

National Park Service
U.S. Department of the Interior

Northeast Region
Philadelphia, Pennsylvania



Characterization of Sediment Storage and Remobilization in Valley Creek, Valley Forge National Historical Park

Technical Report NPS/NER/NRTR—2007/095



ON THE COVER

Eroded section of Valley Creek in front of Washington's Headquarters in Valley Forge National Historical Park.
Photograph by: Lisa M. Fraley.

Characterization of Sediment Storage and Remobilization in Valley Creek, Valley Forge National Historical Park

Technical Report NPS/NER/NRTR—2007/095

Lisa M. Fraley, Andrew J. Miller, and Claire Welty

University of Maryland Baltimore County
Center for Urban Environmental Research and Education
1000 Hilltop Circle, Technology Research Center
Baltimore, Maryland 21250

September 2007

U.S. Department of the Interior
National Park Service
Northeast Region
Philadelphia, Pennsylvania

The Northeast Region of the National Park Service (NPS) comprises national parks and related areas in 13 New England and Mid-Atlantic states. The diversity of parks and their resources are reflected in their designations as national parks, seashores, historic sites, recreation areas, military parks, memorials, and rivers and trails. Biological, physical, and social science research results, natural resource inventory and monitoring data, scientific literature reviews, bibliographies, and proceedings of technical workshops and conferences related to these park units are disseminated through the NPS/NER Technical Report (NRTR) and Natural Resources Report (NRR) series. The reports are a continuation of series with previous acronyms of NPS/PHSO, NPS/MAR, NPS/BSO-RNR, and NPS/NERBOST. Individual parks may also disseminate information through their own report series.

Technical Reports are the designated medium for initially disseminating data and results of biological, physical, and social science research that addresses natural resource management issues; natural resource inventories and monitoring activities; scientific literature reviews; bibliographies; and peer-reviewed proceedings of technical workshops, conferences, or symposia.

Natural Resources Reports are the designated medium for information on technologies and resource management methods; "how to" resource management papers; proceedings of resource management workshops or conferences; and natural resource program descriptions and resource action plans.

Mention of trade names or commercial products does not constitute endorsement or recommendation for use by the National Park Service.

This report was accomplished under Cooperative Agreement 309701200, Task Agreement Number J3097-03-800 with assistance from the NPS. The statements, findings, conclusions, recommendations, and data in this report are solely those of the author(s), and do not necessarily reflect the views of the U.S. Department of the Interior, National Park Service.

Print copies of reports in these series, produced in limited quantity and only available as long as the supply lasts, or, preferably, file copies on CD may be obtained by sending a request to the address on the back cover. Print copies also may be requested from the NPS Technical Information Center (TIC), Denver Service Center, PO Box 25287, Denver, CO 80225-0287. A copy charge may be involved. To order from TIC, refer to document D-103.

This report may also be available as a downloadable portable document format file from the Internet at <http://www.nps.gov/nero/science/>.

Please cite this publication as:

Fraley, L. M., A. J. Miller, and C. Welty. 2007. Characterization of Sediment Storage and Remobilization in Valley Creek, Valley Forge National Historical Park. Technical Report NPS/NER/NRTR—2007/095. National Park Service. Philadelphia, PA.

Table of Contents

	Page
Figures	v
Tables	ix
Appendixes	xi
Abstract	xiii
Executive Summary	xv
Acknowledgments	xix
Introduction	1
Study Area	5
Geology, Geomorphology, and Land Use	5
Climate and Hydrology	7
Methods	11
Longitudinal Profile	11
Cross-section Analysis	11
Bankline Analysis	13
Depth of the Mobile Layer	15
Particle Size Distributions	15
Sediment Transport	18
Results	21
Channel Characterization	21
Longitudinal Profile	21
Cross-section Surveys and Sampling	30
Fine Sediment Storage in the Streambed	43
Bankline Surveys and Analysis	45

Table of Contents (continued)

	Page
Sediment Yield	51
Tracer Gravels	56
Discussion	59
Bed Material Particle Size	59
Channel Erosion and Sedimentation	61
Comparison of Sediment Sources	63
Recommendations for Continued Monitoring	67
Management Recommendations	70
Conclusions	73
Summation of Conclusions of the Research	73
Management Implications	74
Literature Cited	77

Figures

	Page
Figure 1. Location map for Valley Creek watershed.	2
Figure 2. Aerial photograph of the 3.7-km (2.3-mi) portion of Valley Creek that runs through Valley Forge National Historical Park.	3
Figure 3. Valley Creek geology (from McGinty [2003], based on Bascom and Stose [1938] and CCPC [1973]).	6
Figure 4. Progressive urbanization in Valley Creek watershed. The 1946 and 1980 photos show development in the watershed upstream of Interstate 76, the southern boundary to Valley Forge National Historical Park.	8
Figure 5. Valley Creek annual peak streamflow at the USGS gage located just upstream of the Interstate 76 overpass.	9
Figure 6. Calculations for determining the area of change in a cross-section.	13
Figure 7. Calculation for the volume of bank erosion based on surveys of bank tops and bottoms after significant storm events.	14
Figure 8. Four-piece sampling frame with an adjustable grid of elastic bands (left). Detail of the corner piece with mounted threaded pins is shown and the joining using corner pieces and wing nuts (right) (Bunte and Abt 2001).	16
Figure 9. Cumulative particle size distribution showing the 1,113 particle pilot study and a randomly selected 200 particle subset.	17
Figure 10. Preliminary channel characterization of Valley Creek based on initial reconnaissance, July and September 2003.	22
Figure 11. Refined subdivisions of the preliminary channel characterization of Valley Creek.	23
Figure 12. Channel characterization of Valley Creek based on flow regime and sediment accumulation.	24
Figure 13. Twelve chosen sample reaches of Valley Creek, including locations of 36 cross-sections.	25

Figures (continued)

	Page
Figure 14. Longitudinal profile of the portion of Valley Creek that runs through Valley Forge National Historical Park, September 2003–May 2004.	26
Figure 15. Section of a 1911 map of Valley Forge National Historical Park showing the extent of an old cotton mill dam on Valley Creek (Burk 1928).	27
Figure 16. Valley Creek water surface slope with distance upstream, September 2003–May 2004.	29
Figure 17. Valley Creek cross-section 1B located in a downstream reach: a) cross-section, b) cumulative particle size distribution, and c) pebble count histogram.	31
Figure 18. Valley Creek cross-section 9B located mid-way upstream: a) cross-section, b) scour chain data, c) barrel sample histogram, d) cumulative particle size distribution, and e) pebble count histogram.	32
Figure 19. Valley Creek cross-section 12B located in an upstream reach: a) cross-section, b) scour chain data, c) barrel sample histogram, d) cumulative particle size distribution, and e) pebble count histogram.	34
Figure 20. Valley Creek cross-section 8A showing the cyclic pattern of scour and deposition.	26
Figure 21. Cross-section deposition and scour in Valley Creek from the baseline survey in the summer of 2004 to the 3 rd storm event on April 2, 2005.	38
Figure 22. Reach-averaged deposition and scour in Valley Creek from the baseline survey in the summer of 2004 to the 3 rd storm event on April 2, 2005.	39
Figure 23. Normalized reach-average deposition and scour in Valley Creek from the baseline survey in the summer of 2004 to the 3 rd storm event on April 2, 2005.	39
Figure 24. Pebble count data for sampled Valley Creek cross-sections: a) D ₅₀ , b) primary mode, and c) number of modes.	41

Figures (continued)

	Page
Figure 25. Relationships between channel slope and D_{50} for Valley Creek: a) D_{50} vs cross-section water surface slope, b) D_{50} vs reach-average water surface slope, and c) water surface slope profile and D_{50}	42
Figure 26. Bank erosion locations for Valley Creek.	46
Figure 27. (a) Valley Creek longitudinal profile of bed, water surface, and banks (September 2003–May 2004) with study reach boundaries and geologic contacts. (b) Valley Creek longitudinal pattern of bank erosion from cross-section and bankline surveys (July 2004–2005) and longitudinal pattern of median bed particle size (2004 and 2005).	47
Figure 28. Relationship between suspended sediment (SED) concentration in mg/L and turbidity in NTUs for Valley Creek at the USGS stream gage between October 2005 and August 2006.	52
Figure 29. Scatter plot showing trends in the turbidity–discharge relationship for Valley Creek at the USGS stream gage.	53
Figure 30. Plot showing discharge and turbidity for a complex hydrograph in June 2006 for Valley Creek at the USGS stream gage.	53
Figure 31. Plot showing hysteresis loops for the two large hydrograph peaks shown in Figure 30.	55
Figure 32. Peak discharge versus sediment load for Valley Creek at the USGS stream gage for 36 storm events from July 25, 2005 through September 30, 2006.	55
Figure 33. Tracer gravel data for Valley Creek cross-section 11B: a) location of tracer gravels along cross-section, b) distance moved by tracer gravels, and c) particle size mobilized as a function of maximum discharge.	57

Tables

	Page
Table 1 (a) Bulk density estimates for streambed sediment obtained from Smith and Wheatcraft (1993); (b) Bulk density estimates for Valley Creek particle size distributions based on and interpolated from Smith and Wheatcraft (1993).	44
Table 2. Estimated mass of sediment stored in the streambed of Valley Creek in Valley Forge National Historical Park (summer 2004).	44
Table 3. Mass of deposition and scour of the streambed of Valley Creek within Valley Forge National Historical Park from the baseline survey in the summer of 2004 to the 3 rd storm event on April 2, 2005.	44
Table 4. Measured erosion from repeat bankline surveys of Valley Creek from the baseline survey in the summer of 2004 to the 3 rd storm event on April 2, 2005.	48
Table 5. Volume and mass of bank erosion for the 10 surveyed Valley Creek bankline locations in Valley Forge National Historical Park for the period July 2004–2005.	50
Table 6. Cumulative volume and mass of bank erosion estimated from field measurements along Valley Creek for the period July 2004–2005.	50
Table 7. Regional sediment yield comparisons with Valley Creek.	65

Appendices

	Page
Appendix A. Description of the 78 subdivisions of Valley Creek from the second channel characterization, completed May 2004 (see Figure 11).	81
Appendix B. Valley Creek longitudinal profile, September 2003 – May 2004.	89
Appendix C. Water surface and thalweg slopes for Valley Creek, September 2003–May 2004.	93
Appendix D. Flood frequency analysis using PEAKFQ from data at Valley Creek USGS stream gage at PA Turnpike.	95
Appendix E. Baseline and storm data from 36 cross-sections of Valley Creek (summer 2004 to summer 2005).	99
Appendix F. Valley Creek cross-section and reach analysis of change between the baseline survey in the summer of 2004 and the resurvey after the 2 nd storm of September 28, 2004.	171
Appendix G. Calculations for the amount of sediment stored in the Valley Creek streambed within Valley Forge National Historical Park, summer 2004.	175
Appendix H. Calculations for the change in mass of the streambed of Valley Creek from scour and deposition within Valley Forge National Historical Park between the baseline survey in the summer of 2004 to the 3 rd storm event on April 2, 2005.	177
Appendix I. Photographs from Valley Creek bank erosion locations identified in Figure 26.	179
Appendix J. Particle size distributions of bank material at the 10 Valley Creek bankline survey locations on June 30, 2005.	199
Appendix K. Tracer gravel data for Valley Creek cross-sections.	209
Appendix L. Statistical comparison of successive pebble counts.	227

Abstract

National Park Service managers have been concerned for several years about potential impacts of sediment associated with upstream urban development on the 3.7-km (2.3-mi) portion of Valley Creek that runs through Valley Forge National Historical Park (VAFO) upstream of its confluence with the Schuylkill River. A study was conducted between September 2003 and September 2006 to obtain baseline inventories and to monitor suspended sediment and the distribution of sediment storage, bank erosion, and channel instability. Field investigations included a total-station survey of the longitudinal profile of Valley Creek, cross-section and bankline surveys after significant storm events (including the second highest discharge on record for Valley Creek), pebble counts and volumetric barrel samples to measure particle size distribution of the streambed, and use of tracer gravels to determine the sediment particle sizes mobilized during storm events. Sediment load estimates were compiled using turbidity data collected at 15-minute intervals at the USGS Valley Creek stream gage between July 2005 and September 2006 and preliminary USGS unit flow value records for the same period. Estimated suspended sediment yield for the watershed for the 2006 water year was 41.4 metric tons/km²/yr—much lower than historical sediment yields from watersheds in areas of agricultural land use or in early phases of urban development, but comparable with an area of mixed development in suburban Maryland. Results of field surveys suggest that bank erosion may be a dominant source of sediment, but also indicate that fine sediment stored in and remobilized from the bed may be a significant fraction of annual sediment yield in Valley Creek.

Executive Summary

The 3.7-km (2.3-mi) reach of Valley Creek in Valley Forge National Historical Park (VAFO) is located in the downstream portion of Valley Creek watershed. Upstream of the park boundary Valley Creek watershed has been affected by rapid urbanization during the period between 1970 and the present, while land within the park remains relatively undeveloped. During storm events the stream turns muddy brown; this was originally believed to be the result of increased sediment flux resulting from the effects of urbanization in the watershed. VAFO professional staff expressed concern over the threat to the aesthetic and ecological value of Valley Creek, which has been designated as an Exceptional Value (EV) stream by the Commonwealth of Pennsylvania.

In order to address National Park Service (NPS) concerns, University of Maryland, Baltimore County, in cooperation with the NPS and the U. S. Geological Survey (USGS), conducted an investigation of sediment along the portion of Valley Creek within VAFO. The purpose was to assess the longitudinal patterns of bed sediment storage, bank erosion, and channel instability, as well as the patterns of change over the study period in relation to the sequence of flow events mobilizing sediment. Multiple components of the sediment budget were investigated, including bank erosion as a sediment source, the mass of fine sediment stored and remobilized from the streambed, and suspended sediment load passing the USGS stream gage on Valley Creek just upstream of the park boundary.

Field methods were developed and tested based on information collected as part of an extensive literature review. These methods include the survey of the longitudinal profile with a total station, repeat surveys of 36 channel cross-sections, and bankline surveys of 10 significant erosion locations. Particle size distributions of bed sediment at multiple locations along the stream were analyzed with grid-based pebble counts and volumetric barrel samples. Tracer gravels were used to determine the sediment particle size mobilized during several storm events. A sediment station was also installed at the USGS gage just upstream of the park boundary, consisting of a YSI turbidity optical sensor calibrated to suspended-sediment concentrations collected by an ISCO sampler. Field investigations began with a reconnaissance phase in July and September 2003; monitoring of channel bank and bed conditions was conducted primarily from June 2004 to August 2005. Turbidity and sediment concentration data were collected beginning in July 2005 and ending in September 2006. Suspended sediment load estimates for this period are based on turbidity and discharge records collected at 15-minute intervals. Statistical relationships between turbidity and discharge were used to estimate suspended sediment load for the period July 2004 to July 2005 for comparison with estimated loads derived from bank erosion and from remobilization of bed sediment during the period of field investigation.

Banklines were found to be high (averaging 3 m [9.8 ft] in height) in relation to the water surface from the confluence of Valley Creek with the Schuylkill River to the location of a covered bridge approximately 2 km (1.24 mi) upstream. By comparison, banklines were found to be lower in relation to the water surface from the covered bridge to the upstream boundary of the park at the Interstate 76 overpass, 1.7 km (1 mi) upstream of the covered bridge. High banklines in the downstream reaches are a result of historical land use along the channel, where the stream is

eroding legacy sediments that had been stored behind former dams. Between 1.3–2.0 km (0.8–1.24 mi) upstream, the channel is forced between two bedrock knobs known as Mount Misery and Mount Joy. This stretch of channel has moderately high banklines that have been extensively stabilized with anthropogenic structures, including riprap and concrete walls.

Bank height was found to have a major influence on the amount of scour and deposition along the channel. The average depth of scour and deposition was greatest in the downstream reaches. These reaches have high banks and the channel has limited connection to the floodplain. Channel gradient, and therefore the rate of energy expenditure, is also higher in the downstream reaches. Flow is constrained within the channel, generating scour as well as sediment deposition. In the middle and upstream reaches, a moderate amount of scour was observed, but virtually no deposition. These reaches have low banklines and a greater degree of channel connection with the floodplain. Little deposition occurs in the active channel; whereas, substantial volumes of sediment appear to have been deposited on the adjacent floodplain areas.

Streambank stability is also related to the longitudinal profile and planimetric form of the channel. The measured longitudinal profile illustrates elevation changes of the banklines, thalweg, and water surface (during low-flow conditions) with distance upstream. Half of the 10 erosion locations chosen for repeat bankline surveys were located along meander bends, which are areas of significant erosion due to steep velocity gradients and high shear stress along the outer bank. The 10 erosion locations also have larger particle sizes on the streambed than other locations that are not experiencing significant bank erosion. However, further surveys are recommended to verify this trend. The largest volume of bank erosion per unit length of the channel occurred in the downstream reaches. The lowest volumes of measured bank erosion per unit length of the channel occurred in the upstream reaches, where a smaller portion of the total discharge is retained within the banks at high flow.

The particle size distribution of the streambed was found to be related to the longitudinal profile. Larger particle sizes were found in the downstream reaches and appeared to be correlated with both geology and water surface gradient. The reaches furthest downstream had the most pronounced streambed coarsening over the study period. With distance upstream, the magnitude of coarsening decreased. It is likely that these trends, like those described above, are related in part to the role of bank height in either constraining flow within the channel at high stages or in allowing flow to spill out over the floodplain. High velocity flows winnow fines from the streambed. The upstream reaches have flatter gradients and lower velocity flows; where high flows are not constrained within the channel and fines are more likely to be deposited on the floodplain.

Sediment yield for Valley Creek watershed for the period October 1, 2005–September 30, 2006 was estimated to be $41.4 \text{ t/km}^2/\text{yr}$ from turbidity data collected with the YSI turbidity optical sensor and ISCO sampler installed at the USGS gage. This estimate is much lower than was initially expected based on preliminary examination of sediment data from other watersheds in the region. An estimation procedure to calculate a value of sediment yield for the period July 18, 2004–July 17, 2005 was used for comparison with field measurements of sediment derived from bank erosion and bed scour for the same period. The derived value of sediment yield was $78 \text{ t/km}^2/\text{yr}$. The mean streamflow for that period, $1.59 \text{ m}^3/\text{s}$ ($56 \text{ ft}^3/\text{s}$), was larger than the maximum value of annual mean streamflow ($1.50 \text{ m}^3/\text{s}$ [$53 \text{ ft}^3/\text{s}$]) for any water year (October 1–

September 30) in the 24-year gage record. If it is assumed that the relationship between sediment concentration and discharge observed during the study period is representative for the period 1983–2006, the median annual sediment yield can be inferred to be around 30 t/km²/yr and the maximum sediment yield approximated as 80 t/km²/yr.

Considering all components of the sediment budget, results of this study show that (1) the mass of sediment sand size (2 mm [0.078 in]) and finer stored in the 3.7 km (2.3 mi) of streambed within VAFO is about three times greater than the estimated median annual suspended sediment load, and the mass of sediment smaller than 0.075 mm (0.003 in) stored in the streambed is about 91% of the estimated median suspended sediment load; (2) the net mass of sediment sand size (2 mm [0.078 in]) and finer scoured from the streambed within VAFO over the survey period is about 35% of the suspended sediment load at the gage estimated for that same time period, and the net mass of scoured sediment finer than 0.075 mm (0.003 in) is between 11–12% of the suspended sediment load for that period; (3) bank erosion along Valley Creek within VAFO generated a mass of fine sediment (e.g. less than 0.075 mm [0.003 in]) equivalent to 55.7% of the estimated suspended sediment load for the same time period, and the mass derived from bank erosion including medium and coarse sand (<2 mm [0.078 in]) amounts to 76.3% of the estimated suspended sediment load; (4) because the period July 2004–July 2005 included so many large storms and had an average streamflow larger than the maximum value in the 24-year record at the Valley Creek gage, suspended sediment load, streambed scour, and bank erosion are all thought to have been much higher during the period July 2004–July 2005 than would be expected in most years, yet the masses of fine sediment stored in the streambed and derived from bank erosion are both of the same order of magnitude as the annual suspended sediment load; the net scour from the streambed is a smaller but still significant fraction of the annual total.

Two significant storm events occurred during the study period: a 10-year flood event on September 28, 2004 that produced the second-highest discharge on record, and a 5-year flood event on April 2, 2005. In response to these high-magnitude events, net scour and general coarsening of the streambed occurred. Large portions of the bank were also eroded. It is possible that the channel response of Valley Creek to the two significant storm events during the study period is only temporary. Resurveys over a series of years in Valley Creek would be beneficial in determining the long-term effects of relatively frequent events. Monitoring of changes in the bed and banks of Valley Creek has provided insight into the dynamic response of the channel to the flow regime and the influx of sediment.

This research has important implications for management of the Valley Creek watershed. The implementation of continued monitoring of suspended sediment, banklines, and cross-sections is recommended. Continued monitoring will provide insight into the total sediment yield of the watershed. Resurveys of banklines with varying rates of erosion and over varying flow conditions will provide a better indication of the bank erosion component of the total sediment yield. Cross-section resurveys will also provide more insight to the channel response over a longer timeframe and more frequent flow events than were captured in this study.

Acknowledgments

Partial support of this project was provided by National Park Service under Task Agreement J3097-03-800 to Cooperative Agreement 309701200. Financial support for all new equipment used in the project and C. Welty's time were provided by the U.S. Environmental Protection Agency (USEPA) under grants R-82818201-0 and CR83105801 and NOAA grant NA06OAR4310243. Support for L. Fraley was also provided in part by USEPA grant CR83105801. Support of A. J. Miller's academic-year time was provided by the University of Maryland, Baltimore County (UMBC). The authors are grateful to Robert J. Ryan for his participation in many aspects of this project and, in particular, for his advice on sediment measurement techniques and overall knowledge of Valley Creek watershed. Completion of this project was made possible with the help of numerous students and volunteers to assist with field work—we thank Jane Diehl, Matt Ballantine, Matt Young, Luanne Steffy, Hyun Jin Kim, Christy Laudadio, and Jeffrey McNeal for their efforts. Allen Gellis (USGS, MD-DE-DC) and Mike Langland (USGS, PA) provided valuable assistance on installation of the sediment monitoring station. Allan Ruddy (USGS, PA) helped install the sediment monitoring equipment and maintain it on a regular basis. Alan Ellsworth provided guidance as the NPS Regional Hydrologist having oversight of the project. We thank Margaret Carfioli of VAFO for assistance with all logistical aspects of carrying out the project in the park, including housing and lab space provided onsite by VAFO. We dedicate this report in memory of Brian Lambert, NPS Natural Resource Specialist with VAFO, who had the vision and perseverance to bring this project to fruition.

Introduction

This study was conducted in order to assess sediment conditions along Valley Creek in Valley Forge National Historical Park (VAFO), located approximately 30 km (18.6 mi) west of Philadelphia, PA (Figures 1 and 2). The mission of VAFO, as defined by the park's enabling legislation (PL94-337) and the park's Strategic Plan, is to tell the story of the 1777–1778 encampment of the Continental Army and to preserve encampment-related resources. VAFO's Statement for Management, General Management Plan (GMP), and Cultural Landscape Report (draft) identify Valley Creek as an important cultural resource critical to the interpretation of the encampment. The Pennsylvania Fish and Boat Commission (PFBC) has classified the creek as a Class A wild trout fishery and has designated it as an Exceptional Value Waterway, the state's highest and most protective category. Managing Valley Creek has always been a high priority for park resource specialists. VAFO's Resource Management Plan contains 12 project statements directly related to monitoring and protecting the creek. Managing Valley Creek as a natural system set in a cultural landscape is a stated park management objective in the GMP.

Sediment has been identified by the PFBC and the Pennsylvania Department of Environmental Protection (PADEP) as the single, most detrimental pollutant in the streams of Pennsylvania. Valley Creek flows through a suburban watershed with extensive commercial construction and residential development. Valley Forge is at the downstream end of the watershed and the reach of Valley Creek within VAFO is affected by stormwater and sediment derived from developed areas upstream of the park.

Observations by National Park Service (NPS) personnel in recent years have raised concerns about whether sediment accumulation on or in the bed could affect benthic invertebrate populations as well as fish habitat and spawning. In addition, several locations along the Valley Creek channel are unstable and experiencing rapid bank erosion. These issues have been referenced in several previous reports (Reed 1981; Sloto 1988; Gutowski and Stauffer 1996; CCWRA et al. 2004).

In response to these concerns, the NPS requested and funded a study to establish baseline information about sedimentation and erosion in Valley Creek. The research questions listed below were formulated after initial reconnaissance of the Valley Creek channel within VAFO in summer 2003.

- (1) What are the volumes and rates of sediment accumulation and scour on the bed of Valley Creek within the park? What are the grain size distributions of the sediment deposits? How do natural geologic controls and anthropogenic controls (such as dams, bridges, etc.) affect the spatial pattern of sediment storage along Valley Creek within VAFO? How do flow events of different magnitudes affect the pattern of storage?
- (2) What is the spatial distribution of bank erosion rates and patterns of bank instability along Valley Creek within the park and how much sediment is derived from bank erosion?

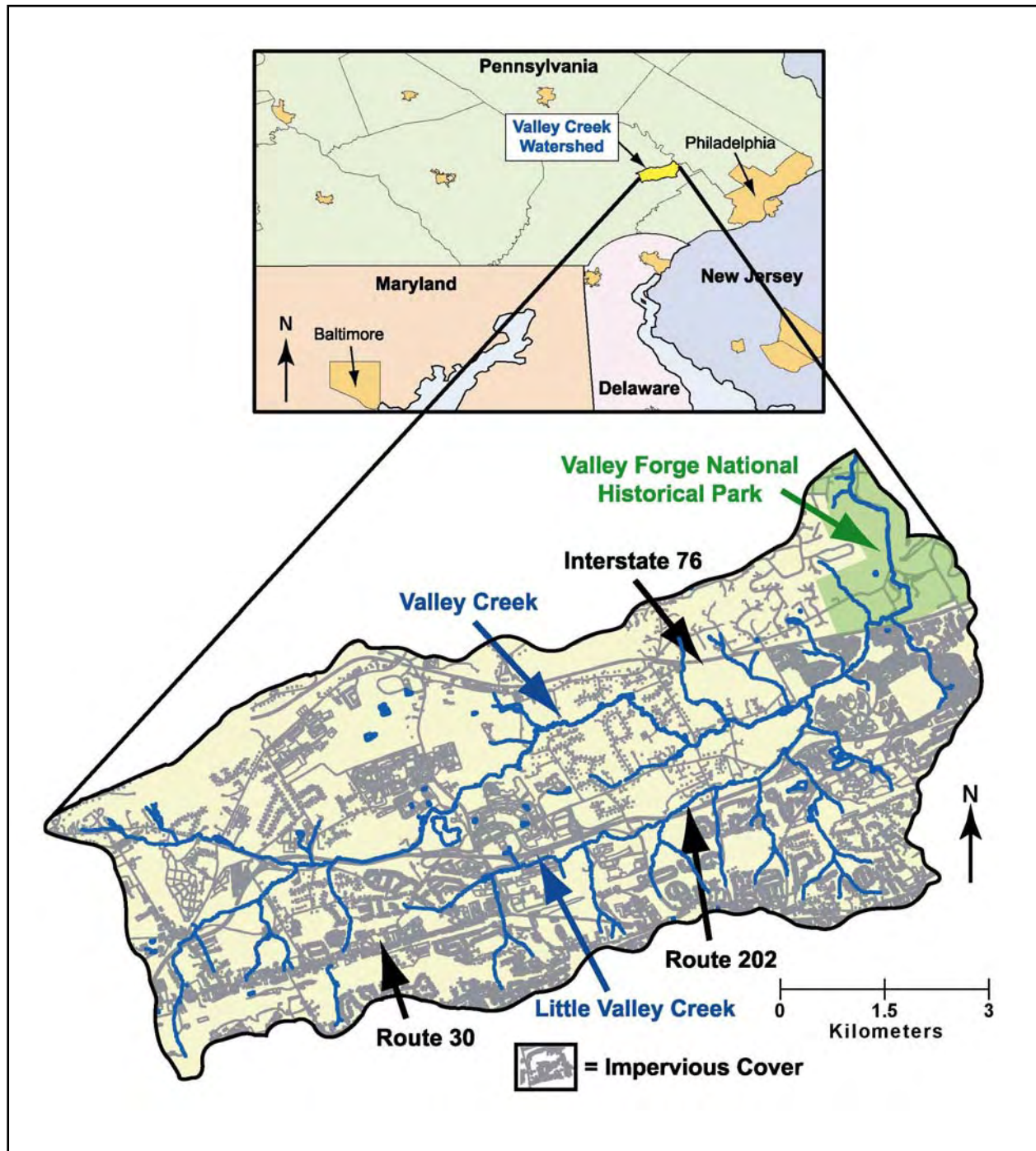


Figure 1. Location map for Valley Creek watershed.

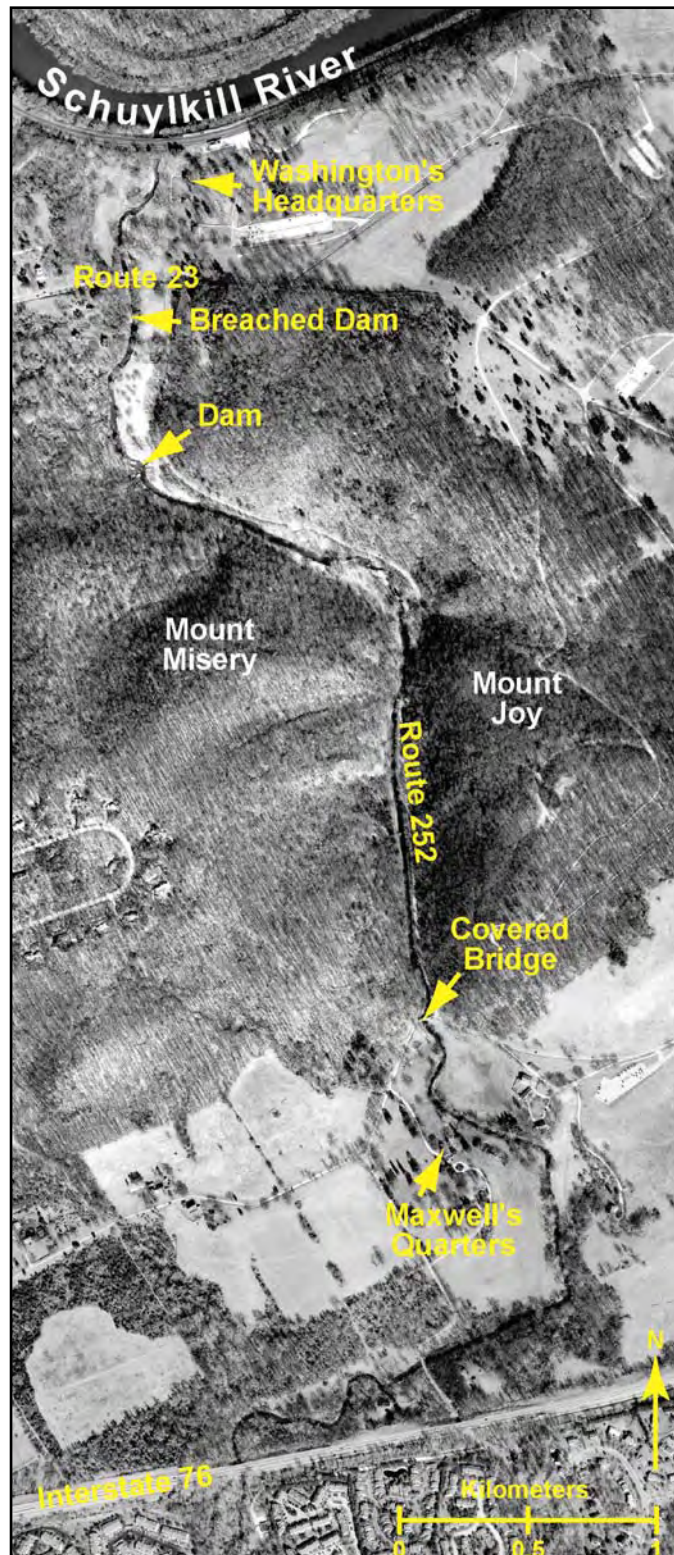


Figure 2. Aerial photograph of the 3.7-km (2.3-mi) portion of Valley Creek that runs through Valley Forge National Historical Park.

(3) Within the budget constraints of this project and technical limitations of available measurement techniques, what approximations can be made for estimating transport rates of sediment in Valley Creek at the VAFO upstream boundary? What is the relative importance of bank erosion and bed storage and remobilization as compared to upstream sediment sources?

(4) What are low-cost methodologies that can be used by VAFO personnel that would allow them to easily continue to monitor changes in erosion, deposition, and grain-size distributions in Valley Creek within the park over time?

(5) What management recommendations can be provided that could aid VAFO in addressing any negative impacts of the sediment load on Valley Creek?

A program of field measurements was developed in order to address these questions. The elements of this study involved: (1) survey of a detailed longitudinal profile of Valley Creek within VAFO, including thalweg, water surface, and left and right banks; (2) identification of sites with visible evidence of channel instability and repeat bankline surveys at selected sites to calculate erosion rates and associated volume and mass of sediment mobilized; (3) baseline and repeat surveys of 36 monumented channel cross-sections within VAFO to quantify changes in the channel bed; (4) repeat measurements of the particle size distribution of bed sediment in the immediate vicinity of each of the monumented cross-sections to quantify the relative amounts of sediment stored in the bed in different size ranges and to track changes in particle size distribution over time; and (5) monitoring of turbidity as a surrogate for a continuous record of sediment concentration at the USGS stream gage immediately upstream of the park boundary in order to estimate the sediment load entering VAFO from the upstream watershed.

Study Area

Valley Creek is a third-order stream that is tributary to the Schuylkill River about 32 km (20 mi) west of Philadelphia, PA within the Delaware River Basin (Figure 1). The creek drains a 60.6-km² (37.65-mi²) area, including portions of seven municipalities within Chester and Montgomery counties. The watershed includes an estimated 55 km (34 mi) of streams, with Valley Creek and Little Valley Creek (tributary) as the main water courses. Segments of Interstate 76, Route 202 (a multi-lane highway), and Route 30 (a multi-lane major arterial road) cross the watershed.

Geology, Geomorphology, and Land Use

The valley of the watershed consists principally of carbonate rocks and is flanked by hills of less erodible crystalline rock. The stream headwaters emanate from the North and South Hills and the main branches of the stream flow through the carbonate rocks that comprise the central valley. The North Hills are composed of non-carbonate rocks including the Stockton Formation (sandstone), the Chickies Formation (quartzite and quartz schist), and the Harpers (phyllite and schist with quartzite) and Antietam (quartzite and quartz schist) Formations; the Octoraro Formation (albite chlorite schist, typically a phyllite) comprises the South Hills. Carbonate rocks of the valley (limestones and dolomites) make up the largest portion of the geologic formations within the watershed and include the Ledger (coarsely crystalline dolomite and partly siliceous), the Elbrook (siliceous limestone with beds of dolomite in between), the Conestoga (impure limestone containing shale pieces) with small areas of Kinzers (limestone containing shale), and the Vintage (dolomite with marble at its base) scattered on the western side of the watershed (Bascom and Stose 1938; CCPC 1973). Longitudinal faults have been mapped in the western half of the watershed where the Ledger and Chickies Formations meet, as well as where the Ledger and the Elbrook Formations meet. A cross-fault is oriented perpendicular to the faults that are aligned longitudinally along the outcrop areas of the Kinzers, Ledger, Elbrook, and Conestoga Formations. The formations range in age from the youngest Stockton (Triassic) to oldest Chickies (Late and Middle Proterozoic) with the remainder belonging to the Cambrian Era. A geologic map of Valley Creek watershed is shown in Figure 3.

The stream has an average channel slope of 1.2% and is dominated by cobbles and gravel, with patchy deposits of sand and silt. Exposed bedrock is present in some sections of the channel (Gutowski and Stauffer 1996). Over 75% of the entire length of Valley Creek is characterized as either runs or riffles. Within VAFO, near the covered bridge by Maxwell's Quarters (Figure 2), the channel changes substantially. The land bordering the channel is relatively flat upstream of the bridge; however, downstream of the bridge, the stream is forced into a narrow gorge between two bedrock knobs known locally as Mount Misery and Mount Joy (Figure 2). Despite this change in terrain, the longitudinal profile of the channel does not show a significant slope break at the covered bridge. Several silted-up mill ponds once existed along this stretch. The remnant "legacy" sediments of these ponds form the existing high streambanks, which are unstable and easily eroded (Gutowski and Stauffer 1996).

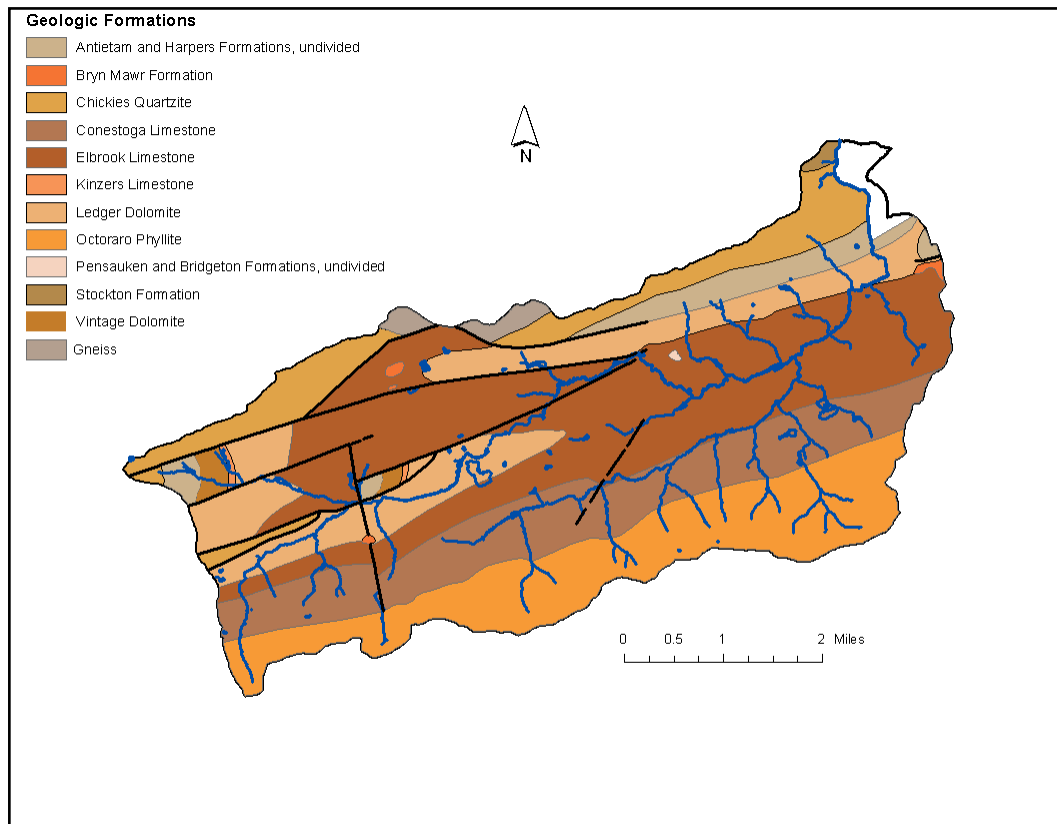


Figure 3. Valley Creek geology (from McGinty [2003], based on Bascom and Stose [1938] and CCPC [1973]).

The plan form of the channel is nearly straight along most of the downstream two-thirds of the study area. The gorge is almost perfectly straight and the alignment of the channel is dominated by bedrock control; the channel downstream of the gorge is flanked by an alluvial valley with several open meanders that are closely aligned with the valley walls. These features are visible in Figure 2. Upstream of the covered bridge the channel alternates between moderately sinuous meandering reaches and a straight reach with a single sharp bend; the straight portions of the channel are aligned either with regional strike or joint patterns.

VAFO is located in the Piedmont physiographic province. Prior to European settlement, the Piedmont was heavily forested. Sediment loads supplied to the streams through physical erosion were relatively small due to thick soils and absorbent forest litter that reduced overland flow to negligible amounts. During the first hundred years of settlement on the Piedmont, virgin forests were transformed to cleared land, and then to abandoned fields that supported second-growth forests. However, only the best land was kept in cultivation and sediment supplies were increased only moderately above natural background levels that occurred when the land was forested (Jacobson and Coleman 1986).

Since the mid-1800s, land use has transitioned from agriculture to scrub wood lots to suburban growth areas. Figure 4 illustrates progressive urbanization that can be seen in 1946, 1980 and 2000 aerial photographs of Valley Creek watershed upstream of Interstate 76, the southern boundary to VAFO. Current land use in the Valley Creek watershed includes dense urban development along the Route 30 corridor, scattered suburban, commercial, and industrial development, and major limestone quarry operations (CCWRA et al. 2004). These land-use transitions have changed the natural flow regime of Valley Creek, resulting in sediment transport and channel morphology alterations (Reed 1991). Areas such as parking lots, roads, and roofs account for the current 18% impervious land-cover condition and allow precipitation to flow quickly into the stream.

Climate and Hydrology

The average annual rainfall is 104.5 cm (41.1 in) at Philadelphia, PA based on 133 years of record (NCDC 2005). A USGS stream gage (01473169, Valley Creek at PA Turnpike Bridge near Valley Forge, PA) has operated from October 1982–present (USGS 2005). The average annual discharge between the 1983 and 2004 water years was $0.9 \text{ m}^3/\text{s}$ ($31 \text{ ft}^3/\text{s}$) (USGS 2004). Figure 5, generated from the USGS annual maximum stream flow at the Valley Creek gage, shows a gradually increasing trend in peak annual streamflow from the 1983 to 2004 water years. The trendline, based on a linear regression of annual maximum discharge against water year (excluding the 1999 peak due to Hurricane Floyd), suggests that the expected annual peak discharge has increased by approximately 100% over the 20-year record.

The observed increase in magnitude of annual flood peaks has occurred at the same time as significant commercial and residential development and accompanying increase in impervious surface area (Reed 1991). As an area undergoes urbanization, the runoff volume and peak discharge of streams generally increase (Wolman 1967). The USGS, in cooperation with Chester County Water Resources Authority (CCWRA), previously conducted a study to determine the effect of urbanization on the runoff volume and peak discharge of Valley Creek (Sloto 1988). The basin's current value of 18% impervious land cover implies that runoff volume for precipitation depths equivalent to those modeled by Sloto has increased between 12–27%, while peak discharge has increased between 13–27% of its 1988 value (Sloto 1988). Although it is commonly recognized that urban development tends to alter watershed hydrology in ways that cause increases in peak discharge (Hammer 1972; Dunne and Leopold 1978), the peak flow data for urbanizing watersheds do not always provide such a clear signal as that shown by Figure 5. From 2000–2020 an 8% increase in residential population growth is projected for the Valley Creek watershed; this raises concerns about additional stormwater and pollutant runoff problems and increasing flooding (CCWRA et al. 2004).

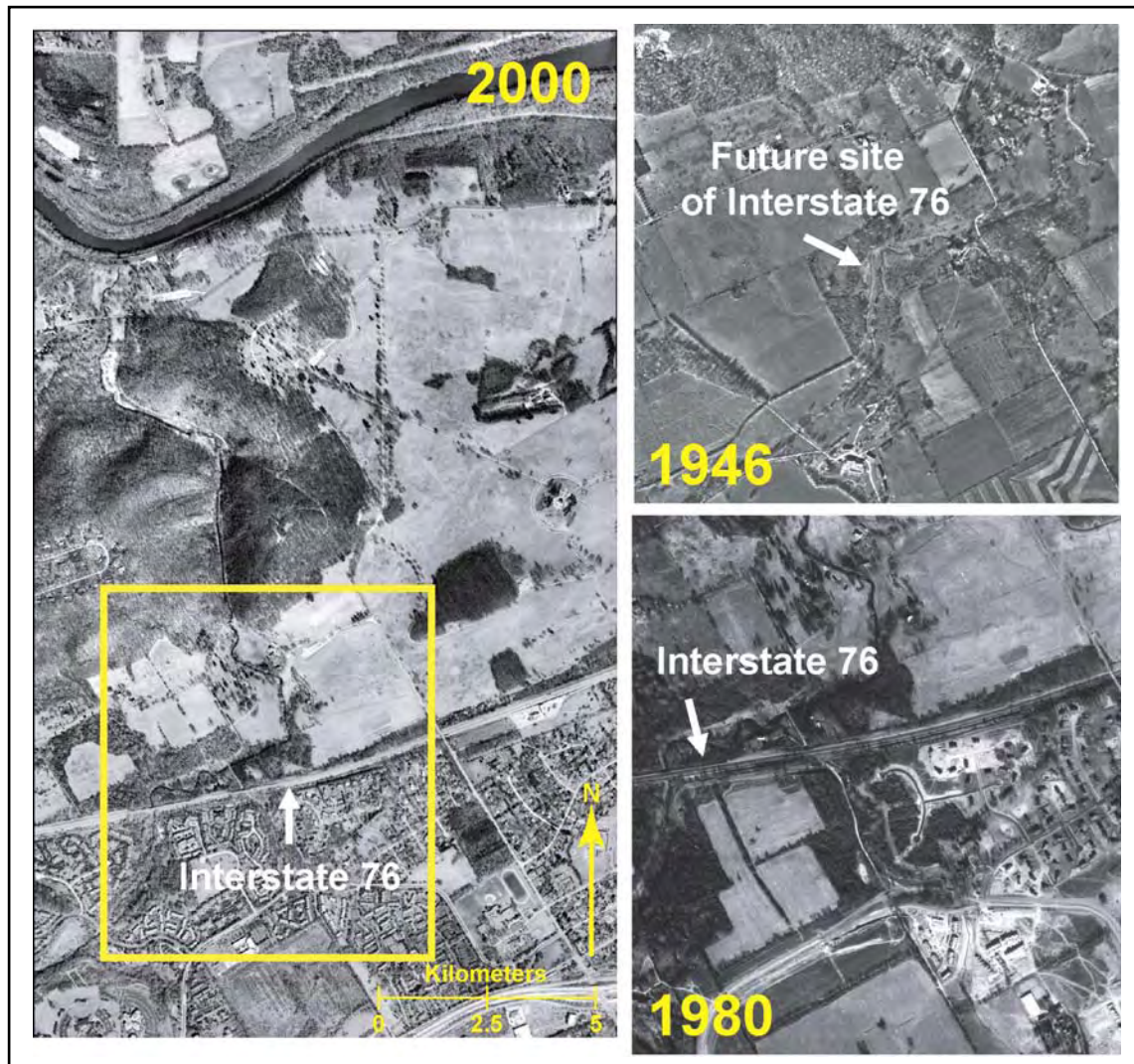


Figure 4. Progressive urbanization in Valley Creek watershed. The 1946 and 1980 photos show development in the watershed upstream of Interstate 76, the southern boundary to Valley Forge National Historical Park.

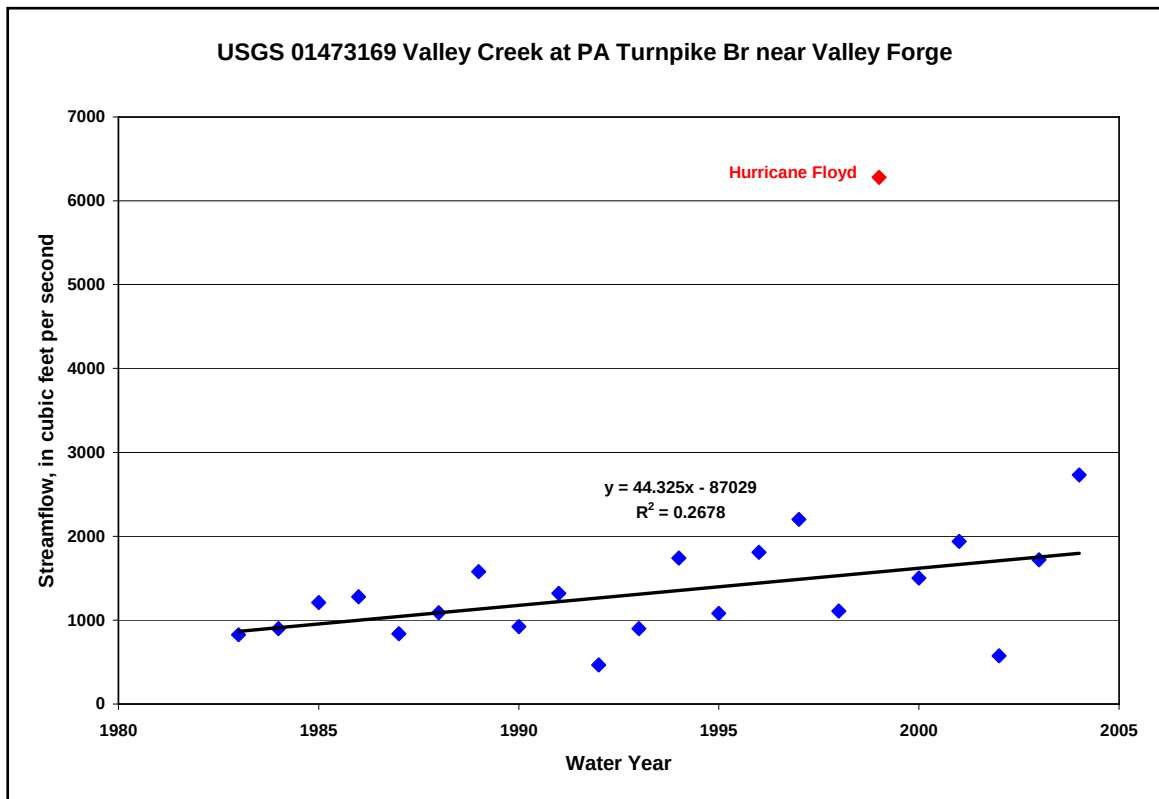


Figure 5. Valley Creek annual peak streamflow at the USGS gage located just upstream of the Interstate 76 overpass.

Methods

The methods used in field investigations for this project included: (1) field survey of a longitudinal profile; (2) channel cross-section and bankline analysis; (3) installation and monitoring of scour chains as indicators of bed mobility; (4) measurement of channel bed particle size distributions; (5) turbidity measurement and estimation of suspended sediment load; and (6) emplacement and short-term monitoring of tracer gravels. In order to select representative field sites and assess the spatial pattern of sediment distribution in the channel, it was first necessary to conduct field reconnaissance and use the resulting observations to subdivide the channel for sampling purposes. Observations included qualitative descriptions of planform, geology, flow, riparian land cover, channel bed characteristics, and anthropogenic features (dams, bridges, culverts, etc.). Locations of bank instability were documented based on visual observation of bank failures. Initial subdivision of the channel was based on the flow regime (riffles, pools, runs, and glides), as well as locations of significant sediment accumulation. This scheme was then simplified to create a set of 12 reaches for sampling purposes. Areas with similar flow regimes, channel morphology, and sediment storage characteristics were grouped together. Some reaches were dynamic and included sites where hydraulic conditions in the channel have led to alternating storage and remobilization of significant deposits of sediment. Others tended to have simpler morphology and a greater tendency for sediment to move through without forming substantial accumulations; they were, therefore, more stable in form.

Longitudinal Profile

A Sokkia SET510 total station was used to survey elevations approximately every 2 m (6.5 ft) along the water's edge, the thalweg, and the top of the left and right banks of the 3.7-km (2.3-mi) portion of Valley Creek within VAFO. This detailed survey was carried out between September 2003 and May 2004. Reference point coordinates were obtained from a 2000 orthophoto (CCPC [<http://dsf.chesco.org/planning>]), which was projected in the state plane coordinate system. All elevation measurements were referenced to an arbitrary zero point based on the thalweg depth on the upstream side of a railroad bridge just downstream of the location of Washington's Headquarters (Figure 2), near the confluence with the Schuylkill River. All elevation and distance measurements were converted from feet to meters and plotted together. The longitudinal profile was measured from the railroad bridge to the USGS gage, just upstream of the Interstate 76 overpass. Superimposed geologic information was obtained from the PADEP as a GIS shapefile.

Cross-section Analysis

In each of the 12 designated sampling reaches, three representative locations were chosen for cross-section installation. The cross-sections were positioned perpendicular to the direction of flow. Pieces of 0.6-m (2-ft) tagged rebar were installed on the left and right streambanks to monument the endpoints. The rebar monuments were hammered flush to the ground to minimize vandalism. The total station was then used to survey channel elevations between the endpoints at approximately 0.3-m (1-ft) intervals, as well as locations along the cross-section where

significant breaks in streambed elevation occurred. Cross-section installation and baseline surveys were conducted from June to August 2004.

Resurveys were used to monitor changing channel-bed elevations and bankline locations. Rebar monuments were relocated using a Schonstedt GA-52Cx magnetic locator. Survey protocol called for resurveys either at the end of a year or after large floods thought to be capable of causing substantial changes in the bed and banks. A series of three storm events with estimated recurrence intervals of about two years occurred through July and the beginning of August 2004. A July 12, 2004 storm produced a peak discharge of $33 \text{ m}^3/\text{s}$ ($1,160 \text{ ft}^3/\text{s}$); a July 28, 2004 storm produced a peak discharge of $39 \text{ m}^3/\text{s}$ ($1,370 \text{ ft}^3/\text{s}$); and an August 8, 2004 storm produced a peak discharge of $39 \text{ m}^3/\text{s}$ ($1,360 \text{ ft}^3/\text{s}$). After this series of storm events a reconnaissance study to assess evidence of channel change was completed during August 4–6, 2004 along Valley Creek. Only those cross-sections that visually appeared to have changed were resurveyed due to time constraints on finishing the remainder of the planned summer fieldwork. On September 28, 2004 (referred to as Storm 2 in Results section) a storm event with an estimated recurrence interval of 10 years occurred, producing a discharge peak of $78 \text{ m}^3/\text{s}$ ($2,740 \text{ ft}^3/\text{s}$), the second-highest discharge on record for Valley Creek. All cross-sections were resurveyed after this storm event between October 3, 2004 and December 4, 2004, except for six that were in locations too deep to survey in chest waders. Most of these locations were in the pool behind the dam and required use of a raft to transport the surveyors and carry out the survey across the channel. Due to time and personnel constraints these locations were not surveyed again until after April 2, 2005 (referred to as Storm 3 in Results section), when another significant storm event occurred producing a discharge of $58 \text{ m}^3/\text{s}$ ($2,060 \text{ ft}^3/\text{s}$) with an estimated recurrence interval of 5 years. After this event all cross-sections were resurveyed between April 9, 2005 and June 9, 2005. The resulting dataset, combined with information on flow conditions, shows changes in sediment accumulation, scour of the channel bed, and bankline changes. Because there were so many large flow events during the study period (including the second-largest flood on record), the data collected provide clear evidence concerning the relative mobility of the bed under high-flow conditions.

In order to quantify the amount of cross-section change, the areas of deposition and scour on the bed and the amount of change in the channel banks were measured between the baseline survey and subsequent storm events. Figure 6 shows the basis for these calculations. After calculating all of the trapezoid and triangle areas, those that represented scour were added together, and those representing deposition were added together separately to obtain total areas for scour and deposition. Net changes on each cross-section were found by subtracting the total area of scour from the total area of deposition.

Although cross-section measurements were referenced to monuments on the bank, the area of change from the baseline survey was calculated separately for the bed and banks. Changes on the bed were calculated between the left and right edge of water at low flow. Bank erosion was calculated based on areas of change above the waterline. An additional set of surveys was conducted to measure changes in the planimetric location of the top and bottom banklines at selected sites identified as potentially unstable based on field reconnaissance.

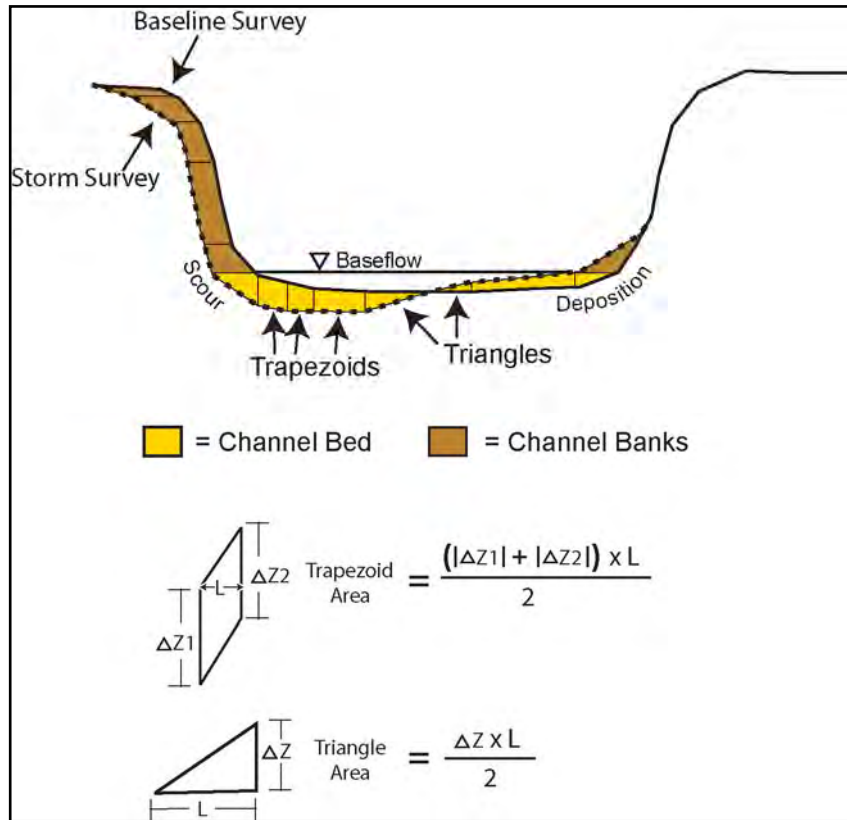


Figure 6. Calculations for determining the area of change in a cross-section.

Bankline Analysis

Thirty-eight locations of bank instability were documented during the channel characterization process (Figure 6) and a subset of 10 locations that showed the most evidence of severe bank erosion was chosen for monitoring. The total station was used to survey bank tops and bottoms of these locations at approximately 0.3-m (1-ft) intervals. Baseline surveys were conducted between June 30, 2004 and July 2, 2004. As with the cross-sectional resurveys, these detailed bankline surveys were conducted after significant storm events. After the events that occurred through July and the beginning of August 2004, only those banklines that appeared to have changed were resurveyed from August 4–6, 2004. All banklines were resurveyed after each of the two larger events in September 2004 (resurveyed between October 3, 2004 and December 4, 2004) and April 2005 (resurveyed between April 16, 2005 and June 3, 2005).

The collected data provide estimates of bank erosion over time that can be compared with the flow and antecedent bank conditions that generated the change. Analysis of the data was carried out in ArcMap 9 and results were calculated in Microsoft Excel. Survey points for the bank tops and bottoms taken after each of the storm events were plotted in ArcMap on the 2000 orthophoto. The area of top bank change and bottom bank change was then found by drawing a polygon connecting the surveyed banklines from one storm event to the next. This area was

divided by the surveyed length of bank to get the average lateral distance of bank retreat between storm events.

The resulting data were used in combination with data from cross-section resurveys to estimate sediment influx to the fluvial system due to bank instability (see Results chapter for details on the calculated volumes and masses derived from these two information sources). For the bankline survey sites, the net volume of sediment eroded from the streambank was calculated using information on the average rate of top and bottom bank retreat, multiplied by average bank height. Figure 7 shows the basis for this calculation. To obtain the mass of sediment eroded from the banks, a soil bulk density was used as a conversion factor. Moist bulk density values were obtained from the Natural Resources Conservation Service and the Penn State Geospatial Technology Program for soils constituting the streambanks of Valley Creek (NRCS and Penn State 2005). The moist bulk density is the weight of soil (oven dried) per unit volume of the soil at field-moisture capacity and is expressed in grams per cubic centimeter.

At each of the 10 erosion locations a sample of the bank material was collected and returned to the lab for sieving. A hand shovel was used to scrape a consistent volume of material from the bank top to the bank bottom. The material was then wet sieved in the lab, oven dried, and weighed based on 3.2 cm (1.26 in), 1.0 cm (0.4 in), 2.0 mm (0.08 in), 75 μm (0.003 in), 63 μm (0.0025 in), and 0.45 μm (0.0017 in) sieve size classes. The resulting data were tabulated and used to generate histograms of the particle size distribution of bank material at each of the erosion locations. The proportion of silt and clay in relation to larger particle sizes affects cohesiveness of the bank material, which increases resistance to bank erosion.

The calculated mass of sediment derived from analysis of the repeat surveys can be used as an estimate of the annual bank erosion contribution of sediment to the channel of Valley Creek within VAFO. Because there were so many high-flow events during this time period, it is likely that the volume of bank erosion was higher than would occur during a typical year.

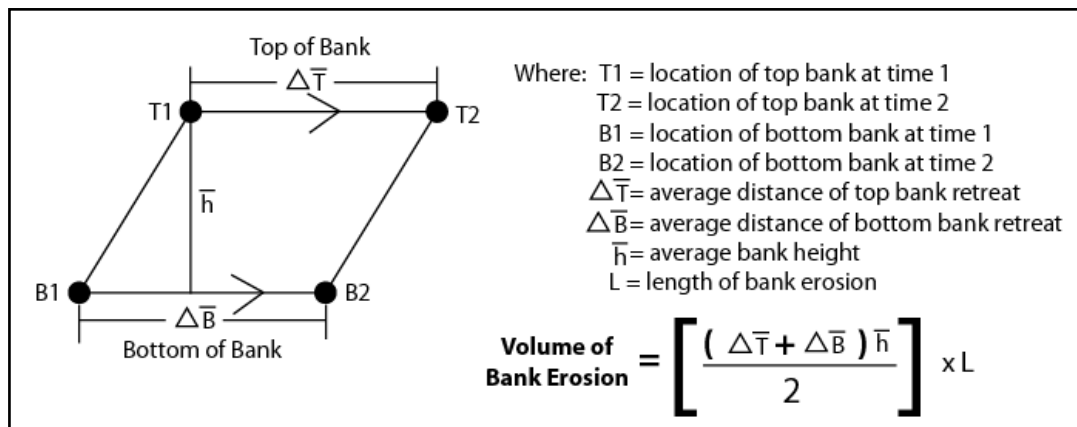


Figure 7. Calculation for the volume of bank erosion based on surveys of bank tops and bottoms after significant storm events.

Depth of the Mobile Layer

The depth of the mobile layer is the depth of sediment which is loose enough to be mobilized by the flow and was measured to supplement the cross-section elevation data by installation of scour chains. The scour chains were installed as follows. An AMS slide hammer with 0.9-m (3-ft) molybdenum extension and rock breaker attachment was used to insert lengths of chain vertically into the streambed. A 0.9-m (3-ft) length of galvanized steel chain, consisting of approximately 22 oval chain links measuring 4.1×1.3 cm (1.6×0.5 in) each was cut from a supply purchased at a local hardware store. A “quick link” was attached to the end of a length of chain to be inserted because the tip of the rock breaker attachment fit snugly into the quick link. The assembly was then placed onto the streambed surface and pounded vertically to the maximum attainable depth. When the chain could not be inserted any further, the slide hammer was pounded up from the streambed, leaving the chain vertically installed. The number of chain links lying over the bed surface was counted and the last link was marked with a fluorescent piece of flagging tape for relocation purposes. Monitoring occurred after significant storm events, as well as after specified time intervals. Upon relocating the chains, the number of links lying over the bed surface was recorded, in addition to the depth of deposition covering the chain. The difference between the length of the chain lying over the original bed surface and the length lying over the final bed surface was used to determine the maximum scour depth.

Chains were installed in cross-sections that were wadeable and where the slide hammer could be inserted to a depth of approximately 0.3 m (1 ft) or greater. Installation to depths less than 0.3 m (1 ft) would have allowed the chains to be easily pulled from the streambed by large storm events or vandalism. The number of chains along these cross-sections varied depending on the bed material and the depth to which the slide hammer could be inserted. Data from the scour chains were used to supplement repeated cross-section surveys.

Particle Size Distributions

Surface Samples

Wolman pebble counts (Wolman 1954) were conducted along all cross-sections where the water depth was shallow enough to allow sampling. A design by Bunte and Abt (2001) was used to create a grid-based approach to the pebble count (Figure 8). The use of a grid to select particles prevents operator bias.

The sampling frame used for the grid was constructed of four aluminum bars, each 0.9 m (3 ft) in length. Four large rubber bands were placed across the frame, creating a grid where the rubber bands intersected in four locations. The resulting grid allowed particles to be selected 0.5 m (1.5 ft) apart at the rubber band intersections. The spacing of grid points was larger than the $D_{\max}$ particle size in most cross-sections to avoid double counting any individual particle in the sampling process.

Two hundred particles were selected and diameters measured in the reach immediately upstream and downstream of each sampled cross-section. The sample size of 200 was determined as a representative particle size distribution based on a preliminary in-depth analysis of a sample

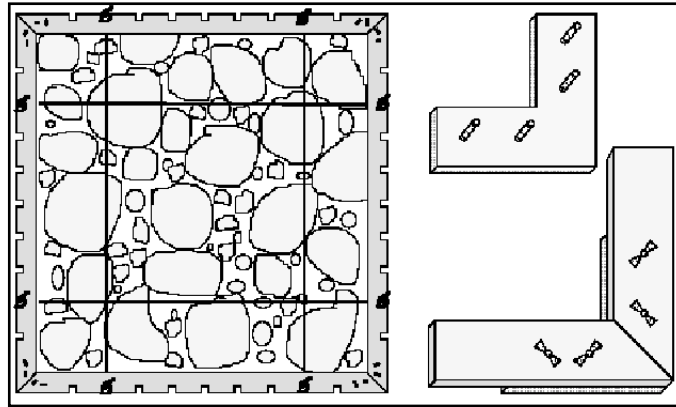


Figure 8. Four-piece sampling frame with an adjustable grid of elastic bands (left). Detail of the corner piece with mounted threaded pins is shown and the joining using corner pieces and wing nuts (right) (Bunte and Abt 2001).

containing 1,113 particles (see Bunte and Abt 2001). A comparison of the cumulative particle size distributions for the 1,113 particle pilot study and a randomly selected subset of 200 particles from the same sample illustrates that the distributions follow the same general trend (Figure 9).

Measurements were made by first placing the sample frame onto the streambed. The particle directly under each rubberband intersection was picked up and its intermediate axis was measured with a gravelometer, an aluminum frame with square holes at half-phi intervals used to measure the sizes of clasts selected from the streambed (Bunte and Abt 2001). After each of the four measurements from the grid intersections was recorded, the sample frame was flipped to the next location, following a transect straight across the channel. Rubberband placement on the sampling frame was such that the frame could be continuously flipped, resulting in a grid sample measuring particles every 0.5 m (1.5 ft), both across the channel and in the longitudinal direction.

The data were analyzed to generate particle size distributions and histograms for each measured cross-section, representing grain sizes found in the channel armor layer. Size classes were first established based on half phi-unit intervals. The number of particles in each size class was counted and subsequently expressed as the percentage of the total number of particles sampled. The number of particles in each size class was plotted to obtain a histogram. To generate the cumulative distribution, the percentage of each size class was added to the percentages of all the smaller size classes. The cumulative percentage was plotted against particle size to obtain the cumulative distribution.

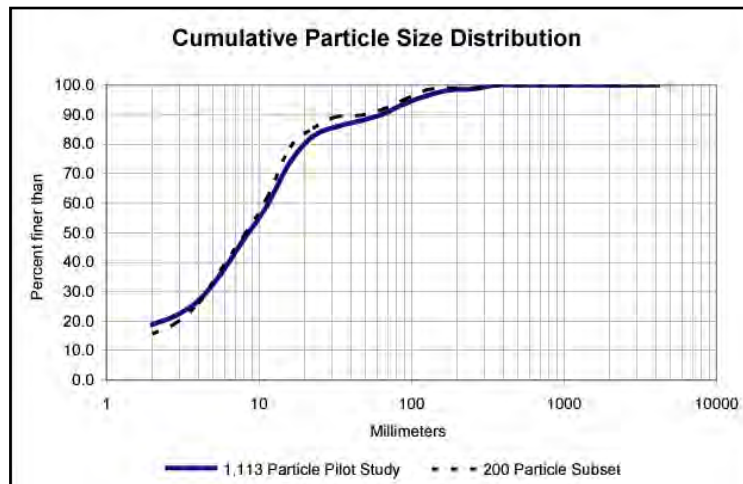


Figure 9. Cumulative particle size distribution showing the 1,113 particle pilot study and a randomly selected 200 particle subset.

Volumetric Samples

A second method for obtaining grain-size distributions was based on a design by Parker and Klingeman (1982) and involves volumetric sampling. A 0.2 m³ (55 gal) steel drum was cut in half and fitted with handles. It was then wedged into the streambed to a depth of approximately 5 cm (2 in). All the sediment within the barrel was scooped out with a small hand shovel. Scooping out the sediment leaves fine particles suspended in the water column within the barrel. A 125-ml (4.2-oz) sample was taken from the water in the barrel after it was thoroughly mixed. The water depth of the barrel was measured after sampling to be used in extrapolating the amount of fine sediment in the 125-ml (4.2-oz) aliquot to the volume of water contained within the barrel.

Five of these measurements were taken across each cross-section that was shallow enough to allow for sampling. The five bed samples were mixed together to form a single sample. After the samples were thoroughly mixed, 1/5 of the sediment scooped from the barrel was returned to the lab. The five 125-ml (4.2-oz) aliquots were also mixed together, and one 125-ml (4.2-oz) aliquot was taken from the combined sample. In the lab, the sediment was sieved, oven dried, and weighed based on 3.2 cm (1.26 in), 1.0 cm (0.4 in), 2.0 mm (0.08 in), 75 µm (0.003 in), 63 µm (0.0025 in), and 0.45 µm (0.0017 in) sieve size classes. The resulting data were used to generate cumulative particle-size distributions and histograms for the measured cross-sections. The barrel sampler provided a volumetric measurement of the surface layer of sediment; however, it is not directly comparable to the pebble count data because, when collecting the samples from the barrel, some of the subsurface sediment could also have been collected. Separating the surface and subsurface layers was based on the operator's perception. By taking a volumetric sample, it was more likely that fine material would be captured than would be measured with the pebble count; therefore, the barrel samples allowed a more accurate estimate

of the amount of fine sediment in the matrix, especially fine gravel and smaller sizes. Conversely, the pebble counts provide a more accurate subdivision of the coarse particle size ranges.

Sediment Transport

Suspended Sediment

Turbidity measurement was used as a practical method of obtaining a continuous record of suspended sediment data. A sediment station was installed as a cooperative effort between UMBC, USGS PA and MD-DE-DC Water Science Centers, and the NPS in July 2005 at the USGS stream gage (01473169 Valley Creek at PA Turnpike Bridge near Valley Forge). The station consisted of a YSI 6136 turbidity optical sensor combined with a YSI 600 OMS sonde placed in the stream at the gaging location. The probe was housed within a permeable hard casing for protection. It was also fitted with a wiper mechanism to prevent the optical path from becoming fouled and recording extraneous or false turbidity measurements. The sonde recorded turbidity measurements at 15-minute intervals, corresponding to the 15-minute intervals of discharge measurement at the gage. Turbidity data were then uploaded automatically to the Internet to allow real-time data access through the USGS Web site (<http://waterdata.usgs.gov/pa/nwis/uv?01473169>). The ISCO sampler model 6712C compact portable sampler was set to collect water samples at water-level thresholds above base flow. USGS collected a total of 25 ISCO samples at the Valley Creek gage on 11 dates between October 2005 and August 2006 with discharges ranging from 0.6–40.4 m³/s (21–1,426 ft³/s). These ISCO samples were filtered, dried, and weighed by USGS. The resulting concentration of suspended sediment was plotted against turbidity, allowing further turbidity measurements to serve as a surrogate for suspended-sediment measurement (Gippel 1995).

Tracer Gravels

Interpretation of the distance traveled by labeled bed-material can help in the understanding of transport processes. Particles representing the median particle size of the streambed were removed from each cross-section where water depth was shallow enough that the channel bed could be reached. The particle sizes used in the monitored cross-section included two from each of the following ranges: 8–11 mm (0.31–0.43 in), 11–16 mm (0.43–0.63 in), 16–22 mm (0.63–0.87 in), 22–32 mm (0.87–1.26 in), 32–45 mm (1.26–1.77 in), 45–64 mm (1.77–2.52 in), and 64–90 mm (2.52–3.54 in). These sizes were chosen because they could be quickly measured with the gravelometer and they represented the particle sizes found in most of the cross-sections.

The particles were painted fluorescent orange and labeled with their size class so they could be easily identified on the streambed. After painting, the particles were placed in a straight line across the cross-sections being monitored. The distance of each particle from the cross-section endpoint was recorded. Once a specified period of time had passed (typically one-week intervals), the particles were relocated and the distance moved from the cross-section recorded, along with the highest discharge occurring during the sampling time. These measurements provide an indication of the threshold conditions under which all, some, or none of the tracer gravels are mobilized. Tracer gravels were installed on June 30, 2005 and were monitored until August 5, 2005. During the sampling period, the range of flows varied between 0.8 m³/s (30

ft³/s) and 18.6 m³/s (656 ft³/s). Plots were created showing the location of the tracer gravels along each cross-section, as well as the recorded distance they moved after each sampling event. Plots of discharge vs. largest particle sizes mobilized were also created.

Results

Channel Characterization

The channel was characterized at various levels of detail to aid in choosing sampling locations. The results of the characterization efforts are summarized as follows:

1. Initial reconnaissance - Areas with similar channel conditions (e.g., backwater effects from the dam; narrow gorge between Mount Misery and Mount Joy; the sinuous stretch the furthest upstream) are grouped together (Figure 10).
2. Longitudinal profile - The profile measurements taken at 2-m (6.6-ft) increments plus extensive field notes on flow regime, channel geometry, streambed material, and anthropogenic modifications were used to add more detail to the previous characterization (Figure 11). A description of each of the 78 subdivisions indicated in Figure 11 is provided in tabular format in Appendix A.
3. Flow regime - Figure 12 designates flow regime, including riffles, runs, pools, and glides. Areas of observed significant sand and fine sediment accumulation are indicated with yellow arrows. The locations of significant channel bars are shown with pink arrows. Other areas of noteworthy sediment deposits are designated by red arrows and described with text boxes directly on the map.
4. Sample reaches - A final characterization was developed to identify sampling locations for the study based on channel morphology and evidence of sediment accumulation, bank erosion, and lateral migration. Twelve reaches and three cross-sections representative of each reach were chosen (Figure 13).

