FLOW RESISTANCE ESTIMATION IN HIGH-GRADIENT STREAMS

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Abstract

Methods for predicting resistance coefficients in high-gradient streams are essential for hydraulic modeling, stream restoration, geomorphic analysis, and quantifying ecological habitat characteristics. Nine figures documenting Manning's *n* and Darcy-Weisbach *ff* are provided for low, mid and near-bankfull flows in cascade, step pool and plane bed stream reaches in the Fraser Experimental Forest, Colorado. Photographs from multiple perspectives and flows are given to illustrate reach characteristics. Profile plots and bed material D_{84} are also included. The stream reaches have slopes ranging from 1.5 to 20 percent, with measurements during discharges ranging from 0.0067 to 0.61 cms (0.23 to 21 cfs). Manning's *n* varied from 0.048 to 0.52.

INTRODUCTION

Flow resistance in open channels is composed of three fundamental components: boundary (grain) resistance from bed and bank interactions; form resistance, from a deflection that causes superelevated and depressed water surfaces, resulting in secondary currents and eddying; and spill resistance, resulting from sudden supercritical flow deceleration, such as at the base of a drop. In lower-gradient streams boundary resistance is often dominant, hence the effectiveness of relative submergence in predicting resistance. In cascade and step pool streams form resistance has many sources, including bed and bank variability, boulders that project through the flow field, and large woody debris (LWD). A large proportion of the resistance can result from spill where rapid flow and waterfalls impact on standing water, resulting in substantial turbulence. In step-pool and cascade streams, spill resistance is typically dominant (Curran and Wohl 2003, MacFarlane and Wohl 2003, Wilcox and Wohl 2006).

For practical applications, flow resistance is typically quantified by Manning's *n*. Commonly-cited references for estimating *n* typically underestimate in steeper streams. For example, the HEC-RAS Hydraulic Reference Manual (Brunner 2008) makes recommendations based upon Chow (1959); a maximum *n* of 0.07 is suggested for "mountain streams" while research indicate substantially higher resistance values are to be expected (Reid and Hickin, 2008; Comiti et al. 2007; Lee and Ferguson, 2002). Manning's *n* typically falls between 0.1 to 0.3 for bankfull flows in steep headwater streams. Other commonly-used references for estimating *n*, such as the use of base and additive values (Cowan 1956, Arcement and Schneider 1989), can also be misleading. Photo guides for visual comparison (Barnes 1967, Aldridge and Garrett 1973, Arcement and Schneider 1989) do not provide sufficient guidance for these stream types. Underestimation of Manning's *n* can lead to substantially-overestimated flow velocities, underestimated travel times, miscategorization of flow regime, and computational instability.

PHOTO-GUIDANCE FOR RESISTANCE COEFFICIENTS SELECTION

Nine figures are provided illustrating stream reach characteristics, with Manning's *n* and Darcy-Weisbach *ff* given for low, mid and approximate bankfull flows. Photographs of the reaches from multiple perspectives and flow magnitudes are provided. Profile plots are also included, to depict the bed and water surface during bankfull flow. The figures are ordered from the lowest to highest bankfull *n* values.

