



## 2 Salmon-driven bed load transport and bed morphology in mountain 3 streams

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9 [1] Analyses of bed load transport data from four streams  
10 in British Columbia show that the activity of mass spawning  
11 salmon moved an average of almost half of the annual bed  
12 load yield. Spawning-generated changes in bed surface  
13 topography persisted from August through May due to lack  
14 of floods during the winter season, defining the bed surface  
15 morphology for most of the year. Hence, salmon-driven bed  
16 load transport can substantially influence total sediment  
17 transport rates, and alters typical alluvial reach morphology.  
18 The finding that mass-spawning fish can dominate sediment  
19 transport in mountain drainage basins has fundamental  
20 implications for understanding controls on channel  
21 morphology and aquatic ecosystem dynamics, as well as  
22 stream responses to environmental change and designing  
23 river restoration programs for channels that have, or  
24 historically had large spawning runs. **Citation:** Hassan,  
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### 29 1. Introduction

30 [2] Physiographic change has been long regarded as a  
31 primary determinant of evolutionary change in biological  
32 systems, but the influence of organisms on their habitat is  
33 less well appreciated. At relatively fine scales, the role of  
34 gophers [e.g., *Yoo et al.*, 2005], ants [*Butler*, 1995], and  
35 termites [*Selby*, 1993; *Butler*, 1995] in hillslope sediment  
36 transport is well known, as is how beavers can greatly alter  
37 river systems [*Butler*, 1995], cattle cause bank erosion  
38 [*Trimble*, 1994], and crayfish shape local bed morphology  
39 [*Statzner et al.*, 2000]. Although the effects of fish on  
40 sediment sorting of streambed gravels during the digging

of nests (redds) have been widely recognized [*Kondolf and* 41  
*Wolman*, 1993; *Kondolf et al.*, 1993; *Montgomery et al.*, 42  
1996], the role of fish on sediment transport remains little 43  
explored due to the difficulty in both collecting bed load 44  
transport data and in discriminating between hydrologic and 45  
biologic transport. 46

[3] The localized geomorphic role of spawning salmon 47  
involves both direct transport during redd excavation that 48  
modifies streambeds and indirect effects through changes 49  
in bed-surface grain size and packing [*Butler*, 1995; 50  
*Montgomery et al.*, 1996]. Specifically, the flexing action 51  
of female salmon creates a series of water jets that mobilize 52  
sediment to excavate a depression ~5–50 cm in depth (for 53  
review, see *DeVries* [1997]). In the process, fine clay, silt 54  
and sand are lifted into the water column and carried 55  
downstream. Coarser pebbles and gravels accumulate in a 56  
pile, called the tailspill, at the downstream edge of the redd. 57  
The floor of a redd consists of large gravel or cobble 58  
particles that the fish cannot move, and this is where the 59  
eggs are deposited [e.g., *Chapman*, 1988]. Once the eggs 60  
have been fertilized by the male, the female covers them 61  
with fresh gravel excavated upstream. Again, bed materials 62  
are disturbed, fine sediment is carried downstream, and the 63  
eggs are covered with relatively coarse grains [*Kondolf and* 64  
*Wolman*, 1993; *Kondolf et al.*, 1993; *Rennie and Millar*, 65  
2000]. Salmon tend to spawn on the upstream and down- 66  
stream ends of riffles, and the edges of bars [*Gottesfeld et* 67  
*al.*, 2004]. But in streams with high spawning densities their 68  
redds may disturb the entire channel bed [*Montgomery et* 69  
*al.*, 1996; *Gottesfeld et al.*, 2004]. *Gottesfeld et al.* [2004] 70  
documented coarse sediment dispersion by floods and fish, 71  
and showed that although spawning salmon do not move 72  
material particularly far, the burial depths achieved by fish 73  
are of the same range as those yielded by floods. However, 74  
*Gottesfeld et al.* [2004] did not evaluate the influence of 75  
spawning salmon on net sediment yields. 76

