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The timing of scour and fill in a gravel-bedded river measured with buried accelerometers

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SUMMARY

A device that measures the timing of streambed scour and the duration of sediment mobilization at specific depths of a streambed was developed using data-logging accelerometers placed within the gravel substrate of the Cedar River, Washington, USA. Each accelerometer recorded its orientation every 20 min and remained stable until the surrounding gravel matrix mobilized as sediment was transported downstream and scour reached the level of the accelerometer. The accelerometer scour monitors were deployed at 26 locations in salmon-spawning habitat during the 2010–2011 flood season to record when the streambed was scoured to the depth of typical egg-pocket deposition. Scour was recorded at one location during a moderate high-flow event (65 m^3/s; 1.25–1.5-year recurrence interval) and at 17 locations during a larger high-flow event (159 m^3/s; 7-year recurrence interval). Accelerometer scour monitors recorded periods of intermittent sediment mobilization and stability within a high-flow event providing insight into the duration of scour. Most scour was recorded during the rising limb and at the peak of a flood hydrograph, though some scour occurred during sustained high flows following the peak of the flood hydrograph.

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1. Introduction

Streambed scour, i.e. the mobilization of streambed substrate during high flows, influences geomorphic processes like sediment transport (DeVries, 2002) and benthic organisms including periphyton (Biggs et al., 1999; Matthaei et al., 2003; Segura et al., 2011), macroinvertebrates (Cobb et al., 1992; Death and Winterbourn, 1995; Townsend et al., 1997), and incubating salmon embryos (Montgomery et al., 1996; Rennie and Millar, 2000; DeVries, 2008). The effect of streambed scour on stream ecology has been studied through hydraulic modeling (e.g., May et al., 2009; McDonald et al., 2010) and the deployment of scour monitoring devices in the field (Montgomery et al., 1996; Nawa and Frissell, 1993). Most field-collected scour data describe the spatial distribution of depth of scour (removed sediment) and fill (deposited sediment) that occurs during a flood or flood season. These data have been measured by different types of scour monitors including scour chains (Emmett and Leopold, 1965; Lisle, 1989) and sliding-ball monitors (Klassen and Northcote, 1986; Tripp and Poulin, 1986; Nawa and Frissell, 1993).

Previous scour chain and sliding-ball monitor investigations have shown that much variability exists in the range and spatial distribution of scour depths; while the maximum scour depths in parts of the channel may greatly exceed the thickness of the surface armor layer, little to no scour may be observed in other parts of the channel (Hassan, 1990; Haschenburger, 1999; Rennie and Millar, 2000). This variability in scour depths reflects the complex interaction between hydraulic forces acting on the streambed, which are not only influenced by heterogeneous bed material and channel morphology but also by changing hydraulic conditions during a flood event and even temporary obstructions such as passing large woody debris. Although the spatial variability in the depth of scour is well established in a variety of fluvial systems, the temporal record of scour and streambed mobilization during high flows has not been intensively studied and few field methods to measure it exist.

Scour monitors that record the timing of streambed scour are necessary to assess the relation between streambed scour and geomorphic conditions during a high-flow event. Methods to measure the timing of scour during a flood include continuous monitoring of neutrally buoyant radio transmitters buried within stream gravels (Cascades Environmental Services, 1991). Dislodgement indicated when bed scour reached the transmitter burial depth; however, this approach required continuous monitoring by field personnel precluding precise determination of the timing of scour. In addition, transmitters were lost upon dislodgement preventing determination of the timing or depth of subsequent fill. DeVries

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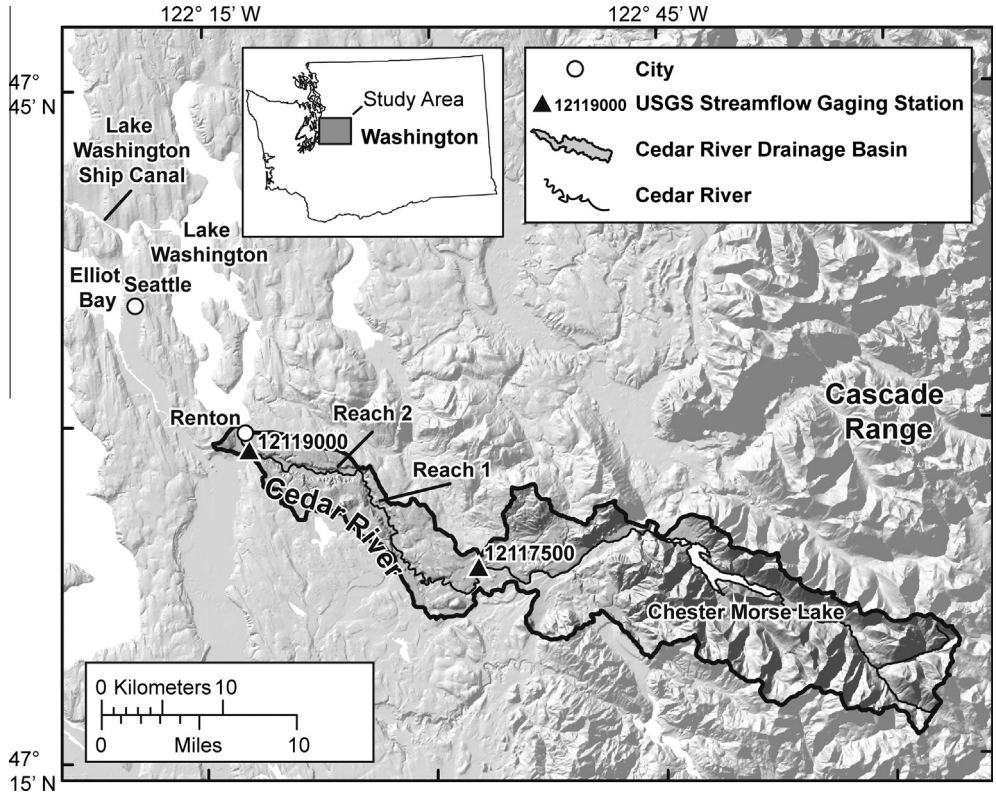

Fig. 1. Location of study reaches within the Cedar River drainage basin, Washington.

et al. (2001) developed another method called the electronic scour monitor for determining the timing of streambed scour by modifying conventional sliding-ball scour monitors so that they recorded when a magnet within each ball passed a magnetic reed switch after it was exhumed from the streambed.