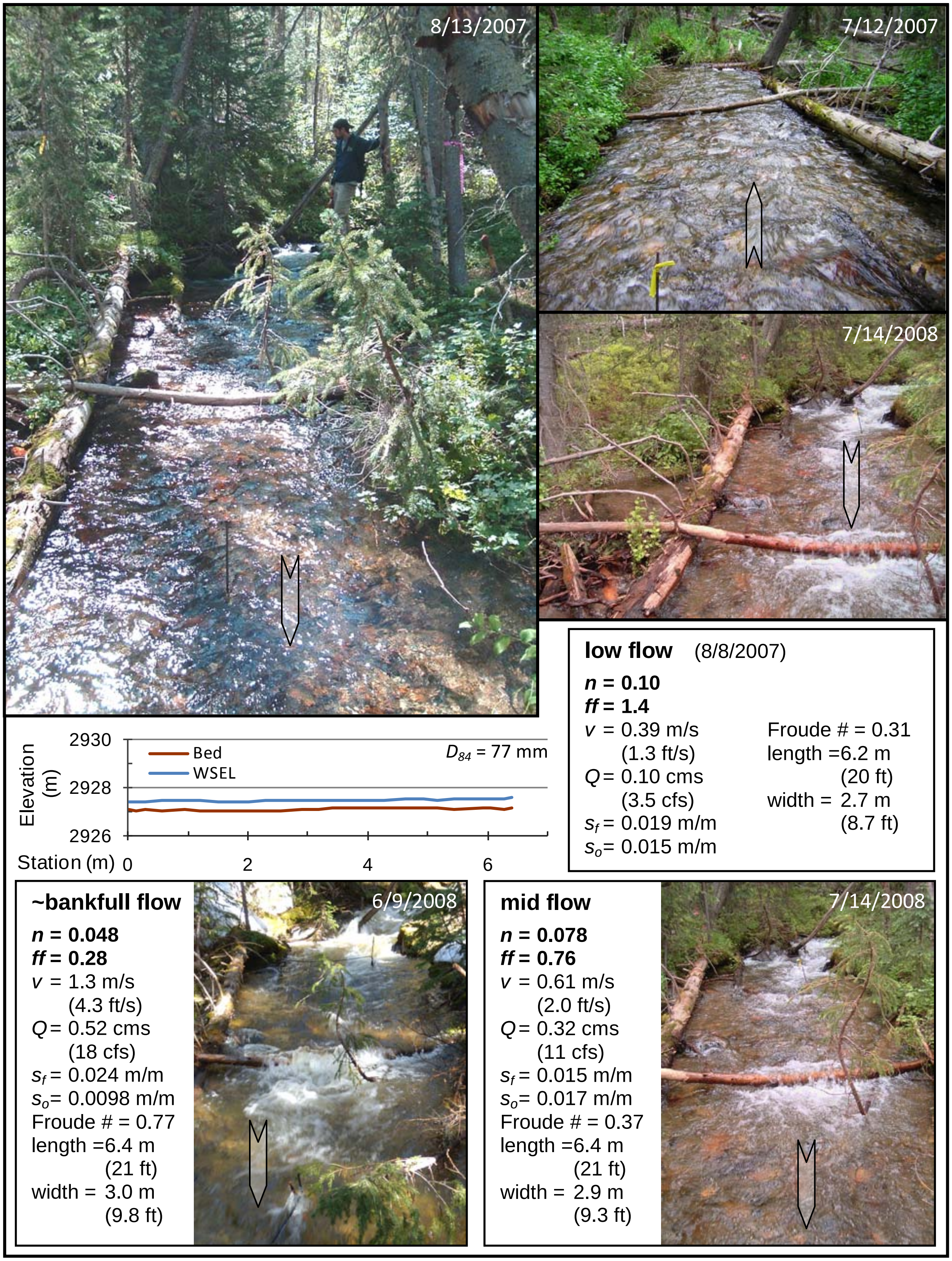
Methodology

Data collection was performed in the Fraser Experimental Forest, on East Saint Louis and Fool Creeks. The Fraser Experimental Forest is located in the Fraser River Watershed, in the Upper Colorado Basin west of the town of Fraser, approximately 115 km west of Denver, Colorado. Precipitation is primarily in the form of snow, with average annual total estimates (1961-1990 PRISM) ranging from 64 to 89 cm (25 to 35 in). All fifteen stream reaches, which were classified as being cascade, step pool and plane bed in form (Montgomery and Buffington 1997), are just upstream of gaging stations monitored by the U.S. Forest Service using sharp-crested weirs. Large woody debris were present, with many of the steps formed by clasts-anchoring debris material. The elevation of the stream reaches range from 2915 to 3217 m (9560 to 10,600 ft), with slopes varying from 1.5 to 20 percent.

Data collection was composed of bed, bank and floodplain surveying; longitudinal water surface profiles, at high, medium and low flows; average reach velocity measurements; and bed material characterization. A brief summary of the methods is provided; additional details are provided in Yochum et al. (in review).

Reach surveying was performed with a tripod-mounted LiDAR (Light Detection and Ranging) scanner for above-water surface features and a gridded laser theodolite survey for below-water features. Additionally, a laser theodolite was used for measuring longitudinal profiles of the bed and water surface during each resistance measurement, at the thalweg, left and right edge of water. A common coordinate system was established using a system of control points, to ensure geometric data compatibility. Cross sections were developed from the pointcloud data at an interval of 0.75 to 1.50 m (2.4 to 4.9 ft) over the 6 to 35 m (20 to 115 ft) reach lengths, for a total of 9 to 27 sections per reach. The surveyed thalweg lengths followed the path of the estimated center of mass of the flow, which provides the most hydraulically-representative reach length for a specific flow. Bed gradation was measured using a 300-point, spatially-referenced pebble count.

Average reach velocities were characterized with Rhodamine WT dye tracing, using fluorometers mounted on rebar in the thalweg at the upstream and downstream reach limits. Rhodamine concentrations were measured at a one second time step; the dye was released as a slug in midstream. A single-pass three-point median smoothing methodology was applied to the tracer data, to address data noise. To calculate average reach velocity, a spatial harmonic mean travel time was computed, as detailed by Walden (2004).



low flow (8/8/2007)

***n* = 0.10**

***ff* = 1.4**

v = 0.39 m/s (1.3 ft/s)

Q = 0.10 cms (3.5 cfs)

s_f = 0.019 m/m

s_o = 0.015 m/m

Froude # = 0.31

length =6.2 m (20 ft)

width = 2.7 m (8.7 ft)

~bankfull flow

***n* = 0.048**

***ff* = 0.28**

v = 1.3 m/s (4.3 ft/s)

Q = 0.52 cms (18 cfs)

s_f = 0.024 m/m

s_o = 0.0098 m/m

Froude # = 0.77

length =6.4 m (21 ft)

width = 3.0 m (9.8 ft)

mid flow

***n* = 0.078**

***ff* = 0.76**

v = 0.61 m/s (2.0 ft/s)

Q = 0.32 cms (11 cfs)