[4] Here we expand and further analyze this unique data 77  
set to show that the mass spawning activity of salmon can 78  
be a primary control on the transport of coarse sediment 79  
(bed load) and sub-reach scale morphology. Specifically, we 80  
calculate sediment yield to assess the relative influence of 81  
snowmelt (nival), summer storm floods, and spawning 82  
salmon on rates of bed load transport. The extent to which 83  
we find that mass spawning salmon shape their environment 84  
is particularly significant because originally abundant and 85  
widely distributed runs of native salmon in Europe, northern 86  
Asia, and North America have been massively reduced 87  
historically and are now the focus of substantial river resto- 88

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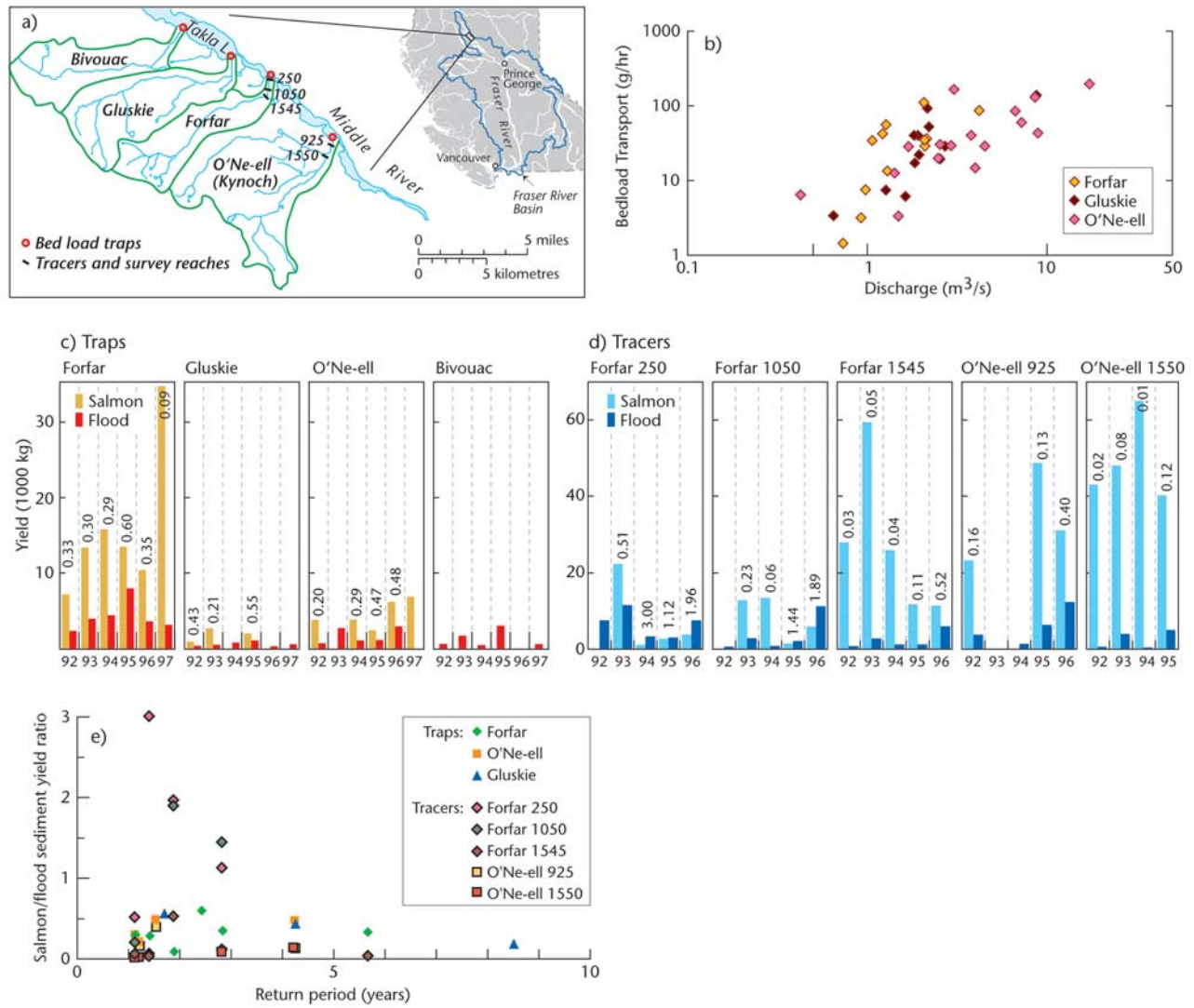
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**Figure 1.** (a) Location map of the study streams. (b) Rating curve between sediment transport rate and discharge as measured using pit traps (Forfar  $g = 9.54Q^{2.00}$ ,  $r^2 = 0.56$ ; O'Ne-ell  $g = 8.31Q^{0.96}$ ,  $r^2 = 0.71$ ; and Gluskie  $g = 8.32Q^{1.56}$ ,  $r^2 = 0.60$ ;  $g$  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.