Longitudinal Profile

Figure 14 shows the longitudinal profile (elevations of the banklines, thalweg, and low-flow water surface), as well as the geologic divisions, designated sampling reaches, and anthropogenic modifications (dams, bridges, and overpasses). The x-axis shows distance upstream from the confluence of Valley Creek with the Schuylkill River and the y-axis displays the elevation. A more detailed profile can be found in Appendix B, showing the locations of surveyed cross-sections.

The characteristics of the profile are strongly influenced by the history of human activity along Valley Creek. Between 1812 and 1814 a dam was built in the downstream reaches of Valley Creek near Washington's Headquarters to provide power for a cotton mill. Burk (1920) described the dam as creating a lake where visitors could rent small boats and row all the way to a scenic bridge some distance to the north. Figure 15 shows the planimetric extent of the lake created by the dam and Figure 14 shows the extent of the lake in relation to the longitudinal profile. The dam was built slightly upstream of the modern location of the Route 23 overpass. The lake formed upstream of the dam extended approximately to the division between reaches 8 and 9, which is also where the gorge between Mount Misery and Mount Joy becomes the narrowest. Silt raised the valley floor considerably. By 1920, the park commission demolished

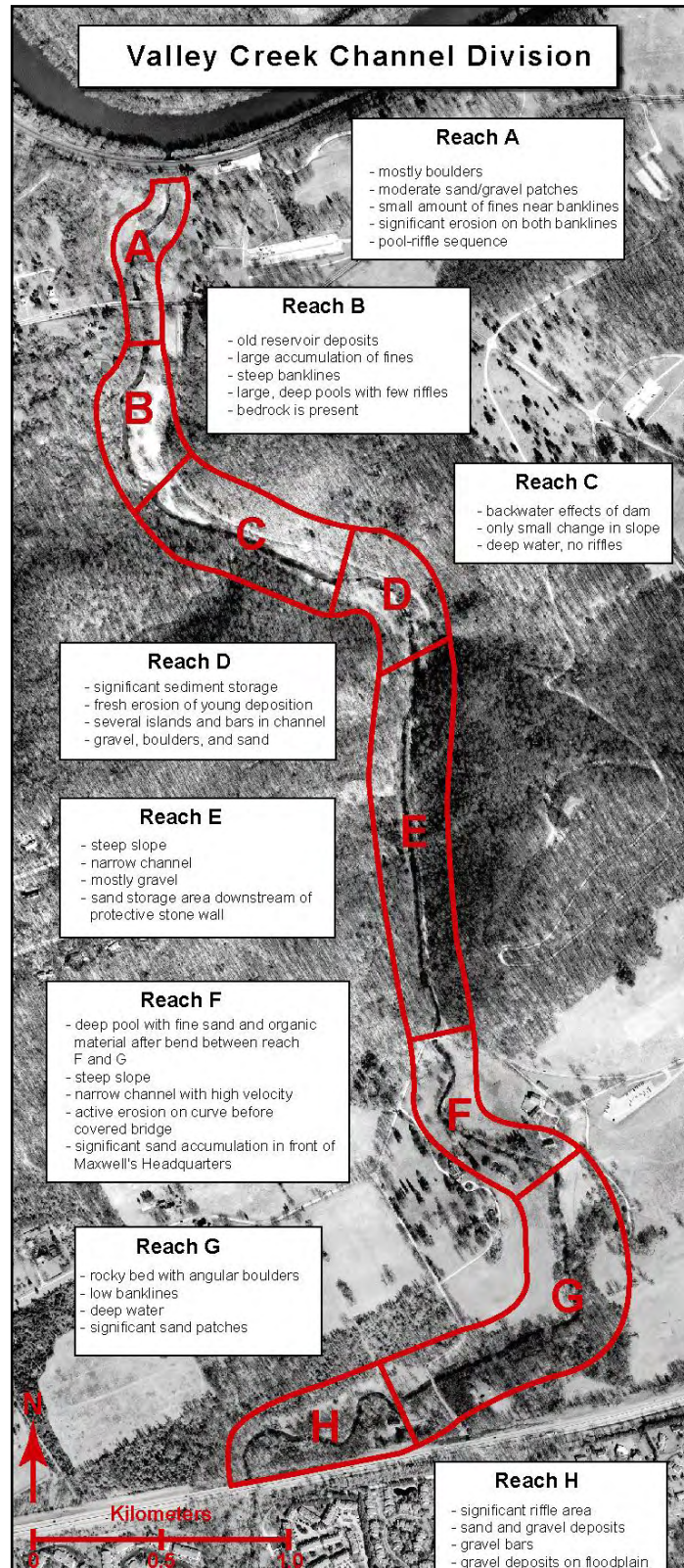


Figure 10. Preliminary channel characterization of Valley Creek based on initial reconnaissance July and September 2003.

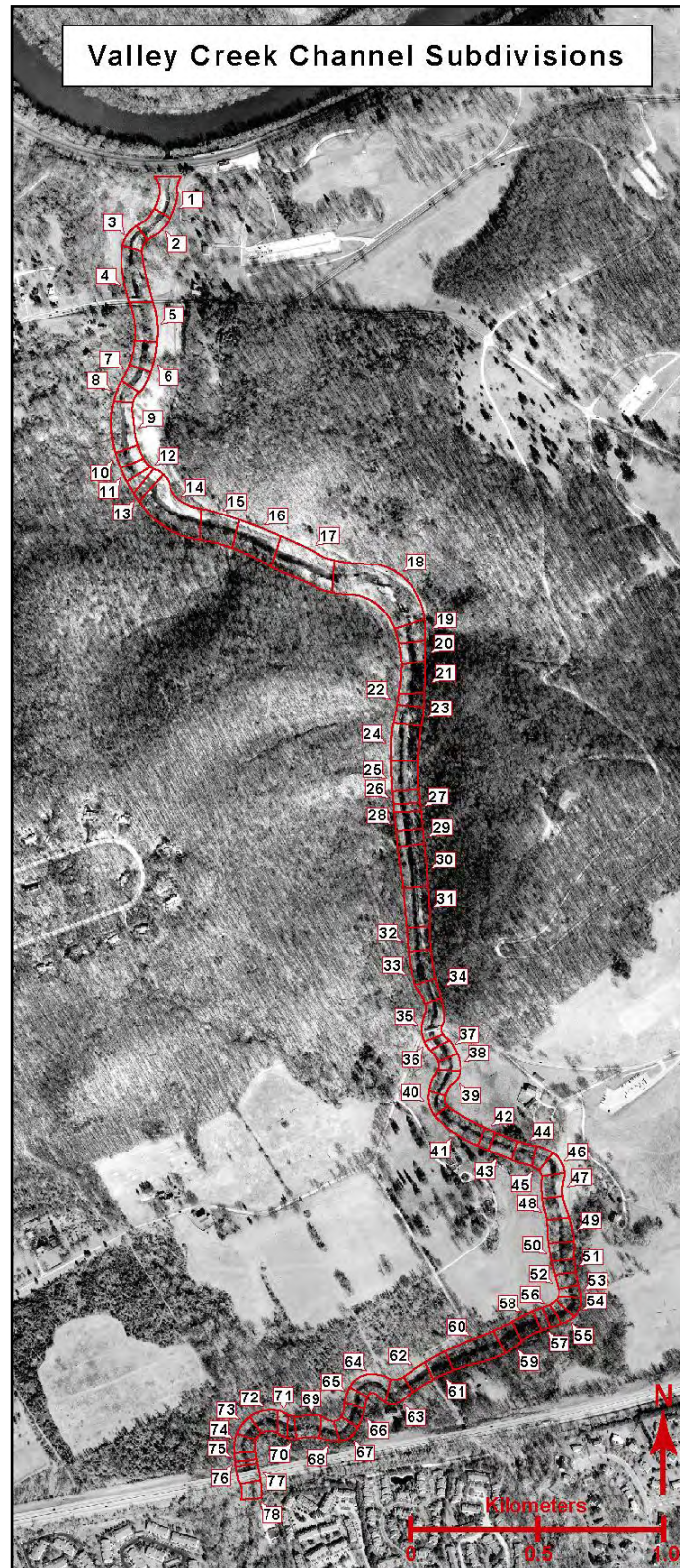


Figure 11. Refined subdivisions of the preliminary channel characterization of Valley Creek.

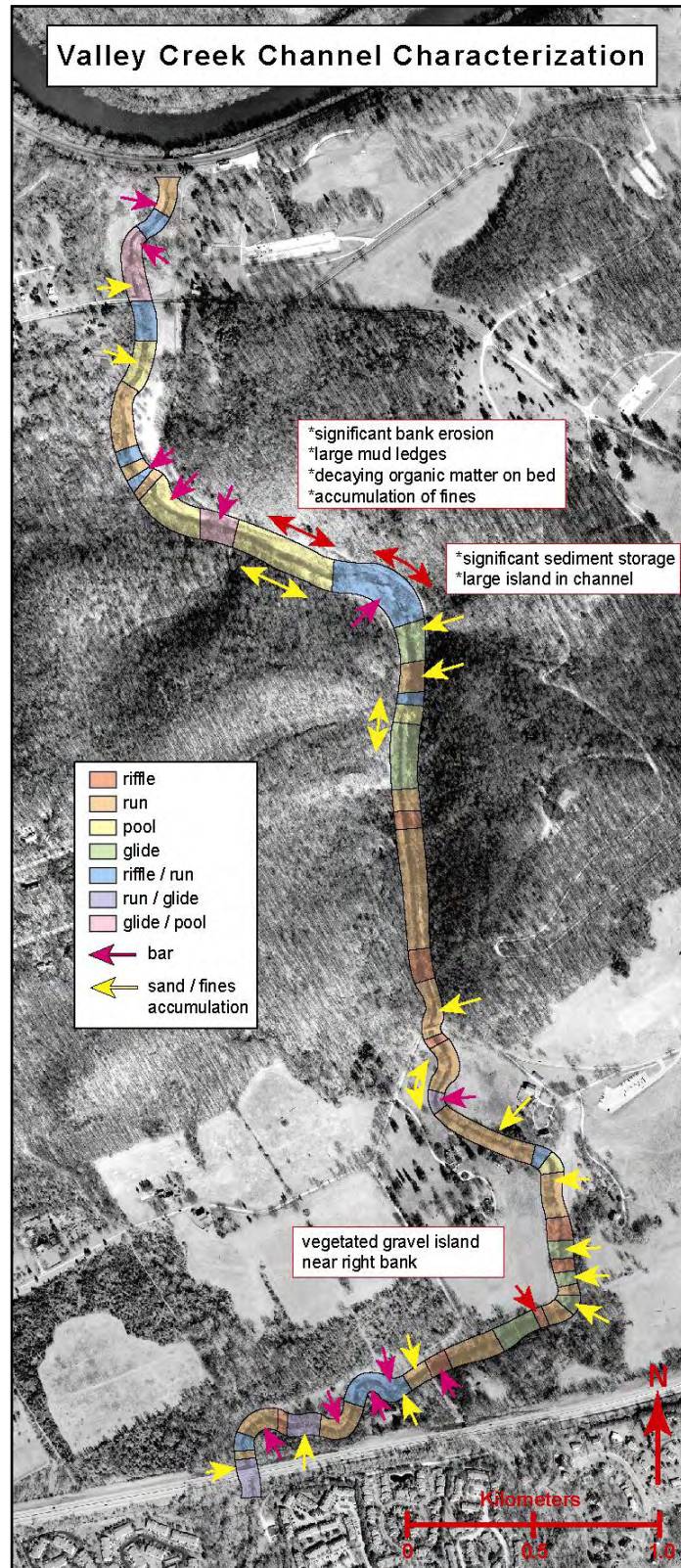


Figure 12. Channel characterization of Valley Creek based on flow regime and sediment accumulation.

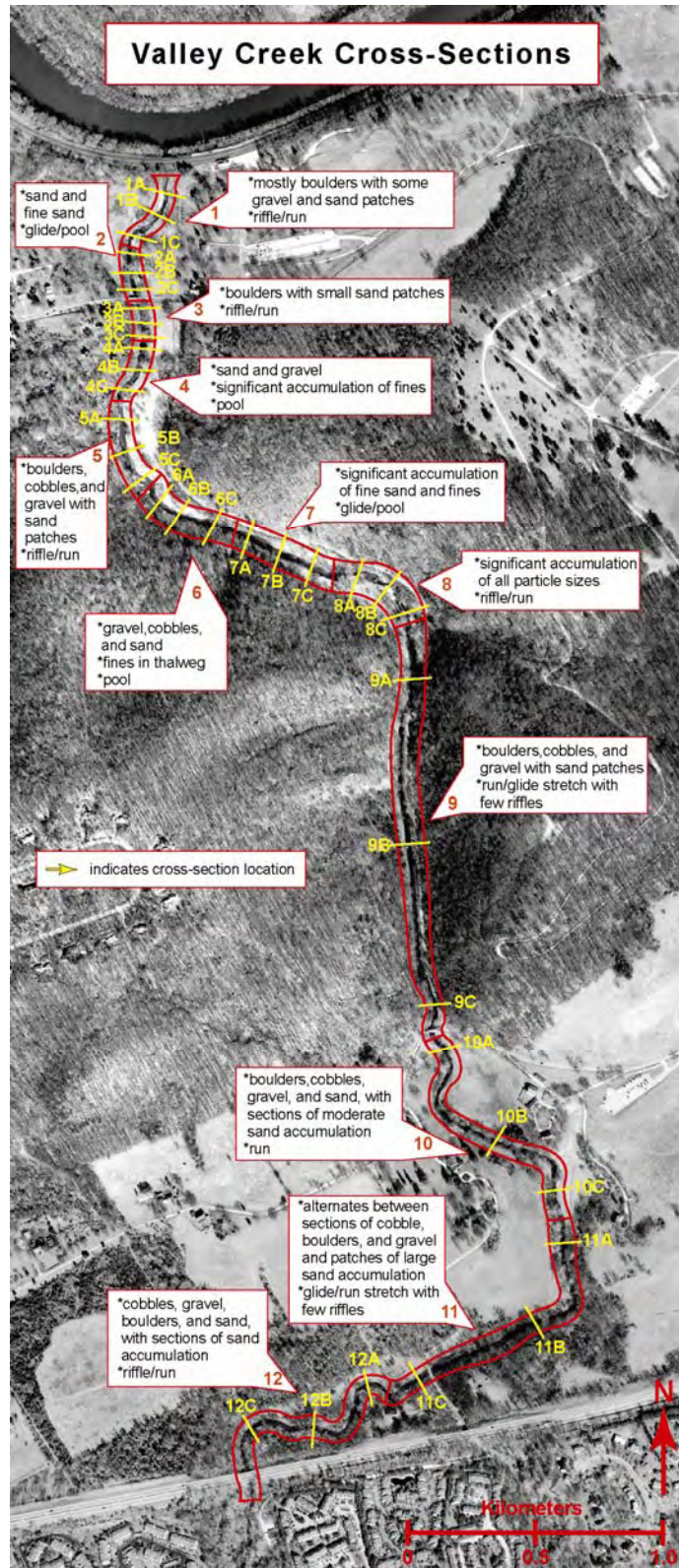


Figure 13. Twelve chosen sample reaches of Valley Creek, including locations of 36 cross-sections.

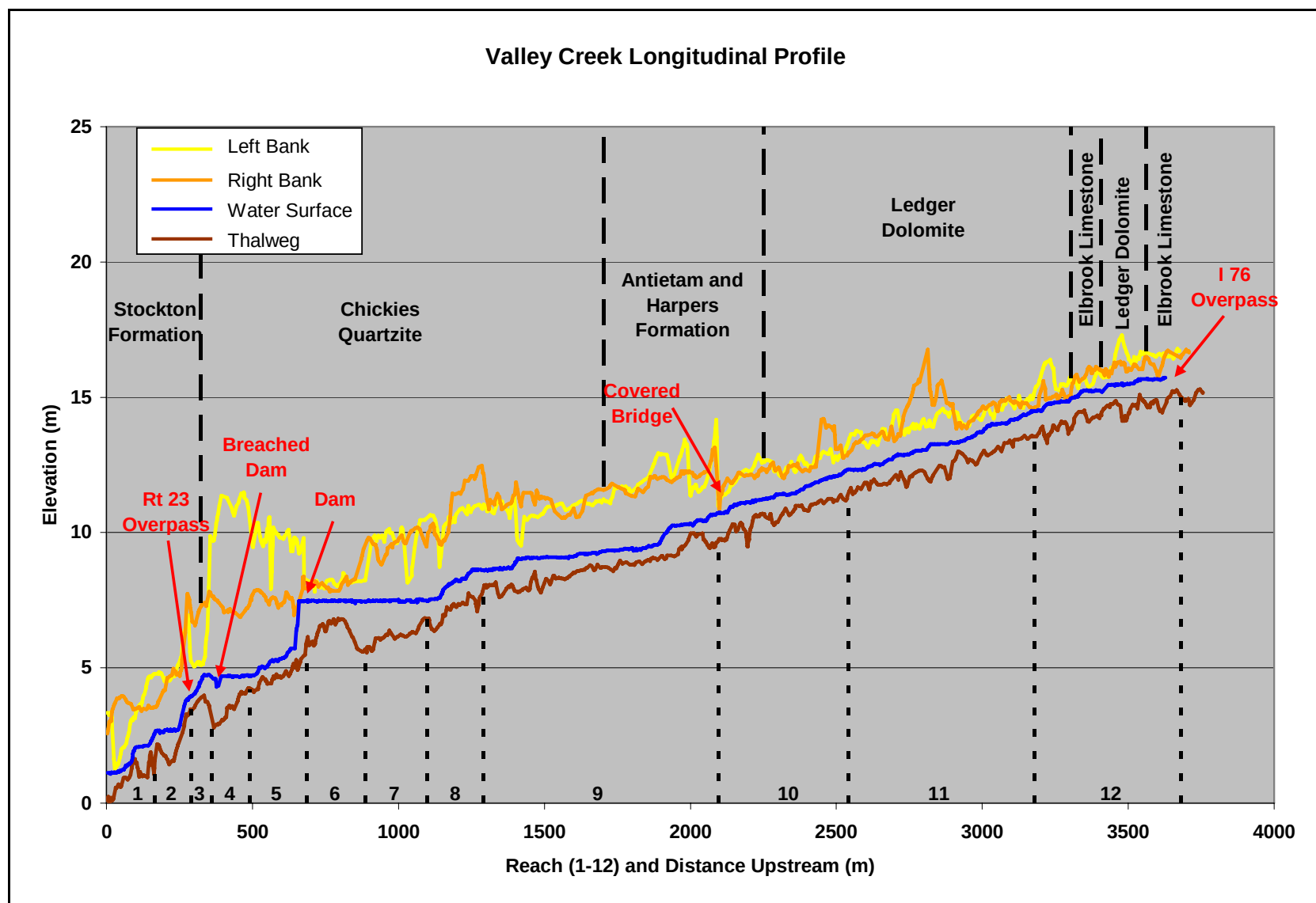


Figure 14. Longitudinal profile of the portion of Valley Creek that runs through Valley Forge National Historical Park, September 2003–May 2004.

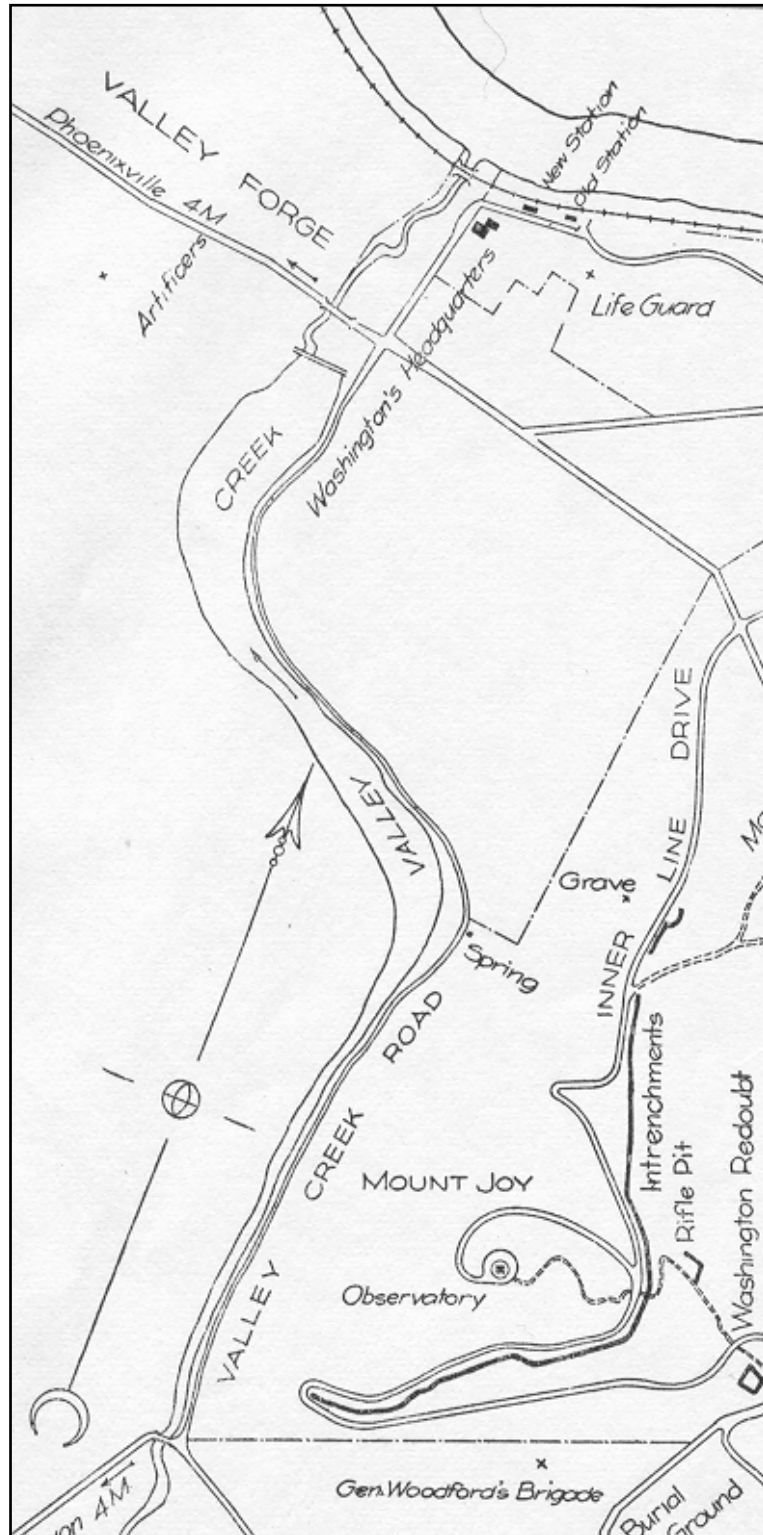


Figure 15. Section of a 1911 map of Valley Forge National Historical Park showing the extent of an old cotton mill dam on Valley Creek (Burk 1928).

the dam and in 1921 park workers graded the area where the old mill dam had been (Treese 1995). Valley Creek is now cutting through legacy deposits from the old cotton mill dam and reworking the stack of sediments stored in the aggraded floodplain. A new dam built after 1920 is upstream of the original dam and is located on the longitudinal profile at the division between reaches 5 and 6. The newer, low-head dam traps sediment on the channel floor (as indicated by the mound on the thalweg profile immediately upstream of the dam), but its backwater extends only as far as the boundary between reaches 7 and 8.

Thalweg and Water Surface Profiles

The thalweg has a sharp slope break near the location of the existing dam. The downstream 850-m (2,788-ft) average thalweg gradient is 0.0068; whereas upstream the average thalweg gradient is 0.0032, with only modest longitudinal variations. The steepest parts of the channel are also characterized by the coarsest bed-particle sizes, as discussed below in the section on particle size distribution. The water-surface profile is characterized by multiple steps and pools caused by ponding behind existing or partially breached structures as well as hydraulic controls caused by longitudinal irregularities in bed and channel morphology. These are prevalent downstream of the covered bridge (at a longitudinal distance of about 2,100 m [6,890 ft]); upstream of the covered bridge the water-surface profile is much smoother and shows no major breaks in slope.

The variation in water surface slope is shown in Figure 16 using a moving average window of 45 elevation data points. The greatest amplitudes and the steepest gradients are associated with the stepped profile in the downstream reaches, but even the profile upstream of the covered bridge shows some apparent periodicity in gradient that may be associated with pools and riffles or variations in channel planform. The downstream reaches are underlain by the Stockton and Chickies Quartzite geologic formations. Moderate gradients occur midway upstream where the channel crosses through the Antietam and Harpers Formation. In the upstream reaches, the gentlest gradients occur where the channel traverses the Ledger Dolomite and Elbrook Limestone. A plot showing the variability in both thalweg and water surface gradient is shown in Appendix C.

Bank Profiles and Lake Deposits

High banklines (2–5 m [6–16 ft] above the low water surface) extend from 0–2,000 m (0–6,562 ft) upstream of the confluence with the Schuylkill River. The banks upstream of the old cotton mill dam, including those upstream of the existing dam, exhibit considerable spatial variation in height. The extreme high banks along the left side of the channel reflect the presence of a steep rocky slope; the height of the right bank is most likely a result of the deposition of lake sediments behind the old dam. Bank heights are relatively low for a short distance upstream of the existing dam, but high banks resume on both sides of the channel and extend up to the boundary between reaches 8 and 9, just below the gorge between Mt. Misery and Mt. Joy (Figure 14).

Valley Creek passes through the narrow gorge between Mount Misery and Mount Joy in the reach between 800–2100 m (2,625–6,890 ft) upstream of the confluence with the Schuylkill River. There is little to no floodplain development. The banklines in this area are the edge of

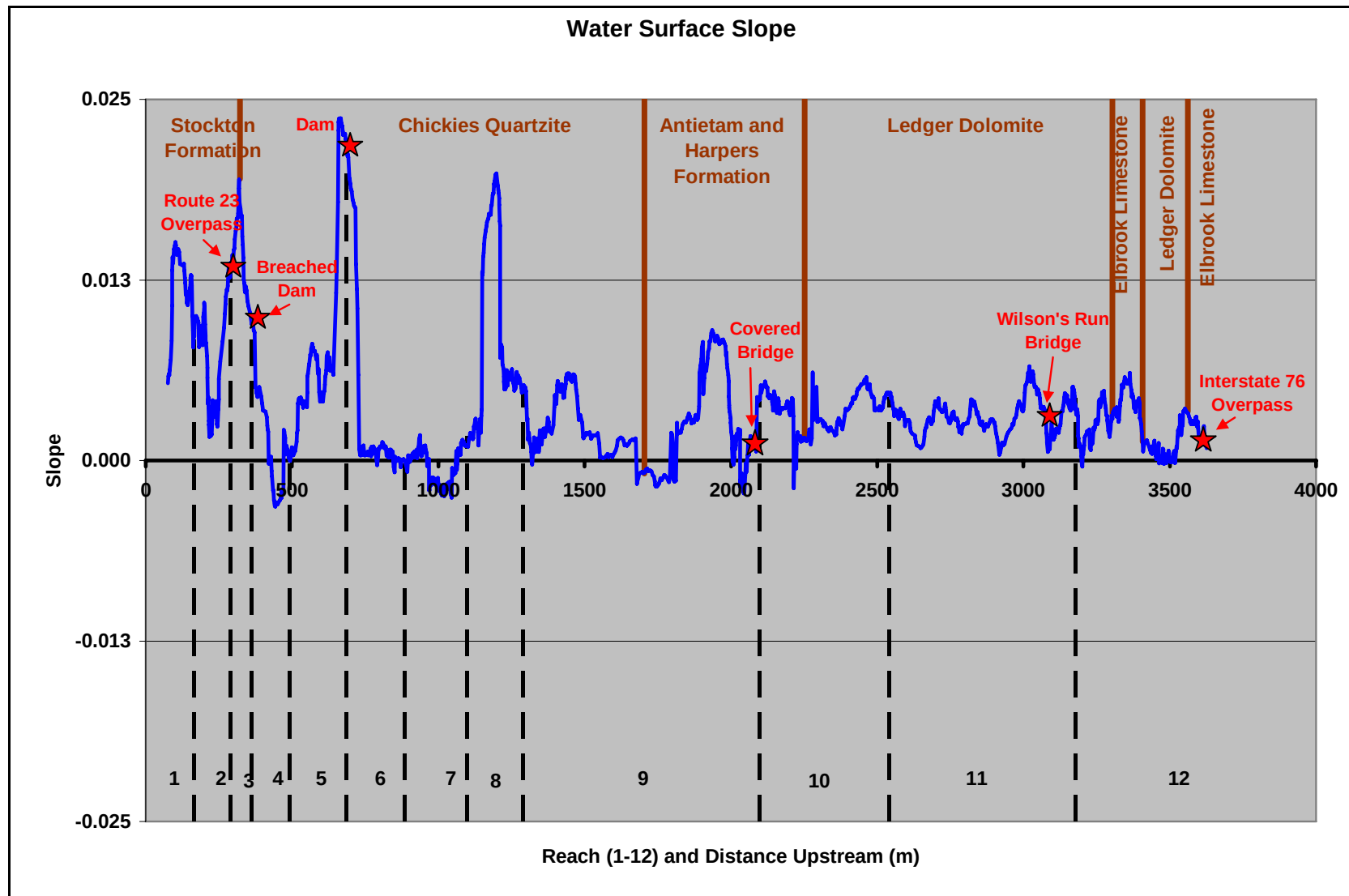


Figure 16. Valley Creek water surface slope with distance upstream, September 2003–May 2004.

Route 252 road embankment on the right side of the channel and the edge of Valley Creek trail on the left side of the channel. Most of the lengths of the channel banks within the gorge are protected by stabilization structures, including riprap and concrete walls, and, therefore, bank lines within the gorge cannot be interpreted as natural geomorphic features. Upstream of the covered bridge, which also marks the upstream limit of the gorge, bank heights once again decrease. Low banklines (1–2 m [3.3–6.6 ft] above low-water surface) extend upstream to the park boundary at the Interstate 76 overpass. This part of the channel is bordered by a well-developed floodplain which is frequently inundated by flows which overtop the channel banks.

Cross-section Surveys and Sampling

Cross-section Surveys

Baseline surveys were conducted during the summer of 2004. Resurveys of channel topography and repeat measurements of bed particle size distribution were conducted after significant storm events. Results of the flood frequency analysis (Appendix D) indicate that the series of three storm events occurring in July and the beginning of August 2004 were approximately 2-year flood events. On September 28, 2004, a $78 \text{ m}^3/\text{s}$ ($2,750 \text{ ft}^3/\text{s}$) flood peak with a 10-year recurrence interval occurred, producing the second-highest discharge on record for Valley Creek. The final survey was conducted after a 5-year event ($58 \text{ m}^3/\text{s}$ [$2,048 \text{ ft}^3/\text{s}$]), which occurred on April 2, 2005. Three cross-sections are displayed in Figures 17–19, which were chosen to illustrate patterns representing different areas of Valley Creek within VAFO. The locations of these cross-sections are shown on Figure 13. A complete summary of data for all cross-section surveys and sediment samples is provided in Appendix E.

Figure 17 shows cross-section 1B, which is located in reach 1. Cross-section 9B is located mid-way upstream as shown in Figure 18. Figure 19 shows cross-section 12B, located along the reach furthest upstream. As can be seen from Figures 17–19, the amount of change occurring in each cross-section varied with location along Valley Creek. Cross-section 1B changed the most of the three cross-sections displayed in this section, ranging from approximately 0.8 m (2.6 ft) of maximum deposition to 0.5 m (1.6 ft) of maximum scour between the baseline survey in the summer of 2004 and the final survey after the 5-year flood event on April 2, 2005. No significant changes were found along cross-section 9B, with maximum scour of less than 0.1 m (0.3 ft) and no deposition. Cross-section 12B also exhibits no deposition on the channel bed, but scoured to a moderate depth of 0.3 m (1.0 ft) between the baseline and final survey. A similar trend is found among all 36 surveyed cross-sections: bed scour appears to be a dominant process in the downstream reaches and decreases with distance upstream. Areas of deposition do occur in the downstream reaches, but typically at a smaller magnitude than the amount of scour.

A few areas show evidence of repeated episodes of scour and fill. After the 10-year flood event in September 2004 repeat surveys were conducted. The yellow line on the graph of cross-section 8A (Figure 20) shows the channel bed elevation after this event and cumulative scour since the baseline survey. After the 5-year flood event in April 2005 an additional set of surveys was conducted. Results show erosion measured after the September 2004 event and deposition measured after the April 2005 event. Continued monitoring would be needed to ascertain whether continued deposition tends to restore the original profile of the bar at the base of the left bank.

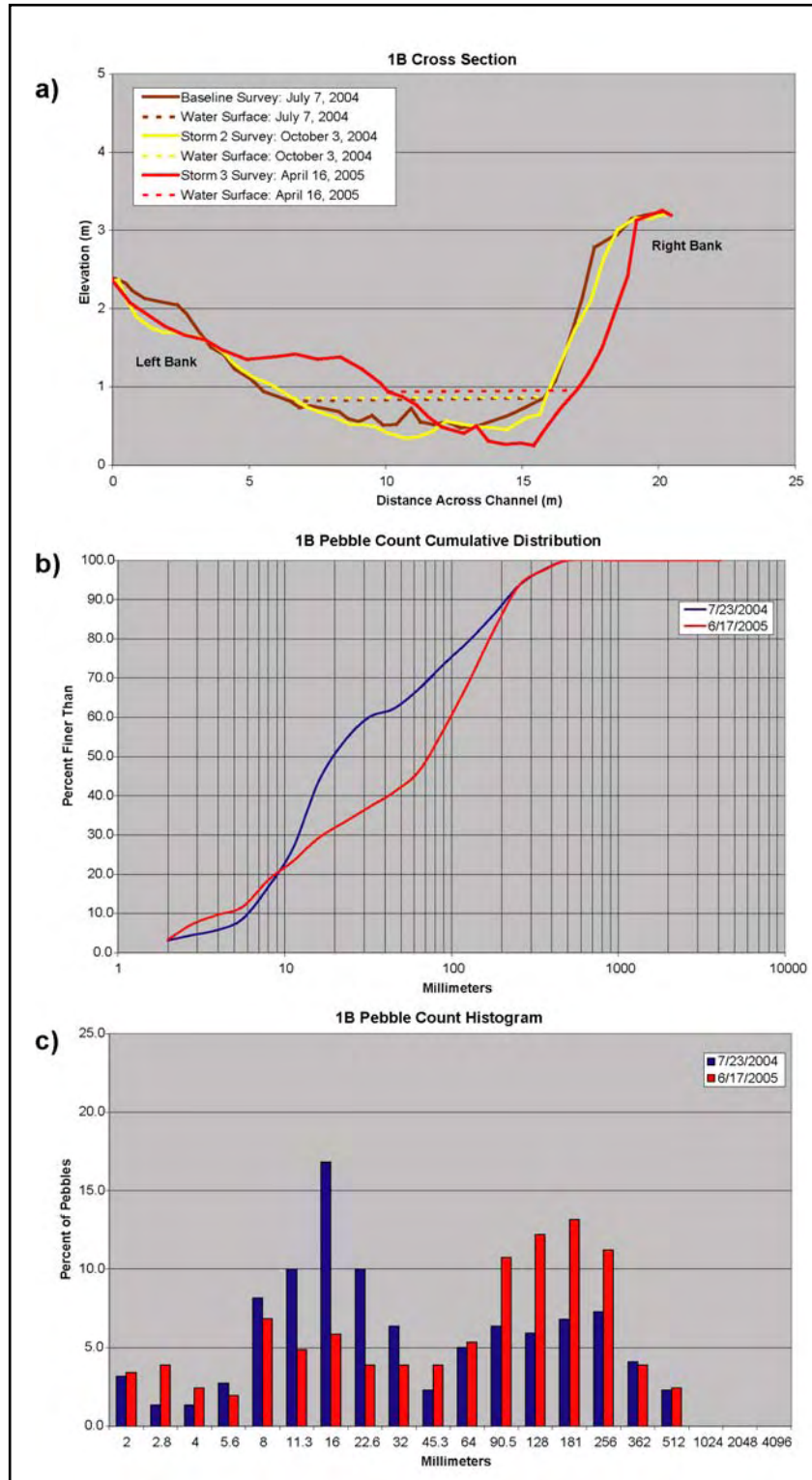


Figure 17. Valley Creek cross-section 1B located in a downstream reach: a) cross-section, b) cumulative particle size distribution, and c) pebble count histogram.

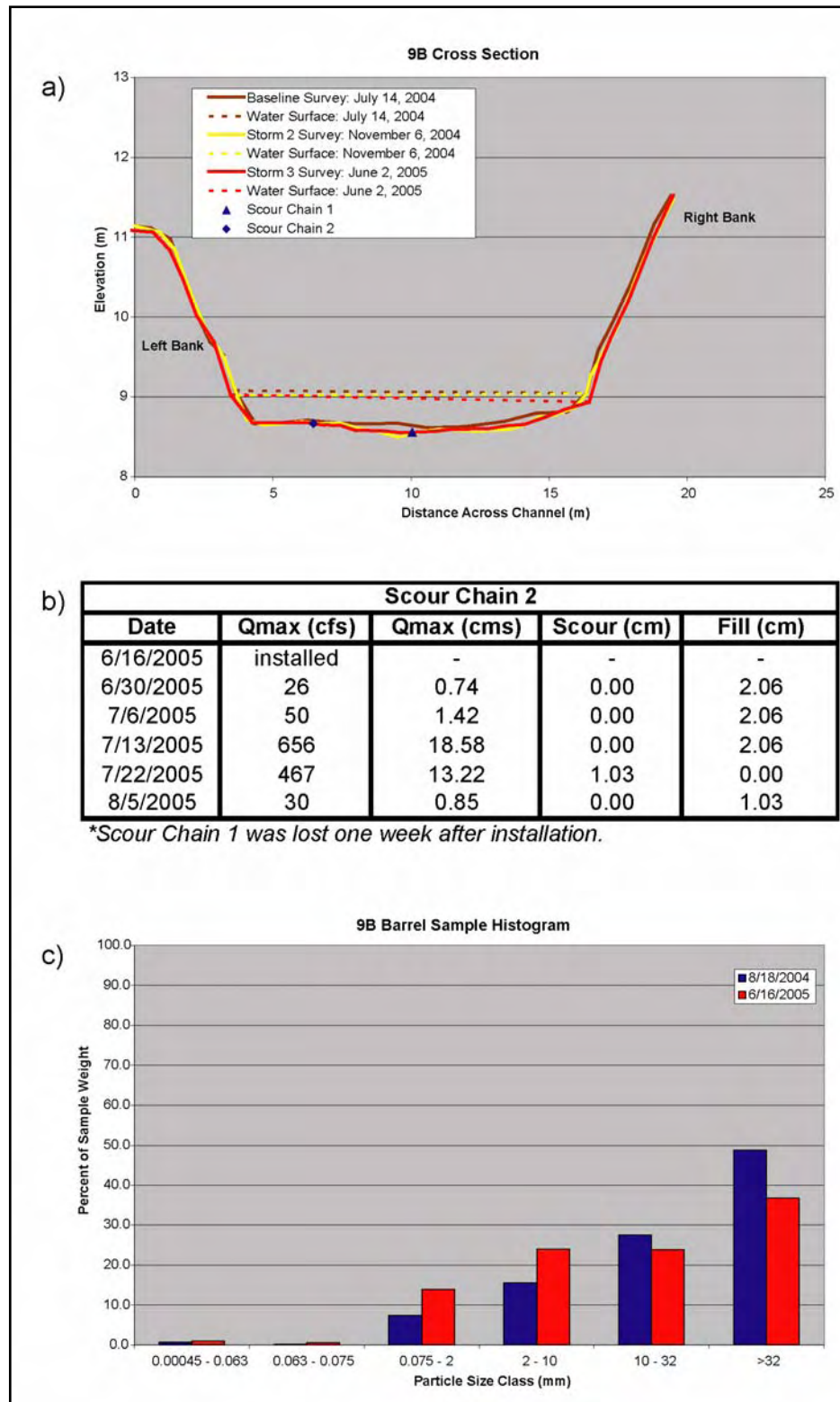


Figure 18. Valley Creek cross-section 9B located mid-way upstream: a) cross-section, b) scour chain data, c) barrel sample histogram, d) cumulative particle size distribution, and e) pebble count histogram.

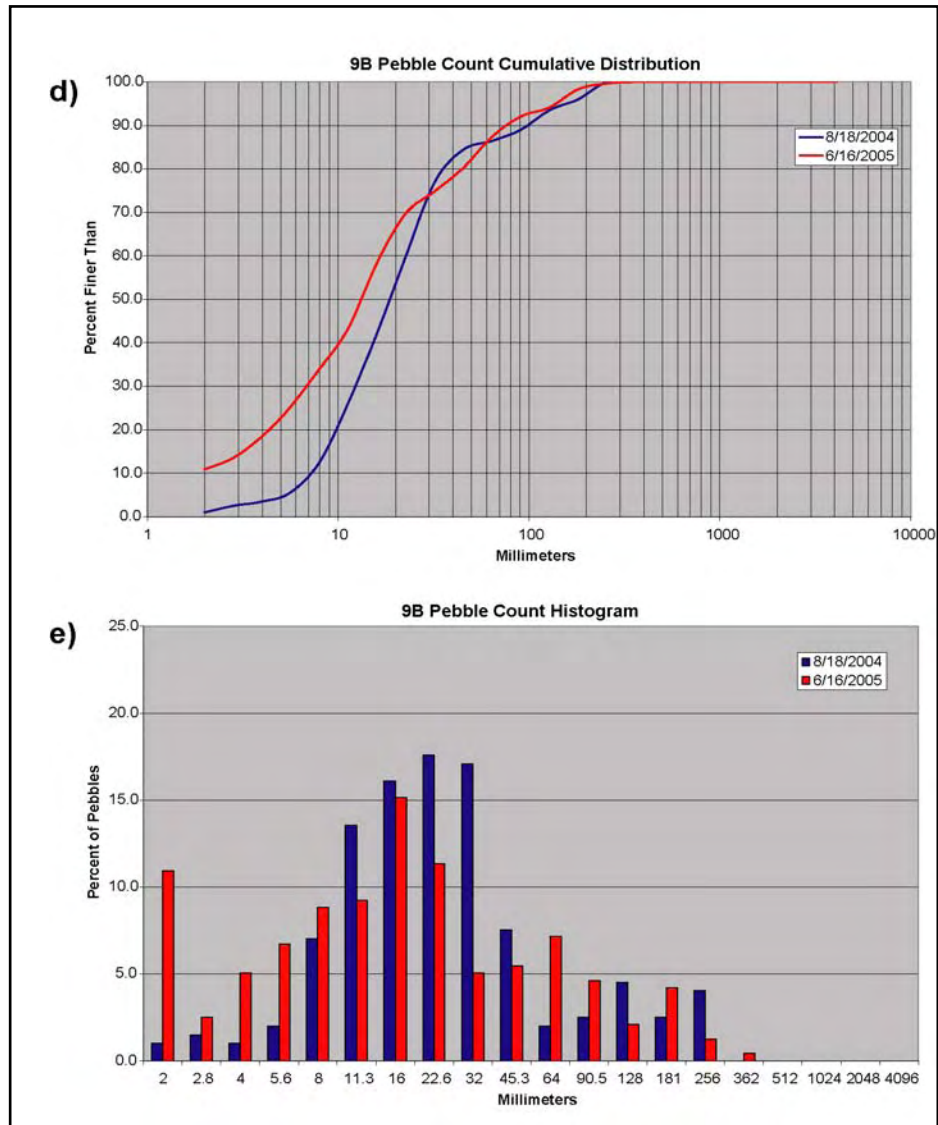


Figure 18. Valley Creek cross-section 9B located mid-way upstream: a) cross-section, b) scour chain data, c) barrel sample histogram, d) cumulative particle size distribution, and e) pebble count histogram (continued).

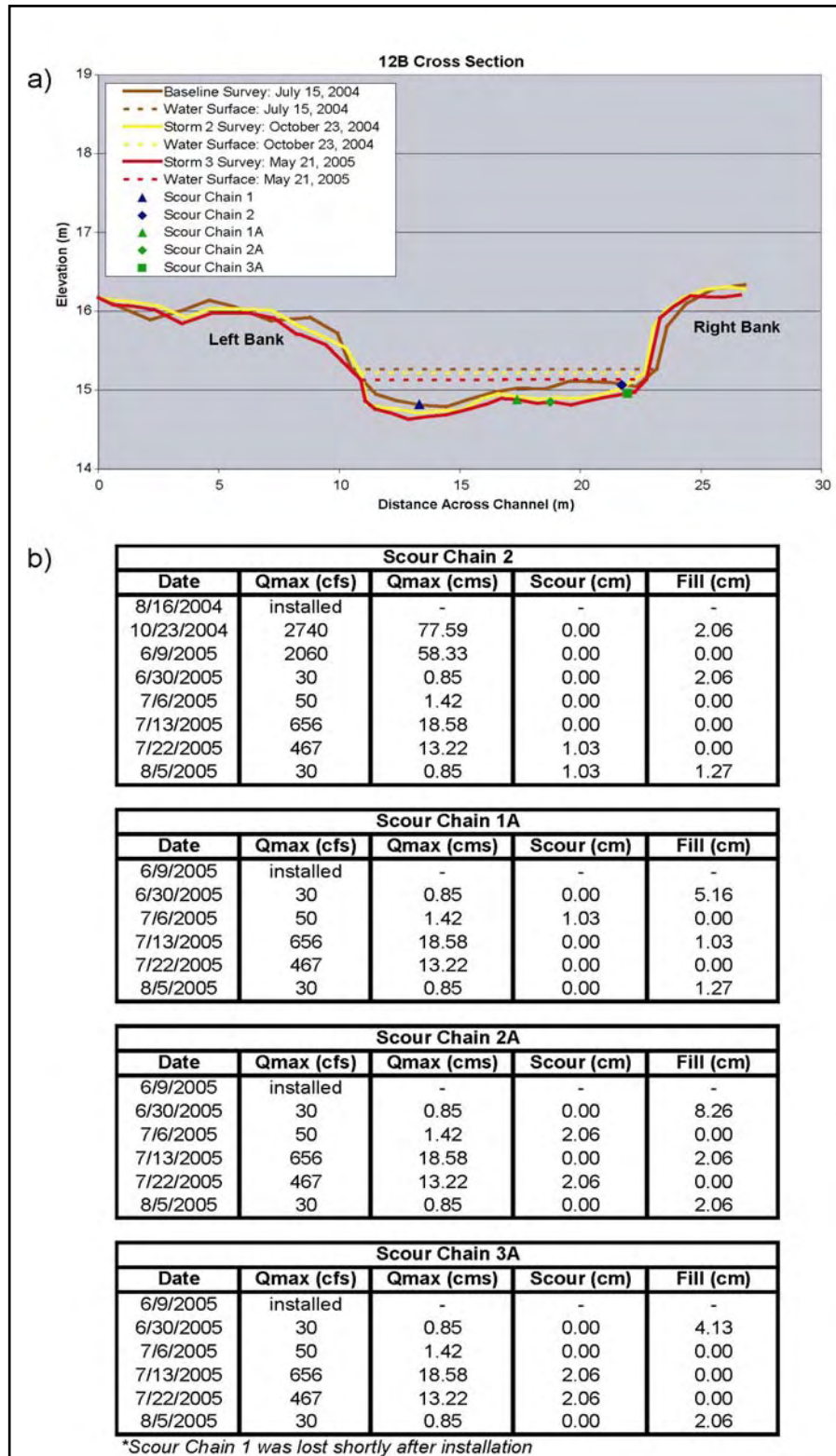


Figure 19. Valley Creek cross-section 12B located in an upstream reach: a) cross-section, and b) scour chain data c) barrel sample histogram, d) cumulative particle size distribution, and e) pebble count histogram.

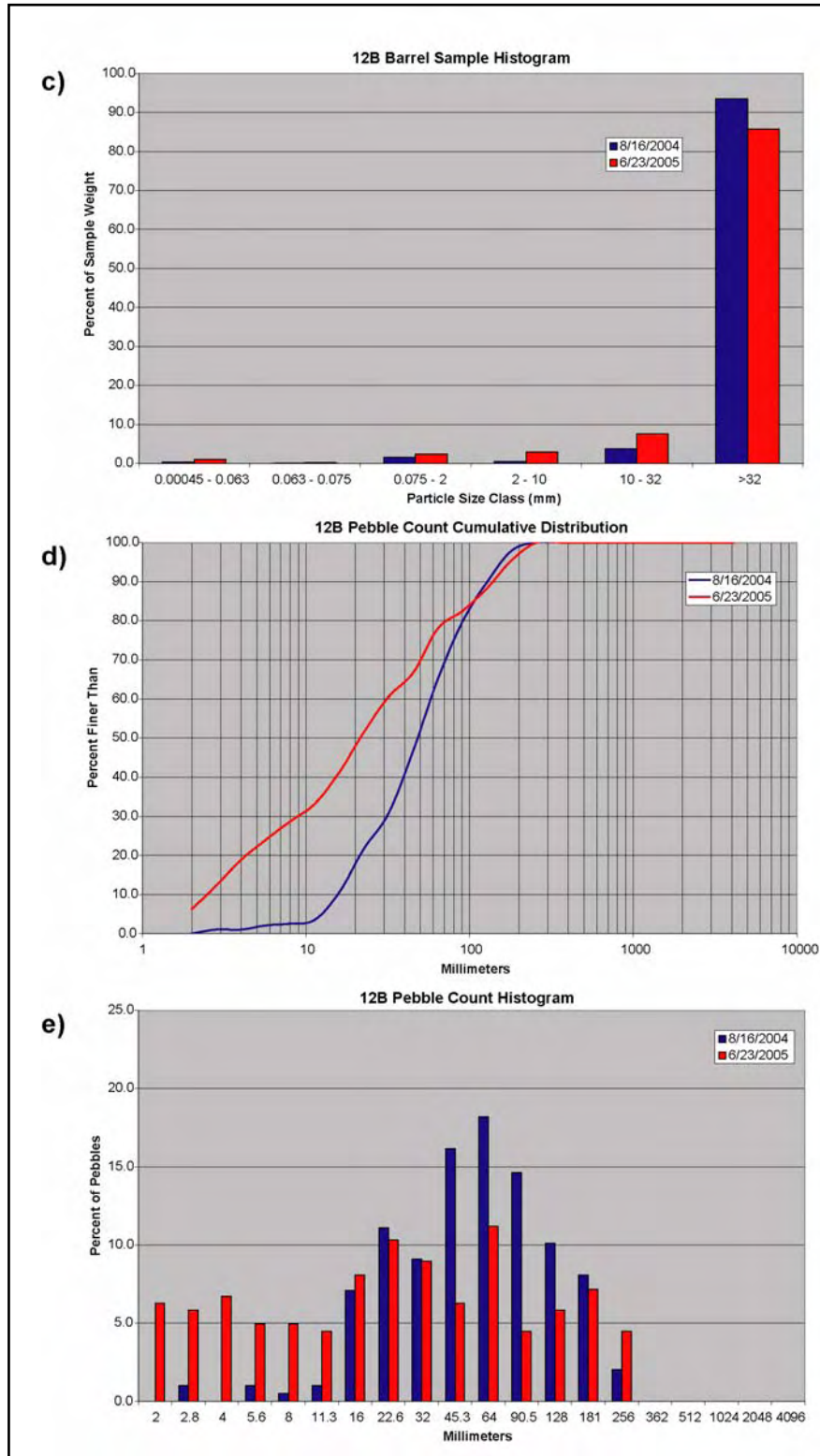


Figure 19. Valley Creek cross-section 12B located in an upstream reach: a) cross-section, and b) scour chain data c) barrel sample histogram, d) cumulative particle size distribution, and e) pebble count histogram (continued).

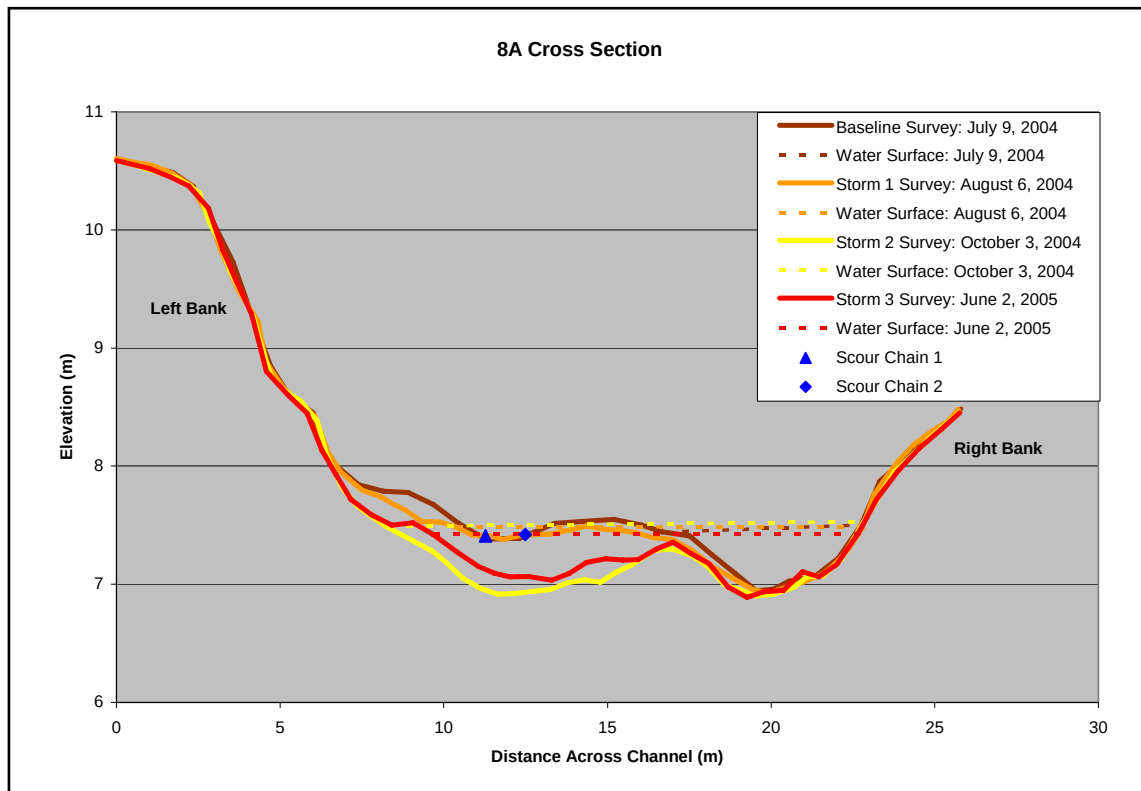


Figure 20. Valley Creek cross-section 8A showing the cyclic pattern of scour and deposition.

Scour chains were installed in six of the 36 surveyed cross-sections, most of which were located in upstream reaches. The resistance of the streambed in the downstream reaches prevented the chains from being installed; however, they were beneficial in supplementing data collected from the cross-section surveys upstream to show that only minor changes in streambed elevation occurred.

Scour chain locations are plotted on the cross-section graphs (Figure 19a), with the results displayed in tabular format (Figure 19b). The monitoring date is provided in the first column, followed by the maximum discharge that occurred between each of the monitoring intervals in the second and third columns. Column 4 shows the amount of scour, which was determined by the difference in the number of chain links exposed on the bed surface between each of the monitoring dates, as described in the Methods section. The amount of scour from the chains in cross-section 12B (Figure 19b) ranged from 0–2 cm (0–0.8 in). The final column provides the amount of sediment deposition found on top of the chain links at the time of measurement. Scour chains in cross-section 12B measured between 0–8 cm (0–3.3 in) of sediment deposition.

Data from most of the scour chains also show that as sediment was scoured during one event, it would then be deposited during another. For example, scour chain 3A in cross-section 12B

(Figure 19) indicates an initial deposition of approximately 4 cm (1.6 in) after installation. Further monitoring revealed that 2 cm (0.8 in) of scour occurred in two separate events, followed by 2 cm (0.8 in) of deposition.

Figure 21 displays the amount of deposition and scour in m^2 for each cross-section, along with the longitudinal profile and designation of major geologic formations. Negative values on the y-axis indicate scour and positive values indicate deposition. The images shown here contain the most complete dataset, covering the period from the baseline survey to the final survey conducted after storm 3. Appendix F shows the changes that occurred from the baseline survey to the second storm event on September 28, 2004.

Figure 21 shows that the largest changes in bed topography occurred in the downstream reaches (1–5) of Valley Creek, ranging from approximately 5.5 m^2 (59.2 ft^2) of scour to 2.5 m^2 (26.9 ft^2) of deposition. These reaches are located in the Chickies Quartzite and Stockton geologic formations. In the middle (6–9) and upstream (10–12) reaches, a moderate amount of scour is observed, but virtually no deposition. Maximum scour is approximately 2.5 m^2 (26.9 ft^2); deposition is less than 0.5 m^2 (5.4 ft^2). Geologic formations in these areas include the Antietam and Harpers Formation, Ledger Dolomite, and Elbrook Limestone.

The data from the three cross-sections in each reach were combined to calculate the normalized deposition and scour by section area for each reach. This masks out some of the local within-reach variability, but highlights larger-scale trends. Results from this analysis are presented in Figure 22. To determine the net change along each reach, the normalized scour was subtracted from the normalized deposition. These results are plotted in Figure 23. Negative values on the y-axis indicate scour and positive values indicate deposition.

The normalized plots of scour and deposition show the same general trends as those in Figure 21. Cross-section resurveys along the middle and upstream reaches indicate a moderate amount of scour and virtually no deposition, although scour chains do indicate transient deposition of 2–8 cm (0.8–3.1 in) during the summer of 2005. Most scour and deposition occurred in the downstream reaches. Maximum deposition (approximately $0.17 \text{ m}^3/\text{m}^2$) occurred in reach 1, and maximum scour ($0.25 \text{ m}^3/\text{m}^2$) occurred in reach 4. Figure 23 shows almost the same trend in terms of net scour and deposition, but net change in the upstream reaches is somewhat larger than net change along the middle reaches because scour and deposition tend to cancel each other out along the middle reaches. Overall, the entire length of Valley Creek within VAFO is dominated by scour between the baseline survey and the 3rd resurvey after the storm event on April 2, 2005. Only three of the 12 reaches from Figure 23 show net deposition: reach 1, reach 3, and reach 8.

Particle Size Distributions

Grid-based Pebble Counts: A total of 24 cross-sections included a pebble count measurement (Appendix E), three of which are shown in Figures 17–19. The histogram and cumulative distribution for cross-section 1B show a general coarsening of the streambed between the summers of 2004 and 2005. In contrast, the streambed in cross-sections 9B and 12B became finer over the sampling interval.

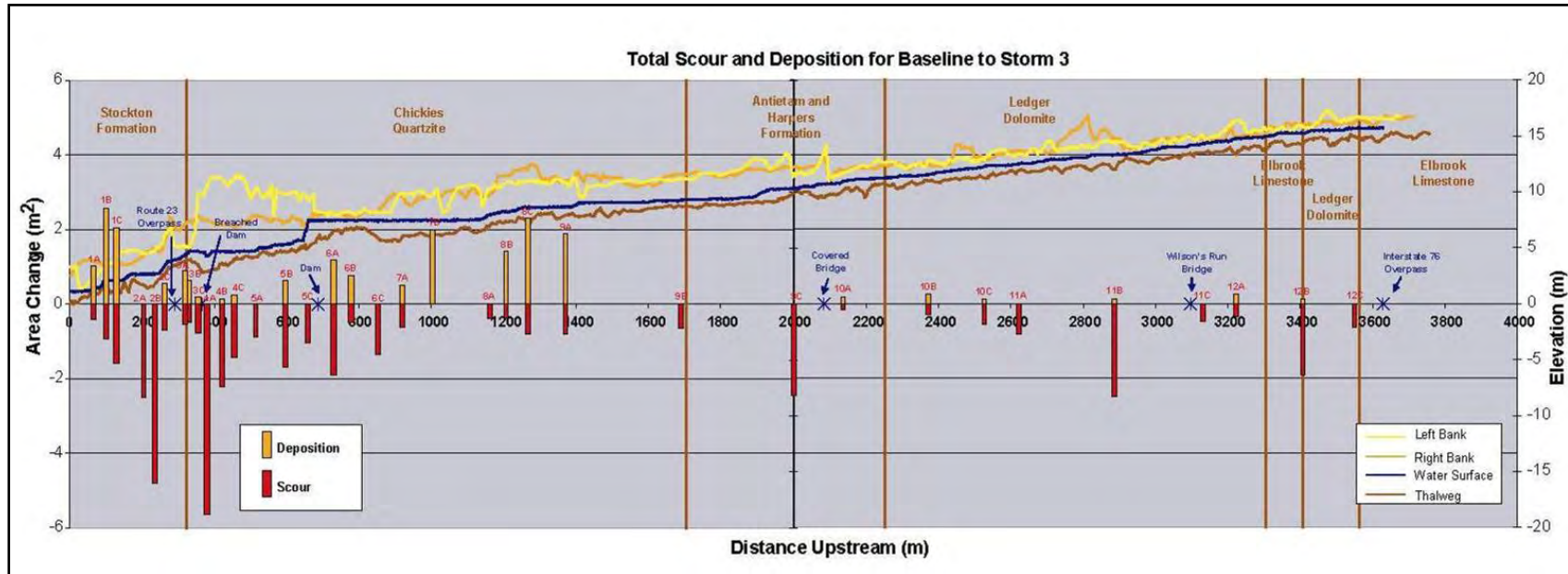


Figure 21. Cross-section deposition and scour in Valley Creek from the baseline survey in the summer of 2004 to the 3rd storm event on April 2, 2005.

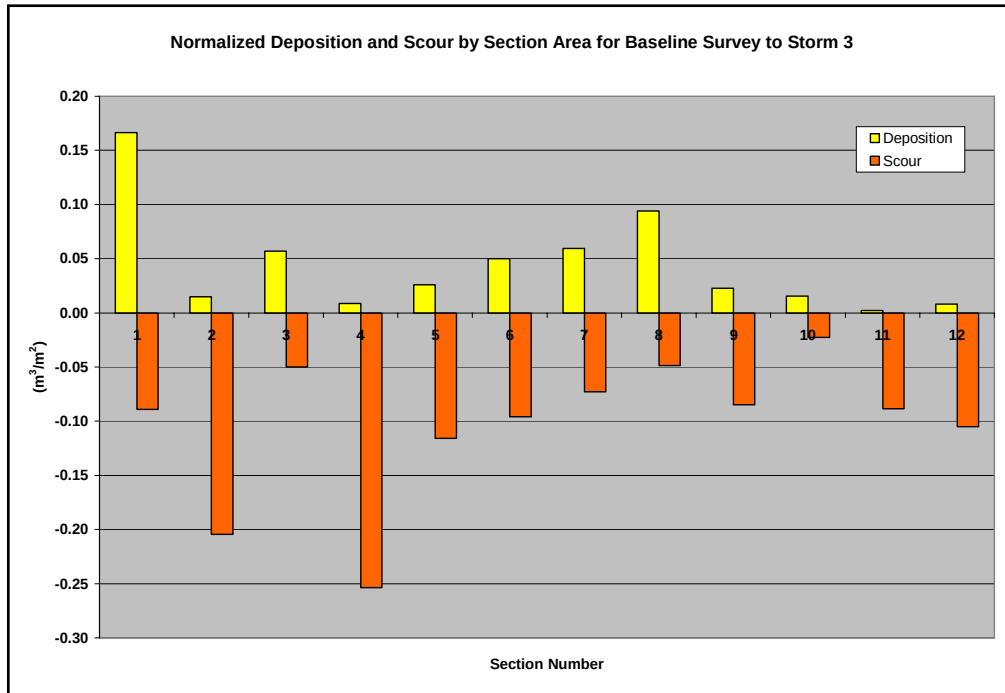


Figure 22. Reach-averaged deposition and scour in Valley Creek from the baseline survey in the summer of 2004 to the 3rd storm event on April 2, 2005.

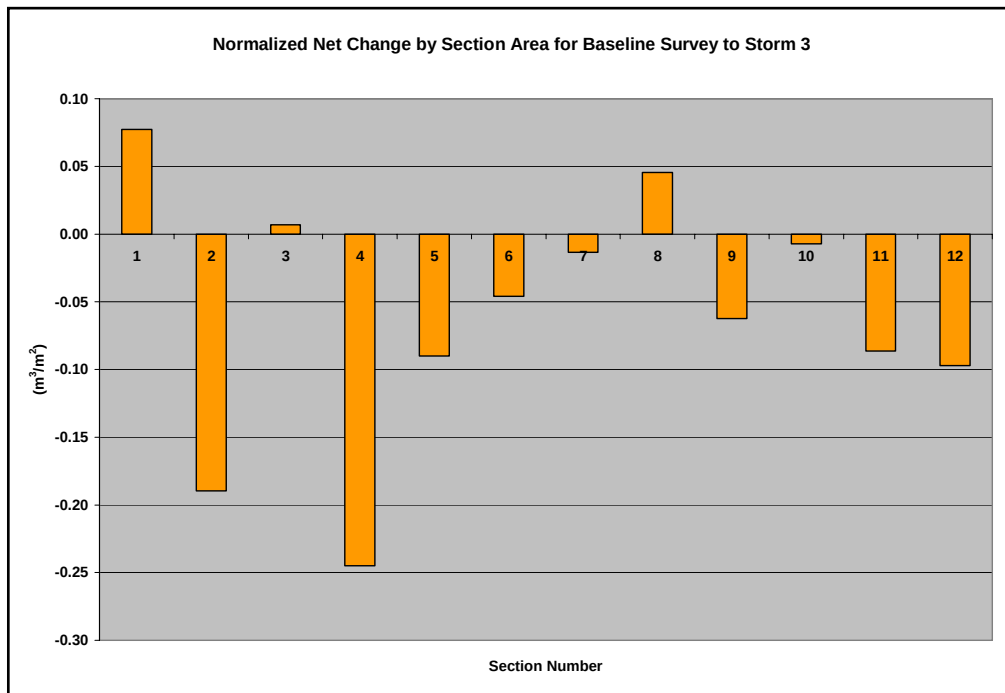


Figure 23. Normalized reach-average deposition and scour in Valley Creek from the baseline survey in the summer of 2004 to the 3rd storm event on April 2, 2005.

In order to quantify the particle size data for all cross-sections, D_{50} and mode were determined for each particle size distribution. D_{50} is the median particle size, and the mode is the most frequently occurring particle size in the sample. Some distributions can have more than one mode. As shown by Figure 17c, the primary mode in 2004 was 16 mm (0.6 in); the primary mode in 2005 was 181 mm (7.13 in). A plot showing the number of modes for each cross-section is presented in Figure 24, together with plots of D_{50} and mode for each cross-section during the summers of 2004 and 2005 sampling period.

The streambed in the reaches furthest downstream had the most coarsening, while some of the cross-sections in the upstream reaches became finer between 2004 and 2005. D_{50} was largest in the downstream reaches and gradually decreased with distance upstream. Analysis of the primary modes shows this same general trend. In the downstream reaches the primary mode increased dramatically, and in many of the cross-sections in the upstream reaches the primary mode decreased between 2004 and 2005. In cross-section 1B for example, D_{50} increased from 20–72 mm (0.8–2.8 in) and the mode increased from 20–180 mm (0.8–7.1 in) between 2004 and 2005. With distance upstream, the magnitude of coarsening decreased. In many of the cross-sections located midway upstream, D_{50} increased by only 10 mm (0.4 in) or less. The upstream reaches coarsened the least over the sampling interval.

When D_{50} is plotted against the cross-section and reach-averaged gradients (Figure 25 a and b), the data are scattered and there appear to be no trends. However, when D_{50} is plotted in conjunction with the water surface gradient in Figure 25c, a visual trend can be discerned. The graph shows that areas with the steepest gradients also have the largest D_{50} values. This is especially apparent in the downstream reaches, where the steepest gradients occur and exhibit a strong periodicity. The peaks in gradient in the downstream reaches are between 0.013 and 0.025. The corresponding peaks in D_{50} range from 60–90 mm (2.4–3.5 in). In comparison, lower gradients in the upstream reaches have the finest D_{50} values. Gradients in the upstream reaches are less than 0.006, while the corresponding D_{50} values range from 15–50 mm (0.6–2 in).

Volumetric Sampling: Grain-size distributions for two barrel samples (cross-sections 9B and 12B) are shown in Figures 18c and 19c. Tabulated data for barrel samples from all cross-sections can be found in Appendix E. Cross-sections 9B and 12B both show an increase in the fine material within the streambed surface between 2004 and 2005, which is consistent with the particle size distributions becoming finer in those two reaches.

Coarsening or fining trends surveyed with the barrel sampler agreed with trends in the pebble count data at eight of the 16 cross-sections where both data sources were available. For five of the remaining eight cross-sections, the barrel samples indicated that the bed surface became finer, whereas the pebble counts indicated that the bed surface became coarser (cross-sections 6B, 8A, 8B, 10A, and 10C).

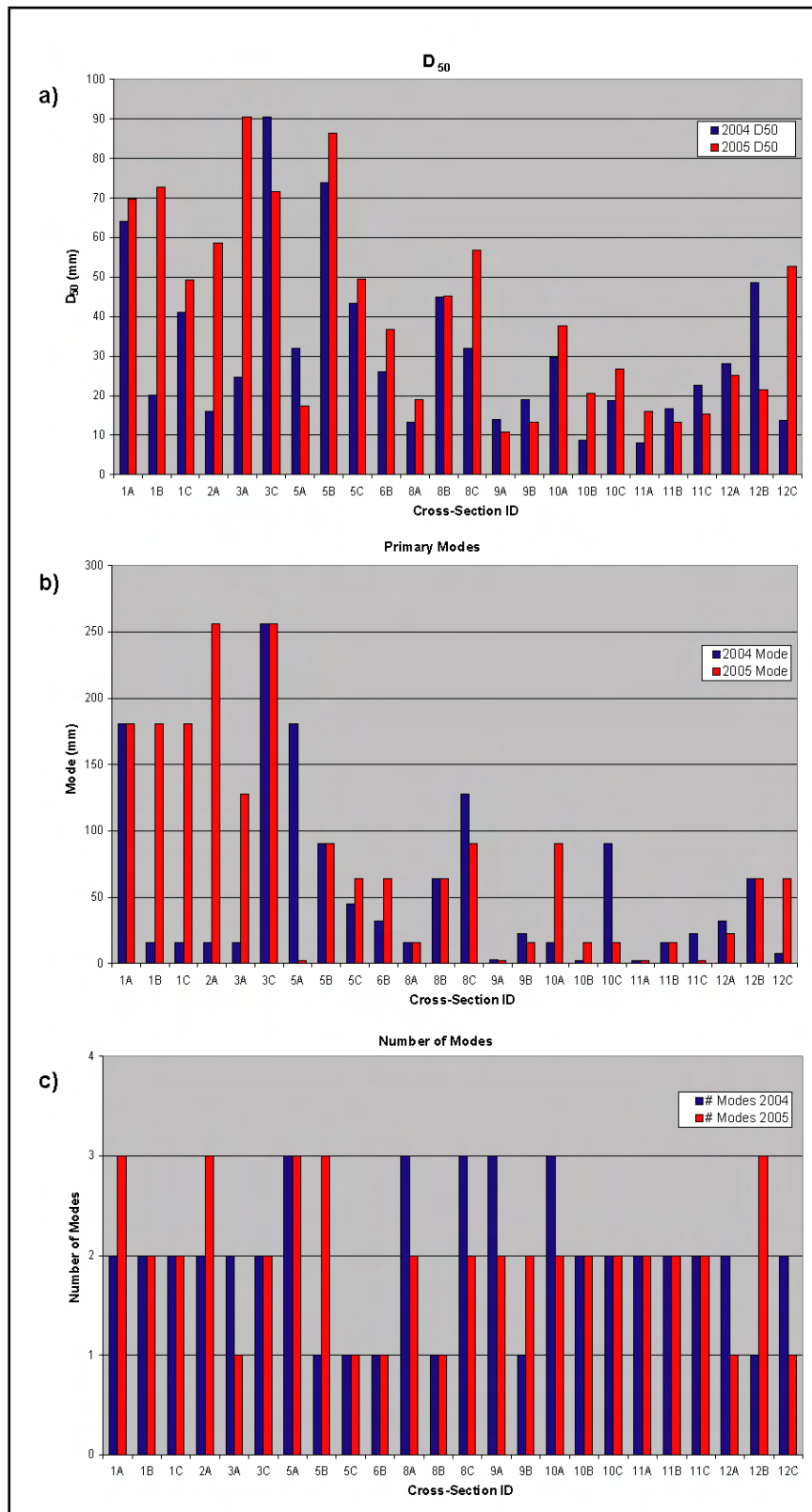


Figure 24. Pebble count data for sampled Valley Creek cross-sections, a) D₅₀, b) primary mode, and c) number of modes.

