

FLOW RESISTANCE ESTIMATION IN HIGH-GRADIENT STREAMS

Steven Yochum, Hydrologist, USDA Natural Resources Conservation Service & Colorado State University, Fort Collins, CO, steven.yochum@co.usda.gov; **Brian Bledsoe, Associate Professor**, Colorado State University, Fort Collins, CO, brian.bledsoe@enr.colostate.edu

prepared for the 4th Federal Interagency Hydrologic Modeling Conference
June 27 - July 1, 2010, Riviera Hotel, Las Vegas, Nevada.

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 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 f 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 length 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).

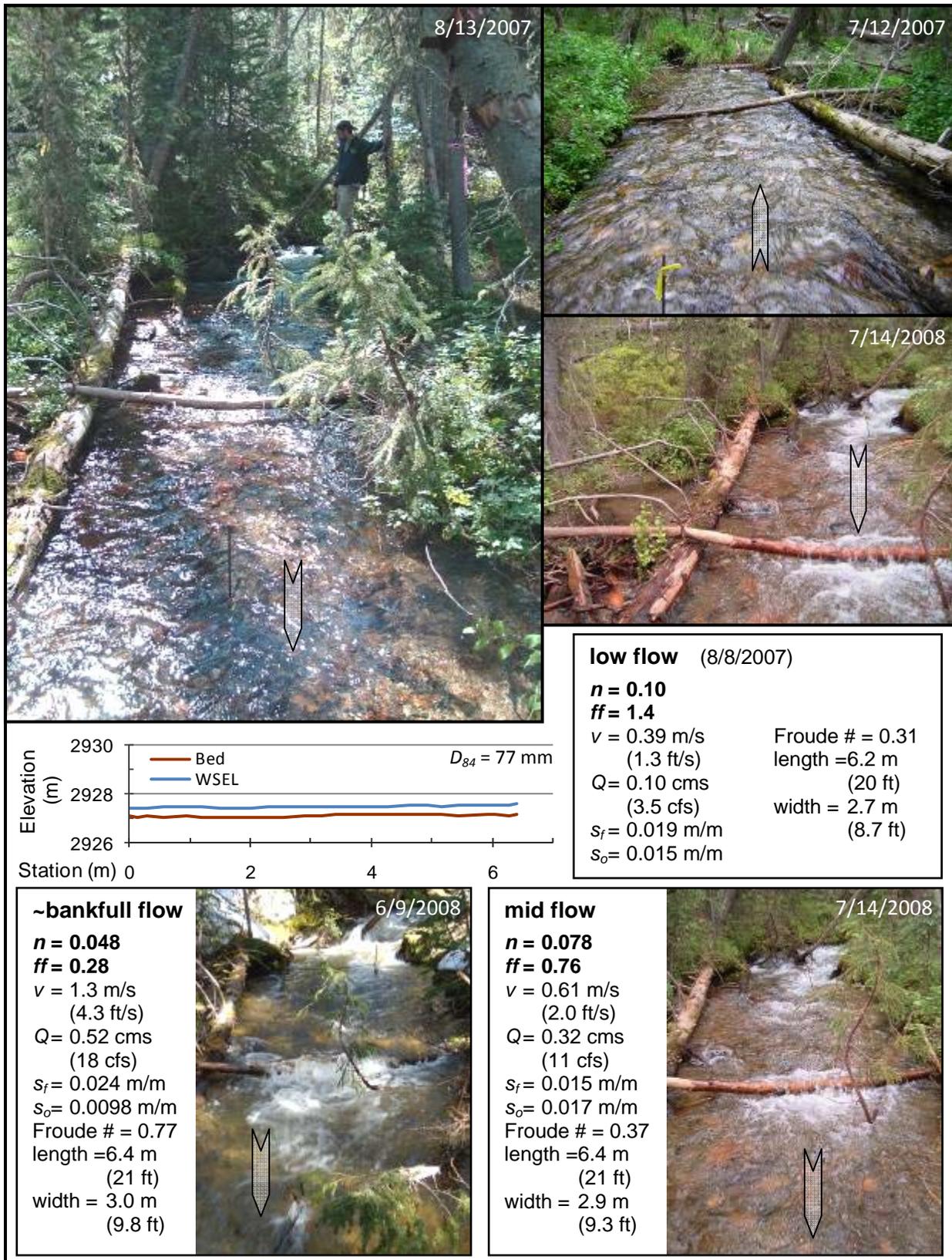


Figure 1: East Saint Louis, reach ESL6 (plane bed).