s_f = 0.015 m/m

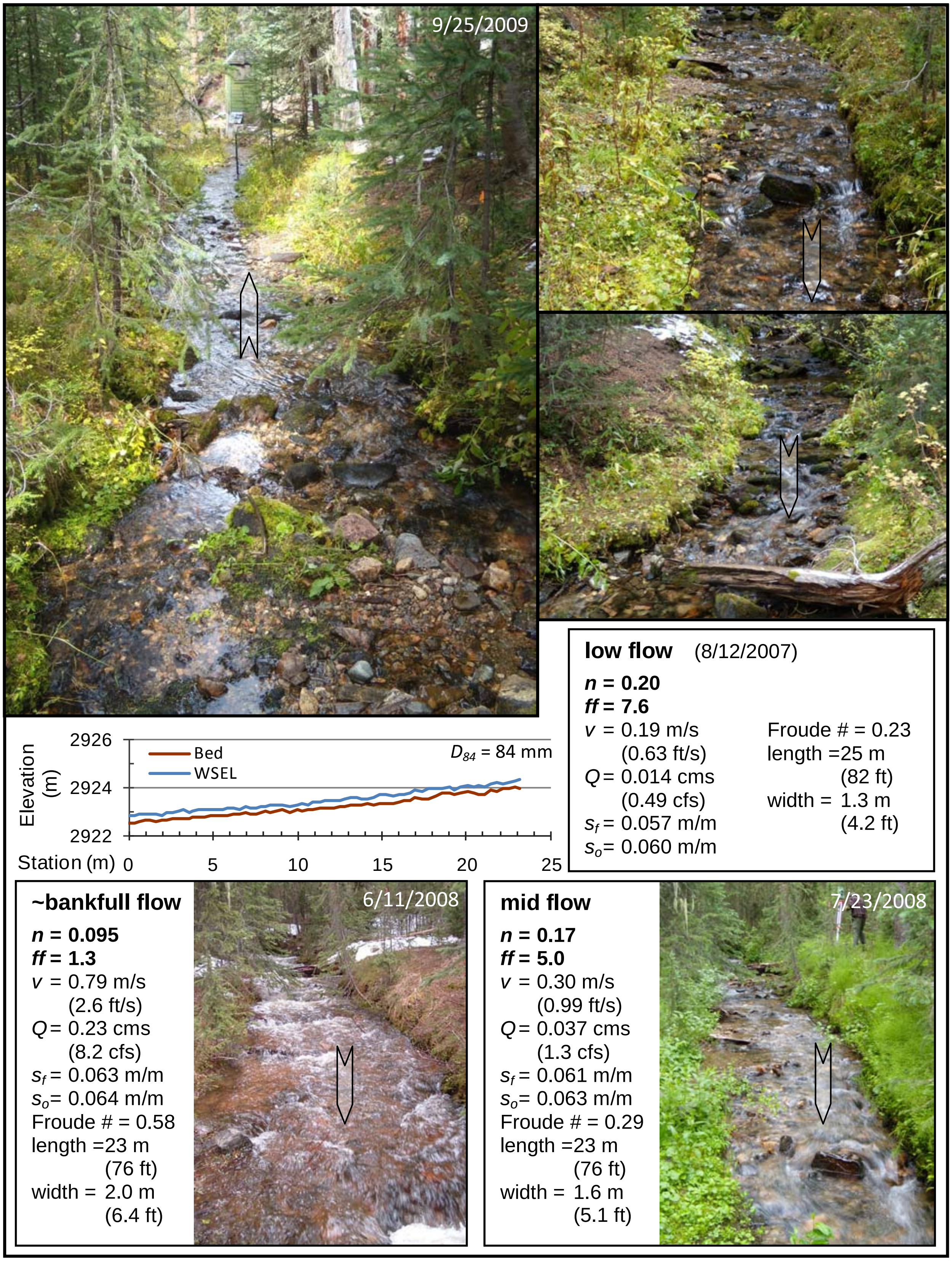
s_o = 0.017 m/m

Froude # = 0.37

length =6.4 m (21 ft)

width = 2.9 m (9.3 ft)

Figure 1: East Saint Louis, reach ESL6 (plane bed).



9/25/2009

low flow (8/12/2007)

***n* = 0.20**

***ff* = 7.6**

v = 0.19 m/s (0.63 ft/s)

Q = 0.014 cms (0.49 cfs)

s_f = 0.057 m/m

s_o = 0.060 m/m

Froude # = 0.23

length =25 m (82 ft)

width = 1.3 m (4.2 ft)

~bankfull flow

***n* = 0.095**

***ff* = 1.3**

v = 0.79 m/s (2.6 ft/s)

Q = 0.23 cms (8.2 cfs)

s_f = 0.063 m/m

s_o = 0.064 m/m

Froude # = 0.58

length =23 m (76 ft)

width = 2.0 m (6.4 ft)

6/11/2008

mid flow

***n* = 0.17**

***ff* = 5.0**

v = 0.30 m/s (0.99 ft/s)

Q = 0.037 cms (1.3 cfs)