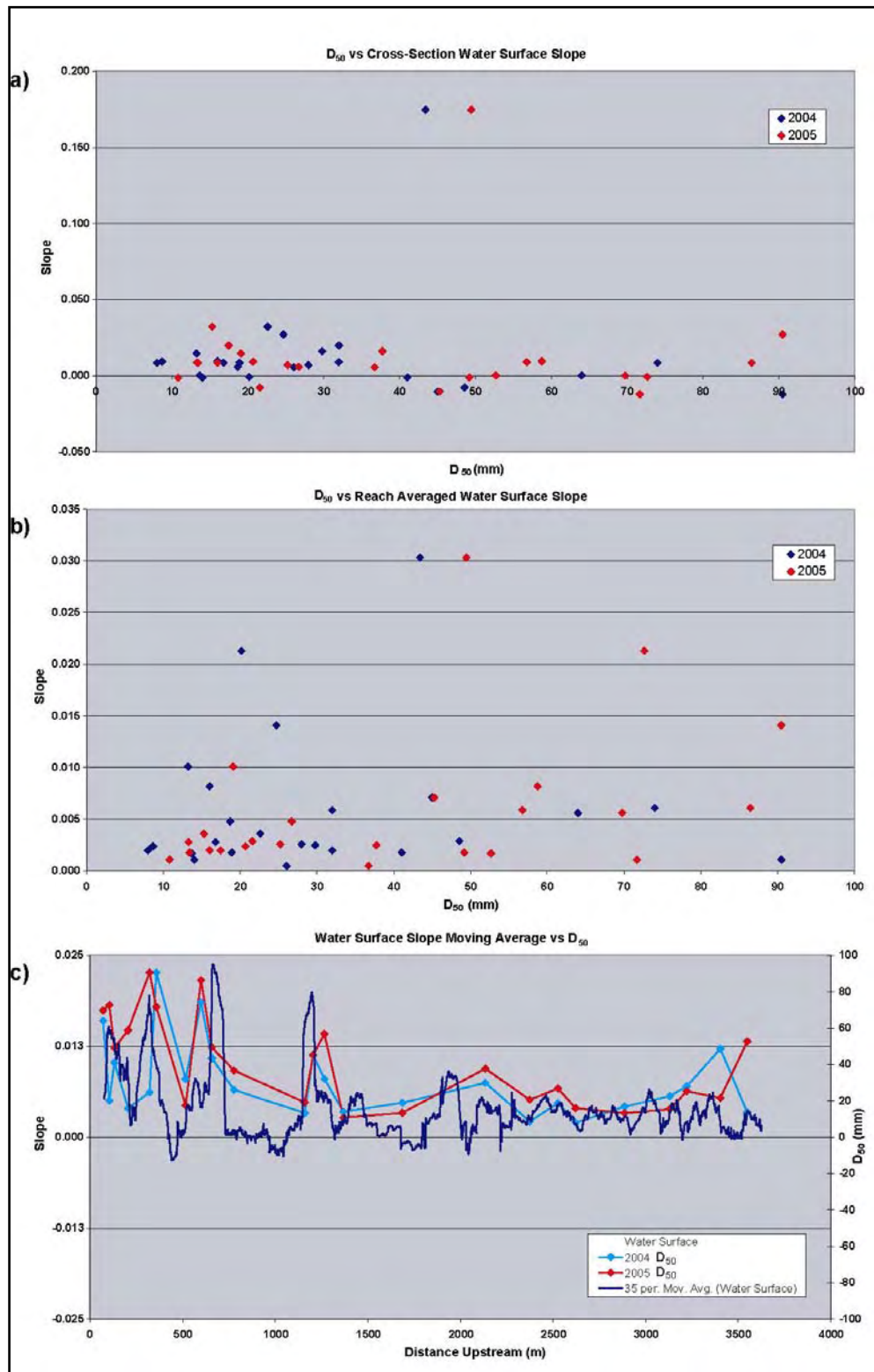


Figure 25. Relationships between channel slope and D_{50} for Valley Creek: a) D_{50} vs cross-section water surface slope, b) D_{50} vs reach-average water surface slope, and c) water surface slope profile and D_{50} .

Fine Sediment Storage in the Streambed

In order to estimate the mass of fine sediment stored in and potentially remobilized from the streambed, the depth of maximum scour was determined for each cross-section between the baseline survey in summer 2004 and the final survey after the 5-year event in April 2005. The depth of maximum scour was then multiplied by the channel width, which is the distance between the left and right edge of water, to obtain the area of maximum possible scour for each cross-section. This area was multiplied by the length of channel that each cross-section represents to estimate the volume of sediment in m^3 which can potentially be mobilized in the channel.

The estimated volume of sediment was converted to mass using bulk density estimates based on particle size distributions of the streambed. Particle size distributions were obtained from the barrel samples because they measure more of the fine bed material than is sampled with the pebble counts. Barrel samples were measured for 19 of the 36 cross-sections in summer 2004 and 16 of the 19 cross-sections in summer 2005. Particle size distributions were used from the summer 2004 data because more cross-section data are available for this dataset (19 compared to 16 cross-sections) and the 2004 data represent the particle sizes that were initially available for transport at the beginning of the study period. For cross-sections where the bed was too coarse to measure with the barrel sample, the pebble count data were used as a surrogate. Some cross-sections were too deep to be measured by either the barrel sampler or pebble counts. For these cross-sections, estimates of the particle size distributions were made based on visual comparison of the streambed with other cross-sections where measurements were available. Bulk density values were obtained from Smith and Wheatcraft (1993) and are provided in Table 1a–b. For the Valley Creek particle size classes where estimates from Smith and Wheatcraft (1993) were unavailable (2–10 mm [0.08–0.4 in] and 10–32 mm [0.4–1.26 in]) the bulk densities were obtained by interpolation between bulk density for the previous size class and the solid rock (>32 mm [1.26 in]) bulk density of 2.65 g/cm^3 .

The volume of sediment represented by each cross-section was multiplied by the bulk density estimate of streambed sediment based on particle size to obtain the mass of sediment stored in the channel. Calculations for the mass of fine sediment stored in the bed can be found in Appendix G. Table 2 shows the result of these calculations.

The total mass of sediment sand size and smaller stored in the mobile layer of the streambed within VAFO is estimated to be 4,700 tons. The amount of very fine sand, clay, and silt (particle size <0.075 mm) stored in the mobile layer of the streambed is estimated to be 1,500 tons.

To determine the change of fine sediment stored in the bed between the baseline survey (summer 2004) and the final survey after the 5-year event in April 2005, the amount of scour and deposition calculated from cross-section surveys (Figure 21) was used. The area of change was multiplied by the length of channel that each cross-section represented to estimate the volume of scour and deposition. Bulk density estimates were then used to calculate the mass of scour and deposition as described in the previous paragraphs. Calculations for the mass of sediment scoured and deposited in the streambed are provided in Appendix H. The results from these calculations are shown in Table 3. The estimated net change in the mass of sediment sand size

Table 1a. Bulk density estimates for streambed sediment obtained from Smith and Wheatcraft (1993).

Sediment Classification	Bulk Density (g/cm ³ = metric tons/m ³)
Clay	1.59–1.06
Silt	1.72–1.33
Fine Sand	2.12–1.46
Coarse Sand	2.25–1.72

Table 1b. Bulk density estimates for Valley Creek particle size distributions based on and interpolated from Smith and Wheatcraft (1993).

Sediment Classification	Particle Size Class (mm)	Bulk Density (g/cm ³ = metric tons/m ³)
Clay and Silt	0.00045–0.063	1.33
Very Fine Sand	0.063–0.075	1.46
Very Fine to Very Coarse Sand	0.075–2	1.72
Very Fine to Medium Gravel	2–10	2.25
Medium to Coarse Gravel	10–32	2.4
Coarse Gravel to Cobbles and Boulders	>32	2.65

Table 2. Estimated mass of sediment stored in the streambed of Valley Creek in Valley Forge National Historical Park (summer 2004).

Sediment Classification	Particle Size Class (mm)	Mass (metric tons)
Clay and Silt	0.00045–0.063	720
Very Fine Sand	0.063–0.075	760
Very Fine to Very Coarse Sand	0.075–2	3200
Very Fine to Medium Gravel	2–10	4000
Medium to Coarse Gravel	10–32	6000
Coarse Gravel to Cobbles and Boulders	>32	19000

Table 3. Mass of deposition and scour of the streambed of Valley Creek within Valley Forge National Historical Park from the baseline survey in the summer of 2004 to the 3rd storm event on April 2, 2005.

Sediment Classification	Particle Size Class (mm)	Deposition (metric tons)	Scour (metric tons)
Clay and Silt	0.00045–0.063	72	230
Very Fine Sand	0.063–0.075	80	250
Very Fine to Very Coarse Sand	0.075–2	310	1000
Very Fine to Medium Gravel	2–10	330	1100
Medium to Coarse Gravel	10–32	440	1700
Coarse Gravel to Cobbles and Boulders	>32	1800	5300

and smaller on the streambed was 1,000 tons of scour. The estimated net change of fine sediment (<0.075 mm) was 330 tons of scour.

Bankline Surveys and Analysis

The locations of sites identified in the field as having unstable banks are shown in Figure 26. Appendix I contains photos from each of the locations shown in the figure. Banklines from ten locations with visual evidence of severe erosion (1, 2, 4A, 4B, 10, 11, 21, 22, 35, 38) were chosen for detailed surveys. These ten locations represent bank lengths ranging from 10–80 m. Survey data were used to calculate bank erosion volume per unit length of bank in m^3/m as well as average distance of top bank retreat. Additional information on bank erosion rates was derived from the set of 36 resurveyed cross-sections that were used to measure changes on the bed. Figure 27 shows the average cross-sectional area (calculated as volume per unit length) of bank retreat for the ten bankline survey locations (shown as vertical bars) and for the 36 cross-sections (shown as a series of points connected by line segments). The longitudinal profile is superimposed on these plots, as well as the major geologic divisions and locations of anthropogenic features (overpasses, dams, and bridges).

Although only the values of erosion volume per unit length are plotted, lateral rates of bank retreat (area per unit length over the measurement period, or m of bank retreat) follow the same general pattern. The highest erosion rates are measured along the downstream section of the channel where gradients are steeper, the bed is coarser, and banks generally are high, most notably in reaches 1–5; a secondary maximum occurs along the transition from reach 7 to reach 8. By contrast, bank erosion rates are relatively low along the upstream 1,800 m (5,905 ft) of Valley Creek within VAFO. The bankline surveys overlap the locations of surveyed cross-sections in some cases, but even where they do overlap, the cross-section represents a single point along the bankline and there is no reason to expect a perfect match with the average for the more extensive bankline survey. Along reach 10 there are two bankline survey locations; the larger value ($2.2 \text{ m}^3/\text{m}$) is somewhat anomalous and is not representative of the rest of reach 10. This location was selected for study specifically because it was a local maximum, in order to account for the volume of sediment derived from bank erosion at that site.

The amount of bank retreat illustrated in Figure 27 represents changes measured between the original baseline survey in summer 2004 and the final resurvey after the 5-year flood event on April 2, 2005. Initial surveys were conducted at the end of June and beginning of July 2004 and final surveys were conducted between early April and mid-June of 2005, but most of the observed bank erosion occurred as a result of one of the major storm events described previously. Qualitative observations of the banklines, based on numerous visits to the erosion sites between storm events, suggested that little change occurred during the time interval between these storms. Although Figure 27 does not depict the values measured during the intervals between major storms within the study period, those values have been tabulated and are presented for the 10 bankline survey locations in Table 4. The volume of bank erosion and distance of bank retreat was greater for the 10-year flood event of September 2004 than the 5-year event in April 2005 for locations 1 and 2 in the downstream reaches, as well as for 21, 35, and 38 in the upstream reaches. Erosion location 1, for instance, had $2.1 \text{ m}^3/\text{m}$ of erosion and 0.6 m of bank retreat from the 10-year event. In comparison, the 5-year event generated $0.5 \text{ m}^3/\text{m}$ of erosion and 0.3 m of bank retreat. For the remainder of the banks, the volume of erosion and rate

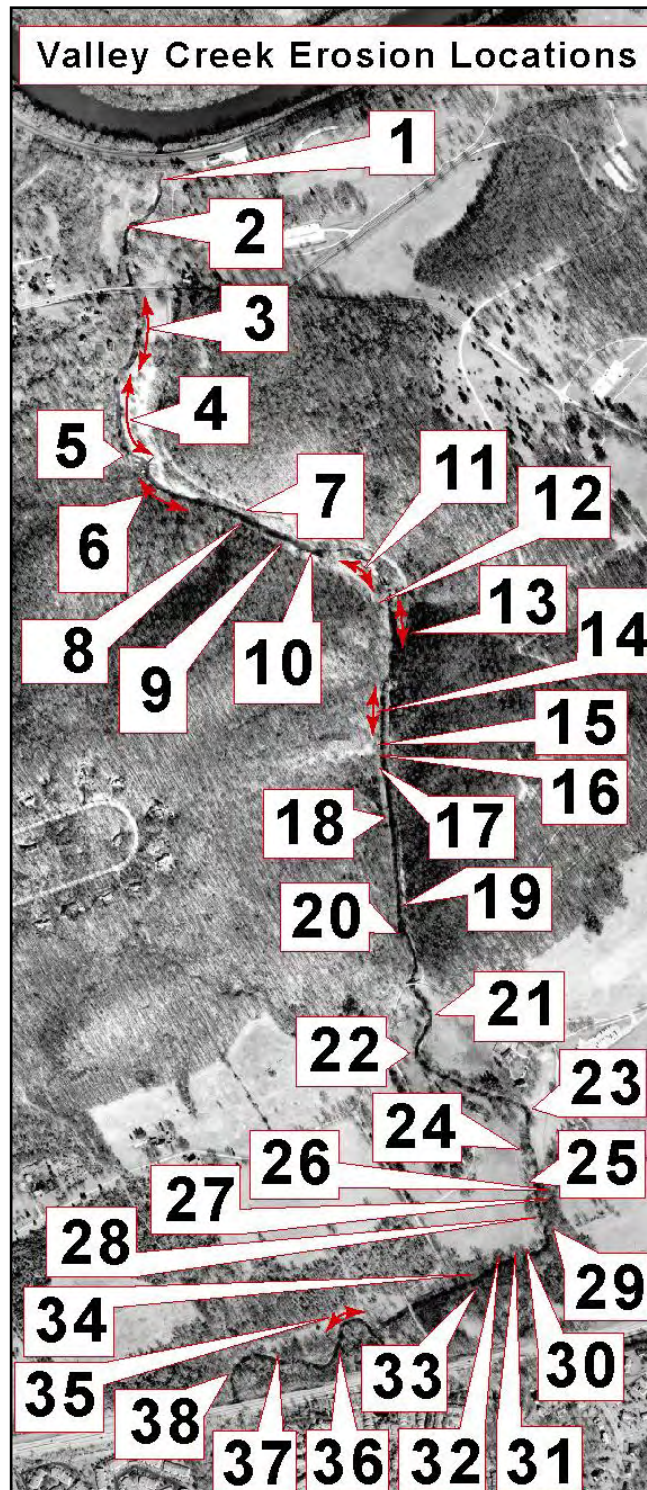
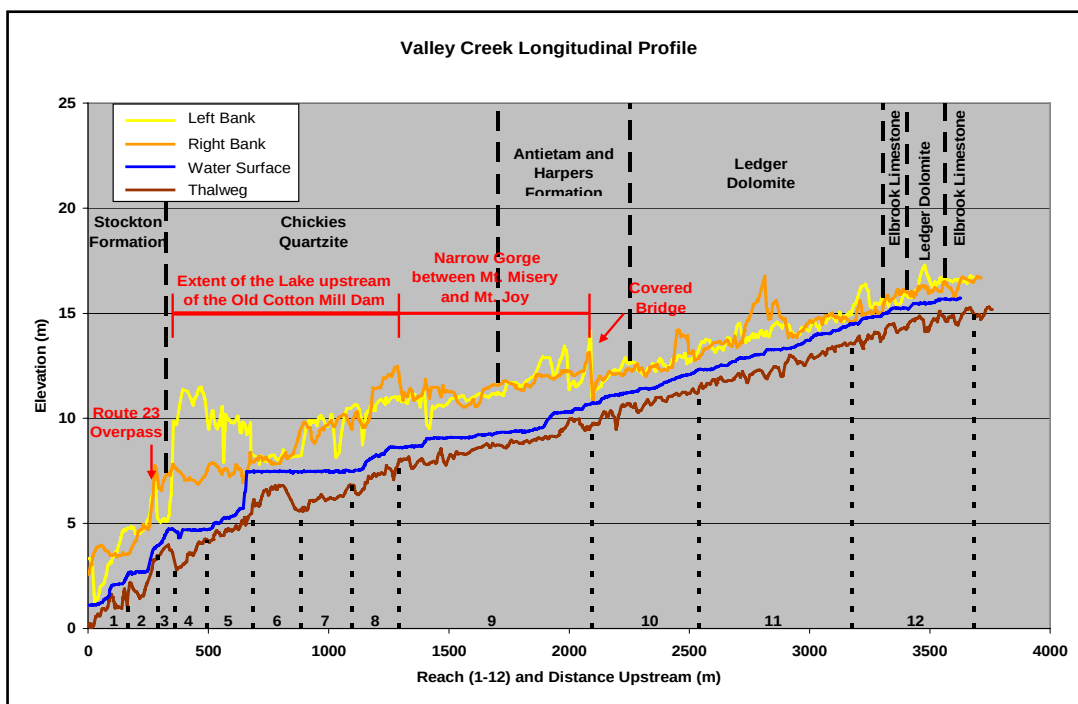


Figure 26. Bank erosion locations for Valley Creek. Detailed bankline surveys were carried out at locations 1, 2, 4A, 4B (erosion location 4 was split into 4A and 4B after further field investigation to better capture the variability of bank characteristics at that location), 10, 11, 21, 22, 35, and 38 which had the most severe erosion. The long straight stretch of channel between erosion locations 11 and 21 is located between Mount Misery and Mount Joy.

a.



b.

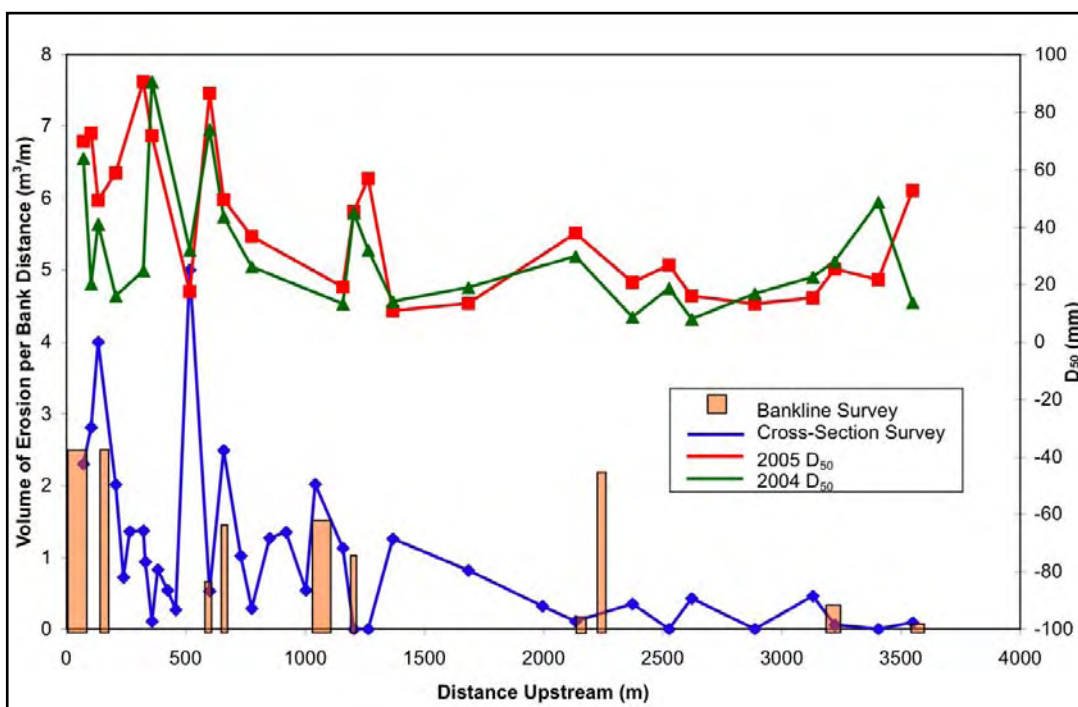


Figure 27. (a) Valley Creek longitudinal profile of bed, water surface, and banks (September 2003–May 2004) with study reach boundaries and geologic contacts; (b) Valley Creek longitudinal pattern of bank erosion from cross-section and bankline surveys (July 2004–2005) and longitudinal pattern of median bed particle size (2004 and 2005).

Table 4. Measured erosion from repeat bankline surveys of Valley Creek from the baseline survey in the summer of 2004 to the 3rd storm event on April 2, 2005.

Bankline Survey Location	Distance Upstream (m)	Total Volume Eroded (m ³)			Volume Eroded per Length of Channel (m ³ /m)			Average Distance of Top Bank Retreat (m)			Average Distance of Bottom Bank Retreat (m)		
		Post-Sept. 2004 Storm	Post-April 2005 Storm	Total	Post-Sept. 2004 Storm	Post-April 2005 Storm	Total	Post-Sept. 2004 Storm	Post-April 2005 Storm	Total	Post-Sept. 2004 Storm	Post-April 2005 Storm	Total
1	41	156.5	34.7	191.2	2.05	0.46	2.51	0.56	0.29	0.85	1.06	-0.36	0.70
2	160	43.3	24.9	68.2	1.59	0.92	2.51	0.57	0.34	0.91	0.86	0.53	1.39
4B	592	15.2	7.1	22.3	0.47	0.22	0.69	0.05	0.2	0.25	0.42	-0.16	0.26
4A	660	12.5	12.5	25.0	0.74	0.74	1.48	0.21	0.45	0.66	0.57	0.36	0.93
10	1068	64.5	56.8	121.3	0.83	0.73	1.55	0.35	0.36	0.71	0.11	0.20	0.31
11	1202	11.4	12.3	23.7	0.51	0.55	1.06	0.15	0.25	0.4	0.19	0.15	0.34
21	2158	6.7	1.7	8.3	0.17	0.04	0.22	0.1	0.04	0.14	0.17	0.02	0.19
22	2240	14.3	40.6	54.9	0.57	1.63	2.20	0.26	0.34	0.6	0.49	0.34	0.83
35	3218	10.5	3.4	13.9	0.27	0.09	0.36	0.24	0.07	0.31	0.13	0.05	0.18
38	3568	1.0	0.1	1.1	0.11	0.01	0.11	0.06	0.00	0.06	0.14	0.01	0.15

of top bank retreat for the 10-year event was less than or equal to that of the 5-year event. At erosion location 22, the 5-year event generated more than twice as much erosion ($1.6 \text{ m}^3/\text{m}$) as the 10-year event ($0.6 \text{ m}^3/\text{m}$).

Locations of bank instability along gravel-bed streams are commonly associated with accumulations of coarse sediment forming channel bars that divert flow against the opposite bank, and several instances of this effect have been observed along Valley Creek, most notably at the erosion sites in reach 1 near Washington's Headquarters and along the transition from reach 7 to reach 8. Reach 8 is located at the upstream end of a pooled section of the channel behind the remaining active dam, and there is a tendency for sediment to accumulate along the steep section of channel just upstream of the pool. There is also a short stretch of meandering channel at this location just upstream of the long, straight pool behind the dam, and field observations indicate a tendency for islands and bars to form here with alternating scour and deposition of the channel bed. The local maximum value of D_{50} at this site is a short distance upstream of the local maximum bank erosion measurements at bankline survey locations 10 and 11. The mass of sediment derived from bank erosion is based on data from bankline and cross-section surveys discussed above (Figure 27); volume was converted to mass using bulk density values from soil maps of the region (NRCS and Penn State 2005). Although the survey period (from July 2004 to April, May or June 2005, depending on location) is less than a full year, qualitative field observations during late spring and early summer 2005 indicated little or no additional erosion. Therefore, the surveyed amounts of bank erosion are considered representative of the annual total for the period July 2004–July 2005.

The cumulative mass of bank erosion calculated for the ten bankline survey locations (Table 5) amounts to 711 metric tons. These ten locations are the most severe erosion sites. In estimating the mass of sediment derived from bank erosion along the entire length of Valley Creek within VAFO (Table 6), bankline changes from surveyed cross-sections (e.g. Figure 27) were used to supplement the bankline surveys. For Table 6 calculations, where one of the cross-sections overlapped a bankline survey location, we used the value from the bankline survey rather than the point value based on the cross-section. Along reaches where there were no bankline surveys we calculated the unit volume of bank erosion for individual cross-sections and multiplied these by channel longitudinal distances that were assigned to each individual cross-section based on field observations; the resulting values of cumulative erosion volume along each reach were cross-checked against an alternative calculation based on multiplying total reach length by a simple arithmetic average of the unit volumes of erosion for the three cross-sections within the reach. Typically, the results did not vary by more than 15–25%, and neither method yielded values that were systematically higher or lower than those derived using the other method. Along reaches where there were both bankline surveys and cross-sections, but where they did not overlap, the cross-section survey values were used to derive unit volumes of erosion for the part of the reach not covered by the bankline surveys. Along reach 9, which was the longest of the 12 reaches in this study, field inspection indicated the presence of riprap and stone walls protecting about 20% of channel length; therefore, the unit volumes of erosion were multiplied by a reach length amounting to 80% of the actual length.

Table 6 provides a summary of the total volume and mass of bank erosion estimated for the survey period by reach. The cumulative total amounts to $2,500 \text{ m}^3$ ($88,286 \text{ ft}^3$) of sediment, with a mass of about 3,400 metric tons (3,747 tons). Thus, the bankline surveys, covering a

Table 5. Volume and mass of bank erosion for the 10 surveyed Valley Creek bankline locations in Valley Forge National Historical Park for the period July 2004–2005.

Bankline Survey Locations*	Total Volume Eroded Baseline Survey to Storm 3 (m ³)	Bulk Density (g/cm ³)	Total Mass (metric tons)
1	191	1.35	258
2	68	1.35	92
4B	22	1.35	30
4A	25	1.35	34
10	121	1.35	164
11	24	1.35	32
21	8	1.30	11
22	55	1.30	71
35	14	1.30	18
38	1	1.30	1
Total:			711

*see Figure 26

Table 6. Cumulative volume and mass of bank erosion estimated from field measurements along Valley Creek for the period July 2004–2005.

Stream Reach*	Volume (m ³)	Mass (metric tons)
Reach 1	425	574
Reach 2	183	247
Reach 3	73	98
Reach 4	70	95
Reach 5	365	493
Reach 6	173	234
Reach 7	266	359
Reach 8	123	166
Reach 9	495	668
Reach 10	136	184
Reach 11	186	251
Reach 12	38	51
Totals	2,530	3,420

*see Figure 13

cumulative channel length of about 365 m (1,200 ft) or slightly less than 10% of the total channel length within VAFO, are believed to account for about 21% of the sediment derived from bank erosion.

Appendix J contains tabulated particle size distributions for the bank material of all 10 bankline survey locations. Seven of the 10 locations had bank compositions with 60% or more silt and clay (<0.063 mm [0.002 in]). The exceptions were erosion location 2 with a bank composition of 87% medium and coarse sand (0.075–2 mm [0.003–0.8 in]), erosion location 4A with a bank composition of 30% silt and clay and 32% medium and coarse sand, and erosion location 22 with a bank composition of 70% gravel or larger (>32 mm [1.26 in]). Each set of particle-size measurements was based on five vertically integrated samples taken from bank profiles distributed along the erosion site. As we do not have comparable particle-size data for all of the surveyed cross-sections, we have used these particle-size distribution data in order to estimate the mass of fine sediment derived from bank erosion along Valley Creek within VAFO. For each of the 12 reaches, we generated an estimate for the average percentage of bank sediment falling within each of our measured particle-size ranges based on values from the nearest sampling sites, and these percentages were multiplied by the total mass of bank erosion for the reach. The estimated mass of silt and clay derived from bank erosion along Valley Creek within VAFO for the period July 2004–July 2005 is 2,250 metric tons; the estimated mass of silt, clay, and fine sand, which is the quantity considered most comparable to the particle-size range of suspended sediment, is 2,340 metric tons, and the medium to coarse sand fraction accounts for an additional 865 metric tons.

Sediment Yield

A power law relationship describing suspended sediment concentration as a function of turbidity was derived from a log-log regression based on 25 suspended sediment samples collected by the ISCO sampler at the USGS Valley Creek gage on 11 dates between October 2005 and August 2006 (Figure 28). The regression equation was subsequently used to estimate suspended sediment concentration from turbidity data recorded at 15-minute intervals during the period between July 25, 2005 and September 30, 2006. Suspended sediment concentration and water discharge data were then used to generate a 15-minute time series of suspended sediment discharge values. These were integrated over time in order to calculate suspended sediment loads. Because of delays in the installation of the ISCO and optical probe, there is no overlap between the time series of suspended sediment data and the field measurements of bankline change and cross-section change. However, the data obtained from the ISCO and optical probe do allow us to estimate short-term watershed sediment yield, and the suspended sediment data can be compared with the field data on sediment derived from changes in the channel banks and bed.

For the 2006 water year (Oct. 1, 2005–Sept. 30, 2006), estimated sediment load was 2,230 metric tons (t) or 41.4 t/km²/yr. Suspended sediment loads were also calculated for every consecutive 365-day period between July 25, 2005 and September 30, 2006; the maximum and minimum calculated values were 2,230 t and 1,660 t (30.9 t/km²/yr), respectively.

The relationship between discharge and turbidity shows a broad range of scatter, with up to two orders of magnitude variation in the range of turbidity values associated with a single value of

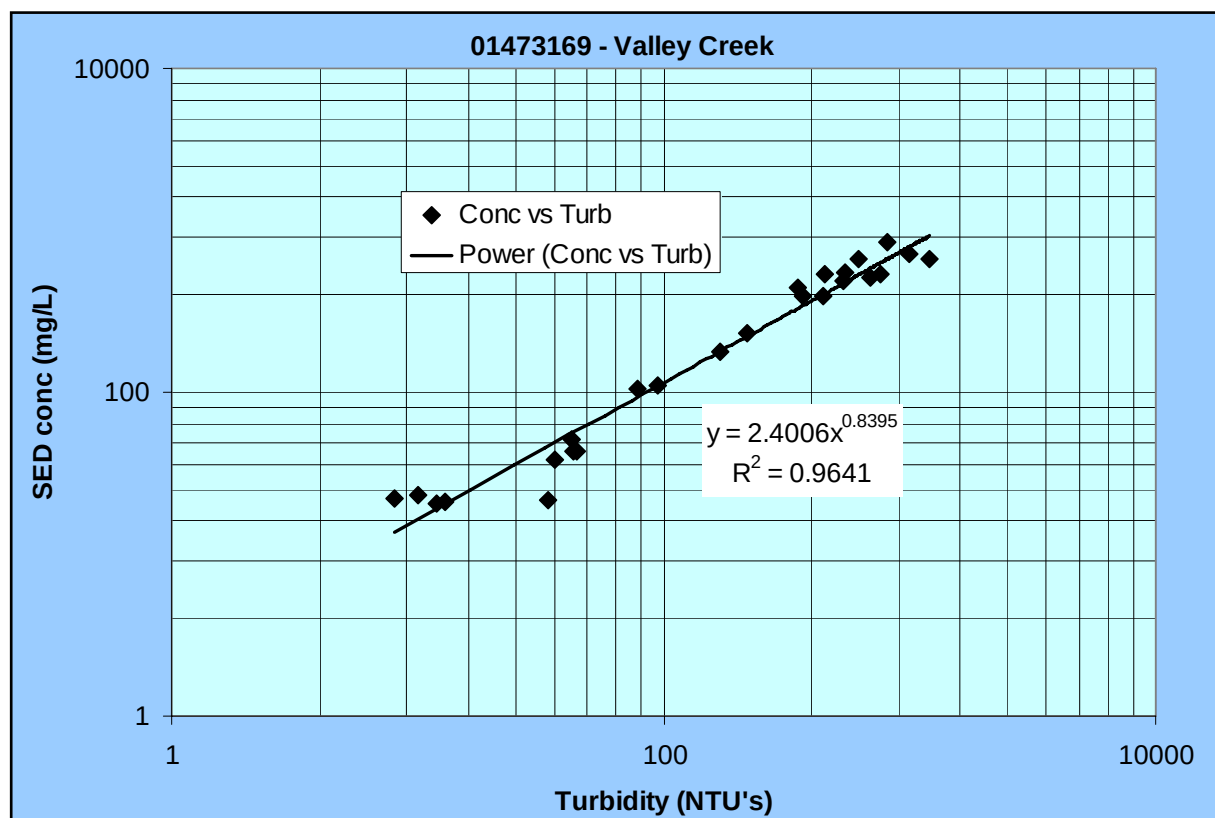


Figure 28. Relationship between suspended sediment (SED) concentration in mg/L and turbidity in NTUs for Valley Creek at the USGS stream gage between October 2005 and August 2006.

discharge over the 14-month period represented by the turbidity data (Figure 29). There does appear to be some seasonality to the relationship: in general values collected during the period of June–August 2006 are higher than the values collected during the period of October–November 2005, and values collected during the period of February–April 2006 fall in between these two ranges. On the other hand, there is also the potential for year-to-year variation in the same month that shows even greater separation than the separation between seasons, as indicated by the comparison of September 2005 and September 2006. This suggests that the sequencing of weather events may play an important role in determining the amount of sediment produced by runoff events and that simple seasonal relationships may not be reliable predictors of sediment concentration or sediment load for any particular year.

A considerable amount of variation may be observed even over the duration of a single storm event. The complex hydrograph shown in Figure 30 has two major peaks and four subsidiary peaks. The figure clearly shows that for the two major peaks turbidity reaches a maximum on the rising limb of the hydrograph and then quickly drops to a small fraction of the maximum value while discharge is still near its peak. The resulting pattern of hysteresis in the

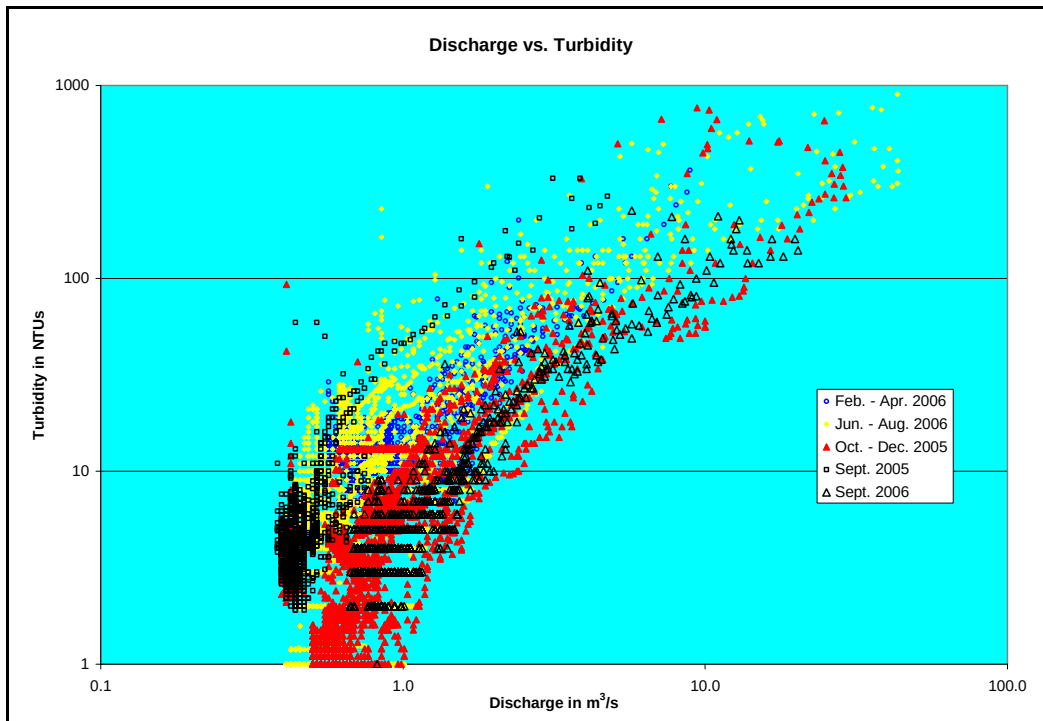


Figure 29. Scatter plot showing trends in the turbidity–discharge relationship for Valley Creek at the USGS stream gage.

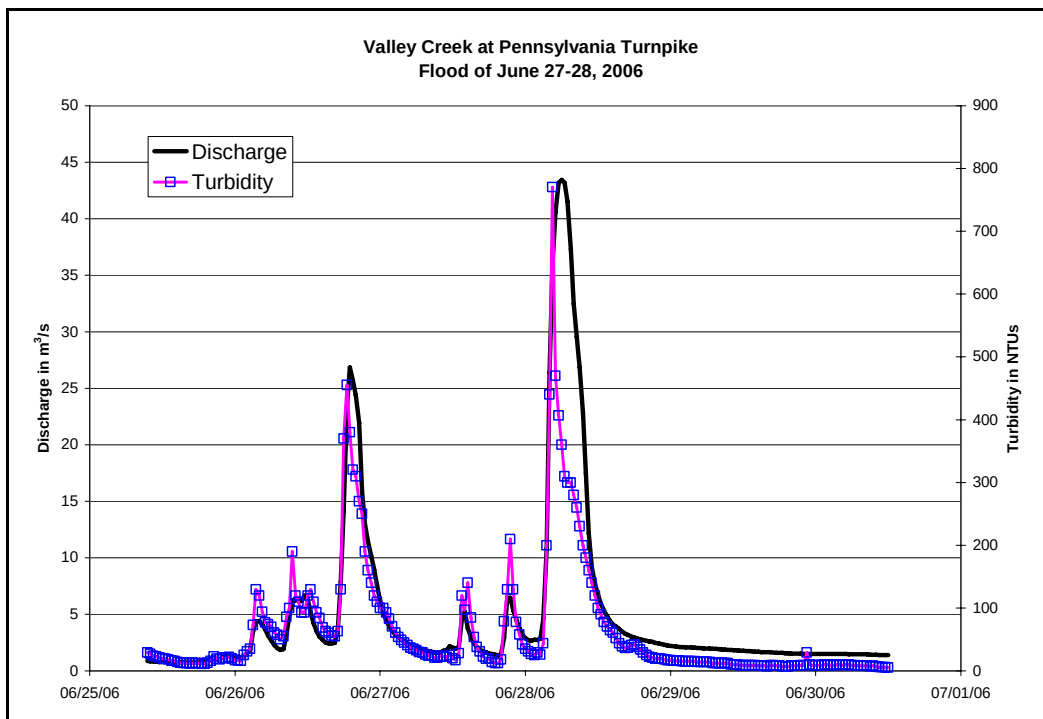


Figure 30. Plot showing discharge and turbidity for a complex hydrograph in June 2006 for Valley Creek at the USGS stream gage.

concentration-turbidity relationship is illustrated in Figure 31 for the two large hydrograph peaks during this storm event. These figures illustrate that even within a single storm it is impossible to define a simple rating curve relating turbidity to discharge; therefore, it is equally impossible to define a simple discharge-concentration relationship for instantaneous flow rates.

Nevertheless, it is likely that some of the variability can be explained by changing patterns of sediment availability. For example, the rising limb of hydrograph 2 has much lower turbidity values than the rising limb of hydrograph 1, but is fairly close to the trend on the falling limb of hydrograph 1, suggesting the possibility that some depletion of the readily available sediment supply may have occurred during the earlier part of this multiple-peak event

Although the discharge-turbidity relationship suggests that it would be difficult to predict sediment concentrations based on discharge alone, it is, in fact, possible to generate predictions of suspended sediment load integrated over the entire hydrograph simply using peak discharge as an explanatory variable. Gellis (2003) reached the same conclusion in a study of a tropical watershed in Puerto Rico. For Valley Creek, storm-period sediment loads were calculated for 36 individual events with peak discharge above $2 \text{ m}^3/\text{s}$ ($70 \text{ ft}^3/\text{s}$) for which both flow and turbidity data were available at the stream gage, and a power-law relationship was developed for prediction of storm-period sediment load as a function of peak discharge. The data and the fitted trend are illustrated in Figure 32. Although there is considerable scatter around the trend, the trend has an R^2 value of 0.905 and is considered a more reasonable predictor if applied to a series of storm events in calculating cumulative sediment load than if we were seeking a reliable value for a single storm.

The sum of the storm-period sediment loads predicted for these 36 events based on the power function is equal to 95.3 percent of the sum of the storm-period sediment loads calculated from the original data and is, therefore, a reasonable surrogate for estimating general trends in the relationship between flow and suspended sediment load. The 36 storm events used in the analysis accounted for 87.7 percent of the total suspended load for the period between July 25, 2005 and September 30, 2006. The six largest discharge peaks accounted for 60 percent of the total and the three largest peaks accounted for 40.2 percent of the total. Using the derived power-law relationships from Figure 32 together with discharge records from the USGS gage, we estimate that flow events with peak discharge exceeding $2 \text{ m}^3/\text{s}$ ($70 \text{ ft}^3/\text{s}$) during the period July 18, 2004–July 17, 2005 accounted for a cumulative 3,930 t ($73 \text{ t}/\text{km}^2/\text{yr}$) of suspended load.

This period was chosen because it coincides with the 12-month period during which the field data on bank erosion and channel change were collected. If we assume that lower flows during the remainder of this 12-month period accounted for about 280 t of suspended sediment (as was the case for the 2006 Water Year), we can estimate a total suspended load of about 4,200 t and a sediment yield of $78 \text{ t}/\text{km}^2/\text{y}$, nearly double the values calculated for the 2006 Water Year. This same 12-month period had an average discharge of $1.49 \text{ m}^3/\text{s}$ ($52 \text{ ft}^3/\text{s}$), more than double the average for the 2006 water year ($0.59 \text{ m}^3/\text{s}$ [$20 \text{ ft}^3/\text{s}$]) and about 60% higher than the average for all years of record from 1983 to 2004. Thus, the projection establishes a basis for comparison between suspended load at the Valley Creek gage and other components of the Valley Creek sediment budget during the same time period.

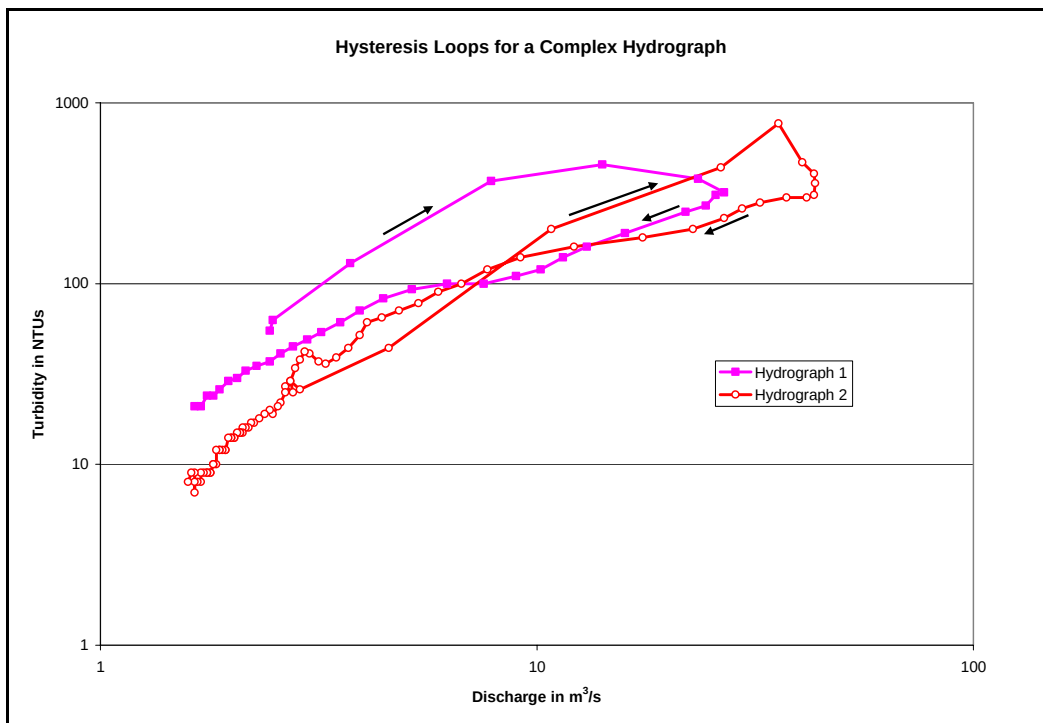


Figure 31. Plot showing hysteresis loops for the two large hydrograph peaks shown in Figure 30.

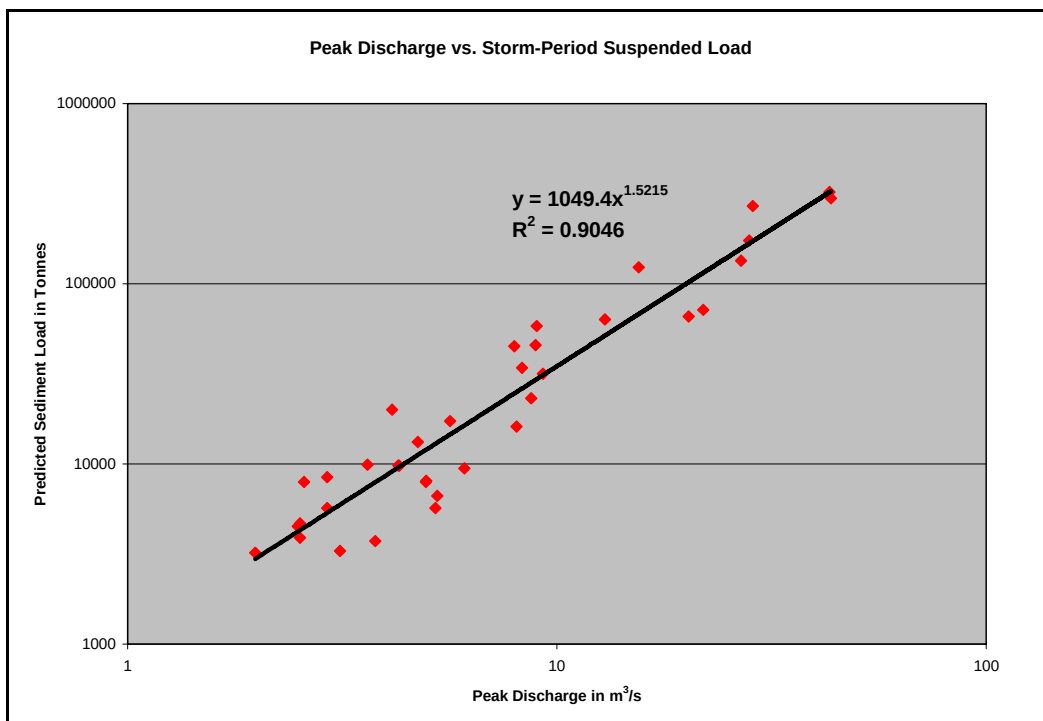


Figure 32. Peak discharge versus sediment load for Valley Creek at the USGS stream gage for 36 storm events from July 25, 2005 through September 30, 2006. The power-law relationship can be used to estimate storm-period sediment load for storms with peak discharge exceeding 2 m³/s (70 ft³/s).

Tracer Gravels

Tracer gravels were used to determine the distance traveled by labeled bed particles, as well as the particle sizes mobilized as a function of discharge. Eight cross-sections were monitored with this technique based on their accessibility and the probability that the gravels would not be disturbed by recreational users of the stream. Figure 33 shows the tracer gravel data for cross-section 11B. Data for the other seven cross-sections can be found in Appendix K. The ID number assigned to each particle is indicative of its size class. For example, the number 32 indicates that the particle was measured by a gravelometer and fell within the range of 32–45 mm. Two particles of each size class, identified as A and B, were placed in the cross-section.

Figure 33b shows that particle 11B moved backwards into the flow approximately 50 cm (19.7 in). This was most likely caused by disturbance from a recreational user. This cross-section is occasionally used by fishermen. Many of the particles were not relocated, especially during the last couple of monitoring periods.

The particle size classes used in the tracer gravel study ranged from 8–90 mm (0.31–3.5 in). The results show that particle size mobilized as a function of discharge is highly variable. During low flow events, the largest particles were mobilized in some cross-sections. When the discharge was less than $2 \text{ m}^3/\text{s}$ ($70 \text{ ft}^3/\text{s}$) between sampling intervals, the largest particle size class of 64–90 mm (2.5–3.5 in) was mobilized at cross-section 11B. In comparison, some of the high-flow events did not mobilize the largest particle sizes that were previously mobilized by low flow. For example, when the discharge was approximately $13 \text{ m}^3/\text{s}$ ($459 \text{ ft}^3/\text{s}$), a smaller size class of 32–45 mm (1.25–1.75 in) was mobilized.

The same observation is made with the other seven cross-sections and shows that sediment transport is highly variable. However, the tracer gravels do provide an indication of the likelihood of particles being mobilized, as well as the net distance of transport that might be expected over a range of storm events.

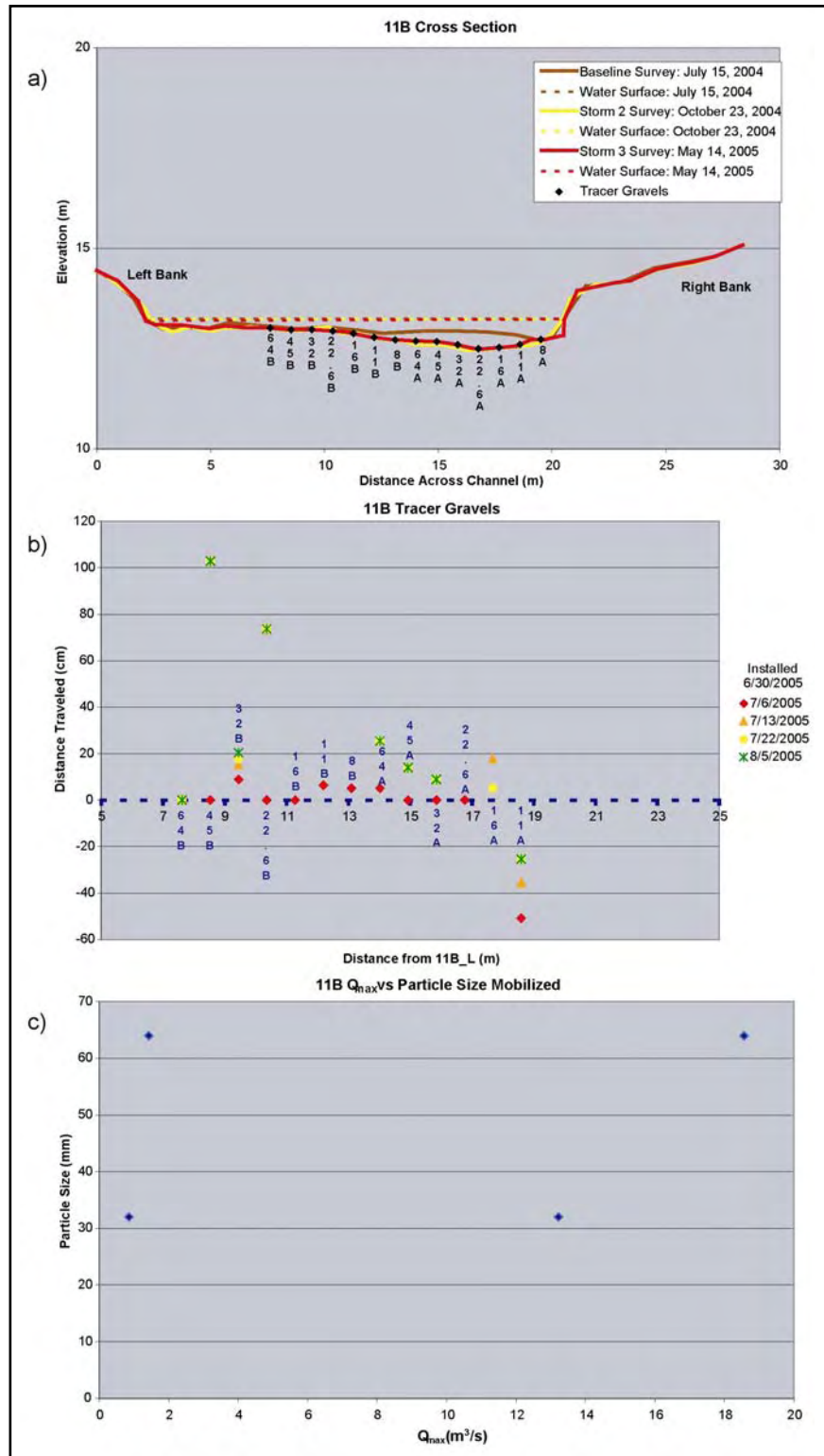


Figure 33. Tracer gravel data for Valley Creek cross-section 11B: a) location of tracer gravels along cross-section, b) distance moved by tracer gravels, and c) particle size mobilized as a function of maximum discharge.

Discussion

In this section we provide interpretation of key results presented in the previous chapter with the objective of addressing their relevance and applicability to conditions in VAFO.

Bed Material Particle Size

Measurement of bed material particle size is important for evaluation of the fine sediment content of spawning gravels and substrate suitability for other habitat needs (Kondolf 1997). The stream bed particle size also influences channel hydraulics, mediates the exchange of water between flow and bed, and determines the sediment available for transport (Wilcock and DeTemple 2005). Both surficial grid-based pebble counts and volumetric barrel samples were used to estimate changes in streambed particle size between the summers of 2004 and 2005. Volumetric barrel samples were not collected along most of reaches 1 through 5 because the bed was too coarse for the barrel to be used.

Comparison of Measurement Methods

In our view, the pebble count data are better indicators of the surface particle size distribution than the barrel samples. Although the barrel method is intended to sample the surface layer of the streambed, it is subject to more sampling errors than the pebble counts. In the barrel method, separating the surface and subsurface layers is based on the operator's perception; whereas, in the pebble count method, the grid-based approach specifies precise locations for particle collection. Additional error may be introduced into the barrel samples based on the sample size collected. Reid and Dunne (1996) recommend collection of large enough samples such that the largest stone represents less than 5% of the total sample weight. However, this was not possible for many locations in Valley Creek. Large cobbles and small boulders can be found throughout the channel and some were included in the barrel samples. Samples large enough to meet the 5% criterion would require sample sizes of 50 to 100 kg (110–220 lb) or even larger.

Although the barrel method is subject to error as described above, it does provide an indication of the amount of fine sediment in the streambed. The smallest particle size measured with the pebble count was coarse sand. By comparison, the material obtained from the volumetric barrel sample was sieved and provided an indication of the relative amounts of coarse, medium, and fine sand, as well as combined silt and clay in the streambed. This was our only means of characterizing fine sediment storage in the bed of Valley Creek.

Because the barrel could not be inserted any further than 5 cm (2 in) due to resistance from the substrate, the volumetric samples are mostly representative of the surface material, or armor layer, and not the subsurface. Analysis of the subsurface compared to the surface would be valuable, but the amount of effort needed for sampling would have been considerably higher than was feasible, given the scope of this project.

As indicated in the results chapter, half of the 16 cross-sections sampled volumetrically with the barrel sampler showed the same patterns of change between 2004 and 2005 as the grid-based pebble counts, and the other half of the barrel samples showed inconsistencies with the pebble count data. In the latter case, most often the pebble count indicated that the cross-section

coarsened, while the barrel sample indicated that it had become finer. The discrepancy between the two sampling techniques is probably attributable to the inclusion of matrix material stirred up in the process of extracting the barrel samples.

Longitudinal Patterns of Particle Size

As indicated in Figures 24 and 25, there is a pronounced longitudinal trend in the median particle size on the bed of Valley Creek in VAFO, and particle size appears to vary in tandem with channel gradient. Gradients are steeper and median particle size is coarser along the downstream reaches (particularly reaches 1–5) than elsewhere within VAFO, and the longitudinal variability of particle size and gradient are also more pronounced along the downstream reaches. Although we cannot reconstruct a highly articulated fine-scale relationship between lithology and particle size, it is clear that the downstream reaches are dominated by the more resistant rock types, the Chickies Quartzite and Stockton Formation. The coarsest particles on the bed of Valley Creek, which are found along the steepest parts of the creek, are derived from Chickies Quartzite. The Ledger Dolomite and Elbrook Limestone, both moderately resistant to non-resistant, are the dominant lithologies farther upstream; the Antietam and Harpers Formations are dominant for about 500 m (1,640 ft) of channel in the middle section of the longitudinal profile and are variably resistant to weathering. Most of the cross-sections with significant percentages of fine sediment are located in upstream reaches of the park (reaches 10–12), and downstream of these reaches the channel generally lacks a significant percentage (or absolute volume) of fine sediment.

Temporal Changes in Bed Material Particle Size

The channel of Valley Creek exhibited general coarsening of the streambed during the period of study (Figures 24, 25, and 27; see Figures 17–19 for detailed information on individual cross-sections). This coarsening can most likely be attributed to the two largest storm events that occurred during the sampling period: a 10-year event in September 2004 and a 5-year event in April 2005. The pebble counts revealed that the reaches farthest downstream coarsened the most over the sampling interval. In the downstream reaches, flood flows are mostly contained within the high banks, creating greater stream power and greater capacity for winnowing fines from the streambed as compared with the upstream reaches. Coarsening of the bed during the period of the study was less pronounced upstream, and in some upstream locations (e.g., cross-sections 11B, 11C, 12A, and 12B) the streambed actually became finer between 2004 and 2005 (Figures 24 a and b). The upstream reaches have flatter gradients, lower velocities, and lower stream power than the downstream reaches. The channel form is more sinuous, the banklines are lower, and a well-developed floodplain is present. High flows, therefore, are not constrained within the channel and are less likely to winnow fines from the bed.

Even at the sites in reaches 11 and 12 where our sediment samples indicate fining of the streambed between 2004 and 2005, there appears to have been net scour of the streambed during the same time period. This seems counterintuitive; scour should lead to coarsening of the bed or leave the armor layer essentially the same. Although the subsurface layer is typically finer than the armor layer, transport conditions capable of mobilizing the armor layer also tend to flush fines from the newly exposed subsurface and result in the formation of a new armor layer (Parker and Klingeman 1982). One possible explanation of the apparent discrepancy observed here is

that the fining is not significant enough to be statistically meaningful. A paired-sample t-test (parametric) and Wilcoxon signed ranks test (non-parametric) were conducted to determine whether the change in D_{50} was statistically significant for the four cross-sections (11B, C; 12 A, B) where fining appears to coincide with net scour. For three of these four cross-sections the tests suggest that the change in particle size is statistically significant (Appendix L). Another possible explanation of cross-section fining in conjunction with net scour of the streambed is that bed scour occurred during the larger floods and was followed by deposition of finer sediment during subsequent smaller storm events. The final set of particle size measurements was made two to three months after the 5-year storm event in April 2005 and several smaller storms occurred during that time interval.

Channel Erosion and Sedimentation

Channel response to urban development is a result of the combined influences of altered watershed hydrology and altered sediment yield (Wolman 1967; Guy and Ferguson 1962; Yorke and Herb 1978). In the active construction phase of development channels may be inundated by sediment derived from soil erosion; however, once construction is complete, sediment yield from upland sediment sources may decrease to background levels, while watershed hydrology retains a strong urban signal with increased peak flows and flashier hydrographs. The imbalance between increased flow and reduced sediment load supplied from the land surface may result in progressive channel erosion (e.g. Wolman 1967; Hammer 1972). As channels begin to unravel, however, the amount of sediment derived from the channel network increases, leading to locally varying patterns of deposition and scour of bed material as well as bank instability and erosion.

Upstream of the park boundary, Valley Creek watershed has undergone significant urbanization since 1970. Land cover is currently 18% impervious and the trend toward increasing urban development may be responsible for the observed increase in annual peak flow (Figure 5). Bank erosion has been identified as a serious problem within the watershed, with approximately 30% of stream reaches designated as “severely eroded” (CCWRA et al. 2004). Within VAFO, Valley Creek shows evidence of alternating bed scour and deposition, as well as significant bank erosion at several locations.

Patterns of Bed Scour and Deposition

Comparison of cross-section surveys conducted during the study period reveals longitudinal patterns of scour and deposition on the bed of Valley Creek within VAFO. The most dramatic changes occurred in the downstream reaches (e.g. cross-section 1B in Figure 17). In this case, the channel eroded on the right bank, whereas, sediment deposition occurred on the bar along the left bank. Many other areas of the channel are relatively stable and show little or no change throughout the survey period (e.g. cross-section 9B, Figure 18). Only a few areas show evidence of cyclic cross-section change (e.g. Figure 20, as described in the section on cross-section surveys in the Results chapter).

Figure 23 shows that nine of the 12 reaches experienced net scour during the period covered by field measurements. Most scour was caused by the large storms of September 2004 and April 2005. Gupta and Fox (1974) and Costa (1974) found that channel morphology changes measured along streams in the Maryland Piedmont in the aftermath of Tropical Storm Agnes in

1972 were only temporary. Within a year, deposition by normal flows returned channel widths almost back to their preflood values. It is possible that the channel response of Valley Creek to the two significant storm events during the study period was similarly only temporary. Long-term monitoring results would be needed to place the channel changes observed during the study period in context.

Most of the deposition measured in the channel occurred along the downstream one-third of Valley Creek within VAFO (reaches 1–8), where the banklines were the highest and where the longitudinal variability of channel gradient was greatest (Figures 16, 21, 22). In these reaches, the channel has little connection with its floodplain and sediment cannot be deposited and stored in this reservoir. Instead, it is contained within the channel and is either deposited in the downstream reaches or transported to the confluence with the Schuylkill River. Upstream of the covered bridge, where the banklines are lower and Valley Creek has a well-developed floodplain, a larger proportion of flood flow inundates the floodplain. Although little deposition occurred during the study period within the active channel in these upstream areas, substantial volumes of sediment appear to have been deposited on the adjacent floodplain areas.

Bank Erosion

The spatial trend in bank erosion within VAFO is essentially similar to the trends described above with respect to bed scour and deposition. Both volumetric erosion rates and lateral rates of bank retreat are highest along the downstream reaches where banks are high and bed texture is coarse (Figure 27), and local particle-size maxima are, in turn, associated with the steepest and most variable channel gradients (Figure 25). The most severe erosion is associated with a high bank at Washington's Headquarters, just upstream of the confluence with the Schuylkill River. As discussed above, the confining effect of high banks—some of which are associated with legacy sediment deposits left behind by historic mill dam impoundments—leads to greater velocities and more erosive shear stresses in the channel. Local accumulations of coarse sediment on the bed are associated with channel bends and with breaks in channel gradient, and these, in turn, help to steer the flow against the banks causing localized instability. Although there are significant spatial differences in the percentage of silt and clay in bank materials—and therefore, presumably, significant differences in cohesiveness and resistance to erosion (Simons and Li 1982)—there is not enough evidence to suggest a connection between bank material properties and erosion rates. Our working assumption is that local channel morphology and channel hydraulics exert a controlling influence on patterns of bank erosion. It is noteworthy, for example, that the highest measured bank erosion rate along the upstream 2,000 m (6,561 ft) of Valley Creek (location 22, Figures 26, 27) is associated with the outside bank at a sharp bend in the channel.

The temporal pattern of bank erosion is clearly related to the hydraulic conditions associated with major flood events—notably the September 2004 and April 2005 floods, discussed above. Repeat surveys were conducted after each of these floods and Table 4 presents a comparison of volumetric erosion and distance of lateral retreat calculated for each of the 10 bankline survey locations following these two major floods. Although the September 2004 event is estimated as a 10-year flood and the April 2005 event is estimated as a 5-year flood (Appendix D), peak discharge in September 2004 ($78 \text{ m}^3/\text{s}$ [$2,750 \text{ ft}^3/\text{s}$]) was only about 34% higher than in April 2005 ($58 \text{ m}^3/\text{s}$ [$2,048 \text{ ft}^3/\text{s}$]), and peak stage at the gage was about 35 cm (14 in) higher; in other

respects, the hydrographs of the two events are quite similar. In fact, it would be reasonable to anticipate that an April event might actually be more effective than a September event in terms of erosion. Knighton (1973) found that when the soil is preconditioned in winter and early spring due to saturation or exposure to frost action, intermediate to high discharges are the most effective at eroding bank material because the banks are more susceptible to erosion due to a decrease in the required shear stress. Wolman (1954) found that a large summer flood produces little erosion when it attacks dry banks. However, lesser winter flows generate considerable bank retreat when acting against thoroughly wetted banks. During the April 2005 storm, the banks could have had higher antecedent moisture content, making them more susceptible to fluvial entrainment. Freeze-thaw processes throughout the winter could also have weakened the banks, leading to greater amounts of top bank retreat.

Available results from bankline surveys (Table 4) indicate that at several sites the September 2004 flood is associated with about twice as much erosion as the April 2005 flood; at several sites the reverse is true; and at several sites the amounts of erosion are roughly comparable. The erosion volume measured following September 2004 at these 10 locations (336 m^3 [$11,865 \text{ ft}^3$]) is about 73% higher than the volume measured following the April 2005 event (194 m^3 [$6,850 \text{ ft}^3$]). The average distance of top bank retreat for all erosion locations was 0.3 m (0.9 ft) for the September 2004 event and 0.2 m (0.8 ft) for the April 2005 event. These results are not inconsistent with a simple comparison of the two floods; they do not provide convincing evidence one way or the other about the relative effectiveness of winter-spring vs. summer-autumn floods.

Comparison of Sediment Sources

Valley Creek Sediment Yield in a Regional Context

The present study was requested by the National Park Service based on the concerns of personnel at VAFO about possible impacts of sediment loads derived from increasing urban development during recent decades. Although it is preferable to assess sediment yield based on multiple years of monitoring data, the initial monitoring effort allows us to make a preliminary comparison of Valley Creek sediment yield with other watersheds in the region.

Our suspended sediment data for Valley Creek at PA Turnpike Bridge gaging station covers the 14-month period between July 25, 2005 and September 30, 2006. We calculated both (arithmetic) mean streamflow and sediment yield for every 365-day period within that time range in order to estimate maximum and minimum values for comparison with the longer hydrologic record, as well as a value for the USGS 2006 Water Year (Oct. 1, 2005–Sept. 30, 2006). The minimum sediment yield calculated for any 365-day period within the 14-month record at the gage was $30.9 \text{ t/km}^2/\text{yr}$ and the corresponding value of 365-day mean streamflow was $0.94 \text{ m}^3/\text{s}$ ($33 \text{ ft}^3/\text{s}$), only slightly more than the median value of annual mean streamflow ($0.91 \text{ m}^3/\text{s}$ [$32 \text{ ft}^3/\text{s}$]) for the 24 years from 1983–2006. The value of sediment yield estimated for the 2006 Water Year was $41.4 \text{ t/km}^2/\text{yr}$ and mean streamflow for that time period is $1.06 \text{ m}^3/\text{s}$ ($37 \text{ ft}^3/\text{s}$), which would place within the upper quartile of annual streamflow values at the Valley Creek gage. In the Results section we also used an estimation procedure to calculate a value of sediment yield for the period July 18, 2004–July 17, 2005 for comparison with field measurements of sediment derived from bank erosion and bed scour. The derived value of

sediment yield was 78 t/km²/yr and the mean streamflow for that period, 1.59m³/s (56 ft³/s), is larger than any other value of annual mean streamflow for the 24-year gage record (1.50 m³/s [53 ft³/s]). If we assume that the relationship between sediment concentration and discharge observed during the study period is representative for the period 1983–2006, we can infer that the median annual sediment yield is around 30 t/km²/yr and that the maximum sediment yield is around 80 t/km²/yr.

In order to place these values within the regional context we examined sediment data for other sites in the Piedmont physiographic province in the mid-Atlantic region. We also examined literature values to assess trends in sediment yield associated with urban development. Data from both of these sources are summarized in Table 7 and are discussed further as follows.

It is well-known that construction sites can generate enormous amounts of sediment, particularly in the absence of sediment control measures. Guy and Ferguson (1962) estimated construction-site sediment yields in the Washington, DC metropolitan area in the range 8,750–17,500 t/km²/yr, and Wolman (1967) cited values of the order of 35,000 t/km²/yr. Yorke and Herb (1978) published sediment yield data for the period 1963–1974 for the watershed of the Northwest Branch Anacostia River near Colesville, MD. During this period the Anacostia watershed was experiencing rapid urbanization and sediment control measures were not introduced in the region until the early 1970s. The range of sediment yield values was 90–510 t/km²/yr and the median value was 244 t/km²/yr; about 8 times as large as our estimated median value for Valley Creek at Pennsylvania Turnpike Bridge. Gellis et al. (2005) tabulated sediment yield data for other watersheds draining to Chesapeake Bay; maximum values for the Pennsylvania Piedmont are from the Conestoga River watershed in Lancaster County and range from 61 t/km²/yr (Conestoga River at Conestoga) to 368 t/km²/yr (Little Conestoga Creek near Churchtown). These sites are characterized by predominantly agricultural land cover. By contrast, the Little Patuxent River at Savage, MD drains an area of mixed land use with increasing urban development over the last three decades within the context of regional sediment controls; sediment yield for the years 1987, 1988, and 1990 averages 36.4 t/km²/yr; comparable with our estimates for Valley Creek.

Sediment data are also available for multiple stations in and near the Schuylkill River watershed; however, the records are typically of short duration and several records are limited to the late 1940s and early 1950s. Preliminary analysis suggests that some of these values may be anomalous and, therefore, we rely more heavily on comparisons with the more recent data. The longest record (1948–1981, plus 1983 and 1986) was collected for the Schuylkill River at Manayunk, Philadelphia. If the early part of the record is excluded from consideration, the maximum sediment yield recorded for the period 1960–1986 is 190 t/km²/yr and the median value is 59 t/km²/yr. The other long record (1948–1981) was collected for the Schuylkill River at Berne; if we exclude the early part of the record from consideration, the maximum sediment yield recorded for the period 1960–1981 is 87.2 t/km²/yr and the median is 19.5t/km²/yr. Other stations from the Piedmont of Pennsylvania with useful sediment records include Brandywine Creek at Chadds Ford. Maximum and median sediment yields for the period 1964–1977 are 122.8 and 45.5 t/km²/yr, respectively. Perkiomen Creek at Graterford has sediment data for the years 1950–1952, 1964–1965 and 1972–1973. At this station the data from the early 1950s are consistent with the patterns from the other years in the record; maximum and median sediment

Table 7. Regional sediment yield comparisons with Valley Creek.

Station	Drainage area (km ²)	Period Of Record	Maximum sediment yield (t/km ² /y)	Median Sediment yield (t/km ² /y)	Mean Sediment yield (t/km ² /y)
Schuylkill R at Port Carbon, PA (USGS gage 01467470) ¹	70.2	1950, 1976–1977	189	109	
Schuylkill R at Berne, PA (USGS gage 01470500) ¹	919	1960–1981	87.2	19.5	
Schuylkill R at Manayunk, Philadelphia, PA (USGS gage 01473800) ¹	4,740	1960–1981, 1983, 1986	190	59.0	
Perkiomen Ck at Graterford, PA (USGS gage 01473000) ¹	723	1950–1952, 1964–1965, 1972–1973	98.8	73.9	
Brandywine Ck at Chadds Ford, PA (USGS gage 01481000) ¹	743	1964–1977	123	45.5	
NW Branch Anacostia R nr Colesville, MD (USGS gage 01650500) ²	54.9	1963–1974	514	244	
Little Patuxent River at Savage, MD (USGS gage 01594000) ³	255	1987, 1988, 1990			36.4
Little Conestoga Ck site 3A nr Morgantown, PA (USGS gage 0157608335) ³	3.68	1986, 1988–1991			116
Little Conestoga Ck nr Churchtown, PA (USGS gage 01576085) ³	15.1	1985–1992			368
Mill Ck at Eshelman Mill Rd, PA (USGS gage 01576540) ³	139.9	1993–1995			112
Conestoga R at Conestoga, PA (UGSG gage 01576754) ³	1,217	1985–1988, 2001			60.9
Valley Ck at PA Turnpike Bridge (USGS gage 01473169)	53.9	07/2004–09/2006	78	30	

¹ Data available from <http://waterdata.usgs.gov/pa/nwis/>

² Yorke and Herb (1978), Table 3, p. 13

³ Gellis et al. (2005), Table 5, p. 30–31

yields are 98.8 and 73.9 t/km²/yr, respectively. The Schuylkill River at Port Carbon has sediment data for 1950, 1976, and 1977; maximum and median sediment yields are 188.7 and 108.5 t/km²/yr, respectively.

Although the available data are not consistent in temporal coverage or watershed drainage area, they do provide a useful context for interpretation of the Valley Creek data. We conclude that Valley Creek sediment yield is much lower than values collected in urbanizing watersheds prior to the advent of sediment controls and is consistent with other watersheds in the Pennsylvania Piedmont and within the Schuylkill watershed, but not particularly high by comparison with the maximum values measured in the region. Although this comparison by itself does not tell us whether sediment should be considered a serious problem for environmental conditions within

VAFO, it does indicate that sediment influx from the upstream watershed is not as high as may have been anticipated prior to the study.

Comparison of Sediment Budget Components

For the initial planning of this project, one of the goals was to assess how much fine sediment was stored and remobilized in the bed along the 3.7-km (2.3-mi) length of channel within VAFO, and to compare this quantity with the mass of sediment derived from bank erosion and with suspended sediment crossing the upstream park boundary. Analysis of data from Tables 2 and 3 indicates that, for the period July 2004–July 2005, the mass of sand, silt, and clay finer than 2 mm (0.08 in) in the mobile layer is approximately 4,800 metric tons, and of this total 1,500 metric tons is finer than 0.075 mm (0.003 in). The estimated sediment mass scoured from the bed during the survey period finer than 2 mm (0.08 in) is 1,480 metric tons; of this total 480 metric tons is fine than 0.075 mm (0.003 in). The estimated mass of sediment derived from bank erosion for the same time period is 3,420 metric tons for all size fractions including gravel. The total mass of sediment less than 2 mm (0.08 in) in size derived from bank erosion is just over 3,200 metric tons; the estimated mass less than 0.075 mm (0.003 in) is 2,340 metric tons.

The results indicate: (1) the mass of sediment sand size (2 mm [0.08 in]) and finer stored in the 3.7 km (2.3 mi) of streambed within VAFO is about 114 percent of the maximum annual suspended sediment load crossing the upstream Park boundary as estimated for the period July 2004–July 2005, and is about three times greater than the estimated median annual suspended sediment load; the mass of sediment smaller than 0.075 mm (0.003 in) stored in the streambed is about 35 percent of the maximum annual suspended sediment load for July 2004–July 2005 and about 91 percent of the estimated median suspended sediment load. (2) The net mass of sediment sand size (2 mm [0.08 in]) and finer scoured from the streambed within VAFO over the survey period is about 35 percent of the suspended sediment load at the gage estimated for that same time period, and the net mass of scoured sediment finer than 0.075 mm (0.003 in) is between 11 and 12 percent of the suspended sediment load for that period. (3) Bank erosion along Valley Creek within VAFO generated a mass of fine sediment (e.g. less than 0.075 mm [0.003 in]) equivalent to 55.7 percent of the estimated suspended sediment load for the same time period, and the mass (<2 mm [0.08 in]) derived from bank erosion including medium and coarse sand amounts to 76.3 percent of the estimated suspended sediment load. (4) Because the period July 2004–July 2005 included so many large storms and had an average streamflow larger than the maximum value in the 24-year record at the Valley Creek gage, suspended sediment load, streambed scour, and bank erosion are all thought to have been much higher during the period July 2004–July 2005 than would be expected in most years. Nevertheless, the comparison among these components of the sediment budget is considered to be valid for that time period.

