Flow Regulation and Protecting Incubating Cedar River Salmon From Streambed Scour

Introduction

Mobilization of streambed substrates and lowering of the streambed during periods of high stream flows, termed streambed scour, is generally accepted as one of the major factors influencing salmonid egg-to-fry survival in Pacific Northwest rivers (Schuett-Hanes et al, 1996). As flows increase and streambed scour occurs, salmon redd substrates and incubating eggs and alevins within redds can be mobilized, resulting in high egg-to-fry mortality rates. In regulated river systems, the potential for stream bed scour can be decreased by storing flood water behind dammed reservoirs and managing the magnitude and duration of high flows through reservoir release and storage operations before, during and after large storm events. A better understanding of the relation between streamflow and the potential for streambed scour allows water managers to improve their ability to effectively regulate flow to minimize the impacts of redd scour on incubating salmonids. This is especially important in river systems that are heavily impacted by development actions that confine and straighten river channels resulting in higher propensities for streambed scour.

The Cedar River in Washington State is a regulated system that provides spawning and rearing habitats for several species of salmonids including a large population of sockeye salmon. The Cedar River also functions as the primary water supply for the City of Seattle and the surrounding communities. In 2000, Seattle Public Utilities (SPU) began implementation of a Habitat Conservation Plan (HCP) for the Cedar River (Seattle Public Utilities, 2000). As part of the HCP, the Cedar River Instream Flow Commission (IFC) was formed to advise SPU regarding water supply and instream flow regulation decisions. The IFC is a stakeholder group comprised of natural resource professionals that represent federal, state, local, and tribal agencies. One of the primary objectives of the IFC is to promote water supply and flow regulation strategies that will minimize impacts to instream resources including salmon. To support this objective, the IFC provides funding and recommendations regarding research and monitoring efforts designed to inform water management decisions and operations. The relationship between instream flow and streambed scour in the Cedar River was recognized by the IFC as a key study topic that warranted further investigation. This report documents the results and recommendations from the most recent redd scour study in the Cedar River.

Background

Two previous studies have investigated streambed scour in the Cedar River. In 1991, Cascade Environmental Services (CES) utilized buried neutrally buoyant radio transmitters in an effort to determine the minimum flow at which stream bed scour occurs (Cascades Environmental Services, 1991). This technique was unable to determine the exact time of substrate mobilization which lessened the precision of flow estimates for the occurrence of redd scour. In addition, sample locations may not have accurately represented the physical condition of redd substrates because there was no way to verify that radio transmitters had been incorporated into incubating redds. Results of the CES study suggested that substrate mobilization was initiated at flows exceeding 1,800 cfs at the USGS Gage 12119000 in Renton. From 1991 to 2011, SPU and the IFC applied the resulting 1,800 cfs threshold opportunistically to guide instream flow management operations and prevent or reduce potential redd scour during high flow events.

In 2011, the US Geological Survey designed a scour monitor that utilized accelerometers to measure the timing and duration of streambed scour (Gendaszek et al., 2013). Accelerometers were incorporated into gravel and cobble substrates at specific depths and attached to an anchor deep in the streambed. Results from buried accelerometers that recorded movements exceeding 15 degrees from their initial orientation were presumed to represent scour events. Although accelerometers at some sample sites did verify spawning activity prior to high flow events, the majority of sites did not indicate that accelerometers had been incorporated into redd locations. Furthermore, only two reaches were sampled and sampled substrate depths did not adequately represent the shallowest documented egg pocket depths for sockeye salmon (Devries, 1997), the most abundant salmonid in the Cedar River. Data from recovered accelerometers suggested that initial streambed mobilization occurred when flows reached approximately 2,250 cfs at the Renton Gage. Accordingly, the IFC decided to increase the existing scour threshold from 1,800 cfs to 2,200 cfs (USGS Renton gage).

Due to the aforementioned limitations of both prior studies, the IFC decided to pursue an expanded flow/scour study designed to address the uncertainties in the two previous studies. To improve the applicability of the study results, a supplemental study element was included to address uncertainties regarding egg pocket depths for Cedar River sockeye salmon.

Methods and Materials

In the summer of 2013, scour monitors were placed throughout the Cedar River mainstem to measure scour events over the 2013-14 winter flood season. Monitors were placed at depths to mimic sockeye redd depths and recovered in the summer of 2014.

Scour Measurements – Scour monitors employed accelerometers to detect gravel movement. Methods from Gendaszek et al. (2013) were modified to increase the number of accelerometers per scour monitor from two to three, and to provide additional weight to the scour monitor anchor. In addition, the upper accelerometer in each scour monitor was placed to measure redd substrate depths that were substantially shallower than the previous study. Scour monitors were constructed from 3 Onset accelerometers encased in 6 cm long pieces of PVC tubing (Figure 1). Accelerometers devices measure tilt in 3 dimensions. A change in tilt of 15 degrees from the initial deployment orientation was used as a threshold to determine if streambed scour occurred at the depth of the accelerometer midpoint. Each accelerometer was weighted with lead to emulate the density of stream gravel. Braided and plastic sealed metal fishing line was used to attach accelerometers to one another at predetermined distances. Distances between upper and middle accelerometers and middle and lower accelerometers were 4 cm and 6.5 cm, respectively. A 10-ounce lead ball was used as an anchor located 11 cm from the bottom of the lower accelerometer on each monitor. Each accelerometer was set to record orientation every 30 minutes.

Scour monitors were deployed using a pounding device that created a 6 cm diameter hole in the streambed while minimizing disturbance to adjacent sediment (Klassen and Northcote, 1986). Scour monitors were lowered into the hollow pounding device using a nylon rope which was held taught and fed through the cylinder of the pounding device as the device was removed from the stream substrate. As the pounding device was removed, stream substrates sloughed into the insertion hole, integrating the scour monitor into the stream substrate matrix. Target depth for the top of each upper accelerometer casing was 4 cm although precision was highly variable. Depths of middle and lower accelerometers were determined assuming that each scour monitor was fully vertically extended after deployment.

Figure 1. Photograph of 10 fully constructed scour monitors ready for deployment.

Initial stream bed elevation and location of each scour monitor was recorded using a real-time kinematic GPS unit with a vertical accuracy of plus or minus 3 centimeters. After the winter flood season, the GPS unit was used to relocate scour monitor locations during retrieval efforts. Located scour monitors were excavated and removed from the stream substrate. During recovery, streambed elevation and the elevation of the top of each accelerometer casing was surveyed to determine scour depths and net fill/scour for all sample sites. The time series for accelerometer orientation was downloaded to a computer and timing of movement was correlated to flow volumes at those times for two USGS stream gages, #12117600 below Landsburg Diversion and #12119000 Renton. Accelerometers recorded the time of initial streambed scour (i.e. movement in excess of 15 degrees) and the time for subsequent movements or periods when accelerometers were static. Periods without movement after initial scour signals were recorded were assumed to represent stream sediment deposition (fill) around scoured accelerometers. Accelerometer movements that occurred during the documented spawning periods for sockeye, Chinook and coho salmon, and at flows below 1,000 cfs Renton, were assumed to be caused by digging female salmon moving stream substrates during redd construction. Accelerometers that recorded spawning signals were assumed to represent the susceptibility to scour for substrates in incubating sockeye salmon redds. Chinook salmon redds were assumed to be less susceptible to scour than sockeye redds because Chinook typically use larger substrates to construct redds that contain deeper egg pockets. Movement times for accelerometers were compared to flows at the USGS Renton Gage to estimate flow volume at the time of movement.

