

**SEDIMENT DISPERSION IN SALMON SPAWNING STREAMS:
 THE INFLUENCE OF FLOODS AND SALMON REDD CONSTRUCTION¹**

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ABSTRACT: Magnetically tagged particles were used to investigate the effects of sockeye salmon (*Oncorhynchus nerka*) and floods on the dispersion of coarse bed material in the Stuart-Takla region, British Columbia, Canada. The dominant annual sediment transporting event in the channels is the snowmelt flood events, with lesser activity usually accomplished during summer floods. Annually in August, the channel bed material is reworked by the Early Stuart sockeye salmon spawning, as the fish excavate the streambed to deposit and bury their eggs. These nesting cavities are called redds. Results from 67 tracer recovery experiments over five years were highly variable, subject to the magnitude of floods and the returning population of salmon. Overall, the depositional pattern from nival flood events usually demonstrated a high degree of clast mobilization, long travel distances (up to 150 m), and mean depths of burial up to 18 cm. Summer flood events showed somewhat lower rates of mobilization, distances of travel, and depths of burial. Although the fish did not move the tracers very far, their effect on the bed was generally quite pervasive – up to 100 percent of the clasts were mobilized, and the depth of burial was considerable (mean burial depths up to 14 cm). The amount of vertical mixing of sediment by salmon was often on the same order of magnitude as flood events. The significant vertical mixing of sediments by the fish has important implications for the mobility of sediment in the stream. Since any armoring layer formed during high flows throughout the year is subject to the bioturbation of salmon, this suggests that the transport threshold in the creeks remains relatively low. Salmon likely play an integral role in the sediment transport dynamics and annual sediment budget of the lower reaches of these creeks.

(KEY TERMS: erosion; sedimentation; sockeye salmon; bed load transport; tracer studies; forest hydrology; watershed management; bioturbation.)

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INTRODUCTION

The geomorphic relationships among forest practices, sediment transport, and aquatic habitat have been the focus of a large number of studies in the Pacific Northwest (summarized in Reiser, 1998). Many studies have sought to understand the impacts of sedimentary disturbances, such as logging and associated road construction, on salmonine species (trout and salmon), their habitat, and their reproductive dynamics. The survival of many salmon populations depends greatly on the environmental conditions they encounter in their spawning streams. Hydrological regimen, sedimentary conditions, channel complexity, nutrient and oxygen cycling, and many other variables are often sensitive to the cumulative impacts of forestry and other modifications of the surrounding landscape and riparian zones. Logging techniques used before 1980 have been shown to result in increased sediment supply to channels, alteration of channel morphology, and degradation of river ecosystems (e.g., Swanston and Swanson, 1976; Reid and Dunne, 1984; Rood, 1984; Sidle *et al.*, 1985; Grant and Wolff, 1991). One critical concern is the delivery of fine and coarse material to stream channels (e.g., Beschta, 1978; Sullivan, 1986; Roberts and Church, 1986). The resultant changes in the quality, texture, and mobility of streambed sediment in forested streams may dramatically affect fish and other stream biota.

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While much of the research on salmon habitat has focused on the life cycle of salmon and the various interactions with sedimentary disturbance, relatively few studies have been done to quantify the geomorphic effects of the fish themselves on the channel and their role in the annual sediment budget. In British Columbia, salmon return from the sea to spawn in more than 2,600 streams (Williams *et al.*, 1994). They excavate nesting cavities or “redds” in the channel bed and deposit their eggs. In the course of this excavation, bed material is moved downstream. In some of these streams, so many salmon return that the geomorphic impact of this spawning event likely is significant. In many cases there is an observable effect on channel morphology and local bed topography.

In this paper, the evidence for salmon as geomorphological agents is considered, using data generated within the Stuart-Takla Fish Forestry Interaction Project initiated in 1992 to better understand the fluvial ecology and effects of timber harvesting in northern British Columbia. The dispersion of magnetically tagged particles by both floods and spawning sockeye (*Oncorhynchus nerka*) is described over the course of five years in two headwater streams of the Fraser drainage. The specific objectives of the study are (1) to describe the travel distance and burial depth of the larger fraction of clasts ($> D_{50}$) on the bed after transport by floods and fish spawning and (2) to assess the effects of spawning fish on dispersion of this coarse material. While the impact of fish spawning on the mobility of fine fractions has been documented (e.g., Beaudry, 1998), there has been no such study on the movement of coarse bed material.

Redd Excavation

Salmon and trout spawn in areas of relatively loose gravels where they can easily excavate redds. These areas have high permeability, which ensures abundant oxygen for developing eggs and larvae. Often spawning takes place at the upstream and downstream ends of riffles (Bjornn and Reiser, 1991). The downstream margins of gravel bars are also favored sites, these being sites of emerging hypabyssal flow and consequently relatively cool and oxygenated water. In streams with high spawning densities, salmon are found in all sites in the pool riffle sequences (Tschaplinski, 1998), and their redds may disturb all of the wetted portion of the channel. Redd excavation at the edge of emergent gravel bars often expands the proportion of the channel that carries flow (Gottesfeld, 1998; Poirier, 2003).

Redds are excavated by rapid vigorous tail flapping of female salmon positioned on their sides close to the streambed. The flapping directs a series of water

bursts against the streambed, dislodging and entraining gravel particles. Over the course of one or several days, a depression is created. Once the pit is dug, the female proceeds to deposit her eggs in several “egg pockets” in the deepest part of the pit (Foerster, 1968). After this, the fish bury the eggs under a coarse cover of sediment that is excavated from the bed surface immediately upstream of the pit. The coarser excavated material from redds (“tailspill”) sits unrestrained on the bed and is thus subject to significantly higher rates of entrainment (Montgomery *et al.*, 1996; DeVries, 1997; Lapointe *et al.*, 2000; Rennie and Millar, 2000).

The dimensions of the redd excavation vary greatly with species (see Bjornn and Reiser, 1991). In the case of sockeye salmon, McCart (1969) measured individual spawning redd dimensions near Babine Lake (approximately 100 km southwest of the present study site), and found that redds were roughly ovoid in shape, averaging 0.9 m², with an average depth of 8.9 cm. Montgomery *et al.* (1996) have speculated that salmon tend to lay their eggs at a depth just below the scour level associated with bankfull discharge. Scrivener and Macdonald (1998) measured the depths of redds in the Stuart-Takla streams and found depths of excavation on the order of 20 cm. From the authors’ observations at Forfar and O’Ne-ell creeks, it was found that the boundaries of a given redd difficult to delineate, but the total volume of excavated material would appear to be about 0.3 m³.

There is thus increasing evidence that fish activity in a gravel bed channel will significantly change its physical conditions. The effects in terms of erosion and transport may often be on the same order of magnitude as flood events (Gottesfeld, 1998; Poirier, 2003). The impact of salmonine bioturbation is reflected not only in the direct mobilization of sediment but also in the conditioning of the streambed – particularly with high densities of spawning fish. As the salmon loosen the imbricated (“underloose”) texture of the gravel bed, they promote increased mobility of bed material (e.g., Montgomery *et al.*, 1996; Rennie and Millar, 2000).

