

Salmon-driven bed load transport and bed morphology in mountain streams

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[1] Analyses of bed load transport data from four streams in British Columbia show that the activity of mass spawning salmon moved an average of almost half of the annual bed load yield. Spawning-generated changes in bed surface topography persisted from August through May due to lack of floods during the winter season, defining the bed surface morphology for most of the year. Hence, salmon-driven bed load transport can substantially influence total sediment transport rates, and alter typical alluvial reach morphology. The finding that mass-spawning fish can dominate sediment transport in mountain drainage basins has fundamental implications for understanding controls on channel morphology and aquatic ecosystem dynamics, as well as stream responses to environmental change and designing river restoration programs for channels that have, or historically had large spawning runs. **Citation:** Hassan, M. A., et al. (2008), Salmon-driven bed load transport and bed morphology in mountain streams, *Geophys. Res. Lett.*, 35, L04405, doi:10.1029/2007GL032997.

1. Introduction

[2] Physiographic change has been long regarded as a primary determinant of evolutionary change in biological systems, but the influence of organisms on their habitat is less well appreciated. At relatively fine scales, the role of gophers [e.g., Yoo et al., 2005], ants [Butler, 1995], and termites [Selby, 1993; Butler, 1995] in hillslope sediment transport is well known, as is how beavers can greatly alter river systems [Butler, 1995], cattle cause bank erosion [Trimble, 1994], and crayfish shape local bed morphology [Statzner et al., 2000]. Although the effects of fish on sediment sorting of streambed gravels during the digging

of nests (redds) have been widely recognized [Kondolf and Wolman, 1993; Kondolf et al., 1993; Montgomery et al., 1996], the role of fish on sediment transport remains little explored due to the difficulty in both collecting bed load transport data and in discriminating between hydrologic and biologic transport.

[3] The localized geomorphic role of spawning salmon involves both direct transport during redd excavation that modifies streambeds and indirect effects through changes in bed-surface grain size and packing [Butler, 1995; Montgomery et al., 1996]. Specifically, the flexing action of female salmon creates a series of water jets that mobilize sediment to excavate a depression ~5–50 cm in depth (for review, see DeVries [1997]). In the process, fine clay, silt and sand are lifted into the water column and carried downstream. Coarser pebbles and gravels accumulate in a pile, called the tailspill, at the downstream edge of the redd. The floor of a redd consists of large gravel or cobble particles that the fish cannot move, and this is where the eggs are deposited [e.g., Chapman, 1988]. Once the eggs have been fertilized by the male, the female covers them with fresh gravel excavated upstream. Again, bed materials are disturbed, fine sediment is carried downstream, and the eggs are covered with relatively coarse grains [Kondolf and Wolman, 1993; Kondolf et al., 1993; Rennie and Millar, 2000]. Salmon tend to spawn on the upstream and downstream ends of riffles, and the edges of bars [Gottesfeld et al., 2004]. But in streams with high spawning densities their redds may disturb the entire channel bed [Montgomery et al., 1996; Gottesfeld et al., 2004]. Gottesfeld et al. [2004] documented coarse sediment dispersion by floods and fish, and showed that although spawning salmon do not move material particularly far, the burial depths achieved by fish are of the same range as those yielded by floods. However, Gottesfeld et al. [2004] did not evaluate the influence of spawning salmon on net sediment yields.

[4] Here we expand and further analyze this unique data set to show that the mass spawning activity of salmon can be a primary control on the transport of coarse sediment (bed load) and sub-reach scale morphology. Specifically, we calculate sediment yield to assess the relative influence of snowmelt (nival), summer storm floods, and spawning salmon on rates of bed load transport. The extent to which we find that mass spawning salmon shape their environment is particularly significant because originally abundant and widely distributed runs of native salmon in Europe, northern Asia, and North America have been massively reduced historically and are now the focus of substantial river resto-