Seventy-four scour monitors were deployed in the Cedar River (Figure 2) at 12 sites (Figure 3, Appendix A) to meet multiple objectives including:

1) Testing the new 2,200 cfs scour threshold adopted by the IFC in 2013.
2) Locate scour monitors in gravel substrates where sockeye spawn consistently from year to year.
3) Orient scour monitors vertically to sample the full range of sockeye egg depths in the scientific literature (Devries, 1997).
4) Deploy scour monitors in areas with gradient changes to sample locations with high susceptibility to scour due to increased shear stresses.
5) Deploy scour monitors longitudinally along the main stem to represent spawning habitats from Landsburg Dam to Lake Washington (Figure 3).
6) Deploy scour monitors to represent confined, unconfined and partially confined reaches.
7) Locate scour monitors to represent large, medium and small discrete areas of spawning gravel according to the following distribution: 2 large areas of spawning gravel (approximately 60' by 30') sampled with 13 scour monitors each, 8 medium patches of spawning gravel (20' by 20') sampled with 5 or 6 scour monitors each, and 3 small areas of spawning gravel (8' by 8') sampled with 2 scour monitors each.

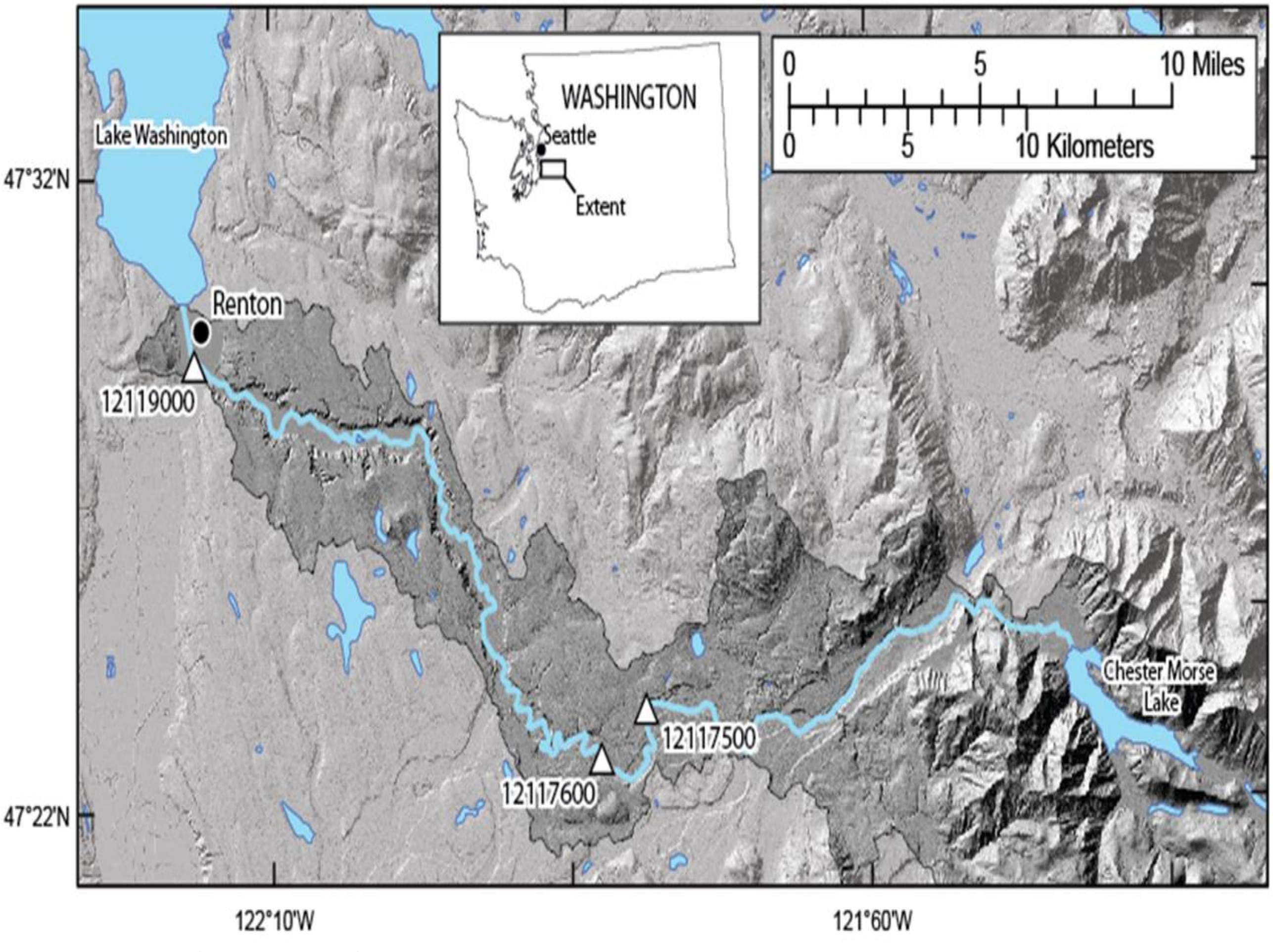

Figure 2. Map of Cedar River from Chester Morse Reservoir to Lake Washington showing USGS Gage locations.

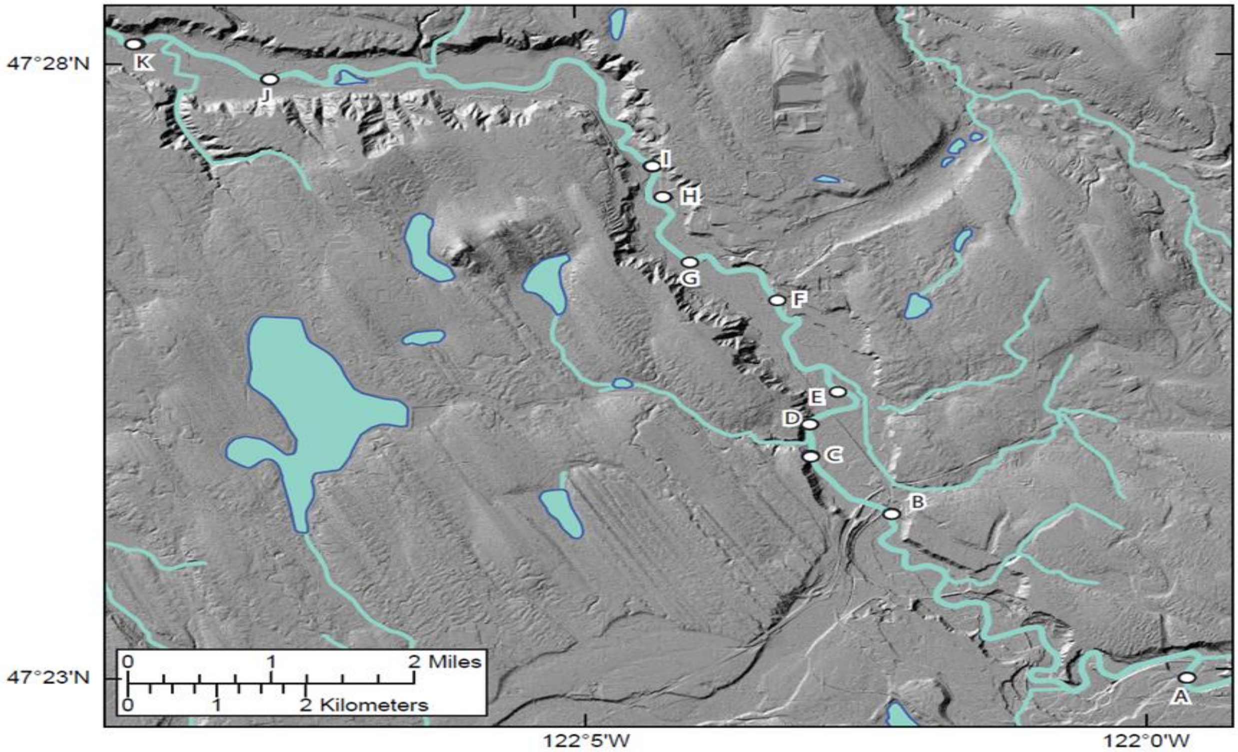

Figure 3. Detailed map showing longitudinal distribution of scour monitor sites in the Cedar River.