These comparisons reflect measurements along a fraction of the total length of Valley Creek, and yet the masses of fine sediment stored in the streambed and derived from bank erosion are both of the same order of magnitude as the annual suspended sediment load; the net scour from the streambed is a smaller but still significant fraction of the annual total. Streambed sediment and bank sediment are both forms of storage in the landscape. Although sediment in the mobile layer of the bed may be considered a more transient form of storage, our measurements show that because of the nature of the armor on the bed of Valley Creek, even very large storms cause only limited scour of the bed. Thus, at least for the surveyed reach of Valley Creek within VAFO,

fine sediment stored in the banks is equally accessible and perhaps more accessible for erosion and transport during large storms than fine sediment stored in the bed.

Because our investigations did not include field measurements of channel sediment or bank erosion in the watershed upstream of the USGS gage, we have no real basis for extrapolation of these numbers to quantify the relative importance of either of these sources for the remainder of Valley Creek and its tributaries by comparison with annual suspended sediment load. However, given the fact that the upstream watershed has a drainage area of nearly 54 km² (21 mi²) together with the observation that approximately 30% of upstream channel length may be experiencing severe bank erosion (CCWRA et al. 2004), we believe one may reasonably infer that these two sources (and bank erosion in particular) are dominant components of the total sediment budget. It is likely that, over the course of the year covered by our measurements, cumulative exchange of fine sediment with the bed throughout the drainage network was of the same order of magnitude as the total suspended sediment load. It is also likely that the total mass of fine sediment derived from bank erosion throughout the drainage network was considerably larger than the total suspended sediment load measured at the gage. If this is true then it must also be true that much of the sediment derived from bank erosion did not leave the watershed, and that floodplain storage is still an active and important component of the sediment budget during years when there are large flood events. The two largest floods that occurred during the study period inundated even the highest banks along Valley Creek, but the extent of flood inundation and opportunities for floodplain deposition of sediment are limited to reaches where the banks are lower during the smaller flood events. The spatial distribution and net amount of floodplain deposition remain to be quantified.

Recommendations for Continued Monitoring

Continued Sediment and Turbidity Monitoring

The sediment record obtained at the USGS gage site using the YSI turbidity probe and ISCO sampler provides important insights that are essential to our understanding of the relative importance of different components of the sediment budget. The continuous record available with the use of the turbidity probe provides information about the time-varying pattern of sediment concentration during flow events that cannot be captured otherwise. However, the period of record is quite short—barely more than one year—and was anomalous with respect to the sequence of flow events and, therefore, with respect to sediment load, as well. In order to place the data in context, continued monitoring is essential. We recommend that sediment monitoring be continued for a period of at least 5 yrs in order to establish a reasonable baseline estimate of watershed sediment loads. Monitoring should be continued beyond the five-year period if the objective is to assess changes over time as a result of altered watershed hydrology and land cover.

Repeat Surveys

The period of field study described in this report was anomalous, in that it included a 12-month period with higher average flow and more large storms than any single year in the 24-year history of the Valley Creek stream gage. Rates of channel change measured during this period are not necessarily representative of long-term rates, and the relative importance of bank erosion

as a sediment source during the study period may be higher or lower than would be indicated by a long-term study. We do believe, however, that even a long-term study would probably confirm that bank erosion is a dominant source.

Field surveys of channel cross-sections and banklines were completed during the study period using monuments that were referenced to the longitudinal profile. However, frequent vandalism made it difficult to maintain the network of monuments in order to allow continued monitoring over time. We recommend establishing permanent monuments far enough from the channel banks to avoid losing them to continued erosion, and with a strong network of triangulated benchmarks that would allow reconstruction of monument locations if and when they are lost. Resurvey at intervals of two-to-five years could provide valuable long-term records of channel stability within VAFO.

A larger number of cross-sections installed in the longer reaches would also be beneficial in measuring channel changes. Longitudinally homogeneous reaches were chosen based on the belief that they could be reasonably represented with a limited number of sampling locations. Three cross-sections were installed in each reach, regardless of reach length. Therefore, the shorter reaches are better represented by the three cross-sections than the longer reaches. For example, the length of reach 3 is only 71 m (233 ft); whereas, the length of reach 9 is 806 m (2,644 ft). The potential for using repeat LiDAR surveys (see below) to characterize longitudinal variations in bank stability would mitigate, somewhat, the sampling problem inherent in monitoring only discrete, monumented cross-section sites.

A site of particular interest for periodic resurvey is the pool upstream of the existing dam (Figure 14), which was too deep for wading and could only be surveyed from a raft. Our surveys indicate that this is one of the few locations along Valley Creek where a significant thickness of fine sediment is able to accumulate, and the approximate thickness and length of the body of sediment stored in the pool can be seen by examining the thalweg profile shown in Figure 14. We were unable to determine how frequently the sediment in this pool is remobilized or how long it remains in the pool; e.g., what the average residence time is. As nutrients and contaminants are preferentially associated with fine-grained sediment, it may be worthwhile to extract several cores from the sediment in the pool to determine whether there are concentrations of nutrients and contaminants (e.g. metals, volatile organic chemicals) that are of potential concern. If this were done it would also be advisable to couple analysis of the vertical distribution of these constituents within these cores with periodic analysis of suspended sediment captured by the ISCO sampler at the USGS gage during major storms. Collection of storm-period suspended sediment samples at or immediately downstream of the dam site and upstream of the pool would be particularly useful in estimating a mass balance for sediment storage in the pool, but would also require a more substantial investment of equipment and personnel time. Periodic resurvey of the channel bed upstream of the dam and along the length of the pool, together with examination of the vertical profiles of sediment cores, could be used to assess temporal patterns of storage and remobilization of fine-grained sediment in the pool.

Analysis of LiDAR

LiDAR (Light Detection and Ranging) is a form of remote sensing data that provides high-resolution topographic information over the entire landscape at costs that are competitive with

traditional aerial photography. The filtered “bare earth” data can provide a mostly unobstructed view of stream channels and flood plains with vegetation and buildings stripped away; although it is not error-free, it provides the most complete and accurate topographic data available over large areas. Its use in geomorphic studies and land-use planning is growing rapidly and many state and local government agencies are now acquiring LiDAR data for their own uses. If the Commonwealth of Pennsylvania acquires complete LiDAR coverage with spatial resolution on the order of 1–2 m (3.3–6.6 ft) and vertical accuracy on the order of 10–15 cm (4–6 in), and if LiDAR surveys are completed at intervals of several years, then it will be possible to track the spatial extent and rate of severe bank erosion not only along Valley Creek within VAFO, but throughout much of the upstream drainage network. Even if the State does not acquire complete coverage, it may be worthwhile for the National Park Service to consider acquiring its own LiDAR data, or to collaborate with other agencies who may be interested in sharing the cost, at repeat intervals of 3–5 years.

Another option to consider is the periodic collection of surface LiDAR data for sites of known severe bank erosion. The University of Delaware owns a scanning LiDAR system that can be used to collect extremely detailed information on stream-bank morphology with a horizontal beam from a position on the opposite bank in a small fraction of the time it would take to collect a much less-detailed bankline survey using a total station. It may be worthwhile to establish monitoring locations for the sites of known severe bank erosion within VAFO and to arrange for periodic repeat LiDAR surveys to quantify the exact amount of material eroded and to provide evidence on the dominant processes involved.

Grid-based and Volumetric Analysis of Bed Particle Size

A continuing program of monitoring to characterize bed particle size along the entire length of Valley Creek within VAFO is probably not warranted, but we recommend that a smaller number of sites be established where periodic repeat analysis would make it possible to track trends over time. These could include two or three locations that were stable throughout the period of this study, as well as several sites where streambed scour and deposition and bank erosion have been identified as significant and ongoing processes. The grid-based method is quicker, and probably more reliable from a statistical perspective, and could easily be repeated either annually or with a somewhat longer period between measurements. The volumetric method is more time-consuming and difficult to use, but, unlike the grid-based pebble count, it does provide some information on fine sediment stored in the bed. Because the study period was so anomalous in terms of the frequency of high flows, it would be worthwhile to select three to five sites for periodic sampling and measurement of percent fine sediment in the bed and to use these sites to gauge whether the amount of fine sediment stored in the bed follows any long-term trends or cyclical patterns of storage and remobilization. Development of rapid sampling protocols capable of flagging major changes in fine sediment storage would also be useful.

Assessment of Bedload Transport

Direct measurement of bedload transport is time-consuming, expensive, difficult, and fraught with error. It is also true that an adequate understanding of patterns of bedload transport is an important aspect of understanding changes in channel form. The question of whether direct measurement of bedload is worth considering depends on the priorities of the National Park

Service. This study has shown that along most of the length of Valley Creek even large floods appear to cause only modest disruption of the armor layer. The difficulty we experienced in placing scour chains in the bed is a testament to the resistance and durability of that armor layer. This does not mean, however, that there is a negligible flux of bed material through VAFO. There are locations along the channel with significant gravel accumulations associated with flow transitions or obstructions; e.g., at bridge crossings, channel bends, and breaks in gradient. Cross-section surveys showing cyclic or transient changes in bed topography indicate that there is net transport through these locations. In lieu of traditional bedload measurement approaches it may be worthwhile to emplace scour chains and tracer gravels at specific locations where large amounts of gravel are found and where survey data suggest the gravel is more mobile than elsewhere. These approaches would provide some guidance as to the frequency of transport and exchange of sediment between the bed and the flow. Repeat photography at fixed locations or even use of the horizontally oriented LiDAR to characterize net change in volume of channel bars at low flow could be an element in a long-term monitoring strategy. If the National Park Service wishes to adopt such a strategy, data in this report can be used as a guide for site selection.

Management Recommendations

The ultimate value of this report for the National Park Service is the information it provides that may be of assistance in managing the resources of the park. The original motivation for the study stemmed from concern about whether excessive amounts of sediment might be coming from the upstream watershed in quantities that would either affect habitat and living resources or affect channel stability and preservation of important historic features. Our conclusion is that the amount of sediment coming into the park along the channel of Valley Creek is not extraordinary by regional or historic standards and that the amount of fine material in the bed is modest. Unless there is a comprehensive effort throughout the watershed to control bank erosion, it is unlikely that there will be major reductions in sediment load entering VAFO from upstream in the near future. We did not conduct any studies of habitat and stream biota; therefore, we cannot translate our findings into an assessment of the risk to biota associated with sediment. It is likely that sediment derived from bank erosion has increased over time with urban development just as storm response has become more pronounced over time; it is also possible that the amount of sediment derived from upland soil erosion has decreased over roughly the same time period with the advent of sediment control regulations for construction sites. A bioassessment study of the diversity and composition of the stream invertebrate community would be needed in order to determine whether this is an issue of current and future concern. If there are significant spawning sites for important fish species these might also be given greater attention in continued monitoring of the channel, and spawning success rates might be studied in tandem with periodic monitoring of local channel changes and sediment particle size.

Although the vulnerability of biotic resources cannot be assessed from this study, it is clear to us, as it has been clear to VAFO managers for some time, that there are serious erosion problems affecting historic resources in some parts of the park. The most serious problems are occurring at the site of Washington's Headquarters, where repeated efforts at bank protection have not been successful. The banks are high and the channel at this location is unstable. Continued efforts to protect the banks probably will not succeed unless there is a more comprehensive effort to control the hydraulics of flow impinging on the bank at high flow, and this, in turn, is affected

by the dynamics of coarse sediment deposition and scour along the channel immediately upstream. Whether groundwater seepage from the bank plays a significant role in undermining the bank at this location is also a question of some interest. Our study was intended to characterize patterns along the length of Valley Creek within VAFO and did not focus on such site-specific questions. Thus, we cannot recommend specific restoration measures at this site or at several others where roads or historic resources are threatened, but we believe that any such measures need to be chosen carefully with reference to recent literature recommending careful geomorphic assessment and continued monitoring. To the extent that flood flows play a significant role in undermining the banks, it needs to be understood that the hydraulics and spatial patterns of flow at high stage may be much different from patterns observed during ordinary flow conditions. Some sites (such as the Washington's Headquarters site) present more complex challenges than other sites (such as some of the road embankments along reach 9, where the channel is straight).

Stream restoration as currently practiced is more art than science and not all practitioners have a strong background in fluvial geomorphology, hydraulics, and sediment transport. Completion of one or more short courses on principles of stream restoration is worthwhile, but cannot substitute for more comprehensive educational background and professional judgment related to the underlying science. There is a national trend toward putting the practice of stream restoration on a more sound scientific footing, which would also entail developing appropriate criteria for assessment and monitoring of project sites before and after construction. Park managers should be aware that there is a tremendous concentration of relevant expertise among academic and agency scientists in Pennsylvania, Delaware, and Maryland, and there are ongoing informal discussions with management agencies and practitioners about developing guidelines to assist in selecting and evaluating restoration project sites and plans. Therefore, we recommend that any consideration of potential stream restoration projects be subject to review by at least two geomorphologists from the region who are familiar with the dynamics and history of Piedmont streams.

Conclusions

Summation of Conclusions of the Research

In response to National Park Service concerns about sediment moving through Valley Creek in VAFO, this project was undertaken to assess the longitudinal patterns of bed sediment storage, bank erosion, and channel instability, as well as the patterns of change over the study period (September 2003–September 2006) in relation to the sequence of flow events mobilizing sediment. Multiple components of the sediment budget were investigated, including bank erosion as a sediment source, the mass of fine sediment stored and remobilized from the streambed, and suspended sediment load passing the USGS stream gage on Valley Creek just upstream of the park boundary. Methods used in field investigations for this project included: (1) field survey of a longitudinal profile; (2) channel cross-section and bankline analysis; (3) installation and monitoring of scour chains as indicators of bed mobility; (4) measurement of channel bed particle size distributions; (5) turbidity measurement and estimation of suspended sediment load; and (6) emplacement and short-term monitoring of tracer gravels.

A series of three storm events with estimated recurrence intervals of about two years occurred through July and the beginning of August 2004. On September 28, 2004, a storm event with an estimated recurrence interval of 10 years occurred, producing a discharge peak of $78 \text{ m}^3/\text{s}$ ($2,740 \text{ ft}^3/\text{s}$), the second-highest discharge on record for Valley Creek. Another significant storm event occurred on April 2, 2005, producing a discharge of $58 \text{ m}^3/\text{s}$ ($2,060 \text{ ft}^3/\text{s}$) with an estimated recurrence interval of 5 years. Because there were so many large flow events during the study period (including the second-largest flood on record), the data collected provide clear evidence concerning the relative mobility of the bed under high-flow conditions, but it is also likely that the volume of bank erosion was higher than would occur during a typical year.

General coarsening of the streambed and significant amounts of scour were observed along a majority of the channel length over a two-year period. Most deposition in the active channel occurred in the downstream reaches with high banklines. In the upstream reaches, banklines are lower, high flows are more likely to spill out of the channel, and flood-transported sediment is stored on the floodplain. The downstream reaches had the highest bank erosion rates where high banklines retain a larger percentage of flood flow within the channel and where confined flow and steeper channel gradients generate higher shear stress along the banks. By comparison, low bank erosion rates were measured along the upstream reaches with lower banklines and gentler gradients. Available results from bankline surveys at active erosion sites indicate that at several of these sites the September 2004 flood is associated with about twice as much erosion as the April 2005 flood; at several the reverse is true; and at several sites the amounts of erosion are roughly comparable. The average distance of top bank retreat for these active erosion locations was 0.3 m (0.9 ft) for the September 2004 event and 0.2 m (0.8 ft) for the April 2005 event.

The suspended sediment load was estimated at 2,230 metric tons for the 2006 water year (October 1, 2005–September 30, 2006) or $41.4 \text{ t}/\text{km}^2/\text{yr}$. Suspended sediment loads calculated for every 365 consecutive-day period between July 25, 2005 and September 30, 2006 yielded a range in values from 1,660 to 2,230 metric tons or 30.9 to $41.4 \text{ t}/\text{km}^2/\text{yr}$. The estimated value of sediment yield for the period July 18, 2004–July 17, 2005 was $78 \text{ t}/\text{km}^2/\text{yr}$ and the mean

streamflow for that period, $1.59 \text{ m}^3/\text{s}$ ($56 \text{ ft}^3/\text{s}$), is larger than any other value of annual mean streamflow for the 24-year gage record ($1.50 \text{ m}^3/\text{s}$ [$53 \text{ ft}^3/\text{s}$]). We infer from our analysis that median annual sediment yield is around $30 \text{ t}/\text{km}^2/\text{yr}$ and that maximum sediment yield is around $80 \text{ t}/\text{km}^2/\text{yr}$. Based on comparison with sediment data from other watersheds in the region between Philadelphia and Washington, DC, we conclude that Valley Creek sediment yield is much lower than values collected in urbanizing watersheds prior to the advent of sediment controls and is consistent with other watersheds in the Pennsylvania Piedmont and within the Schuylkill watershed, but not particularly high by comparison with the maximum values measured in the region. Although this comparison by itself does not tell us whether sediment should be considered a serious problem for environmental conditions within VAFO, it does indicate that sediment influx from the upstream watershed is not as high as may have been anticipated prior to the study.

Comparisons of field measurements show that the mass of fine sediment stored in the streambed and derived from bank erosion along Valley Creek within VAFO are of the same order of magnitude as the annual suspended load; the net scour from the streambed is a smaller but still significant fraction of the annual total. Given the fact that the upstream watershed has a drainage area of nearly 54 km^2 (20 mi^2) together with the observation that approximately 30% of upstream channel length may be experiencing severe bank erosion, we believe that these two sources (and bank erosion in particular) are dominant components of the total sediment budget. It is likely that over the course of the year covered by our measurements, cumulative exchange of fine sediment with the bed throughout the drainage network was of the same order of magnitude as the total suspended sediment load. It is also likely that the total mass of fine sediment derived from bank erosion throughout the drainage network was considerably larger than the total suspended sediment load measured at the gage. If this is true then it must also be true that much of the sediment derived from bank erosion did not leave the watershed, and that floodplain storage is still an active and important component of the sediment budget during years when there are large flood events. The spatial distribution and net amount of floodplain deposition remain to be quantified.

Because the period July 2004–July 2005 included so many large storms and had an average streamflow larger than the maximum value in the 24-year record at the Valley Creek gage, suspended sediment load, streambed scour, and bank erosion are all thought to have been much higher during the period July 2004–July 2005 than would be expected in most years. Nevertheless, the comparison among these components of the sediment budget is considered to be valid for that time period.

Management Implications

The findings from this project point to a need for continued monitoring to place the data from the two-year study in context of longer-term temporal trends for Valley Creek. Continuous monitoring could include the following:

- (1) The sediment record obtained at the USGS gage site using the YSI turbidity probe and ISCO sampler provides important insights that are essential to our understanding of the relative importance of different components of the sediment budget. We recommend that suspended sediment monitoring be continued for a period of at least five years in order to establish a

reasonable baseline estimate of watershed sediment loads. Monitoring should be continued beyond the five-year period if the objective is to assess changes over time as a result of altered watershed hydrology and land cover.

(2) Field surveys of channel cross-sections and banklines were completed during the study period using monuments that were referenced to the longitudinal profile. However, frequent vandalism made it difficult to maintain the network of monuments in order to allow continued monitoring over time. We recommend establishing permanent monuments far enough from the channel banks to avoid losing them to continued erosion, and with a strong network of triangulated benchmarks that would allow reconstruction of monument locations if and when they are lost. Resurvey at intervals of two to five years could provide valuable long-term records of channel stability within VAFO. A larger number of cross-sections installed in the longer reaches would also be beneficial in measuring channel changes. The potential for using repeat LiDAR surveys to characterize longitudinal variations in bank stability would mitigate, somewhat, the sampling problem inherent in monitoring only discrete, monumented cross-section sites. A site of particular interest for periodic resurvey is the pool upstream of the existing dam, which was too deep for wading and could only be surveyed from a raft.

(3) The National Park Service may want to consider acquiring LiDAR (Light Detection and Ranging) data to provide high-resolution topographic information of VAFO. The filtered “bare earth” data can provide a mostly unobstructed view of stream channels and flood plains with vegetation and buildings stripped away; although it is not error-free, it provides the most complete and accurate topographic data available over large areas. If LiDAR data are acquired at a resolution on the order of 1–2 m (3–6 ft) and vertical accuracy on the order of 10–15 cm (4–6 in), and if LiDAR surveys are completed at intervals of several (3–5) years, then it will be possible to track the spatial extent and rate of severe bank erosion not only along Valley Creek within VAFO, but throughout much of the upstream drainage network.

(4) A continuing program of monitoring to characterize bed particle size along the entire length of Valley Creek within VAFO is probably not warranted, but we recommend that a smaller number of sites be established where periodic repeat analysis would make it possible to track trends over time. These could include two or three locations that were stable throughout the period of this study, as well as several sites where streambed scour and deposition and bank erosion have been identified as significant and ongoing processes. The grid-based method is quicker and probably more reliable from a statistical perspective than the volumetric sampling method and could easily be repeated either annually or with a somewhat longer period between measurements. Because the study period was so anomalous in terms of the frequency of high flows, it would be worthwhile to select three to five sites for periodic sampling and measurement of percent fine sediment in the bed and to use these sites to gauge whether the amount of fine sediment stored in the bed follows any long-term trends or cyclical patterns of storage and remobilization. Development of rapid sampling protocols capable of flagging major changes in fine sediment storage would also be useful.

(5) Direct measurement of bedload transport is time-consuming, expensive, difficult, and fraught with error; however, adequate understanding of patterns of bedload transport is an important aspect of understanding changes in channel form. In lieu of traditional bedload measurement approaches it may be worthwhile to emplace scour chains and tracer gravels at

specific locations where large amounts of gravel are found and where survey data suggest the gravel is more mobile than elsewhere. These approaches would provide some guidance as to the frequency of transport and exchange of sediment between the bed and the flow. Repeat photography at fixed locations or even use of the horizontally-oriented LiDAR to characterize net change in volume of channel bars at low flow could be an element in a long-term monitoring strategy. If the National Park Service wishes to adopt such a strategy, data in this report can be used as a guide for site selection.

(6) We did not conduct any studies of habitat and stream biota; therefore, we cannot translate our findings into an assessment of the risk to biota associated with sediment. It is likely that sediment derived from bank erosion has increased over time with urban development just as storm response has become more pronounced over time; it is also possible that the amount of sediment derived from upland soil erosion has decreased over roughly the same time period with the advent of sediment control regulations for construction sites. A bioassessment study of the diversity and composition of the stream invertebrate community would be needed in order to determine whether this is an issue of current and future concern. If there are significant spawning sites for important fish species, these might also be given greater attention in continued monitoring of the channel, and spawning success rates might be studied in tandem with periodic monitoring of local channel changes and sediment particle size.

There are serious erosion problems affecting historic resources in some parts of the park. The most serious problems are occurring at the site of Washington's Headquarters, where repeated efforts at bank protection have not been successful. The banks are high and the channel at this location is unstable. Continued efforts to protect the banks probably will not succeed unless there is a more comprehensive effort to control the hydraulics of flow impinging on the bank at high flow, and this in turn is affected by the dynamics of coarse sediment deposition and scour along the channel immediately upstream. Whether groundwater seepage from the bank plays a significant role in undermining the bank at this location is also a question of some interest. Our study was intended to characterize patterns along the length of Valley Creek within VAFO and did not focus on such site-specific questions; thus, we cannot recommend specific restoration measures at this site or at several others where roads or historic resources are threatened, but we believe that any such measures need to be chosen carefully with reference to recent literature recommending careful geomorphic assessment and continued monitoring. To the extent that flood flows play a significant role in undermining the banks, it needs to be understood that the hydraulics and spatial patterns of flow at high stage may be much different from patterns observed during ordinary flow conditions. Some sites (such as the Washington's Headquarters site) present more complex challenges than other sites (such as some of the road embankments, where the channel is straight).

Literature Cited

- Bascom, F., and G. W. Stose. 1938. Geology and mineral resources of the Honeybrook and Phoenixville quadrangles, Pennsylvania. U.S. Geological Survey. Bulletin 891. 145 pp.
- Bunte, K., and S. R. Abt. 2001. Sampling surface and subsurface particle-size distributions in wadable gravel- and cobble-bed streams for analyses in sediment transport, hydraulics, and stream-bed monitoring. U.S. Department of Agriculture Forest Service Rocky Mountain Research Station General Technical Report RMRS-GTR-74. 428 pp.
- Burk, W. H. 1920. The Valley Forge Guide; historical and topographical guide to Valley Forge. North Wales. Norm B. Nuss.
- Burk, W. H. 1928. The Valley Forge Guide; historical and topographical guide to Valley Forge. North Wales. Norm B. Nuss. 281 pp.
- Chester County Planning Commission (CCPC). 1973. Chester County geology. Chester County Planning Commission, Government Services Center. West Chester, PA. 95 pp.
- Chester County Water Resources Authority, Borton-Lawson Engineering, Inc., and Skelly and Loy Engineers-Consultants (CCWRA et al.). 2004. Valley Creek watershed technical compendium: Chester County Water Resources Authority. 196 pp.
- Costa, R. F. 1974. Response and recovery of a Piedmont watershed from Tropical Storm Agnes, June 1972. *Water Resources Research* 10:106–112.
- Dunne, T., and L. B. Leopold. 1978. Water in environmental planning. W. H. Freeman & Company. San Francisco, CA.
- Gellis, A. C. 2003. Suspended-sediment characteristics in four humid tropical watersheds of contrasting land use, Puerto Rico. Ph.D. Dissertation. Colorado State University. Fort Collins.
- Gellis, A. C., W. S. L. Banks, M. J. Langland, and S. K. Martucci. 2005. Summary of suspended-sediment data for streams draining the Chesapeake Bay Watershed, Water Years 1952–2002. U.S. Geological Survey Scientific Investigations Report 2004-5056. 59 pp.
- Gippel, C. J. 1995. Potential of turbidity monitoring for measuring the transport of suspended solids in streams. *Hydrological Processes* 9:83–97.
- Gupta, A., and H. Fox. 1974. Effects of high magnitude floods on channel form; a case study in Maryland Piedmont. *Water Resources Research* 10:499–509.
- Gutowski, M., and J. Stauffer. 1996. Management guidelines for Valley Creek, Valley Forge National Historical Park, Pennsylvania. National Park Service. 108 pp.

- Guy, H. P., and G. E. Ferguson. 1962. Sediment in small reservoirs due to urbanization. American Society of Civil Engineers. *Journal of the Hydraulics Division* 88(HY2):27–37.
- Hammer, T. R. 1972. Stream channel enlargement due to urbanization. *Water Resources Research* 8(6):1530–1540.
- Jacobson, R. B., and D. J. Coleman. 1986. Stratigraphy and recent evolution of Maryland Piedmont flood plains. *American Journal of Science* 286:617–637.
- Knighton, A. D. 1973. Riverbank erosion in relation to streamflow conditions, River Bollin-Dean, Cheshire. *East Midland Geographer* 6:416–426.
- Kondolf, G. M. 1997. Application of the pebble count; notes on purpose, method, and variants. *Journal of the American Water Resources Association* 33(1):79–87.
- McGinty, A. L. 2003. Geostatistical analysis of the impacts of urbanization on spring water quality in Valley Creek watershed, Chester County, Pennsylvania. M.S. Thesis. Drexel University, Department of Civil, Architectural, and Environmental Engineering. September 2003. 155 p.
- National Climatic Datacenter (NCDC). 2005. 2004 Local climatological data, annual summary with comparative data, Philadelphia, PA. United States Department of Commerce, Publication # ISSN0198-4535.
- Natural Resources Conservation Service (NRCS), and Penn State Geospatial Technology Program. 2005. SoilMap v.2. Available at <http://soilmap.psu.edu/home.asp>.
- Parker, G., and P. C. Klingeman. 1982. On why gravel bed streams are paved. *Water Resources Research* 18(5):1409–1423.
- Reed, J. C. 1981. Disequilibrium profile of the Potomac River near Washington, D.C. – a result of lowered base level or Quaternary tectonics along the Fall Line? *Geology* 9(10): 445–450.
- Reed, W. B. 1991. An evaluation of the effects of 300 years of changing land use on the peak flows, base flow, and flood frequency of a small Pennsylvanian stream. Eastern Region Technical Attachment, Number 91-2A. National Weather Service, 10 pp.
- Reid, L. M., and T. Dunne. 1996. Rapid evaluation of sediment budgets. Reiskirchen, Catena Verlag GmbH. 164 pp.
- Simons, D. B., and R.-M. Li. 1982. Bank erosion on regulated rivers. In Hey, R. D., J. C. Bathurst, and C. R. Thorne, eds. *Gravel-Bed Rivers; Fluvial Processes, Engineering and Management*. John Wiley and Sons Ltd. NY., 717–754.

- Sloto, R. A. 1988. Effects of urbanization on storm-runoff volume and peak discharge of Valley Creek, Eastern Chester County, PA. United States Geological Survey Water-Resources Investigations Report 87-4196. 32 pp.
- Smith, L., and S. W. Wheatcraft. 1993. Groundwater flow. *In* Maidment, D. R., ed. Handbook of Hydrology, Ch. 6 McGraw-Hill. NY.
- Treese, L. 1995. Valley Forge: making and remaking a national symbol. The Pennsylvania State University Press. 269 pp.
- United States Geological Survey (USGS). 2004. 2004 Water Year Schuylkill River Basin, 01473169 Valley Creek at PA Turnpike Bridge near Valley Forge. Accessed October 2005. <http://pa.water.usgs.gov/ar/wy04/news-pdfs/spQ01473169.pdf>.
- United States Geological Survey (USGS). 2005. Real-time water data for 01473169 Valley Creek at PA Turnpike Bridge near Valley Forge. Accessed October 2005. <http://waterdata.usgs.gov/pa/nwis/uv?01473169>.
- Wilcock, P. R., and B. T. DeTemple. 2005. Persistence of armor layers in gravel-bed streams. Geophysical Research Letters, Vol. 32. 4 pp.
- Wolman, M. G. 1954. A method of sampling coarse river-bed material. Transactions of the American Geophysical Union 35:951–956.
- Wolman, M. G. 1967. A cycle of sedimentation and erosion in urban river channels. Geografiska Annaler 49:385–395.
- Yorke, T. H., and W. J. Herb. 1978. Effects of urbanization on streamflow and sediment transport in the Rock Creek and Anacostia River Basins, Montgomery County, Maryland, 1962–74. U.S. Geological Survey Professional Paper 1003. 71 pp.

Appendix A. Description of the 78 subdivisions of Valley Creek from the second channel characterization, completed May 2004 (see Figure 11).

Subdivision #	Flow Type	Bank Height	Water Depth	Flow Velocity	Bed Characterization	Comments
1	run	high R bank, moderate L bank	moderate with deep thalweg	moderate / high	predominantly boulders with some gravel / few small sand patches	narrow channel with deep thalweg / boulder bar on L bank / major erosion at R bank (erosion location 1)
2	riffle / run	moderate	moderate	moderate	predominantly small boulders / small amount of gravel / moderate sand deposition between boulders / riffles are predominantly moderate boulders / fines near banklines	gravel bar at L bank
3	glide / pool	low R bank / moderate to high L bank	shallow near bar / deep thalweg	low	mixture of boulders, gravel, and sand	narrow channel bend / boulder, gravel, and sand bar at R bank / significant erosion at L bank (erosion location 2)
4	glide / pool	low / moderate	moderate	low	sand / fine sand / few small boulders / boulders underneath bridge	thalweg deepens near bridge / steep decrease in slope directly downstream of bridge
5	riffle / run	low / moderate	shallow	high	predominantly large boulders / small sand patches between boulders	
6	pool	moderate	deep	low	sand and small gravel with a significant amount of fines / few boulders near banks	deep pool / significant erosion at r bank (erosion location 3)
7	pool	moderate	moderate / deep	low	predominantly sand / small amount of small gravel / few boulders near banks	bedrock is near banks / significant erosion at R bank (erosion location 3)
8	run	moderate	moderate	moderate	boulders near L bank / sand, fines, and gravel near R bank	bedrock is near banks / significant erosion at R bank (erosion location 3)
9	run	moderate	moderate	moderate	small boulders and cobble / patches of gravel and sand / accumulation of fines near eroding R bank	significant erosion at R bank (erosion location 4)

Subdivision #	Flow Type	Bank Height	Water Depth	Flow Velocity	Bed Characterization	Comments
10	riffle / run	moderate	shallow	moderate	small boulders / cobble / some gravel	
11	run	moderate	shallow / moderate	moderate	boulders / sand and gravel patches	bedrock is present
12	riffle / run	moderate	shallow / moderate	moderate	small boulders / cobble	bedrock is present / gravel bar at R bank
13	run	moderate	moderate	high	boulders / gravel / cobble / fines near banklines	
14	pool	low	moderate / deep	low	gravel and cobble near R bank / fines and sand near L bank (in thalweg)	gravel and cobble bar at R bank which transitions to deep thalweg at L bank / deepest part of reach is from the dam to approximately 10 feet upstream
15	pool / glide	low	moderate / deep	low	sand / gravel / fines near banks	gravel and cobble bar at R bank which transitions to deep thalweg at L bank
16	pool	high	moderate / deep	low	predominantly fine sand / cobble near banks	clear division between low banks in section 15 and high banks in section 16 / deep thalweg near L bank
17	pool	high L bank, low R bank	deep	low	fine sand / fines	entire width of channel is deep / significant erosion (erosion locations 9 and 10) / large mud ledges near banks / approx. ¾ ft decaying organic matter on bed
18	riffle / run	high	moderate with deep thalweg in a few areas	high	patches of sand / gravel / cobbles / boulders	Bar at L bank transitions from sand to gravel to cobbles with some boulders from downstream to upstream / significant erosion at L bank (erosion location 11) / shallow depth on bar transitions to deep thalweg / significant island in channel
19	glide	low / moderate	shallow to moderate	low	predominantly fine sand / small amount of gravel and cobble	
20	glide	low / moderate	moderate	low	cobble and small boulders / few patches of fines	significant erosion at R bank (erosion location 13)

Subdivision #	Flow Type	Bank Height	Water Depth	Flow Velocity	Bed Characterization	Comments
21	run	low L bank, wall at R bank	moderate	moderate / high	cobble and small boulders / large sand patches	
22	riffle / run	walls at both banks	shallow / moderate	high	cobble and boulders	shallow with moderately deep thalweg near R wall
23	pool	moderate	deep	low	predominantly fines / some cobbles, small boulders, and sand / boulders near banks	
24	glide	moderate	shallow / moderate	low	sand and gravel / small boulders near banks	row of trees along banks, angling in toward channel
25	glide	moderate	shallow / moderate	low	small boulders / gravel / sand / few fines	erosion at L bank (erosion location 15) / row of trees along banks, angling in toward channel
26	run	moderate	shallow	moderate	predominantly cobbles / some small boulders, sand, and gravel / fines underneath cobbles	significant erosion at L bank (erosion location 17)
27	run	moderate	shallow	moderate	sand and gravel / small amount of fines below sand and gravel	
28	riffles	moderate	shallow	moderate	large cobbles / small boulders / gravel	gabions
29	run	moderate	moderate	moderate	small boulders / small sand patches / small amount of gravel	gabions
30	run	moderate	shallow	moderate	small boulders / cobble / small amount of gravel	
31	run	moderate	shallow	moderate	small boulders / cobble / few sand patches / large boulders near banks	
32	run	moderate	shallow	moderate	cobbles / gravel	erosion at R bank (erosion location 19)
33	riffles	moderate / high	shallow	high	boulders / small amount of gravel / some cobbles	
34	run	moderate / high	shallow	moderate	boulders / cobble / small amount of gravel / sand patches	
35	run	low	moderate with deep thalweg	moderate / high	predominantly boulders / small amount of cobble / significant sand and small gravel patches	

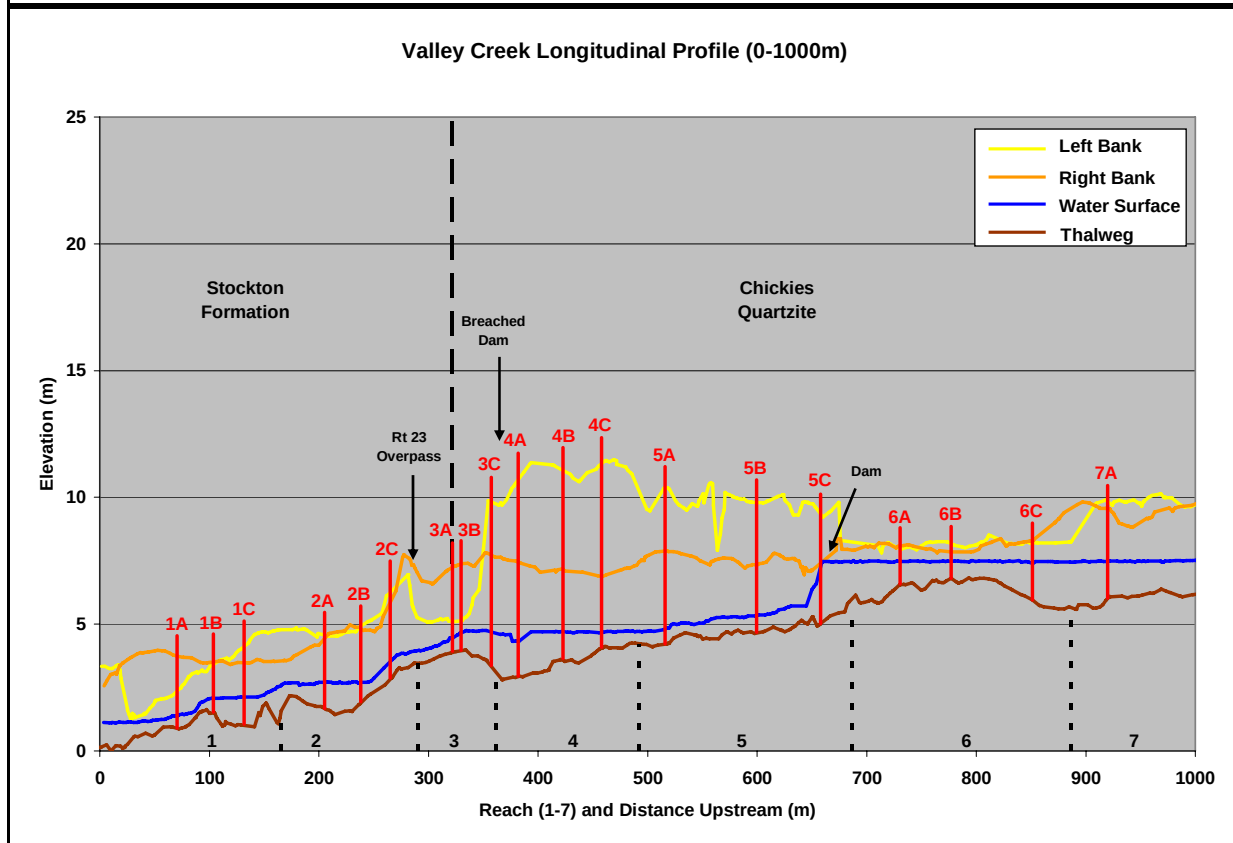
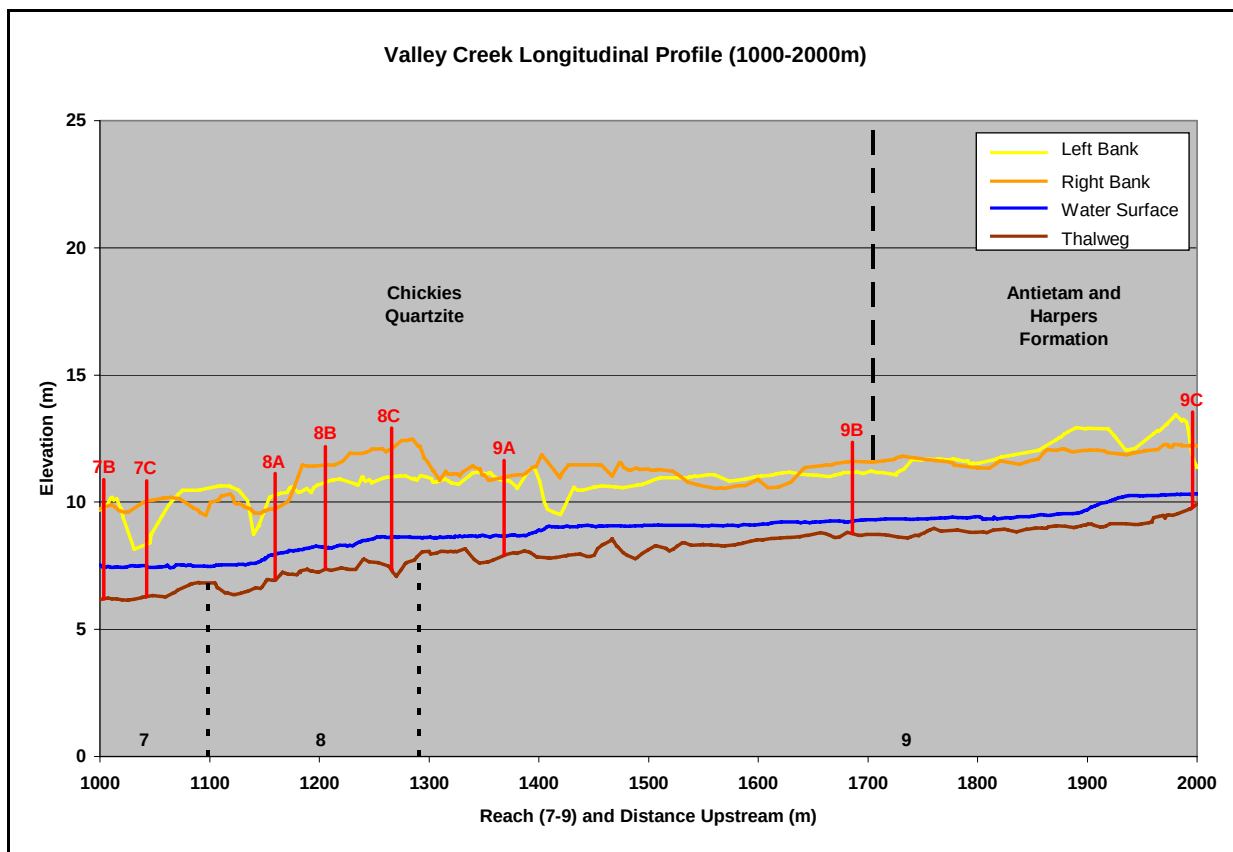
Subdivision #	Flow Type	Bank Height	Water Depth	Flow Velocity	Bed Characterization	Comments
36	riffles	low	shallow	high	boulders / cobble	
37	run	low	shallow	moderate / high	predominantly cobble / small amount of sand and gravel	
38	run	low	moderate with deep thalweg	moderate / high	cobble / small boulders / significant sand patch	
39	run	low	moderate	moderate	predominantly boulders and cobble / small amount of sand and gravel	
40	run / glide	low	moderate with deep thalweg	moderate	cobble / small boulders / sand	sand and gravel bar at R bank / deep thalweg near L bank with cobbles and boulders
41	run	low	shallow	moderate	cobble / sand / gravel / moderate sand patches	
42	run	low	shallow	moderate / high	cobble / small amount of gravel	
43	run	low	shallow	moderate	cobble / small boulders / significant sand and small gravel patches	
44	run	low	shallow	moderate	cobble / small boulders / small amount of gravel	
45	riffles / run	low	shallow / moderate	high	cobble and small boulders in thalweg / gravel and small sand patches near banks	
46	small pool	low / moderate	moderate	moderate	predominantly small boulders / cobble / small amount of sand	
47	run	low / moderate	shallow / moderate	moderate	predominantly sand / small amount of gravel / some cobbles and small boulders near banks	
48	run	low / moderate	shallow / moderate	moderate	cobble / gravel / few small boulders	
49	riffles	low / moderate	shallow / moderate	moderate / high	small boulders / cobble / small amount of gravel	trees angles into stream on L bank, but erosion is vegetated
50	glide	low / moderate	moderate	low	sand / small gravel / few cobble and boulders / thin film of fines	
51	riffles	low / moderate	shallow	moderate	cobble / gravel / small boulders / small amount of sand	

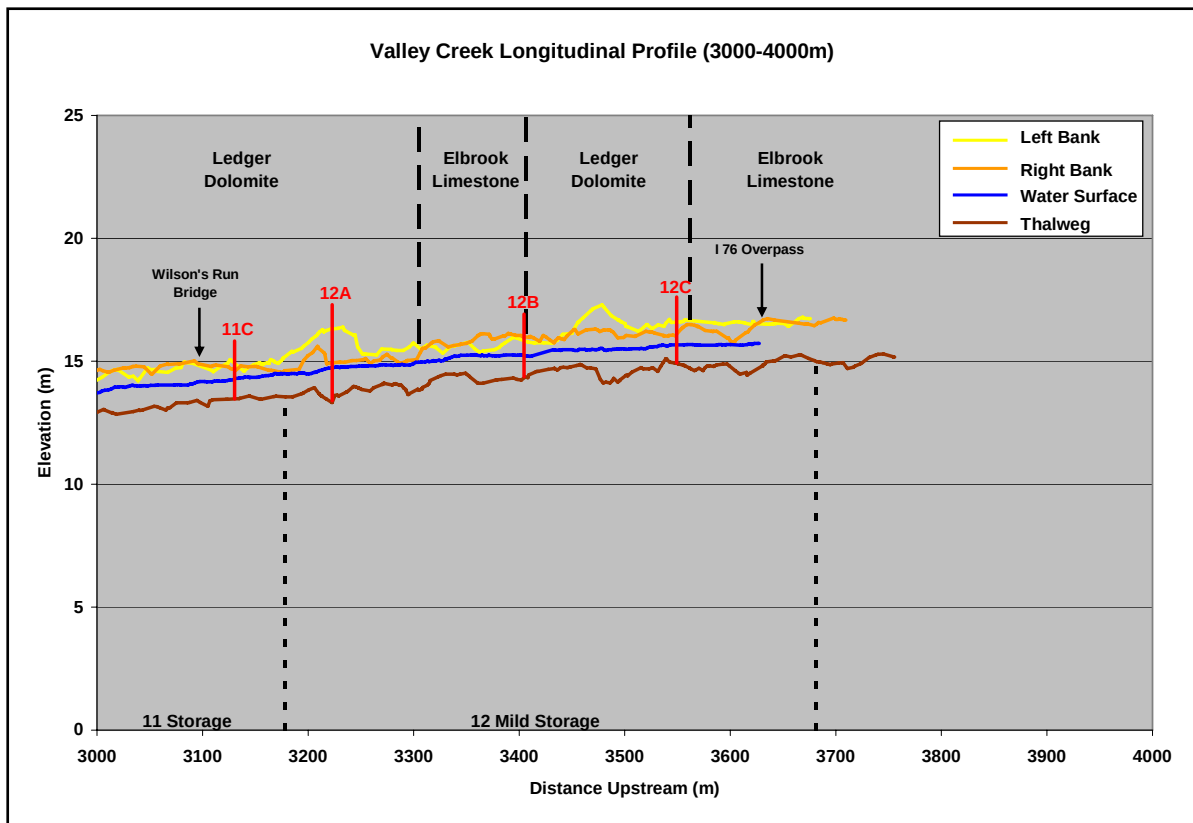
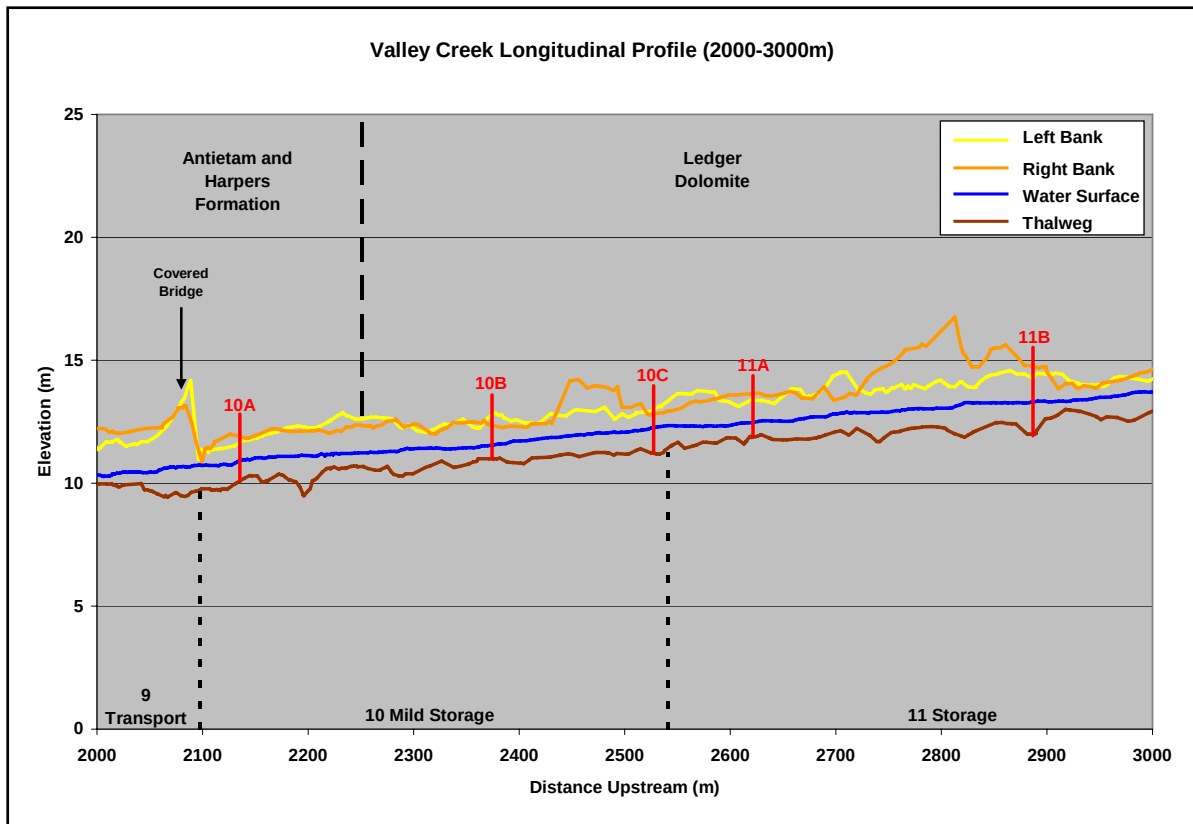
Subdivision #	Flow Type	Bank Height	Water Depth	Flow Velocity	Bed Characterization	Comments
52	glide	low / moderate	shallow / moderate	low	cobble / predominantly sand with a small amount of gravel near R bank / thin film of fines	algae growth on rocks
53	run	low L bank, moderate R bank	moderate	moderate	boulders / significant sand patches / small amount of cobble and gravel	
54	glide	moderate	moderate with deep thalweg	low	predominantly bedrock / cobble / sand / significant accumulation of sand, gravel, and fines at L bank	
55	run	moderate	shallow / moderate	moderate	cobble / small boulders / small amount of sand and gravel	
56	run	moderate	moderate	low / moderate	boulders / sand / gravel	
57	riffle	moderate	moderate with deep thalweg	high	predominantly gravel / small boulders and sand in thalweg	gravel island near R bank with vegetation on top
58	glide	Low	shallow / moderate	low	gravel / sand / thin film of fines	
59	glide	low	shallow / moderate	low	cobble / small boulders / sand / gravel	Significant erosion at R bank (erosion location 33)
60	run	low	shallow	moderate	small boulders / cobble / gravel / sand	
61	riffles	low	shallow with moderately deep thalweg	moderate / high	boulders / cobble / gravel / few sand patches	small boulder and cobble bar at R bank / moderately deep thalweg near L bank
62	run	low	moderate	low / moderate	small boulders / sand / gravel / large sand patches / predominantly sand in thalweg	
63	riffles / run	low	moderate with deep thalweg	moderate	small boulders / cobble / moderate amount of sand and gravel / film of fines / sand patches in thalweg	large gravel bar at L bank / deep thalweg near R bank
64	riffles / run	low R bank / moderate L bank	moderate with deep thalweg	moderate / high	boulders / gravel	sand and gravel bar at R bank / significant erosion on L bank (erosion location 35)

Subdivision #	Flow Type	Bank Height	Water Depth	Flow Velocity	Bed Characterization	Comments
65	riffles / run	low	shallow	high	compacted armor layer of cobble and gravel / moderate amount of fines under armor layer	film of fines and algae
66	run	low	shallow	moderate	cobble / small boulders / small amount of sand and gravel / moderate amount of fines under armor layer	film of fines and algae / erosion on R bank (erosion location 36)
67	run	low	moderate with deep thalweg	moderate / high	boulders / cobble / sand patches in thalweg	gravel, cobble, and sand bar at L bank / cobble and small boulder bar at L bank upstream of first bar with significant amount of fines and algae on bar
68	run	low	shallow	high	boulders / cobble / small amount of sand	
69	run / glide	low	deep	low	sand / few cobbles and boulders in thalweg	
70	run / glide	low	deep	low	Sand / patches of cobble and boulders	
71	riffles	low	shallow with moderately deep thalweg	high	cobble / small boulders / small amount of gravel	gravel and small boulder bar at R bank / sand bar downstream of gravel bar / algae growth
72	Run	Low	moderate with deep thalweg	low / moderate	cobble / small boulders / small amount of sand and gravel / thin film of fines	sand and gravel bar at R bank / algae growth / trees on banks are angled into stream, but no significant erosion
73	run	low	moderate with deep thalweg	low / moderate	sand / gravel / cobble / small boulders	large sand and gravel bar at R bank / deep thalweg near L bank is predominantly cobbles and small boulders
74	riffle / run	low	moderate with deep thalweg	high	boulders / cobble / gravel / film of fines near R bank	
75	run	low	shallow / moderate	high	cobble / small boulders / gravel / small amount of sand / most sand located near banks	
76	run / glide	low	moderate	low / moderate	gravel / sand / few cobbles and small boulders	

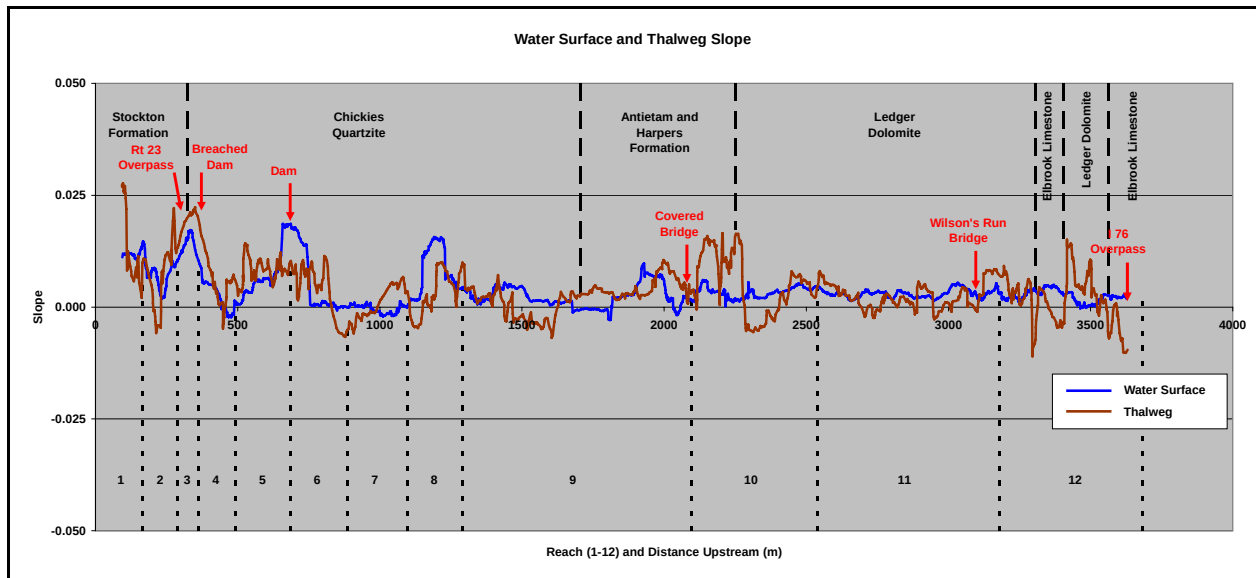
Subdivision #	Flow Type	Bank Height	Water Depth	Flow Velocity	Bed Characterization	Comments
77	run / glide	low	moderate	low / moderate	sand / few boulders	
78	run / glide	low	moderate	low / moderate	gravel / sand / boulders in thalweg	

Appendix B. Valley Creek longitudinal profile, September 2003–May 2004.





Appendix C. Water surface and thalweg slopes for Valley Creek, September 2003–May 2004 (the data series was smoothed by averaging the data over a distance of approximately 90 m in order to filter out noise and reveal trends).



Appendix D. Flood frequency analysis using PEAKFQ from data at Valley Creek USGS stream gage at PA Turnpike.

1

U. S. GEOLOGICAL SURVEY
ANNUAL PEAK FLOW FREQUENCY ANALYSIS
Following Bulletin 17-B Guidelines
Program peakfq
(Version 4.1, February, 2002)

--- PROCESSING DATE/TIME ---

2005 SEP 8 22:16:19

--- PROCESSING OPTIONS ---

Plot option = Graphics device
Basin char output = None
Print option = Yes
Debug print = No
Input peaks listing = Long
Input peaks format = WATSTORE peak file

1

U. S. GEOLOGICAL SURVEY
ANNUAL PEAK FLOW FREQUENCY ANALYSIS
Following Bulletin 17-B Guidelines
Program peakfq
(Version 4.1, February, 2002)

Station - 01473169 Valley Creek at PA Turnpike Br near Valley Forge
2005 SEP 8 22:16:19

I N P U T D A T A S U M M A R Y

Number of peaks in record	=	22
Peaks not used in analysis	=	0
Systematic peaks in analysis	=	22
Historic peaks in analysis	=	0
Years of historic record	=	0
Generalized skew	=	0.663
Standard error of generalized skew	=	0.550
Skew option	=	STATION SKEW
Gage base discharge	=	0.0
User supplied high outlier threshold	=	--
User supplied low outlier criterion	=	--
Plotting position parameter	=	0.00

***** NOTICE -- Preliminary machine computations. *****
***** User responsible for assessment and interpretation. *****

WCF134I-NO SYSTEMATIC PEAKS WERE BELOW GAGE BASE.		0.0
WCF162I-SYSTEMATIC PEAKS EXCEEDED HIGH-OUTLIER CRITERION.	1	4989.9
WCF195I-NO LOW OUTLIERS WERE DETECTED BELOW CRITERION.		341.1
*WCF151I-17B WEIGHTED SKEW REPLACED BY USER OPTION.	0.733	0.803 -1

1

Station - 01473169 Valley Creek at PA Turnpike Br near Valley Forge
2005 SEP 8 22:16:19

ANNUAL FREQUENCY CURVE PARAMETERS -- LOG-PEARSON TYPE III

	FLOOD BASE		LOGARITHMIC		
	DISCHARGE	EXCEEDANCE PROBABILITY	MEAN	STANDARD DEVIATION	SKEW
SYSTEMATIC RECORD	0.0	1.0000	3.1155	0.2399	0.803
BULL.17B ESTIMATE	0.0	1.0000	3.1155	0.2399	0.803

ANNUAL FREQUENCY CURVE -- DISCHARGES AT SELECTED EXCEEDANCE PROBABILITIES

ANNUAL EXCEEDANCE PROBABILITY	BULL.17B ESTIMATE	SYSTEMATIC RECORD	'EXPECTED PROBABILITY' ESTIMATE	95-PCT CONFIDENCE LIMITS FOR BULL. 17B ESTIMATES	
				LOWER	UPPER
0.9950	473.9	473.9	444.4	314.6	621.0
0.9900	501.7	501.7	474.0	338.5	651.9
0.9500	606.3	606.3	585.1	430.9	767.7
0.9000	685.5	685.5	669.1	502.8	855.4
0.8000	813.1	813.1	801.7	620.5	998.4
0.5000	1213.0	1213.0	1213.0	986.5	1475.0
0.2000	2007.0	2007.0	2058.0	1639.0	2606.0
0.1000	2729.0	2729.0	2883.0	2163.0	3812.0
0.0400	3924.0	3924.0	4376.0	2954.0	6067.0
0.0200	5061.0	5061.0	5970.0	3655.0	8447.0
0.0100	6449.0	6449.0	8137.0	4465.0	11610.0
0.0050	8142.0	8142.0	11160.0	5406.0	15780.0
0.0020	10960.0	10960.0	17160.0	6888.0	23390.0
0.6667	977.4	(1.50-year flood)			
0.4292	1330.6	(2.33-year flood)			

1

Station - 01473169 Valley Creek at PA Turnpike Br near Valley Forge
2005 SEP 8 22:16:19

I N P U T D A T A L I S T I N G

WATER YEAR	DISCHARGE	CODES	WATER YEAR	DISCHARGE	CODES
1983	826.0		1994	1740.0	
1984	899.0		1995	1080.0	
1985	1210.0		1996	1810.0	
1986	1280.0		1997	2200.0	
1987	838.0		1998	1110.0	
1988	1090.0		1999	6280.0	
1989	1580.0		2000	1500.0	
1990	924.0		2001	1940.0	
1991	1320.0		2002	576.0	
1992	464.0		2003	1720.0	
1993	900.0		2004	2730.0	

Explanation of peak discharge qualification codes

PEAKFQ CODE	WATSTORE CODE	DEFINITION
D	3	Dam failure, non-recurrent flow anomaly
G	8	Discharge greater than stated value
X	3+8	Both of the above
L	4	Discharge less than stated value
K	6 OR C	Known effect of regulation or urbanization
H	7	Historic peak

1

Station - 01473169 Valley Creek at PA Turnpike Br near Valley Forge
2005 SEP 8 22:16:19

EMPIRICAL FREQUENCY CURVES -- WEIBULL PLOTTING POSITIONS

WATER YEAR	RANKED DISCHARGE	SYSTEMATIC RECORD	BULL.17B ESTIMATE
1999	6280.0	0.0435	0.0435
2004	2730.0	0.0870	0.0870
1997	2200.0	0.1304	0.1304
2001	1940.0	0.1739	0.1739
1996	1810.0	0.2174	0.2174
1994	1740.0	0.2609	0.2609
2003	1720.0	0.3043	0.3043
1989	1580.0	0.3478	0.3478
2000	1500.0	0.3913	0.3913
1991	1320.0	0.4348	0.4348
1986	1280.0	0.4783	0.4783
1985	1210.0	0.5217	0.5217
1998	1110.0	0.5652	0.5652
1988	1090.0	0.6087	0.6087
1995	1080.0	0.6522	0.6522
1990	924.0	0.6957	0.6957
1993	900.0	0.7391	0.7391
1984	899.0	0.7826	0.7826
1987	838.0	0.8261	0.8261
1983	826.0	0.8696	0.8696
2002	576.0	0.9130	0.9130
1992	46		

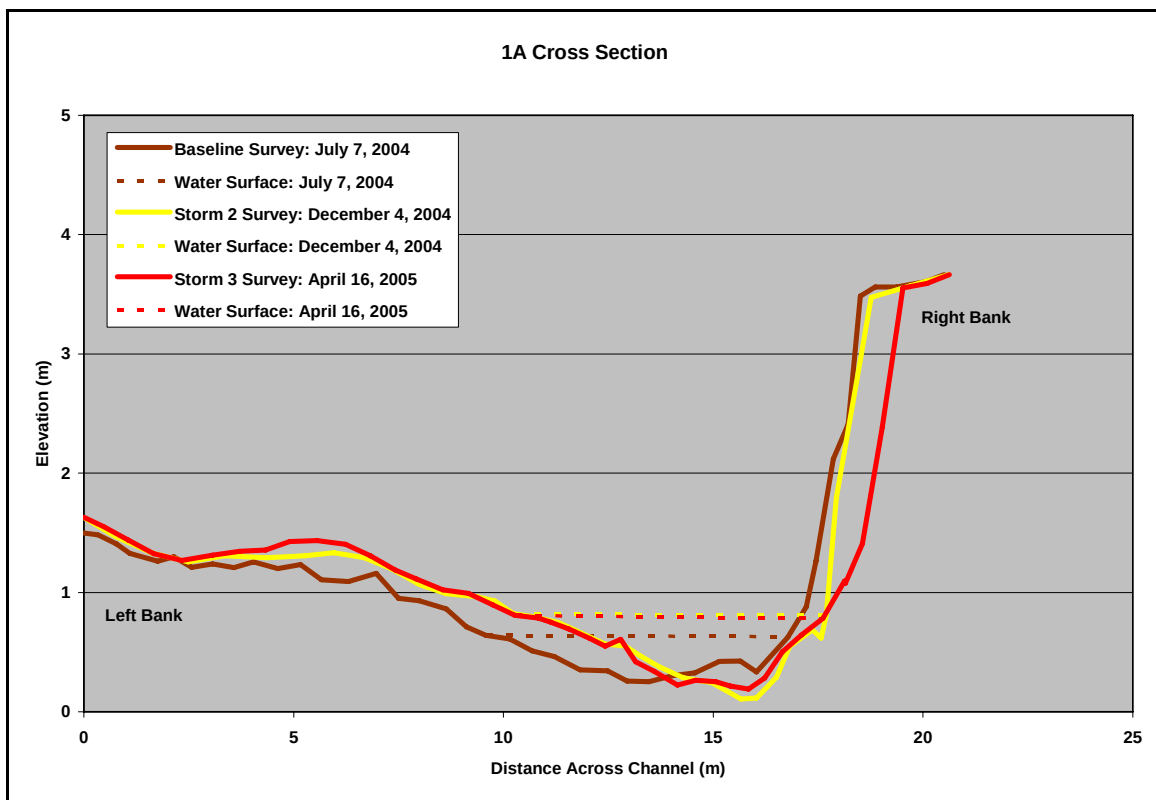
Appendix E. Baseline and storm data from 36 cross-sections of Valley Creek (summer 2004 to summer 2005).