89 ration programs in Europe and North America [Montgomery,  
90 2003].

91 **2. Study Creeks and Methods**

92 [5] We analyzed repeated bed surface surveys and bed  
93 load transport data from four watersheds in the Fraser River  
94 basin, British Columbia, Canada (Figure 1a). These data  
95 provide a unique opportunity to evaluate the role of mass  
96 spawning salmon on sediment transport and channel morpho-  
97 logy because repeated sub-annual monitoring allows  
98 quantification of the relative influence of floods and spawn-  
99 ing activity on channel morphology and sediment transport.  
100 The watersheds are between 36 and 77 km<sup>2</sup>, stream gradient  
101 of the study reaches range between 0.2 and 1.7%, median

particle size ranged between 20 and 40 mm, and stream 102  
width ranged from 5 to 20 m. These gravel-bed, pool-riffle 103  
channels represent highly productive habitat for sockeye 104  
salmon, as well as resident salmonids [Scrivener and 105  
Macdonald, 1998]. Spawning densities are greatest within 106  
two to three km of the river mouth and spawning occurs 107  
when discharge is well below the threshold discharge for 108  
initiating sediment transport, making it possible to unam- 109  
biguously distinguish between flood and fish-induced 110  
transport. 111

[6] Gottesfeld *et al.* [2004] reported that the range and 112  
median travel distances of tagged particles mobilized by 113  
nival floods and spawning fish were comparable in areas of 114  
high spawning return each year between 1992 and 1996. 115  
Burial depths of tagged particles were typically shallow; 116

117 58% of tagged clasts transported in May and 43% of those  
118 transported in August were recovered from within the  
119 surface layer of the gravel. Average burial depths ranged  
120 from  $2D_{50}$  to  $10D_{50}$  (where  $D_{50} \sim 40$  mm, is the median  
121 size of the bed material), and was approximately equivalent  
122 after transport by either floods or salmon bioturbation.

123 [7] In addition to the data on particle burial depths and  
124 travel distances reported by *Gottesfeld et al.* [2004], bed  
125 load transport was measured over six years (1992–1997) at  
126 six reaches in the four study watersheds. Bed load sediment  
127 transport during flood and spawning periods was measured  
128 using bed load traps (Forfar, O’Ne-ell, Gluskie, and Biv-  
129 ouac, Figure 1a) and magnetically tagged particles (Forfar  
130 and O’Ne-ell). Pit traps (20 L plastic buckets inserted flush  
131 with the bed surface) were installed in the study reaches  
132 roughly 200 m upstream of the channel mouth to collect  
133 sediment and were monitored through the spring snowmelt,  
134 summer storm, and salmon spawning seasons [*Scrivener*  
135 *and Macdonald*, 1998]. During high flows bed load traps  
136 can fill, resulting in underestimates of actual transport  
137 [*Hassan and Church*, 2001]. Our estimated transport rates  
138 for salmon spawning and summer floods are based on  
139 measurements from bed load traps partially filled during  
140 low to intermediate flows, and are therefore considered  
141 reliable. However, our estimates for high flow events,  
142 especially during the nival floods, may be biased by trap  
143 filling and hence somewhat underestimate sediment trans-  
144 port during these floods.