Egg Pocket Depth Measurements - Seventeen discreet sockeye redd mounds were excavated opportunistically during the sockeye spawning period in 2013 to determine minimum egg pocket depths for Cedar River sockeye salmon. A level string was attached to 2 rebar stakes placed on either side of a sockeye salmon redd mound. The location of the string on the stakes was marked. The distance between the string and the top of the mound was recorded. The string was removed from the stakes and redd mound substrates were removed manually until 2 or more eggs were located visually. The level string was reattached to the marked points on the stakes and the distance from the string to the top of the egg pocket was recorded. By subtracted the distance to the top of the redd mound from the distance to the top of the egg pocket we determined the minimum egg pocket depth from the top of the redd mound. Observed redd pocket depths were compared to depths for accelerometers that displayed movement signals from spawning salmon and to scientific literature for sockeye egg pocket depths.

Net Scour/Net Fill Measurements - Stream bed elevation was measured at most sites before scour monitor deployment and subsequent retrieval to determine the net amount of fill and scour that occurred during the winter flood season. Estimates focused on scour monitor locations where visual observations of spawning salmon and/or spawning signals from recovered accelerometers provided verification of salmon spawning activity. Sample locations where scour monitors were lost downstream due to deep scour during a peak flow event in March 2014, were also included. Thirteen scour monitor locations were not included in the net fill/net scour estimates because they were buried by a landslide in April, 2014. Data from scour monitors in sites A and E, and scour monitor 57 were also not included because vertical cliffs prevented proper GPS function or GPS equipment malfunction prevented accurate stream bed elevation measurements.

Results

In Water Year 2014, streamflow estimates at Renton did not exceed 2,200 cfs until March 5th. Maximum annual discharge occurred on March 11th with estimated flows at Renton reaching approximately 3,860 cfs. Of the 74 scour monitors deployed, 46 (62%) were recovered, 13 were lost downstream when their anchors were mobilized during peak flow event in early March 2014, 13 were irretrievable after they were buried and/or displaced by a landslide (Figure 4), one scour monitor was not found due to excessive sediment sloughing during excavation, and 1 was stolen by vandals soon after deployment. All recovered scour monitors were fully intact when recovered except one, Monitor K-54, which was missing the upper accelerometer.

Figure 4. Photograph of Landslide that covered and/or moved all 13 accelerometers in site C.

Accelerometer readings from retrieved scour monitors provided three outcomes including: no movement, movement from spawning (i.e. spawning signals), and movement from spawning signals and movement from streambed scour (i.e. spawning signals and scour signals) (Figure 5).

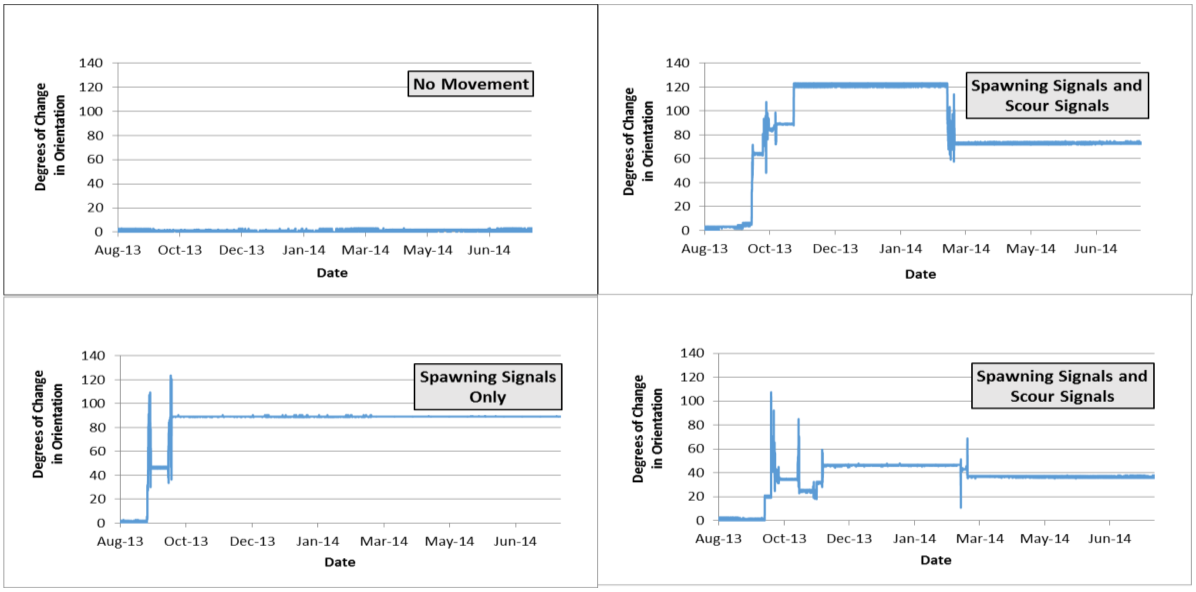

Figure 5. Examples of movement signals from retrieved accelerometers.

Sockeye Salmon Egg Pocket Depth Estimates Derived from Accelerometer Movements and Redd Excavations

The majority of recovered scour monitors (87%) recorded movement signals associated with salmon redd construction (i.e. spawning signals). These movements occurred during documented spawning periods for Cedar River sockeye and Chinook salmon, and, to a lesser extent, coho salmon. All of the spawning signals were recorded when instream flows were substantially below flow levels that could have caused streambed scour. Accelerometers recorded 167 discrete spawning signals between September 7th and December 27th, 2013. Field observations verified that all spawning signals prior to November 15th were produced by sockeye salmon. Chinook salmon completed spawning prior to November 15th. Spawning signals after November 15th were assumed to originate from late spawning sockeye salmon or coho salmon. Mean burial depth of accelerometer that recorded movements caused by spawning sockeye was 14.4 cm (SE = 1.0). Scour monitors that detected spawning signals by both upper and middle accelerometers outnumbered scour monitors displaying spawning signals for all three accelerometers and scour monitors that only detected spawning signals at the upper accelerometer (Table 1).

Table 1. Summary table of accelerometer movements and burial depths caused by spawning sockeye salmon.

	Scour Monitors with Upper Accelerometer Movements Only	Scour Monitors with Upper and Middle Accelerometer Movements	Scour Monitors with Upper, Middle and Lower Accelerometer Movements
% of Total Recovered Accelerometers with Spawning Signals	40%, (n = 16)	42.5% (n= 17)	17.5% (n = 7)
Range of Burial Depths at Deployment for Recovered Accelerometers with Spawning Signals (cm)	3 to 14 cm (n=14)	13 to 22 (n = 15)	30.5 to 34.5 (n = 6)
Mean Burial Depth at Deployment (cm), and Standard Error for Recovered Accelerometers with Spawning Signals	9.9 , SE = 0.7	17.5, SE = 0.5	32.5, SE = 0.9

Estimates for spawning depths derived from accelerometer movements were supplemented by egg pocket depth observations made during the excavation of 17 sockeye redds. Observed minimum egg pocket depths from excavated redds ranged from 7 cm to 22.5 cm with a mean of 13.9 cm (SE = 0.9) (Figure6).