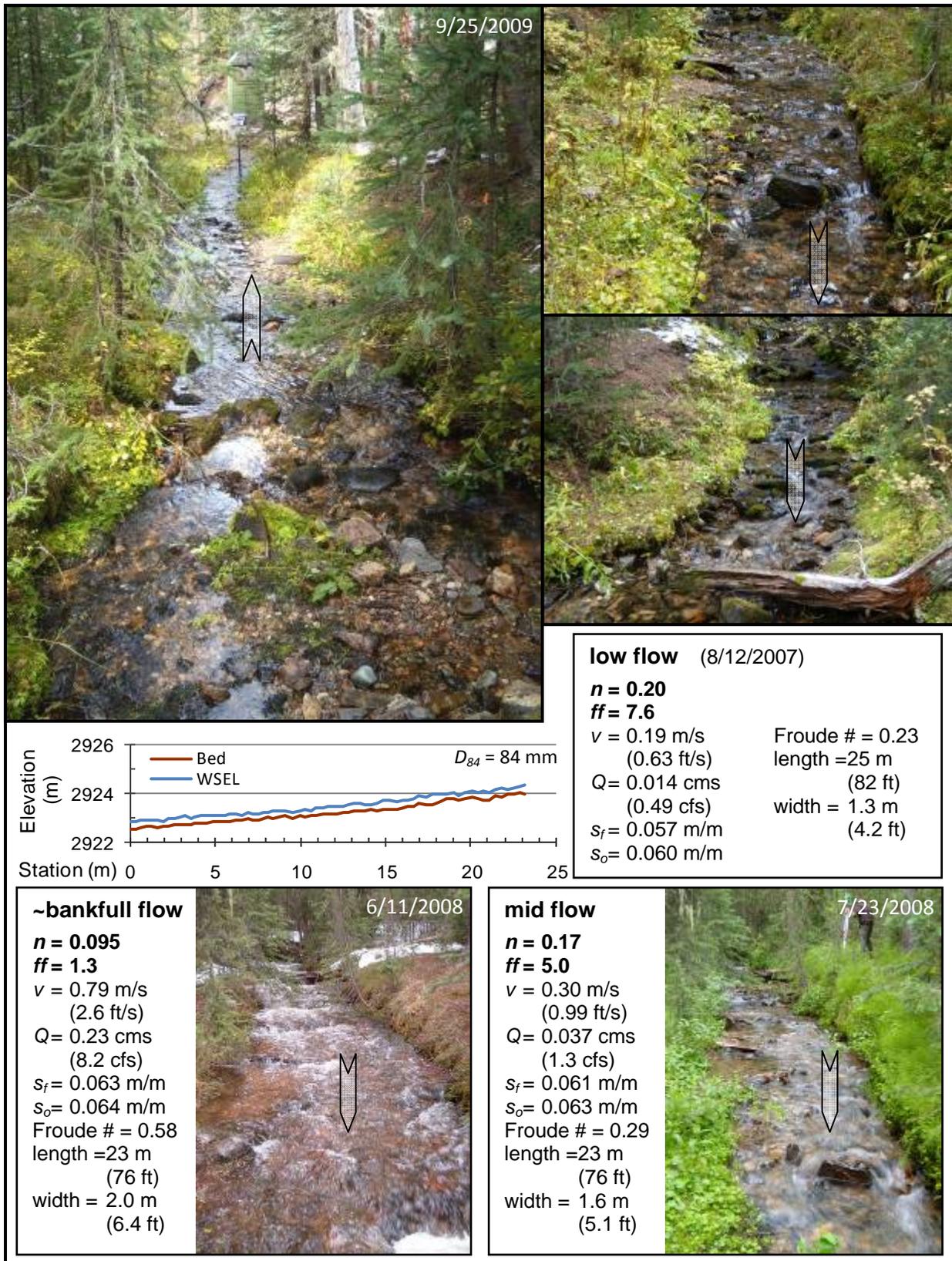


Figure 2: Fools Creek, reach FC1 (transitional between plane bed and step pool).