145 [8] Because of such concerns we compare the bed load  
146 trap data with sediment transport rates estimated from tracer  
147 data, which represent transport from the whole flood, in  
148 order to provide additional data and evaluate the potential  
149 magnitude of any such bias. As described by *Gottesfeld et*  
150 *al.* [2004], particles 40–200 mm in diameter collected from  
151 the surface of a riffle were magnetically tagged, marked for  
152 identification, and replaced in lines across the channels (of  
153 the same reaches in Forfar and O’Ne-ell). We extend  
154 *Gottesfeld et al.*’s [2004] analysis to use the tracer data to  
155 estimate sediment yield for the study reaches.

156 [9] Bed surface changes produced by floods and spawn-  
157 ing activity were documented over two years (1996–1997)  
158 by repeated, detailed topographic mapping of channel  
159 morphology in five reaches with extensive salmon spawn-  
160 ing activity from two of the watersheds (3 reaches in Forfar  
161 and 2 reaches in O’Ne-ell). Using a total station, total reach  
162 lengths ranging between 4 and 9 channel widths were  
163 surveyed; with a survey data density range of between 4  
164 and 9 points per  $m^2$  of channel bed area. Seasonal measure-  
165 ments allow calculation of the net changes in channel  
166 elevation between transport episodes and independent eval-  
167 uation of the erosional and morphological effects of both  
168 floods and spawning fish. Changes in the frequency and  
169 amplitude of bed forms created from flood and spawning  
170 events were analyzed through repeated surveys of longitu-  
171 dinal profiles of the stream bed topography. Specifically, for  
172 each study area and time period, three longitudinal profiles  
173 (one meter from each bank and one in the middle) were  
174 extracted from bed survey data to analyze the wavelength,  
175 amplitude and spatial frequency of the channel topography.

176 [10] Flow data near the river mouth were measured  
177 between 1991 and 2007. Based on this record, our obser-  
178 vations cover flows with return periods ranging from 1.3 to

9 years. Due to the short length of the record we addition- 179  
ally used nearby long-term gauge stations to estimate the 180  
return period of the observed events (Environment Canada 181  
Stations 08JA014 and 08EE008). The return period of the 182  
largest measured event is between 10 and 20 years. We used 183  
a rating curve to evaluate the relationship between flow 184  
discharge and sediment accumulated in pit traps. The 185  
amount of sediment moved during spawning was estimated 186  
using trap data and tagged particles. The trap data were 187  
combined to estimate total bed load transport for the 188  
spawning season. For the tagged particles, the mobilized 189  
sediment for the spawning season was estimated using a 190  
combination of mean travel distance, mean burial depth and 191  
channel width. 192