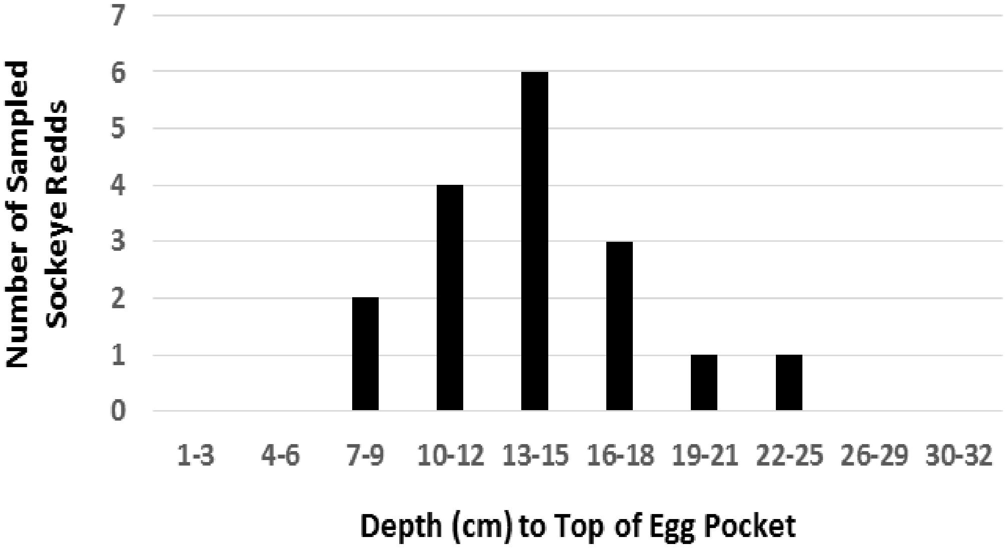

Figure 6. Distribution of depth to top of egg pocket for excavated Cedar River sockeye redds.

Accelerometer Movements Resulting from Streambed Scour

Six of the 46 recovered scour monitors detected stream bed scour resulting from high instream flows in March, 2014. Eleven out of 18 accelerometers contained in the 6 scoured monitors showed scour signals at times when instream flows at Renton were between 2,010 and 3,730 cfs. Of the 11 scoured accelerometers, 5 were upper (shallow) accelerometers, 4 were middle accelerometers and 2 were lower (deep) accelerometers (Table 2). The mean scour flow for all 11 accelerometers was 2,987 cfs Renton (SE = 177). The majority of accelerometer movements from scour (9 of 11) occurred on the ascending leg of the hydrograph prior to the peak flow on March 11th (Figure 7). Movement signals from scoured accelerometers indicated that accelerometer movement periods after initial scour ranged from a matter of hours to multiple weeks.

Mean scour flows for shallow, middle, and deep accelerometers were 3026 cfs (SE = 294), 2818 cfs (SE = 348), and 3230 (SE = 60) cfs, respectively. The relationship between flow and scour depth was not consistent and, in two scoured sample monitor locations (i.e. E 74 and J 60, Table 2), scour occurred at increasing depths as flows decreased. In addition, regression analysis showed that the relationship between flow and scour depth for scoured accelerometers was not statistically significant ($p = .05$, r-sq = .02). Accelerometer J 60 was located in a reach where all 10 deployed scour monitors were displaced downstream during the March peak flow event. Only J 60 was located and retrieved on the shore near the J site. We assumed the scour initiation data from the J 60 monitor were similar to the 9 lost monitors from the J site.

All but one scour monitor (E74) that moved as a result of scour were located in the two lowest sample reaches, J and K (Appendix A). Scour monitors that were lost downstream during the peak flow event were also located in sample reaches J and K. Sample reach J was one of two confined reaches sampled in the study and sample reach K was one of two unconfined sample reaches. Sample reach E, where scour was detected at relatively high streamflow (over 3,400 cfs, Renton) was located in a partially confined reach.

Table 2. Scour initiation flows at Renton gage and initial burial depths for 11 recovered accelerometers that moved as a result of scour. Numbers in **red** indicate accelerometers that were also moved by spawning sockeye salmon. Depths for accelerometers in scour monitor K42 were estimated using the mean burial depths for upper, middle and lower K site accelerometers, respectively.

Sample Site, Accelerometer Array #	**Scour Initiation Flow (cfs, Renton), Initial Burial Depth (cm)**		
	Shallow Accel.	Middle Accel.	Deep Accel.
E, 74	**3730, 5**	**3420, 15**	No Scour, 27.5
J, 60	**3470, 9**	**3420, 19**	3290, 31.5
K, 42	**2960, 7**	No Scour, 17	No Scour, 29.5
K, 45	**2010, 8**	**2230, 18**	No Scour, 30.5
K, 46	**2960, 7**	No Scour, 17	No Scour, 29.5
K, 54	Not recovered, 7	**2200, 17**	3170, 29.5

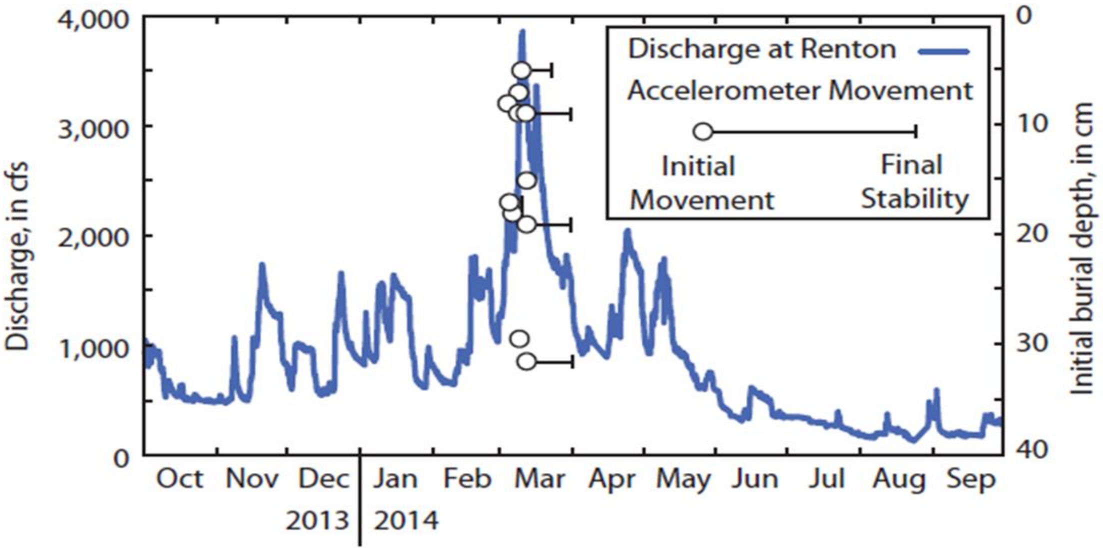

Figure 7. Cedar River mean daily streamflow at Renton (USGS Gage 12119000) showing March, 2014 peak flow event magnitude and timing, and burial depths for accelerometer movements caused by scour.

Net Fill and Net Scour

Fifty two scour monitor locations with verified sockeye spawning activity were assessed for net scour or net deposition (fill). Locations where scour monitors were lost downstream during the March peak flow event were used to assess minimum scour depths based on the recorded depths of the respective scour monitor anchors. Thirty two scour monitor locations that did not experience scour during the March peak flow event experienced varying levels of sediment deposition over the top of existing sockeye redds. Fill depths ranged from 2 cm to 75 centimeters with a mean of 30 cm (SE = 3 cm).