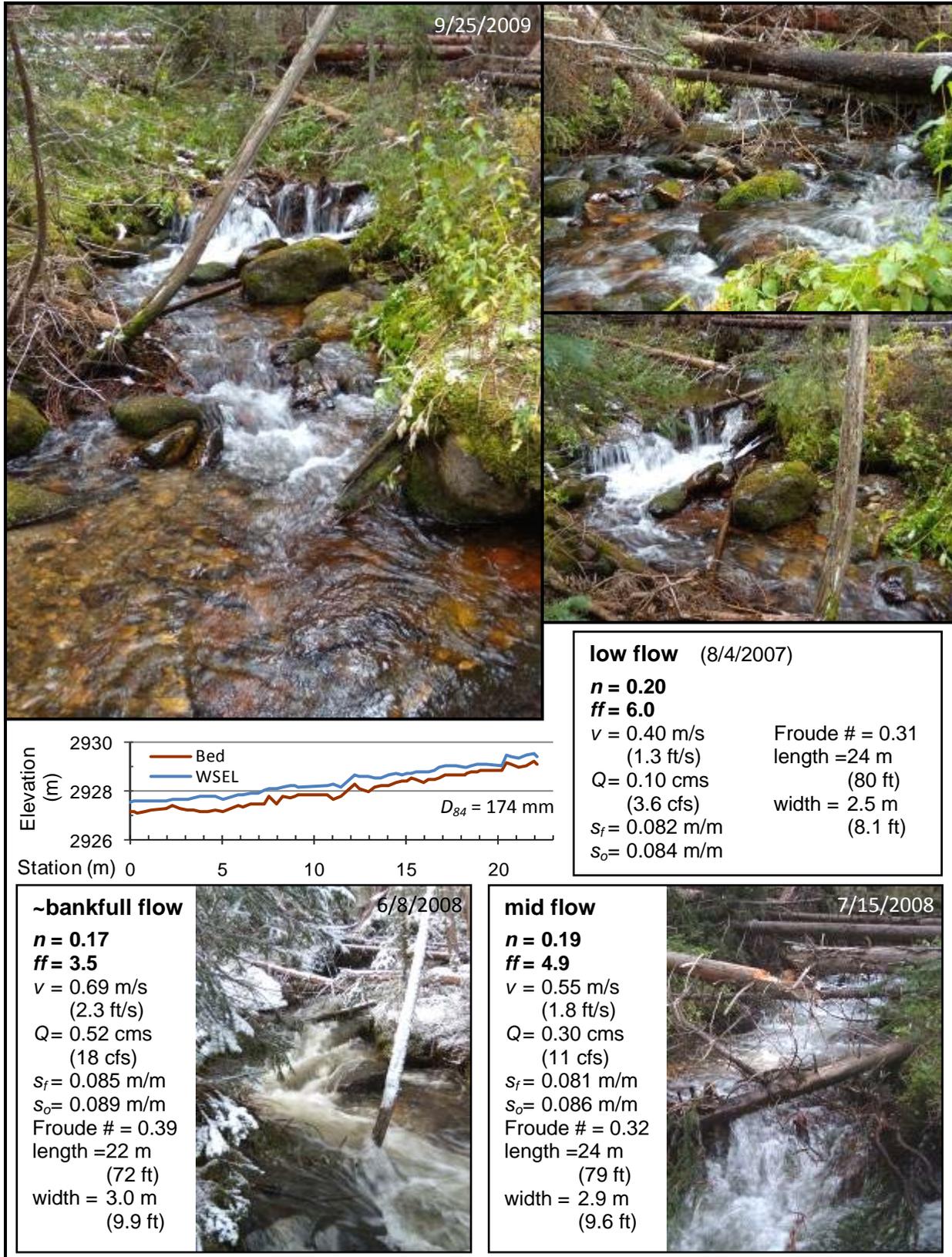


Figure 3: East Saint Louis, reach ESL7 (cascade).