Study Basins and Methods

The study was conducted in the Stuart-Takla experimental watersheds in the northernmost portion of the Fraser Basin, about 150 km northwest of Fort St. James, British Columbia, Canada (Figure 1). Five study reaches were selected in the lower 2 km of Forfar and O’Ne-ell Creeks, adjacent tributaries of the Middle River. Spring snowmelt, often accompanied by heavy rains, produces flooding in May, June, or early July that may last for two weeks or more. In July and

August there may be one or two brief, intense summer rainstorms and some smaller events throughout the autumn. In the decade of 1991 to 2000, Forfar Creek had an average annual sockeye escapement of 11,109; O'Ne-ell Creek had an average escapement of 14,936 (Fisheries and Oceans Canada, 2001). Salmon arrive in July, and the peak of spawning is usually in the first two weeks of August. The channel flows discussed in the text were measured at stream gauges located adjacent to bridges over the study creeks on the Forest Service road (see Figure 1).

The Stuart-Takla study site is underlain by the Cache Creek Complex, which consists of metamorphosed fine clastic sedimentary rocks of Pennsylvanian to Triassic age. The Forfar Creek Basin and portions of the upper O'Ne-ell Creek Basin are situated on a younger (Mid-Jurassic to Cretaceous) intrusive body of granodiorite. Most of the Forfar and O'Ne-ell watershed extents are blanketed by tills, with depths usually exceeding 3 m in the lower valley reaches (Plouffe, 2000). From their headwaters at approximately 1,500 m elevation, Forfar and O'Ne-ell Creeks descend steeply through outwash fan material that has been incised considerably since the close of the Fraser glaciation (Ryder, 1995). As the creeks approach the Middle River lowland at 700 m, their slopes have eased to less than 1 percent.

Three reaches on Forfar Creek and two reaches on O'Ne-ell Creek were selected for study. The study reaches are named according to their distance (m) upstream of the creek mouth, thus the O'Ne-ell 1910 reach is located approximately 1,910 meters from the outlet at Middle River (Figure 1). The average bankfull width of the channels ranges from 10.8 to 14 m. In both creeks, the baseflow is about 0.1 m³/s. Mean channel gradients extend from 0.5 percent in the lower sites to 2.0 percent for the higher ones. In Forfar Creek, the pool riffle spacing of individual reaches ranges from 1.7 to 3.8 channel widths. The spacing is somewhat shorter in O'Ne-ell, ranging from 1.2 to 1.4 channel widths. The morphology of the channels is influenced to a high degree by the abundance of large woody debris (Hogan *et al.*, 1998). The study reaches have a number of important distinctions among them. The higher reaches generally have a greater slope, somewhat higher stream power, and coarser bed. Lower reaches such as Forfar 250 have a relatively low gradient and low stream power. Differences between the two creeks are related to the hydrologic response of the basins and sedimentary conditions. O'Ne-ell generally experiences higher flows than Forfar, as it has a greater contributing area. Since a greater percentage of O'Ne-ell's basin area is located in the alpine zone, the nival events are noticeably larger than those in Forfar.

In years of low numbers of returning fish, spawning activity extends more than 2.5 km upstream from the mouth of O'Ne-ell and Forfar Creeks. In years of high abundance, spawning extends several kilometers farther upstream. Spawner density tends to be low near the stream mouths where sandy sediment is abundant. For approximately the next 2 km upstream, higher spawning density is associated with higher quality spawning gravels, gradually declining at the upstream limits where the coarsening bed material ($D_{90} \geq 128$ mm) limits the opportunities for

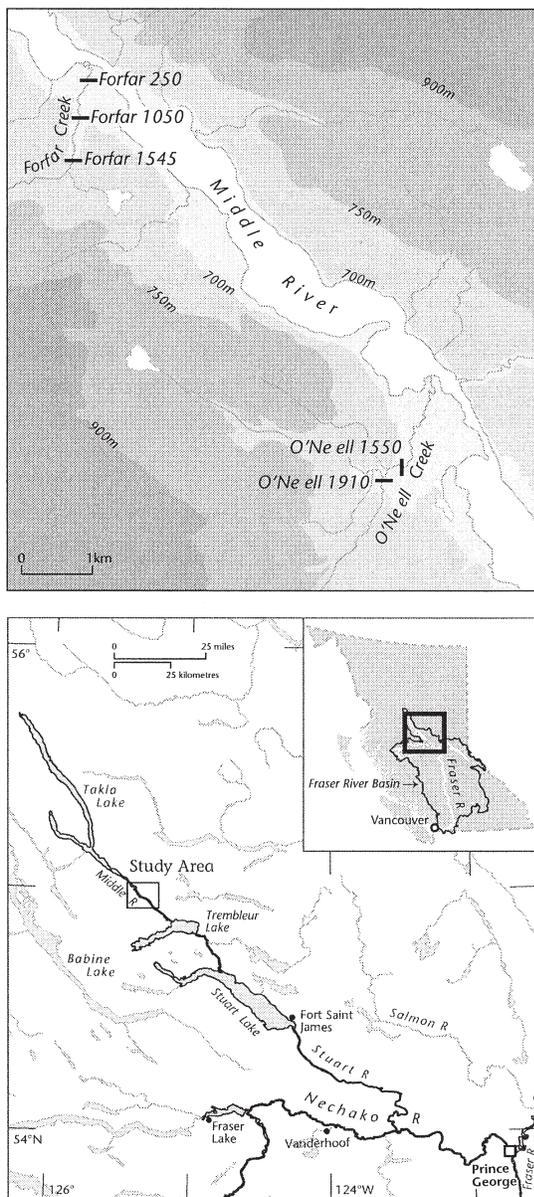


Figure 1. Location Map of the Study Creeks. Reach number indicates distance from the river mouth.

fish excavation. The study reaches are all within the zone that historically has had the highest returning populations every year. Within the study reaches the fish are distributed in a fairly uniform pattern (Tschaplinsky, 1994, 1998) in years of both high and low abundance.

Field Methods

Gravel samples were collected from the surface of riffles located near the upper end of each study reach. Clasts larger than 50 mm were taken to the laboratory, where their characteristics (e.g., size, petrology, and roundness) were recorded. A groove was cut in each clast with a diamond blade, and neodymium magnets and a numbered tag were embedded in clear epoxy resin refilling the groove (for details see Hassan *et al.*, 1991). The clasts were then replaced in bands in the streambed at their original positions. In 1992, 200 to 300 tracers were prepared for each study reach. Additional marked clasts were produced when the stock of original clasts declined.

The experimental sites were frequently visited during the snow free period of the year. Whenever clasts were seen to have moved, the tracers were recovered, and their positions and burial depths were surveyed. Buried particles were located using a magnetometer. If the clast was visible at the surface, it was scored as 0 depth. If the clast was not visible, the burial depth was measured from the particle top to the local bed surface; this gives the net aggradation by the flow event. These measurements therefore cannot be used to directly estimate the thickness of the active layer (e.g., Hassan and Church, 1994). The minimum thickness of the active layer is estimated from measurements made to the base of the particle. The thickness of the particles within the bed material, the *c*-axis, should be added in order to estimate the depth active layer (Hassan and Church, 1994; Gottesfeld, 1998).

After each recovery, the tagged particles were lined up again at the same starting positions. While the particles were shoved into the bed so as not to be overly exposed to flows, they were nonetheless only partially constrained and were thus more likely to be transported than similar sized bed grains that are naturally held in surface structures. This methodology avoids the problem of variable starting conditions, in terms of burial depth and entrainment, and allows a direct comparison of sediment mobility between floods and fish activity (e.g., Hassan, 1990; Hassan and Church, 1994).

RESULTS

Particle travel distance and burial data are available from five field seasons (67 recoveries) extending from April 1992 to May 1997. The recovery rate of tracer clasts was high, ranging between 60 and 90 percent after nival events and 90 to 100 percent following spawning. After five years of tracer recovery work, about 60 percent of the original tagged population were retained. At all study reaches, the median size of the tagged particles was greater than the median size of the bed material. The size range of the tracers represents more than D_{60} of the size distribution of bed material (50 to 180 mm). Nearly all marked clasts recovered had been incorporated, to some degree, into the streambed.