Eight scour monitor locations experienced varying degrees of scour followed by sediment deposition that resulted in net fill. Four of the eight "scour/net fill" locations had retrieved accelerometers and four locations had their scour monitors lost downstream during the peak flow event. Initial minimum scour depths for the 4 locations with retrieved accelerometers ranged from 7 cm to 18 cm with a mean scour depth of 12 cm (SE = 3). Net fill at these 4 locations ranged from 23 cm to 75 cm with a mean net fill of 46 cm (SE = 12). Initial minimum scour depths for the 4 scour/net fill locations, where relatively deep scour occurred and scour monitors were lost downstream, ranged from 46 cm to 52 cm with a mean of 50 cm (SE = 1.3). Net fill estimates for these locations ranged from 7 cm to 15 cm with a mean net fill depth of 10 cm (SE = 1.8).

Twelve scour monitor locations experienced net scour (i.e. decrease in bed elevations after the peak flow event). Ten of the twelve net scour locations were in the J site, which experienced relatively deep scour that displaced scour monitors downstream. Only one of the J-reach monitors was found. Net scour for these 10 locations as determined from bed elevations before and after the peak flow event, ranged from 59 cm to 99 cm with a mean net scour depth of 72 cm (SE = 8.9). The retrieved scour monitor from the J reach indicated that scour was initiated at flows between 3,290 cfs and 3470 cfs. The two additional net scour locations had scour monitors that did not record movement but the net scour measurements were relatively shallow with net scour depths of 0.6 cm and 6 cm.

Discussion

In the Cedar River main-stem, the potential for streambed scour can be decreased by storing water in Chester Morse Reservoir behind Masonry Dam. Water management operations are used to manage the magnitude and duration of high flows through reservoir operations before, during and after large storm events. As forecasted storms approach the Cedar River Basin, water is released from Chester Morse Reservoir to provide additional reservoir storage capacity (flood pocket) for inflows from rain and snowmelt. To prevent scour, reservoir releases are decreased or discontinued immediately prior to the storm event to avoid scour as accretion flows below the dam increase during the storm event. After the storm event, reservoir releases resume to restore the flood pocket. Releases are typically designed to provide flows at Renton that are slightly below the current scour threshold of 2,200 cfs (USGS Gage #12119000). Chester Morse Reservoir was designed primarily as a water storage reservoir not a flood protection reservoir. Due to the relatively small volume of the reservoir compared to projects that are specifically designed for flood storage, in most years scour events do occur, especially when the basin receives multiple storms over a short period and efforts to re-establish a flood pocket are not possible. Therefore, it is important to understand the relation between flow and redd scour to allow water managers to maximize dam releases and flood pocket volumes without reaching streamflow levels that can scour salmon spawning habitat and decrease egg-to-fry survival.

The vast majority of observed accelerometer scour signals occurred at flow levels in excess of 2,200 cfs Renton. Scour signals from retrieved scour monitors, combined with information for scour monitors lost downstream during evulsion events, suggest that even at flows of 3,860 cfs Renton, only one third of the deployed scour monitors experienced scour. Only one scour monitor, K-45, showed scour signals below the current scour threshold. The upper and middle accelerometers in monitor K-45 exhibited sockeye spawning signals in the fall of 2013 and streambed scour signals in March of 2014. Scour signals for these accelerometers occurred at estimated flows of 2010 cfs and 2230 cfs (Renton) respectively. Monitor K-45 was located in the lowest sample reach, in a section of the main-stem that was impacted by a large, earthquake-triggered landslide in February, 2001. The substrate scour depths associated with these 2 scoured accelerometers were 8 cm and 18 cm, well within the extent of egg pocket depths observed during sockeye salmon redd excavations, which ranged from 7 cm to 22.5 cm with a mean of 13.9 cm. It is important to note that sediment from the 2001 landslide is still being sorted by river hydraulics and distributed downstream. Therefore, the recent sediment inputs delivered by the landslide will likely have higher levels of substrate instability and susceptibility to scour relative to the majority of the main-stem, which has not experienced recent landslides. In addition, the K reach was characterized by a wide, unconfined channel that had relatively robust amounts of large woody debris that moved and increased in volume as a result of the March, 2014 peak flow event (Figure 8).

Figure 8. Aerial Photos of the K reach, before (upper photo) and after (lower photo) the March, 2016 peak flow event. After photo suggests LWD movement during peak flows resulting in increased LWD volumes at K-site and some LWD exported downstream.

Indeed, the movement of wood during the peak flow event may have caused scour at relatively low flows due to turbulence around LWD as logs moved through the site. This hypothesis is further supported by the missing upper accelerometer in scour monitor K 54, which was also located in the 2001 landslide reach. Monitor K-54 was the only retrieved scour monitor that was not found intact and the missing upper accelerometer may have been physically removed by LWD moving through the reach. The middle accelerometer in scour monitor K-54 recorded scour signals at 2,200 cfs Renton. The remaining retrieved scour monitors recorded scour at flows between 2,960 cfs and 3,730 cfs Renton, well above the scour flows observed in monitors K-45 and K-54.

Complete evulsion of scour monitors occurred in two sites; J and K, the 2 lowermost sites in the study. All scour monitors in the J site were scoured at least to the level of their anchors, and displaced downstream. Scour monitor J-60 was the only J site monitor that was found after the evulsion event. Scour signals from J-60 accelerometers suggested that evulsion in the J reach occurred at flows between 3290 cfs and 3470 cfs (Table 2). The minimum depth of scour for monitor J-60 was 41.5 cm, substantially deeper than the top of the deepest excavated sockeye egg pocket and the deepest accelerometers that were moved by spawning sockeye (Figure 6, Table 2). Four out of ten scour monitors in K reach were lost downstream during an evulsion event but none were recovered. Depths of scour to monitor anchors in the K site were also substantially deeper than the top of the deepest excavated sockeye redd pockets and the deepest accelerometers showing spawning signals. These evulsion data indicate that evulsions during flow events that exceed 3,300 cfs Renton have the capacity to fully mobilize the redd substrate and egg pockets in some Cedar River sockeye redds. Evulsions of scour monitors occurred in one highly confined reach (J) and one unconfined reach (K). The other highly confined and unconfined reaches (A reach and H reach) did not experience scour. Given the limited number of highly confined and unconfined sample reaches, these results do not provide adequate information to compare the effects of confinement on susceptibility to redd scour.

Top of sockeye egg pocket depths from excavated redds were similar to data from four previous studies (Table 3), although the deepest Cedar River sockeye egg pockets in our sample (22.5 cm) were shallower than the deepest sockeye egg pockets in the other studies. Although the sample size for excavated redds was small, our egg pocket data suggests that Cedar River sockeye redds may be more susceptible to scour because the deepest egg pockets for Cedar River sockeye are not as deep in the streambed as the deepest sockeye egg pockets in other studied systems.

Table 3. Previous studies with recorded burial depths for the top of sockeye salmon egg pockets.