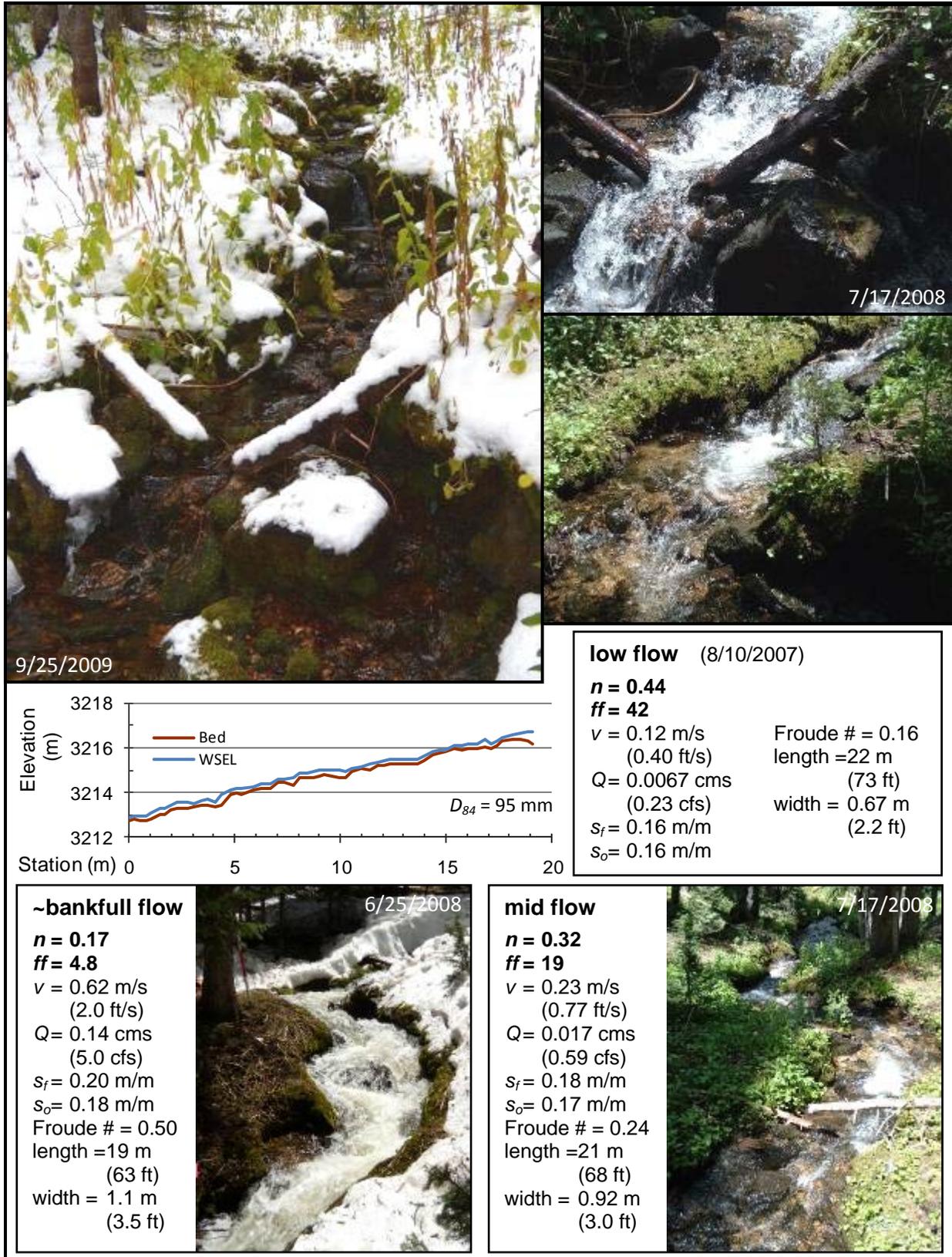


Figure 4: Fool Creek, reach FC6 (cascade).