Table 1 presents a summary of the major transporting flow events and observations of sediment dispersion by both floods and fish, indicating total travel distance and depth of particle burial in a given reach each year. Detailed analysis of the division of sediment transport work between floods and fish in each reach is presented in the following sections.

Nival Flood Events

Most of the annual transport work was achieved during the nival event, and tracer activity during this period was generally high (Table 1). Transport distances of marked clasts was greater in the nival floods than in other types of events, but a smaller proportion of clasts was moved and buried than in sockeye redd excavation activities. The highest sustained flows recorded at O'Ne-ell Creek during the study period occurred during the snowmelt event in late May 1993. The maximum travel distance of a clast at O'Ne-ell 1910 was 344 m. The average transport distance of the 25 percent of the tracers recovered was 49 m. Apparently, tracer recovery was selective in favor of less dispersed particles, since more complete recovery after a second transport event, a relatively small summer flood, showed a mean displacement of 155 m (Table 1). Farther downstream at O'Ne-ell 1550, clast recovery was not attempted until after sockeye spawning in August 1993; thus the particles may have moved three times. The annual cumulative travel distance was 20 m. At this site, abundant sediment supply from upstream buried the new set of tagged particles *in situ* in the following nival flood of 1994.

On Forfar Creek the 1994 nival peak flow was slightly higher than that of 1993, although its duration was much shorter. Even though the nival flood in 1994 had a higher peak flow, the proportion of moved

TABLE 1. Summary Data for Stuart-Takla Bed Load Transport Experiments.

Event	Type ^a	Discharge (m ³ /s) ^b			Forfar 250				Forfar 1050				Forfar 1545			
		N	Recov. ^c	Percent Moved	L (m) ^d	D (cm) ^e	N	Recov. ^c	Percent Moved	L (m) ^d	D (cm) ^e	N	Recov. ^c	Percent Moved	L (m) ^d	D (cm) ^e
June 6 1992	NF															
August 1992	SyS	274	96	96	5.0	11	301	100	69	1.2	4	83	93	49	19.8	4
May 20, 1993	NF	248	94	73	9.2	18	298	72	95	10.7	14	249	94	46	0.8	3
June 28, 1993	SF	244	99	43	1.5	2	215	99	14	2.1	0	234	61	86	32.0	12
August 1993	SyS	240	97	99	4.7	16	241	94	98	3.0	11	149	100	79	5.5	9
Jun13, 1994	NF	236	99	36	2.0	2	240	92	44	10.0	12	165	98	86	2.2	7
August 1994	SyS	234	100	99	2.4	11	222	96	55	1.4	4	162	60	92	26.7	6
May 14, 1995	NF	236	97	29	4.8	3	218	100	17	3.0	3	104	95	94	1.3	4
July 10, 1995	SF	231	99	32	0.6	2	221	100	34	0.8	2	217	94	54	10.0	9
August 1995	SyS	228	95	96	2.3	8	220	92	100	3.0	4	206	97	69	3.2	2
June 3, 1996	NF	219	99	46	5.4	3	205	99	85	8.8	5	201	96	77	1.5	2
July-August 1996	M	203	99	100	6.2	8	205	85	99	12.2	8	198	77	82	11.8	6
Event	Type ^a	Discharge (m ³ /s) ^b			O'Ne-ell 1550				O'Ne-ell 1910							
		N	Recov. ^c	Percent Moved	L (m) ^d	D (cm) ^e	N	Recov. ^c	Percent Moved	L (m) ^d	D (cm) ^e	N	Recov. ^c	Percent Moved	L (m) ^d	D (cm) ^e
June 1, 1992	NF	29	86	40	12.2	7	85	65	67	52.2	5					
August 1992	SyS	262	92	15	1.2	14	236	78	15	0.8	2					
May 20, 1993	NF	242					185	24	98	48.7	9					
June 28, 1993	SF	242					138	46	97	154.9	8					
August 1993	SyS	242	63				110	96	92	3.6	7					
June 12, 1994	NF	153	99	0	0.0	13	113	61	62	66.8	7					
August 15, 1994	SyS	174	98	91	1.4	2	72	96	67	0.5	6					
May 14, 1995	NF	173	69	100	22.7	8	72	74	34	62.2	6					
July 9, 1995	SF	125	98	91	6.9	0	158	97	60	4.9	2					
August 1995	SyS	126	94	93	8.1	3	155	95	77	1.8	5					
June 4, 1996	NF	135	63	93	19.6	5	157	46	29	75.1	8					
July-August 1996	M	90	67	100	6.2	7										

^aEvent Types: SyS = Sockeye spawning, NF = Nival flood, SF= summer flood, and M = multiple events of more than one type.
^bDischarge values are maximum daily flows for flood events and mean values for spawning periods. The July to August 1996 interval had a summer flood followed immediately by sockeye spawning. The maximum flood flow is given.
^cPercent recovered is the ratio of the number of clasts placed out and the number recovered after movement by a single transport event.
^dThe mean distance of travel by floods or fish, transported clasts only.
^eThe mean burial depth by flood or fish, buried clasts only.

particles was smaller than that of 1993 (Table 1). In the Forfar 250 reach, a large proportion of the tracers were buried *in situ* or after only very short distances of movement. The mean burial depth of the particles that were not moved was 20.7 cm. For the upper two reaches, the mean travel distance accomplished by the flood was higher than that obtained at Forfar 250 but quite low for the size of the event. In 1995, three small nival flood peaks occurred in mid-May and early June; only the largest discharge is shown on Table 1. Except at O'Ne-ell 1550, relatively few particles were transported, and those that moved only moved short distances.

Summer Floods

Storm floods, occurring in late June or July, have a hydrologic pattern that is distinct from the nival floods. The flows are generally brief, lasting a day or sometimes only hours, yet the flows may exceed those of the nival event. The largest flows are rainstorms occurring on the declining limb of the nival flow. Most summers throughout the study period saw at least one large storm peak, the largest being the storm of July 18, 1996, which generated flows of 18.9 m³/s in the O'Ne-ell channel and 7.26 m³/s in Forfar (Table 1).

In 1993, two transport events were recorded: the (nival) May 20 event was approximately 1.9 times larger than a later storm event on June 28. While a large proportion of the particles were entrained and buried by the May 20 event, a smaller proportion of the tracers became buried in the June event. Both the mean distance of travel and burial depth of the particles suggest that sediment transport in the summer storm event was very local and confined to the bed surface layer. Tracer particles in Forfar 1545 traveled almost twice as far as those in lower reaches and significantly farther than those moved by fish activity. At Forfar 1050, the event did not scour the bed, and all particles were found on the bed surface.

Sockeye Spawning Events

Sockeye redd excavation moved a larger proportion of bed material clasts than floods, and a larger proportion of the clasts were likely to end up below the surface layer of the streambed (Table 1). The average depth of burial after sockeye bioturbation was comparable to that of stream transport, being less than the burial depths of the nival floods but greater than the depths of summer floods. Sockeye bioturbation resulted in much shorter transport distances than flood transport (Table 1). Overall, the travel distance of all

particles by the spawning event was one order of magnitude less than that obtained in nival events.

In 1992, the mean travel distance by the nival event in O'Ne-ell 1550 was an order of magnitude higher than that initiated by the fish activity (Table 1). However, the mean burial depth of the tracers achieved by fish was about twice that of the flood. In 1993, comparison among transport events in Forfar 250 shows that fish related mean travel distance was about half that of the nival event and about three times farther than the summer flood that year. The burial depth achieved by the fish was considerable – roughly the same as that of the June 28 flood event.