s_f = 0.061 m/m

s_o = 0.063 m/m

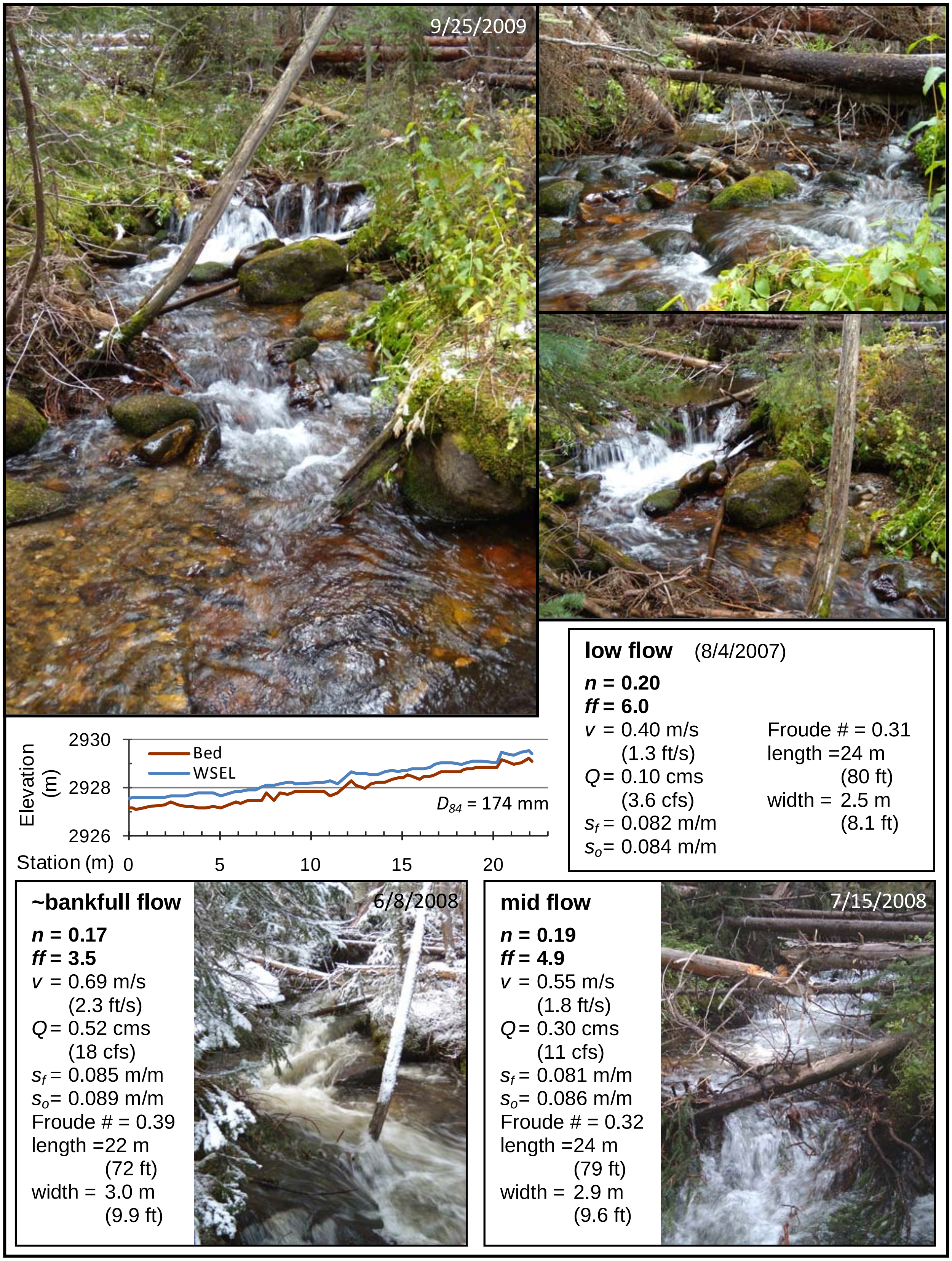
Froude # = 0.29

length =23 m (76 ft)

width = 1.6 m (5.1 ft)

7/23/2008

Figure 2: Fool Creek, reach FC1 (transitional between plane bed and step pool).



low flow (8/4/2007)

***n* = 0.20**
***ff* = 6.0**
v = 0.40 m/s (1.3 ft/s)
Q = 0.10 cms (3.6 cfs)
s_f = 0.082 m/m
s_o = 0.084 m/m
Froude # = 0.31
length = 24 m (80 ft)
width = 2.5 m (8.1 ft)

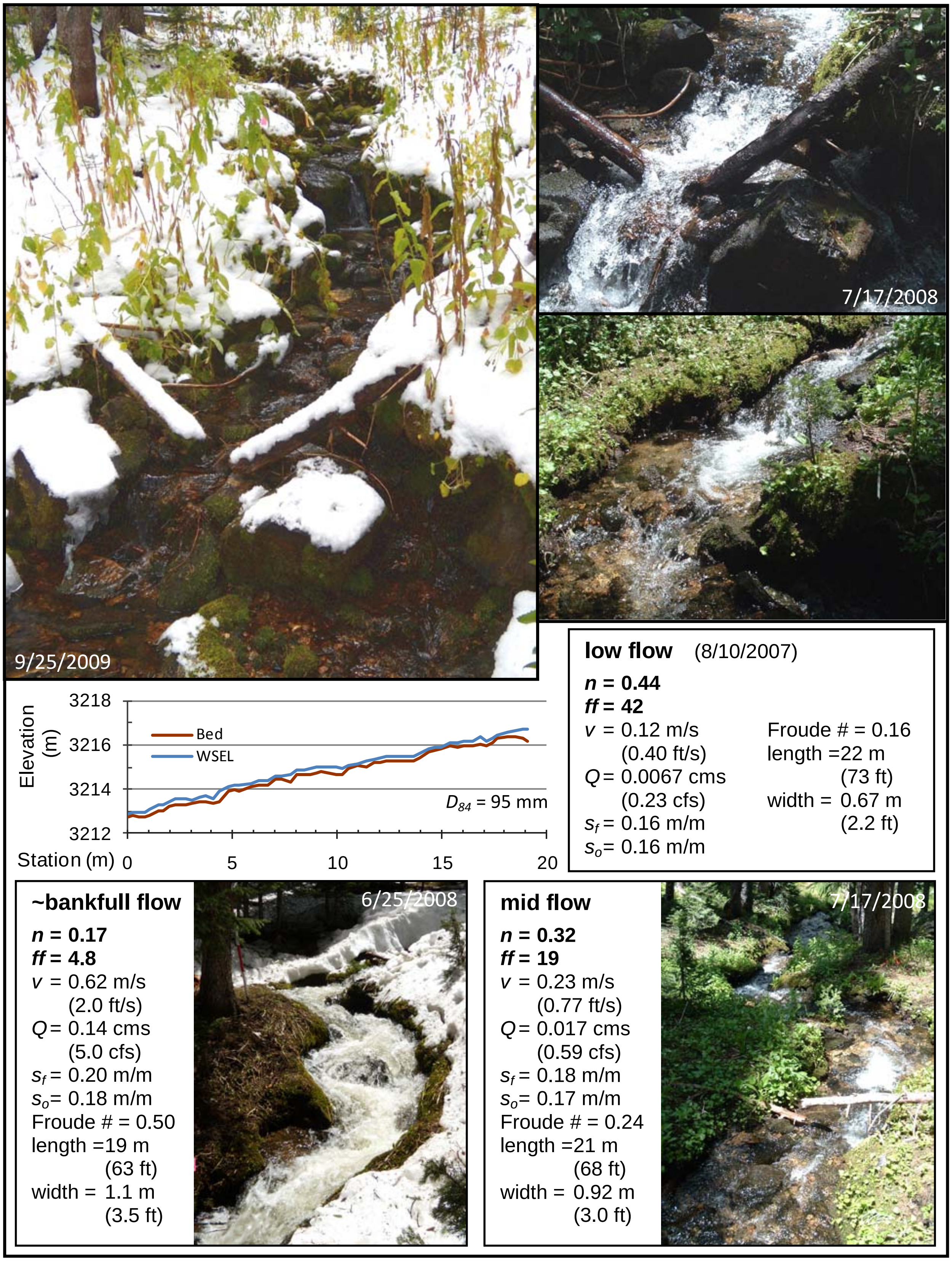
~bankfull flow

***n* = 0.17**
***ff* = 3.5**
v = 0.69 m/s (2.3 ft/s)
Q = 0.52 cms (18 cfs)
s_f = 0.085 m/m
s_o = 0.089 m/m
Froude # = 0.39
length = 22 m (72 ft)
width = 3.0 m (9.9 ft)

mid flow

***n* = 0.19**
***ff* = 4.9**
v = 0.55 m/s (1.8 ft/s)
Q = 0.30 cms (11 cfs)
s_f = 0.081 m/m
s_o = 0.086 m/m
Froude # = 0.32
length = 24 m (79 ft)
width = 2.9 m (9.6 ft)