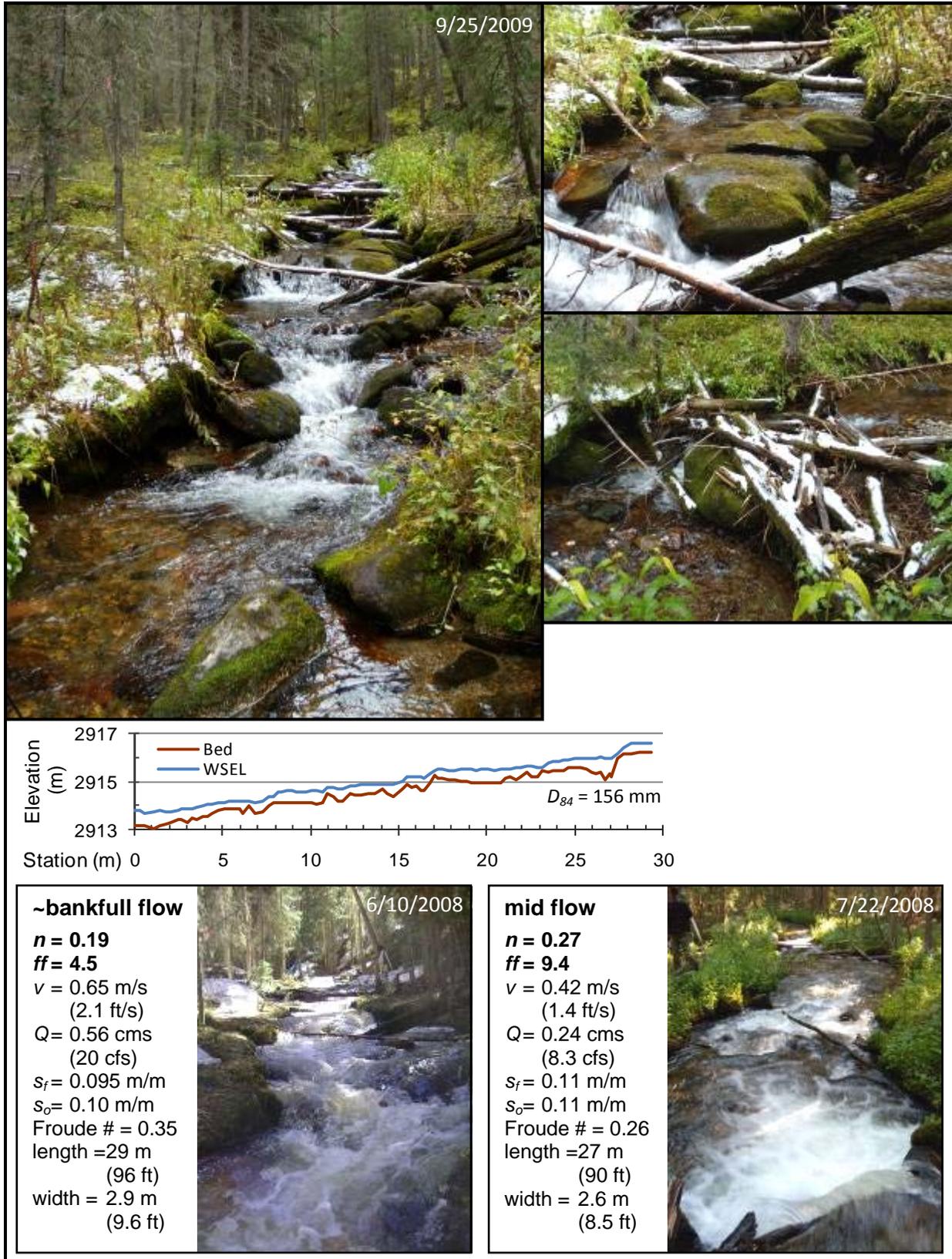


Figure 5: East Saint Louis Creek, reach ESL1 (step pool).

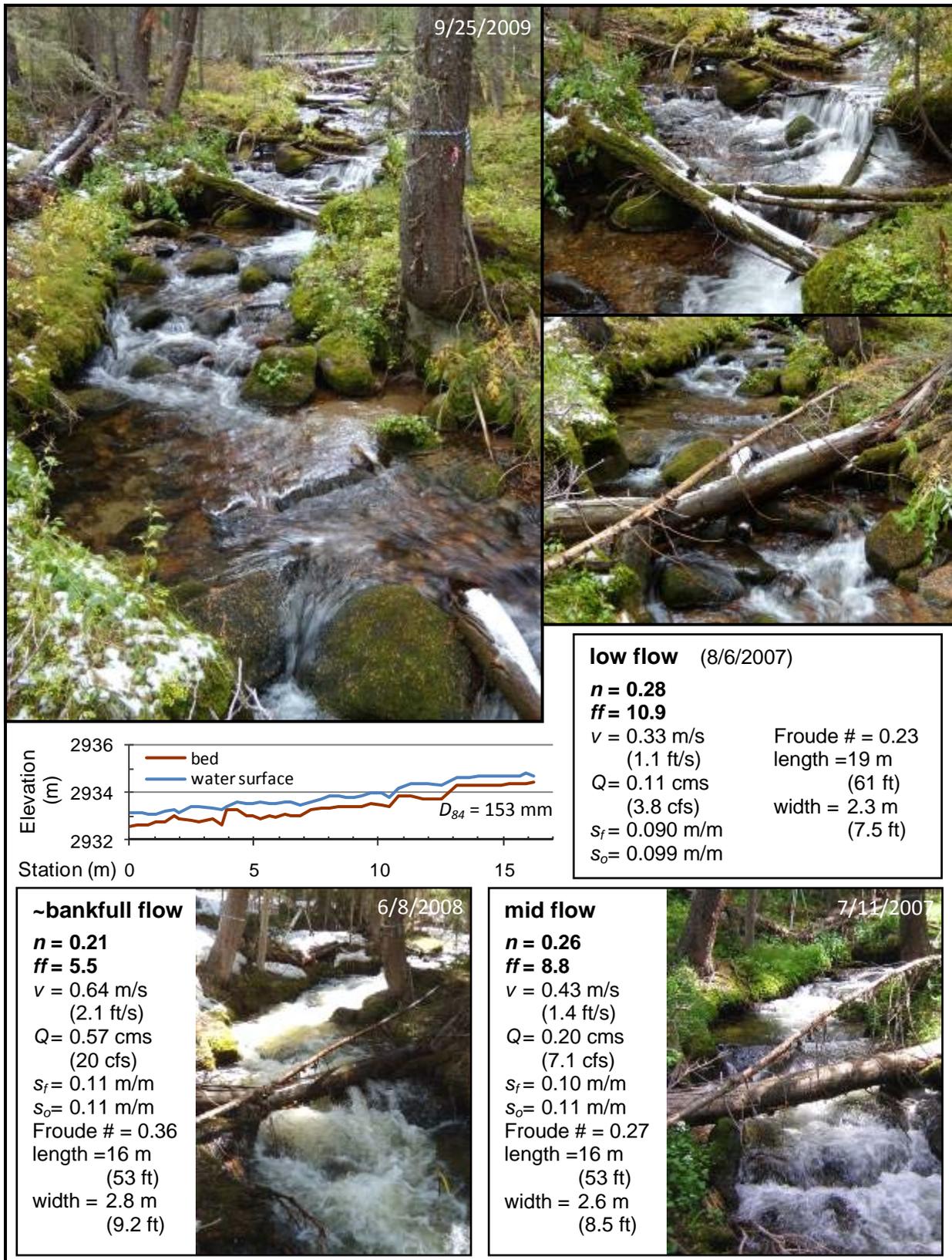


Figure 6: East Saint Louis Creek, reach ESL9 (step pool).

