributed. Two parameters were examined: total scour depth at monitor locations and the percentage of monitor locations where scour reached 20 cm (the mean depth of the top of chum salmon egg pockets in Kennedy Creek; Peterson and Quinn 1996a).

Results

The largest discharge we recorded during the winter of 1991–1992 was 16.7 m³/s on January 29, 1992. The recurrence interval (RI) for this event was calculated at 1.4 years. A smaller peak flow of 6.4 m³/s, having a RI of less than 1 year, occurred on February 22, 1992. Streambed scour and transport of gravel particles were observed during both events. The frequency distribution of scour depth and fill for all 76 locations where scour was monitored are shown in Figures 1 and 2. During chum salmon incubation (December 15–March 15), the average depth of scour was 11 cm (range 0–60 cm), and scour at 19.7% of the monitors reached the 20-cm mean depth of chum salmon egg pockets. The average depth of scour was more than 10 times greater during the January 29 peak flow than during the February 22 event (10.5 and 0.6 cm, respectively; P < 0.001). Scouring to average egg pocket depth occurred at 15 (19.7%) of the cross-section monitors during the larger event but at only one (1.3%) during the subsequent event.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Reach A</th>
<th>Reach B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length (m)</td>
<td>75.0</td>
<td>117.0</td>
</tr>
<tr>
<td>Coarse woody debris (pieces/100 m)</td>
<td>44</td>
<td>80</td>
</tr>
<tr>
<td>Mean bank-full width (m)</td>
<td>16.0</td>
<td>20.9</td>
</tr>
<tr>
<td>Water surface slope</td>
<td>0.0065</td>
<td>0.0072</td>
</tr>
<tr>
<td>Bed texture* (mm)</td>
<td>32.5</td>
<td>25.3</td>
</tr>
</tbody>
</table>

* Median particle diameter ($d_{50}$).

![Table 1. Physical characteristics of two study reaches in Kennedy Creek, Washington, where gravel scour and fill were measured.](image-url)
FIGURE 1.—Frequency distribution of depths of gravel scour recorded in Kennedy Creek, Washington, during the winter of 1991–1992.

Figure 3.—Average scour depth and 95% confidence interval on cross sections by habitat type and site during the chum salmon incubation period (winter of 1991–1992) in Kennedy Creek, Washington.

Figure 4.—Percentage of monitors scoured to 20 cm by habitat type and site during the chum salmon incubation period (winter of 1991–1992) in Kennedy Creek, Washington.

Scour occurred on all cross sections in all habitat types, but patterns of scour and fill differed between riffle-type habitats (rifles, lower riffles, and glides), and pool-type habitats (pool tailouts and pool lateral bars). The average depth of scour was greatest at pool lateral bars (20 cm) and pool tailouts (16 cm; Figure 3). Average depth of scour at lower riffles (9 cm) and glides (8 cm) was intermediate, and scour at riffles was lowest (2 cm). Scour to mean egg pocket depth followed a similar trend. The percentage of monitors scoured to 20 cm was greatest at pool lateral bars (38.5%) and pool tailouts (27.8%), was lower at glides (16.7%) and lower riffles (15.8%), and did not occur at riffles (Figure 4; P < 0.05).

Processes causing scour and fill also differed between the riffle-type and pool-type habitats. In riffle-type habitats, scour to egg pocket depth was uncommon and usually associated with lateral migration of the thalweg, scour of new pools or extension of existing pools into the riffle. Scour to egg pocket depth in pool-type habitats was associated with the mobilization of material deposited in pool lateral bars and tailouts or redirection of flow due to the movement of pool-forming woody debris jams. The average depth of scour in reach B (14 cm) was nearly twice that of reach A (8 cm); however, this difference was not statistically significant (Mann–Whitney test, P = 0.11). Because of small sample sizes and the relatively large variation in the data at each site (coefficients of variation >100%), the power of this test was low (<0.50) for detecting differences between the reaches of 100% or less. More of the monitors were scoured to egg pocket depth (20 cm) in reach B (27.9%) than in reach A (9.1%; P = 0.04).