Figure 3: East Saint Louis, reach ESL7 (cascade).



low flow (8/10/2007)

***n* = 0.44**
***ff* = 42**
v = 0.12 m/s (0.40 ft/s)
Q = 0.0067 cms (0.23 cfs)
s_f = 0.16 m/m
s_o = 0.16 m/m
Froude # = 0.16
length =22 m (73 ft)
width = 0.67 m (2.2 ft)

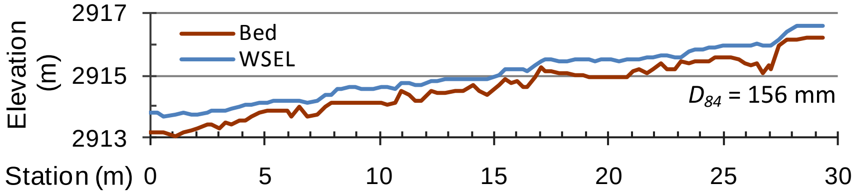
~bankfull flow

***n* = 0.17**
***ff* = 4.8**
v = 0.62 m/s (2.0 ft/s)
Q = 0.14 cms (5.0 cfs)
s_f = 0.20 m/m
s_o = 0.18 m/m
Froude # = 0.50
length =19 m (63 ft)
width = 1.1 m (3.5 ft)

mid flow

***n* = 0.32**
***ff* = 19**
v = 0.23 m/s (0.77 ft/s)
Q = 0.017 cms (0.59 cfs)
s_f = 0.18 m/m
s_o = 0.17 m/m
Froude # = 0.24
length =21 m (68 ft)
width = 0.92 m (3.0 ft)

Figure 4: Fool Creek, reach FC6 (cascade).



~bankfull flow

***n* = 0.19**
***ff* = 4.5**
v = 0.65 m/s (2.1 ft/s)
Q = 0.56 cms (20 cfs)
s_f = 0.095 m/m
s_o = 0.10 m/m
Froude # = 0.35
length = 29 m (96 ft)
width = 2.9 m (9.6 ft)

mid flow

***n* = 0.27**
***ff* = 9.4**
v = 0.42 m/s (1.4 ft/s)
Q = 0.24 cms (8.3 cfs)
s_f = 0.11 m/m
s_o = 0.11 m/m
Froude # = 0.26
length = 27 m (90 ft)
width = 2.6 m (8.5 ft)

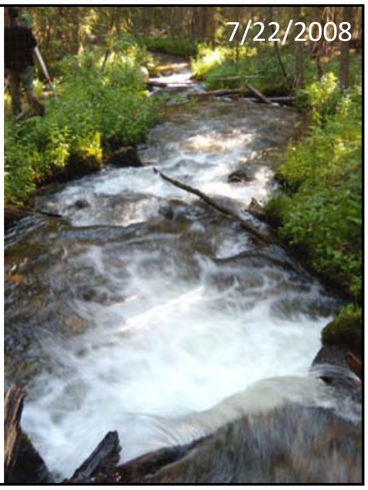
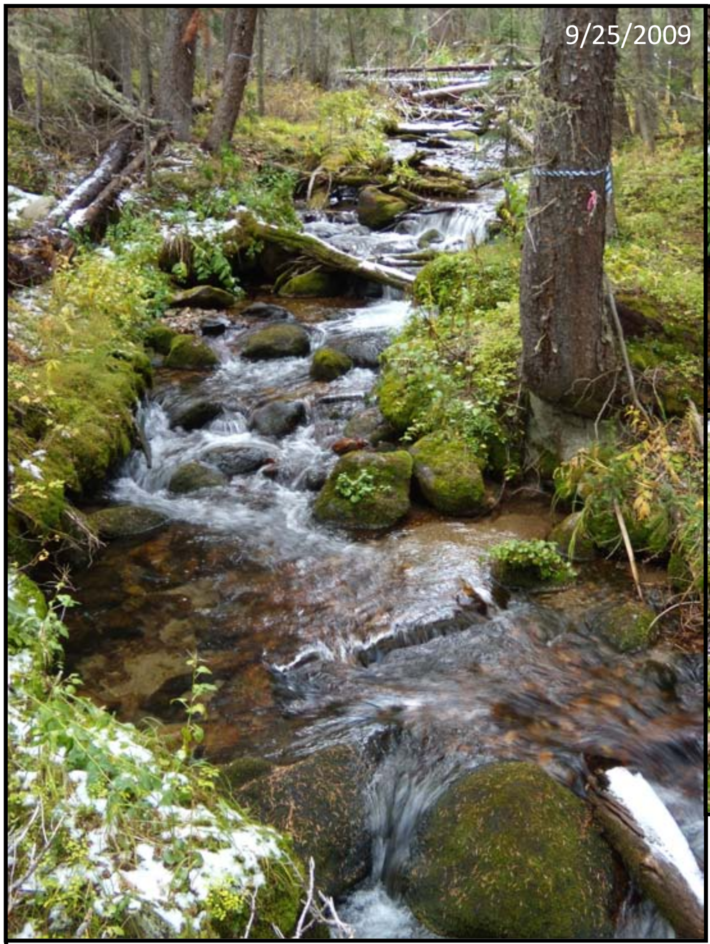
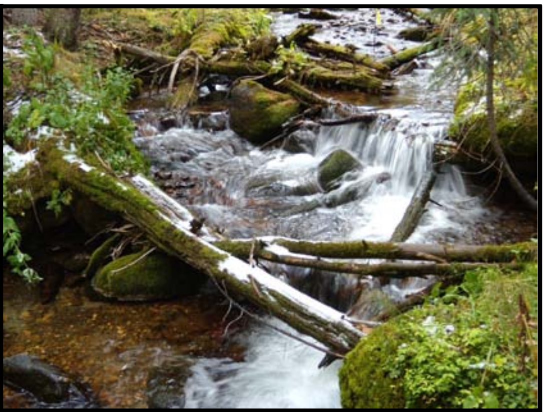
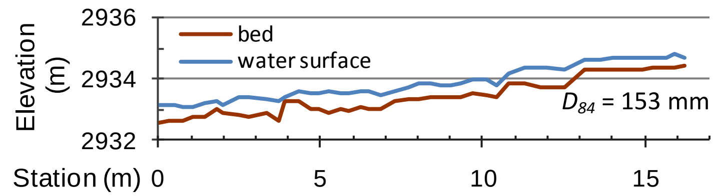