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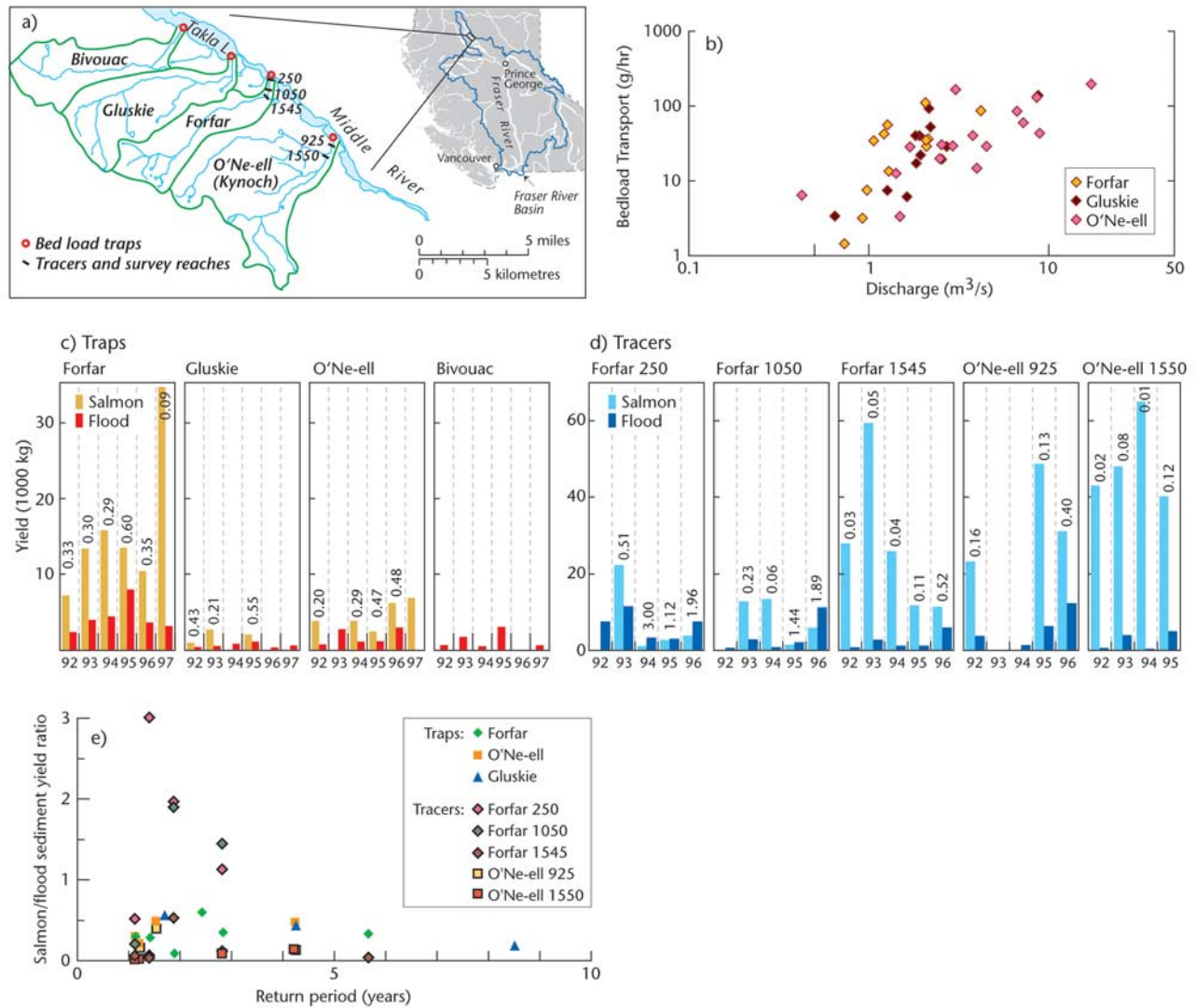


Figure 1. (a) Location map of the study streams. (b) Rating curve between sediment transport rate and discharge as measured using pit traps (Forfar $g = 9.54Q^{2.00}$, $r^2 = 0.56$; O'Ne-ell $g = 8.31Q^{0.96}$, $r^2 = 0.71$; and Gluskie $g = 8.32Q^{1.56}$, $r^2 = 0.60$; g is transport rate and Q is discharge). Sediment yield as estimated for floods and fish spawning for the years 1992–1997 using (c) pit traps and (d) tracer data; annual yield for tracers was estimated using the mean depth, width, and distance of travel data. Numbers presented for each year indicate the fish/flood bed load yield ratio (note that no flood data are available for Bivouac Creek). (e) Relationship between the fish/flood annual yield ratio and flood return period (calculated using data from 1991–2007) for the three creeks for which data on transport by both fish and floods were available.

ration programs in Europe and North America [Montgomery, 2003].