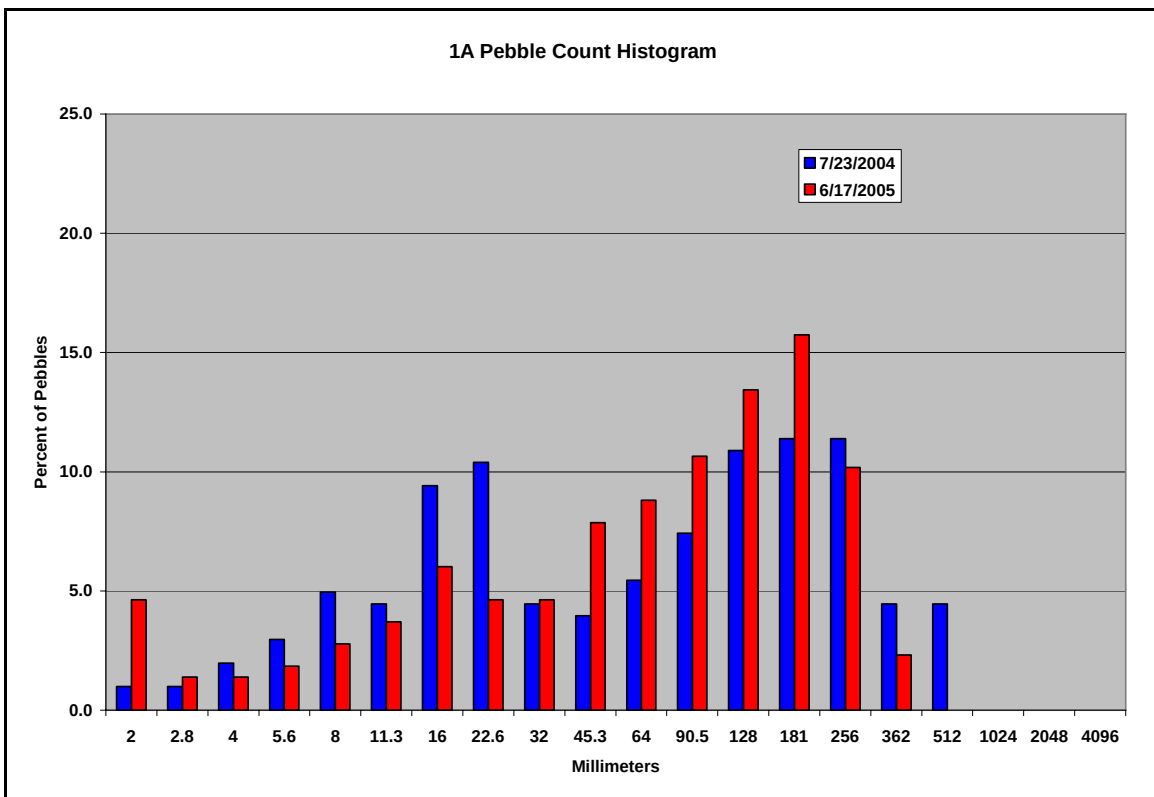
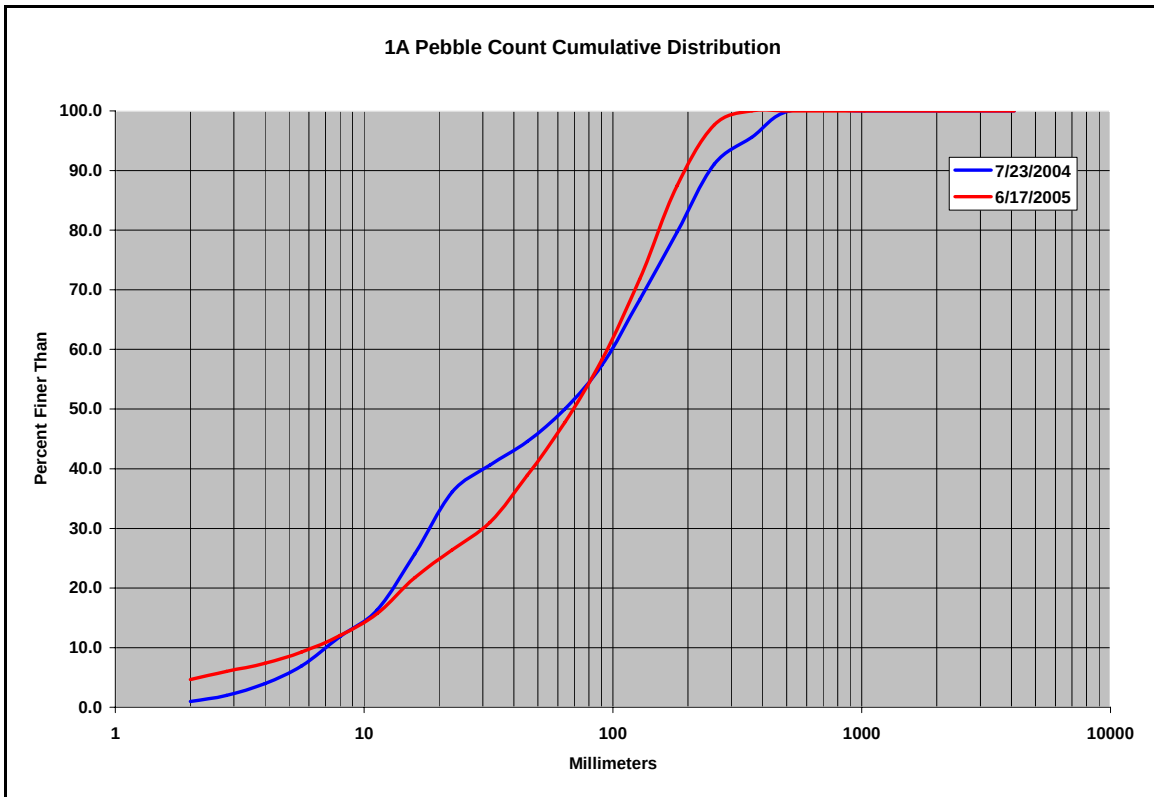
REACH 1



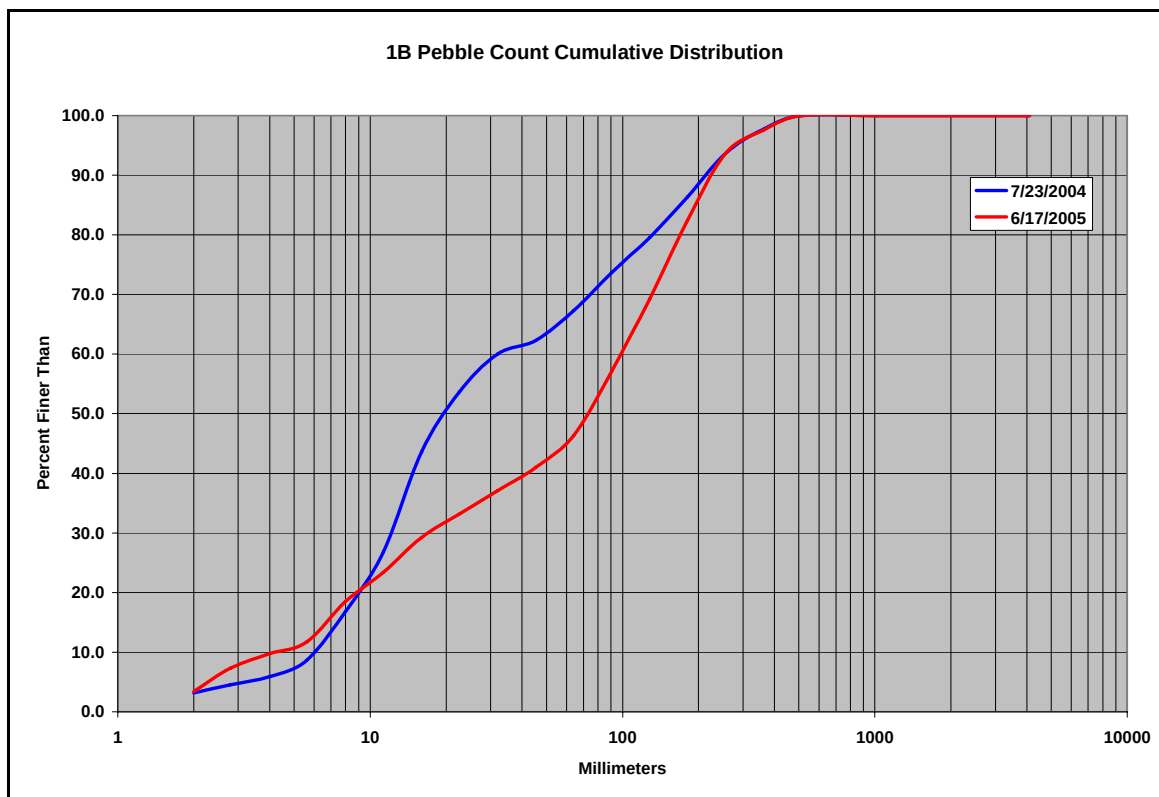
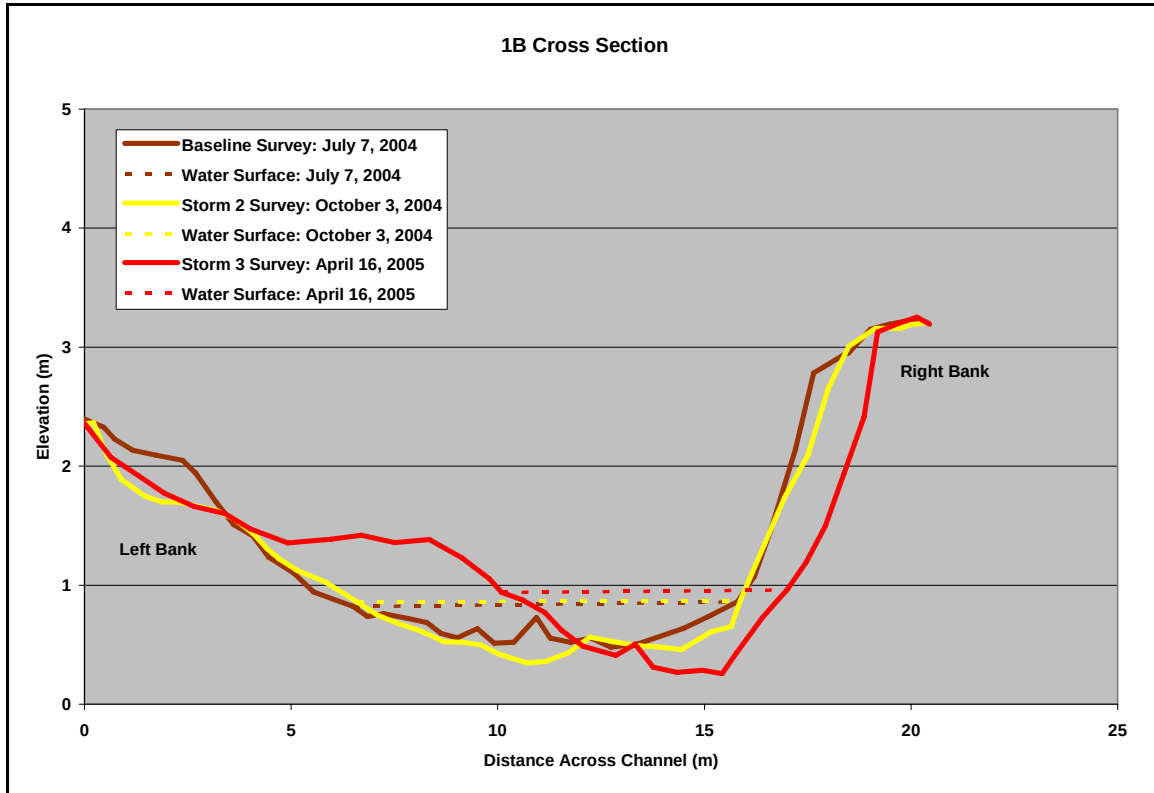
Reach 1 Cross-Sections

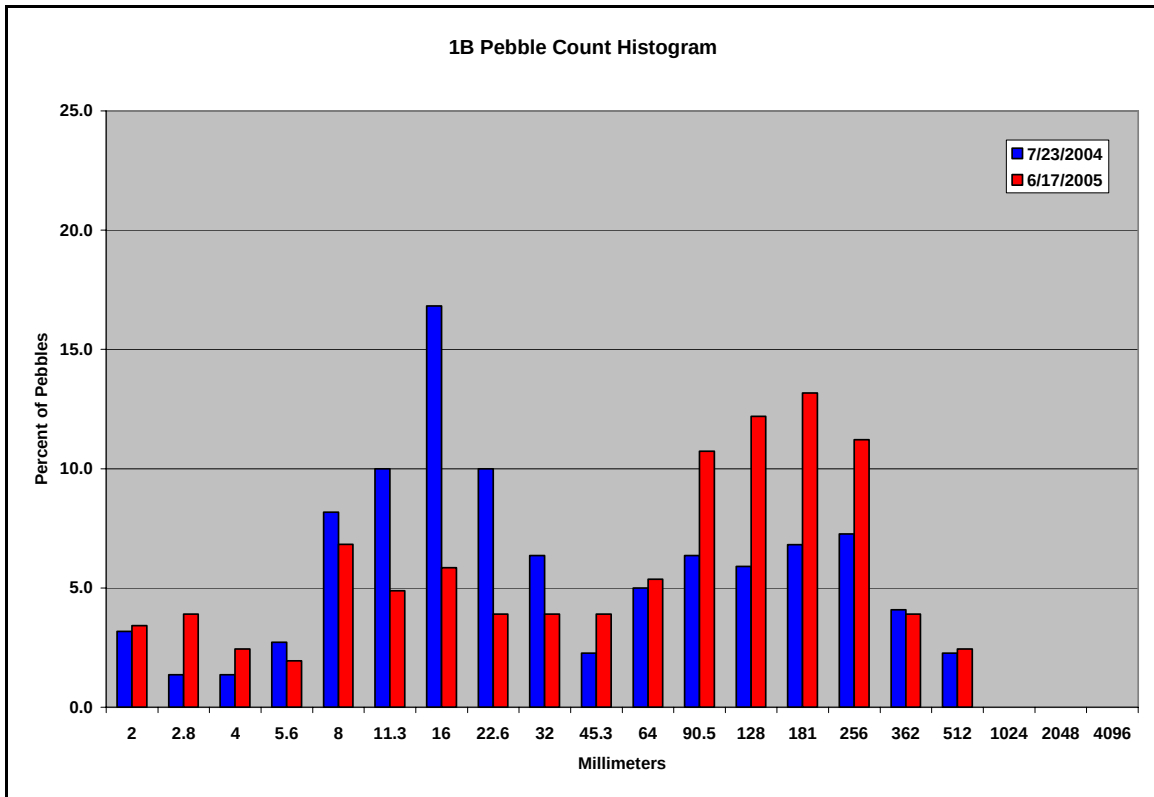
Cross-Section 1A



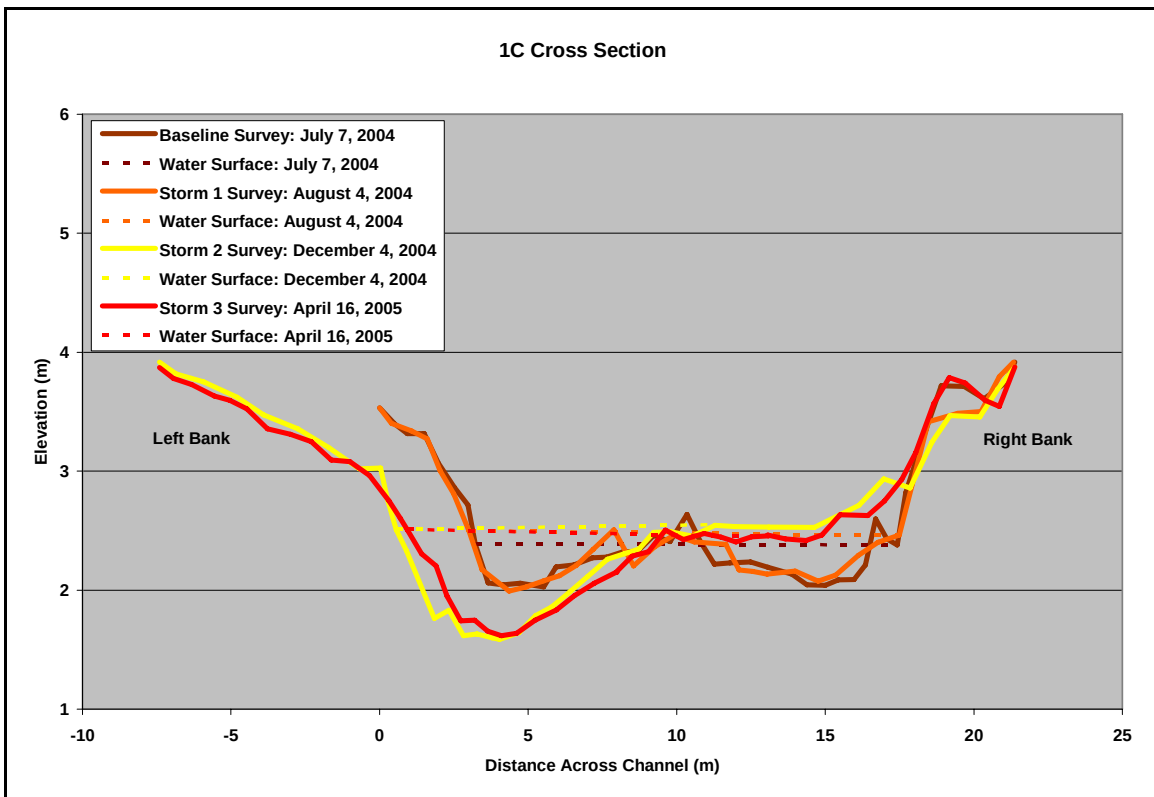


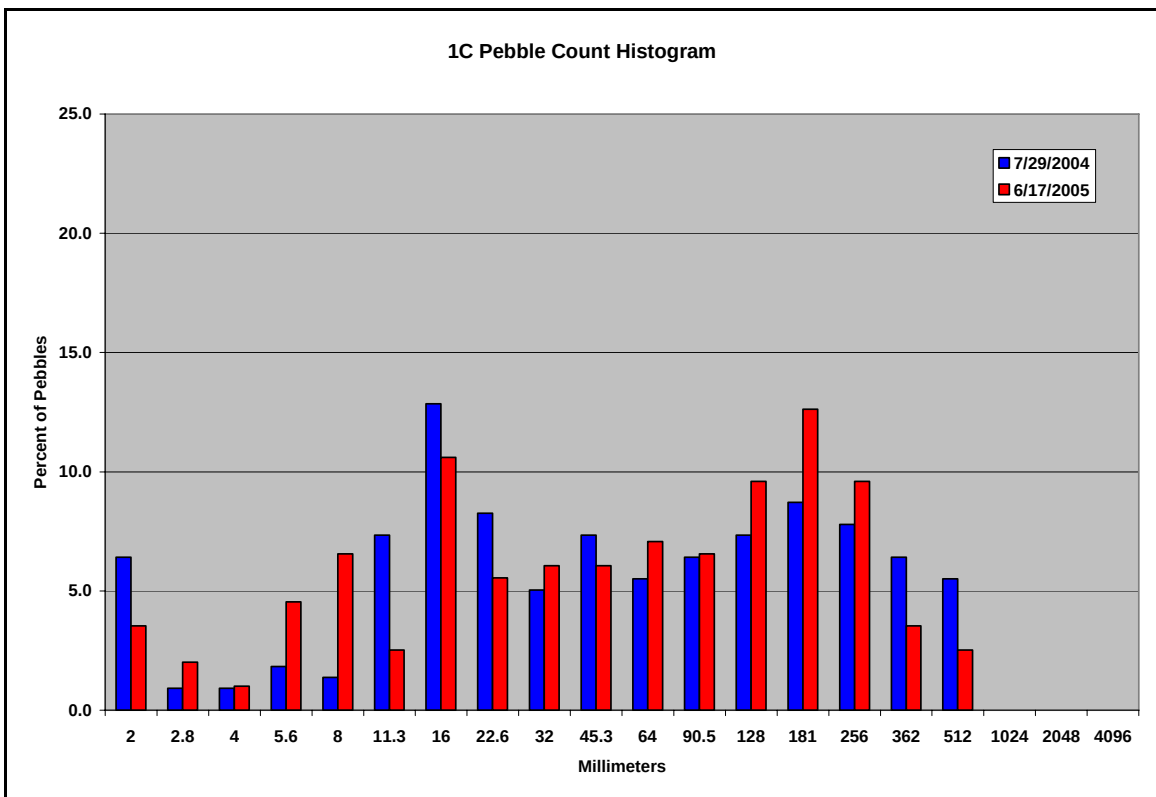
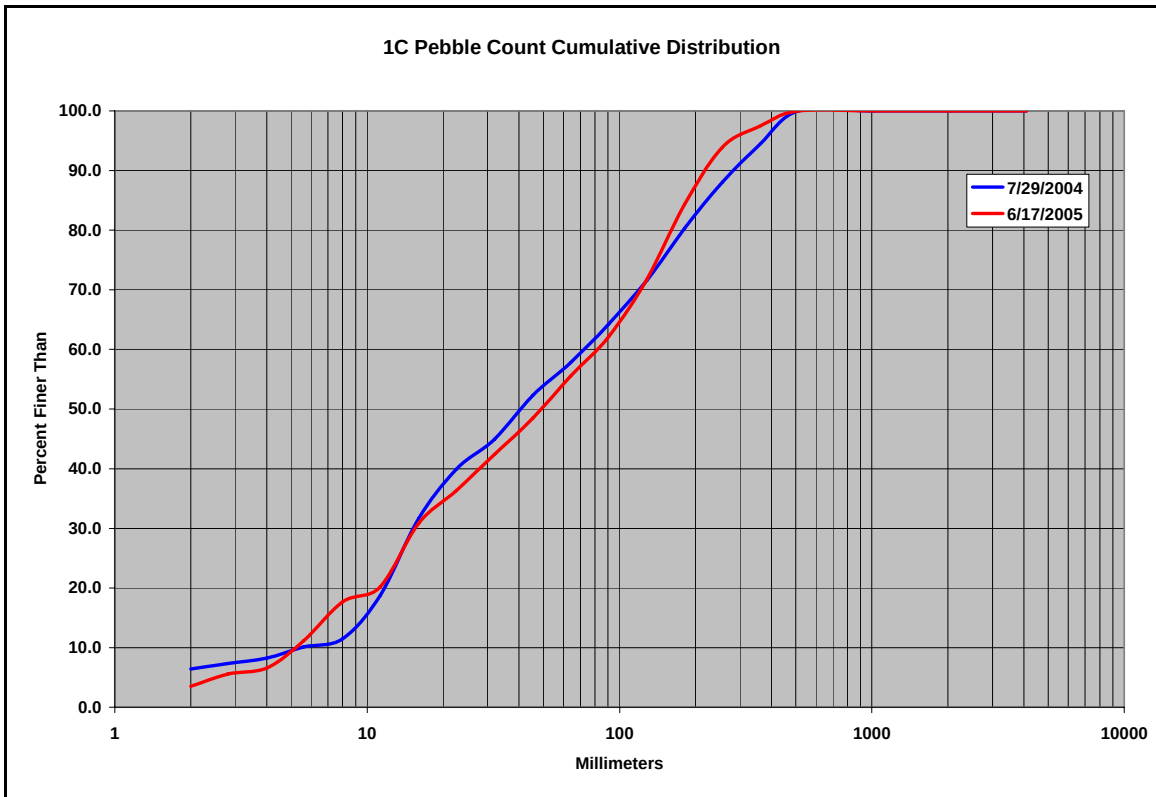
Cross-Section 1B





Cross-Section 1C



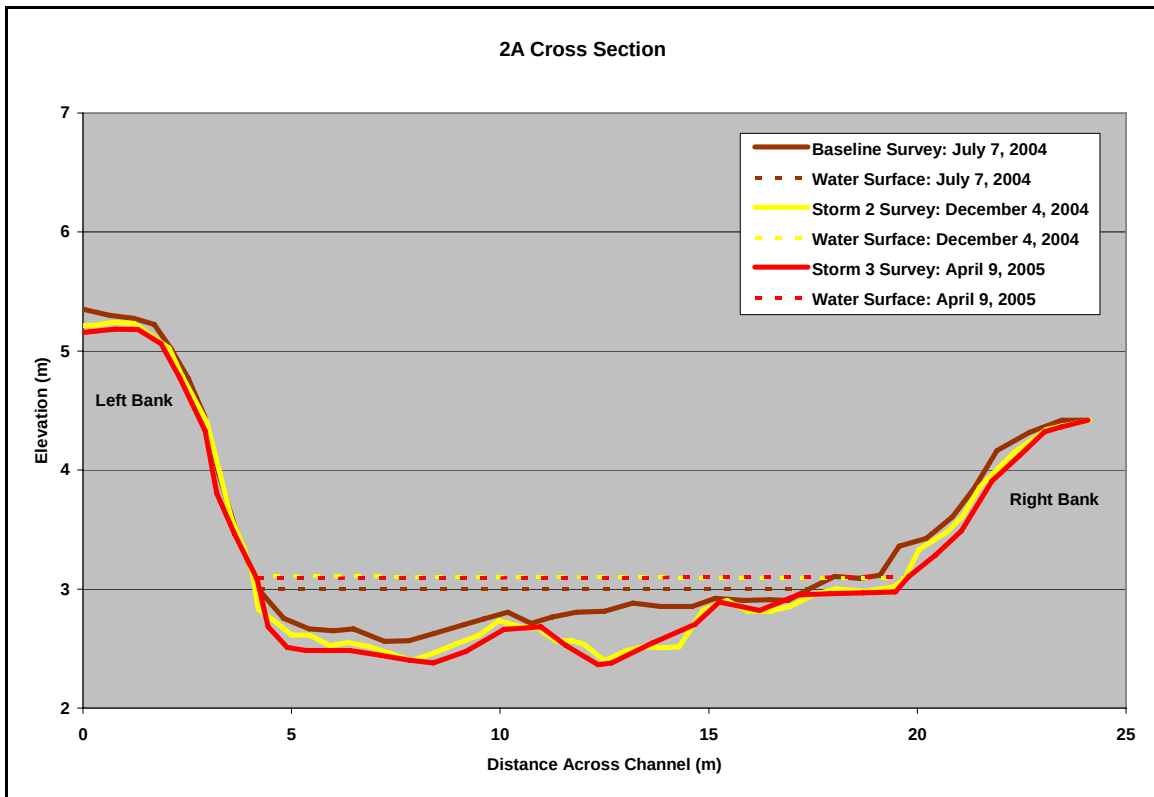


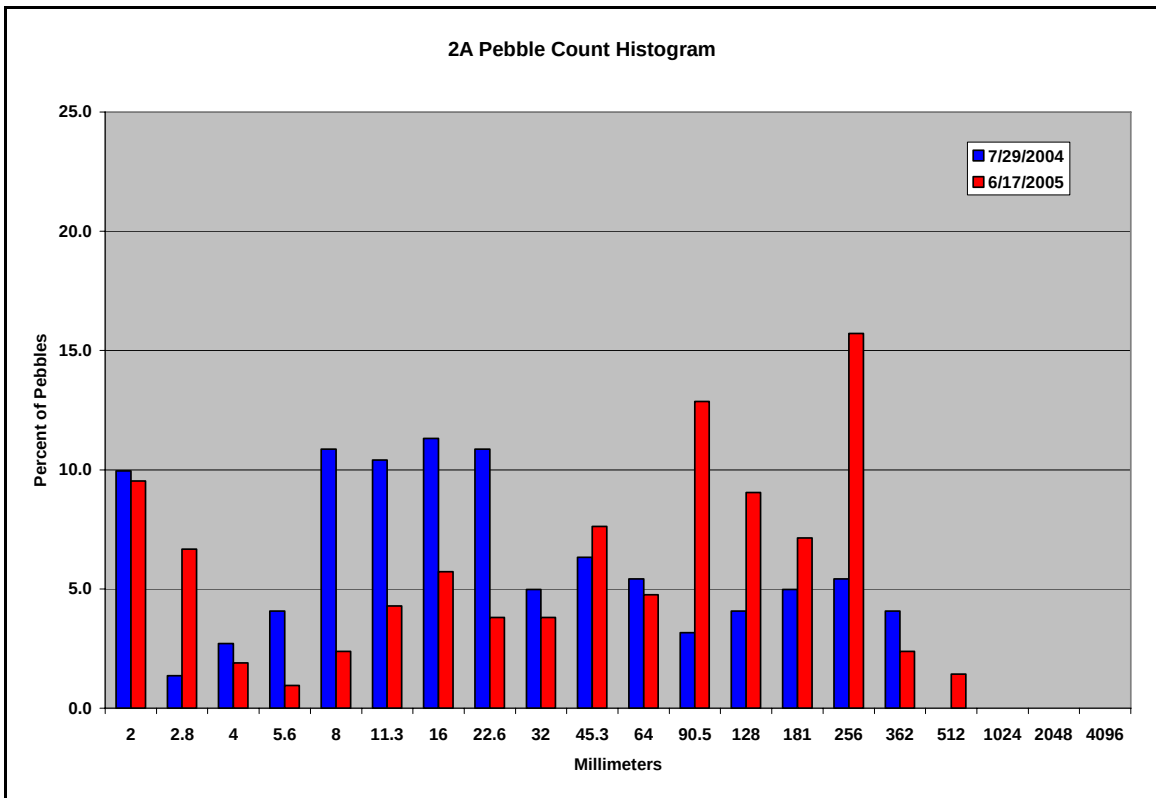
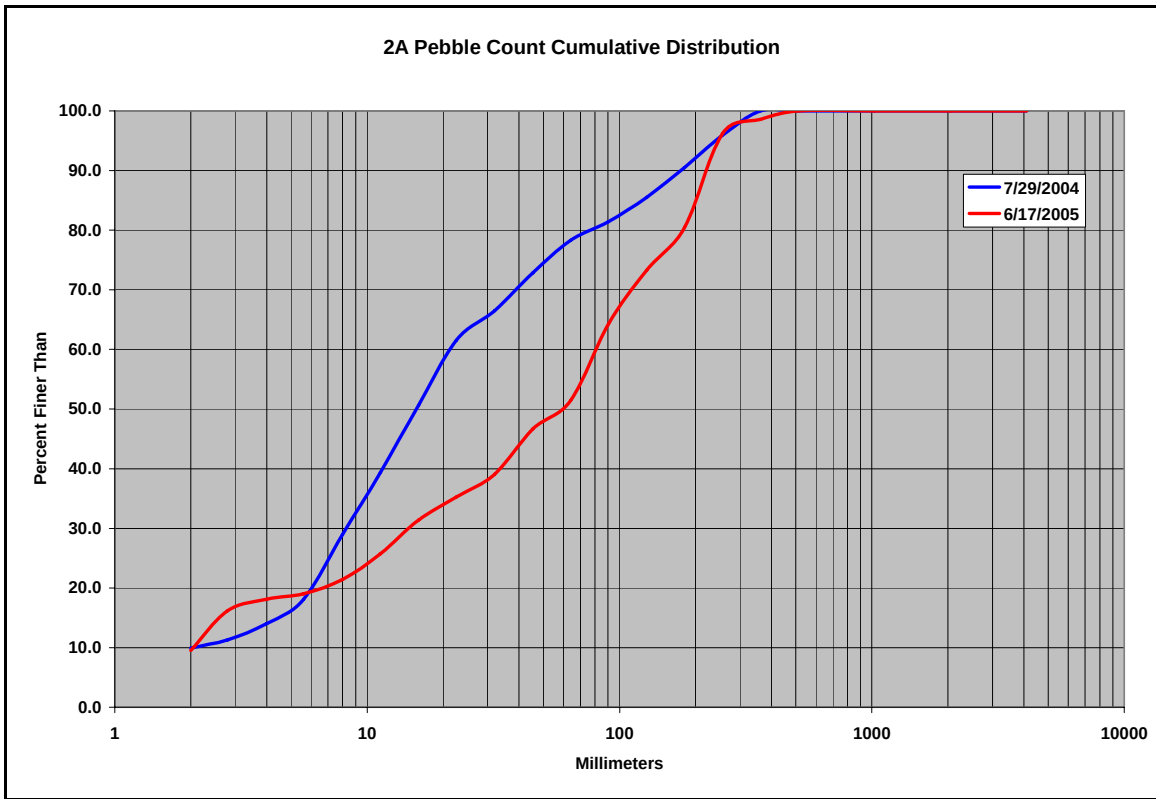
REACH 2



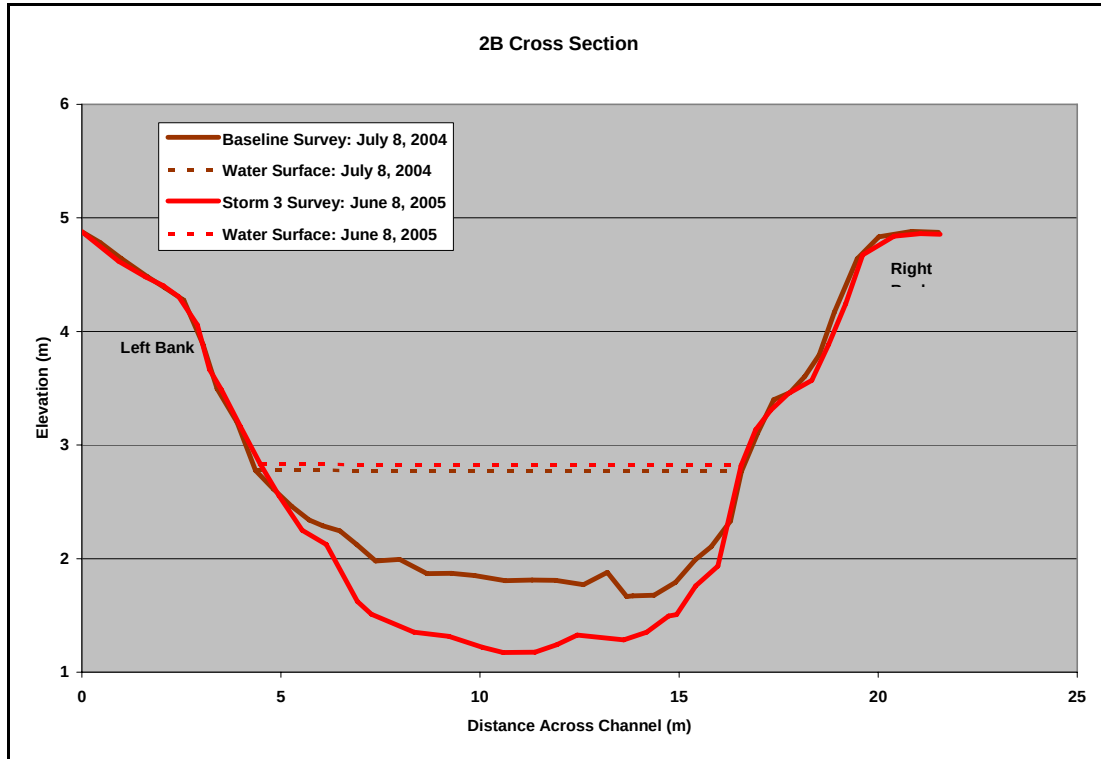
Reach 2 Cross-Sections

Cross-Section 2A

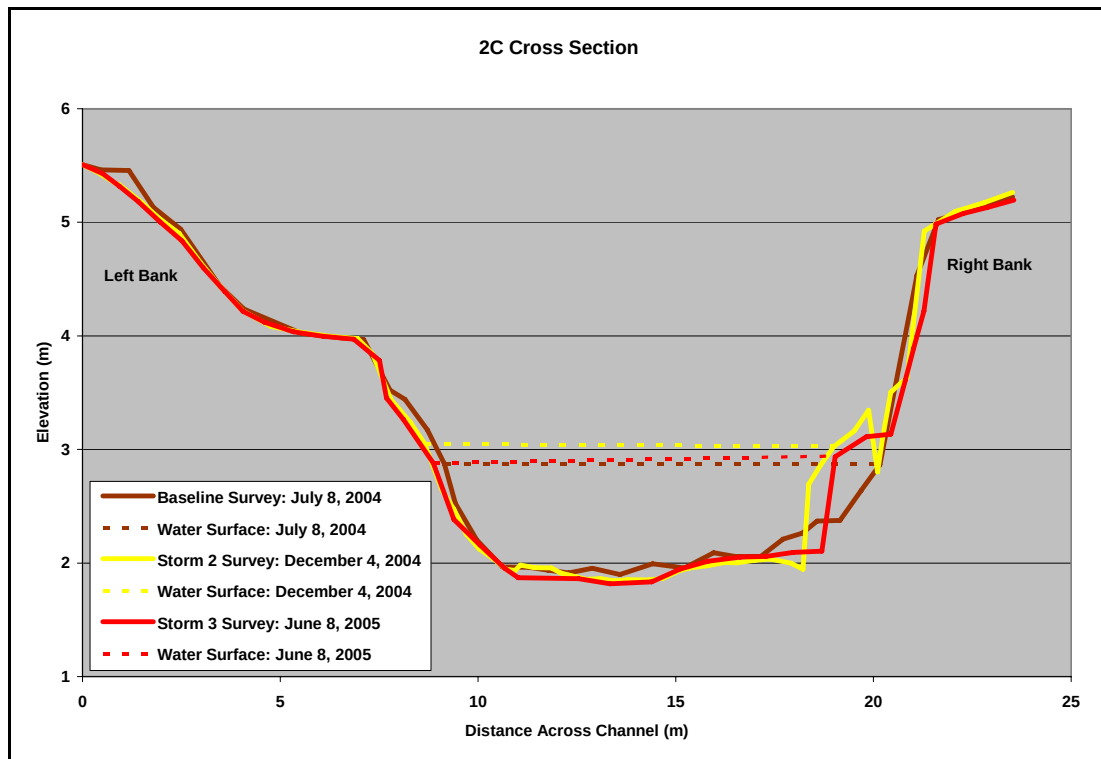




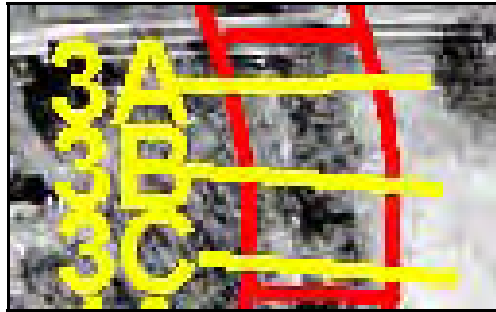
Cross-Section 2B



Cross-Section 2C

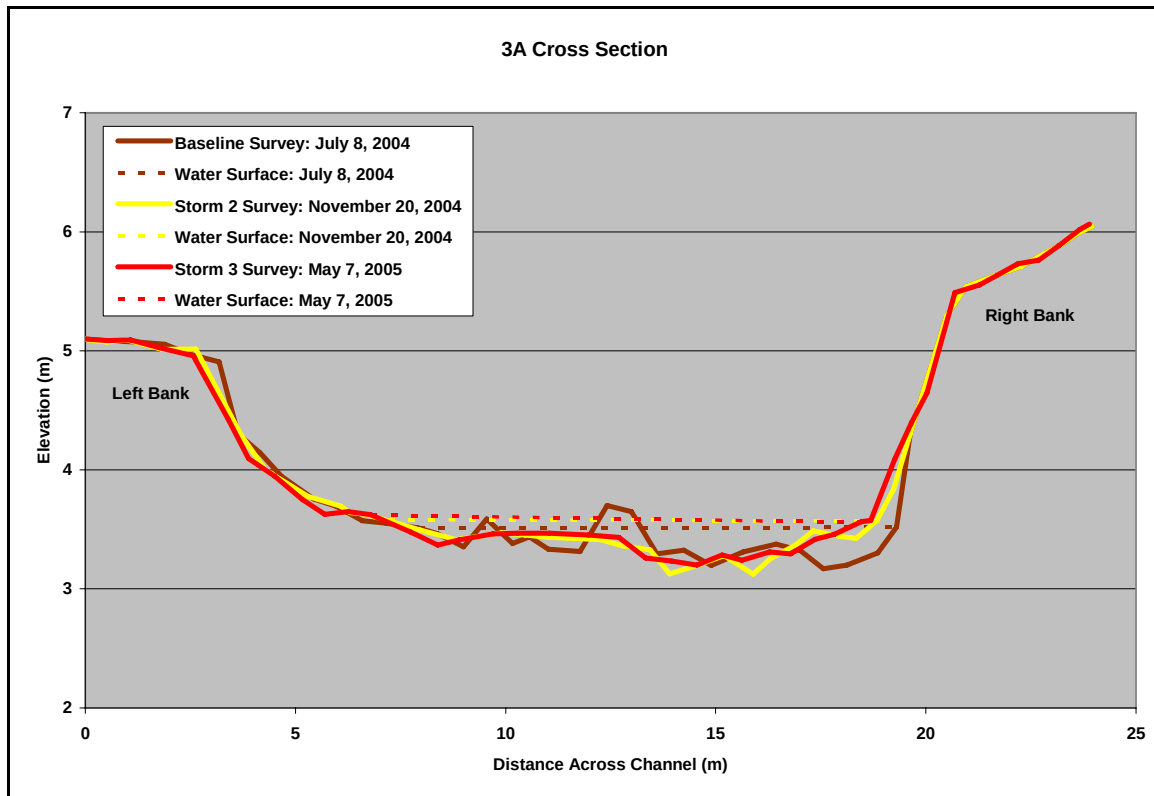


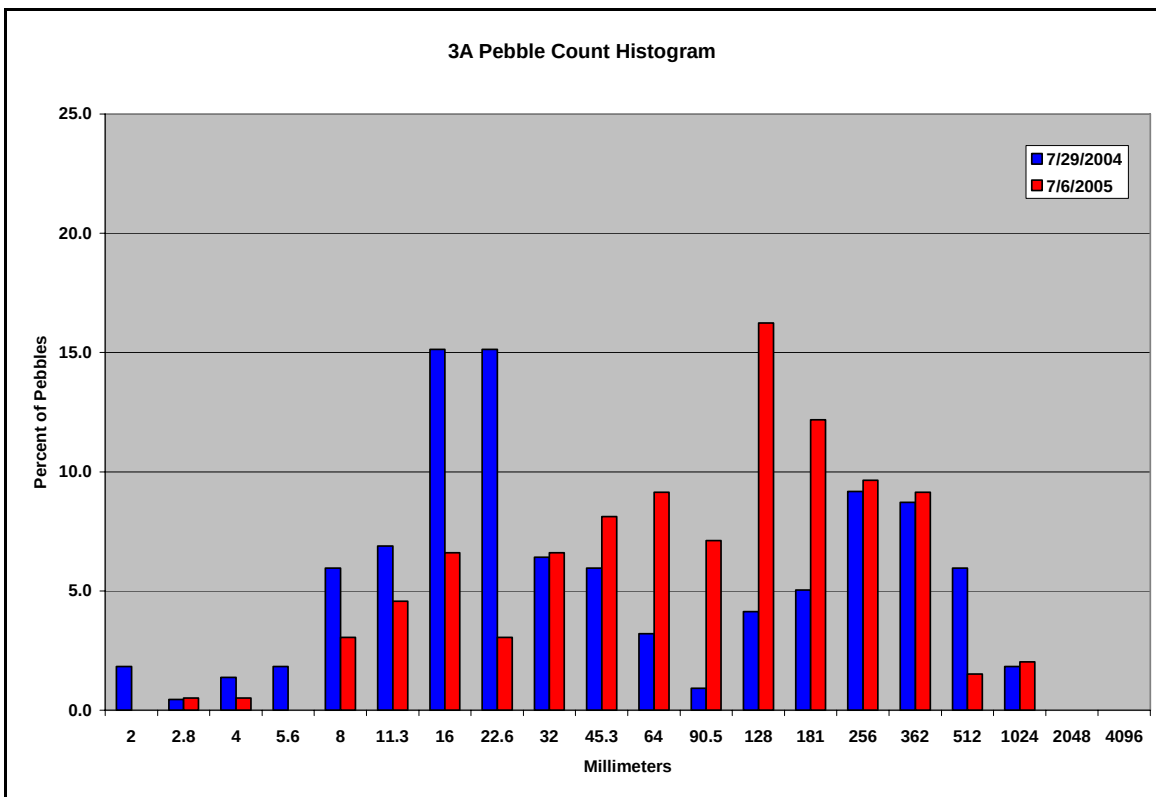
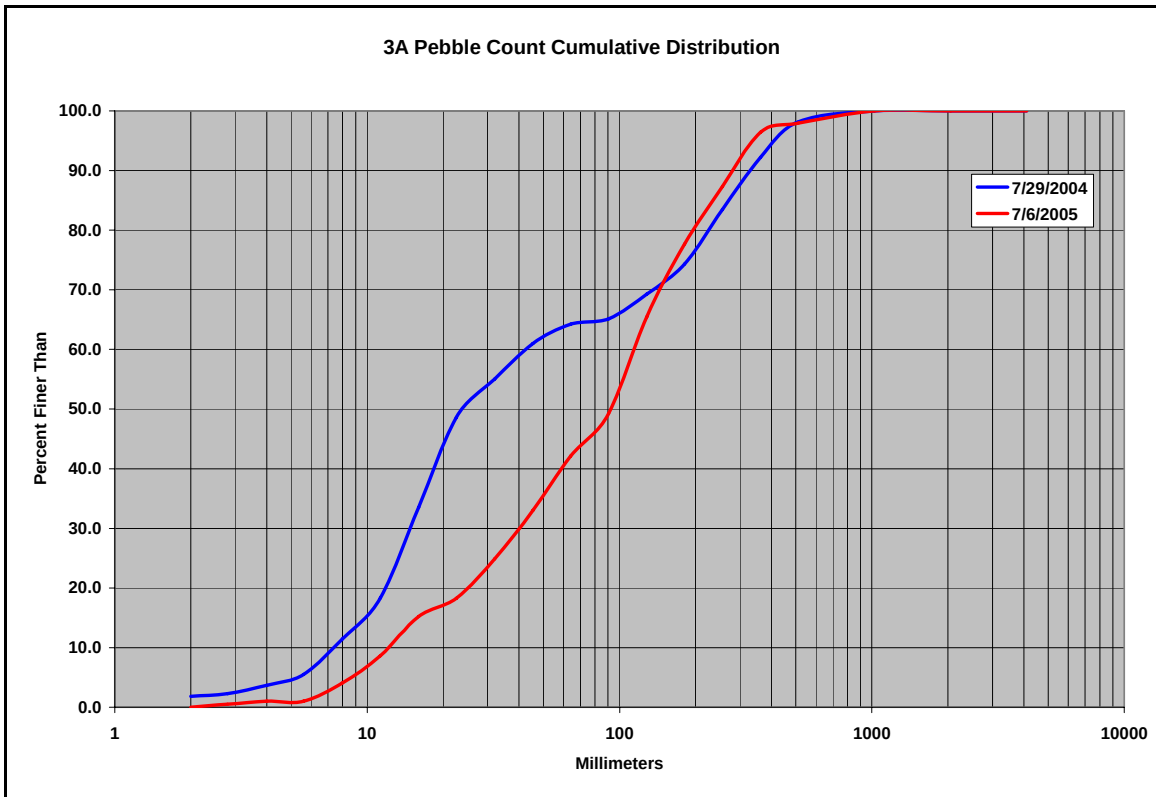
REACH 3



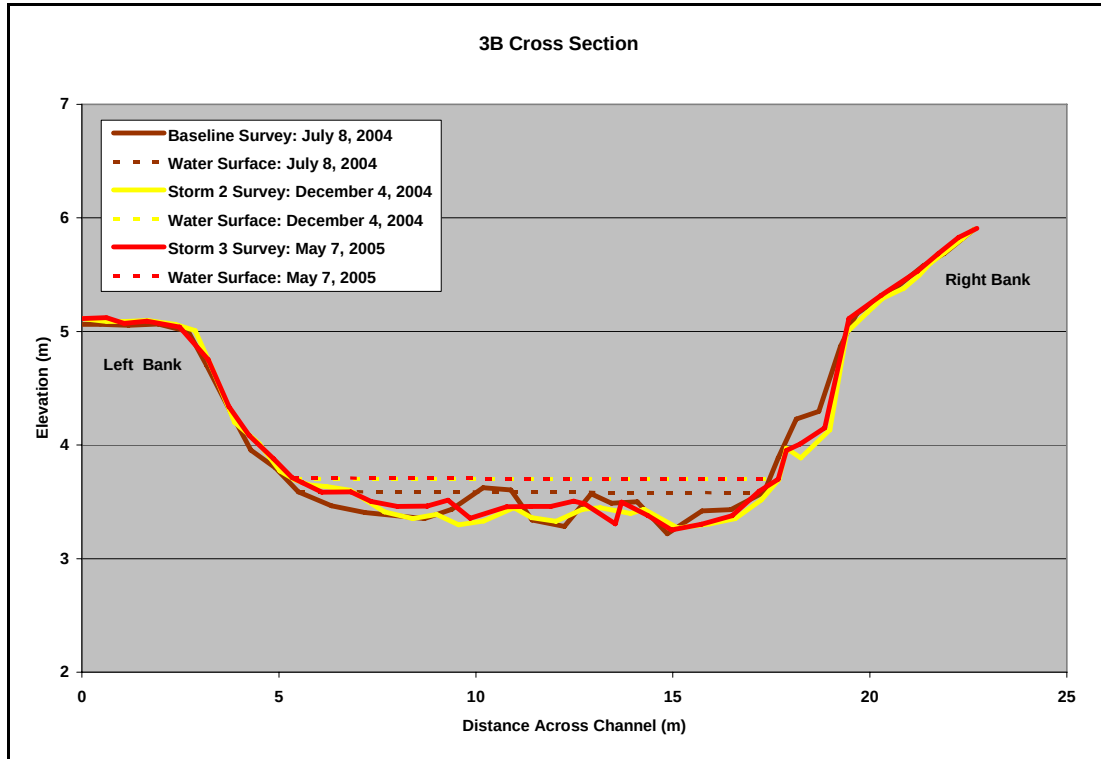
Reach 3 Cross-Sections

Cross-Section 3A

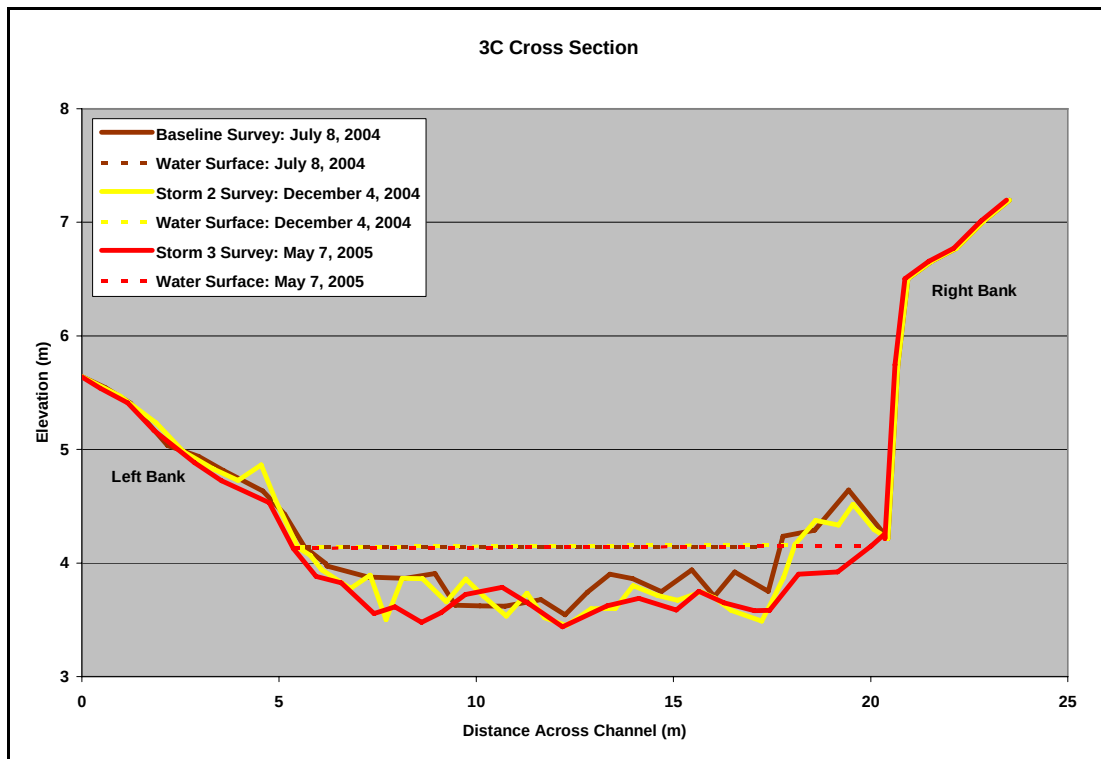


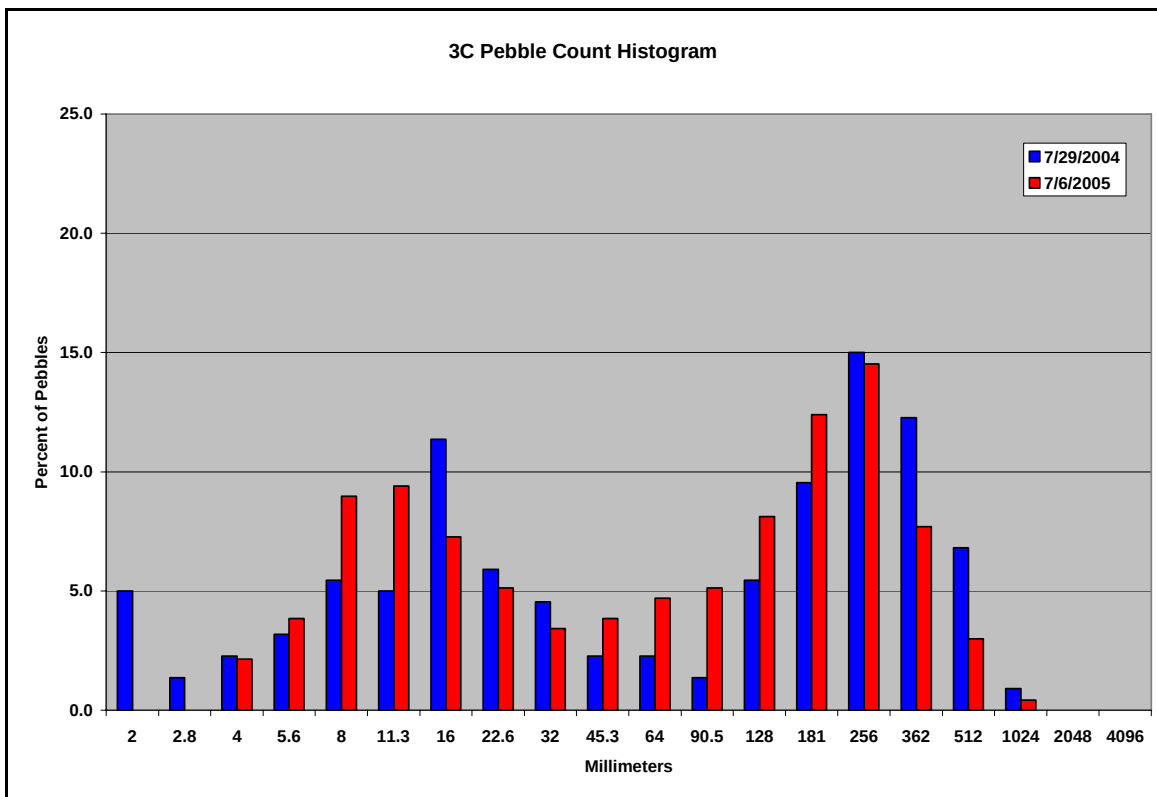
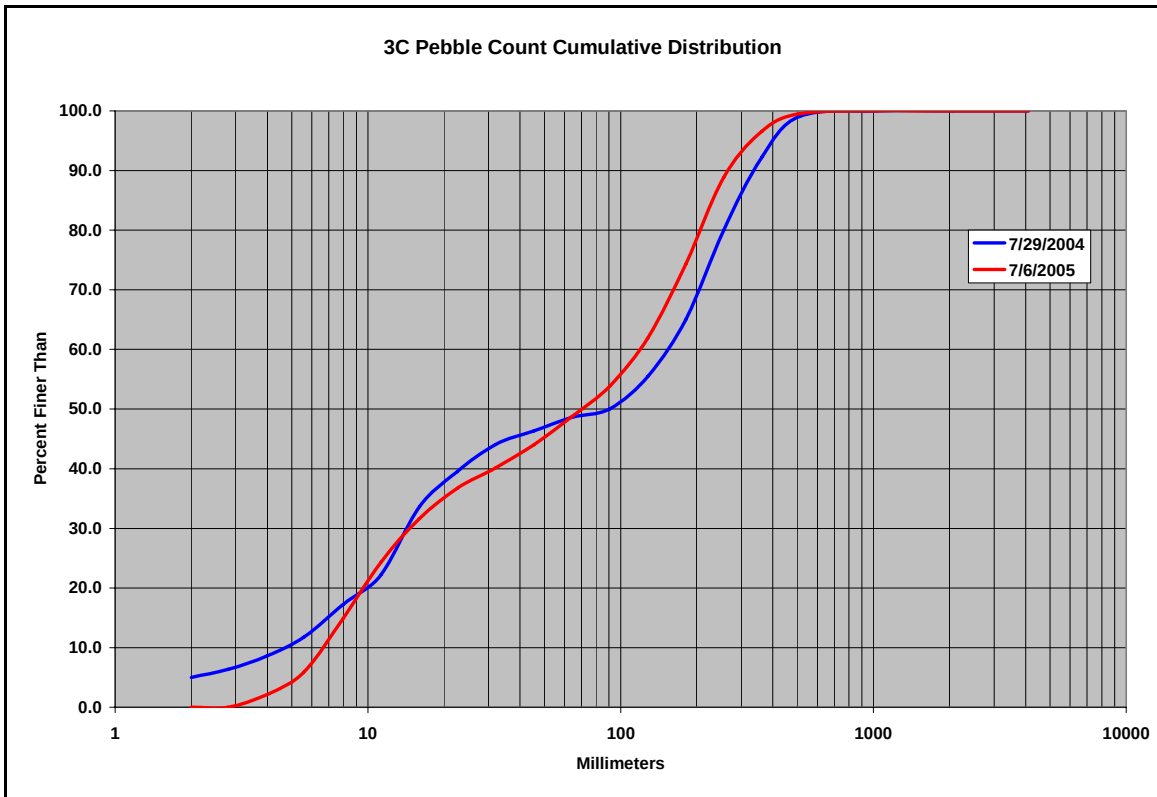


Cross-Section 3B



Cross-Section 3C



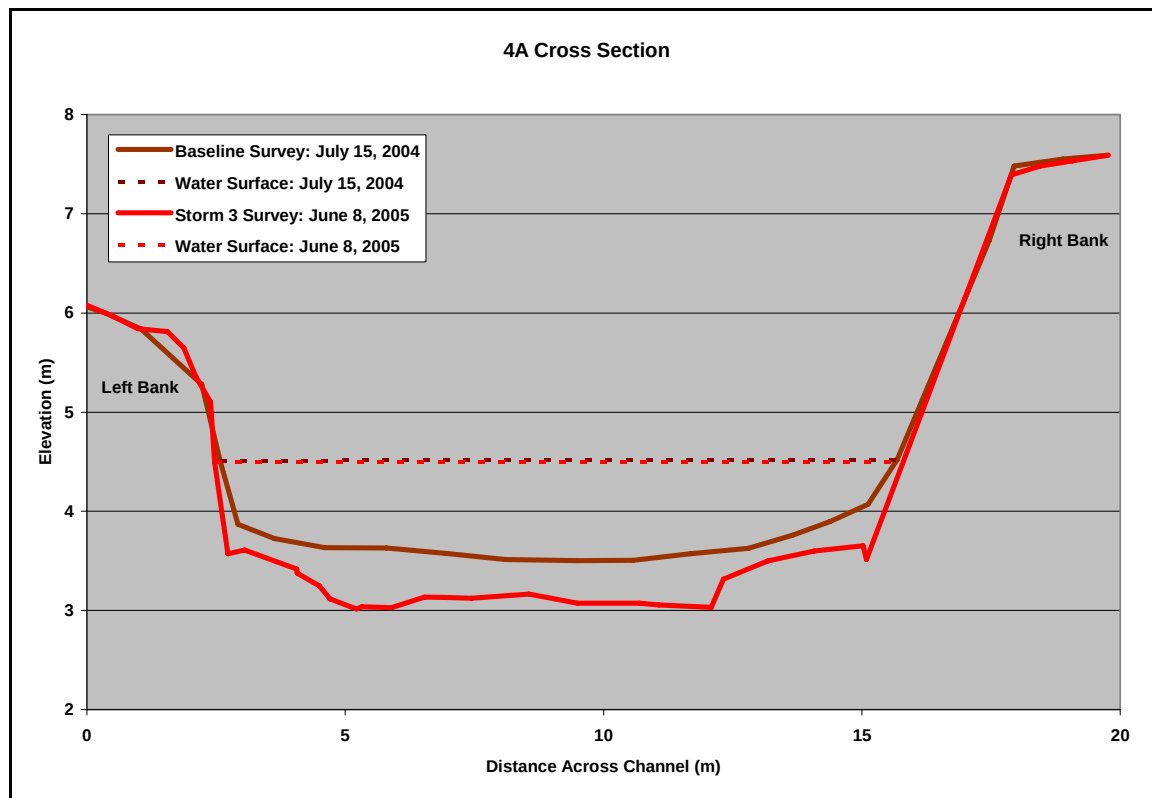


REACH 4

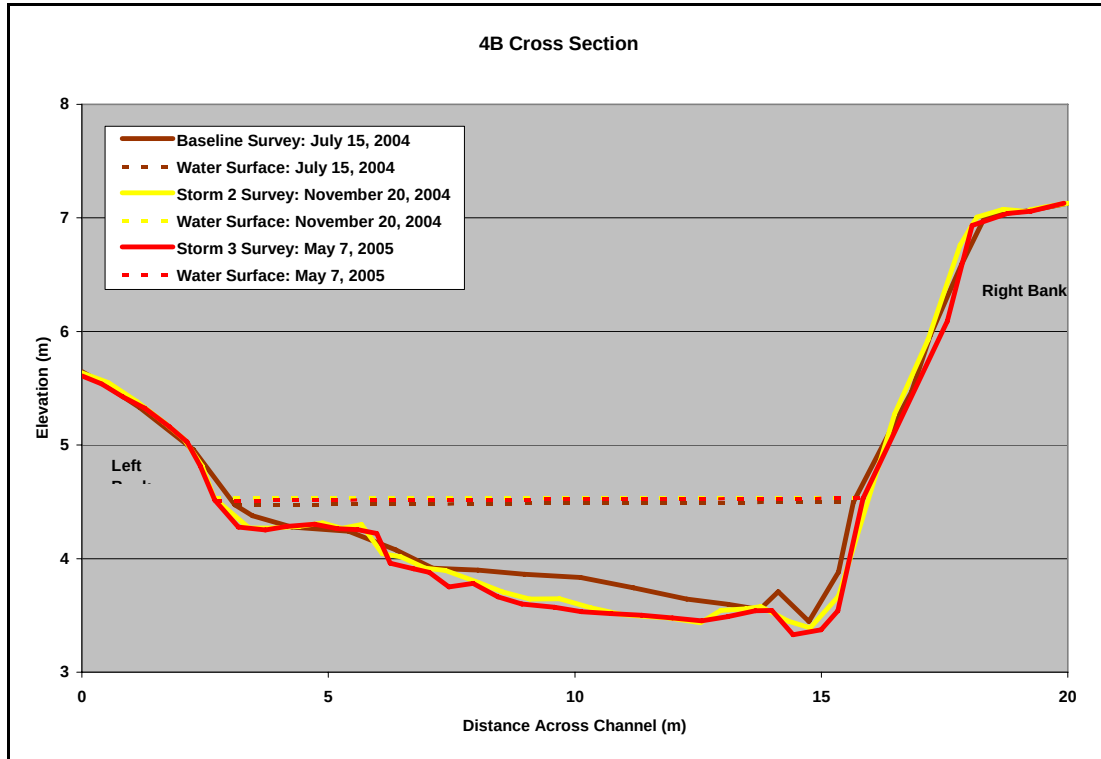


Reach 4 Cross-Sections

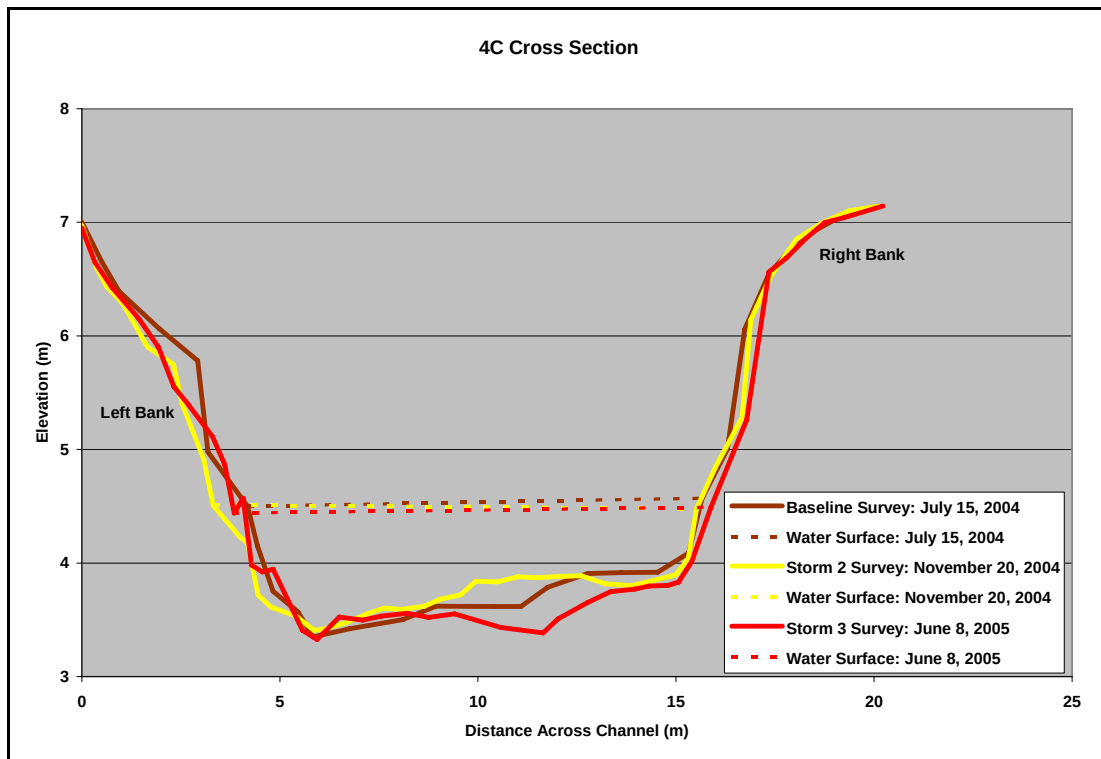
Cross-Section 4A



Cross-Section 4B



Cross-Section 4C

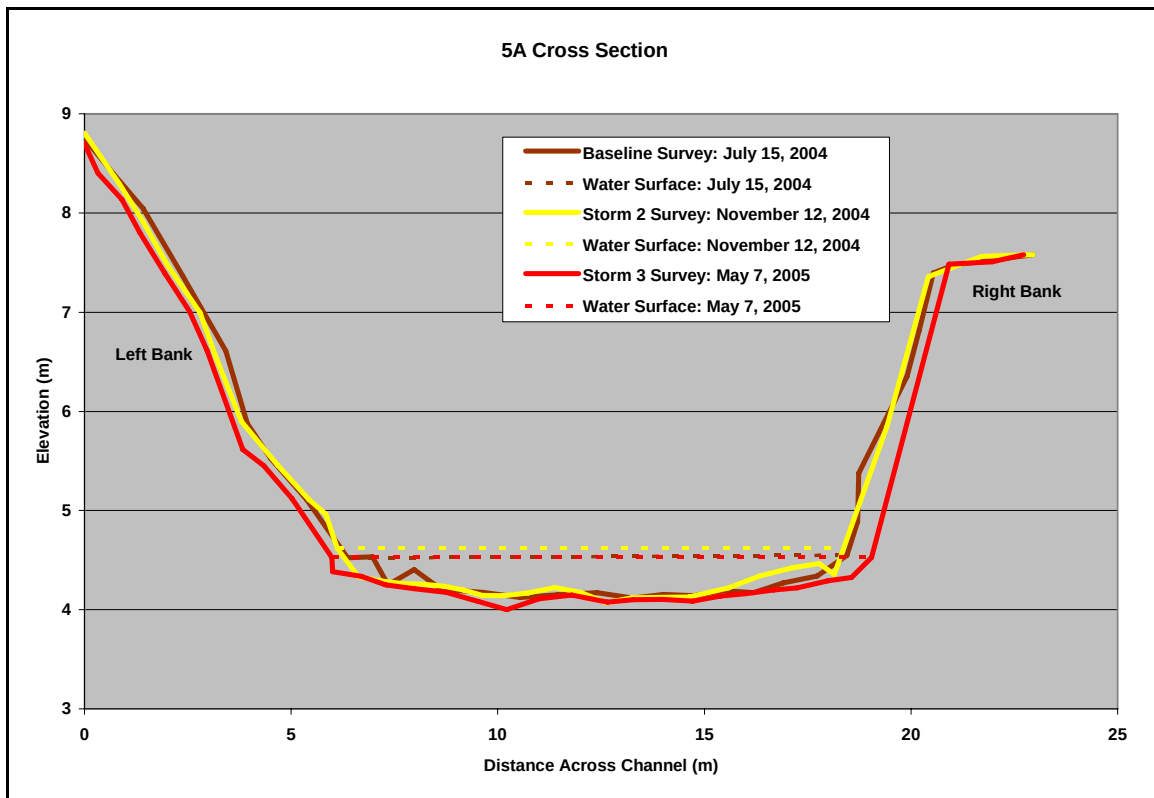


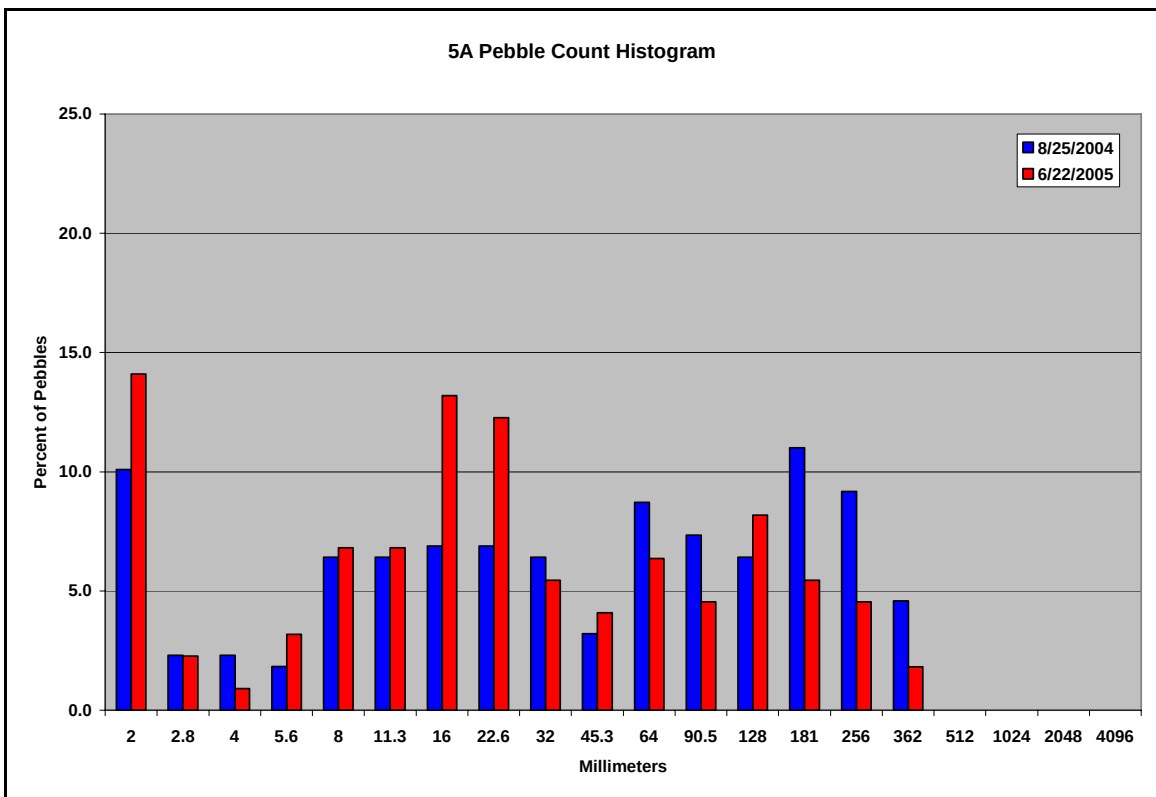
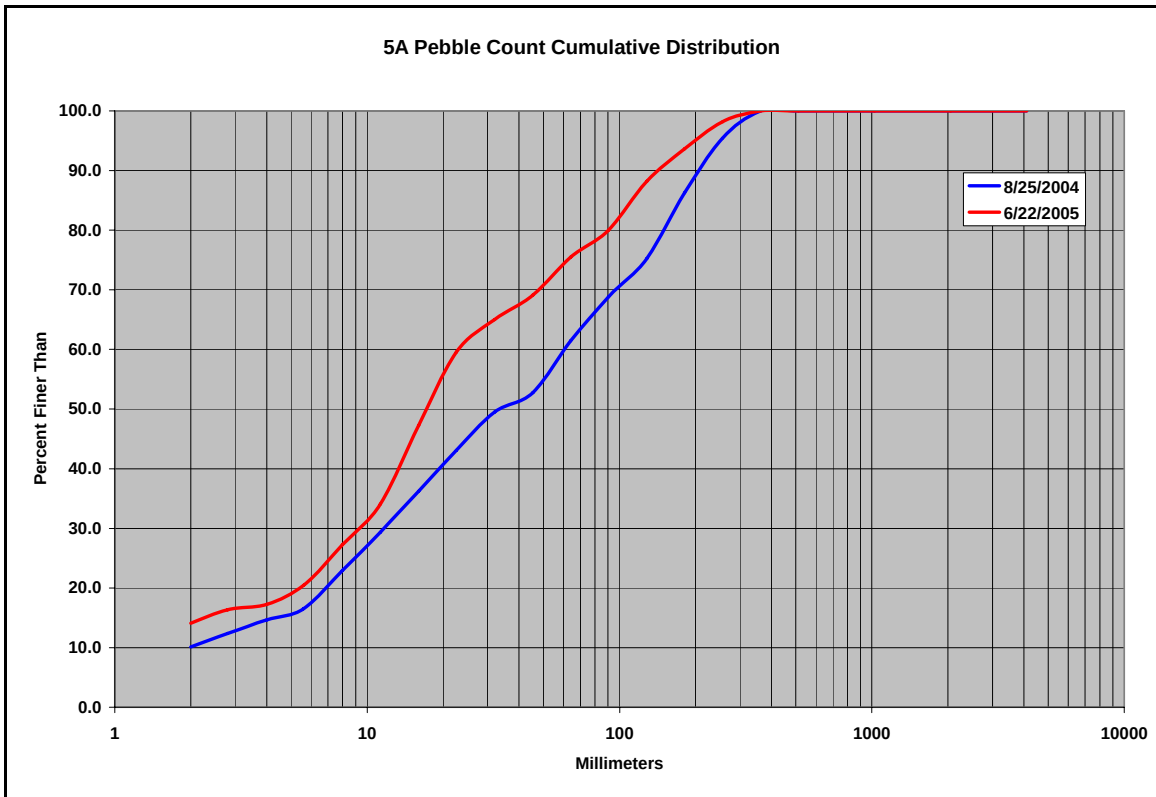
REACH 5



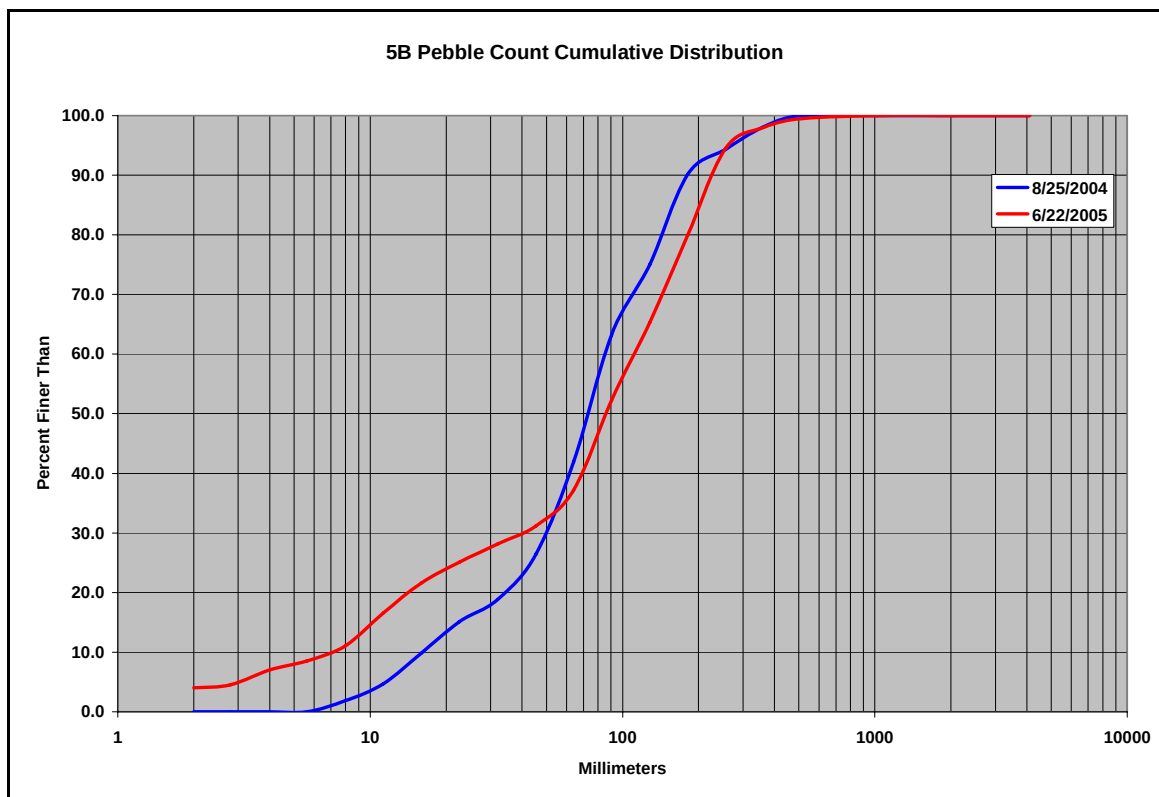
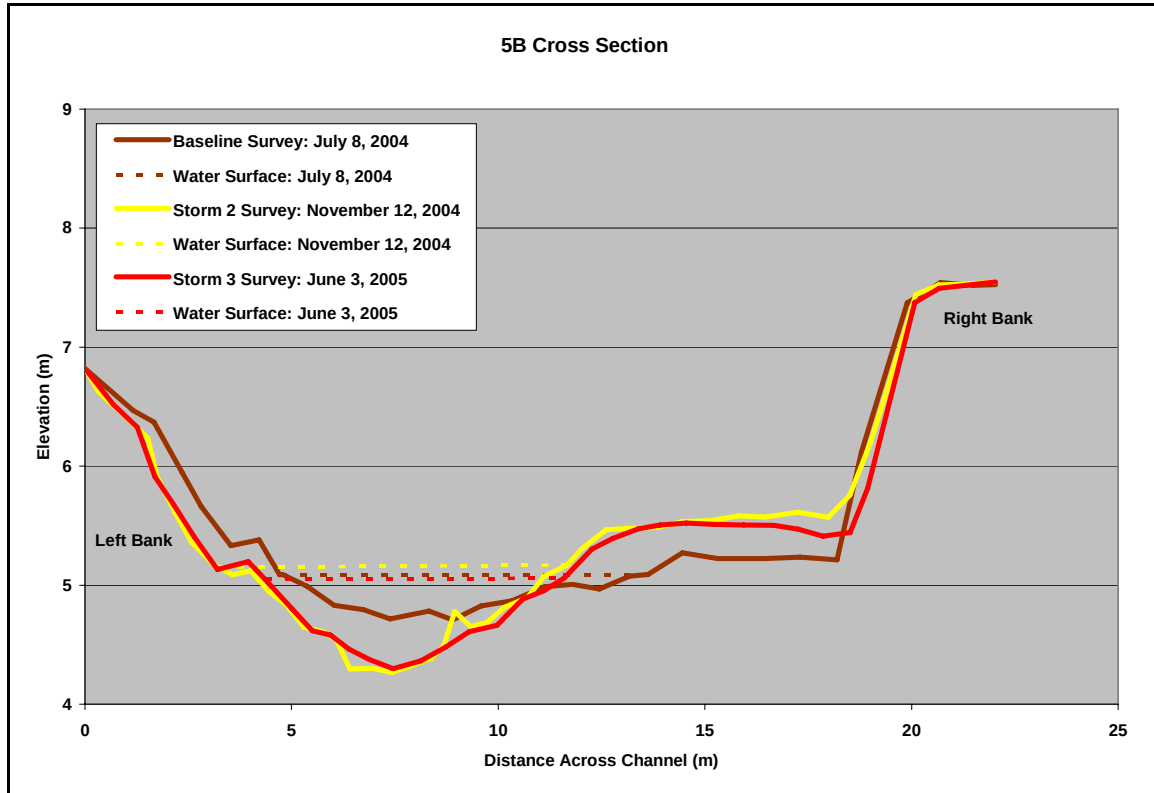
Reach 5 Cross-Sections