In 1994 at Forfar 250, the mean distance of travel of all particles during fish spawning was higher than that of floods. In this year and in 1995, the mean depth of buried particles during fish activity was much higher than during floods; the opposite was true for the 1545 reach. Similar trends were obtained for the 1996 field season (Table 1).

In 1992 at O'Ne-ell 1910, the mean distance of movement by flood was two orders of magnitude higher than that associated with the fish, but the burial depth was roughly of the same order. Relative to other years and to fish activity, the two flood events of 1993 moved the highest percentage of particles the farthest distances recorded in the study.

In general, a larger proportion of clasts was buried by sockeye than by flood transport, but the depth of burial is generally similar (Table 1). In 1994, the burial depth of sediment by fish was about five times larger than that obtained for the flood, in the case of the 250 reach. The opposite is true in the case of the two higher reaches; here the mean burial depth by the flood exceeded that of the fish. This was particularly evident at Forfar 1050, where burial depths attributed to fish overall were much lower, the distance of movement was very short, and some particles were buried *in situ*.

Travel Distance

In the analysis of travel distance, the focus was the transported particles; the stationary particles were excluded. Figure 2 shows a plan form diagram of the channel, with travel distance of tracer particles during floods and fish during the 1993 and 1994 seasons in Forfar 1050. Although the travel distance during spawning activity is short, a high proportion of the particles shows some degree of movement (Table 1).

To compare the distribution of travel distances by floods and fish, the data were scaled by dividing the displacement distance of each particle by the channel width at the seeding site. The scaled distances were

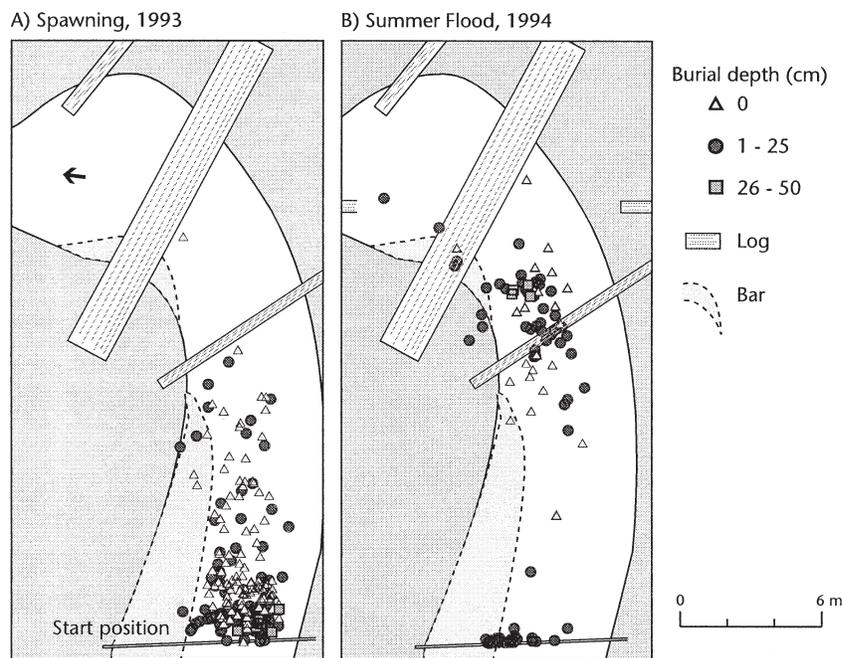


Figure 2. Distribution of Tagged Particles by Floods and Fish (A) in 1993 and (B) 1994 in the Forfar 1050 Reach.

then grouped into intervals equal to 0.25 of the channel width for the events. This scaling was used rather than the mean travel distance typically employed in tracer studies (e.g., Hassan *et al.*, 1991) as a means of taking the event magnitude into consideration. The choice of channel width as a scaling element simplifies comparing data from Forfar and O'Ne-ell creeks and reaches with varying widths.

Figure 3 shows observed distributions for floods and fish spawning for both creeks. The events and the reaches presented in Figure 3 were selected to represent the range of results that have been obtained.

Given the relatively small sample numbers (n is 2 through 5 for each reach) and the nonnormal nature of their distribution, the cumulative distributions of the travel distance by floods and fish were compared using the nonparametric Kolmogorov-Smirnov (K-S) test. The null hypothesis for each test is that the cumulative travel distance distributions of any two sets of observations (i.e., fish versus flood for a given year and reach) are similar. The K-S test is particularly well suited to this application, since it enables the direct comparison of two cumulative distributions without splitting the observations into subjective categories (see Swan *et al.*, 1995). This has positive implications for detecting deviations in the tails of the distributions, where observations tend to be fewer.

Results from the statistical test are shown in Table 2. To avoid interannual variability the comparison was restricted to surveys taken within a few months

of a single year. Three examples taken from the Forfar 250 reach are presented in Figures 3a through 3c. About 80 percent or more of the tracers' travel distances are less than or equal to one channel width by the nival floods. Similar results were obtained for the fish bioturbation during the 1993 season and the combined summer flood and salmon bioturbation transport in 1996. During the 1995 season, however, all tracer transport distances induced by fish were less than one channel width. The K-S test for the 1993 and 1994 seasons shows that the distributions of travel distances by floods and fish were similar at the significance level of 0.1 (Table 2), while the 1995 season was similar at the significance level of 0.01.

The fish related travel distances measured for the Forfar 1050 reach showed that more than 90 percent of the tracers moved within one channel width (Figures 3d-3f). The 1993 flood mobilized most of the particles and some moved long distances; 42 percent of the tracers traveled distances less or equal to one channel width, and about 20 percent traveled more than two channel widths. The 1994 flood yielded a bimodal distribution, one mode at 2 m (0.5 channel width) and the second at 18 m (2.5 channel width). The first mode was composed mainly of particles that became buried immediately downstream of the seeding line. The 1995 and 1996 flood and spawning events had similar travel distance distributions as shown by the K-S test (Table 2). For the 1993 and 1994 transport events, the K-S test indicates that the