2. Study Creeks and Methods

[5] We analyzed repeated bed surface surveys and bed load transport data from four watersheds in the Fraser River basin, British Columbia, Canada (Figure 1a). These data provide a unique opportunity to evaluate the role of mass spawning salmon on sediment transport and channel morphology because repeated sub-annual monitoring allows quantification of the relative influence of floods and spawning activity on channel morphology and sediment transport. The watersheds are between 36 and 77 km², stream gradient of the study reaches range between 0.2 and 1.7%, median

particle size ranged between 20 and 40 mm, and stream width ranged from 5 to 20 m. These gravel-bed, pool-riffle channels represent highly productive habitat for sockeye salmon, as well as resident salmonids [Scrivener and Macdonald, 1998]. Spawning densities are greatest within two to three km of the river mouth and spawning occurs when discharge is well below the threshold discharge for initiating sediment transport, making it possible to unambiguously distinguish between flood and fish-induced transport.

[6] Gottesfeld *et al.* [2004] reported that the range and median travel distances of tagged particles mobilized by nival floods and spawning fish were comparable in areas of high spawning return each year between 1992 and 1996. Burial depths of tagged particles were typically shallow;

58% of tagged clasts transported in May and 43% of those transported in August were recovered from within the surface layer of the gravel. Average burial depths ranged from $2D_{50}$ to $10D_{50}$ (where $D_{50} \sim 40$ mm, is the median size of the bed material), and was approximately equivalent after transport by either floods or salmon bioturbation.

[7] In addition to the data on particle burial depths and travel distances reported by *Gottesfeld et al.* [2004], bed load transport was measured over six years (1992–1997) at six reaches in the four study watersheds. Bed load sediment transport during flood and spawning periods was measured using bed load traps (Forfar, O'Ne-ell, Gluskie, and Bivouac, Figure 1a) and magnetically tagged particles (Forfar and O'Ne-ell). Pit traps (20 L plastic buckets inserted flush with the bed surface) were installed in the study reaches roughly 200 m upstream of the channel mouth to collect sediment and were monitored through the spring snowmelt, summer storm, and salmon spawning seasons [*Scrivener and Macdonald*, 1998]. During high flows, bed load traps can fill, resulting in underestimates of actual transport [*Hassan and Church*, 2001]. Our estimated transport rates for salmon spawning and summer floods are based on measurements from bed load traps partially filled during low to intermediate flows, and are therefore considered reliable. However, our estimates for high flow events, especially during the nival floods, may be biased by trap filling and hence somewhat underestimate sediment transport during these floods.

[8] Because of such concerns we compare the bed load trap data with sediment transport rates estimated from tracer data, which represent transport from the whole flood, in order to provide additional data and evaluate the potential magnitude of any such bias. As described by *Gottesfeld et al.* [2004], particles 40–200 mm in diameter collected from the surface of a riffle were magnetically tagged, marked for identification, and replaced in lines across the channels (of the same reaches in Forfar and O'Ne-ell). We extend *Gottesfeld et al.*'s [2004] analysis to use the tracer data to estimate sediment yield for the study reaches.

[9] Bed surface changes produced by floods and spawning activity were documented over two years (1996–1997) by repeated, detailed topographic mapping of channel morphology in five reaches with extensive salmon spawning activity from two of the watersheds (3 reaches in Forfar and 2 reaches in O'Ne-ell). Using a total station, total reach lengths ranging between 4 and 9 channel widths were surveyed, with a survey data density range of between 4 and 9 points per m^2 of channel bed area. Seasonal measurements allow calculation of the net changes in channel elevation between transport episodes and independent evaluation of the erosional and morphological effects of both floods and spawning fish. Changes in the frequency and amplitude of bed forms created from flood and spawning events were analyzed through repeated surveys of longitudinal profiles of the stream bed topography. Specifically, for each study area and time period, three longitudinal profiles (one meter from each bank and one in the middle) were extracted from bed survey data to analyze the wavelength, amplitude and spatial frequency of the channel topography.