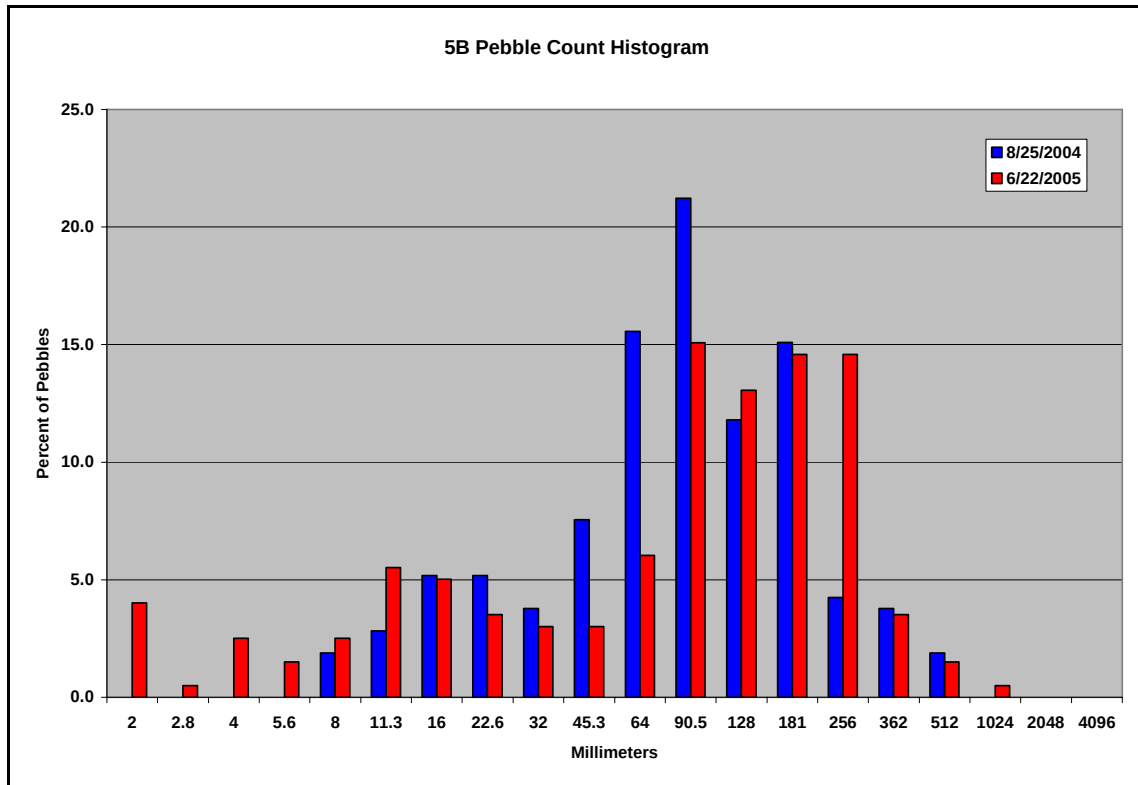
Cross-Section 5A



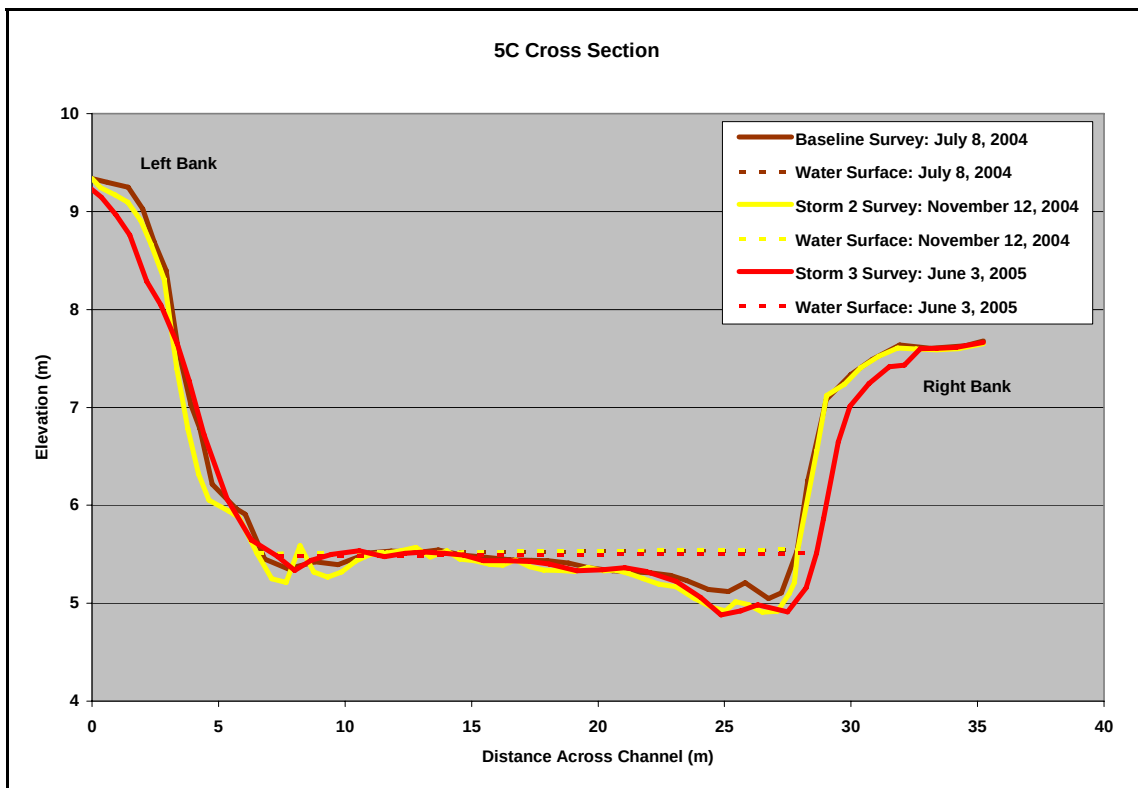


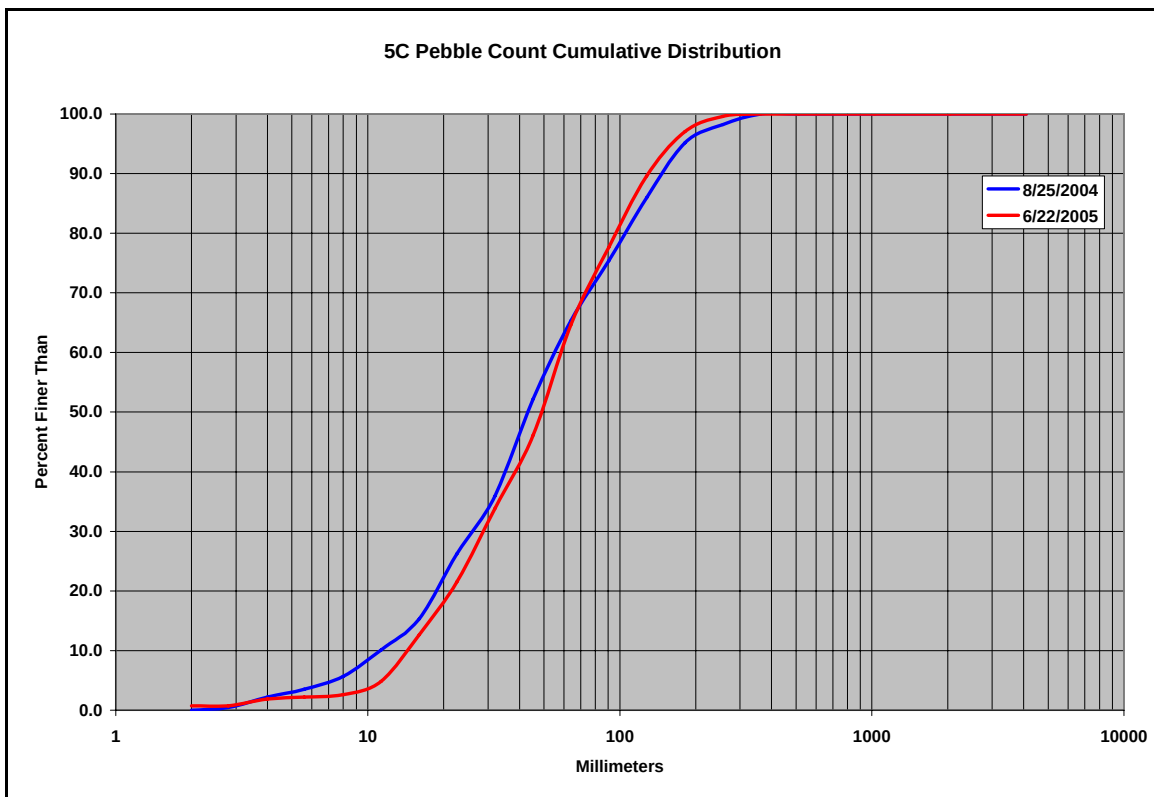
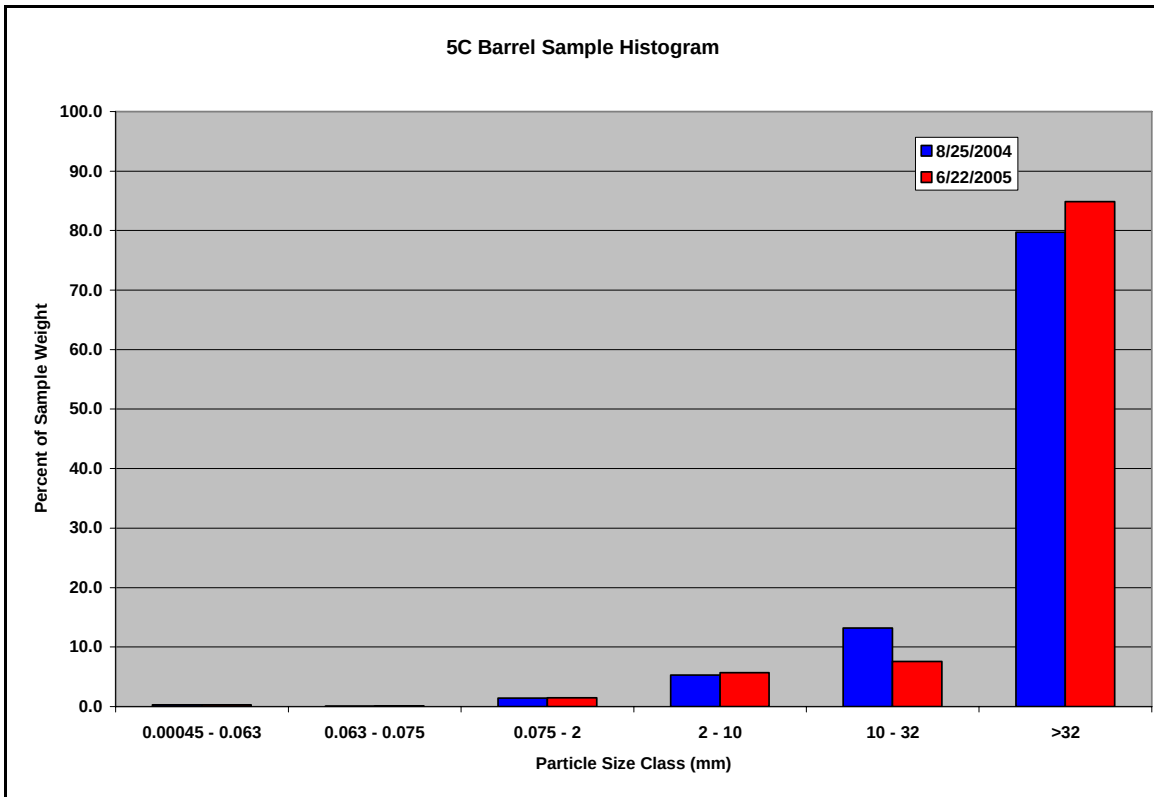
Cross-Section 5B

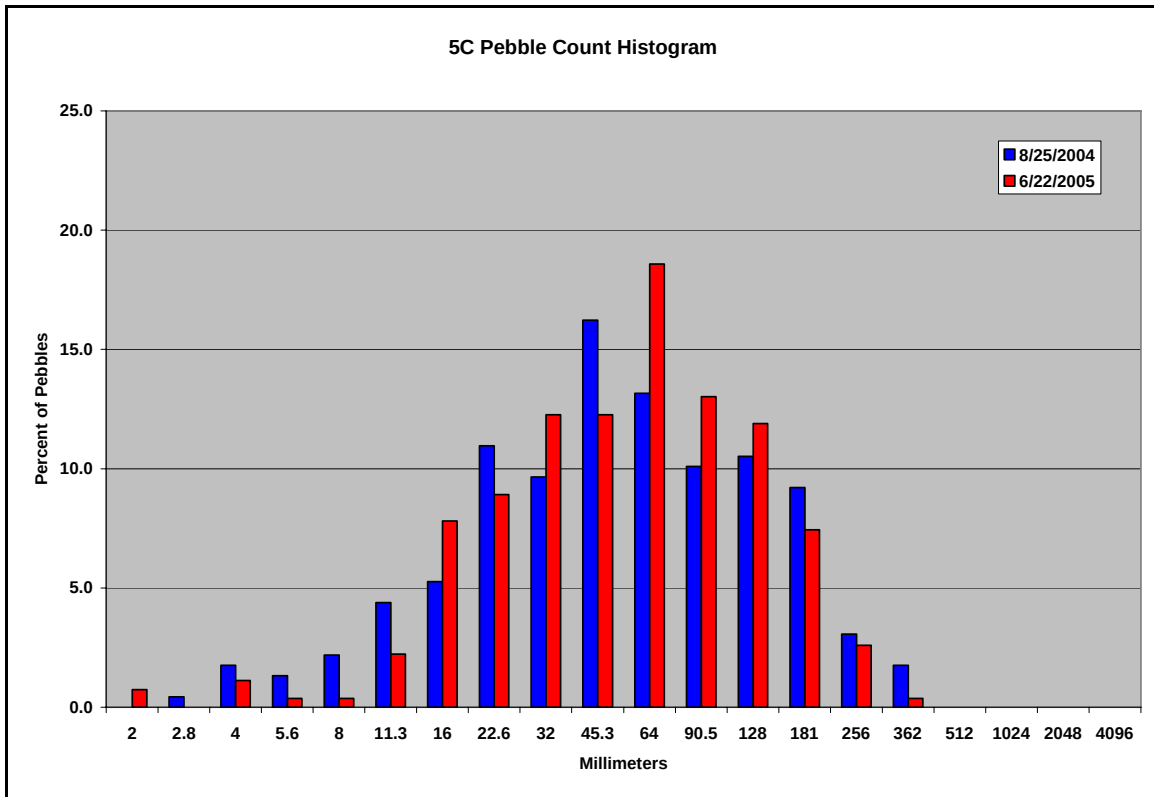




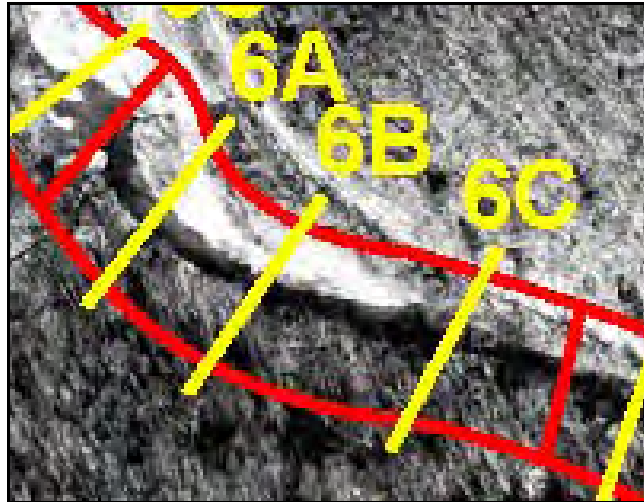
Cross-Section 5C





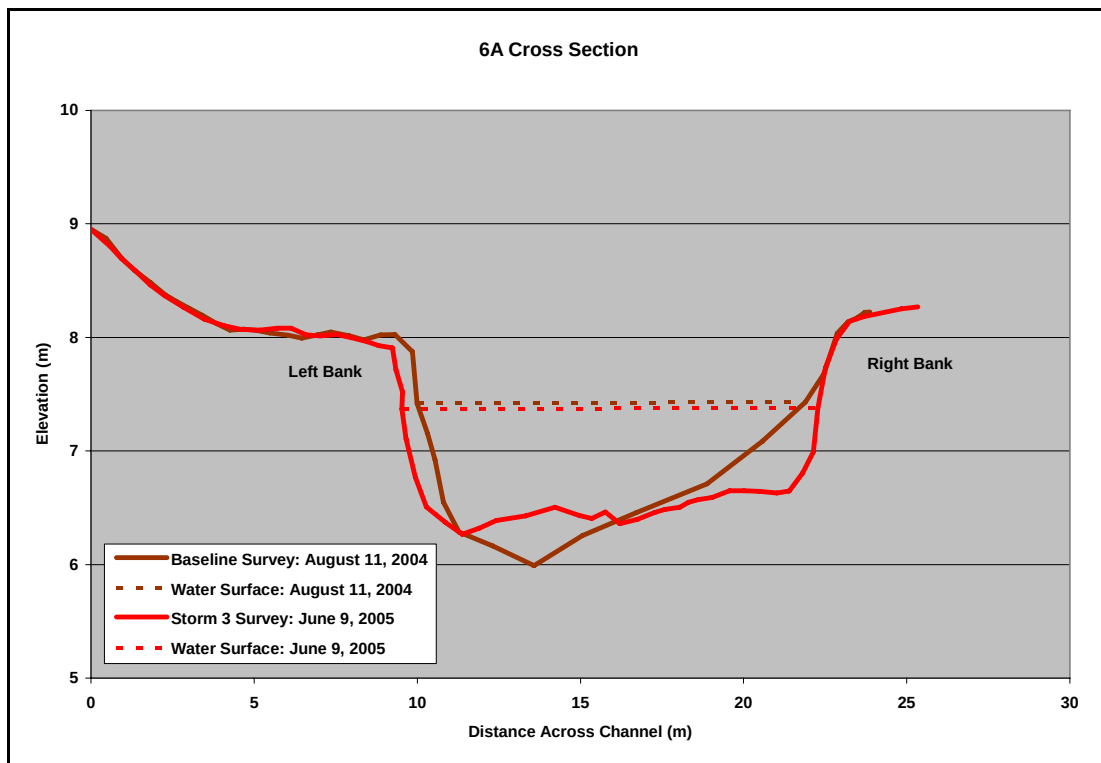


REACH 6

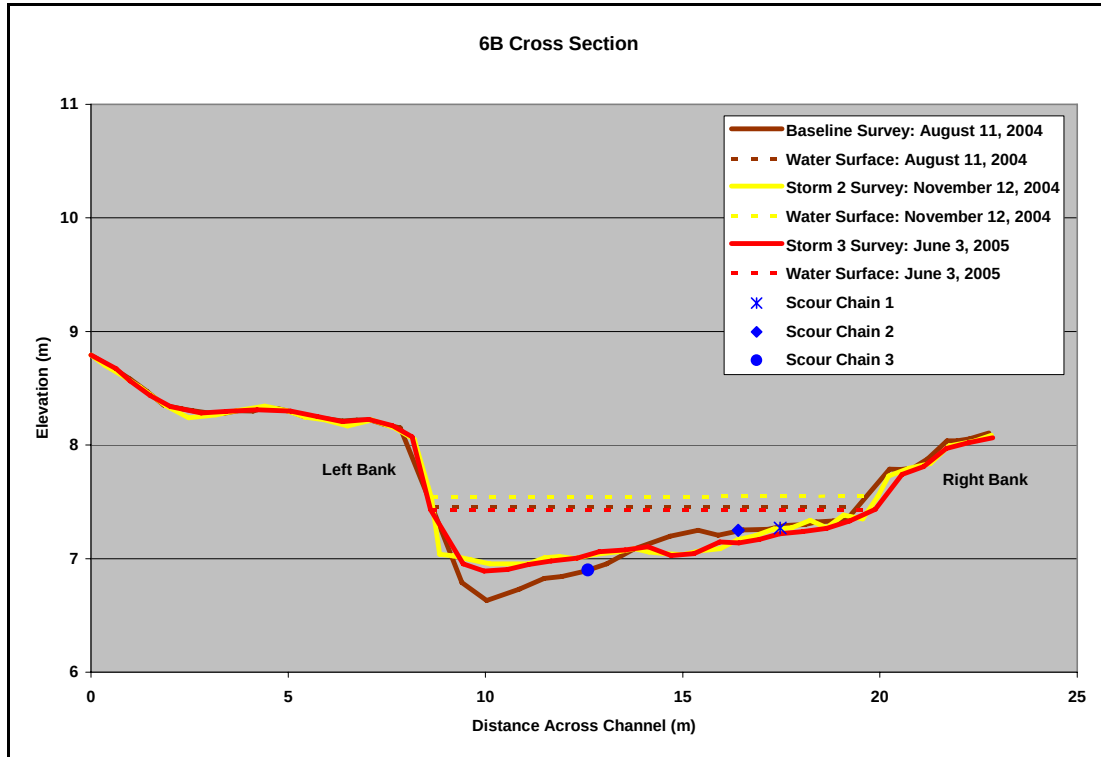


Reach 6 Cross-Sections

Cross-Section 6A



Cross-Section 6B

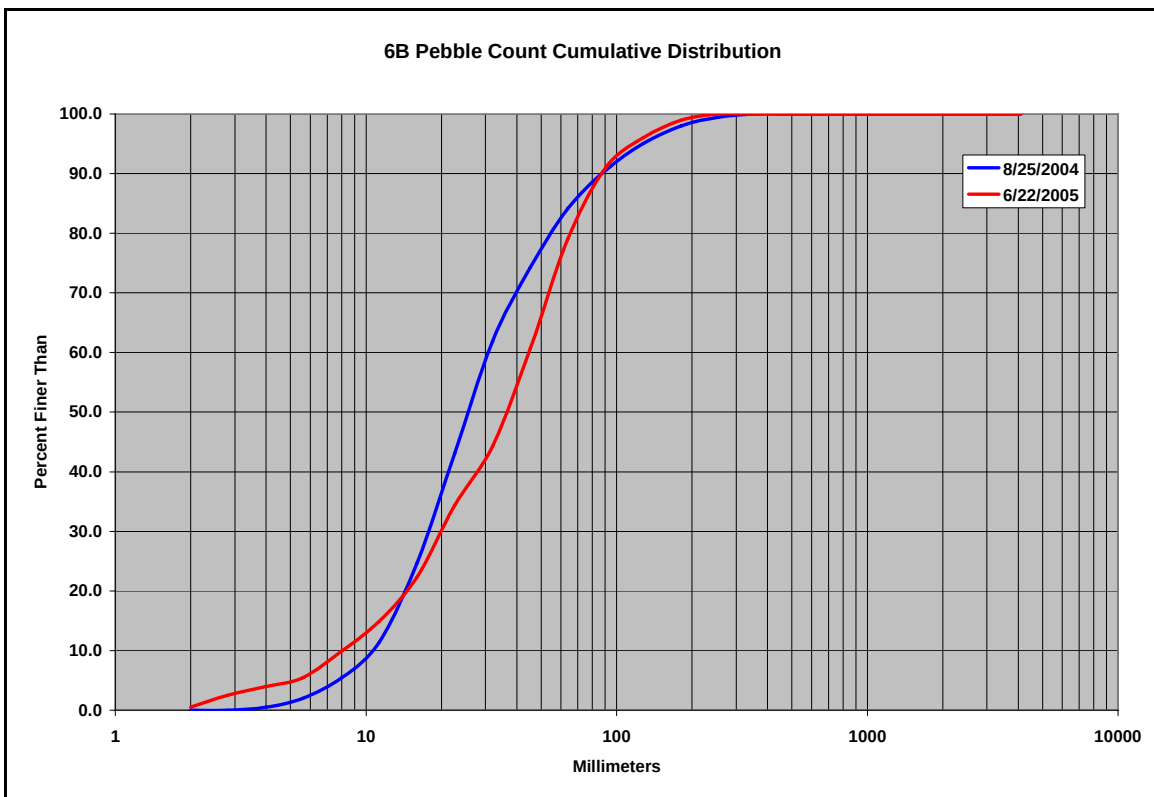
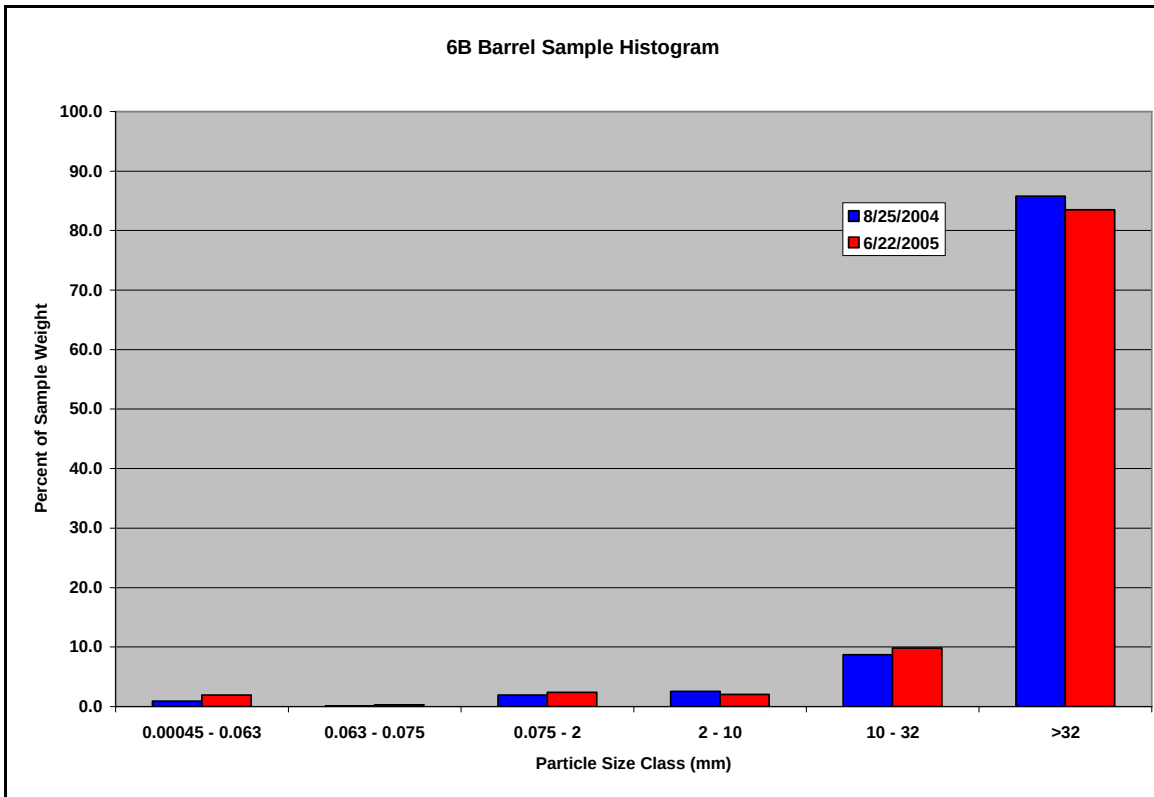


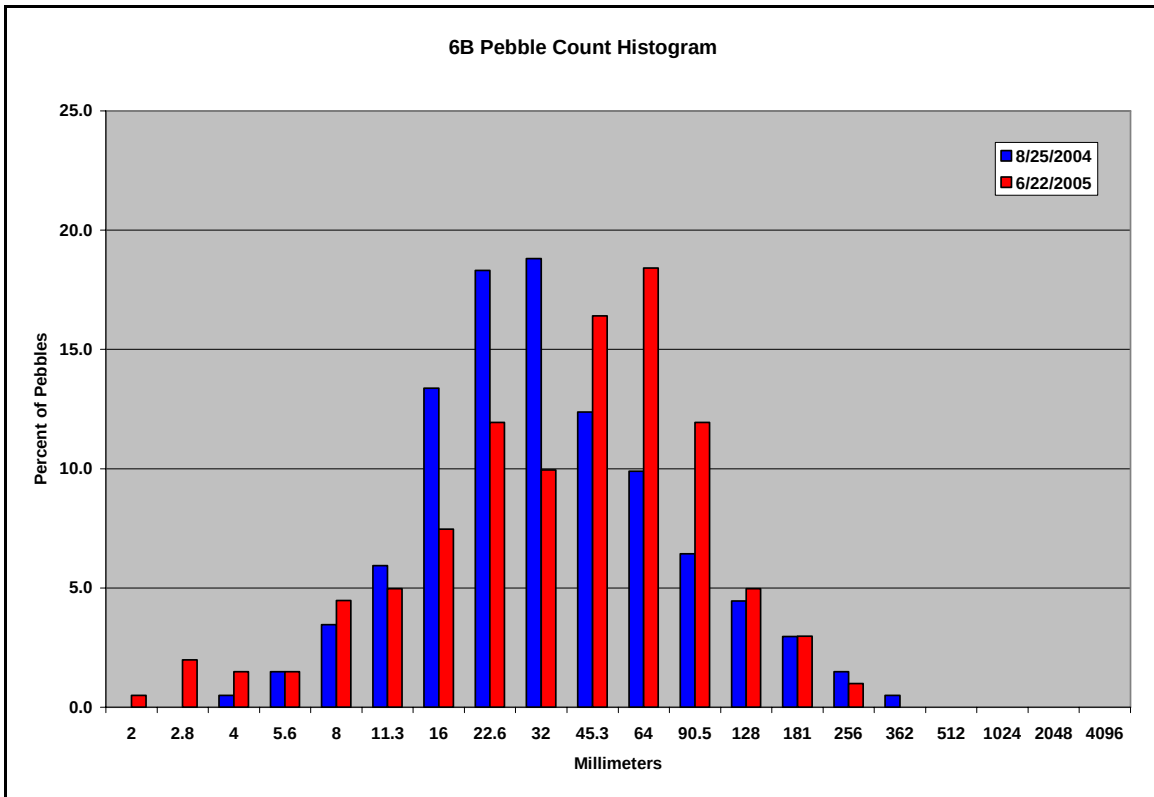
Scour Chain 1				
Date	Qmax (cfs)	Qmax (cms)	Scour (cm)	Fill (cm)
8/25/2004	installed	-	-	-
11/12/2004	2740	77.59	0.00	4.13
6/3/2005	2060	58.33	0.00	2.06
6/30/2005	652	18.46	0.00	2.06
7/6/2005	50	1.42	0.00	0.00
7/13/2005	656	18.58	4.13	0.00
7/22/2005	467	13.22	0.00	0.00
8/5/2005	30	0.85	0.00	0.00

Scour Chain 2				
Date	Qmax (cfs)	Qmax (cms)	Scour (cm)	Fill (cm)
8/25/2004	installed	-	-	-
11/12/2004	2740	77.59	0.00	8.26
6/3/2005	2060	58.33	12.38	0.00
6/30/2005	652	18.46	0.00	6.19
7/6/2005	50	1.42	4.13	0.00
7/13/2005	656	18.58	0.00	0.00
7/22/2005	467	13.22	2.06	0.00
8/5/2005	30	0.85	0.00	1.03

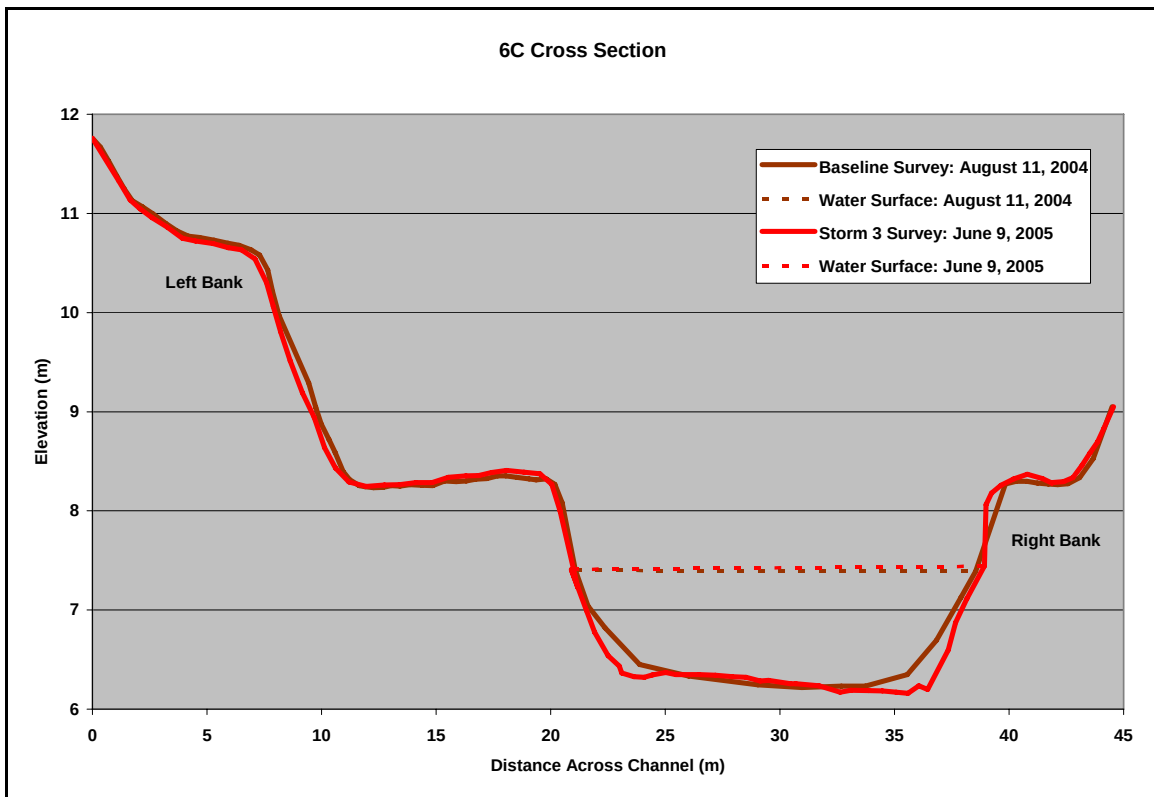
Scour Chain 3				
Date	Qmax (cfs)	Qmax (cms)	Scour (cm)	Fill (cm)
8/25/2004	installed	-	-	-
11/12/2004	2740	77.59	0.00	8.26
6/3/2005	2060	58.33	0.00	3.10
6/30/2005	652	18.46	0.00	3.10
7/6/2005	50	1.42	2.06	0.00
7/13/2005	656	18.58	0.00	0.00
7/22/2005	467	13.22	0.00	0.00
8/5/2005	30	0.85	4.13	1.03

Cross-Section 6B Scour Chains

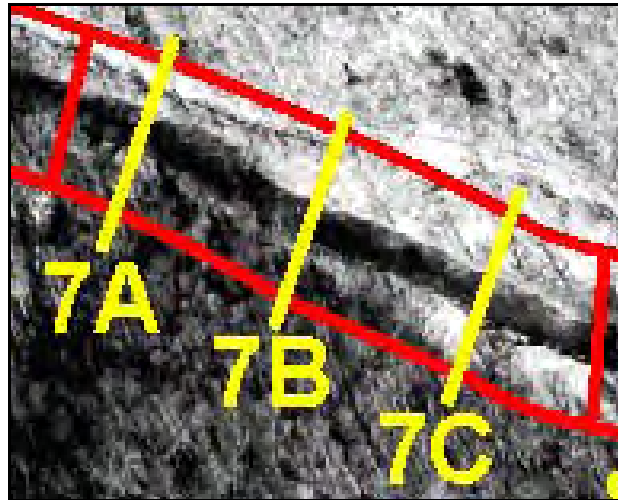




Cross-Section 6C

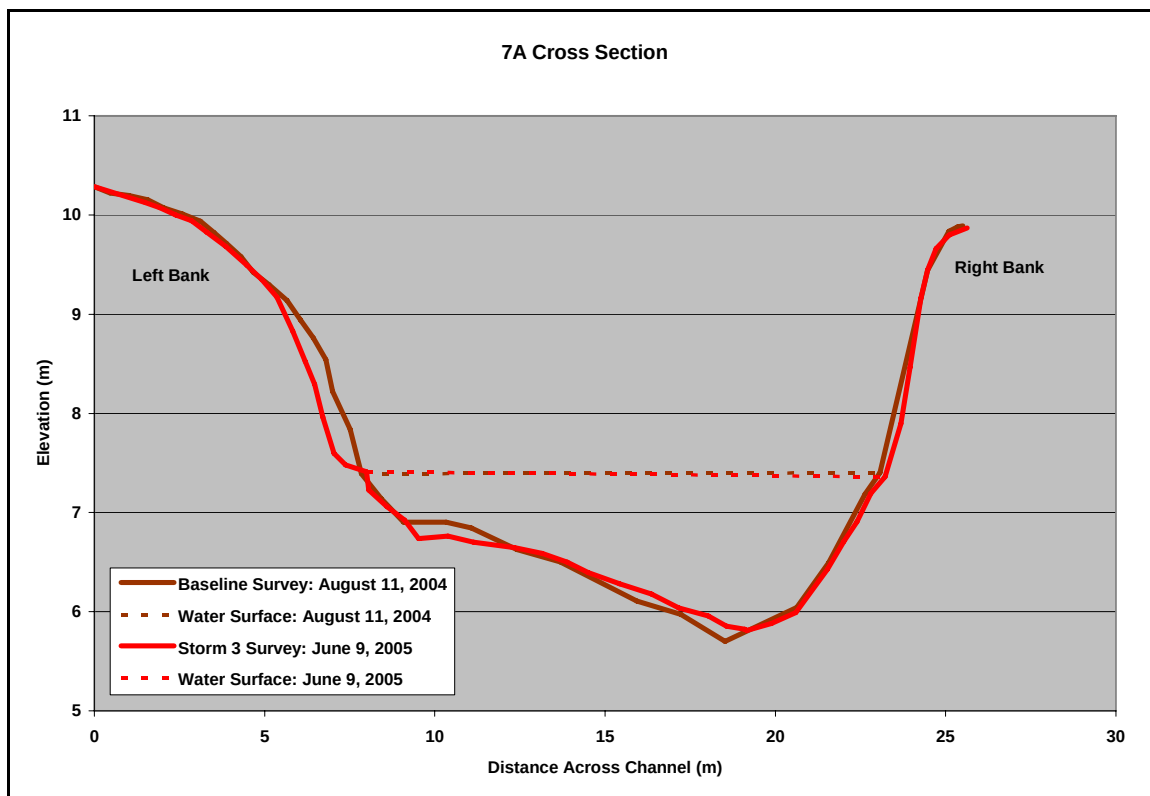


REACH 7

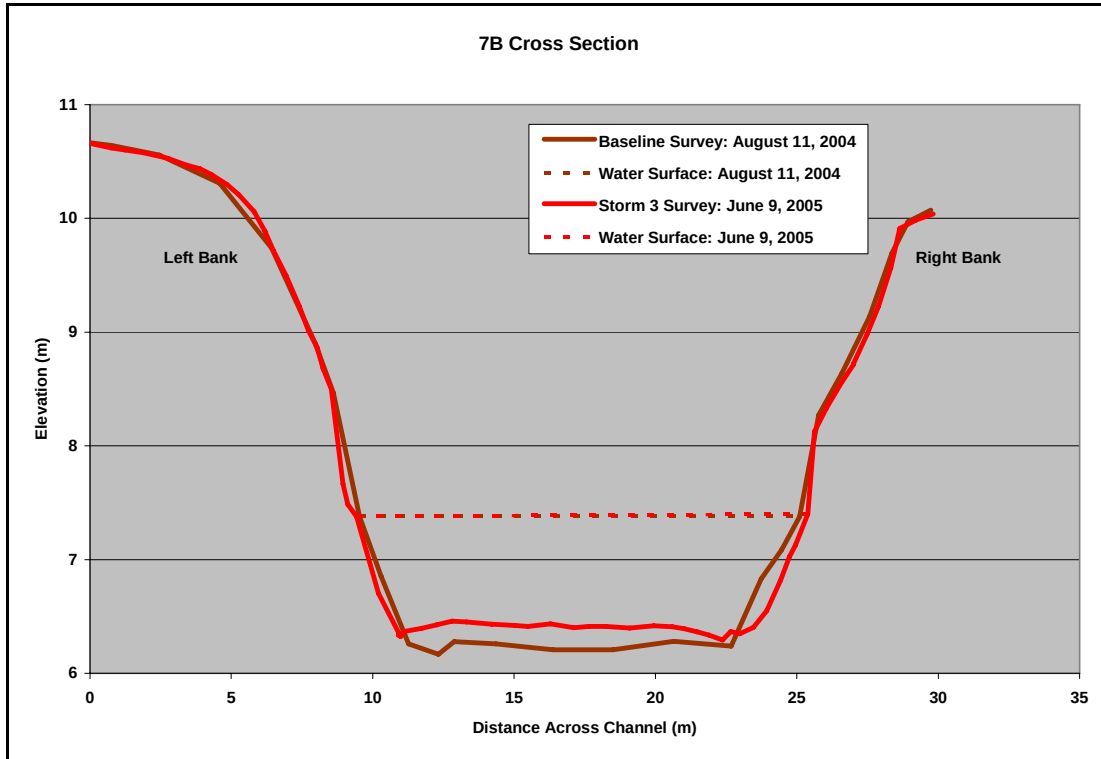


Reach 7 Cross-Sections

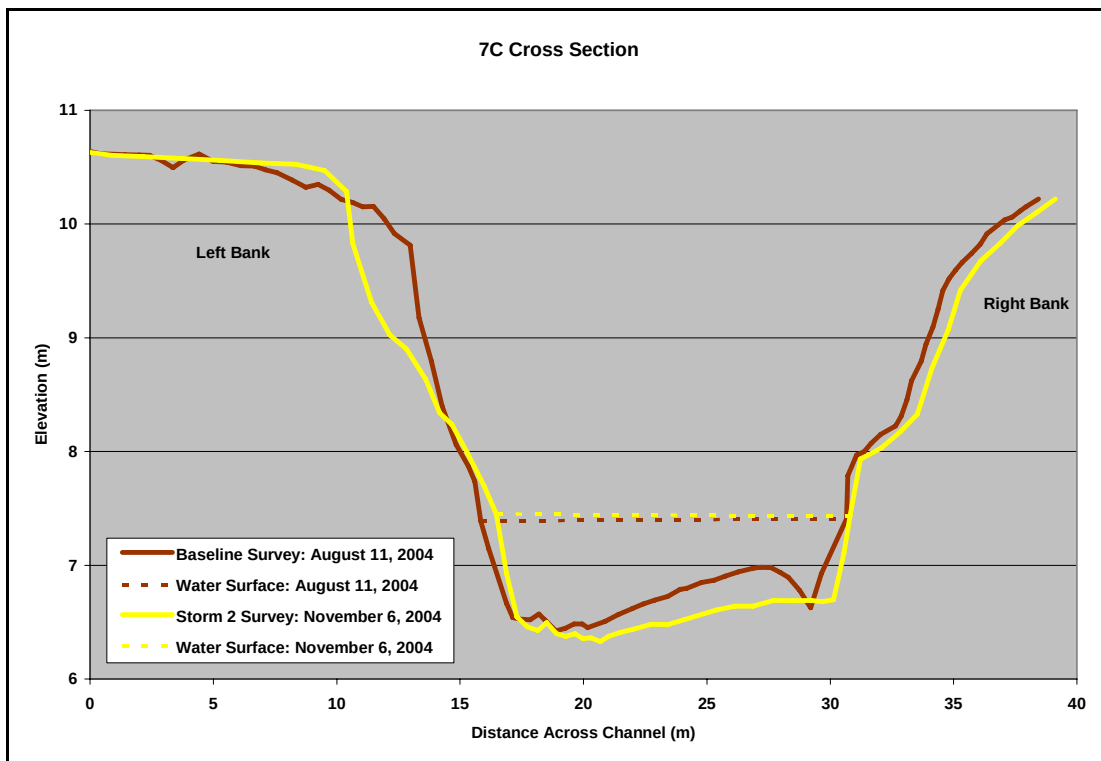
Cross-Section 7A



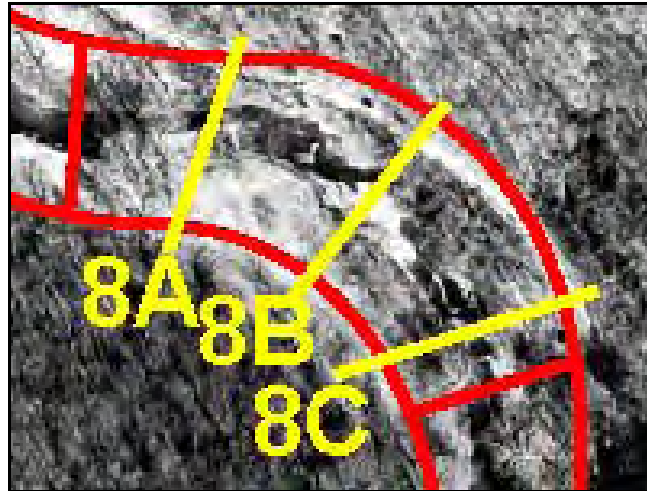
Cross-Section 7B



Cross-Section 7C

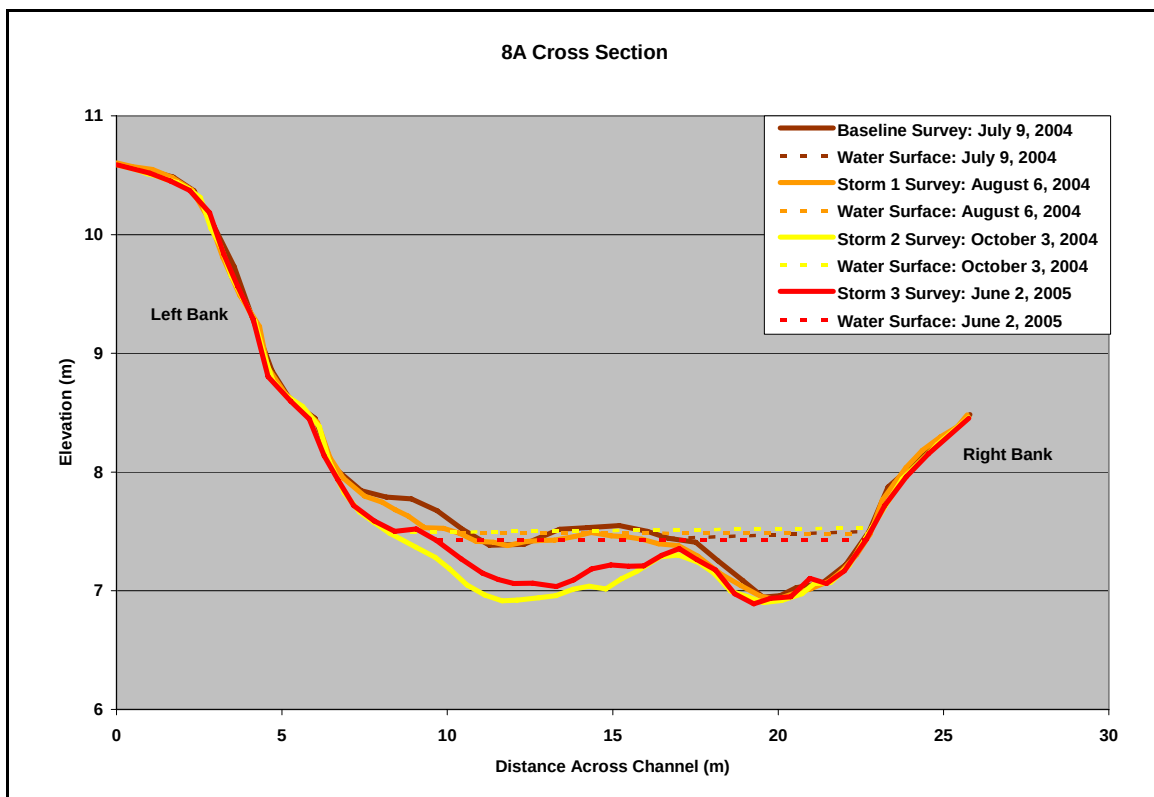


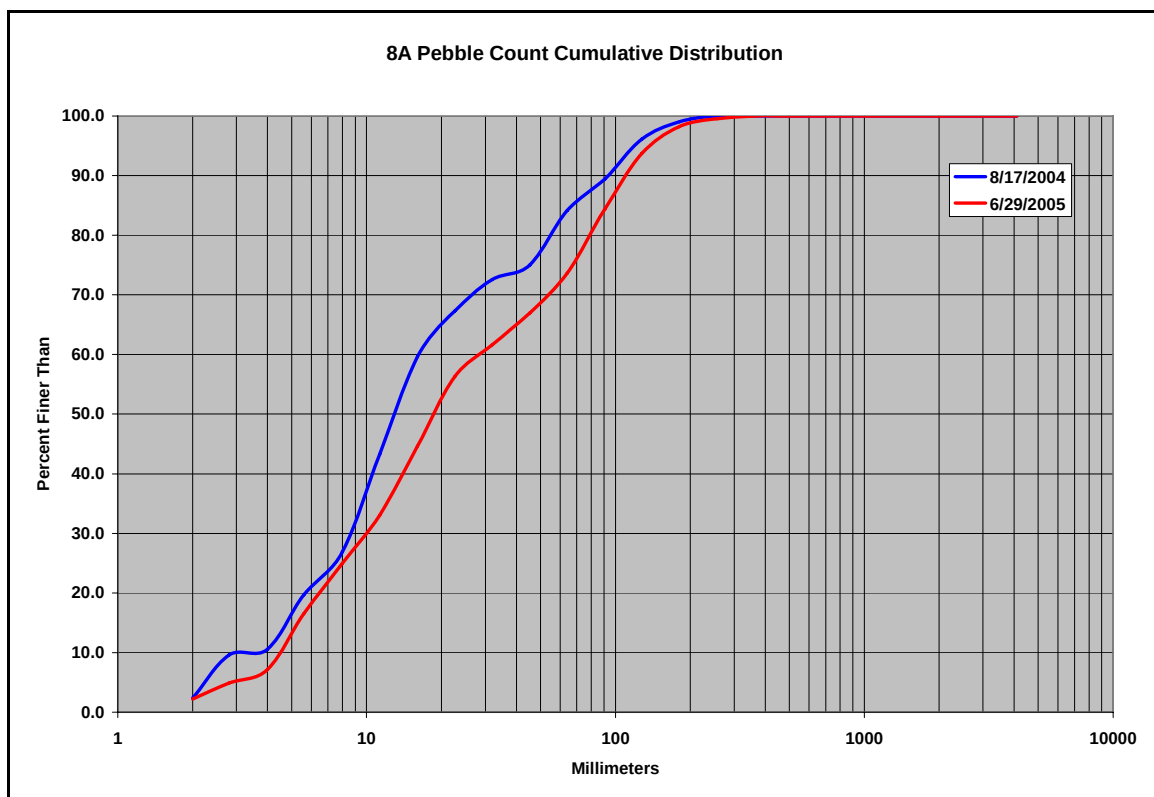
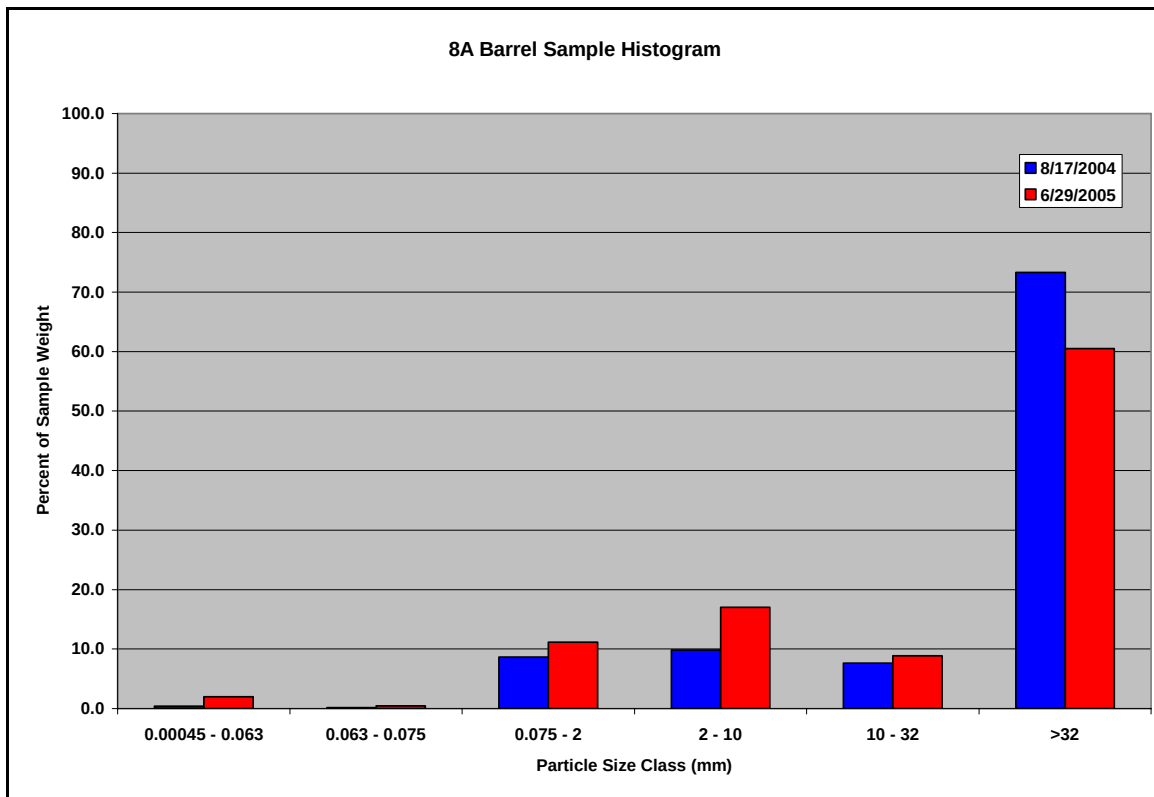
REACH 8

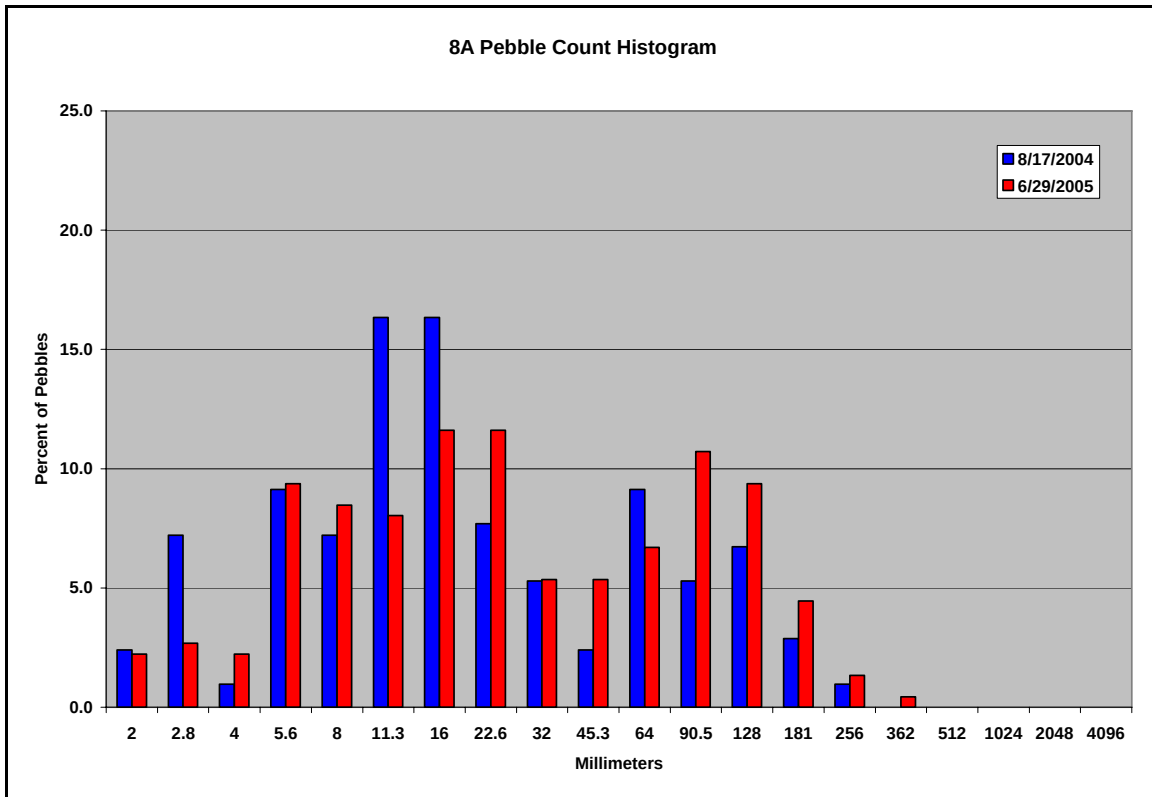


Reach 8 Cross-Sections

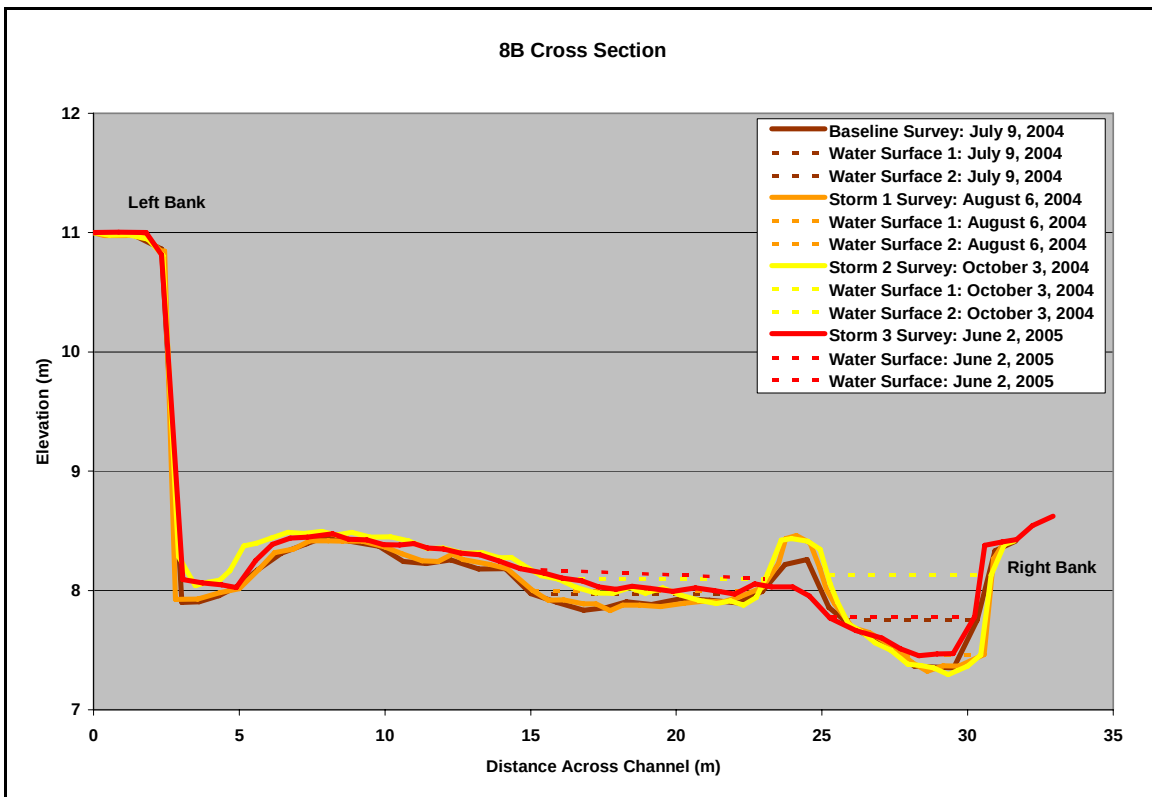
Cross-Section 8A

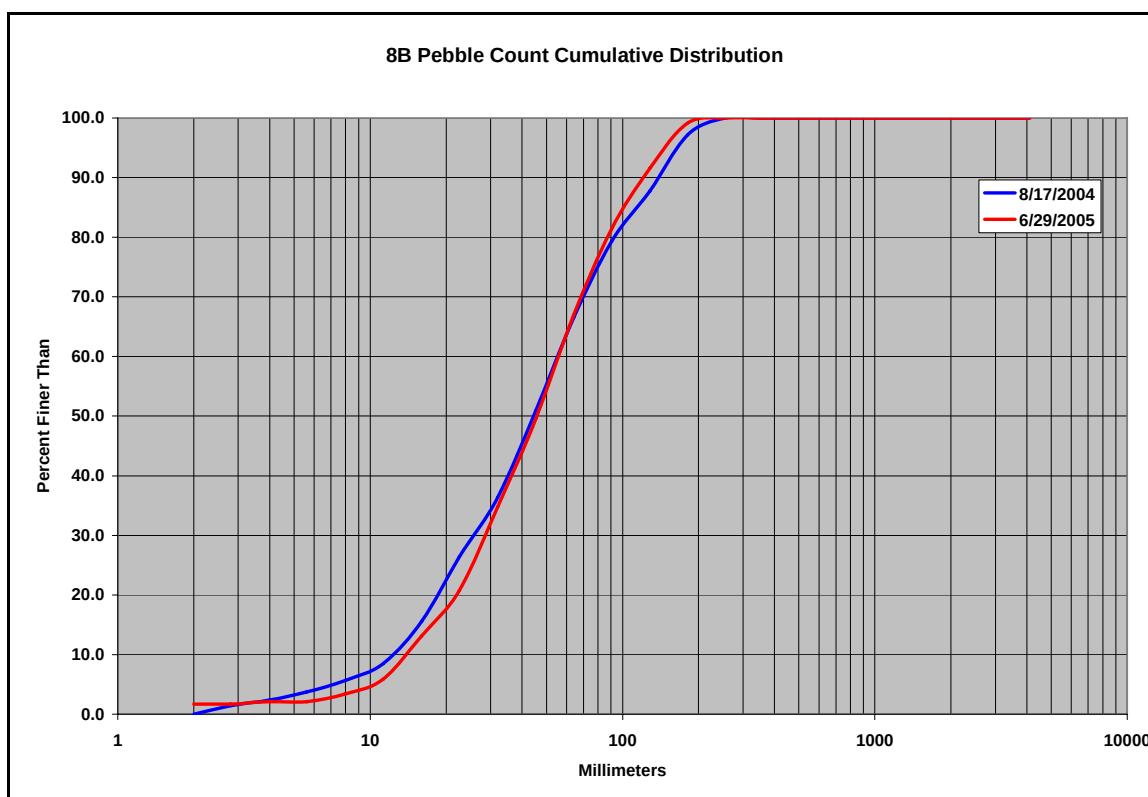
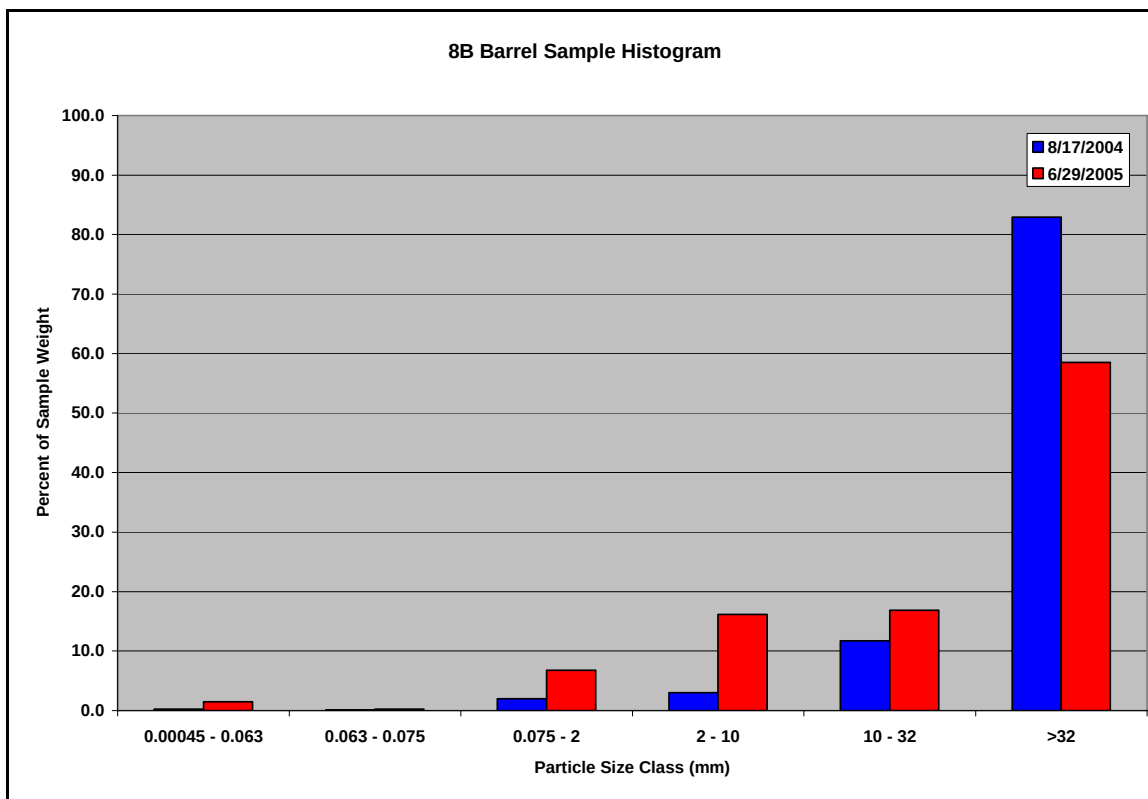


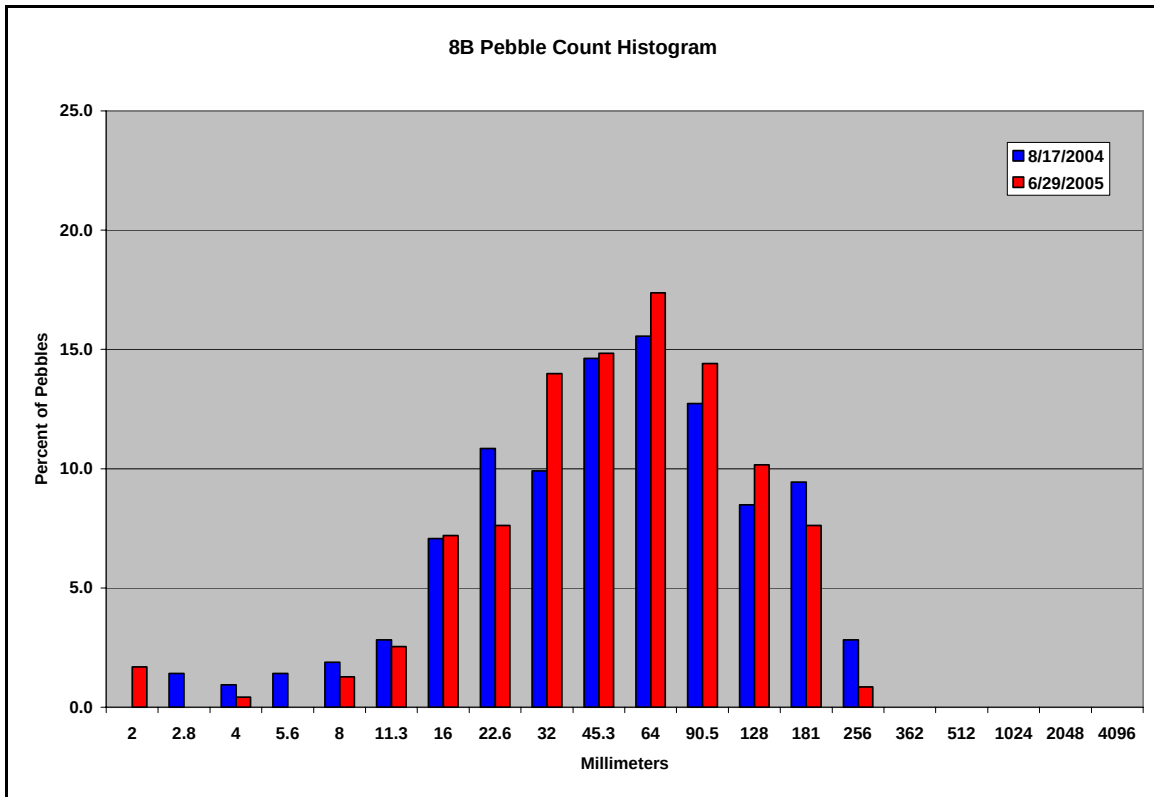




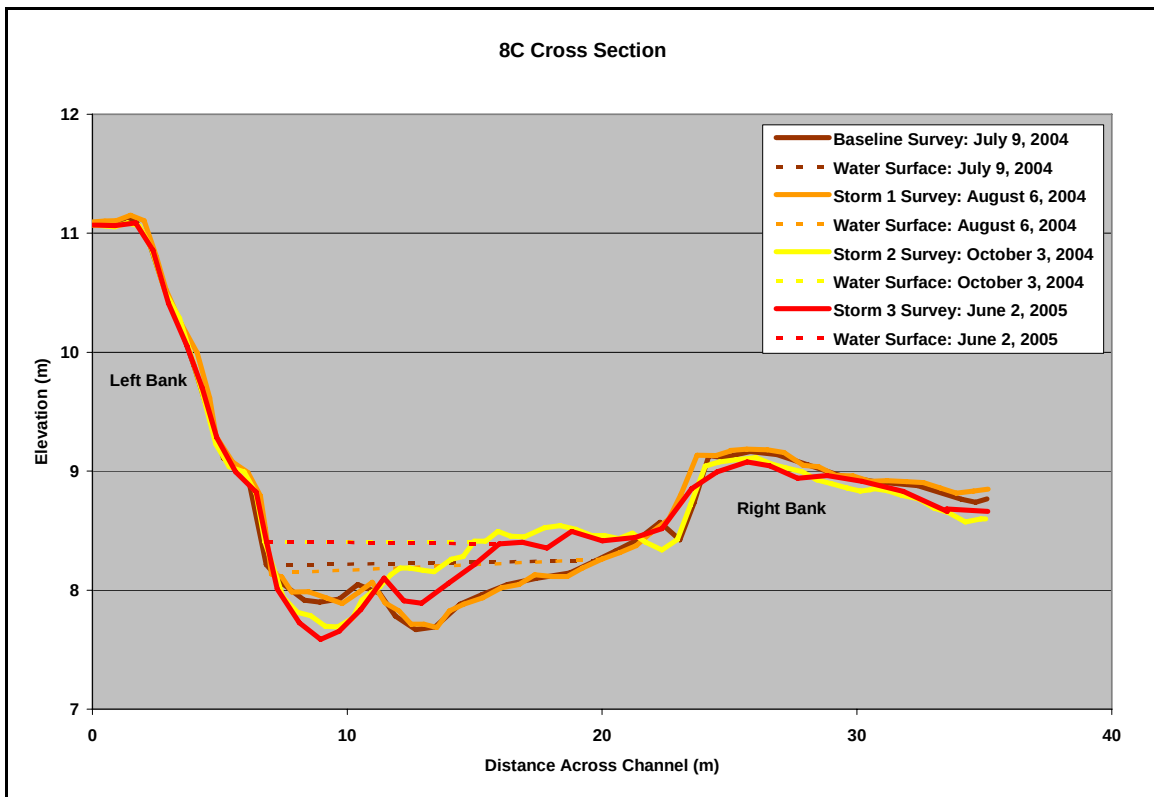
Cross-Section 8B

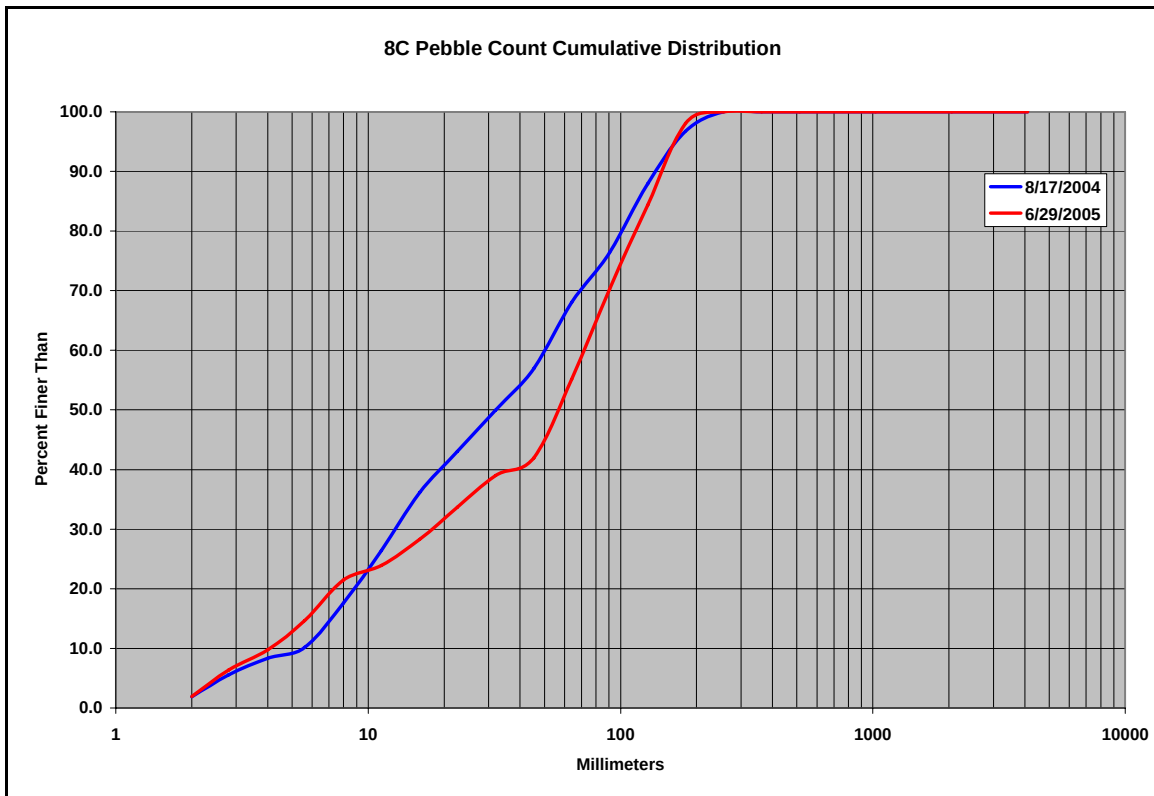
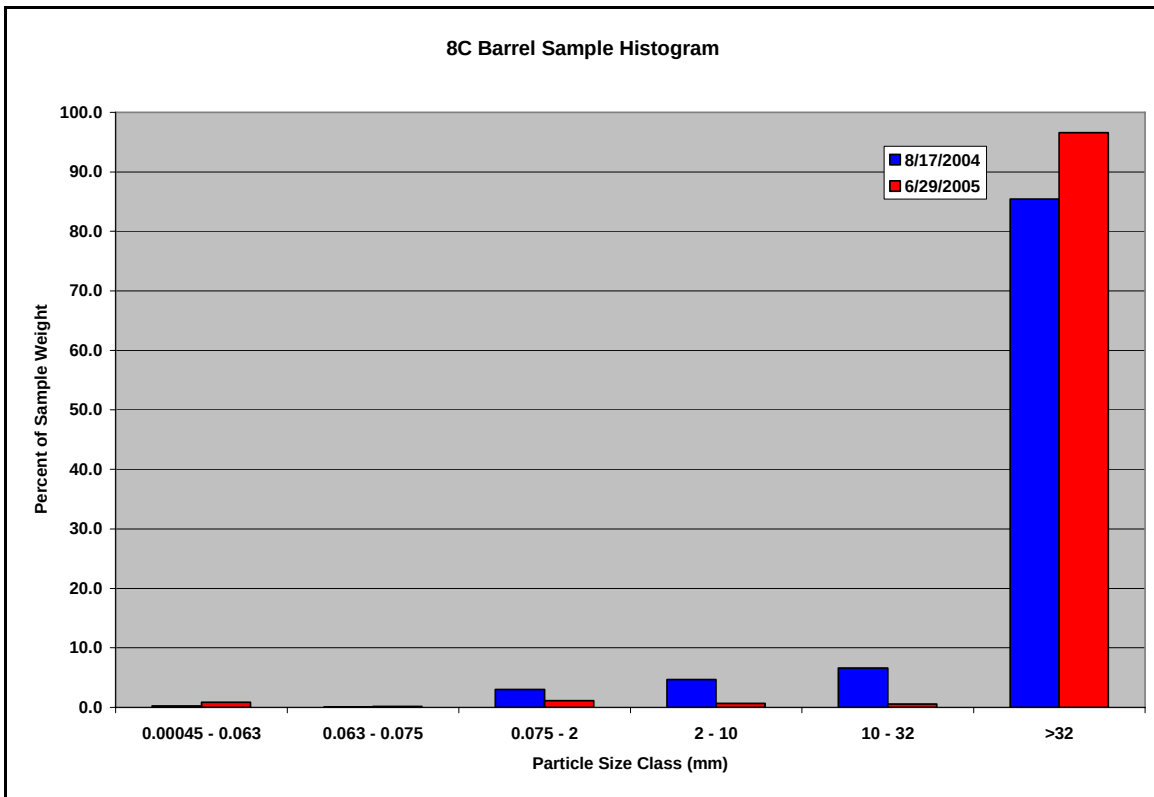