Figure 5: East Saint Louis Creek, reach ESL1 (step pool).





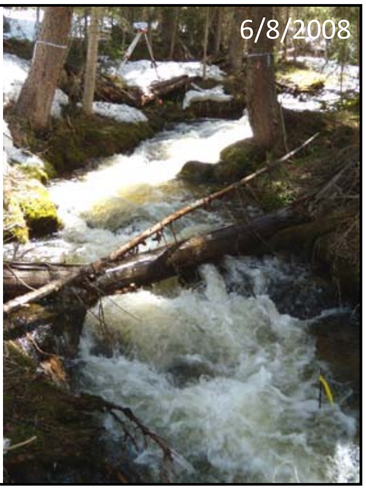


low flow (8/6/2007)

***n* = 0.28**
***ff* = 10.9**
v = 0.33 m/s (1.1 ft/s)
Q = 0.11 cms (3.8 cfs)
s_f = 0.090 m/m
s_o = 0.099 m/m
Froude # = 0.23
length = 19 m (61 ft)
width = 2.3 m (7.5 ft)

~bankfull flow

***n* = 0.21**
***ff* = 5.5**
v = 0.64 m/s (2.1 ft/s)
Q = 0.57 cms (20 cfs)
s_f = 0.11 m/m
s_o = 0.11 m/m
Froude # = 0.36
length = 16 m (53 ft)
width = 2.8 m (9.2 ft)



mid flow

***n* = 0.26**
***ff* = 8.8**
v = 0.43 m/s (1.4 ft/s)
Q = 0.20 cms (7.1 cfs)
s_f = 0.10 m/m
s_o = 0.11 m/m
Froude # = 0.27
length = 16 m (53 ft)
width = 2.6 m (8.5 ft)

Figure 6: East Saint Louis Creek, reach ESL9 (step pool).