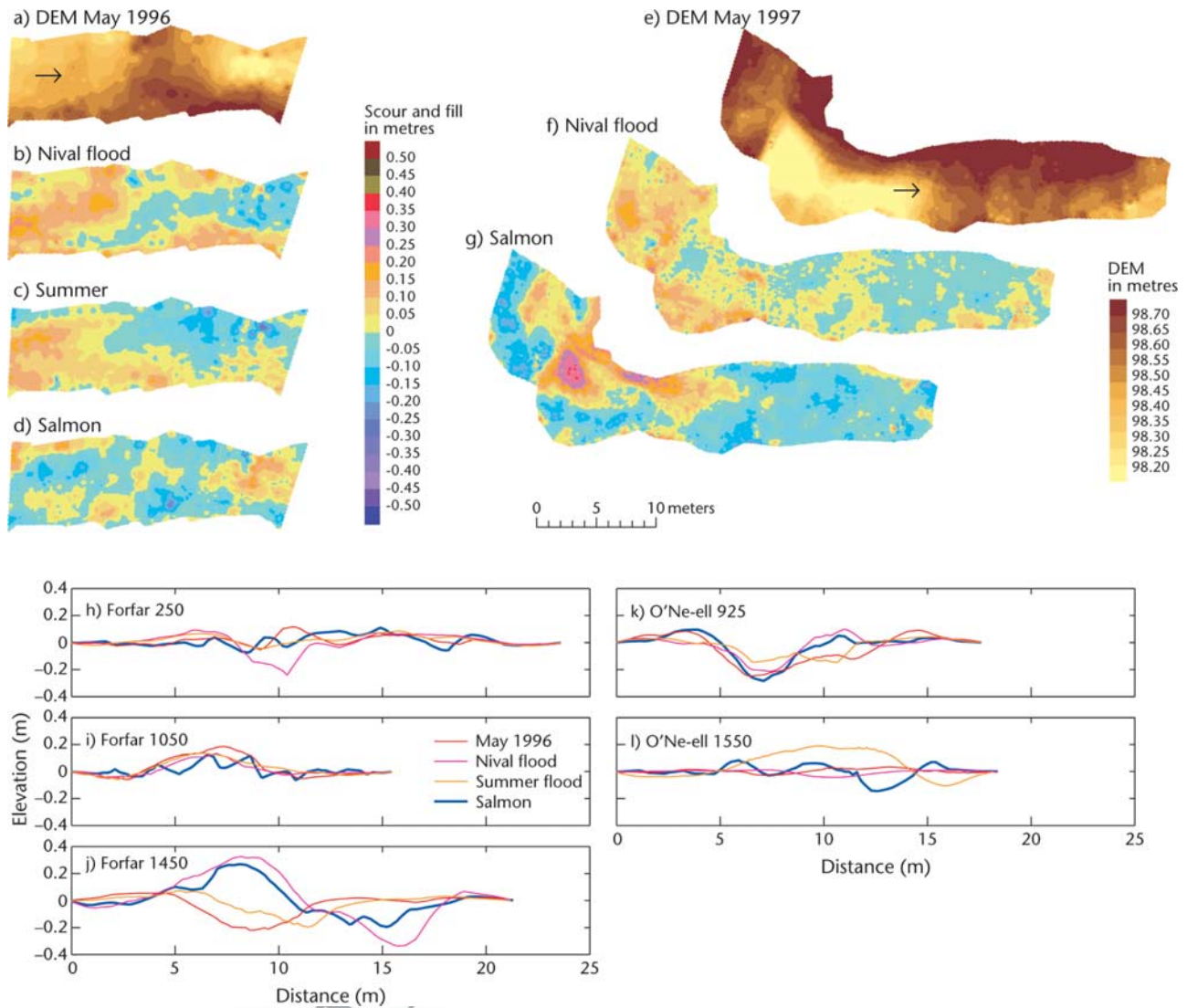
[11] Repeated sampling of freeze-cores [*Scrivener and* 193  
*Macdonald*, 1998] collected from all four watersheds over 194  
the study period to assess modification of bed material by 195  
floods and fish, indicates that frequent disturbance of the 196  
bed surface by fish reduces the vertical sorting and hence 197  
the degree of surface armouring. In order to avoid problems 198  
arising from the small sample size from individual freeze 199  
cores [see *Zimmermann et al.*, 2005], we combined cores 200  
into composite samples of about 100 kg taken before and 201  
after the spawning period in both spawned and undisturbed 202  
areas. Before aggregating the samples each core was divided 203  
into surface and sub-surface material for separate analysis. 204  
Hence, any systematic error introduced by the sampling 205  
methodology will equally affect data from floods and spawn- 206  
ing activity. 207

### 3. Results 208

[12] As in other sediment transport studies [e.g., *Hassan* 209  
*and Church*, 2001], our data display substantial variance 210  
around a trend of increased sediment transport with in- 211  
creased discharge (Figure 1b). Due to gaps in flow record 212  
from Bivouac Creek we could not develop a rating curve 213  
and hence did not estimate bed load yield by floods. The 214  
amount of total sediment mobilized by fish also is weakly 215  
correlated ( $r^2 = 0.20$  for all data) with the total number of 216  
returning salmon. 217