Author, Year	Mean Egg Pocket Depth	Range of Observed Egg Pocket Depths	Location
Kuznetzov, 1928	Not reported	9 cm to 29 cm	USSR
Burner, 1951	12.5 cm	5 cm to 28 cm	Washington
Mathisen, 1955	19 cm	18 cm to 28 cm	Alaska
Mathisen, 1962		8 cm to 30 cm	Alaska

Two thirds of accelerometer locations did not experience scour at the observed peak flow of 3,860 cfs Renton. However, 77% of sample sites that were assessed for net scour/net fill experienced increases in bed elevations. Salmonid survival can be impacted by sediment deposition in two ways. First, fine sediment deposited in redds can decrease circulation and oxygen levels within the redd (Chevalier et al, 1984) causing a decrease in egg to fry survival. Second, sediment deposited over incubating redds can entomb eggs and alevins (Franssen et al., 2012) preventing emergence after incubation is complete. Although these data do not provide flow levels at which the deposited fill sediment was mobilized, the large number of net fill sites and the upper range of fill depths (up to 75 cm) indicate that high flow events in the Cedar River can decrease egg-to-fry survival for salmon not only by redd scour but also by sediment deposition.

Recommendations to Cedar River Instream Flow Commission

We believe that the results of this study suggest that 2,200 cfs (Renton) protects nearly all incubating salmon in the Cedar River from the adverse effects of streambed scour. The landslide area that experienced a small amount of scour at flows below 2,200 cfs will likely become more stable with time and eventually be stable enough to be protected by 2,200 cfs. The majority of accelerometers that moved above 2,200 cfs recorded the initiation of scour at flows exceeding 2,900 cfs. Even at flows as high as 3,860 cfs, the majority of sampled spawning habitats did not experience scour. We recommend that the Cedar River Instream Flow Commission maintains the current scour threshold of 2,200 cfs. When hydrological conditions prevent water management operations from maintaining flows below the scour threshold of 2,200 cfs, we suggest, when possible, that flows are maintained below 2,900 cfs to minimize additional scour and the associated impacts to incubating salmon.

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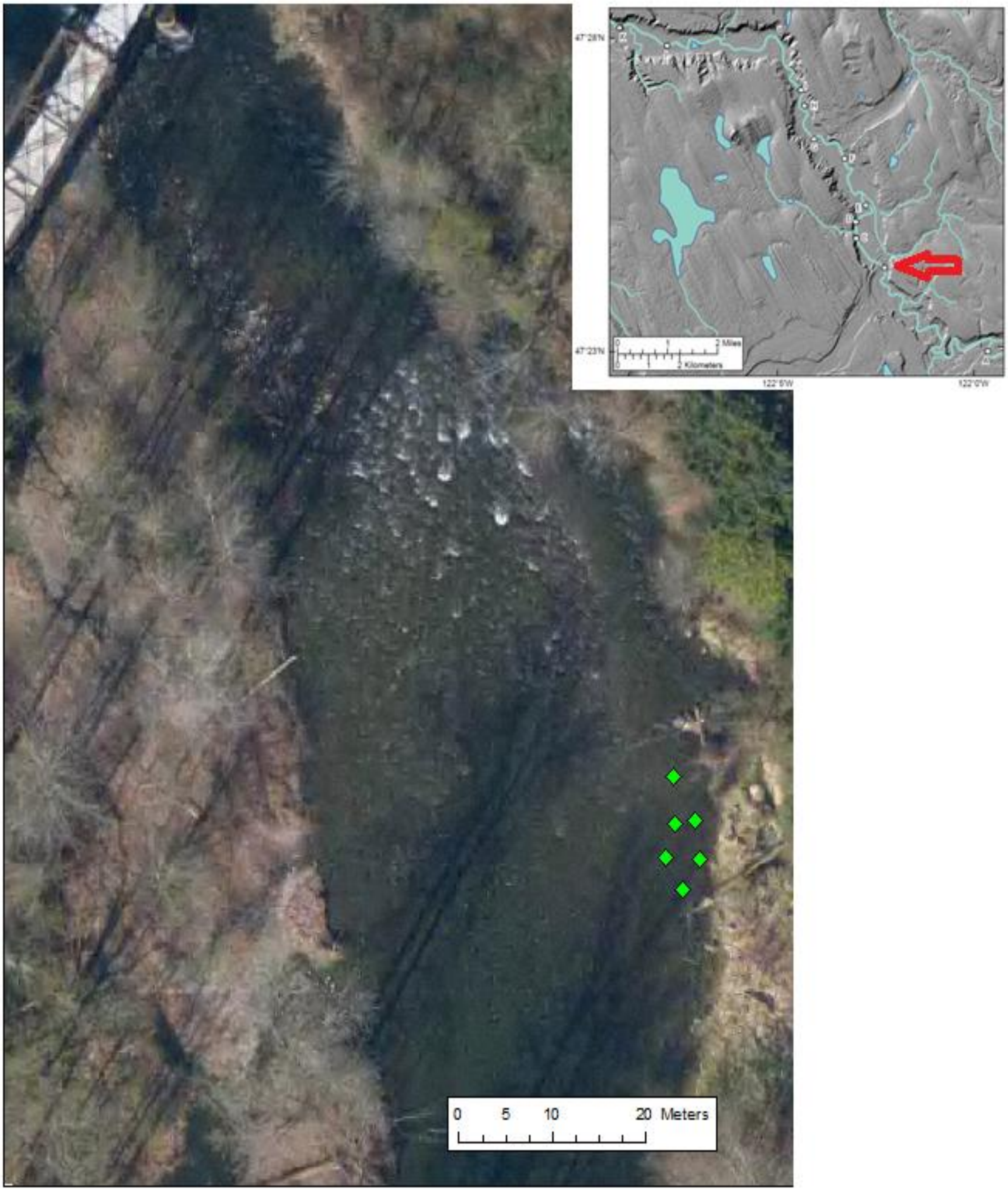
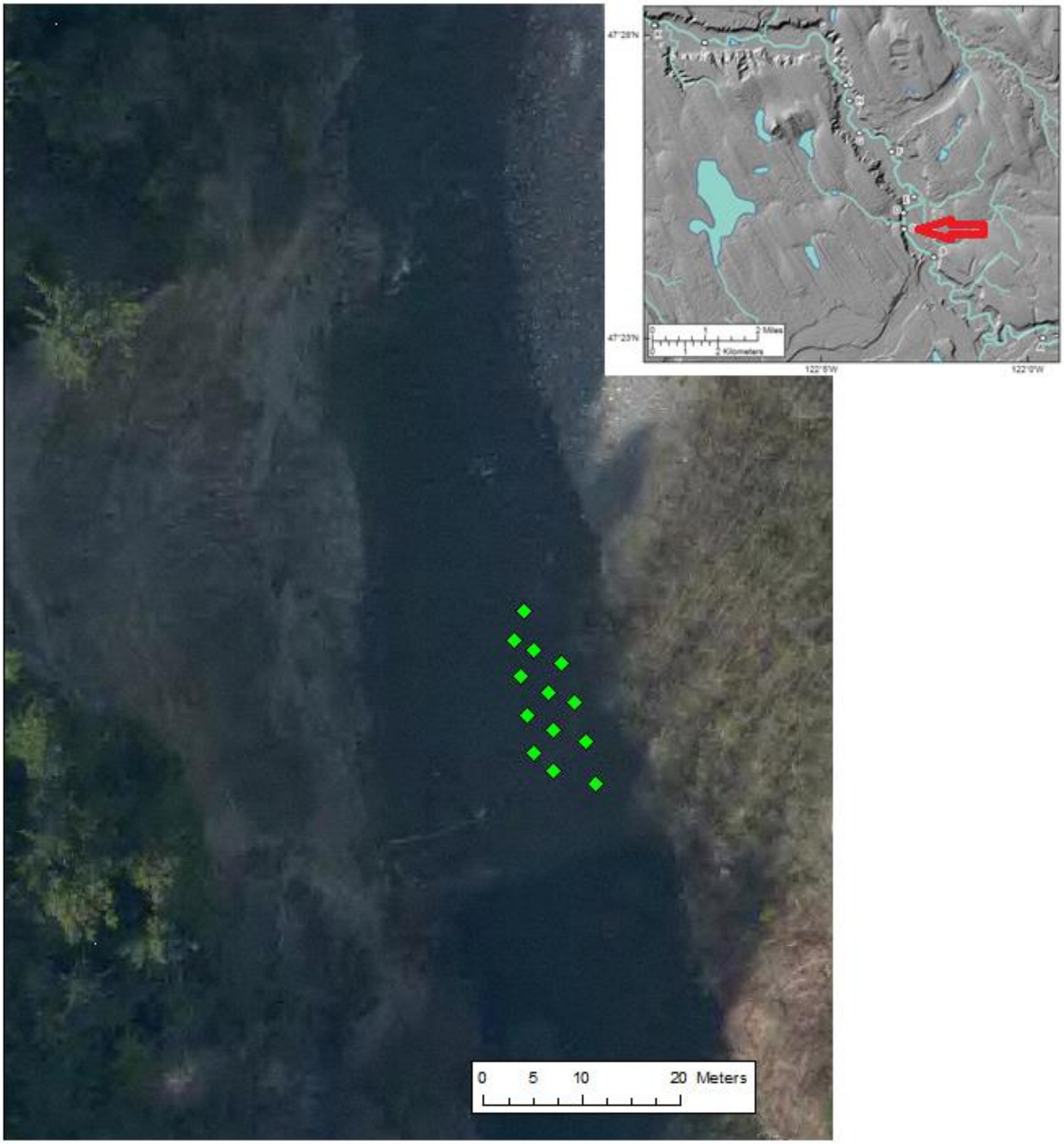
Appendix A – Aerial photos showing scour monitor locations by river reach