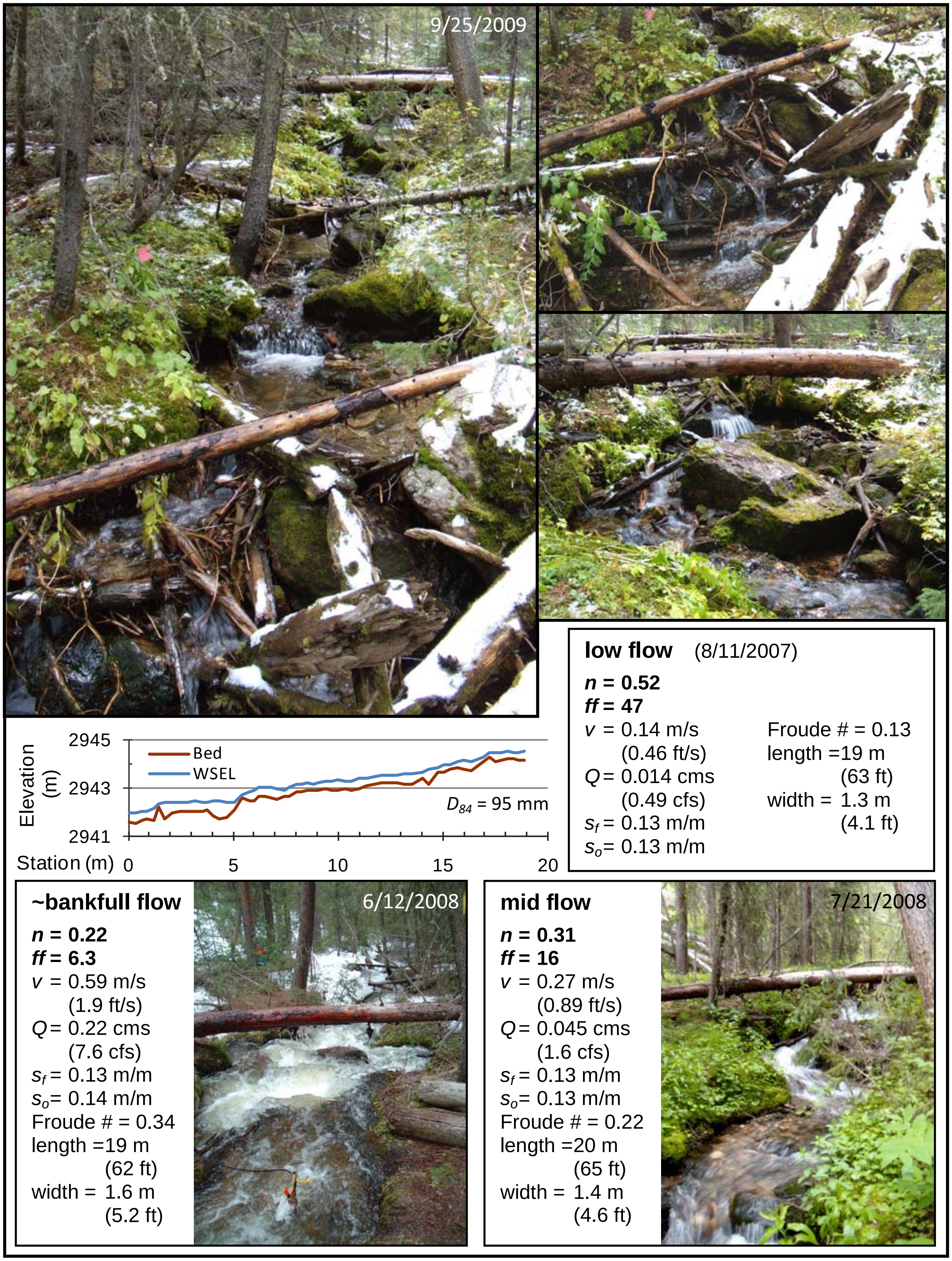
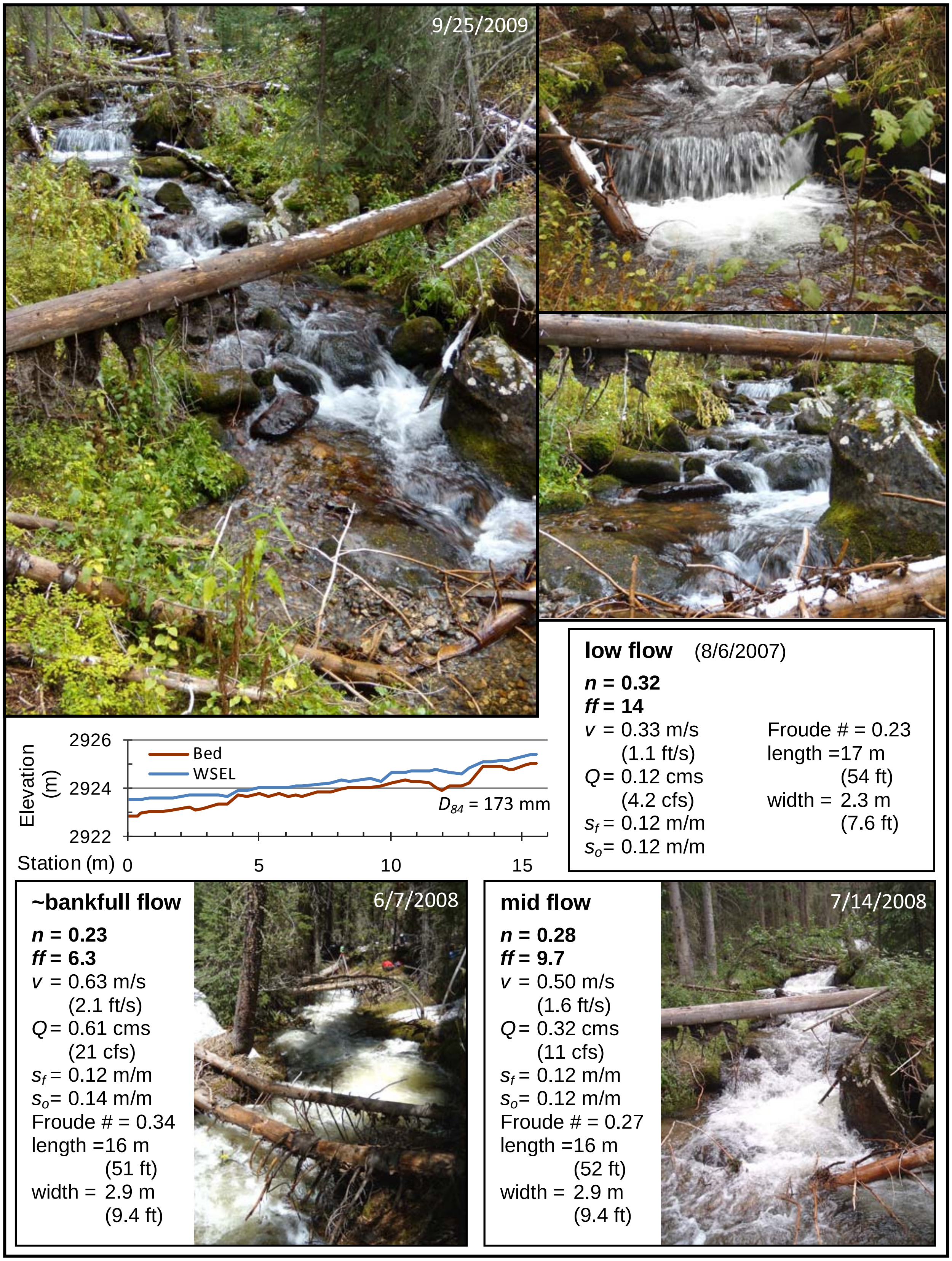


Figure 7: Fool Creek, reach FC4 (step pool).



low flow (8/6/2007)

n = 0.32

ff = 14

v = 0.33 m/s (1.1 ft/s)

Q = 0.12 cms (4.2 cfs)

s_f = 0.12 m/m

s_o = 0.12 m/m

Froude # = 0.23

length = 17 m (54 ft)

width = 2.3 m (7.6 ft)

~bankfull flow

n = 0.23

ff = 6.3

v = 0.63 m/s (2.1 ft/s)

Q = 0.61 cms (21 cfs)

s_f = 0.12 m/m

s_o = 0.14 m/m

Froude # = 0.34

length = 16 m (51 ft)

width = 2.9 m (9.4 ft)

mid flow

n = 0.28

ff = 9.7

v = 0.50 m/s (1.6 ft/s)