The objective of this study was to present a new scour-monitoring method based on data-logging accelerometers installed in the gravel substrate of a streambed and evaluate their ability to record the temporal history of scour in salmon spawning habitat. The accelerometers can be deployed at one or more depths at single locations to measure the time when scour reaches critical depths of the streambed and are capable of recording over several months during a flood season. Moreover, accelerometers record the duration of streambed mobilization providing insight into bedload transport in the field. Time series of the orientation of individual accelerometers were recorded at 26 locations in the Cedar River, Washington (Fig. 1), and were interpreted with respect to the mobilization and stabilization of the adjacent gravel substrate during the 2011 Water Year (October 2010–September 2011).

2. Cedar River: Geography, hydrology, and salmonid spawning

The Cedar River flows 72 km from its headwaters in the Cascade Range into Lake Washington (Fig. 1) and has been regulated by a dam at the outlet of Chester Morse Lake since the early twentieth century. Flow regulation and floodplain alterations, including bank stabilization structures such as revetments, have contributed to channel narrowing, reduced number of side channels, limited channel migration, and reduced sediment supply (Perkins, 1994; Gendaszek et al., 2012). Cedar River hydrology is governed by the temperate, humid Pacific Northwest climate (Mass, 2008). Summers are dry and warm and winters are wet and mild. Flood hydrology is dictated by heavy and prolonged winter-rain events (Neiman et al., 2011) and snowmelt during the spring. The largest peak-flow events typically occur between November and January, while a smaller snowmelt freshet occurs in May or June, which is partially retained by Chester Morse Lake for municipal water supply during the summer. Mean annual streamflow of the Cedar River at Renton was 18.8 m^3/s between 1946 and 2010. During this period, the highest mean monthly streamflow occurred during January (31.1 m^3/s) and the lowest mean monthly streamflow occurred during August (5.4 m^3/s). The highest instantaneous streamflow recorded at this gage was 300 m^3/s on 24 November 1990 (Gendaszek et al., 2012).

The Cedar River is managed to provide 70% of the City of Seattle's municipal water supply, limited flood control along its suburban and urban river corridor, and spawning and rearing habitat for several species of anadromous salmonids. These salmonids include native Chinook salmon (*Oncorhynchus tshawytscha*), coho salmon (*Oncorhynchus kisutch*), and steelhead trout (*Oncorhynchus mykiss*) and introduced sockeye salmon (*Oncorhynchus nerka*). During spawning, female salmonids dig depressions called redds, deposit eggs, and cover them with a clean layer of gravel where they incubate for several weeks to months prior to the emergence of fry (e.g., Peterson and Quinn, 1996). In the Pacific Northwest, the incubation period of several salmonid species coincides with the late fall and early winter flood season. In response to the listing of two salmonid species under the federal Endangered Species Act, Chinook salmon and steelhead trout, resource managers of the Cedar River created a habitat conservation plan (Seattle Public Utilities, 2000) that included protocols to regulate peak flows to minimize scour of salmonid embryos incubating in river gravels.

During the development of salmonid embryos, scour of gravel from the streambed to the depth of egg pockets within redds and the resulting entrainment or crushing of salmonids embryos may adversely affect the survival of salmonid embryos and thus constrain salmonid population viability (Montgomery et al., 1996; LaPointe et al., 2000). In addition, salmonid-embryo survival may

also be reduced by the infiltration of fine-sediment into spawning gravels that can clog interstitial pore space thereby limiting clean, oxygenated water to developing embryos (Greig et al., 2007; Lisle and Lewis, 1992) or entomb salmon embryos preventing their emergence (Chapman, 1988). In the Cedar River, embryo to fry survival of sockeye salmon was found to be negatively related to the magnitude of peak flow (Thorne and Ames, 1987). Salient questions for river managers trying to recover salmonid populations in the regulated Cedar River include how redd scour is related to increasing peak flow magnitude and whether compromises between magnitude and duration of peak flows could be used to mitigate redd scour. In addition, much of the Cedar River is confined by armored revetments and levees that restrict channel migration and increase flow velocity during high-flow events (Gendaszek et al., 2012). Previous scour monitoring suggested that scour to the depth of salmon egg pockets in the Cedar River initiates when discharge exceeds 51 m^3/s at Renton, Washington (USGS Gage 12119000; 1.25–1.5-year recurrence interval) (Cascades Environmental Services, 1991), but little was known about the specifics of the depth or spatial and temporal extent of scour as a function of discharge. Herein, "scour depth" refers to the difference between the elevation of the streambed at the time of spawning and the bottom of the active layer of bedload transport (DeVries, 1997).

3. Accelerometer scour monitors

Accelerometer scour monitors (ASMs) were constructed from one or two Onset HOBO Pendant-G accelerometers (use of trade or brand names in this paper is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey) encased in 8-cm lengths of 4-cm diameter schedule 40 PVC tubing. Each accelerometer was attached independently by braided steel wire to a 10-cm angle-steel anchor (Fig. 2). Accelerometers measure acceleration using silicon beams that deflect with acceleration caused by gravity or motion. As the beams accelerate, their capacitance changes proportionally, which is converted to voltage, measured, and related to acceleration. Three sensors arranged orthogonally allow determination of the static three-dimensional orientation (i.e., tilt) of the accelerometer. Each accelerometer was programmed to record its orientation every 20 min. The PVC tubing was weighted with lead so that each ASM had a density comparable to streambed sediment of approximately 2.6 g/cm^3.