[10] Flow data near the river mouth were measured between 1991 and 2007. Based on this record, our observations cover flows with return periods ranging from 1.3 to

9 years. Due to the short length of the record we additionally used nearby long-term gauge stations to estimate the return period of the observed events (Environment Canada Stations 08JA014 and 08EE008). The return period of the largest measured event is between 10 and 20 years. We used a rating curve to evaluate the relationship between flow discharge and sediment accumulated in pit traps. The amount of sediment moved during spawning was estimated using trap data and tagged particles. The trap data were combined to estimate total bed load transport for the spawning season. For the tagged particles, the mobilized sediment for the spawning season was estimated using a combination of mean travel distance, mean burial depth and channel width.

[11] Repeated sampling of freeze-cores [*Scrivener and Macdonald*, 1998] collected from all four watersheds over the study period to assess modification of bed material by floods and fish, indicates that frequent disturbance of the bed surface by fish reduces the vertical sorting and hence the degree of surface armouring. In order to avoid problems arising from the small sample size from individual freeze cores [see *Zimmermann et al.*, 2005], we combined cores into composite samples of about 100 kg taken before and after the spawning period in both spawned and undisturbed areas. Before aggregating the samples each core was divided into surface and sub-surface material for separate analysis. Hence, any systematic error introduced by the sampling methodology will equally affect data from floods and spawning activity.

3. Results

[12] As in other sediment transport studies [e.g., *Hassan and Church*, 2001], our data display substantial variance around a trend of increased sediment transport with increased discharge (Figure 1b). Due to gaps in the flow record from Bivouac Creek we could not develop a rating curve and hence did not estimate bed load yield by floods. The amount of total sediment mobilized by fish also is weakly correlated ($r^2 = 0.20$ for all data) with the total number of returning salmon.

[13] At Forfar 250 (near the river's mouth), annual sediment trap data show that fish mobilized between 9 and 60% of the amount of sediment annually moved by floods (Figure 1c). Similar trends were obtained for O'Ne-ell and Gluskie, where trap data indicate that fish mobilized between 20 and 48% (O'Ne-ell), and 21 and 55% (Gluski). In Bivouac Creek, where rating curve problems prevented estimating the amount of flood-induced transport, the amount of sediment mobilized by fish is of the same magnitude as the amount moved by fish in O'Ne-ell. Hence, averaged across all years for the three creeks, trap data indicate fish mobilized about 35% of the net transport. Tracer data from Forfar and O'Ne-ell indicate that fish mobilized between 1 and 40% (O'Ne-ell – two reaches) and 4 and 300% (Forfar – three reaches) of the material moved by floods (Figure 1d). Averaged across all years for both creeks, fish mobilized nearly half (55%) of the sediment moved by floods during the study period (see fish/flood ratios in Figure 1e). The ratio of bed load transport by fish to that by floods declines for increasingly large floods from an average of 47% (all available data, with a range of