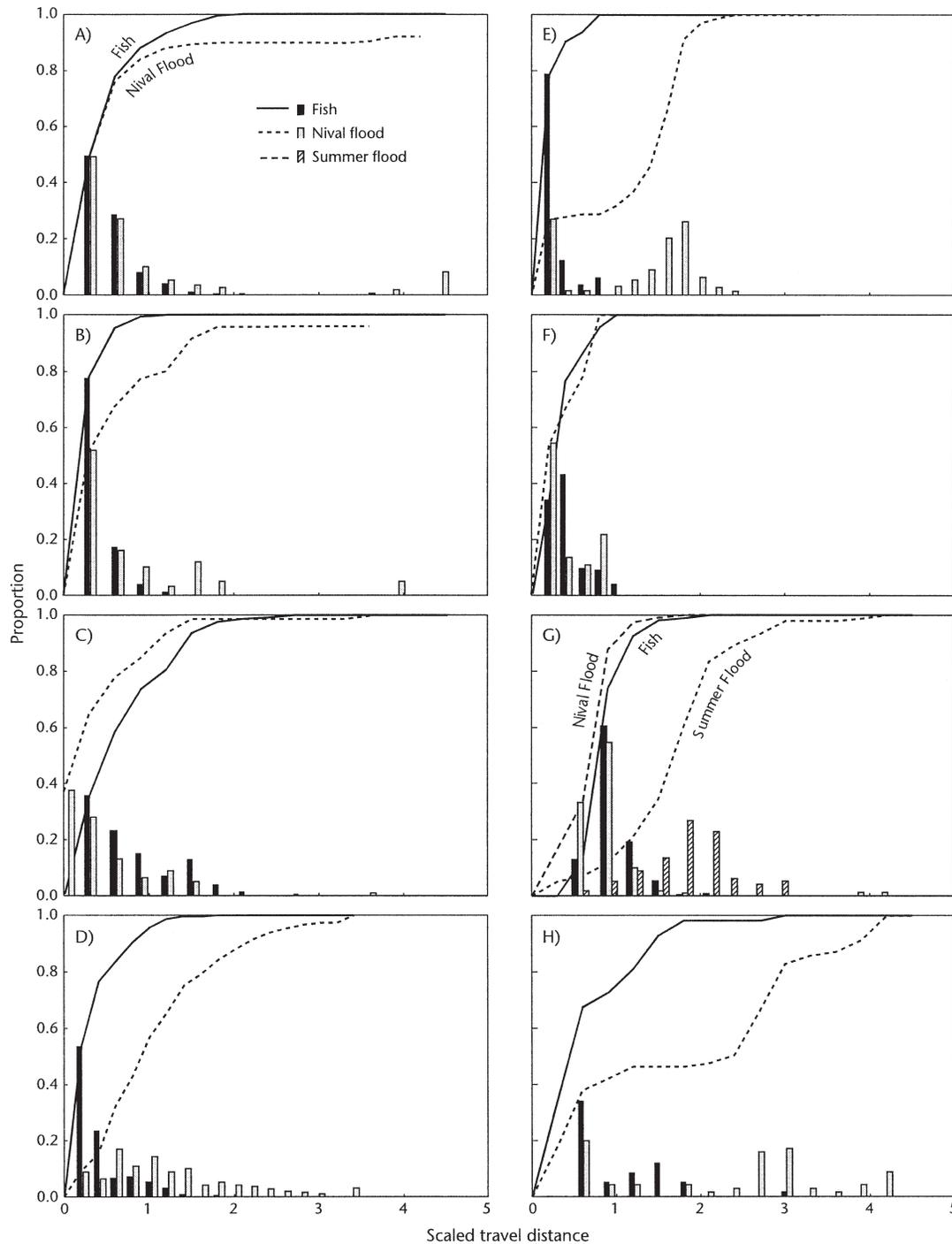


Figure 3. Particle Travel Distance Distribution of Particles Moved by Floods and Fish. (A) Forfar 250, 1993; (B) Forfar 250, 1994; (C) Forfar 250, 1995; (D) Forfar 1050, 1993; (E) Forfar 1050, 1994; (F) Forfar 1050, 1995; (G) O'Ne-ell 1550, 1995; and (H) O'Ne-ell 1550, 1996.

distributions of travel distances by floods and fish were different.

The O'Ne-ell 1550 samples (Figures 3g-3h) present travel distances during the 1995 and 1996 seasons. In the 1995 nival flood, most of the particles (approximately 90 percent) moved more than one channel

width. The pattern of movement by the nival flood and sockeye activity is similar (Table 2); a large proportion of the particles moved short distances. The summer flood yielded a different distribution than the fish dispersal.

TABLE 2. Statistical Interaction Matrix (Kolmogorov-Smirnov) for Travel Distance and Burial Depth Distributions of Clasts Mobilized by Floods and Fish.

Year	Nival		Summer	
	Travel	Burial	Travel	Burial
Forfar 250 / Salmon				
1993	•	•	••	•
1994	•	•••	X	X
1995	•••	•	••	•
1996	•	•	X	X
Forfar 1050 / Salmon				
1993	◆	•	•••	◆
1994	◆	◆	X	X
1995	•	••	••	••
1996	•	•	X	X
Forfar 1545 / Salmon				
1993	◆	•	•	•
1994	◆	••	X	X
1995	•	◆	••	••
1996	•	•	X	X
O'Ne-ell 1550 / Salmon				
1993	X	X	X	X
1994	X	X	X	X
1995	•	•	◆	•••
1996	•••	•	X	X
O'Ne-ell 1910 / Salmon				
1993	•••	•	◆	••
1994	•••	•	X	X
1995	◆	••	•	••
1996	X	X	X	X

Notes: The rejection of the null hypothesis is indicated by (◆). Where the hypothesis was accepted, the level of significance (α) is indicated as follows: • = 0.1, •• = 0.05, and ••• = 0.01. Where no measurements were taken, events are marked with an (X).

Figure 4a presents the relation between mean travel distance and specific discharge. Two main groups of data are evident: one related to fish activity with specific discharge below 0.1 m²/s and another range of flows more typical of floods. However, there are three data points (circled) related to fish activity with specific flow greater than 0.1 m²/s; they represent fish spawning activity during unusually high summer flows. The peak flow values attributed to periods of fish activity in Table 1 span the entire spawning period. In all cases the peak flow occurred early in the spawning interval. As expected, the mean distance of movement by fish is widely scattered, with no relation to flow conditions. In the case of flood transport, the

mean travel distance ranges over three orders of magnitude. The main body of the nival data is relatively scattered; however, there is clearly an increasing trend in the mean travel distance with higher flows [$L = 6.61(q)^{2.54}$; $r^2 = 0.59$]. The summer events are generally located near the upper bounds of the envelope. This suggests that some clasts deposited a few weeks earlier are easily entrained by summer floods.

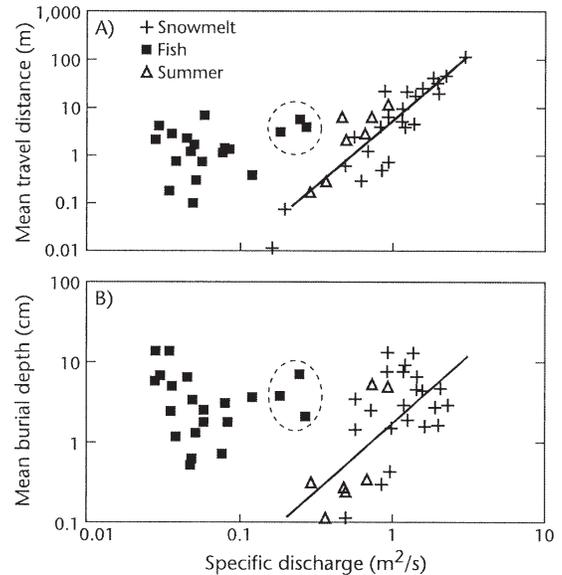


Figure 4. (A) Relation Between Mean Travel Distance and Unit Discharge and (B) Relation Between Mean Burial Depth and Unit Discharge.

Table 1 indicates downstream changes in the sediment mobility attributed to floods and fish. For example, the mean travel distances obtained for floods and fish were comparable in the Forfar 250 reach, whereas the mean travel distance initiated by floods at Forfar 1550 was more than an order of magnitude larger than that of the fish. In order to compare the relative amounts of transport work done under both conditions, the travel ratio was calculated as L_{flood}/L_{fish} , where L_{flood} is the mean travel distance moved in the flood and L_{fish} is the mean travel distance moved during redd excavation. The ratio was then plotted against the reach distance upstream. Data from the three Forfar sites are shown in Figure 5a. This figure shows large within reach variability that may be attributed to interannual variation in the magnitude of transporting events. Some of the factors controlling this variability include flood magnitude, the size of the salmon spawning run, and interactions among the sequential events. Despite the spread in the data points, there is a strong indication in more upstream

reaches that the spawning fish exert less influence and the sediment mobility is increasingly controlled by the high discharge events. For two-thirds of the cases in Forfar 250, the ratio was below one, implying that the influence of fish on particle travel distance and burial was greater than the influence by floods. The same results were obtained for the Forfar 1050 reach. Forfar 1545 reach yielded ratios above one, except for one case that was slightly lower than one. O'Ne-ell reaches yielded very similar results. These results indicate that floods dominate the transporting work in the upper reaches in both creeks and that the fish are more effective contributors downstream.