Average streambed elevation (all cross sections) increased an average of 2.5 cm during the incubation period but only 58% of the monitor locations actually increased in elevation. In reach A, 67% of the monitor locations increased in elevation; the average elevation increased 2.8 cm. In reach B, average bed elevation increased 2.3 cm, but only 51% of the monitor locations increased in elevation. The greatest average increases in bed elevation occurred at riffles (10 cm), followed by glides (6 cm), lower riffles (3 cm), and pool lateral bars (2 cm). The pool tailouts decreased in bed elevation (~5 cm).

Discussion

Substantial variation in scour and fill was observed between the two reaches, among habitat units within reaches and among monitors on the same cross section within habitat units. Other studies have reported similarly high spatial variation (Lisle 1989; Hassan 1990). Despite the variation, the results indicated that peak discharge, sediment transport processes, and channel morphology are
the primary factors affecting the magnitude and distribution of scour and fill in Kennedy Creek. The frequency and magnitude of scour increased with peak discharge over the range of flows observed. The substantial (20%) rate of scour to egg pocket depth observed in Kennedy Creek during a bank-full flow is consistent with observations from other streams (Lisle 1989).

The highest rates of scour to egg pocket depth in Kennedy Creek were observed in pool tailouts and pool lateral bars, indicating that gravel deposits in and around pools were highly mobile at bank-full flow. Active scour and deposition of material in pools during bank-full events have been documented in other streams (Campbell and Sidle 1985). The patterns of scour observed in Kennedy Creek can be explained by differences in the sediment transport processes operating in pools and riffles, which are attributable to contrasting hydraulics and sedimentology. The surface particles in riffles are typically larger, rougher, and more tightly packed and have a high entrainment threshold, whereas sediments in pools are finer and more loosely packed and have a low entrainment threshold (Sear 1996). The relatively low and narrow range of entrainment thresholds for particles on the pool bed and tailout is typically exceeded at or near bank-full flow, and the material is extensively mobilized. The entrainment threshold range for riffle particles is typically higher and more variable if they are coarse and tightly packed (Sear 1996). In Kennedy Creek, it appears that the entrainment threshold of spawning gravel deposited in pool tailouts and pool lateral bars was often exceeded during the bank-full event, whereas the entrainment threshold of riffle particles was not. At some time after scour occurred but before the peak discharge event ended, bedload was redepósited in the pool habitats, so bed-elevation changes at monitor locations was not a reliable indicator of scour depth.

Differences in depth and frequency of scour between reaches A and B appeared to be related to differences in reach-scale morphology, and the amount and location of coarse woody debris. In the classification scheme of Montgomery and Buffington (1993), both our reaches are pool–riffle channels with a wide array of potential responses (including depth of scour) to changes in sediment supply, discharge, and obstructions. At relatively straight, narrow reach A, the channel pattern remained fairly stable during the peak flows observed, and most scour to egg pocket depth occurred at pool lateral bars, as previously described. Reach B was on a large meander bend where the channel was wider and contained midchannel bars, side channels, and more large woody debris (LWD). The channel was more dynamic in this reach due to lateral channel migration, redirection of flow patterns around debris jams, and side-channel formation. Scour processes associated with changes in the pattern of flow were prevalent at reach B, although scour of gravel deposits around pool margins was also widespread. Some deep scour observed in reach B was caused by redirection of flow patterns due to shifting of LWD. However, most LWD pieces in the Kennedy Creek study sites remained in place throughout the winter and appeared to have a stabilizing effect on incubation habitat.

Factors such as antecedent storm history and temporal proximity to channel disturbances (Reid et al. 1985; Sidle 1988), bed compaction and armorng (Reid et al. 1985), sediment size and availability (Sidle 1988), and the stability of upstream sediment storage sites (Sidle 1988) can influence the relationship of discharge and scour. In addition, high densities of spawning salmonids alter surface and subsurface bed texture and bed forms and may reduce the magnitude of scour and fill at short recurrence-interval peak flows (Montgomery et al. 1996). Patterns of scour and fill observed in Kennedy Creek in the winter of 1991–1992 were probably affected by the realignment of the channel and large sediment deposits associated with a large storm event in 1990, as well as by the extensive excavation of the bed by the large number of chum salmon spawning there in the fall of 1991.