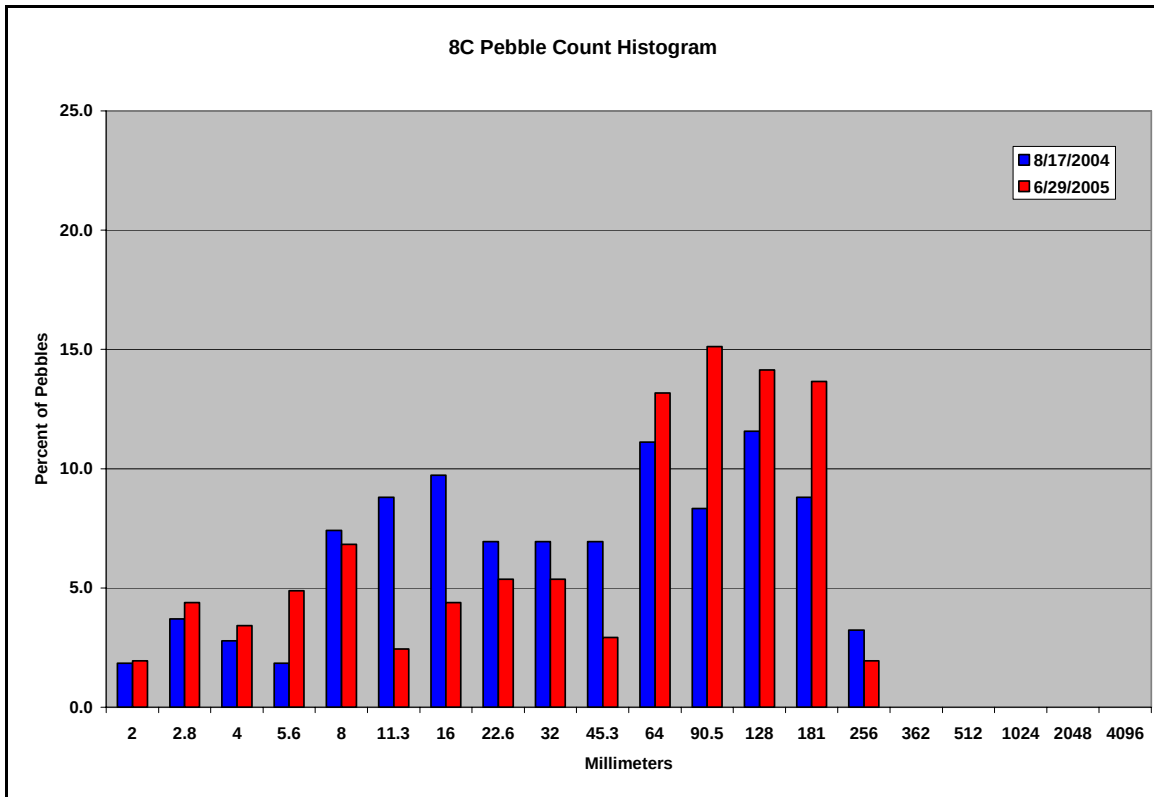




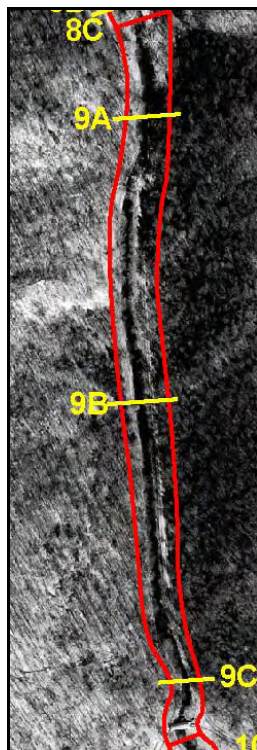
Cross-Section 8C





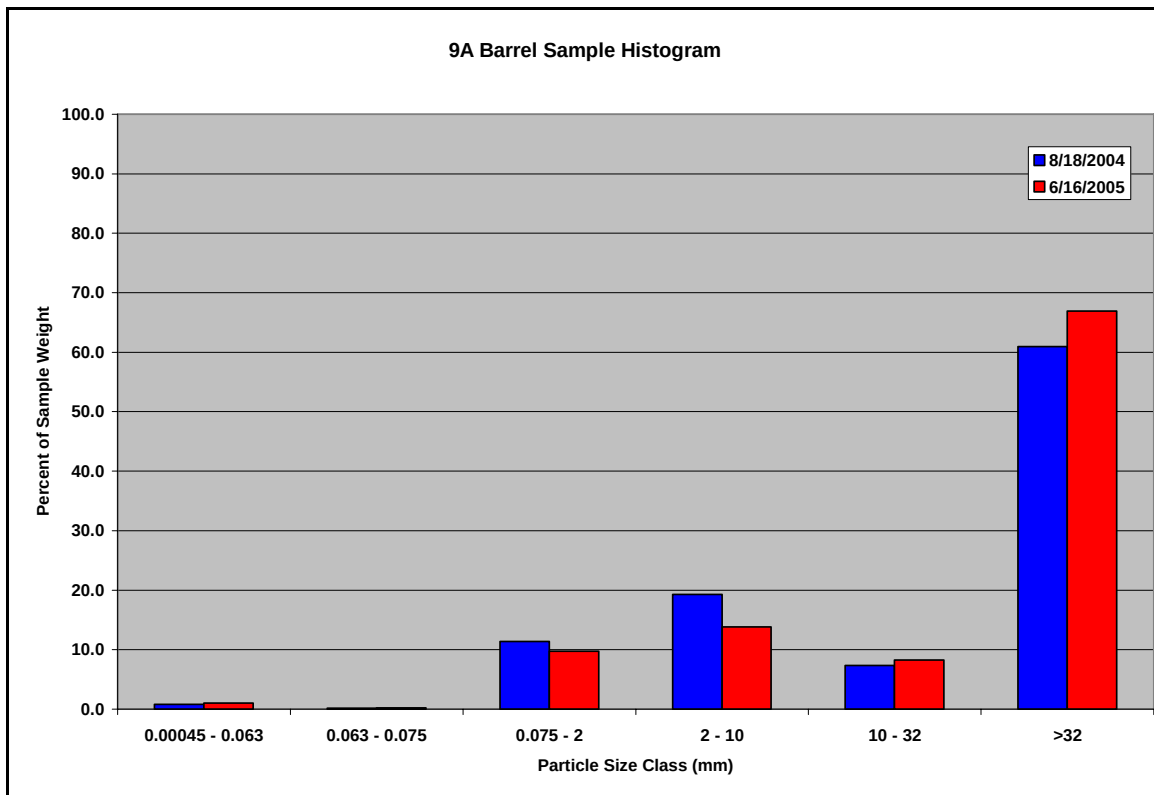
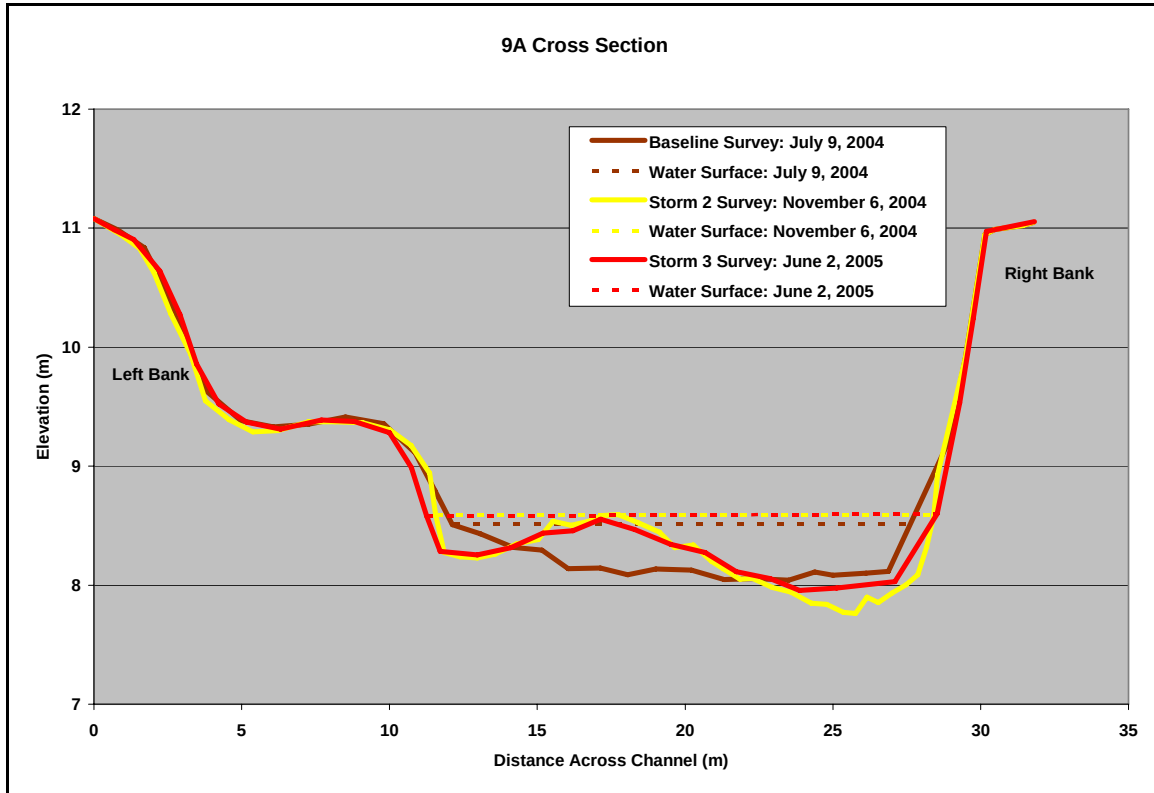


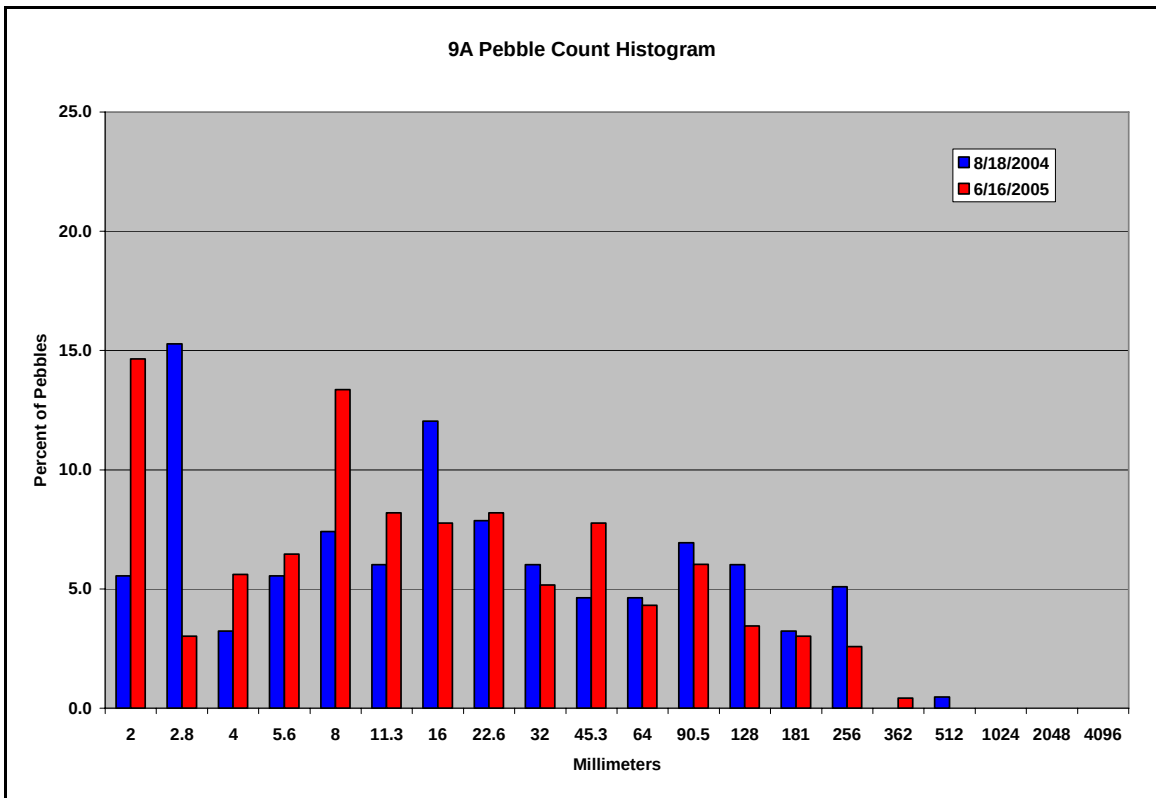
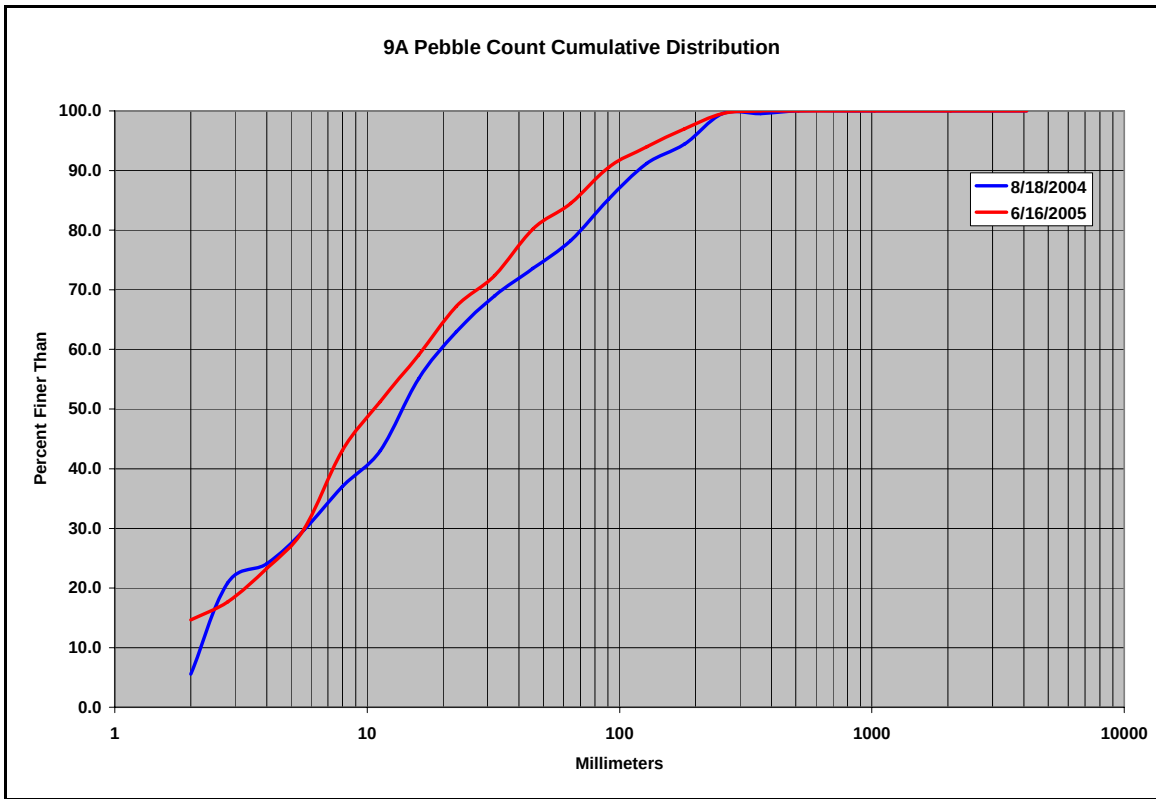
REACH 9



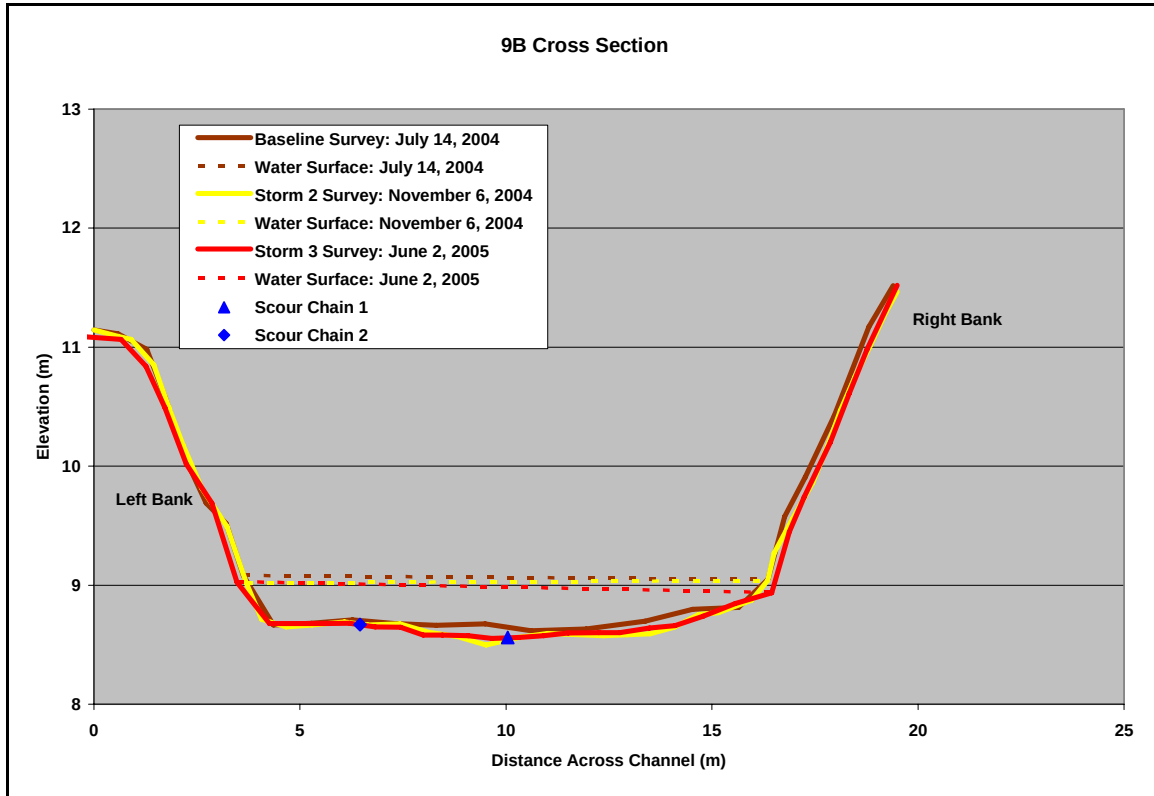
Reach 9 Cross-Sections

Cross-Section 9A





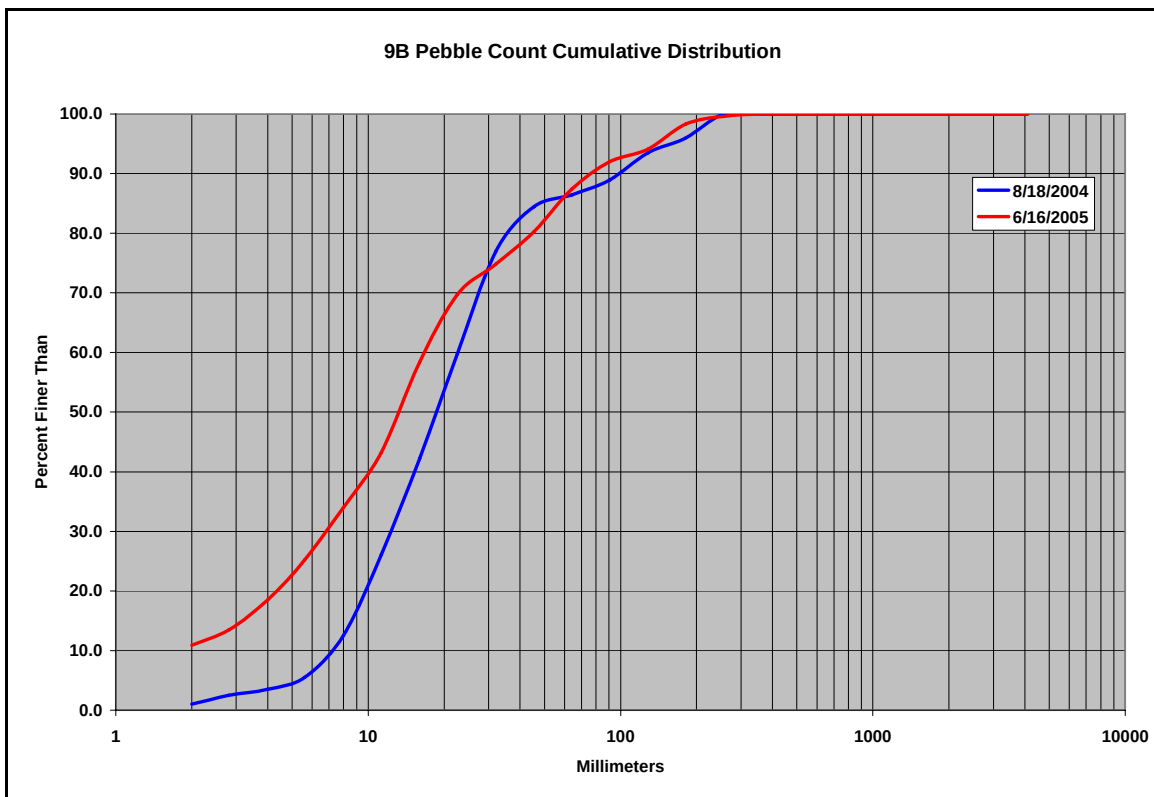
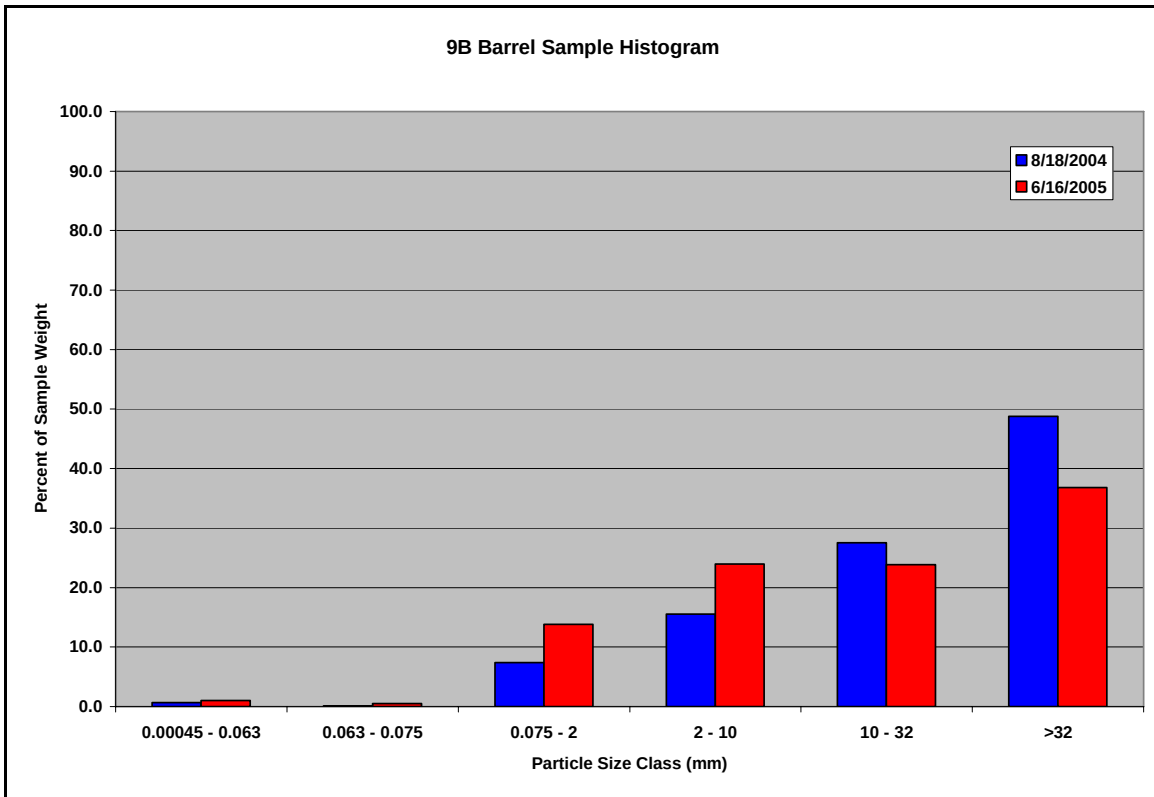
Cross-Section 9B

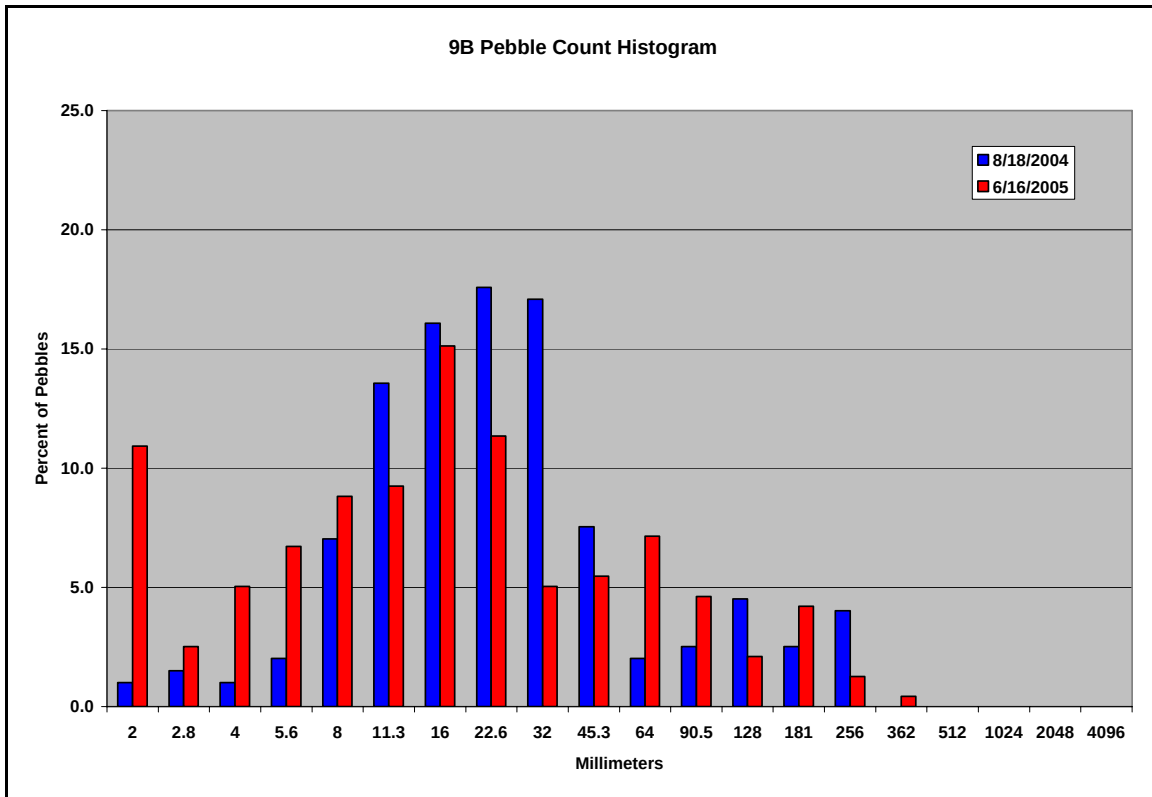


Scour Chain 2				
Date	Qmax (cfs)	Qmax (cms)	Scour (cm)	Fill (cm)
6/16/2005	Installed	-	-	-
6/30/2005	26	0.74	0.00	2.06
7/06/2005	50	1.42	0.00	2.06
7/13/2005	656	18.58	0.00	2.06
7/22/2005	467	13.22	1.03	0.00
8/05/2005	30	0.85	0.00	1.03

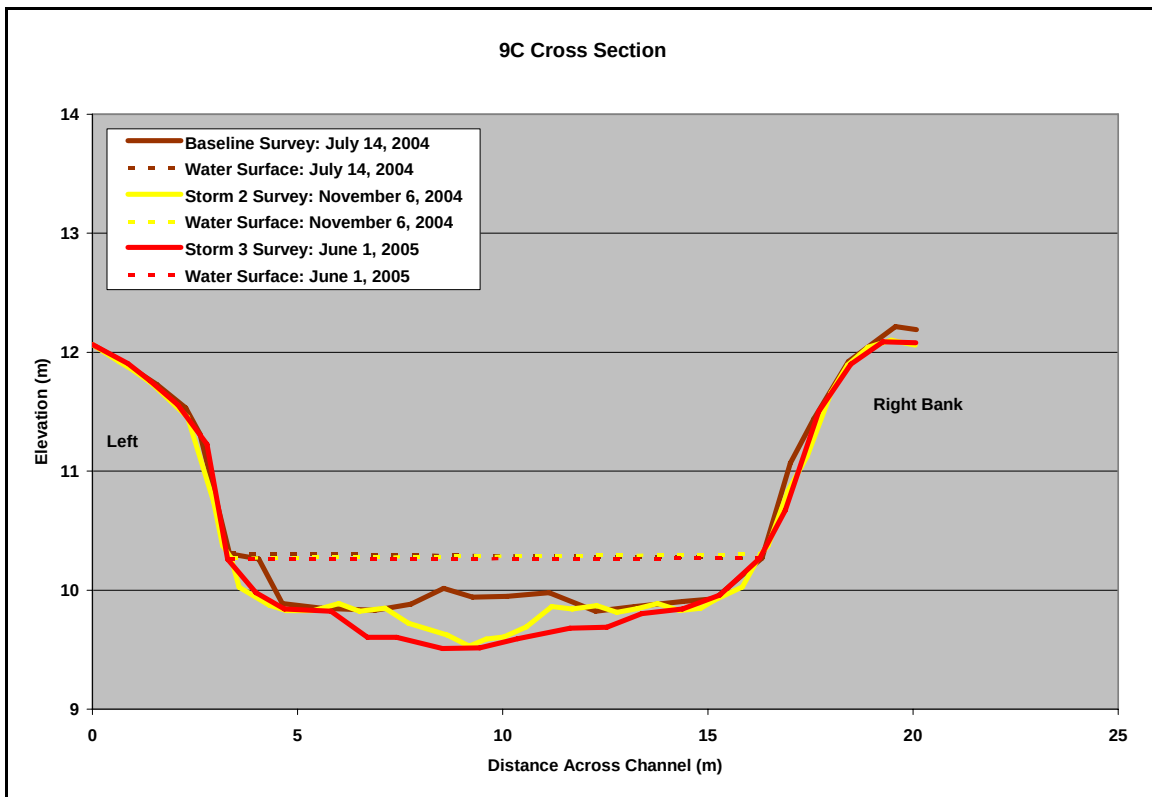
Scour Chain 1 was lost one week after installation.

Cross-Section 9B Scour Chains

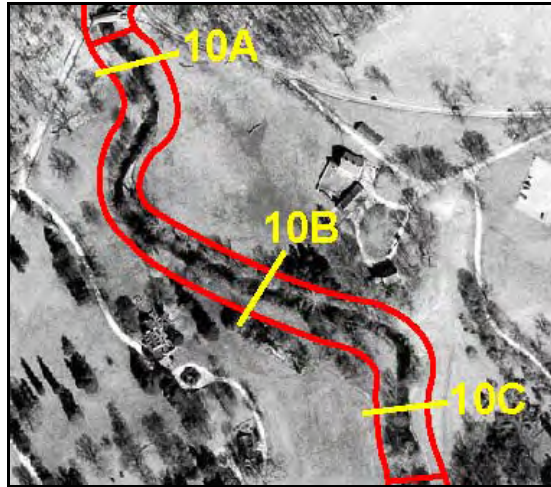




Cross-Section 9C

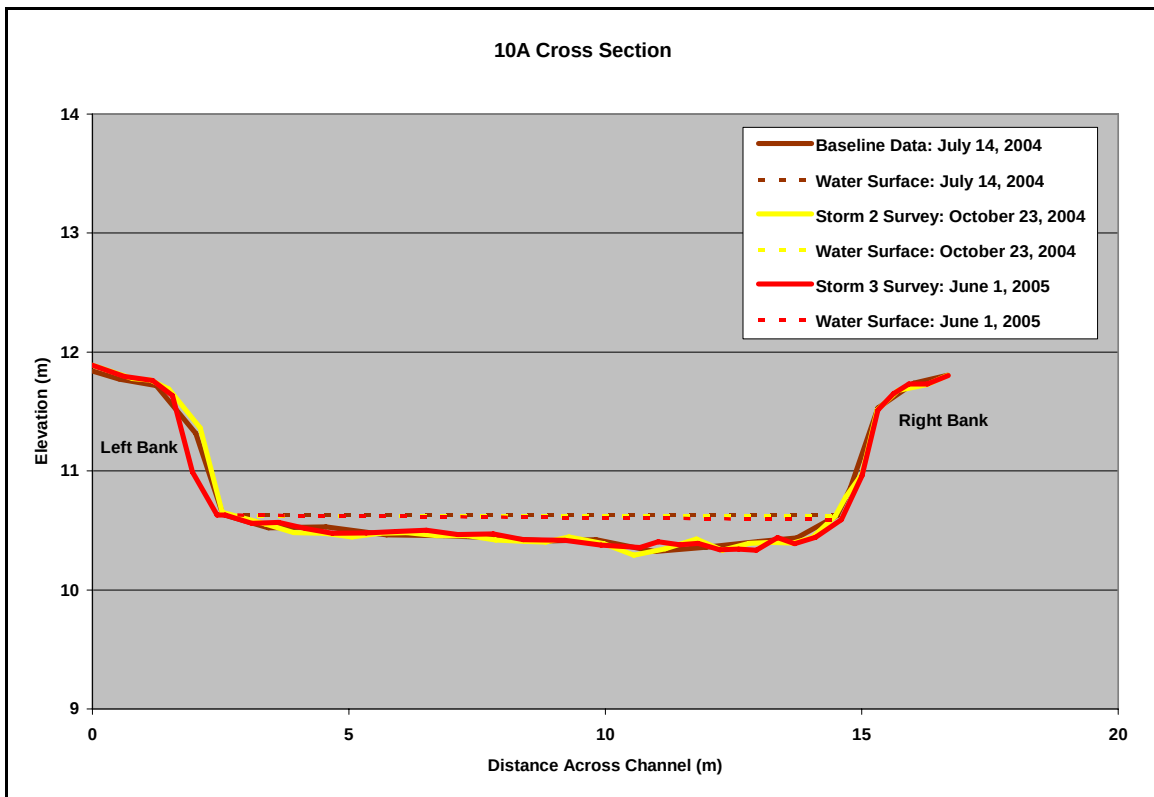


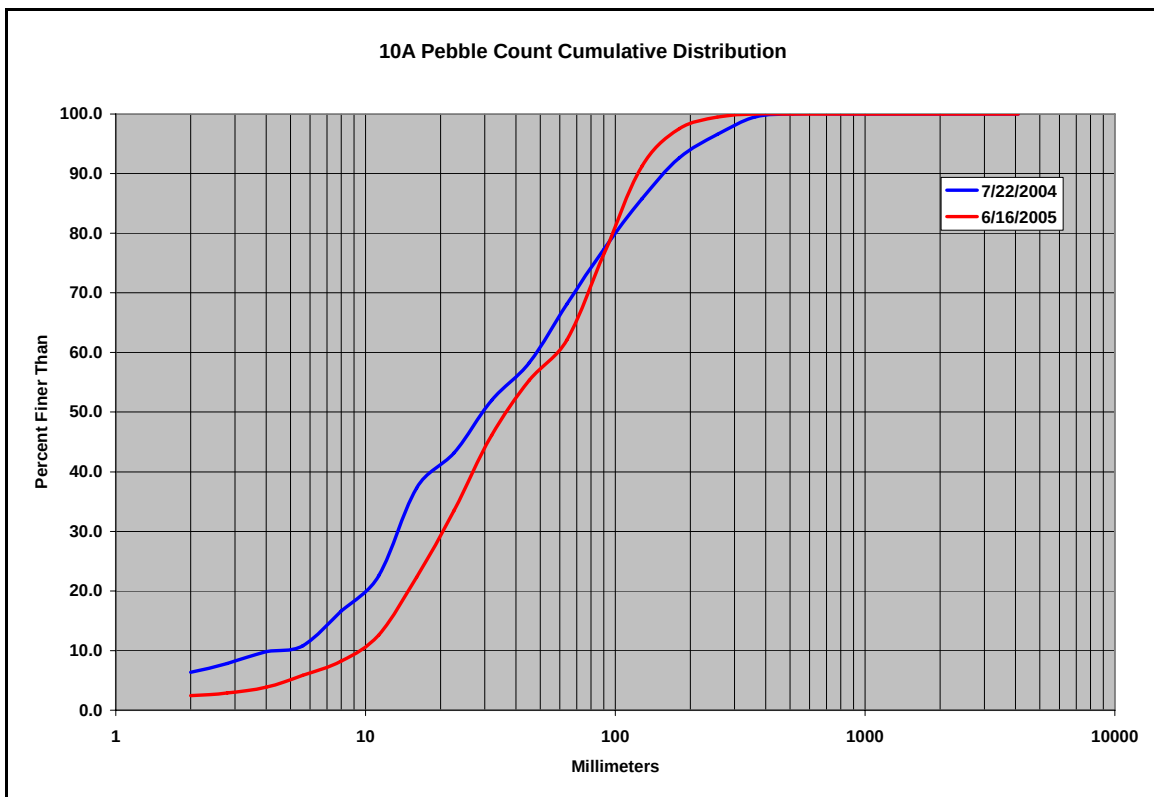
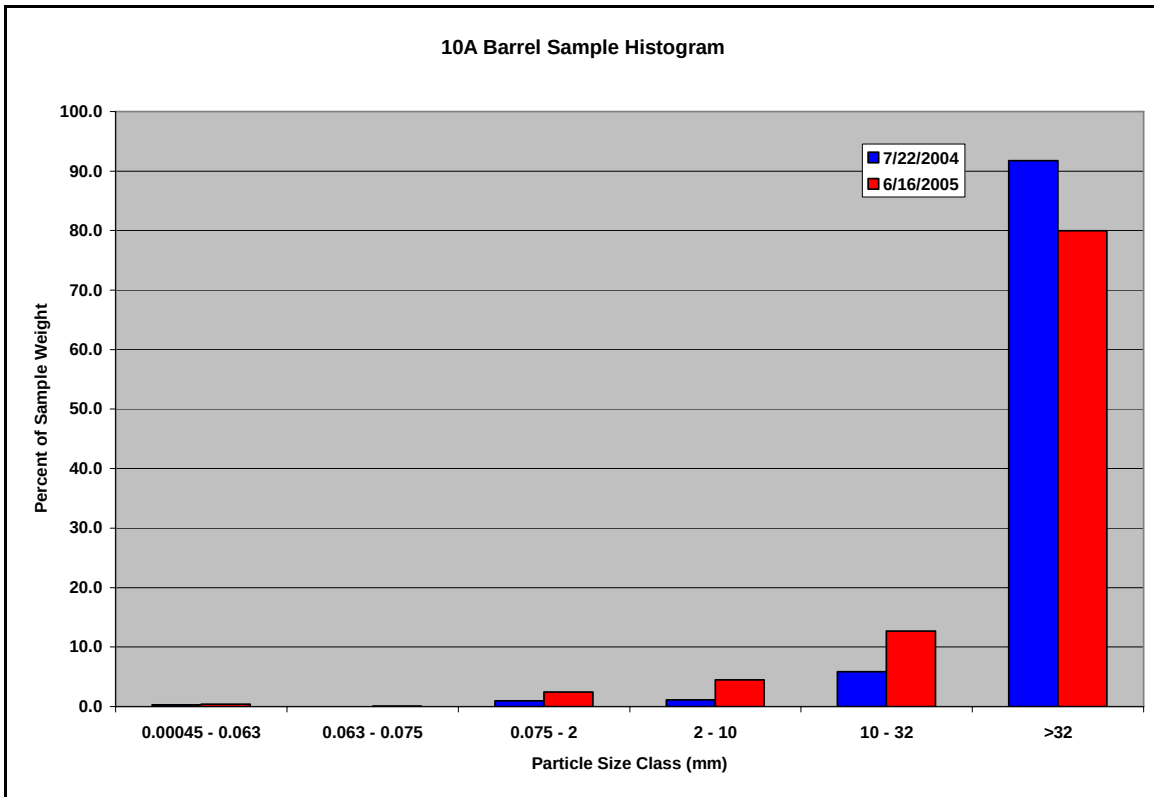
REACH 10

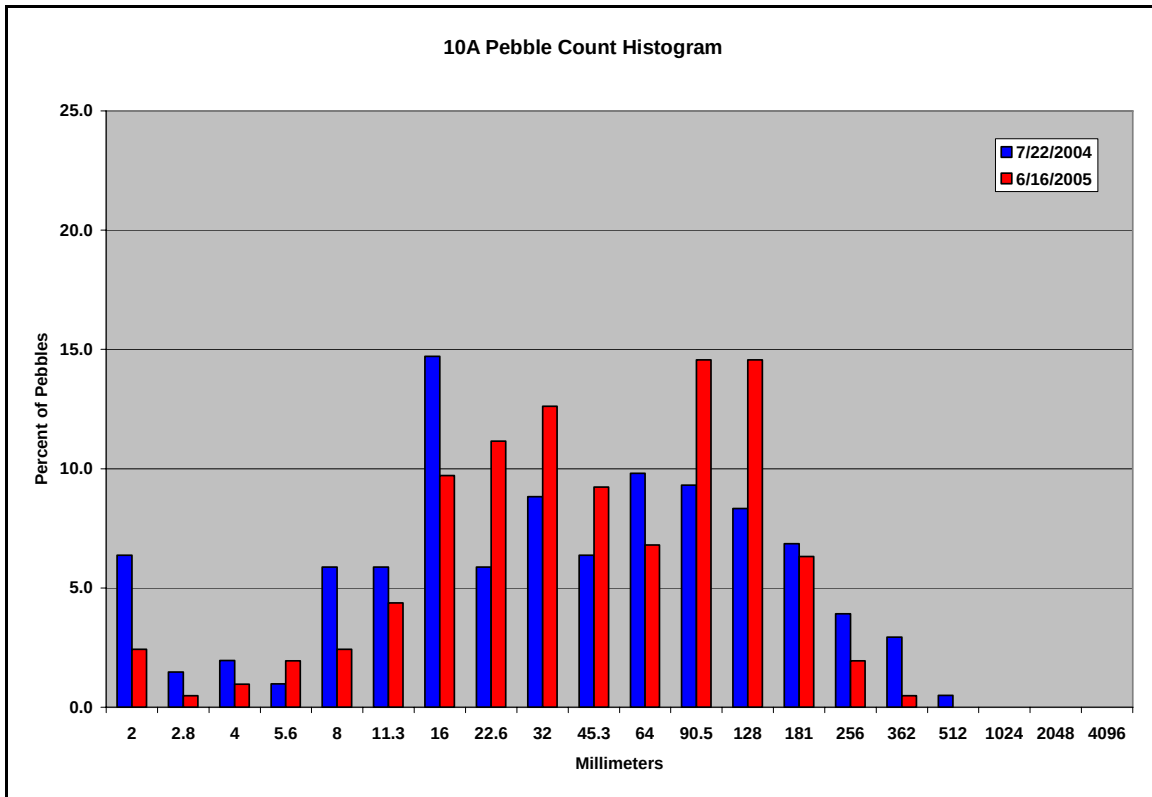


Reach 10 Cross-Sections

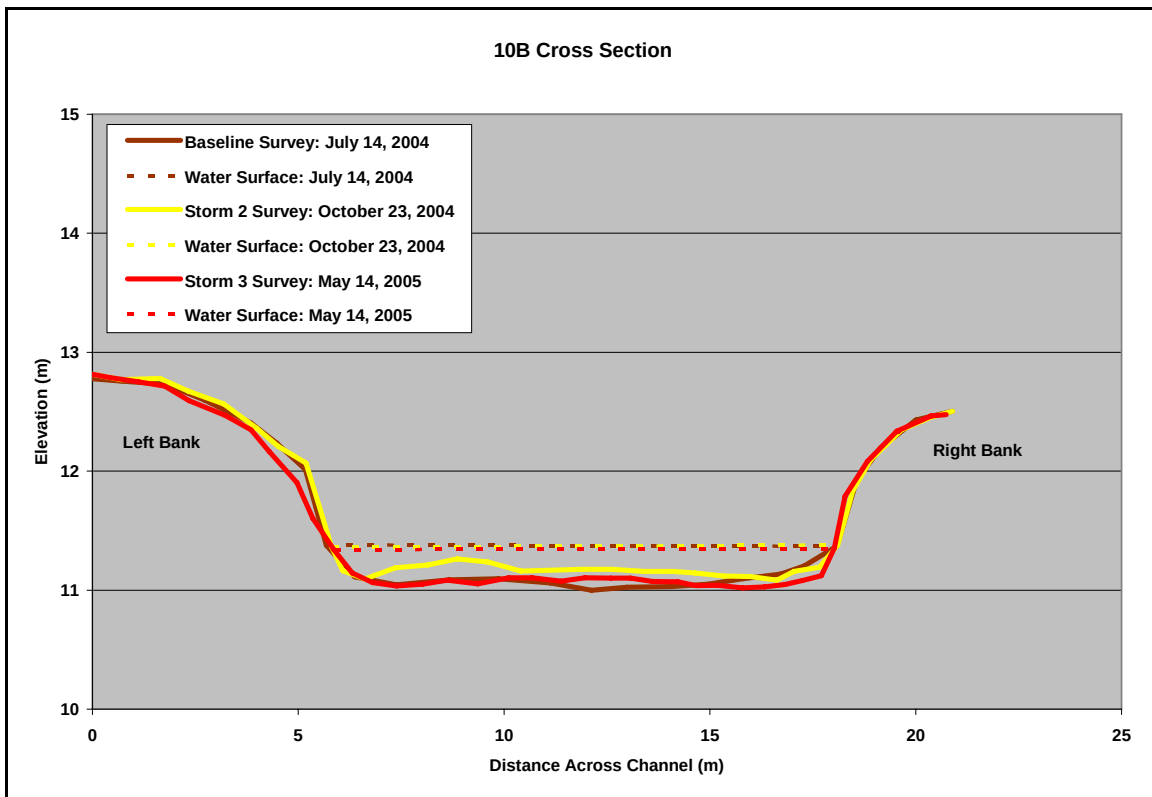
Cross-Section 10A

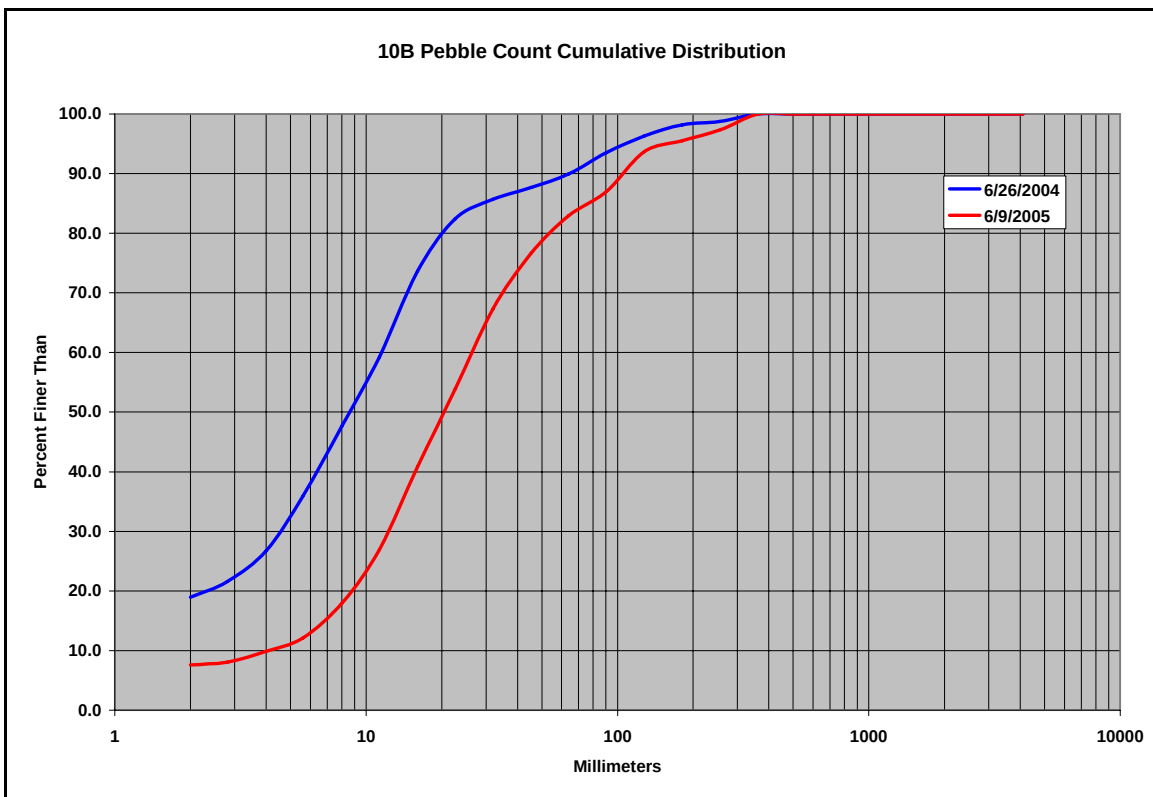
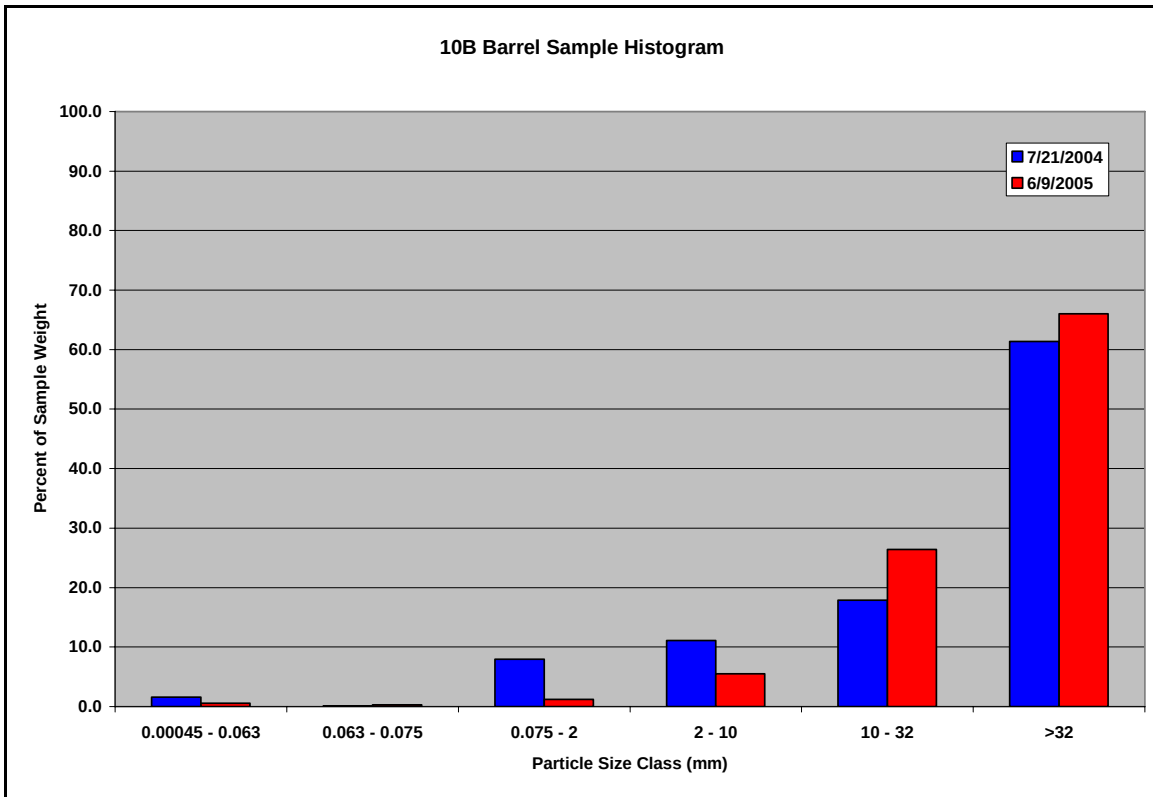


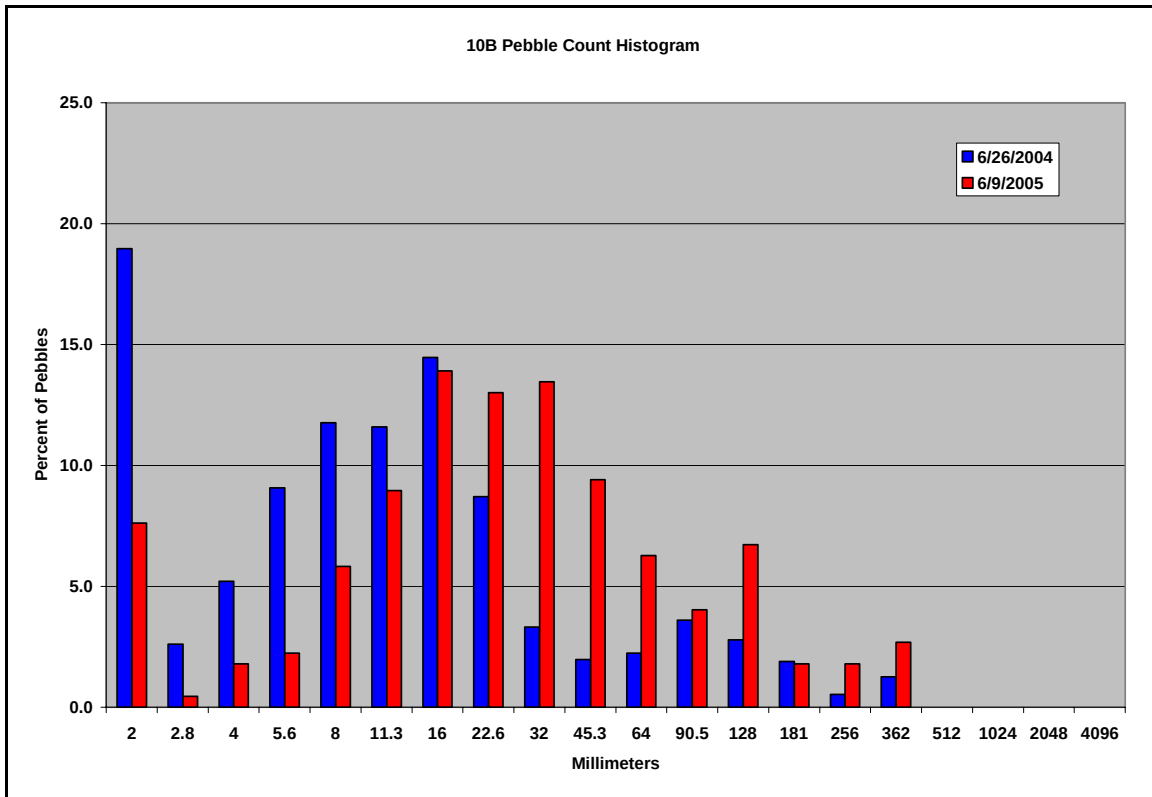




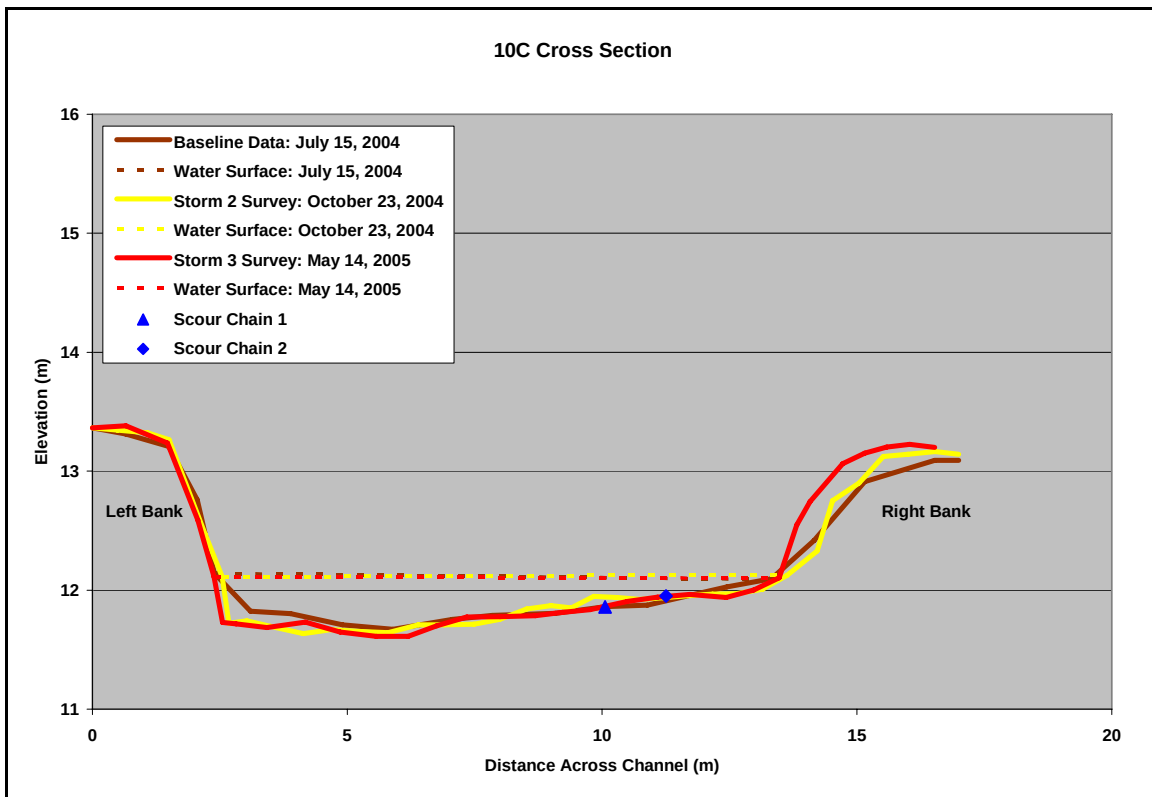
Cross-Section 10B







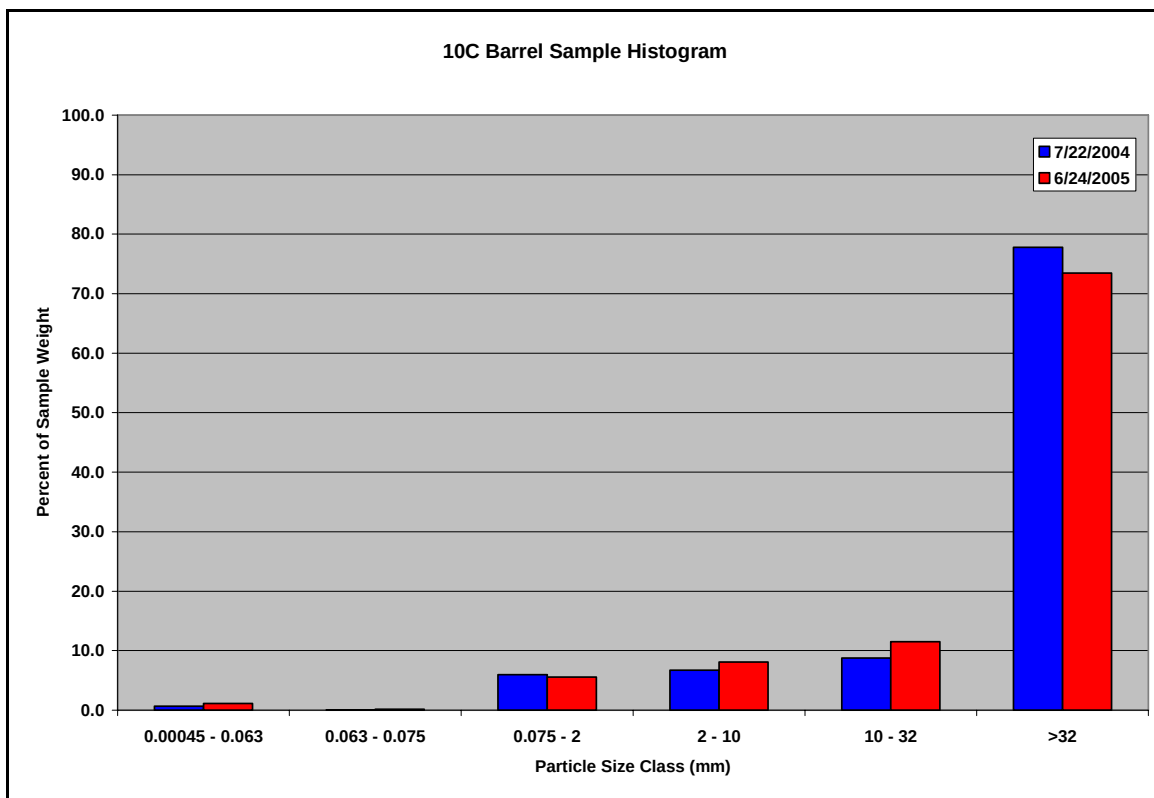
Cross-Section 10C

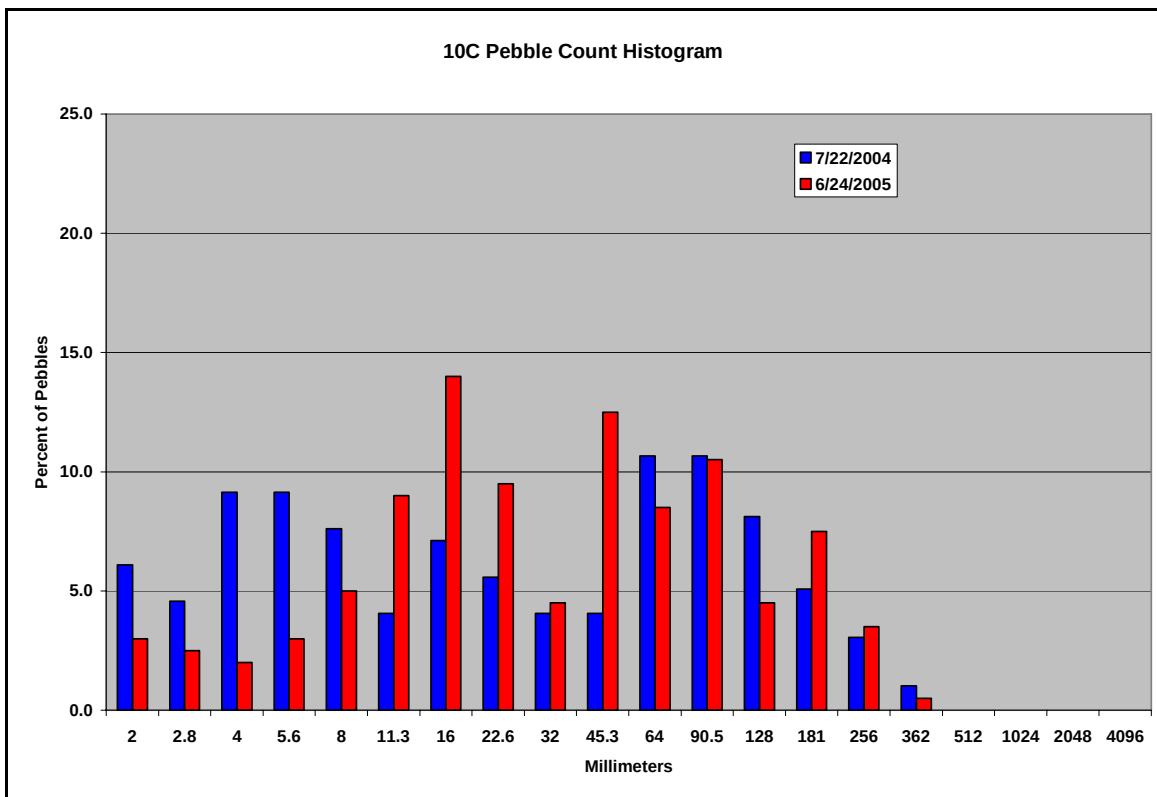
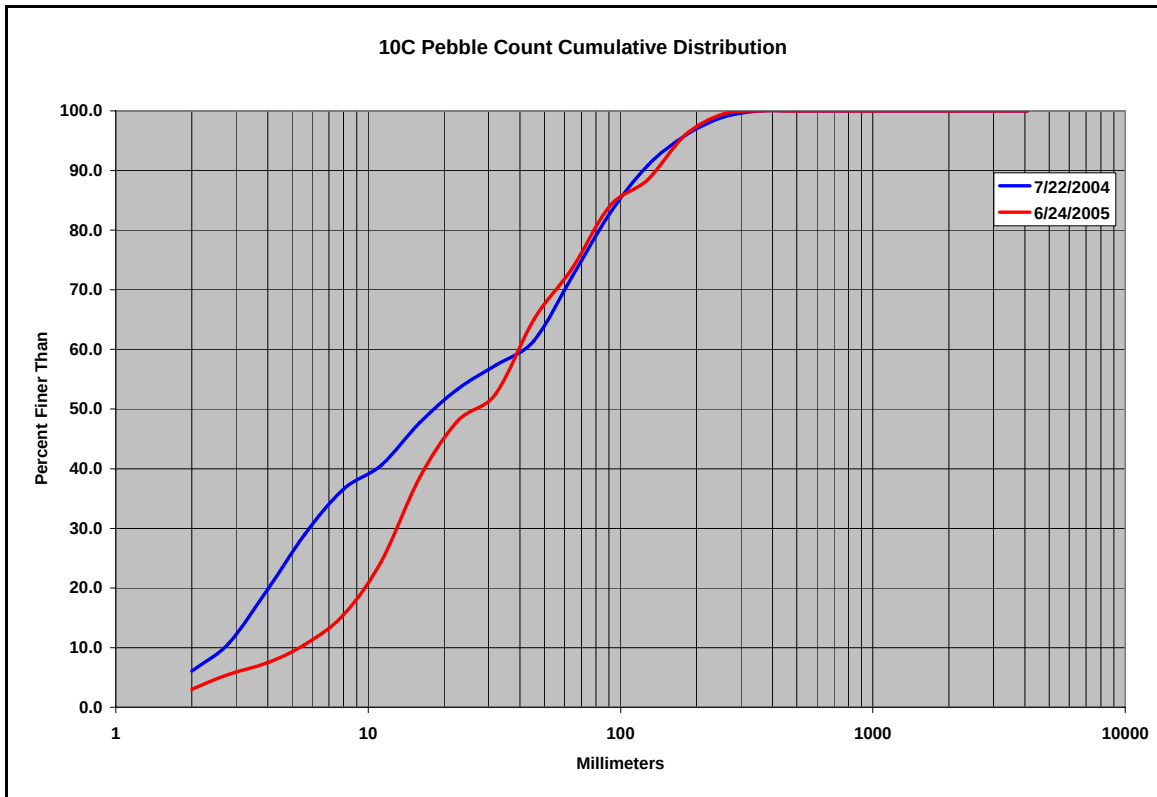


Scour Chain 1				
Date	Qmax (cfs)	Qmax (cms)	Scour (cm)	Fill (cm)
6/15/2005	installed	-	-	-
6/29/2005	26	0.74	2.06	0.00
7/6/2005	50	1.42	0.00	0.00
7/13/2005	656	18.58	0.00	2.06
7/22/2005	467	13.22	2.06	0.00
8/5/2005	30	0.85	0.00	1.03

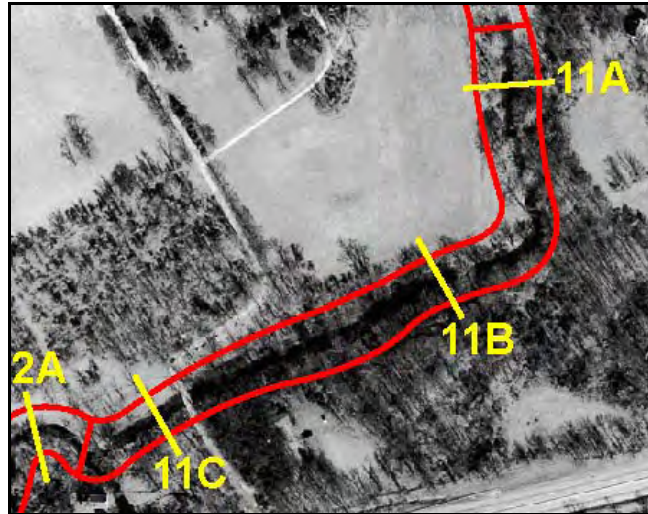
Scour Chain 2				
Date	Qmax (cfs)	Qmax (cms)	Scour (cm)	Fill (cm)
6/15/2005	installed	-	-	-
6/29/2005	26	0.74	0.00	4.13
7/6/2005	50	1.42	1.27	2.06
7/13/2005	656	18.58	4.13	2.54
7/22/2005	467	13.22	0.00	2.06
8/5/2005	30	0.85	0.00	0.00