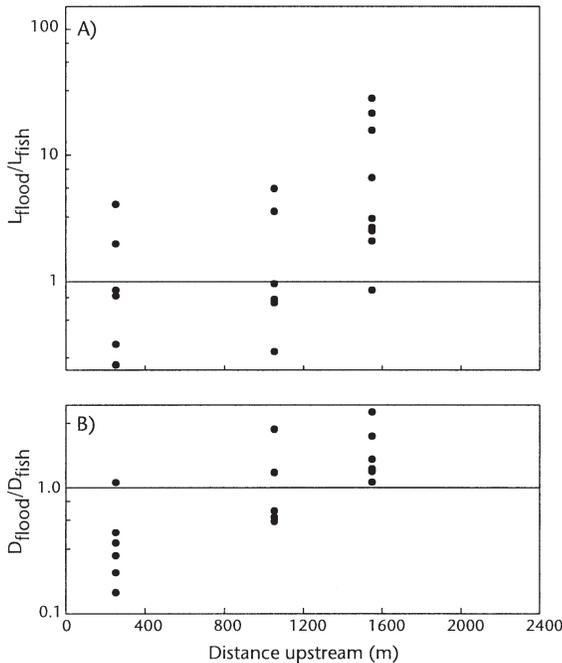


Figure 5. (A) Relation Between $L_{\text{flood}}/L_{\text{fish}}$ and Upstream Distance and (B) Relation Between $D_{\text{flood}}/D_{\text{fish}}$ and Upstream Distance.

Burial Depth of Tracers

The distributions of burial depths produced by each event were examined for any systematic trends. Depths of burial were scaled by the D_{50} , median grain size, of the bed surface material of each reach (see Hassan and Church, 1994). The data were then grouped into intervals equal to the scaled D_{50} . Due to the lack of a distinct relation between channel morphology and particle characteristics, the data were not differentiated on the basis of bed morphology (e.g., pool, riffle) or particle size. As with travel distance (see above), the distributions of the burial depth by flood and fish were compared using the

nonparametric K-S test under the null hypothesis that the cumulative frequency distributions of the measurements are similar.

Representative results from three reaches are shown in Figure 6. At Forfar 250 in 1993 (Figure 6a), the mean burial depth after nival flooding was about 1.5 cm deeper than that obtained after spawning (Table 1). The proportions of particles found on the bed surface were 28 percent and 37 percent for floods and fish, respectively. Higher proportions of clasts in the surface layer were obtained for the subsequent years. During the 1993 season, the median burial depth for both floods and fish were about the same ($3D_{50}$). In 1994 and 1995 (Figure 6b, 6c), the fish burial depth exceeded that of the flood for the reach. The null hypothesis was accepted for the 1993, 1995, and 1996 seasons at the significance level of 0.1 and for the 1994 season at the significance level of 0.01 (see Table 2).

Mixed results were obtained for the Forfar1050 reach (Figures 6d-6f). During large floods the burial depth of the particles exceeded that of the fish for that year. The opposite is true in the case of small events. The median burial depth of most events (floods and fish) ranged between surface and about $2D_{50}$. However, during the 1995 flood and spawning events and the spawning event of 1994, about 90 percent of the tracers were buried within the top $2D_{50}$ layer. The null hypothesis, that the distribution of burial depths was similar, was accepted for 1993, 1995, and 1996 but was rejected for the 1994 field season. At the O'Ne-ell 1550 and 1910 reaches the null hypothesis was accepted for all of the field seasons with sufficient data for comparison (Figures 6g-6h).

The relation between the mean burial depths by floods and fish was related to the specific discharge. As in the travel distance (see above), the analysis yielded two distinct groups: floods and fish (Figure 4b). The flood data indicate an increase in the mean burial depth with higher flows [$D = 1.92(q)^{1.73}$; $r^2 = 0.39$]. Summer floods, which tend to be smaller than the nival peaks, have lower burial depths. The spawning bioturbation burial depths have no relation to the flow conditions but cover the same depth range as the floods.

To evaluate the relative burial work done by floods and fish, the $B_{\text{flood}}/B_{\text{fish}}$ ratio was calculated; B_{flood} and B_{fish} are the mean burial by floods and fish for the year examined, respectively. The outcome presented in Figure 5b was very similar to the travel distance ratios and is subject to the same limitations (e.g., flood magnitude and fish return). At the Forfar 250 reach, the ratio was below one, indicating intense fish activity. The opposite is true for the upper reaches; here the burial work of floods is dominant.