Chum salmon tend to spawn soon after they enter short, low-gradient streams such as Kennedy Creek. Females therefore have a very limited opportunity to sample the diverse available habitat before they spawn. Based on data collected at Kennedy Creek since 1991, chum salmon occupy a narrower range of depths and velocities than would be expected by chance and tend to avoid spawning in riffles (T. P. Quinn, unpublished data). Female chum salmon seemed to favor spawning sites such as pool tailouts that provide good intragravel circulation and dissolved oxygen levels (Peterson and Quinn 1996b) during moderate flow events. These conditions may be important for survival to emergence in a stream with relatively high levels of fine sediment, but our results indicated that pool tailouts had much higher rates of scour to egg pocket depth than other glide or riffle habitats. Thus, the reproductive success of individuals spawning in different habitats may depend on the magnitude of flows and the mortality factors dom-
inant during the incubation period in any given year, but the population may produce relatively stable numbers of fry over a range of winter conditions, as long as diverse habitats are used. Holthby and Healey (1986) pointed out that both gravel quality and scour (as indicated by the fredle index and peak instantaneous discharge, respectively) were correlated with egg-to-fry survival of coho salmon in Carnation Creek. They concluded that acquisition of a spawning site with high gravel quality, traditionally considered optimal, may be incompatible with the goal of minimizing the probability of scour.

Salmonids have coexisted with the fluvial process of streambed scour throughout their evolution, and populations can adapt to the timing and depth of scour by modifying breeding date and body size (Montgomery et al. 1999). However, because their choice of spawning locations and the depth to which they can bury their eggs are limited, they are vulnerable to changes in the frequency and magnitude of scour. Much productive salmon spawning habitat occurs in pool–riffle channels that respond to changes in sediment supply, peak discharge, and LWD loading (Montgomery and Buffington 1993). Land use practices that increase the magnitude or frequency of sediment-transporting peak discharges, increase delivery of bedload sediment to the channel, or reduce LWD abundance or stability should be minimized to avoid increasing depth of scour in pool–riffle channels. We recommend more thorough investigation of the relationships between sediment load, peak flows, LWD, and depth of scour in a variety of channel types.

Finally, fisheries managers establishing escape- ment goals should consider that salmon populations both affect and are affected by the stream channels they inhabit. Selective fisheries that remove the larger individuals can threaten populations spawning in streams with accelerated scour because the progeny of the larger females that bury their eggs the deepest (Steen and Quinn 1999) would have the best likelihood of survival in these environments. State and tribal fisheries management policies allow many chum salmon to return to Kennedy Creek, and spawning salmonids have a considerable effect on the incubation environment, especially in years with relatively minor storm events. Chum salmon spawning activity in Kennedy Creek displaces fine sediment from the gravel bed during redd construction (Peterson and Quinn 1996a) and coarsens the surface substrate, increasing resistance to scour (Montgomery et al. 1996). Widespread excavation and movement of bed material during spawning also caused notable changes in channel morphology (Schuett-Hames 1996). Thus the role of salmon in determining the long-term productivity of stream habitat should be considered when fisheries management goals are established.

Acknowledgments

We thank Andrew Hendry, Larry Dominguez, and Gordy George for assistance with field work and Paul Butler, Gino Lucchetti, C. Jeff Cedermholm, and David Montgomery for helpful comments on the study and for review of the manuscript. The research was funded by the Squaxin Island Tribe, grants from the Washington Department of Natural Resources, the U.S. Forest Service, the Washington Forest Protection Association, and the H. Mason Keeler Endowment to Thomas Quinn. We are also grateful to the Simpson Timber Company for permission to work on their land.

References