[13] At Forfar 250 (near the river’s mouth), annual 218  
sediment trap data show that fish mobilized between 9 219  
and 60% of the amount of sediment annually moved by 220  
floods (Figure 1c). Similar trends were obtained for O’Ne- 221  
ell and Gluskie, where trap data indicate that fish mobilized 222  
between 20 and 48% (O’Ne-ell), and 21 and 55% (Gluski). 223  
In Bivouac Creek, where rating curve problems prevented 224  
estimating the amount of flood-induced transport, the 225  
amount of sediment mobilized by fish is of the same 226  
magnitude as the amount moved by fish in O’Ne-ell. Hence, 227  
averaged across all years for the three creeks, trap data 228  
indicate fish mobilized about 35% of the net transport. 229  
Tracer data from Forfar and O’Ne-ell indicate that fish 230  
mobilized between 1 and 40% (O’Ne-ell – two reaches) 231  
and 4 and 300% (Forfar – three reaches) of the material 232  
moved by floods (Figure 1d). Averaged across all years for 233  
both creeks, fish mobilized nearly half (55%) of the sedi- 234  
ment moved by floods during the study period (see fish/ 235  
flood ratios in Figure 1e). The ratio of bed load transport by 236  
fish to that by floods declines for increasingly large floods 237  
from an average of 47% (all available data, with a range of 238





**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.

239 1–300%), for  $\leq 2$  yr recurrence interval events (Figure 1e).  
 240 Hence, in years with low to intermediate magnitude flood  
 241 events fish moved as much sediment as (or more than)  
 242 floods, whereas in years with large magnitude events the  
 243 floods moved much more sediment than did fish. Nonethe-  
 244 less, the greater frequency of the small events means that  
 245 overall fish can move a large proportion of the net sediment  
 246 transported (as shown above).

247 [14] Two examples of bed surface surveys (Forfar 250 in  
 248 1996 and Forfar 1050 in 1997) illustrate typical patterns of  
 249 response surveyed in these mountain streams. Channel  
 250 morphology prior to the 1996 nival flood shows a typical  
 251 riffle-pool morphology (Figure 2a). The median net scour  
 252 and fill values for both fish and flood events are approxi-  
 253 mately 10 cm (Figures 2b, 2c, and 2d). Few areas in these  
 254 reaches experience more than 30 cm of net erosion or net

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

264 [15] In contrast to the minor morphological effect of high  
 265 flows, the spawning activity of sockeye salmon in August  
 266 produced major changes in channel morphology (Figure 2d).  
 267 Several cycles of redd excavation created a small-scale  
 268 topography of mounds and hollows which persisted into  
 269 early spring. Overall there was a net excavation of those  
 270 areas most suitable for fish spawning (riffles and bars), and

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

280 [16] The hummocky surface created by fish and the  
 281 relatively smooth surface created by the nival and summer  
 282 floods reveal two distinct signatures: one for flood events  
 283 and another associated with fish spawning (Figures 2h–2l).  
 284 Moreover, areas that are scoured by floods are refilled by  
 285 fish activity and visa-versa (i.e., in general, the bed mor-  
 286 phology resulting from fish excavation is spatially antipha-  
 287 sic to the morphology associated with nival and summer  
 288 flood events). This pattern recurs annually, and is affected  
 289 by both flood magnitude and the number of returning  
 290 spawners. Due to the lack of winter floods in these streams,  
 291 the post-spawning bed configuration lasted from August to  
 292 May. Hence, salmon are a primary determinant of sub-  
 293 reach-scale habitat form and dictate the overall bed mor-  
 294 phology of the streams for most of the year.