ASMs were inserted into a 6-cm-diameter hole within the gravel streambed while minimizing disturbance of adjacent sediment using a pounding device similar to that described by Klassen and Northcote (1986). The gravel matrix surrounding the pounding device compacted slightly to accommodate the void created by the pounding device, but the structure of the streambed substrate farther than 6 cm from the pounding device remained largely unaltered. As the pounding device was removed from the streambed, sediment collapsed around the insertion hole and integrated the accelerometers into the adjacent gravel matrix. The depth of the accelerometers relative to the streambed surface was determined from the length of the braided cables attaching the accelerometers to the anchor and direct measurement of the anchor depth prior to removal of the pounding device. Each accelerometer was held with a taut nylon cord as the pounding device was removed from the streambed to ensure that the accelerometers remained at a constant depth and that kinks in the braided cable holding the accelerometers to the anchor did not develop. After an ASM was exhumed from the streambed, local scour due to flow obstruction would scale with the 4-cm diameter of the accelerometer's PVC casing. The initial streambed elevation and location of each ASM was surveyed using a real-time kinematic global positioning system (RTK-GPS), which had a vertical and horizontal accuracy of approximately ±3 cm, comparable to the grain roughness of the streambed. A survey rod with a flat 30-mm base was placed on top of a particle and not allowed to settle into the substrate. At the end of the deployment, ASMs were relocated using the real-time kinematic global positioning system (RTK-GPS), excavated, and recovered. Upon ASM recovery, streambed elevation and the elevation of each accelerometer was surveyed to determine maximum scour depth and net fill and the time series of orientation was downloaded from each accelerometer to a computer.

ASMs recorded the time that scour lowers the streambed to the level where each accelerometer was deployed and the time of subsequent fill from the maximum scour level. Each accelerometer remained stable and at a constant tilt until it was scoured from the streambed as overlying sediment was removed. Upon scour, an accelerometer reoriented to the overlying flow in the downstream

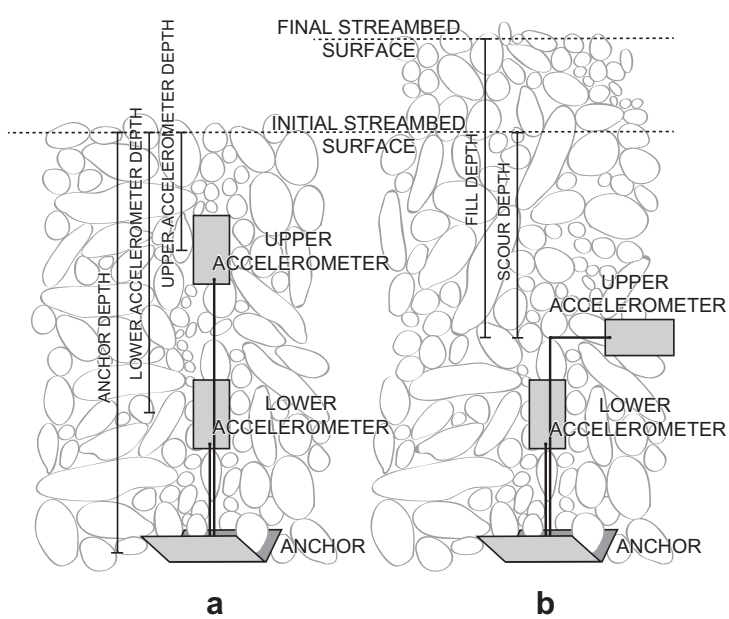

Fig. 2. Schematic of accelerometer scour monitor deployment (ASM) with (a) initial deployment of two accelerometers deployed in series and (b) final orientation of accelerometers after flood season enabling the measurement of maximum scour and net fill depths.

Fig. 3. Location of accelerometer scour monitors (ASM) in Reach 1 shown with 2010 orthoimagery; the white arrow indicates flow direction.

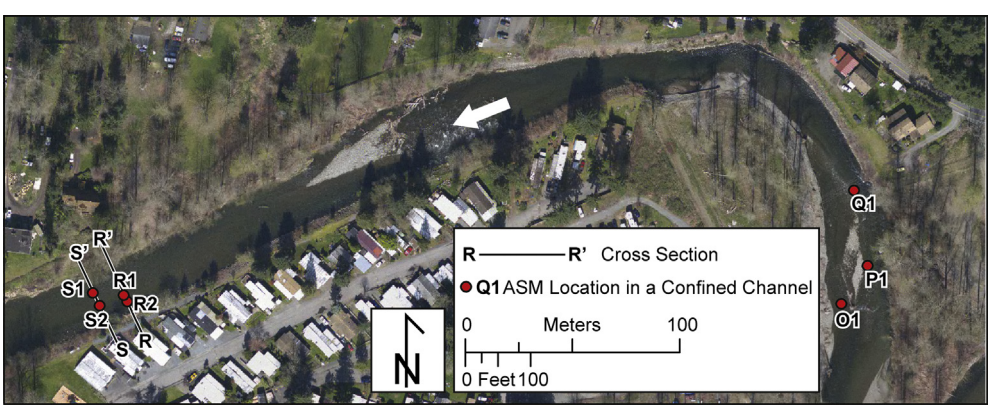

Fig. 4. Location of accelerometer scour monitors (ASM) in Reach 2 shown with 2010 orthoimagery; the white arrow indicates flow direction.

direction and recorded the new orientation within 20 min. An accelerometer did not record a change in its tilt until scour progressed to at least below the top of its 8-cm PVC casing and to at most its base indicating a ±4 cm resolution of measured scour depths. Small changes in tilt of less than 15° were recorded by accelerometers when the streambed was observed to be stable; therefore, only changes in tilt greater than 15° from vertical were attributed to scour. After its initial scour, the accelerometer, which was weighted to be the density of surrounding sediment, remained on the streambed/water interface allowing it to remain at the maximum scour depth if scour lowered the streambed below the installation depth of the accelerometer. Following scour, stability of the accelerometer between the 20-min recording intervals was interpreted to be the onset of fill above the accelerometer; continuous changes in accelerometer tilt was interpreted as no fill.

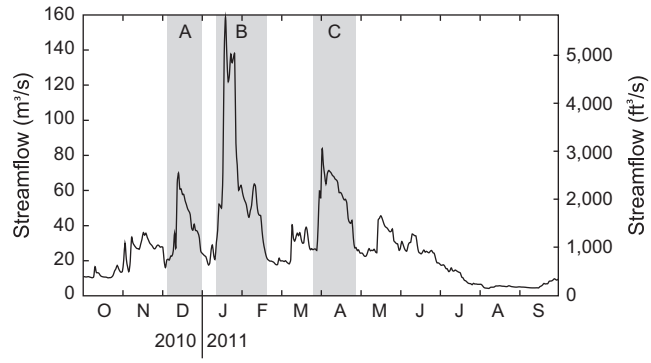

Fig. 5. Mean daily streamflow of the Cedar River at Renton (USGS Gage 12119000). High-flow events A, B, and C are shaded.