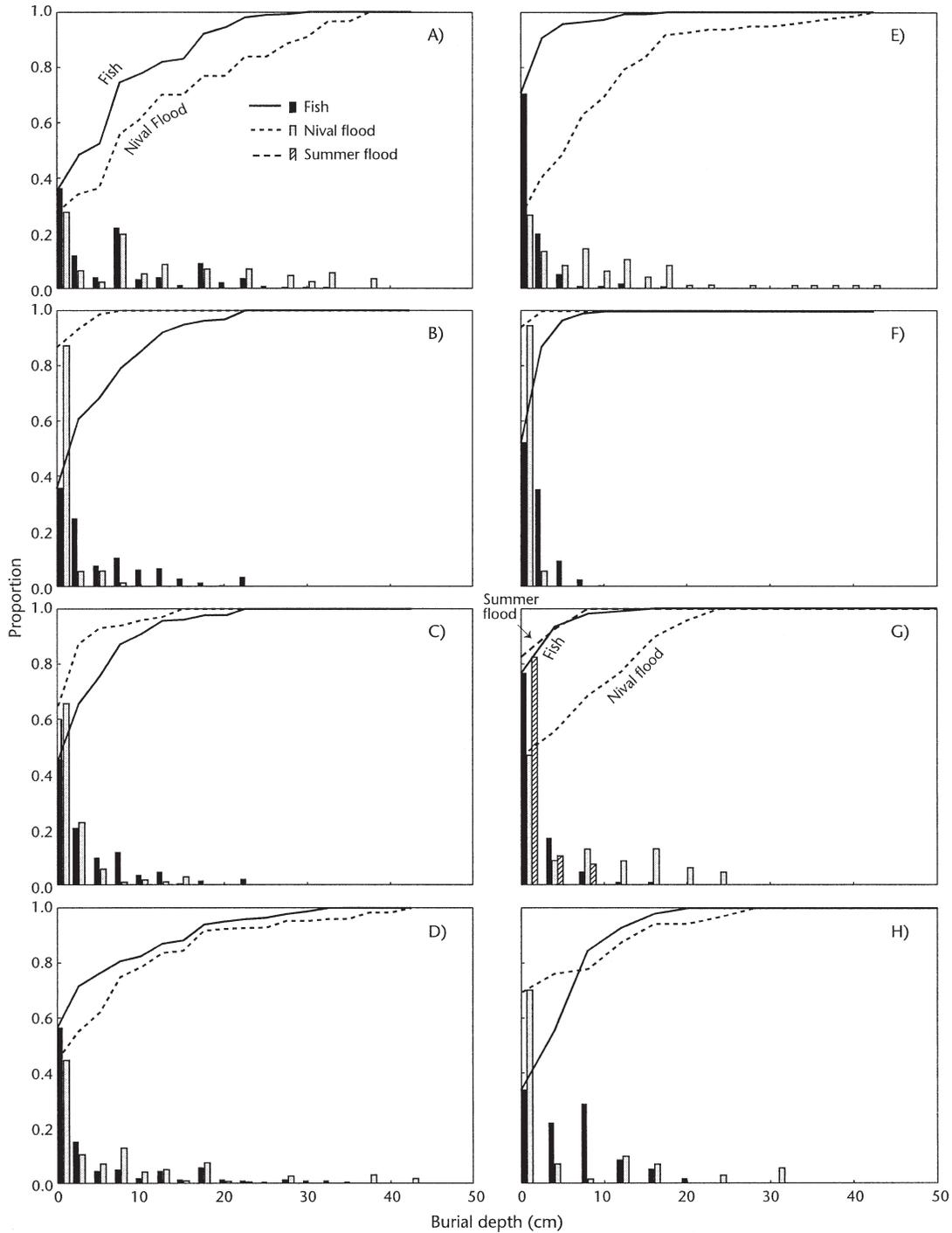


Figure 6. Particle Burial Depth Distribution of Particles Moved by Floods and Fish: (A) Forfar 250, 1993; (B) Forfar 250, 1994; (C) Forfar 250, 1995; (D) Forfar 1050, 1993; (E) Forfar 1050, 1994; (F) Forfar 1050, 1995; (G) O'Ne-ell 1550, 1995; and (H) O'Ne-ell 1550, 1996.

Particle Dispersion and Salmon Return

It is expected that both the distance of movement and burial depth of tracer particles should bear some relation to the abundance of spawning fish. Nearly all

of the work in redd excavation is carried out by female sockeye (Foerster, 1968). Not all sockeye females reaching the spawning stream live to spawn: in various years, prespawning mortality ranged from 0 to 40 percent. Tschaplinsky (1994, 1998) has shown that although the density of sockeye is variable, there

is no pronounced trend in patterns of abundance in the portions of the creeks containing the study reaches. Consequently the distance of transport and burial depth was averaged for the two or three reaches on each creek and this value was compared to the number of spawning sockeye females (Figure 7). The mean travel distance increases with the number of returning salmon. Similar results were obtained for the burial depth (Figure 7b).

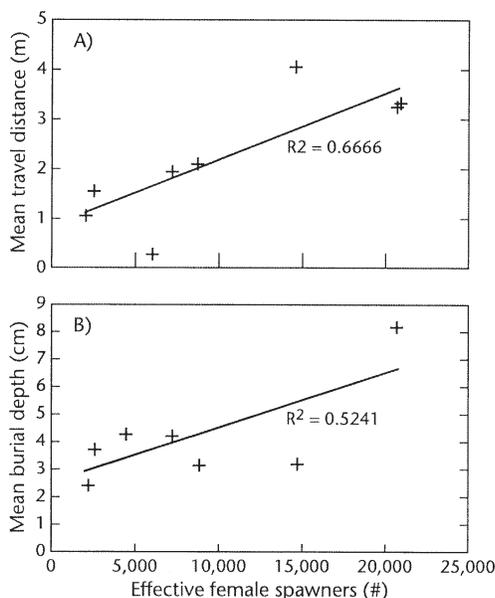


Figure 7. The Relation Between the Adult Numbers During the Spawning Periods and (A) the Mean Travel Distance and (B) the Mean Burial Depth.

Burial Depth of Tracers and Depth of Salmon Disturbance

The depth of the salmon egg pockets was established by freeze core sampling of recently excavated redds (Scrivener and Macdonald, 1998). The depth of tracer particles buried during redd excavation was typically shallower than egg pocket depth. Figure 8 presents the annual mean burial depth by floods, and redd excavation and depth of egg pockets. Error bars overlapping adjacent mean values indicate statistically similar results. At Forfar 250, the mean burial depth by spawning fish was greater than that of the floods in all years except for 1993, when burial depth after the nival flood slightly exceeded the redd excavation depth. Furthermore, most years show that the mean burial depth by floods is statistically different than that achieved by the fish. The mean depth of egg pockets was always larger than that obtained by the

tagged particles for the floods and fish bioturbation (Figure 8a). Data on the egg pocket depth for the Forfar 1050 reach are not available. The comparison here, therefore, is limited to the floods and fish. For this reach, mixed results were obtained (Figure 8b). The mean burial depth of floods exceeded that of the fish for the 1993 and 1994 seasons, while the opposite is true for the 1995 and 1996 seasons. The differences in the burial depth are statistically significant. The Forfar 1545 reach (Figure 8c) shows that in all cases the mean burial depth by floods exceeded that of the fish. However, the differences in 1996 data are not significant. The O'Ne-ell 1550 reach yielded results similar to those of the Forfar 1050 reach (Figure 8d) while the O'Ne-ell 1910 reach results were similar to those of the Forfar 1545 (Figure 8e).

DISCUSSION AND SUMMARY

There are about 2,600 salmon spawning streams in British Columbia. Of these, 364 support annual spawning populations of more than 10,000 fish (Williams *et al.*, 1994). The relative spawner density in these channels is not known (statistical information on stream width and length of channel spawning grounds has not been compiled), though it is likely that in many of the streams it is not as high as it is in the Stuart-Takla streams. The species vary also. The smaller and more abundant pink salmon are much less efficient at moving gravel. The larger Chinook salmon, on the other hand, form large spawning dunes – they are often present in large enough numbers to dominate the transport of the coarse sediment fraction. In addition, since Chinook salmon often prefer river reaches below lakes, flood flows are damped and the salmon are more likely to be able to construct multiyear spawning structures. There are at least nine such localities in northern British Columbia alone: Nechako River, Morice River, Kitwanga River, Bear River, Kitsumkalum River, Babine River, Damdochax River, Meziadin River, and Stuart River.

The survival of salmon eggs increases and a greater proportion of fry are able to emerge from the streambed as the gravel becomes coarser, especially as the sand and finer matrix constituents decrease (McNeil and Ahnell, 1964; Tripp and Poulin, 1986, Bjornn and Reiser, 1991). As reaches develop where salmon are able to strongly influence the sediment movement regime, gravel quality increases through the selective export of fine sediment, and salmon productivity increases generating positive feedback. As the salmon improve the gravels, their egg to fry survival increases, and more salmon survive to return to the spawning ground. As an increasing proportion of