47°28'N
47°23'N
122°6'W
122°0'W
0 1 2 Miles
0 1 2 Kilometers
A
0 5 10 20 Meters

Site A


47°28'N
47°23'N
122°5'W
122°0'W
0 1 2 Miles
0 1 2 Kilometers
0 5 10 20 Meters

Site B

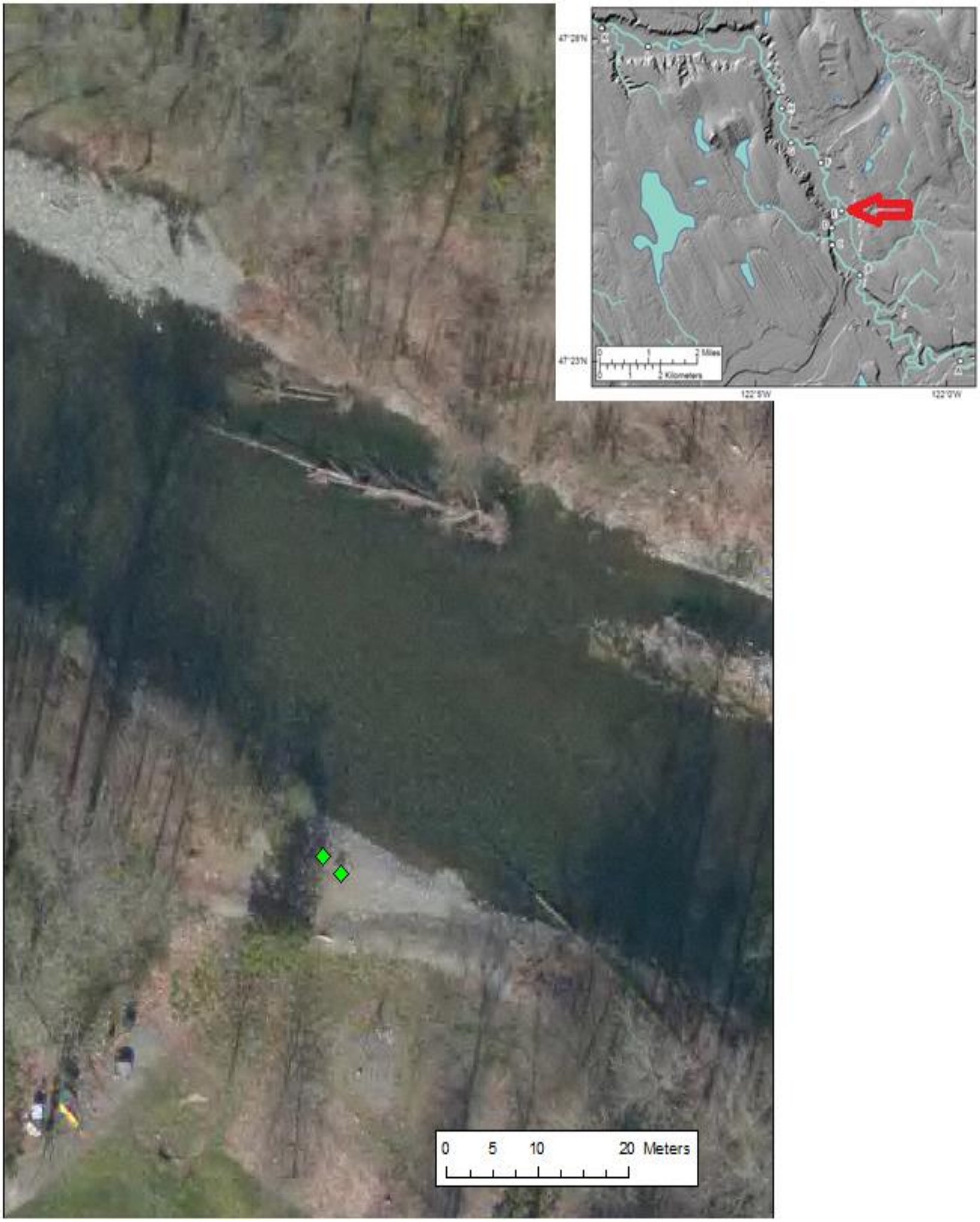

47°28'N
47°23'N
122°5'W
122°0'W
0 1 2 Miles
0 1 2 Kilometers
0 5 10 20 Meters

Site C

Site D


47°26'N
47°23'N
122°6'W
122°0'W
0 1 2 Miles
0 1 2 Kilometers
0 5 10 20 Meters

Site D


47°28'N
47°25'N
0 1 2 Miles
0 1 2 Kilometers
122°5'W
122°0'W
0 5 10 20 Meters

Site E

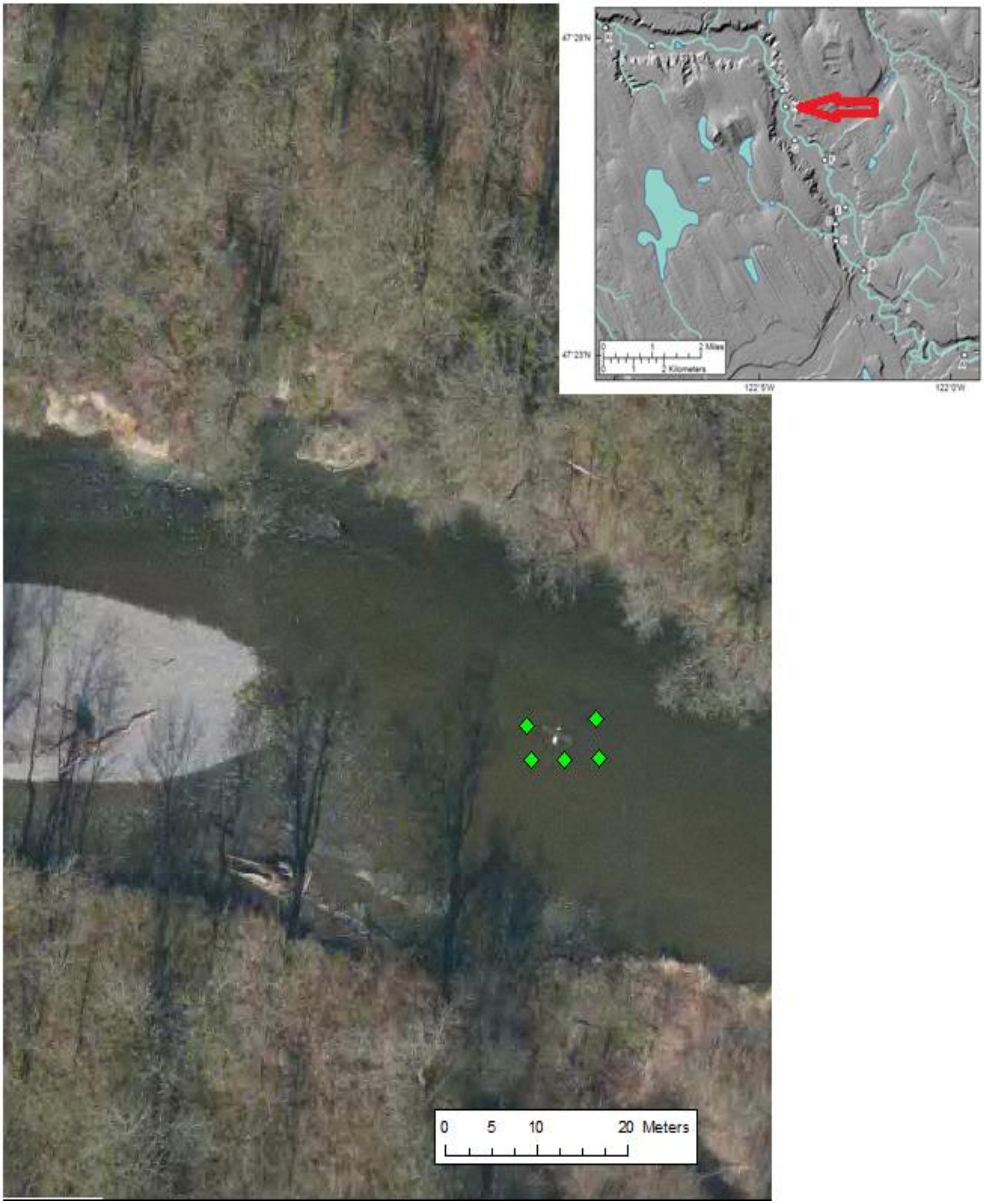

47°28'N
47°25'N
0 1 2 Miles