4. Field sites and accelerometer scour monitor deployment

Two reaches (Reach 1 and Reach 2; Fig. 1) of the Cedar River were selected for ASM installation based on their degree of channel confinement where confined channels were armored on both sides by riprap revetments and the availability of salmonid spawning habitat, which has been documented by regular spawning surveys (Burton et al., 2013). Substrate grain size characterized prior to the 2010–2011 flood season from scaled digital photographs using the methodology of Adams (1979), was predominantly coarse gravel and the median grain size (D50) of each reach was ~20 mm. Reach 1 is 860 m long and is located 17 km upstream of the Cedar River's mouth at Lake Washington. Reach 1 is mostly unconfined by revetments and other bank stabilization structures except for a 150 m long section of the left bank at the upstream end of the reach (Fig. 3). Reach 2 is 500 m long and is confined by riprap revetments on both banks and is located 11.5 km upstream of the mouth of the Cedar River (Fig. 4). The channel in Reach 1 is free to migrate or avulse and is connected to the adjacent floodplain at high flows thereby reducing peak-flow velocities in unconfined reaches relative to confined reaches. The degree of confinement within these two reaches are representative of conditions typical of the rest of the Cedar River (Gendaszek et al., 2012) and other anthropogenically altered rivers in the Puget Lowland (Collins et al., 2003).

ASMs were deployed in sockeye and Chinook salmon spawning habitat at 26 locations within Reaches 1 and 2 (Figs. 3 and 4). Specific locations were chosen based on observed spawning locations in riffles, glides, and pool tailouts within suitable substrate for spawning. After ASM deployment, salmon were observed to build their redds in the locations surrounding the ASMs potentially altering the streambed elevation and substrate at ASM locations. The ASMs were deployed away from large, in-stream wood that could have locally influenced scour. Twenty-two ASM locations consisted of two accelerometers installed at different depths; the other four ASM locations had one accelerometer. The ASMs were inserted so that the mid-point of the upper accelerometer (median depth: 18 cm) was near the top depth of typical Chinook salmon egg pockets and the mid-point of the lower accelerometer (median depth: 45 cm) was near the bottom depth of typical Chinook salmon egg pockets. Egg pocket depths vary between 15–50 cm for Chinook salmon and 10–25 cm for sockeye salmon (DeVries, 1997). Elevation cross-sections at ASM locations were measured using RTK-GPS when the ASMs were deployed and recovered to determine net change in streambed elevation during the flood season.

The ASMs were deployed in August 2010 prior to the 2010–2011 flood season and the return of spawning salmon. The ASMs were programmed to record their orientation at 20-min intervals beginning on 1 October 2010, which allowed continuous data logging until June 2011. ASMs were recovered in August 2011 during low flow. Three high-flow events exceeding Cascades Environmental Services' (1991) 51 m^3/s threshold for the initiation of salmon redd scour occurred during the 2010–2011 flood season (Fig. 5). These high-flow events are hereafter referred to as high-flow event A (December 2010; peak flow at USGS Gage 121190000: 80 m^3/s; 1.25–1.5-year recurrence interval), high-flow event B (January–February 2011; peak flow at USGS Gage 121190000: 168 m^3/s; 7-year recurrence interval), and high-flow event C (March–April 2011; peak flow at USGS Gage 121190000: 89 m^3/s; 1.5–2-year recurrence interval).

Local peak flows in the study reaches were estimated by scaling peak flows measured at the streamflow gage downstream of the study reaches at Renton (USGS Gage 121190000) and upstream of the study reaches near Landsburg (USGS Gage 12117500) by accumulated drainage area and were 65 m^3/s, 159 m^3/s, and 80 m^3/s, for high-flow events A, B, and C, respectively. The same peak flows were applied to Reach 1 and Reach 2 because no major tributaries enter the Cedar River between the two study reaches. A continuous record of streamflow at Reaches 1 and 2 was developed from the estimated peak flows and stage at Reach 1 and Reach 2 as recorded by pressure transducers at each reaches between 28 October 2010 and 1 July 2011. Unless noted, streamflow herein refers to local streamflow interpolated to Reaches 1 and 2.

5. Results

Twenty-four of the 26 deployed ASMs were recovered: two could not be located, 17 recorded streambed scour and 7 recorded no streambed scour (Table 1). Of the 17 ASMs that recorded scour, 3 ASMs recorded scour at both their upper and lower accelerometers and the other 14 ASMs recorded scour either at their upper accelerometer or only contained a single accelerometer. In all, 20 individual accelerometers recorded scour. Two ASMs (A2 and E1) were initially scoured during salmon-spawning in early October when discharge was less than 15 m^3/s. Only one ASM (E1) recorded scour during high-flow event A, on the rising limb of the hydrograph when the discharge was 64 m^3/s. Of the 20 individual accelerometers that recorded scour during high-flow event B (159 m^3/s), 17 accelerometers were scoured before or within several hours of the peak of the hydrograph, representing a 30-h span of time (Fig. 6). The other 3 accelerometers were scoured from 3 to 17 days after the peak of the hydrograph (Table 1). The three ASMs deployed in the upstream section of reach 2 (O1, P1, Q1; Fig. 4) were located where a major channel avulsion occurred during high-flow event B; the data from these ASMs were excluded from the general analysis.

Net fill and scour was evident from differences in cross-sectional geometry surveyed before and after the 2010–2011 flood

Table 1
Summary of ASM data.