Q = 0.32 cms (11 cfs)

s_f = 0.12 m/m

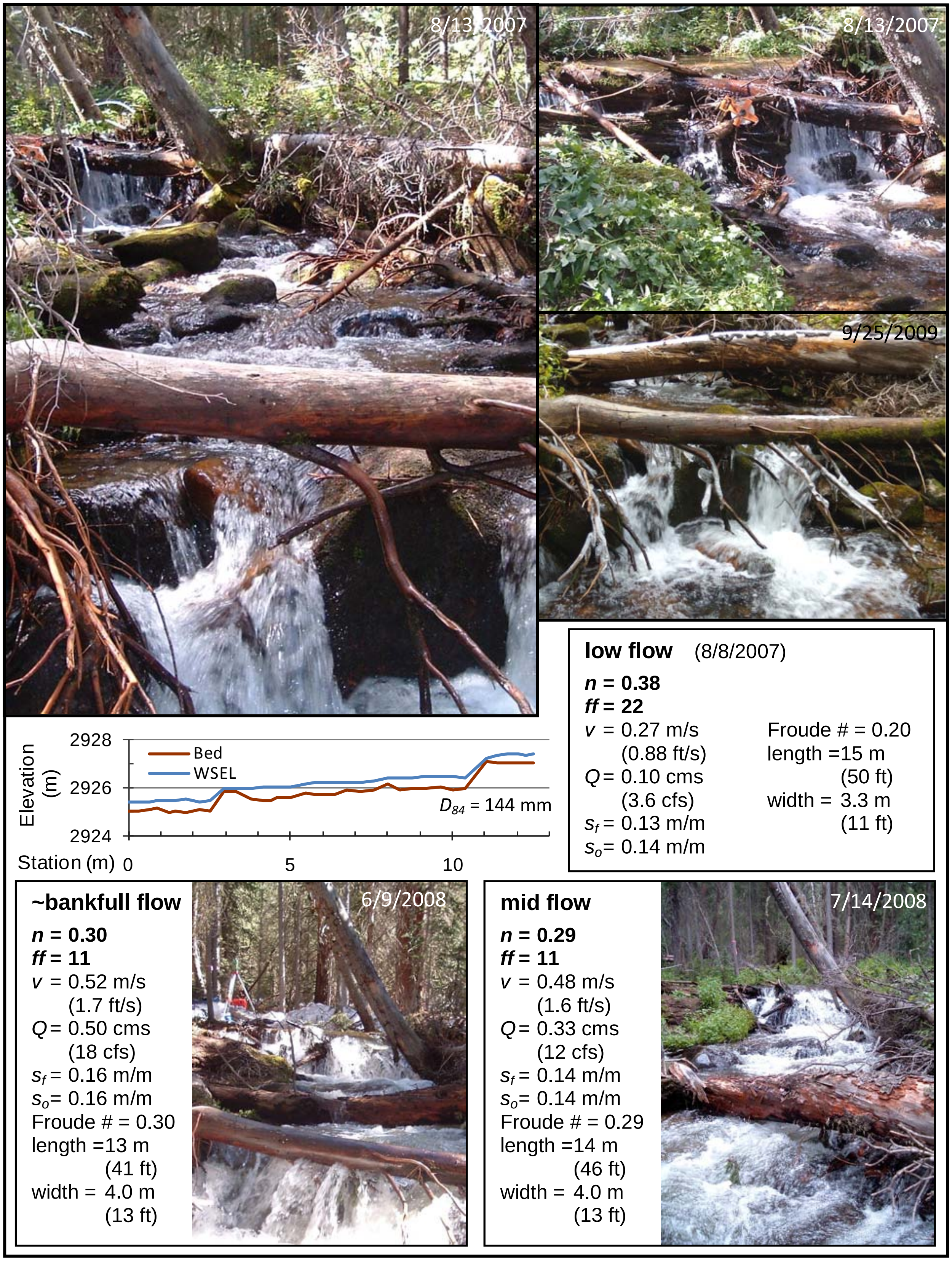
s_o = 0.12 m/m

Froude # = 0.27

length = 16 m (52 ft)

width = 2.9 m (9.4 ft)

Figure 8: East Saint Louis Creek, reach ESL4 (step pool).



low flow (8/8/2007)

***n* = 0.38**
***ff* = 22**
v = 0.27 m/s (0.88 ft/s)
Q = 0.10 cms (3.6 cfs)
s_f = 0.13 m/m
s_o = 0.14 m/m
Froude # = 0.20
length = 15 m (50 ft)
width = 3.3 m (11 ft)

~bankfull flow

***n* = 0.30**
***ff* = 11**
v = 0.52 m/s (1.7 ft/s)
Q = 0.50 cms (18 cfs)
s_f = 0.16 m/m
s_o = 0.16 m/m
Froude # = 0.30
length = 13 m (41 ft)
width = 4.0 m (13 ft)

mid flow

***n* = 0.29**
***ff* = 11**
v = 0.48 m/s (1.6 ft/s)
Q = 0.33 cms (12 cfs)
s_f = 0.14 m/m
s_o = 0.14 m/m
Froude # = 0.29
length = 14 m (46 ft)
width = 4.0 m (13 ft)

Figure 9: East Saint Louis Creek, reach ESL5 (cascade).

CONCLUSION

Photographic guidance is provided for the selection of Manning's *n* and Darcy Darcy-Weisbach *ff* for low, mid and approximate bankfull flows in cascade, step pool and plane bed stream reaches, based upon research in the Fraser Experimental Forest, Colorado. Computed Manning's *n* values are substantially higher than those suggested by commonly-cited references, though are similar to those measured by other researchers in similar stream types. This photographic tool is helpful for general resistance coefficient selection in high-gradient streams, though caution is warranted when judging the wisdom of extrapolating these results to larger streams or reaches where the flow interacts more substantially with non-step-forming large woody debris.

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