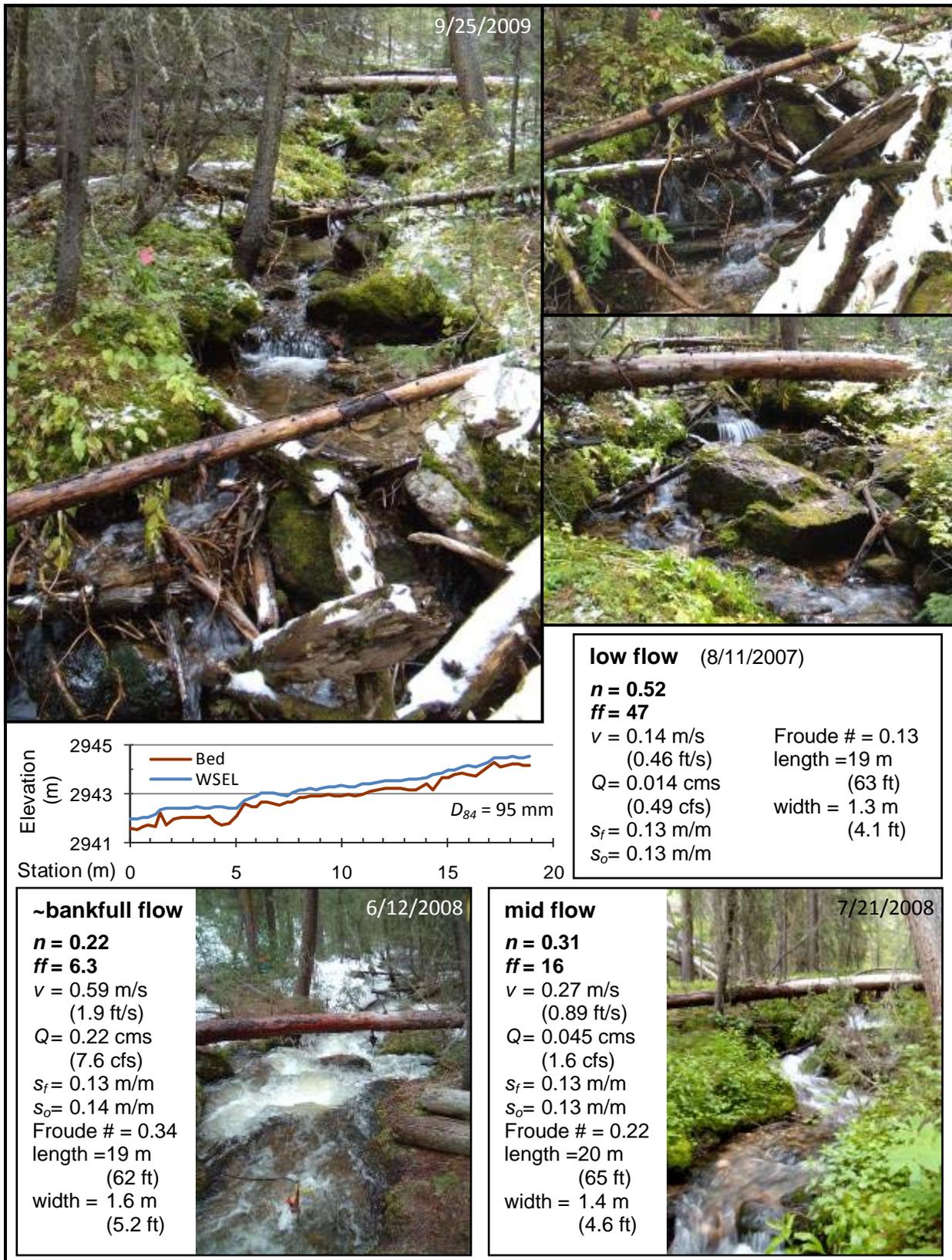


Figure 7: Fool Creek, reach FC4 (step pool).