ASM	Channel confinement/ Geomorphic channel unit	Position	Initial depth	Date and time of first movement	Discharge at first movement: At study reach, at renton	Date and time of final stability	Discharge at Final stability: at study reach, at renton	Maximum scour depth from initial bed surface	Net fill above maximum scour depth	Net bed elevation change from initial bed surface	Surface D50, D90
–	–	–	(cm)	–	(m^3/s)	–	(m^3/s)	(cm)	(cm)	(cm)	(mm)
A1	Confined/Glide	Upper	−7	1/17/2011 11:20	150	1/24/2011 14:40	123	−32	18	−14	17, 43
		Lower	−30	1/24/2011 14:20	123	1/24/2011 14:40	123				
A2	Confined/Glide	Upper	−15	1/17/2011 10:20	147	1/21/2011 18:00	123	−16	21	5	23, 46
		Lower	−34	Not Scoured	–	Not Scoured	–				
A3	Confined/Glide	Upper	−11	1/17/2011 5:40	131	1/24/2011 23:20	133	−12	20	8	34, 89
		Lower	−33	Not Scoured	–	Not Scoured	–				
B1	Confined/Riffle	Upper	−18	1/21/2011 0:20	109	1/24/2011 18:40	131	−25	22	−3	21, 47
		Lower	−44	Not Scoured	–	Not Scoured	–				
B2	Confined/Riffle	Upper	−38	Not Scoured	–	Not Scoured	–	−6 to −38	–	−6	30, 65
		Lower	−54	Not Scoured	–	Not Scoured	–				
B3	Confined/Riffle	Upper	−7	1/17/2011 17:20	153	1/17/2011 17:40	152	−19	22	3	30, 64
		Lower	−43	Not Scoured	–	Not Scoured	–				
C1	Unconfined	Upper	−37	1/17/2011 15:00	154	1/21/2011 16:00	126	−43	53	10	22, 43
	Glide	Lower	−61	Not Scoured	–	Not Scoured	–				
D1	Unconfined	Upper	−15	1/16/2011 18:00	90.4	1/18/2011 1:40	151	−40	33	−7	22, 43
	Glide	Lower	−46	Not Scoured	–	Not Scoured	–				
E1	Unconfined	Upper	−14	12/13/2010 0:20	63.9	1/18/2011 0:00	155	−34	33	−1	22, 43
	Glide	Lower	−30	1/16/2011 20:00	97.3	1/17/2011 20:40	159				
F1	Unconfined/Riffle	Upper	−54	Not Scoured	–	Not Scoured	–	−12 to −54	–	−12	n.m.
		Lower	−63	Not Scoured	–	Not Scoured	–				
G1	Unconfined/Riffle	–	−15	Not Scoured	–	Not Scoured	–	0 to −15	–	11	n.m.
H1	Unconfined/Pool Tailout	Upper	−19	Not Found	–	Not Found	–	–	–	−4	16,37
		Lower	−42	Not Found	–	Not Found	–				
I1	Unconfined/Pool Tailout	Upper	−12	1/16/2011 15:40	81.9	1/19/2011 3:00	138	−39	30	−9	16, 37
		Lower	−39	1/18/2011 5:20	150	1/18/2011 22:00	140				
I2	Unconfined/Pool Tailout	–	−35	1/16/2011 21:00	101	1/16/2011 21:20	105	−35	23	−12	16, 34
J1	Unconfined/Pool Tailout	Upper	−38	Not Scoured	–	Not Scoured	–	−12 to −38	–	−12	16, 35
		Lower	−60	Not Scoured	–	Not Scoured	–				
K1	Unconfined/Glide	Upper	−9	1/17/2011 13:40	154	1/17/2011 14:40	153	−27	25	−2	31, 49
	Unconfined	Lower	−36	Not Scoured	–	Not Scoured	–				
L1	Unconfined/Riffle	Upper	−36	Not Scoured	–	Not Scoured	–	0 to −36	–	57	n.m.
		Lower	−64	Not Scoured	–	Not Scoured	–				
M1	Unconfined/Riffle	Upper	−20	2/3/2011 4:20	51.0	2/15/2011 17:40	36.4	−23	24	1	n.m.
		Lower	−45	Not Scoured	–	Not Scoured	–				

(*continued on next page*)

Table 1 (*continued*)

ASM	Channel confinement/ Geomorphic channel unit	Position	Initial depth	Date and time of first movement	Discharge at first movement: At study reach, at renton	Date and time of final stability	Discharge at Final stability: at study reach, at renton	Maximum scour depth from initial bed surface	Net fill above maximum scour depth	Net bed elevation change from initial bed surface	Surface D50, D90
–	–	–	(cm)	–	(m^3/s)	–	(m^3/s)	(cm)	(cm)	(cm)	(mm)
N1	Unconfined/Riffle	Upper	−17	1/17/2011 7:40	141	1/17/2011 15:40	154	−18	14	−4	n.m.
		Lower	−44	Not Scoured	–	Not Scoured	–				
O1	Confined/Riffle	Upper	−13	Not Scoured	–	Not Scoured	–	0 to −13	68 to 81	68	n.m.
		Lower	−40	Not Scoured	–	Not Scoured	–				
P1	Confined/Riffle	Upper	−28	Not Scoured	–	Not Scoured	–	0 to −28	56 to 84	56	n.m.
		Lower	−56	Not Scoured	–	Not Scoured	–				
Q1	Confined/Riffle	Upper	−26	Not Found	–	Not Found	–	–	–	−69	n.m.
		Lower	−49	Not Found	–	Not Found	–				
R1	Confined/Glide	–	−9	1/16/2011 21:00	101	1/25/2011 22:40	107	−33	43	10	12, 48
R2	Confined/Glide	Upper	−22	1/17/2011 6:00	130	1/18/2011 19:20	143	−37	56	19	12, 48
		Lower	−50	Not Scoured	–	Not Scoured	–				
S1	Confined/Glide	–	−15	1/17/2011 21:40	157	1/17/2011 22:00	157	−15	16	1	12, 48
S2	Confined/Glide	Upper	−17	1/17/2011 12:00	149	1/18/2011 23:40	137	−36	30	6	12, 48
		Lower	−63	Not Scoured	–	Not Scoured	–				

season (Fig. 7). In some cross sections, large-scale geomorphic changes, including the deposition of new gravel bars and the incision of new channels, were evident (e.g., cross sections K–K′, L–L′, and M–M′; Fig. 7). At other cross sections, such as G–G′ (Fig. 7), little net change in streambed elevation was measured during the 2010–2011 flood season and the ASMs, even those placed at shallow depths (e.g., ASM G1, which had an initial burial depth of 15 cm) remained unscoured.

At most ASM locations, the maximum scour depth was larger than the net streambed elevation change over the 2010–2011 flood season. The post-flood-season streambed elevation was within approximately 20 cm of the pre-flood-season streambed elevation at all monitoring locations except ASM L1 where the pre-flood-season streambed aggraded by 57 cm due to a large-scale gravel-bar deposition during high-flow event B. Maximum scour depths and net elevation change over the 2010–2011 flood season were comparable in magnitude between riffles, glides, and pool tailouts (Table 1; Figs. 8 and 9).