0 1 2 Kilometers
122°5'W
122°0'W
0 5 10 20 Meters

Site F

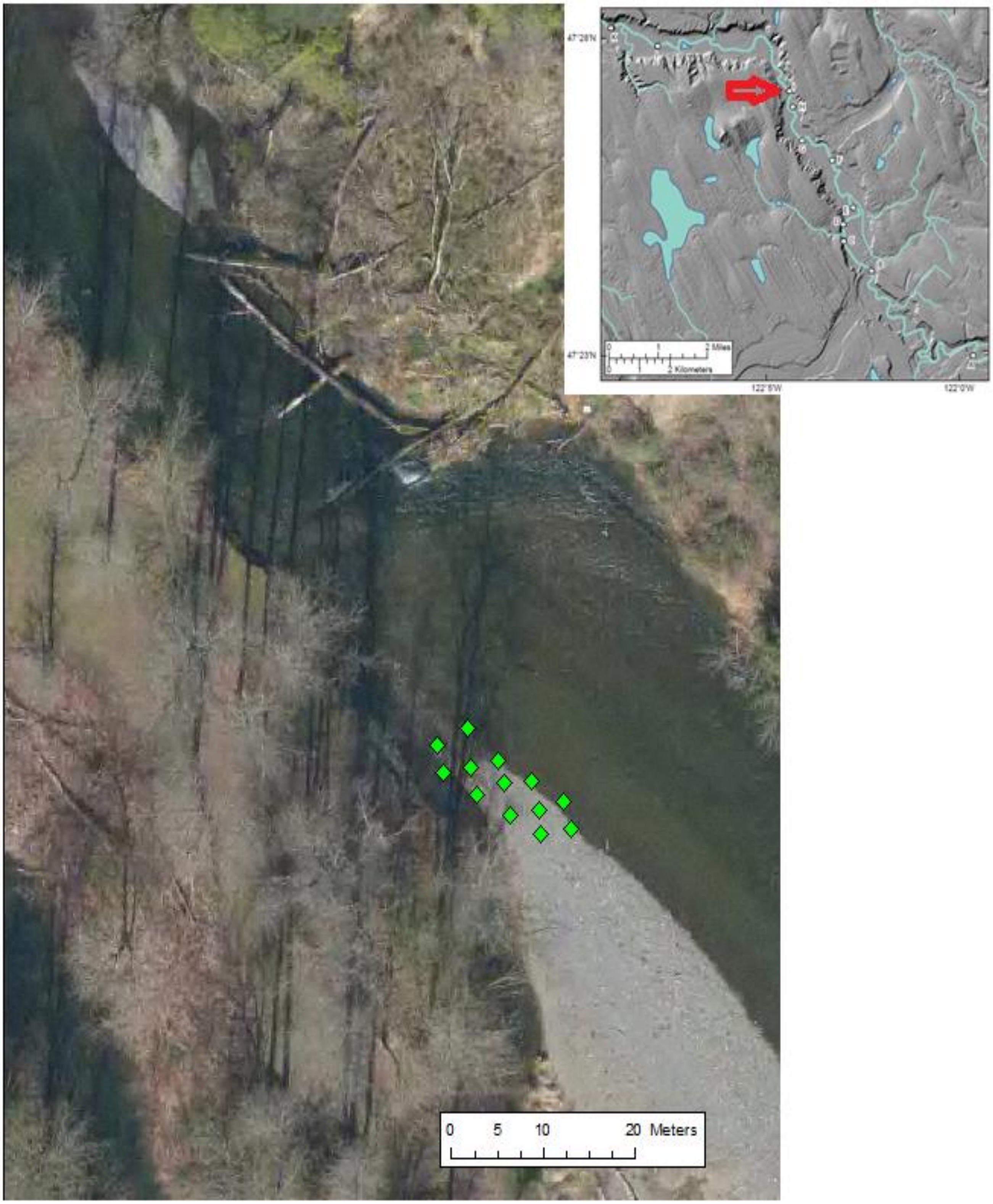

47°28'N
47°23'N
0 1 2 Miles
0 1 2 Kilometers
122°5'W
122°0'W
0 5 10 20 Meters

Site G

Site H


47°28'N
47°25'N
122°5'W
122°0'W
0 1 2 Miles
0 1 2 Kilometers
0 5 10 20 Meters

Site H


47°28'N
47°23'N
122°5'W
122°0'W
0 1 2 Miles
0 1 2 Kilometers
0 5 10 20 Meters

Site I


47°28'N
47°23'N
122°5'W
122°0'W
0 1 2 Miles
0 1 2 Kilometers
0 5 10 20 Meters

Site J

Site K


47°28'N
47°23'N
122°5'W
122°0'W
0 1 2 Miles
0 1 2 Kilometers
0 5 10 20 Meters

Site K