295 [17] Cores from the study reaches were used to evaluate  
 296 the degree of surface coarsening due to both floods and  
 297 spawning activity. The surface layer of river beds in humid  
 298 regions typically has a coarser surface ‘armour’ layer with a  
 299 diminished sand component [e.g., *Dietrich et al.*, 1989;  
 300 *Hassan et al.*, 2006]. The armouring ratio (median surface/  
 301 median subsurface grain size) is usually >2 for gravel-bed  
 302 channels in humid regions [*Hassan et al.*, 2006]. In contrast,  
 303 armouring ratios for the study channels ranged from about 1  
 304 up to 1.4, presumably due to the frequent digging by fish  
 305 disrupting both the vertical sorting and the development of  
 306 stable bed-surface structures [*Hassan et al.*, 2006].

#### 307 4. Discussion and Conclusions

308 [18] Using various complementary methods our analyses  
 309 show that spawning salmon are a first-order, although  
 310 highly variable, control on sediment transport in the study  
 311 streams. Each method has its own limitations (e.g., potential  
 312 for filling of bed load traps), but the close correspondence  
 313 of the bed load estimates from trap and tracer data gives us  
 314 confidence in our results. Moreover, the general agreement  
 315 in the range of scour and fill distributions for both fish and  
 316 flow-induced transport events provides further support for  
 317 the interpretation that salmon spawning is a first-order  
 318 control on bed load transport.

319 [19] More specifically, our analyses of bed load transport  
 320 data indicate that mass-spawning salmon: (1) cause direct  
 321 sediment movement accounting for between a third and half  
 322 the bed load moved; (2) increase bed surface roughness;  
 323 (3) prevent development of well armoured surfaces; and  
 324 (4) create a distinct hummocky channel morphology super-  
 325 imposed on the longer-wavelength pool-riffle bed forms.  
 326 Grain size and roughness effects of spawning activity have  
 327 been commented upon previously [e.g., *Kondolf et al.*,  
 328 1993; *Montgomery et al.*, 1996]. However, the impact on  
 329 channel morphology and direct sediment transport quantify  
 330 previously speculative influences of salmon on their habitat.

[20] In regard to the effect of mass-spawning fish on 331  
 sediment mobility during subsequent flood event, the in- 332  
 crease in bed form roughness from spawning is likely to 333  
 reduce flow strength and hence decrease sediment mobility 334  
 [*Montgomery et al.*, 1996]. However, the disruption of 335  
 surface armouring caused by fish excavation is likely to 336  
 increase sediment mobility by post-spawning flow events. 337  
 Consequently, the net effect of these two opposing factors 338  
 depends on the balance between them, something that we 339  
 do not address here. 340

[21] The observation that mass spawning salmon can 341  
 account for substantial bed load sediment transport — 342  
 averaging between a third and half the annual flux in the 343  
 streams studied — suggests strong, heretofore unquantified, 344  
 links between the biology and channel morphology of 345  
 gravel-bed streams. When considered together with recent 346  
 recognition of the key role of bed load sediment transport 347  
 on setting river longitudinal profiles [*Sklar and Dietrich*, 348  
 1998] our findings further suggest fundamental linkages 349  
 between the population dynamics of mass spawning salmon 350  
 and evolution of their mountain streams. Regional physio- 351  
 graphic change is thought to have spurred the evolution of 352  
 the Pacific salmon [*Montgomery*, 2000], but our results 353  
 suggest that conversely the rise of mass spawning salmon 354  
 may have also influenced channel morphology and sedi- 355  
 ment transport, and potentially thereby reach slopes and 356  
 hence to some degree perhaps even the physiographic 357  
 evolution of the region. Moreover, efforts to recover salmon 358  
 stocks both in Europe and North America through hydro- 359  
 geomorphic (habitat) restoration would be further compli- 360  
 cated if, as suggested here, historic river morphology and 361  
 dynamics were greatly influenced by larger numbers of 362  
 mass-spawning fish. For therein lies a potential conundrum 363  
 for restoration ecologists: what must one recover first, the 364  
 fish or the stream? 365

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