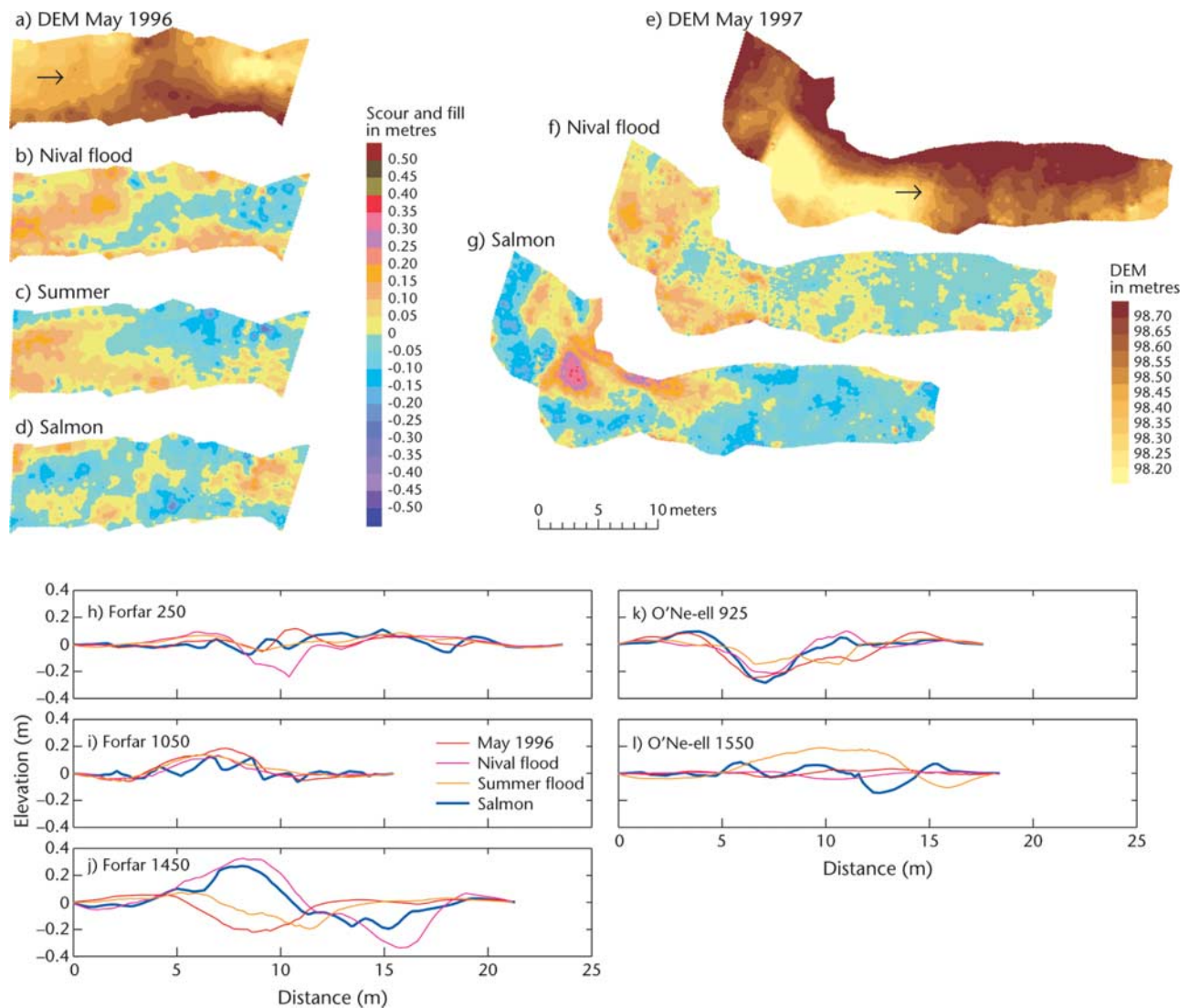


Figure 2. (a) Topographic map of Forfar 250 sub-reach prior to the 1996 nival flood. (b)–(d) Isopach diagrams from topographic surveys of Forfar 250 illustrating patterns of net cut and fill due to nival flood. (e) Topographic map of Forfar 1050 sub-reach prior to the 1997. (f) Isopach diagram of net scour and fill during nival floods. (g) Isopach diagram of net scour and fill during salmon transport. Blue areas indicate decreases in elevation; red areas indicate increases in elevation. (h)–(l) Bed surface profiles for study reaches in 1996 at times of pre-nival flood (May), nival flood, summer flood, and salmon spawning activity.

1–300%), for ≤ 2 yr recurrence interval events (Figure 1e). Hence, in years with low to intermediate magnitude flood events fish moved as much sediment as (or more than) floods, whereas in years with large magnitude events the floods moved much more sediment than did fish. Nonetheless, the greater frequency of the small events means that overall fish can move a large proportion of the net sediment transported (as shown above).

[14] Two examples of bed surface surveys (Forfar 250 in 1996 and Forfar 1050 in 1997) illustrate typical patterns of response surveyed in these mountain streams. Channel morphology prior to the 1996 nival flood shows a typical riffle-pool morphology (Figure 2a). The median net scour and fill values for both fish and flood events are approximately 10 cm (Figures 2b, 2c, and 2d). Few areas in these reaches experience more than 30 cm of net erosion or net

deposition. The nival flood of May 1996 produced a typical uncorrugated sub-reach scale morphology of pools, riffles and bars (Figure 2b). Approximately half of the study area underwent net sedimentation; 40% was scoured and no net change was recorded in the remainder. The 1996 summer flood was small, and its effects were similar to those of the nival flood: riffles were scoured and there was minor filling in the pools (Figure 2c). Similar results were obtained for the 1996 floods in Forfar 1050 (Figures 2e–2g).