6. Discussion

The temporal distribution of scour recorded by ASMs showed an increase in the spatial extent and depth of scour with increasing discharge. Scour at the level of the top of salmon-egg pockets (~10–15 cm) began at a discharge of 64 m^3/s. While only one ASM recorded scour at a shallow depth during the high-flow event A, 17 of the 26 ASMs recorded scour during high-flow event B, which had a much larger peak flow. In addition to recording more spatially extensive scour, ASMs recorded scour reaching progressively deeper depths during high-flow event B (Fig. 6). These observations are consistent with the results of previous scour monitoring studies in gravel bedded rivers that found a relation between scour depth and increasing flow strength (e.g., Haschenburger, 1999; Wilcock et al., 1996) as the bed disturbance depth reaches twice the surface D90 (DeVries, 2002). The relation between flow strength and discharge, however, is complicated and may reflect morphologic evolution of the channel, changes in the size of mobilized sediment, and the proportion of the channel mobilized as flows increase (DeVries, 2008).

The limited number of ASMs and the insensitivity of ASMs to scour above the level of the upper accelerometer precluded a complete characterization of the distribution of scour depths. Most scour was recorded near the surface where all accelerometers deployed less than 10 cm recorded scour, but no accelerometers deployed below 40 cm recorded scour (Fig. 10). No ASM recorded scour during high-flow event C, which was higher in magnitude and longer in duration than high-flow event A. This may be, in part, because it was not possible to reset the ASMs following scour and subsequent filling during high-flow event B. The timing of scour at the ASM locations during high-flow event C was therefore not known.

Scour was detected over two distinct timescales that corresponded to general mobilization of the streambed before peak flow and adjustment to morphologic evolution of the channel after peak flow. Most ASMs recorded scour over ~30 h during the rising limb of high-flow event B's hydrograph (Fig. 6). DeVries et al. (2001) similarly observed that most scour in a pool–riffle sequence occurred at or before the peak of a flood hydrograph. Scour during this time likely represented the large-scale mobilization of an active layer of streambed sediment (Wilcock and McArdell, 1997). In addition to recording when scour initially mobilized the streambed at different depths, ASMs also recorded the duration of bed mobilization (Fig. 6). In general, accelerometers that were buried at shallower depths recorded bed mobilization for longer periods of time than accelerometers buried at deeper depths (Fig. 10). After

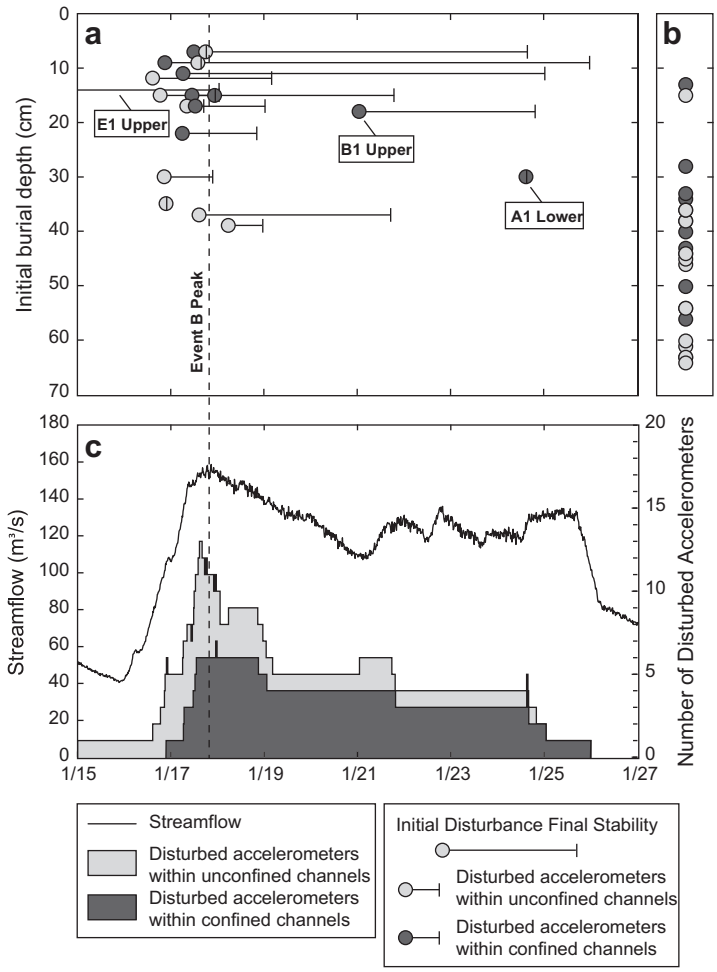

Fig. 6. (a) Timing of accelerometer disturbance and initial accelerometer burial depth during high-flow event B. Accelerometer E1 Upper was initially disturbed during high flow event A. Accelerometers B1 Upper and A1 Lower were initially disturbed days after the peak of event B. (b) Initial burial depth of accelerometers not disturbed during high-flow event B. (c) Streamflow and cumulative disturbed accelerometers in confined and unconfined study reaches during high-flow event B.

peak flow, more ASMs recorded fill than scour (Fig. 6) suggesting a general trend toward bed stabilization during the period of elevated discharge following the peak of high-flow event B. Several ASMs recorded discontinuous periods of movement over the course of high-flow event B (e.g., ASM I1; Fig. 11) indicating repeated scour and fill during the event.

The limited scour that was recorded after peak flow occurred mostly as the post-peak flow channel adjusted to large-scale morphologic changes complicating comparisons between flow strength and scour depth (Fig. 3). For example, ASM M1 was installed in a low-flow secondary channel alongside the left side of a center gravel bar. This ASM did not record scour until 17 days after the peak discharge of high-flow event B when all other ASMs had stabilized. Large-scale morphologic changes that occurred during high-flow event B, including bank retreat just downstream of ASM M1 on channel left, lowering of the center gravel bar, and deposition of over a half meter of sediment on the right side of the channel (near ASM L1), led to the concentration of the flow into the left side of the channel where ASM M1 was located (Fig. 7; cross-sections L and M). With increased flow at the location of M1 and changes in the local hydraulic controls due to morphologic changes, the ASM was scoured on 3 February 2011 when discharge was less than one-third of the peak. This ASM was not stabilized until 15 February 2011 by the subsequent deposition of 24 cm of fill. In addition, the upper accelerometer of ASM A1 first recorded scour on the rising limb of high-flow event B's hydrograph at 150 m^3/s, but the lower accelerometer of ASM A1 scoured at a lower discharge (123 m^3/s) on the falling limb of high-flow event B's hydrograph. This second mode of disturbance was not observed to be as widespread as the first mode, but can occur as many as several days after the peak of the event as long as discharge remains above the critical threshold for bedload transport in the river and the channel continues to move laterally or incise.