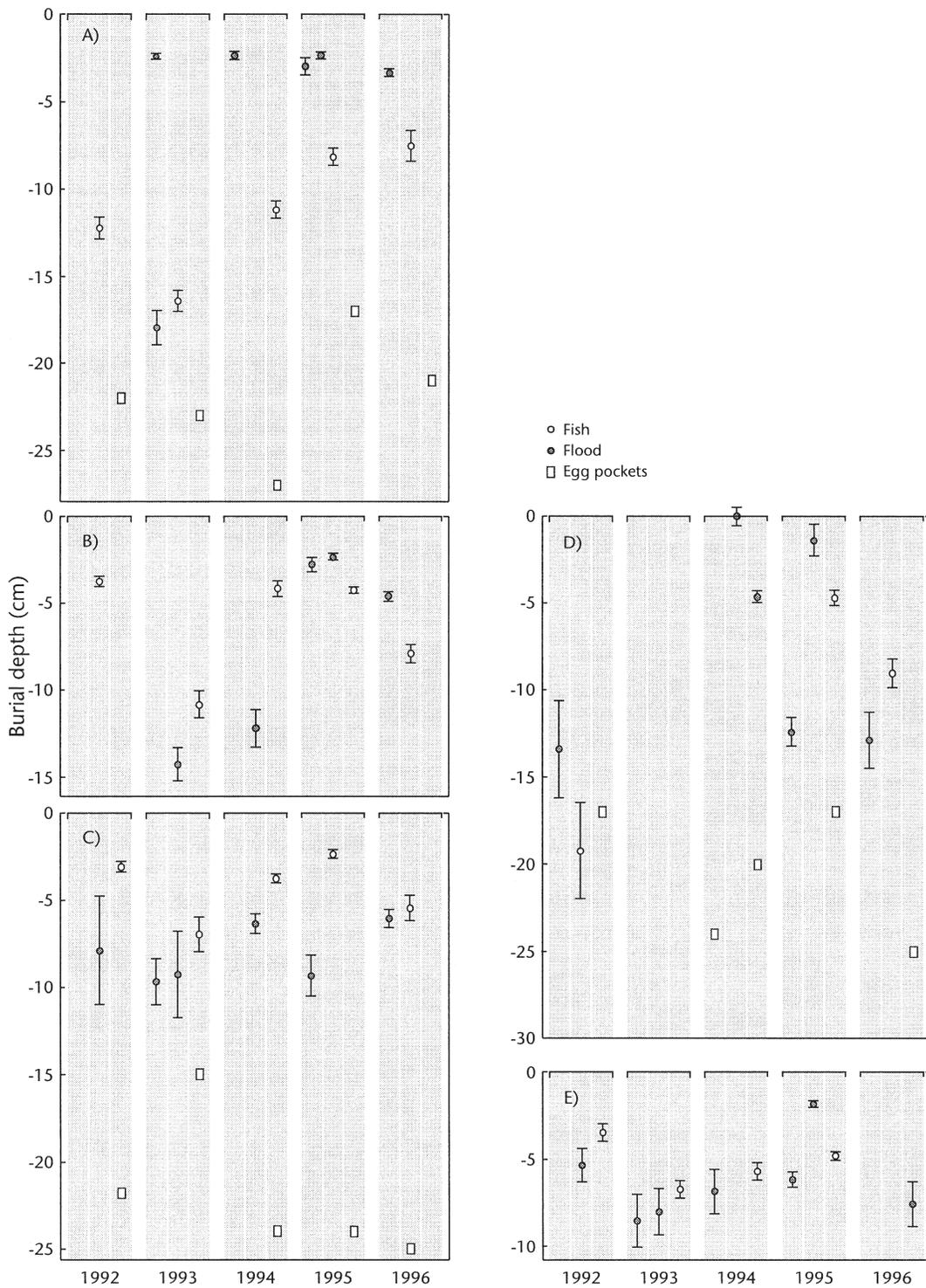


Figure 8. Mean Burial Depth by Floods and Fish of the Tagged Particles in the Study Reaches for the 1992 Through 1996 Field Seasons: (A) Forfar 250, (B) Forfar 1050, (C) Forfar 1545, (D) O'Ne-ell 1550, and (E) O'Ne-ell 1910. The mean depth of egg pockets is plotted for comparison.

the streambed is bioturbated, removing the armor layer, more of the stream area becomes available for new redd excavation. This positive feedback, in part,

explains the frequent pattern in which a few salmon spawning locations come to dominate a watershed's salmon productivity.

This tracer experiments in the lower reaches of two creeks in the Stuart-Takla area have shown that sockeye salmon play a significant role in the interannual transfer of sediment and the adjustment of channel morphology. Although spawning salmon do not move the material particularly far, they do have a pervasive effect on the packing of the sediment grains. After salmon have reworked the bed substrate to a certain degree, the sediment grains are more susceptible to transport than they would be otherwise.

In most cases flood transport moves particles farther than sockeye redd excavation. The variation in the ratio of transport distances shown in Figure 5 may be due in part to interaction between the two transport processes. Salmon were often observed spawning in newly deposited flood gravels that have lower amounts of matrix and are easier to excavate (Poirier, 2003). In the Stuart-Takla streams, nival floods rework streambed surfaces that had been changed little since salmon spawning in the previous summer (Tunncliffe *et al.*, 2000; Poirier, 2003). Filling of the thalweg and pools during redd excavation places particles in positions where transport distances may be higher than average, and therefore floods following large salmon spawning events may be expected to show larger particle travel distances.

Vertical mixing of sediment is part of the fluvial dispersion of sediment and the evolution of the streambed. The depth of tracer particle burial in each event is a function of the integrity of the streambed surface and the tractive stresses exerted by floods or fish. In the case of floods, the depth of scour is controlled by the magnitude and duration of flow; the quantity and texture of subsequent fill is controlled by the stream competence in waning flows. In the case of fish, burial depth is directly related to the intensity of the excavation efforts by the spawning females.

This study has shown that the burial depth achieved by fish is comparable to that of floods. These experiments have shown that the mean burial depth increases as the number of fish within a given reach increases. The increase in particle burial depth suggests two possible explanations. As the streambed is reworked by salmon, depressions are filled and higher streambed portions are removed. Thus particles moved early in the spawning period are buried successively deeper with repeated waves of spawners on the spawning ground, and the average depth of burial increases. Another possibility is that once a patch of gravel is excavated and clast imbrication is removed, subsequent excavation by sockeye salmon is easier. In either case the thicker loose gravel deposits can be expected to be beneficial to sockeye alevin survival in years when there is significant freezing of the streambed surface (Cope and Macdonald, 1998).

In terms of overall sediment transport, it is suggested that tracer burial is a much more important indication of transport work than the distance of grain movement along the bed. This is because the vertical mixing of the sediment to depths of up to $10D_{50}$ prevents the vertical sorting of sediment and weakens or prevents the development of an armored surface layer. A significant proportion of the finer matrix material is likely exported from riffle reaches by the actions of the spawning salmon.

The work during fish spawning is mainly a function of the location in upper or lower reaches of the stream, the intensity of fish activity, and flow conditions. Spawning salmon preferentially excavate the edges of bars and riffles. Tracers located close to these morphological elements are likely to move farther than those located in pools. In fact, local streambed depressions tend to go through phases of filling during the spawning activity. Fish will eject the coarser material a very short distance (generally about 1 m) downstream of excavated pits. However, flows can drag the highly exposed particles farther downstream, resulting in increased fish related distance of travel. In years when flood activity is particularly low and spawning activity is high, travel distances accomplished by fish can exceed those by floods. The opposite is true in years with longer, higher magnitude flood events; the travel distance attributed to fish in these years is relatively marginal.

Recognition of the strong geomorphological and sedimentological effects of salmon redd excavation and of positive feedback with sediment transport from floods provides a perspective on the factors that ultimately condition the supply and quality of spawning gravels. It is unclear what kind of long-term (multi-year) equilibrium has been attained in intensively bioturbated salmon streams and how disturbance from land use or diminishing fish stocks may affect that equilibrium. What does emerge from this study is that sediment transport and habitat quality are more closely interlinked than previously supposed. The optimum spawning habitat that is characterized by loose, matrix-poor gravels is not solely the product of turbulent fluvial deposition: further winnowing and vertical mixing from fish excavation occurs and is essential. The streams with high quality bioturbated gravels are thus special and valuable resources, keystone ecosystems that have been developed over many years of spawning activity. Recovery of normal sediment transport processes will be problematic in the many streams that now have depressed salmon spawning populations. Reestablishment of normal function may take decades of effort to rebuild salmon populations and concurrently restore gravel quality.

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