[15] In contrast to the minor morphological effect of high flows, the spawning activity of sockeye salmon in August produced major changes in channel morphology (Figure 2d). Several cycles of redd excavation created a small-scale topography of mounds and hollows which persisted into early spring. Overall there was a net excavation of those areas most suitable for fish spawning (riffles and bars), and

deep pools were filled with sediment excavated from bars. As stream flow increased due to spring snowmelt and summer floods, sediment deposited in pools by bioturbation was remobilized downstream, replenishing the surface of bars and riffles downstream, providing new areas for salmon spawning, and resulting in further net transport. These patterns were typical of the study streams and net scour and fill distributions measured across all study reaches show comparable ranges for both fish and floods.

[16] The hummocky surface created by fish and the relatively smooth surface created by the nival and summer floods reveal two distinct signatures: one for flood events and another associated with fish spawning (Figures 2h–2i). Moreover, areas that are scoured by floods are refilled by fish activity and visa-versa (i.e., in general, the bed morphology resulting from fish excavation is spatially antiphasic to the morphology associated with nival and summer flood events). This pattern recurs annually, and is affected by both flood magnitude and the number of returning spawners. Due to the lack of winter floods in these streams, the post-spawning bed configuration lasted from August to May. Hence, salmon are a primary determinant of sub-reach-scale habitat form and dictate the overall bed morphology of the streams for most of the year.

[17] Cores from the study reaches were used to evaluate the degree of surface coarsening due to both floods and spawning activity. The surface layer of river beds in humid regions typically has a coarser surface ‘armour’ layer with a diminished sand component [e.g., *Dietrich et al.*, 1989; *Hassan et al.*, 2006]. The armouring ratio (median surface/median subsurface grain size) is usually >2 for gravel-bed channels in humid regions [*Hassan et al.*, 2006]. In contrast, armouring ratios for the study channels ranged from about 1 up to 1.4, presumably due to the frequent digging by fish disrupting both the vertical sorting and the development of stable bed-surface structures [*Hassan et al.*, 2006].

4. Discussion and Conclusions

[18] Using various complementary methods, our analyses show that spawning salmon are a first-order, although highly variable, control on sediment transport in the study streams. Each method has its own limitations (e.g., potential for filling of bed load traps), but the close correspondence of the bed load estimates from trap and tracer data gives us confidence in our results. Moreover, the general agreement in the range of scour and fill distributions for both fish and flow-induced transport events provides further support for the interpretation that salmon spawning is a first-order control on bed load transport.

[19] More specifically, our analyses of bed load transport data indicate that mass-spawning salmon: (1) cause direct sediment movement accounting for between a third and half the bed load moved; (2) increase bed surface roughness; (3) prevent development of well armoured surfaces; and (4) create a distinct hummocky channel morphology superimposed on the longer-wavelength pool-riffle bed forms. Grain size and roughness effects of spawning activity have been commented upon previously [e.g., *Kondolf et al.*, 1993; *Montgomery et al.*, 1996]. However, the impact on channel morphology and direct sediment transport quantify previously speculative influences of salmon on their habitat.

[20] In regard to the effect of mass-spawning fish on sediment mobility during subsequent flood event, the increase in bed form roughness from spawning is likely to reduce flow strength and hence decrease sediment mobility [*Montgomery et al.*, 1996]. However, the disruption of surface armouring caused by fish excavation is likely to increase sediment mobility by post-spawning flow events. Consequently, the net effect of these two opposing factors depends on the balance between them, something that we do not address here.

[21] The observation that mass spawning salmon can account for substantial bed load sediment transport — averaging between a third and half the annual flux in the streams studied — suggests strong, heretofore unquantified, links between the biology and channel morphology of gravel-bed streams. When considered together with recent recognition of the key role of bed load sediment transport on setting river longitudinal profiles [*Sklar and Dietrich*, 1998] our findings further suggest fundamental linkages between the population dynamics of mass spawning salmon and evolution of their mountain streams. Regional physiographic change is thought to have spurred the evolution of the Pacific salmon [*Montgomery*, 2000], but our results suggest that conversely the rise of mass spawning salmon may have also influenced channel morphology and sediment transport, and potentially thereby reach slopes and hence to some degree perhaps even the physiographic evolution of the region. Moreover, efforts to recover salmon stocks both in Europe and North America through hydrogeomorphic (habitat) restoration would be further complicated if, as suggested here, historic river morphology and dynamics were greatly influenced by larger numbers of mass-spawning fish. For therein lies a potential conundrum for restoration ecologists: what must one recover first, the fish or the stream?

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