Except for areas where avulsions occurred or gravel bars were deposited, streambed elevations changed little over the flood season (Fig. 7). The streambed was scoured to the depth of salmon-egg pockets at several locations (e.g., cross sections A–A′, E–E′, I–I′) where channel morphology did not change greatly suggesting a near balance of sediment transported to and from these locations. Portions of the streambed at the depth of salmon-egg pockets remained unscoured even at relatively high flows such as at cross section G–G′. Some ASMs that contained upper accelerometers installed below the maximum scour depth recorded at adjacent ASMs did not record scour (e.g. ASM B2) but provide a lower limit of scour at their respective locations.

The ASM method augments existing scour monitoring methods such as conventional scour chains and electronic scour monitors (DeVries et al., 2001) by measuring the duration of sediment movement at different depths within the streambed in addition to the time when the streambed is scoured to a certain depth. The

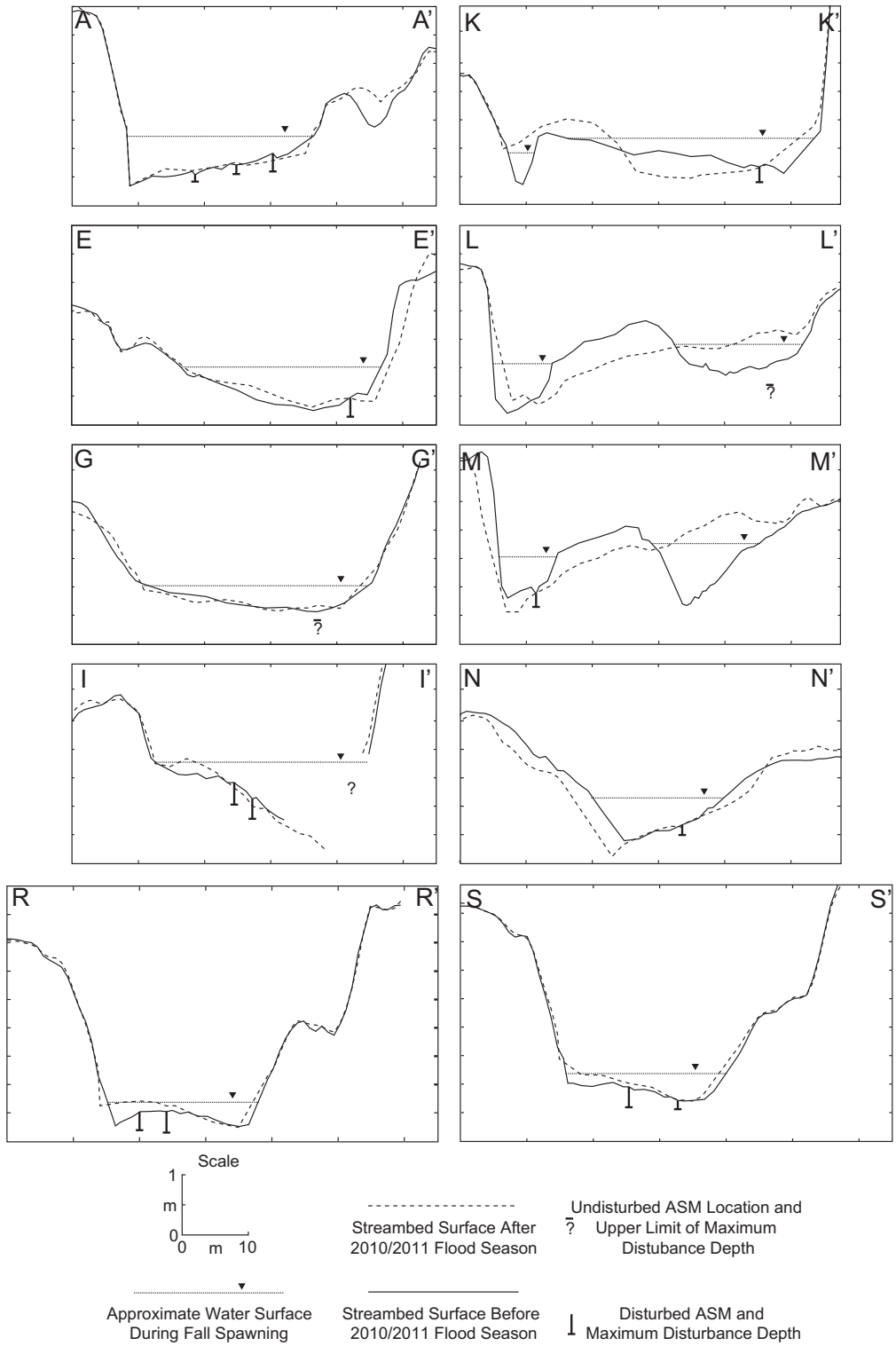

Fig. 7. Cross-sections at selected accelerometer scour monitor (ASM) locations within Reach 1 showing the streambed surface before and after the 2010–2011 flood season, the approximate water surface during fall spawning, and maximum streambed disturbance depths measured at ASM locations. Cross-section locations are shown in Figs. 3 and 4.

accelerometers used in this study were large relative to the dominant size of streambed sediment. As accelerometer and battery technologies advance and instrumentation becomes smaller, ASMs will become commensurately smaller and will be able to be deployed at more vertical intervals permitting investigation of scour processes at finer scales.