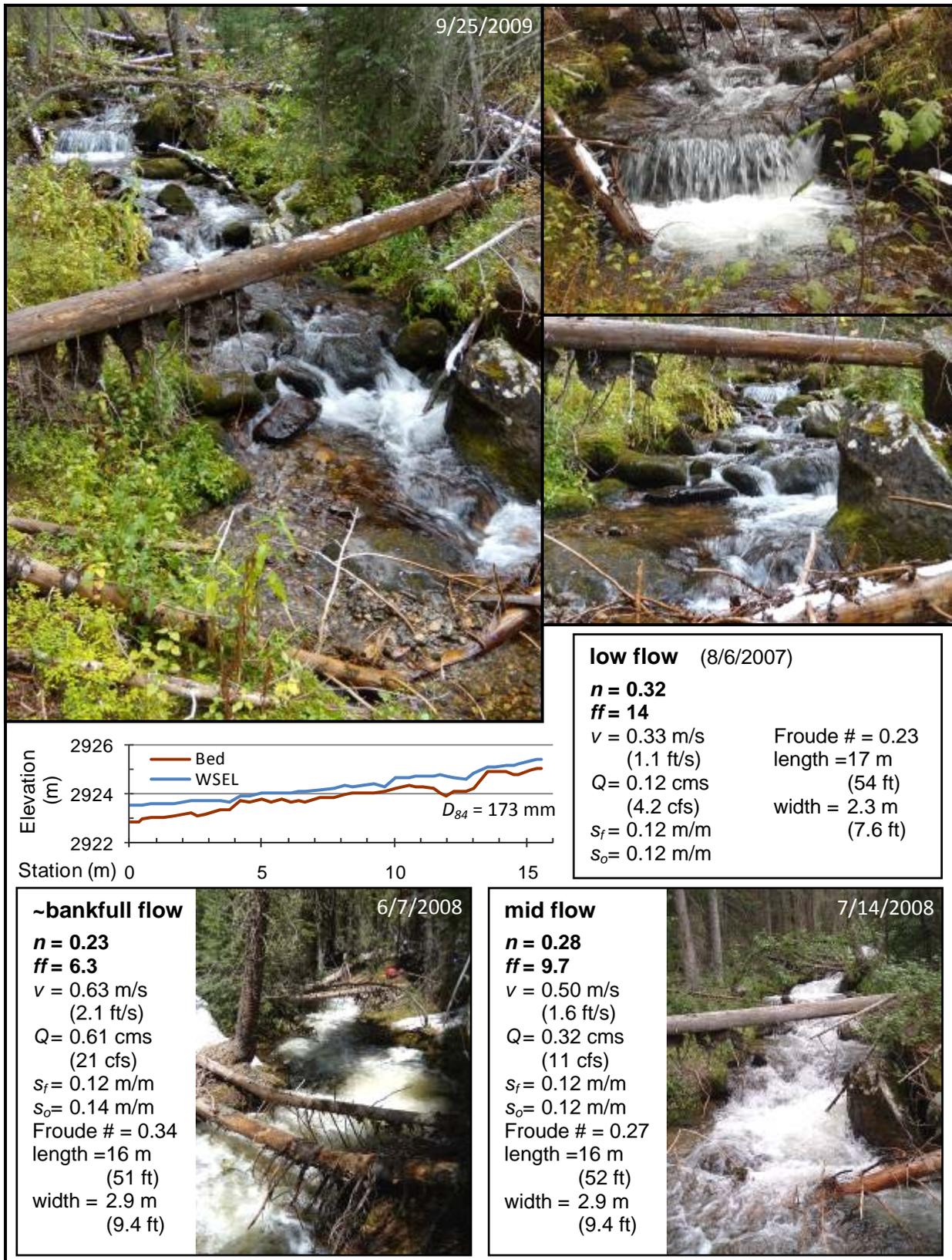


Figure 8: East Saint Louis Creek, reach ESL4 (step pool).