7. Conclusions

The time when the streambed scoured to discrete depths and the duration of streambed mobilization was recorded by ASMs. Although streambed scour is an inherently variable physical process in time and space, the data recorded by ASMs provides details

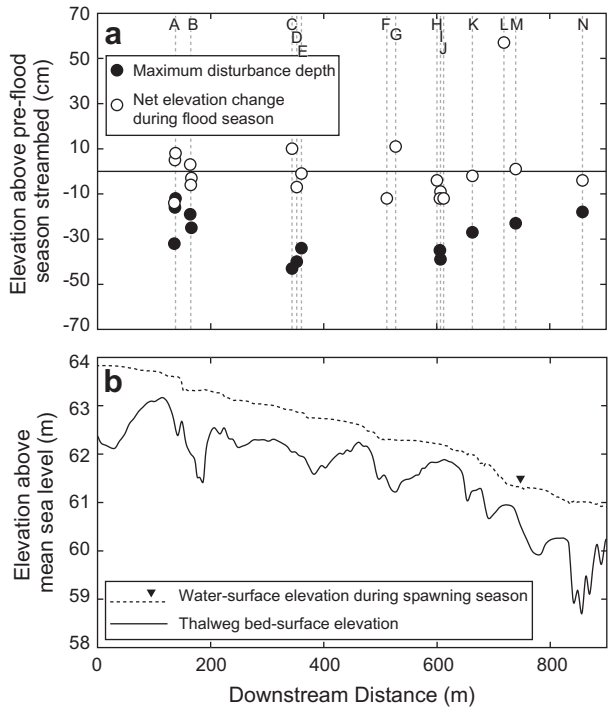

Fig. 8. (a) Longitudinal variation in maximum disturbance depth and net elevation change during the flood season for Reach 1. (b) Thalweg bed surface elevation and water-surface elevation during spawning season for Reach 1.

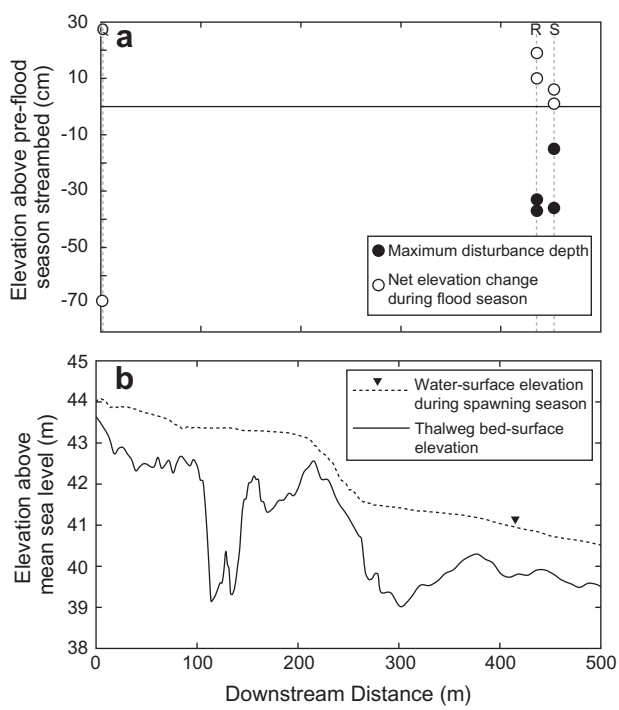

Fig. 9. (a) Longitudinal variation in maximum disturbance depth and net elevation change during the flood season for Reach 2. (b) Thalweg bed surface elevation and water-surface elevation during spawning season for Reach 2.

on the timing, spatial extent, and depth of streambed scour allowing mangers to regulate peak flows in order to minimize the impact of streambed scour on incubating salmon embryos. This includes when the streambed scoured to the top of a salmonid egg pocket (~10–15 cm) during a high-flow event, which was first recorded

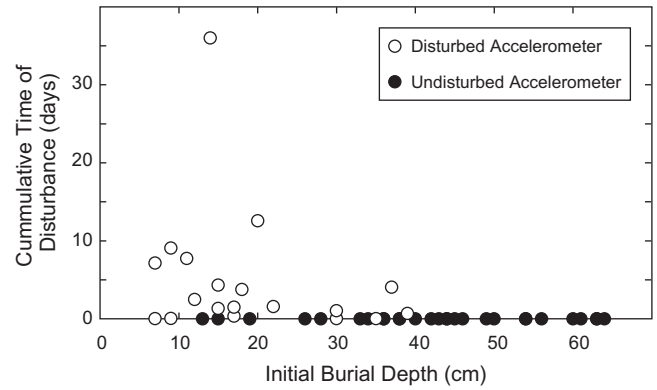

Fig. 10. Initial burial depth versus cumulative time of disturbance recorded by accelerometer scour monitors.

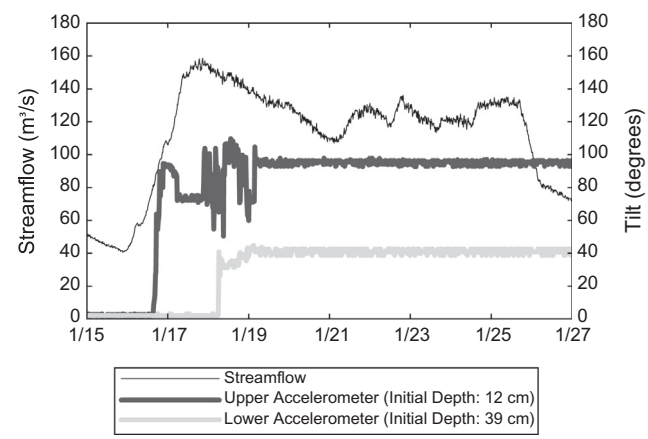

Fig. 11. Streamflow and change in tilt of the upper and lower accelerometers at accelerometer scour monitor I1 during high-flow event B.

when discharge reached 64 m^3/s at the study reaches. Most streambed scour occurred at peak flow of the large high-flow event and limited streambed scour occurred during an extended period of elevated post-peak discharge likely reflecting adjustment to morphologic changes to the channel that occurred during the high-flow event. The ASMs also recorded intermittent scour and fill suggesting localized variability in hydraulics and sediment supply during the studied high-flow events. Analysis of scour was limited by the spatial density of ASMs within the study reach and the size of the accelerometers relative to the substrate; future deployments of ASMs containing smaller accelerometers at a higher spatial density will further elucidate streambed scour during high flow events.

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