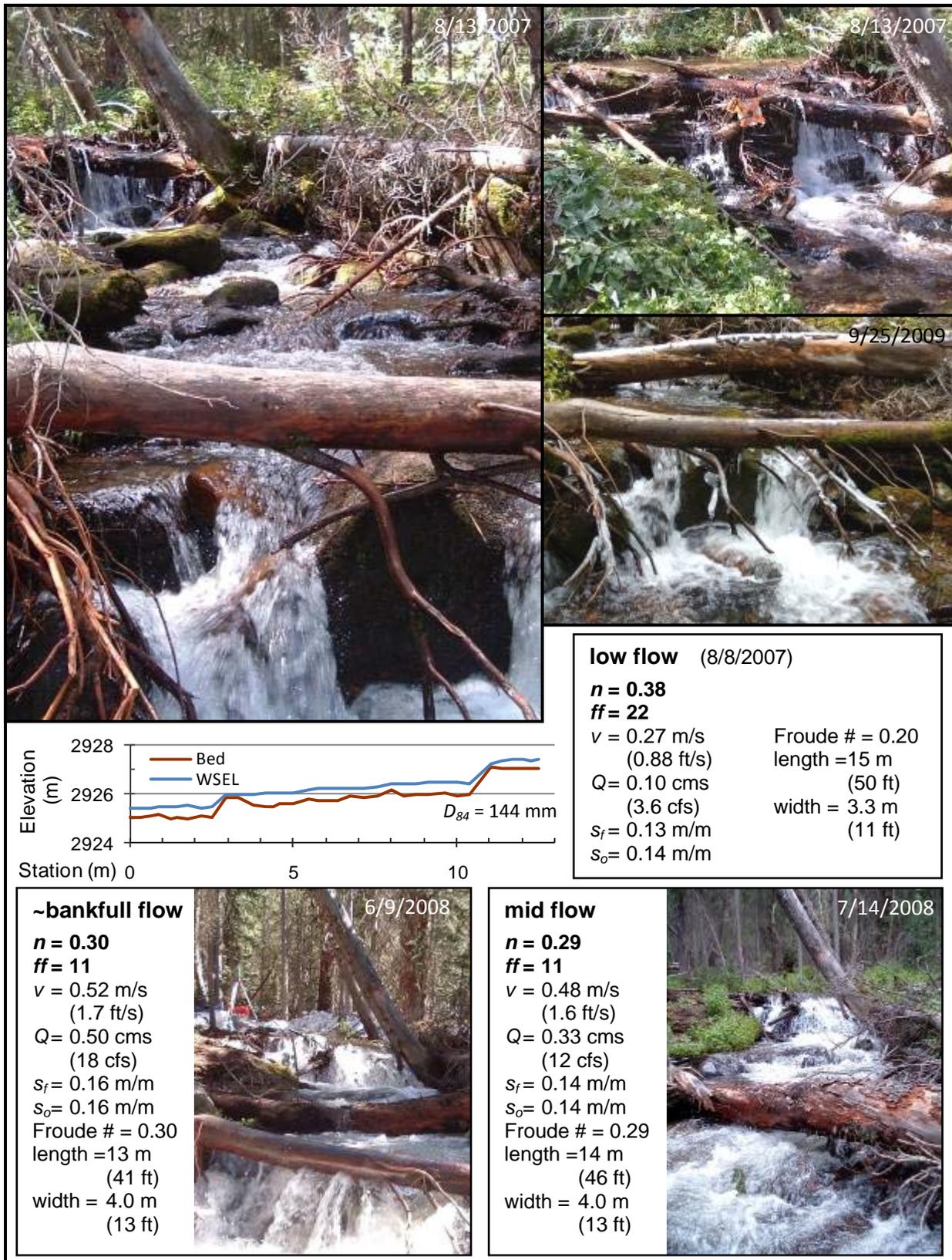


Figure 9: East Saint Louis Creek, reach ESL5 (cascade).

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.

ACKNOWLEDGEMENTS

This research was performed with my co-investigator, Gabrielle David. In addition to Brian Bledsoe, the other principal investigator on the project was Ellen Wohl. Appreciation is expressed to the National Science Foundation for funding (grant number EAR0608918), to the USDA Forest Service Rocky Mountain Research Station for hosting the research on the Fraser Experimental Forest, to the Natural Resources Conservation Service for additional funding, and to our field assistants Mark Hussey, Dan Dolan and Lina Polvi.

REFERENCES

- Aldridge, B.N., and Garrett, J.M. (1973). "Roughness coefficients for stream channels in Arizona," U.S. Geological Survey Open-File Report, Tucson, Arizona.
- Arcement, G.J., and Schneider, V.R. (1989). "Guide For Selecting Manning's Roughness Coefficients for Natural Channels and Flood Plains," U.S. Geological Survey Water-Supply Paper 2339.
- Barnes, H.H., Jr., (1967). "Roughness characteristics of natural channels," U. .S. Geological Survey Water Supply Paper, 1849, 213 pp.
- Brunner, G.W. (2008). "HEC-RAS River Analysis System Hydraulic Reference Manual," U. S. Army Corps of Engineers, Hydrologic Engineering Center.
- Chow, V.T. (1959). "Open Channel Hydraulics," McGraw-Hill Book Company, New York.
- Comiti, F., Mao, L., Wilcox, A., Wohl, E.E., and Lenzi, M.A. (2007). "Field-derived relationships for flow velocity and resistance in high-gradient streams," *Journal of Hydrology*, 340, 48-62.
- Cowan, W.L. (1956). "Estimating hydraulic roughness coefficients," *Agricultural Engineering*, 37, 473-475.
- Curran, J.H. and Wohl, E.E. (2003). "Large woody debris and flow resistance in step-pool channels, Cascade Range, Washington," *Geomorphology*, 51(1-3), 141-157.
- Lee, A.J., and Ferguson, R.I. (2002). "Velocity and flow resistance in step-pool streams," *Geomorphology*, 46, 59-71.
- MacFarlane, W. A., and Wohl, E. (2003). "Influence of step composition on step geometry and flow resistance in step-pool streams of the Washington Cascades," *Water Resources Research*, 39(2).
- Reid, D.E., and Hickin, E.J. (2008). "Flow resistance in steep mountain streams," *Earth Surface Processes Landforms*, 33, 2211-2240.
- Montgomery, D.R., and Buffington, J.M. (1997). "Channel reach morphology in mountain drainage basins," *Geological Society of America Bulletin*, 109(5), 596-611.
- Walden, M.G. (2004). "Estimation of average stream velocity," *Journal of Hydraulic Engineering*, 130 (11), 1119-1122.
- Wilcox, A.C., and Wohl, E.E. (2006). "Flow resistance dynamics in step-pool stream channels: 1. Large woody debris and controls on total resistance," *Water Resources Research* 42.
- Yochum, S., Bledsoe, B., David, G., Wohl, E. (in review). "Resistance coefficients prediction in high-gradient streams," *Water Resources Research*.