Cross-Section 10C Scour Chains



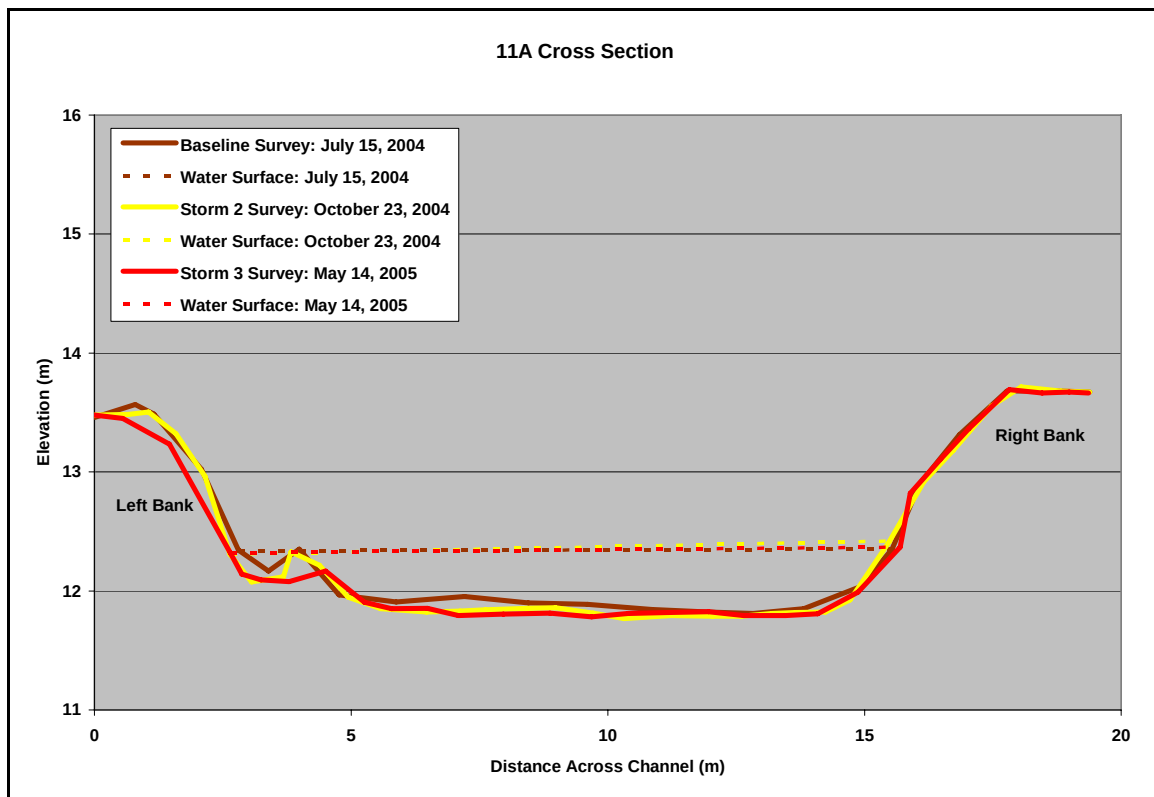


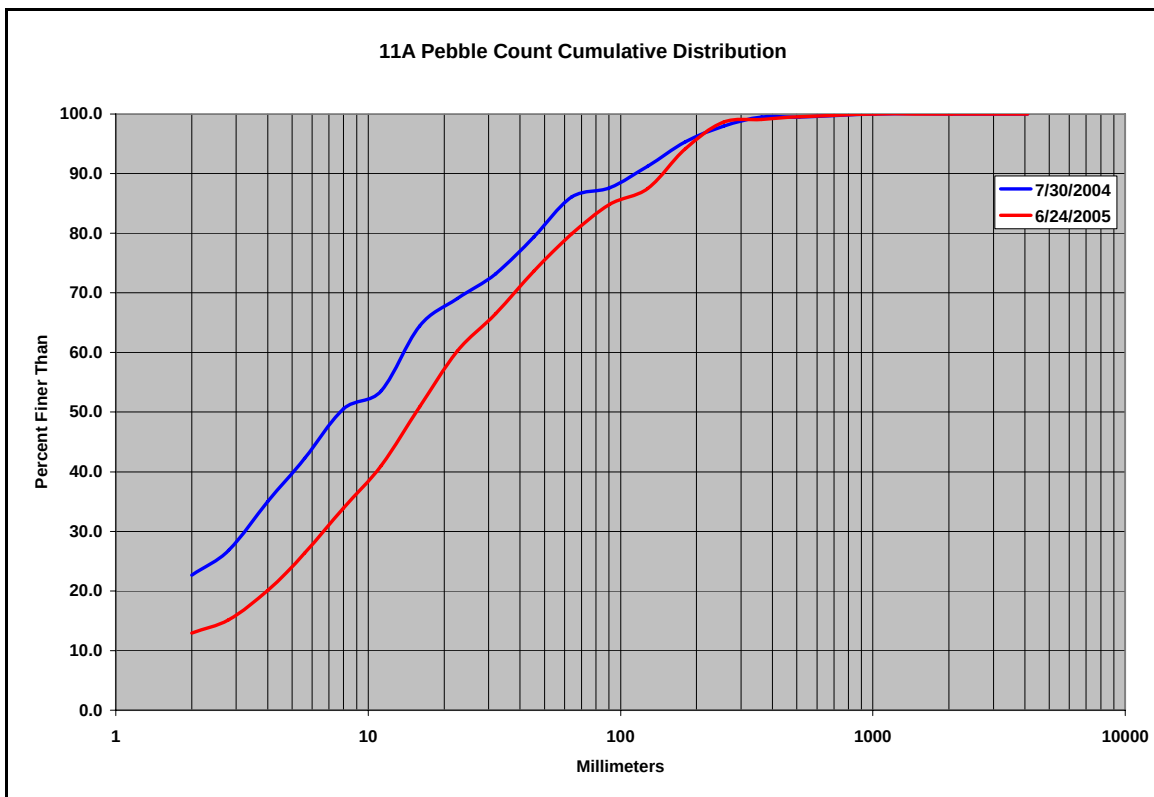
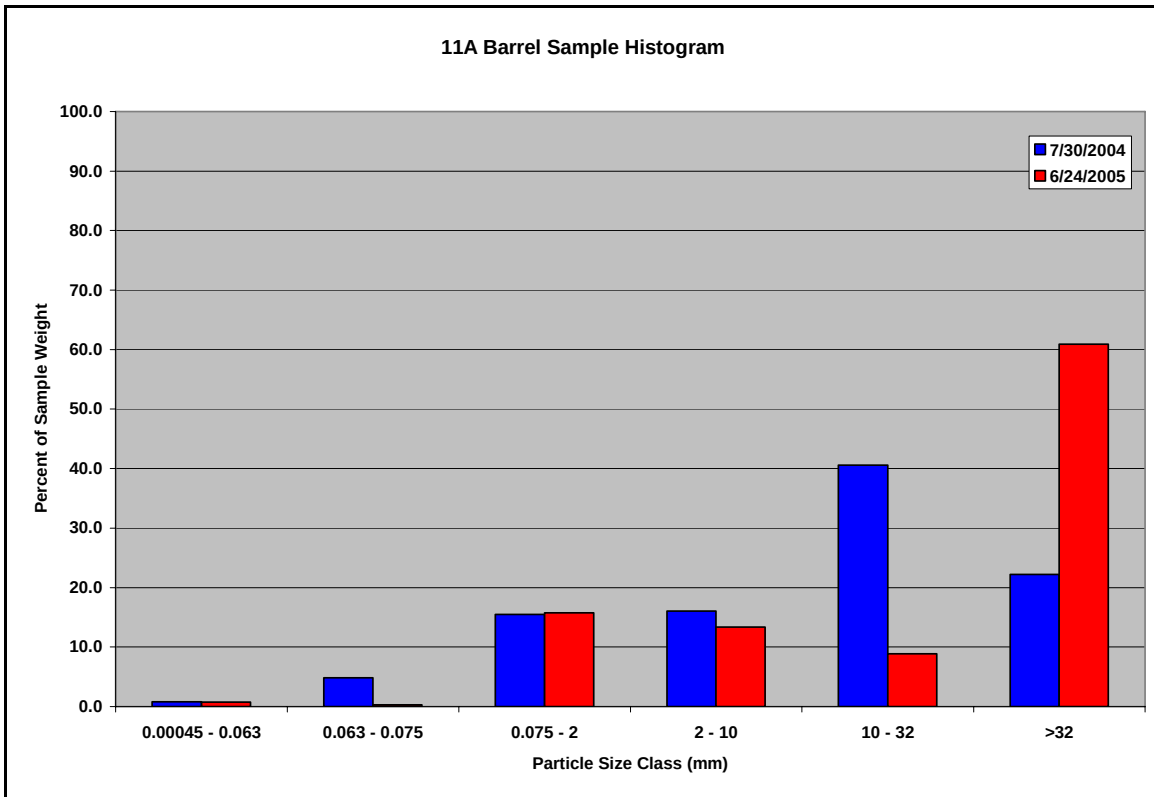
REACH 11

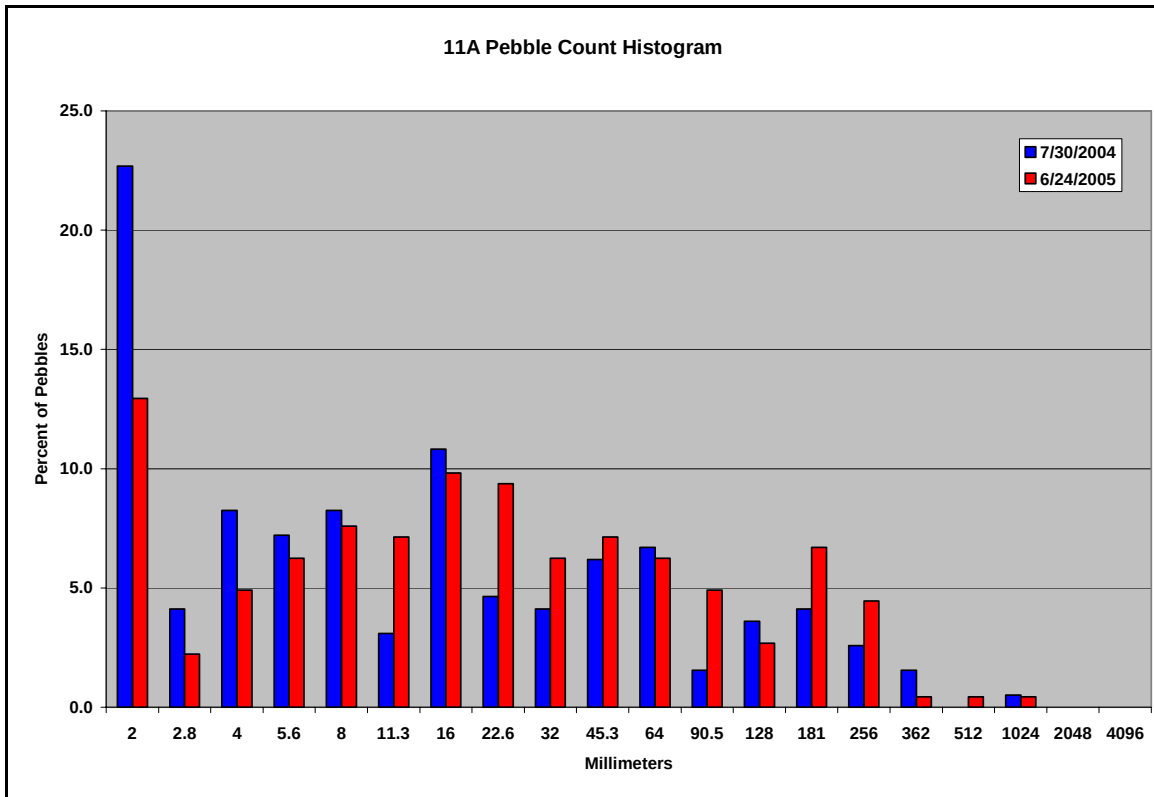


Reach 11 Cross-Sections

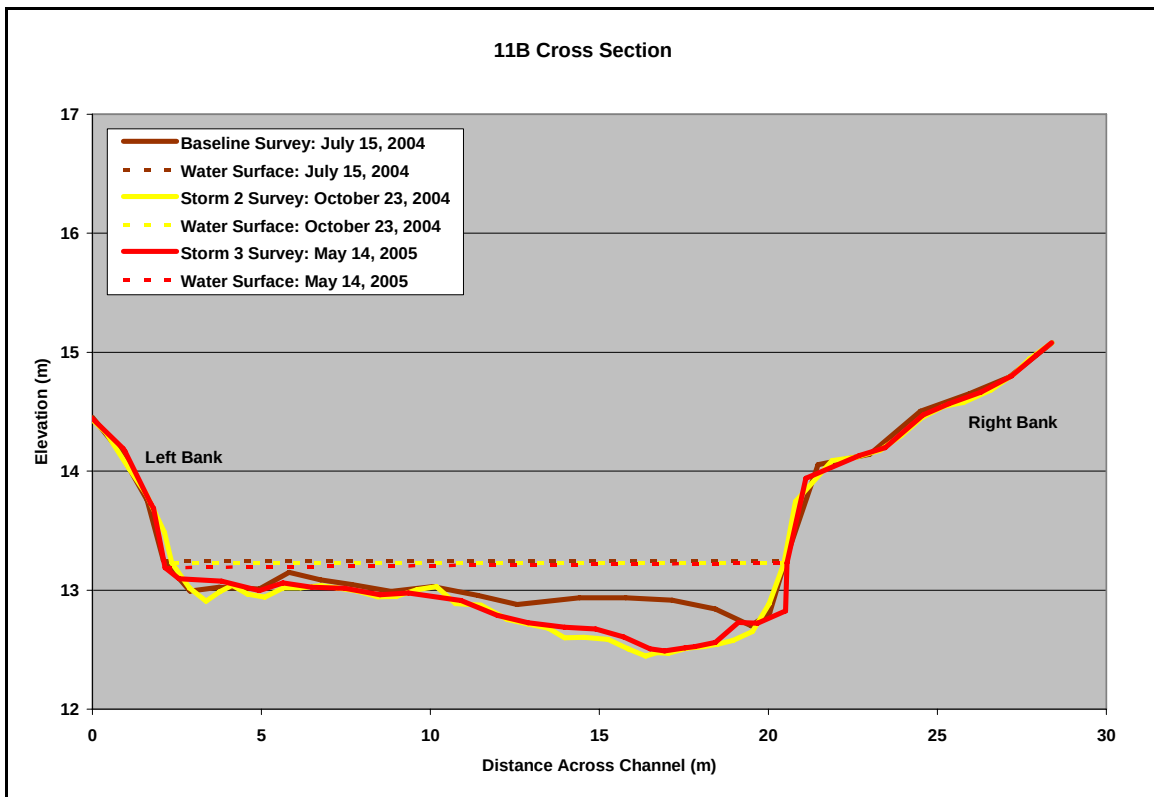
Cross-Section 11A

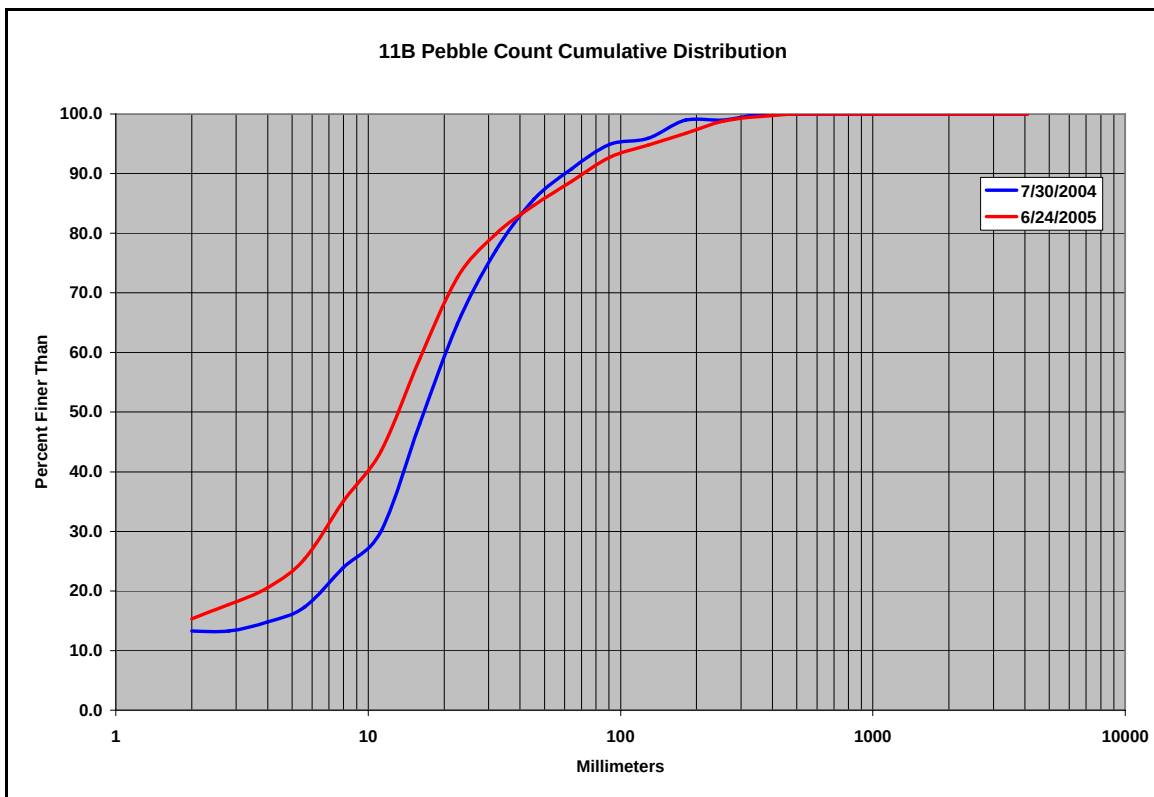
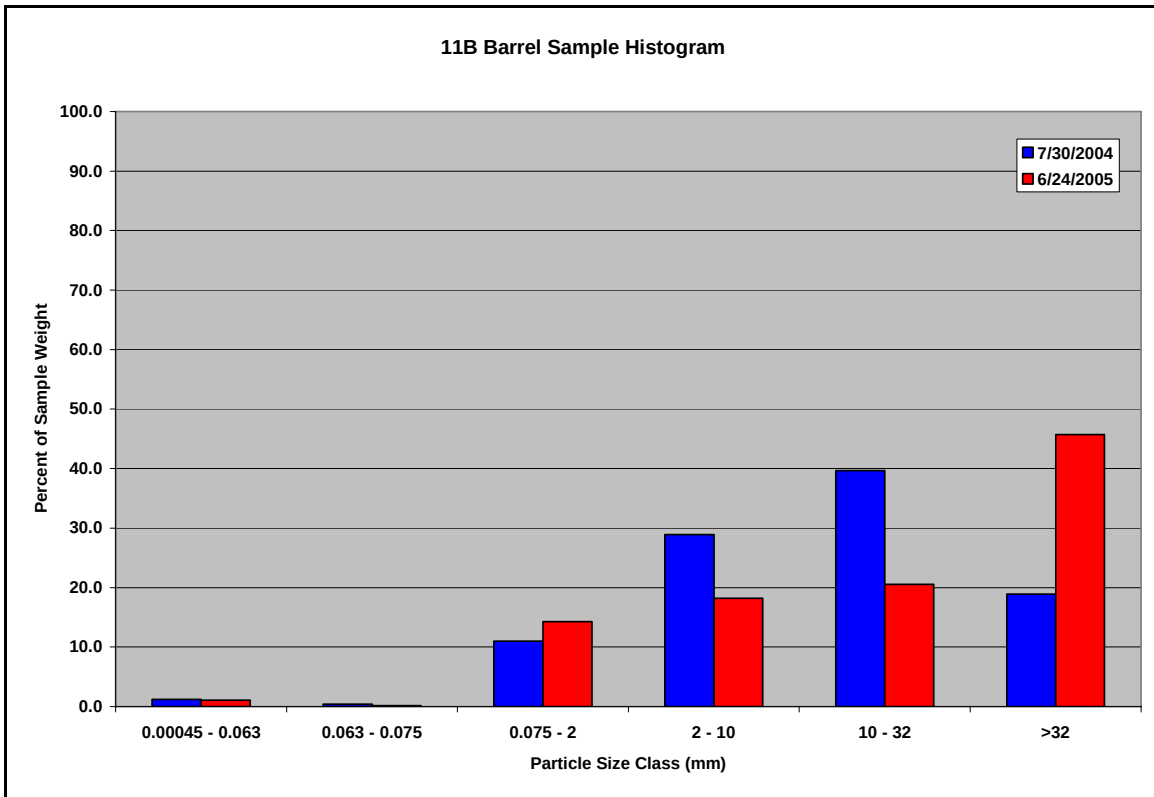


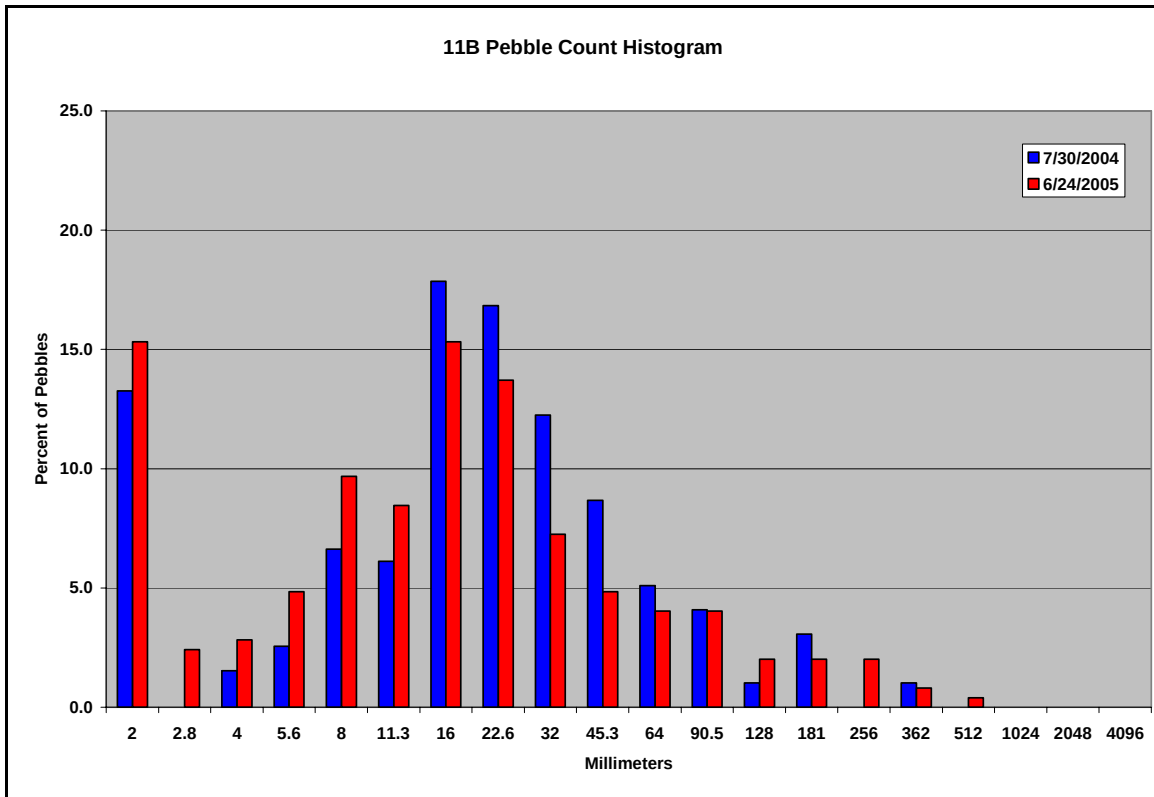




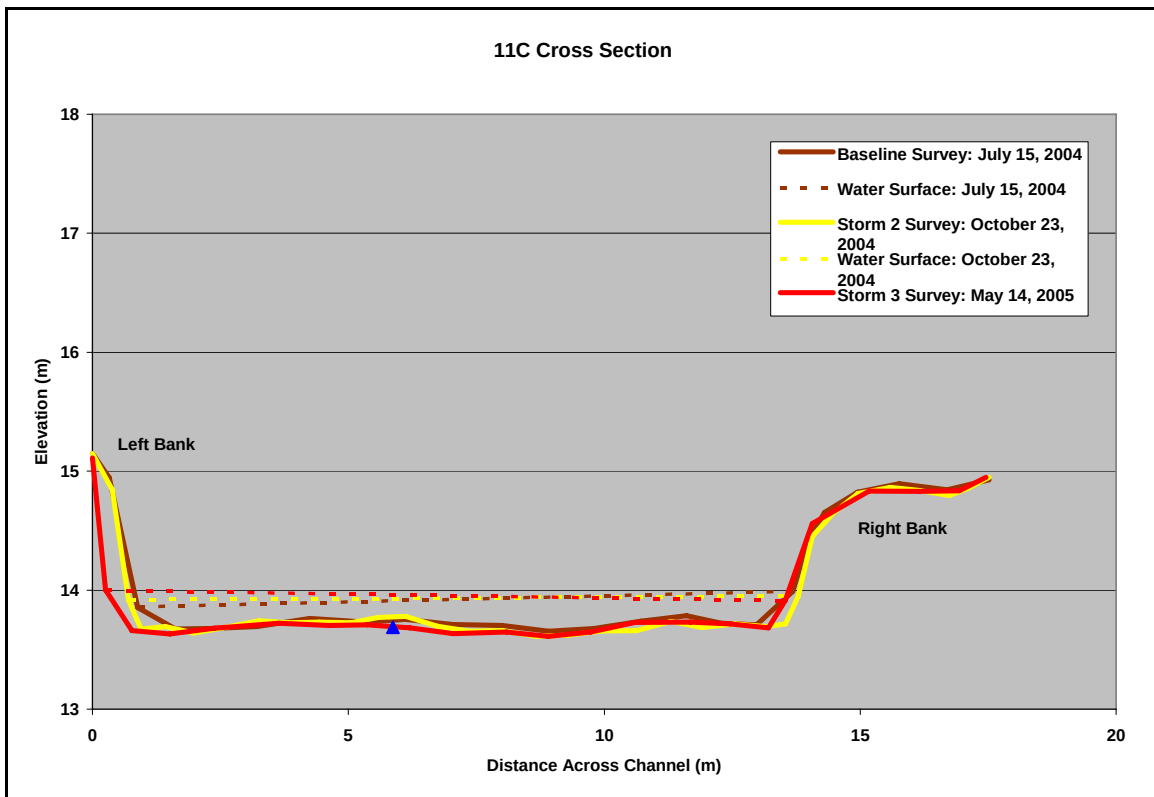
Cross-Section 11B





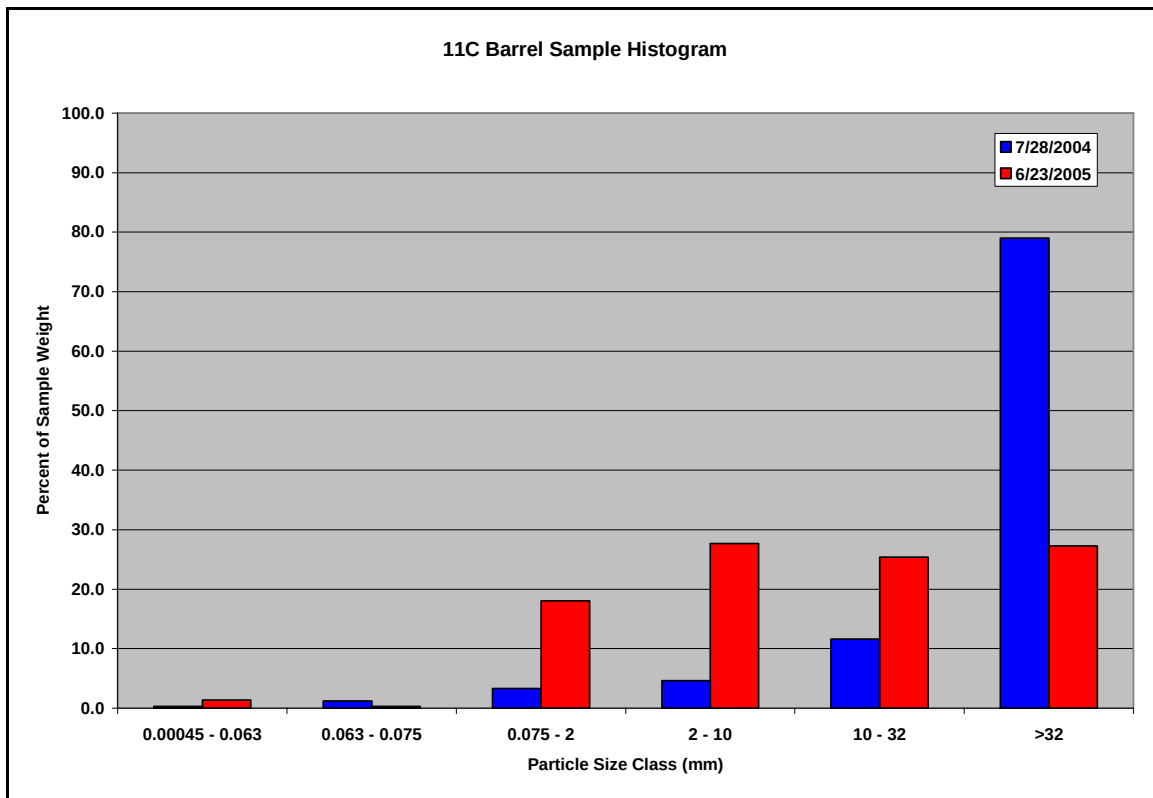


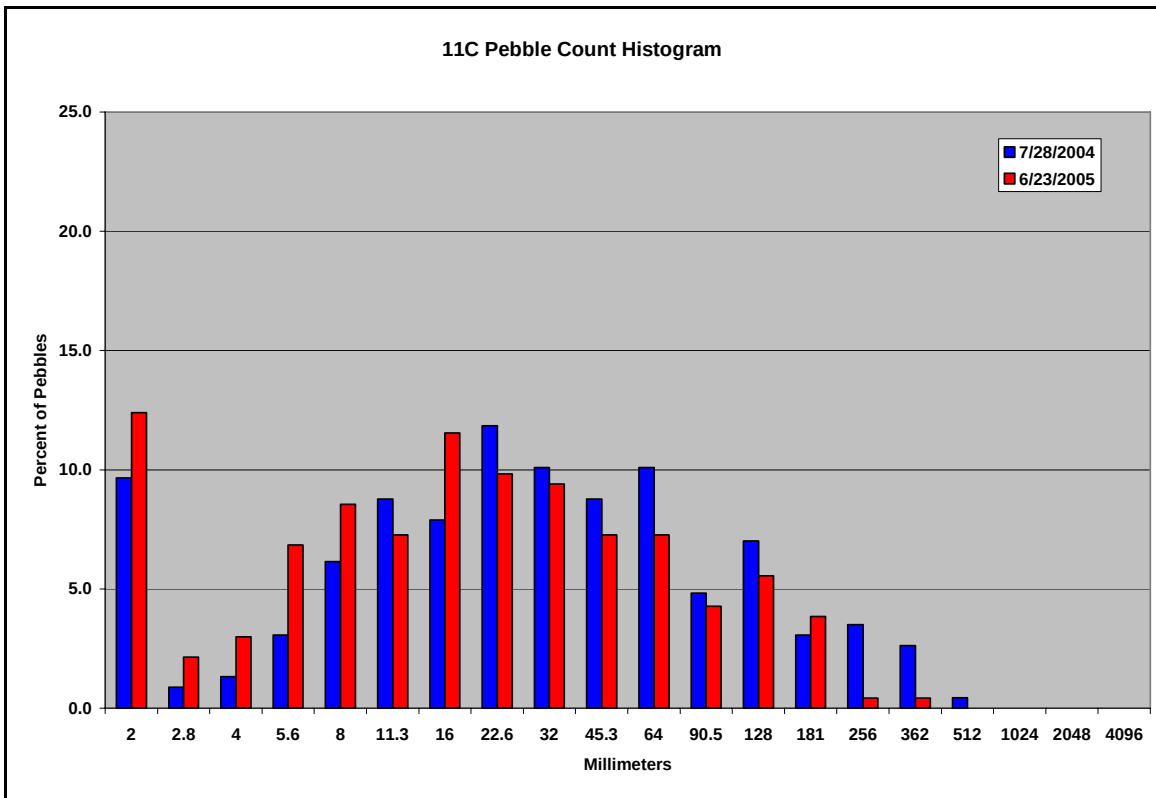
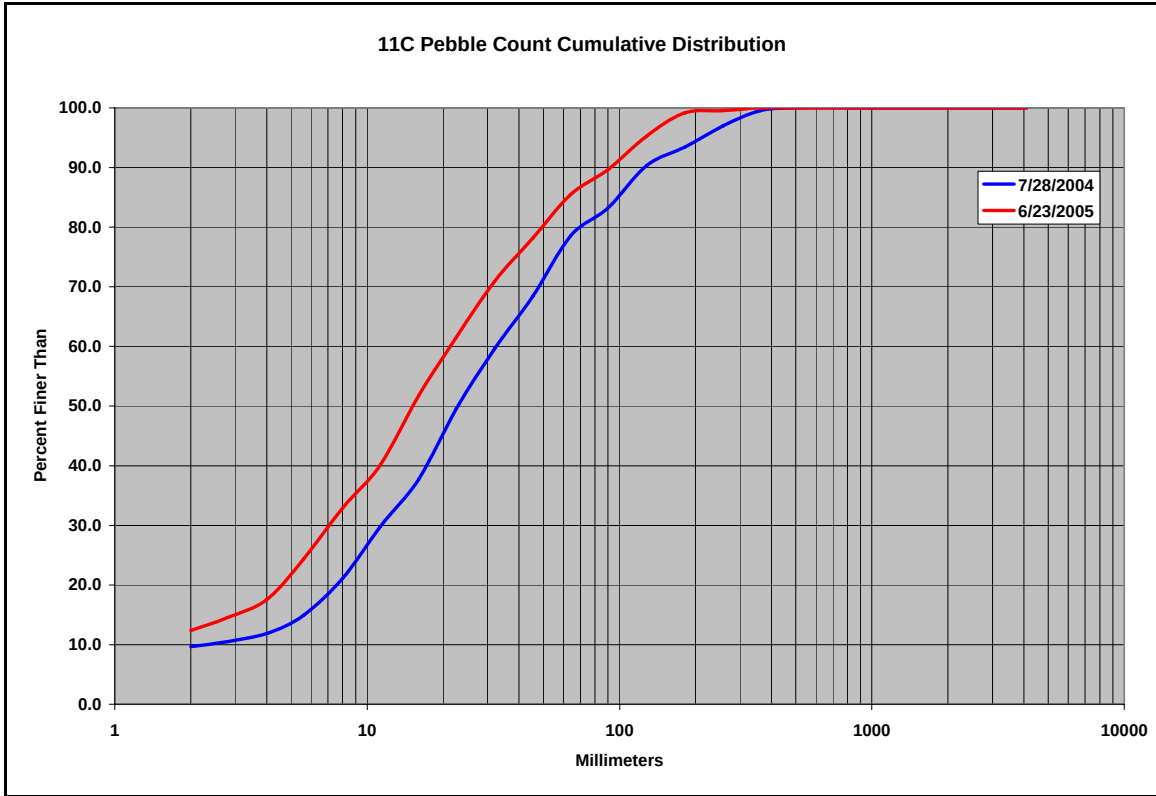
Cross-Section 11C



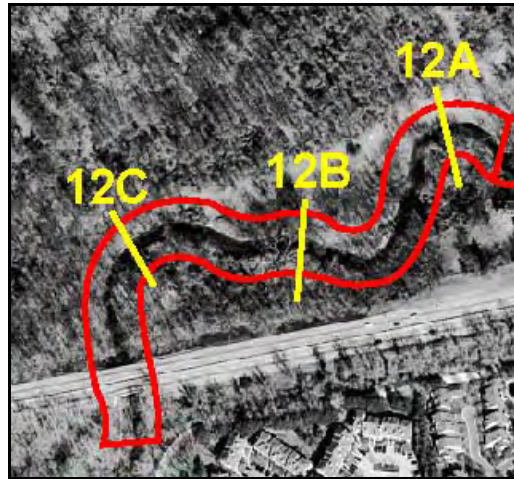
Scour Chain 1				
Date	Qmax (cfs)	Qmax (cms)	Scour (cm)	Fill (cm)
6/15/2005	installed	-	-	-
6/30/2005	26	0.74	0.00	2.54
7/6/2005	50	1.42	1.03	0.00
7/13/2005	656	18.58	7.22	5.08
7/22/2005	467	13.22	2.06	0.00
8/5/2005	30	0.85	2.06	0.00

Cross-Section 11C Scour Chain



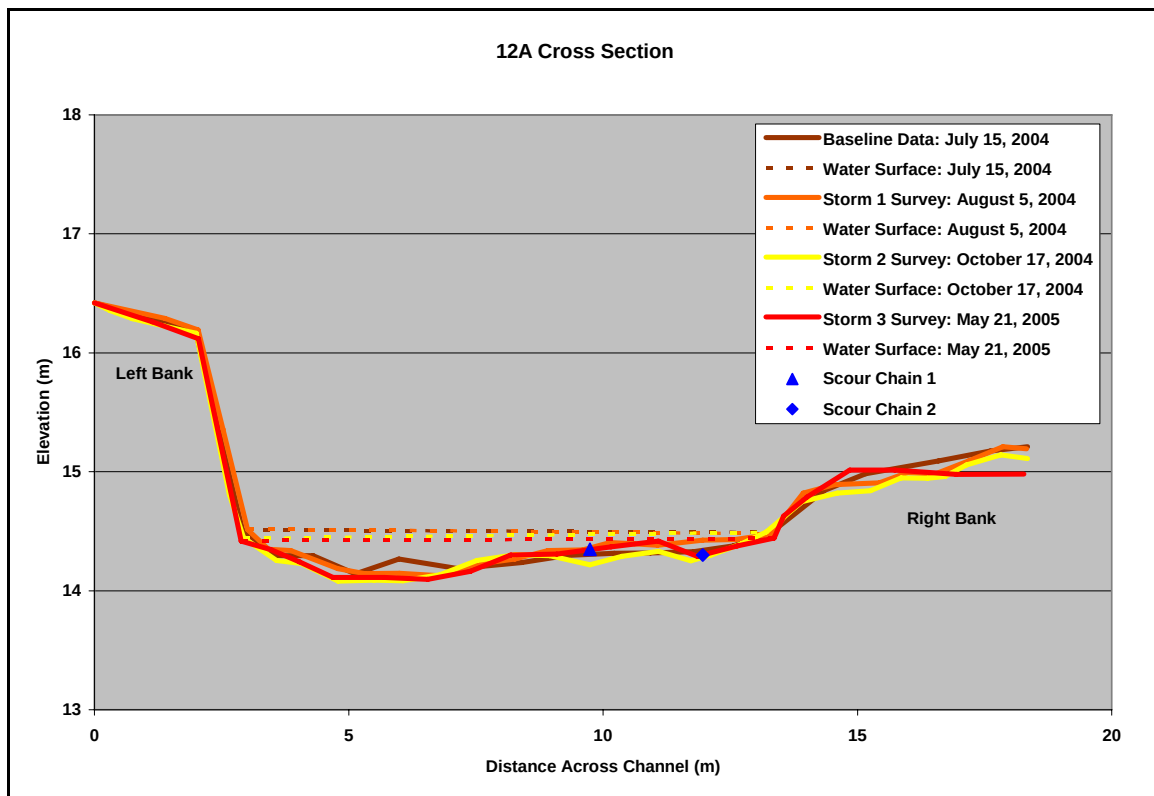


REACH 12



Reach 12 Cross-Sections

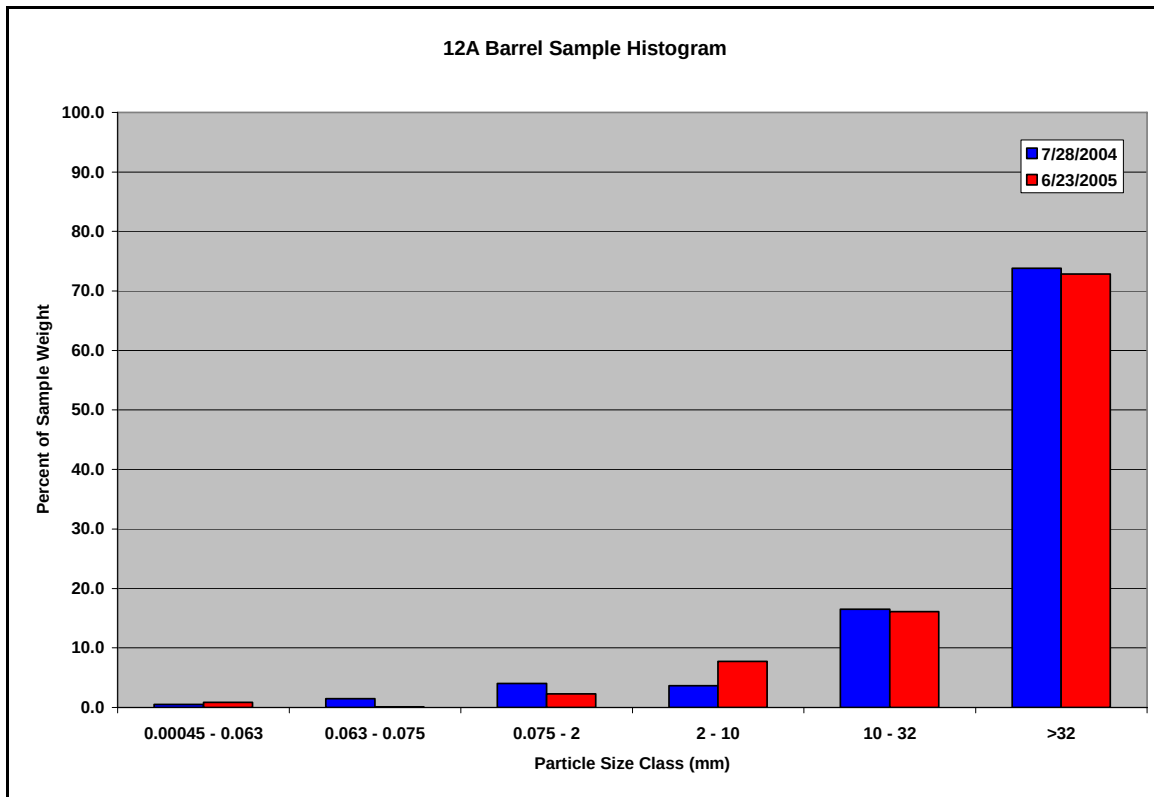
Cross-Section 12A

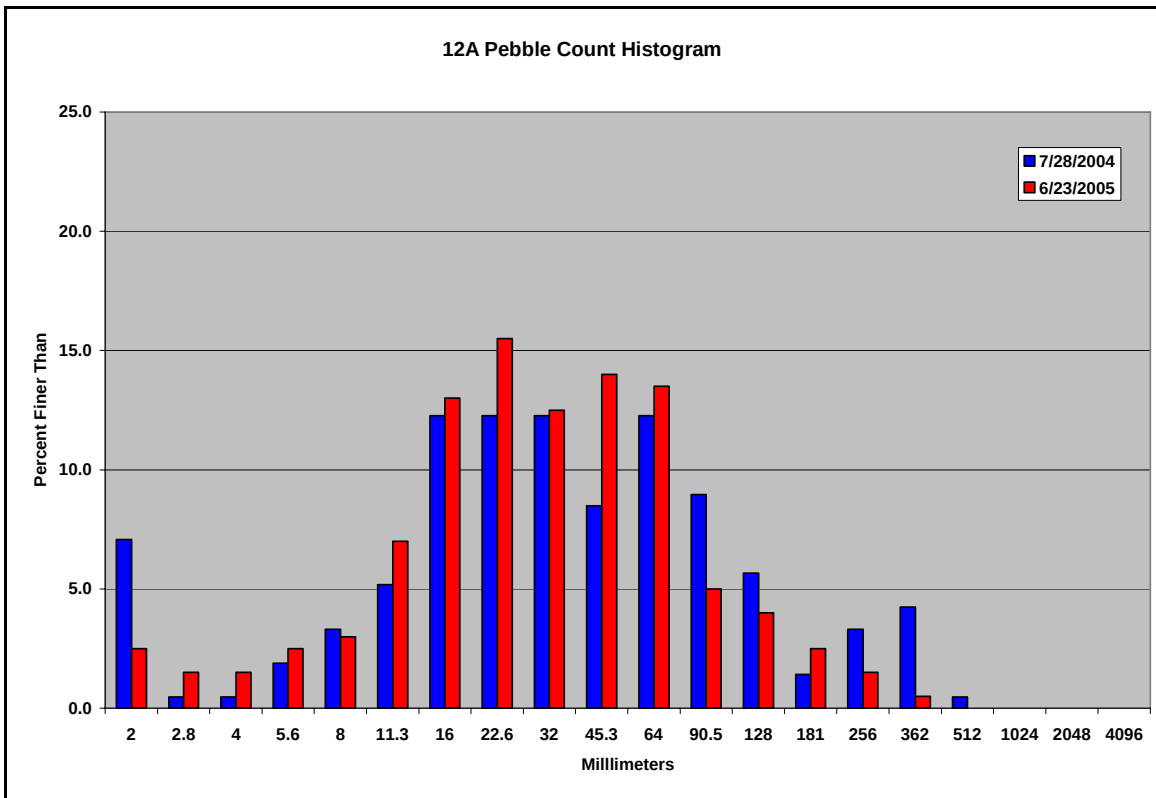


Scour Chain 2				
Date	Qmax (cfs)	Qmax (cms)	Scour (cm)	Fill (cm)
6/9/2005	installed	-	-	-
6/30/2005	30	0.85	0.00	2.06
7/6/2005	50	1.42	0.00	0.00
7/13/2005	656	18.58	0.00	6.19
7/22/2005	467	13.22	2.06	0.00
8/5/2005	30	0.85	0.00	1.03

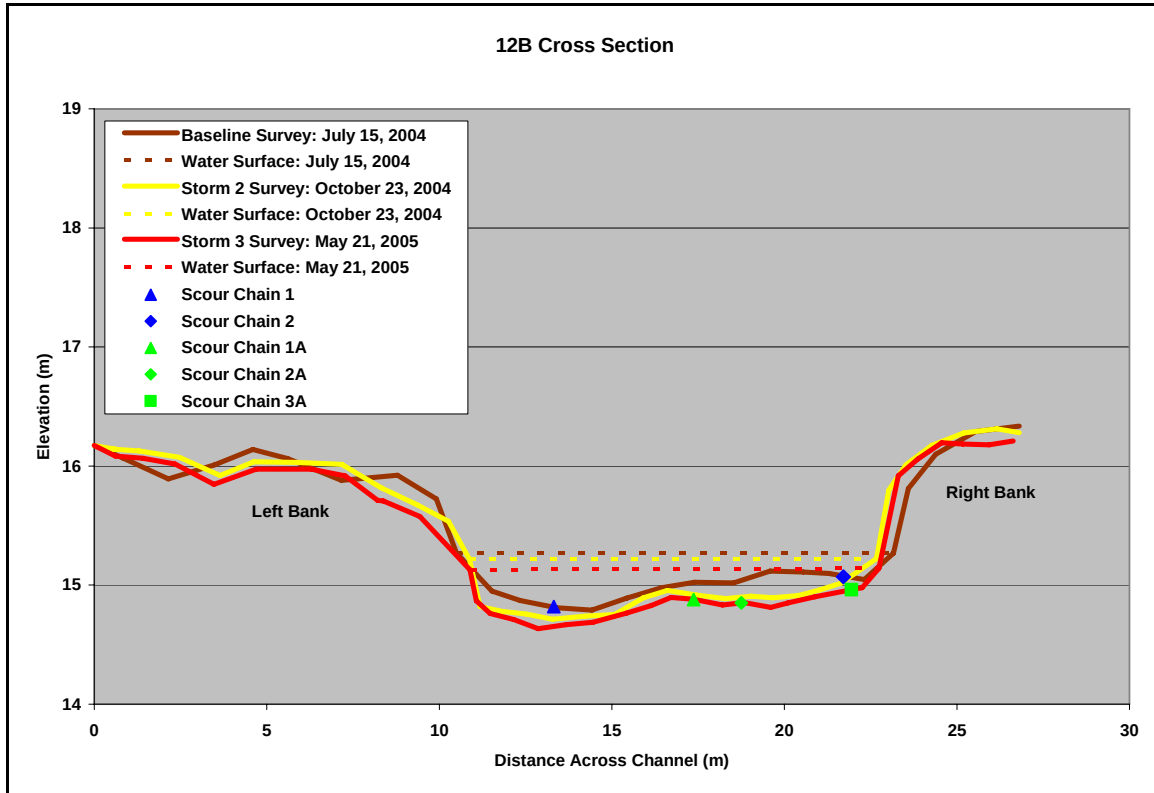
**Scour chain 1 was lost shortly after installation*

Cross-Section 12A Scour Chain





Cross-Section 12B



Scour Chain 2				
Date	Qmax (cfs)	Qmax (cms)	Scour (cm)	Fill (cm)
8/16/2004	installed	-	-	-
10/23/2004	2740	77.59	0.00	2.06
6/9/2005	2060	58.33	0.00	0.00
6/30/2005	30	0.85	0.00	2.06
7/6/2005	50	1.42	0.00	0.00
7/13/2005	656	18.58	0.00	0.00
7/22/2005	467	13.22	1.03	0.00
8/5/2005	30	0.85	1.03	1.27

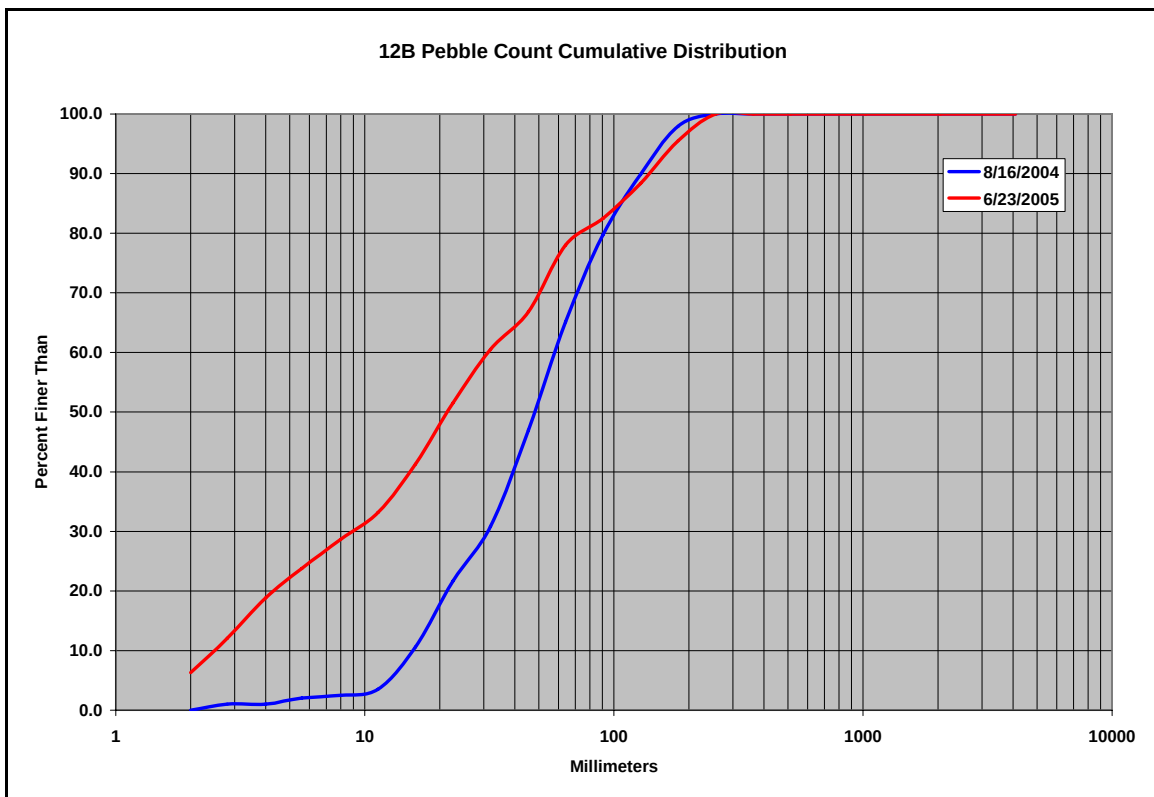
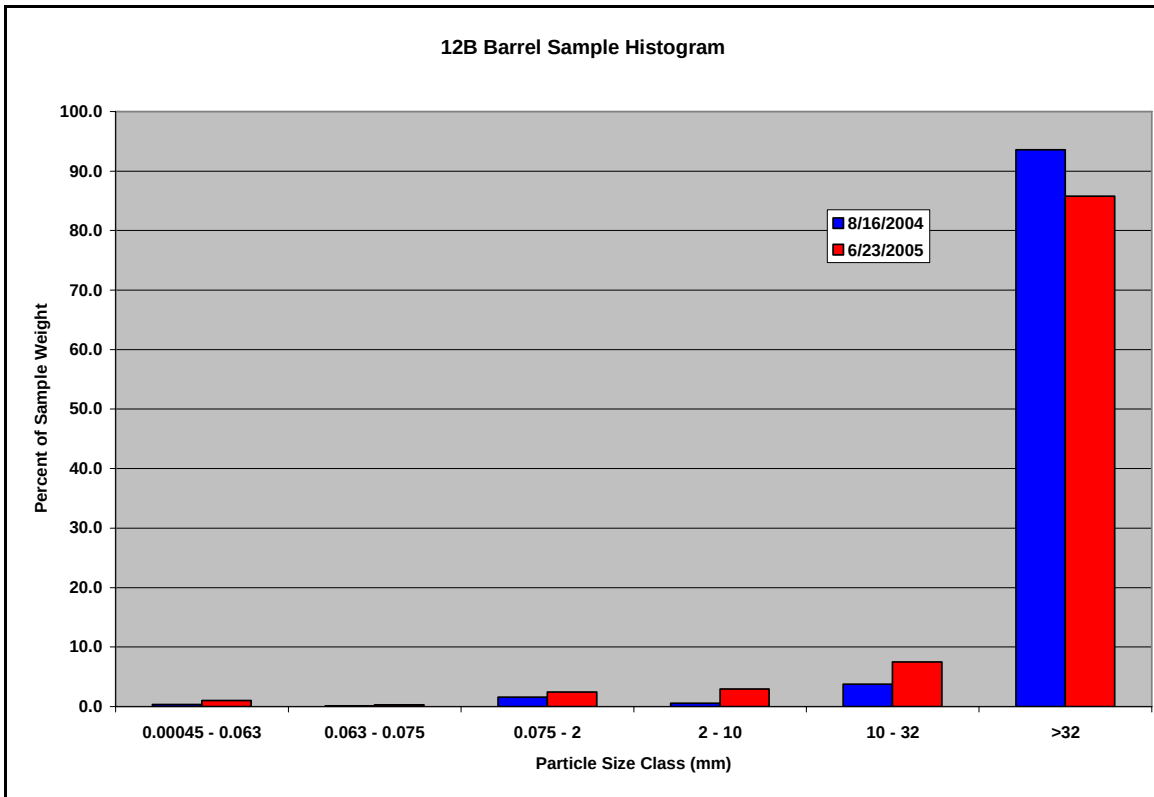
Scour Chain 1A				
Date	Qmax (cfs)	Qmax (cms)	Scour (cm)	Fill (cm)
6/9/2005	installed	-	-	-
6/30/2005	30	0.85	0.00	5.16
7/6/2005	50	1.42	1.03	0.00
7/13/2005	656	18.58	0.00	1.03
7/22/2005	467	13.22	0.00	0.00
8/5/2005	30	0.85	0.00	1.27

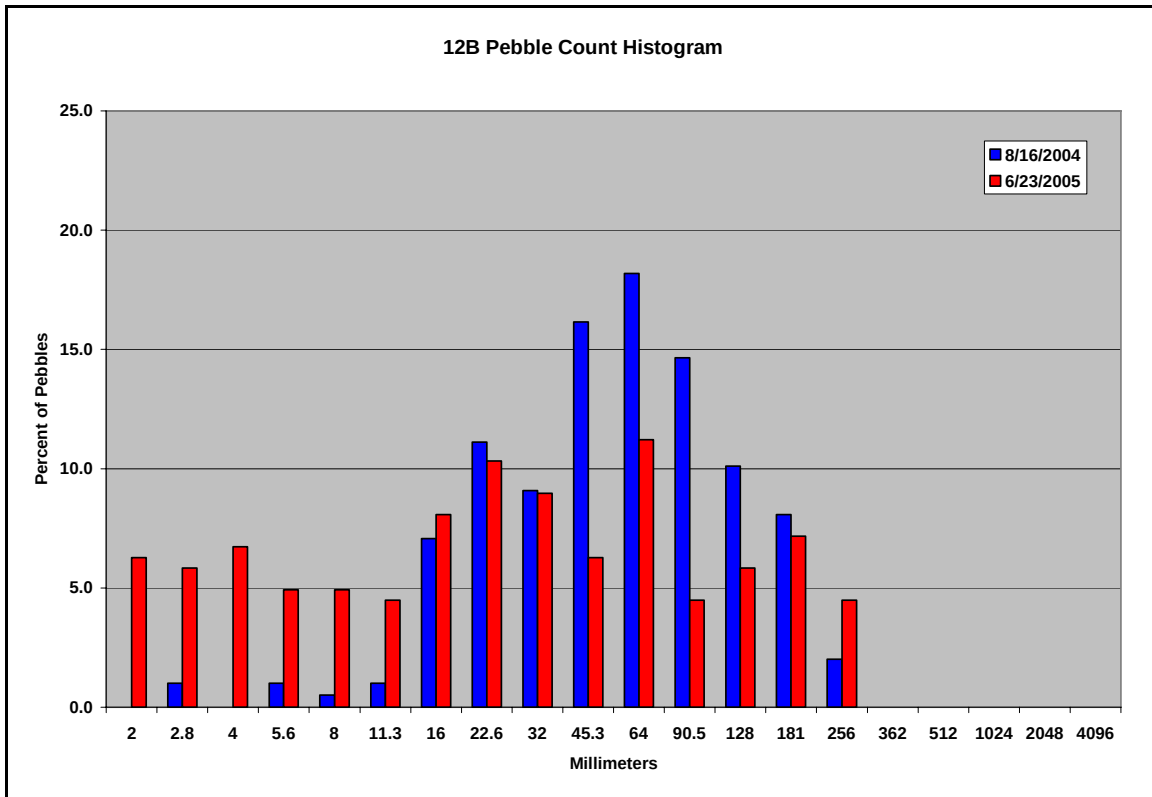
Scour Chain 2A				
Date	Qmax (cfs)	Qmax (cms)	Scour (cm)	Fill (cm)
6/9/2005	installed	-	-	-
6/30/2005	30	0.85	0.00	8.26
7/6/2005	50	1.42	2.06	0.00
7/13/2005	656	18.58	0.00	2.06
7/22/2005	467	13.22	2.06	0.00
8/5/2005	30	0.85	0.00	2.06

Scour Chain 3A				
Date	Qmax (cfs)	Qmax (cms)	Scour (cm)	Fill (cm)
6/9/2005	installed	-	-	-
6/30/2005	30	0.85	0.00	4.13
7/6/2005	50	1.42	0.00	0.00
7/13/2005	656	18.58	2.06	0.00
7/22/2005	467	13.22	2.06	0.00
8/5/2005	30	0.85	0.00	2.06

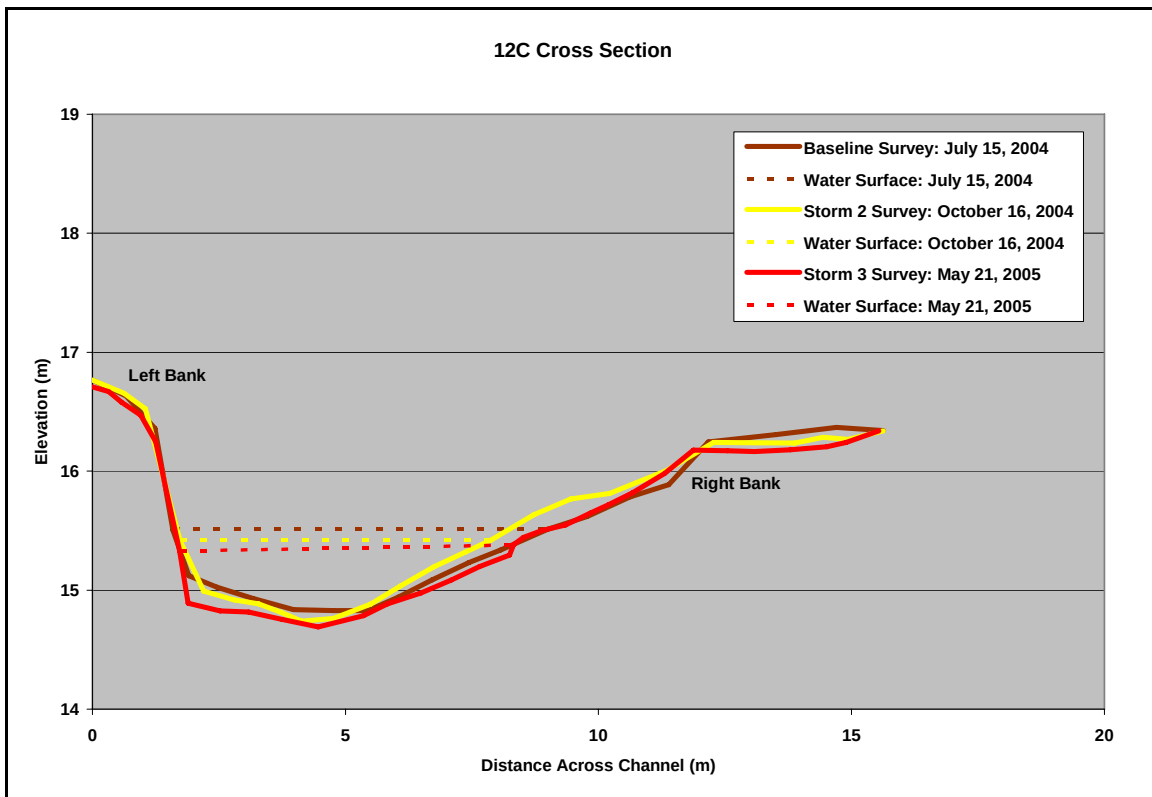
**Scour Chain 1 was lost shortly after installation*

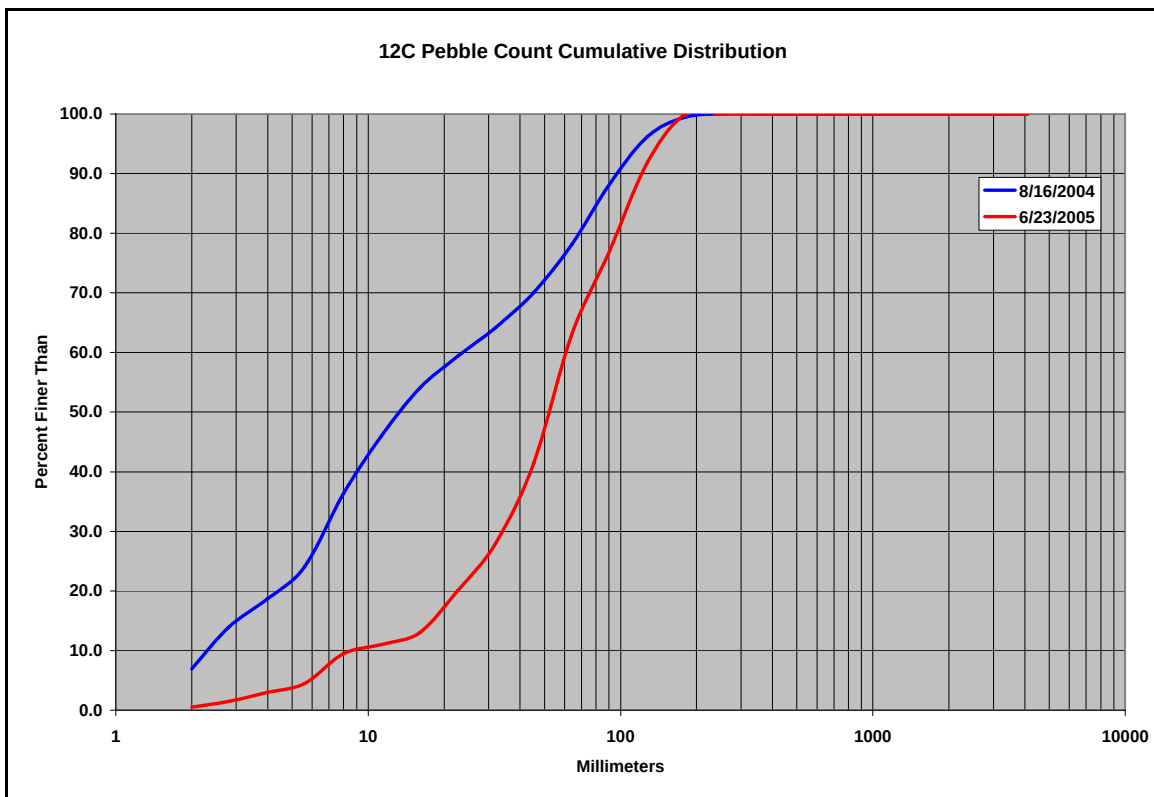
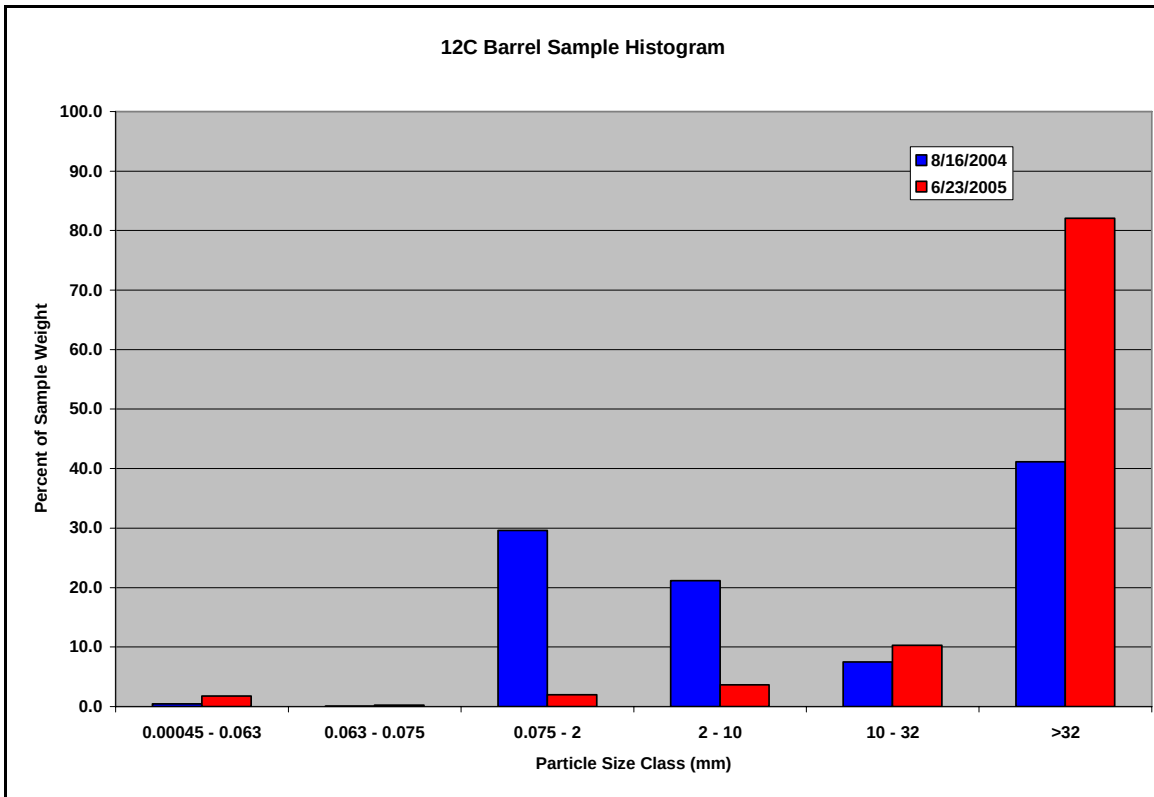
Cross-Section 12B Scour Chains

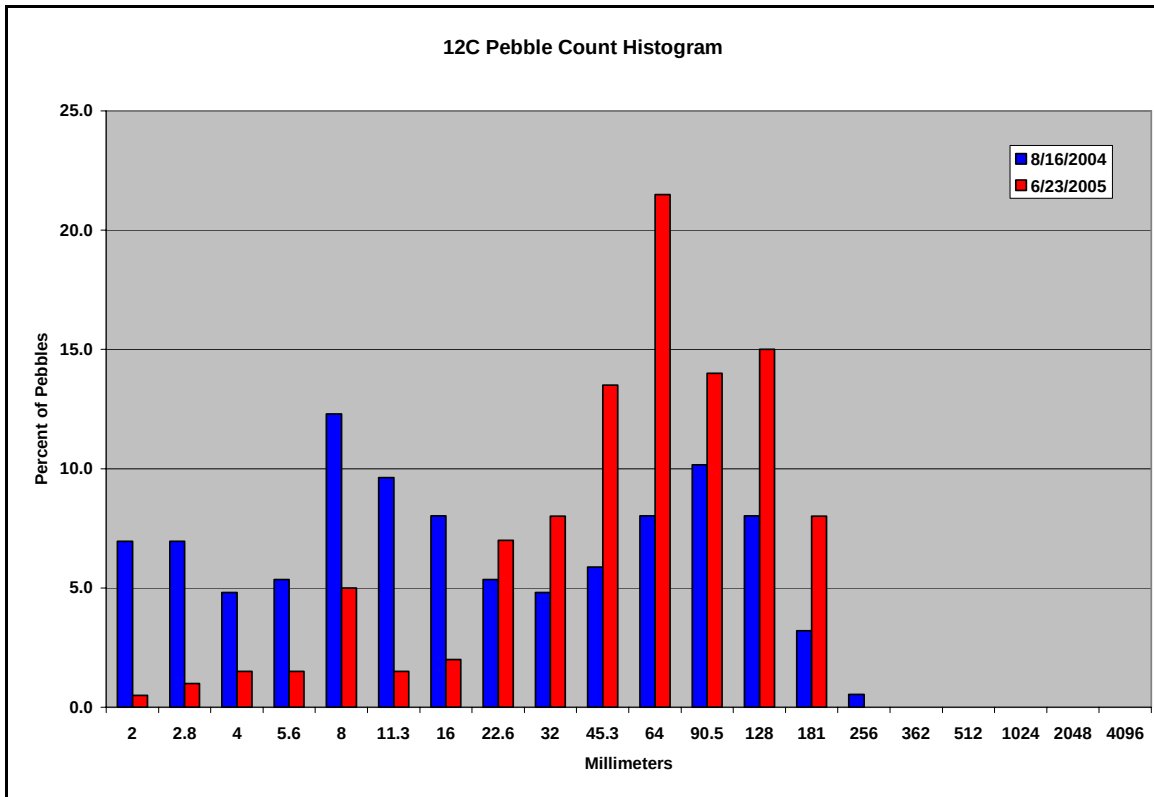




Cross-Section 12C

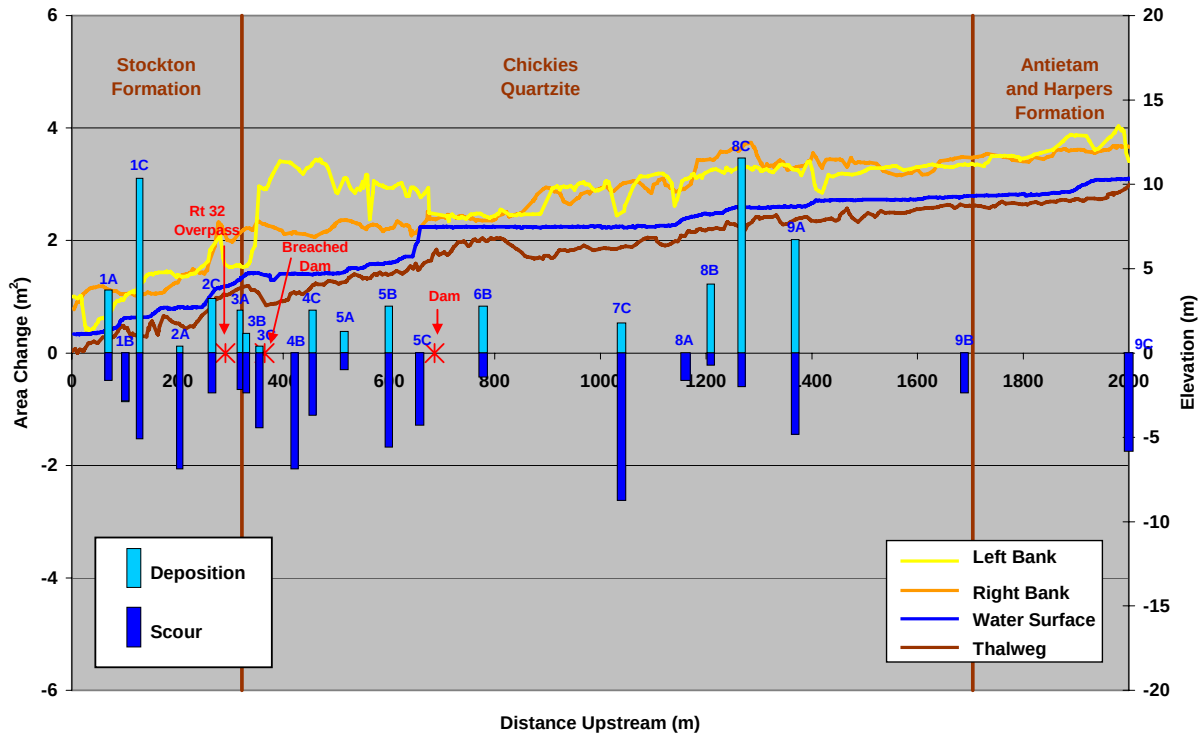




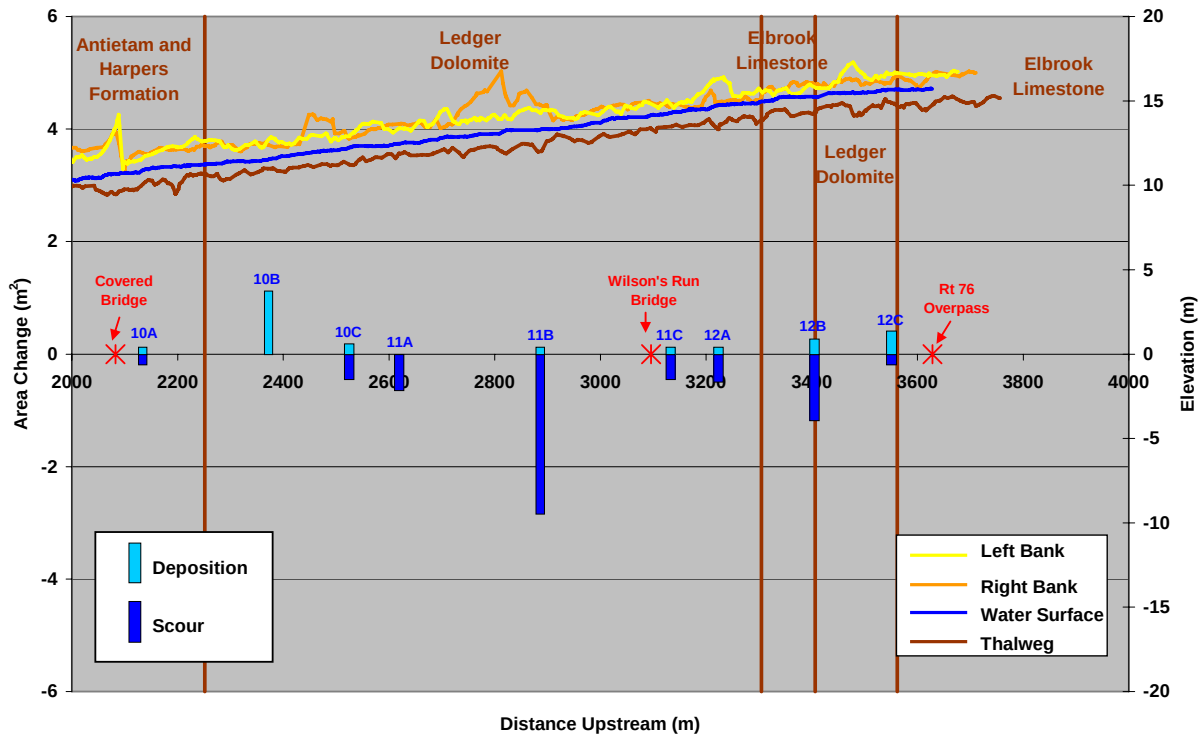


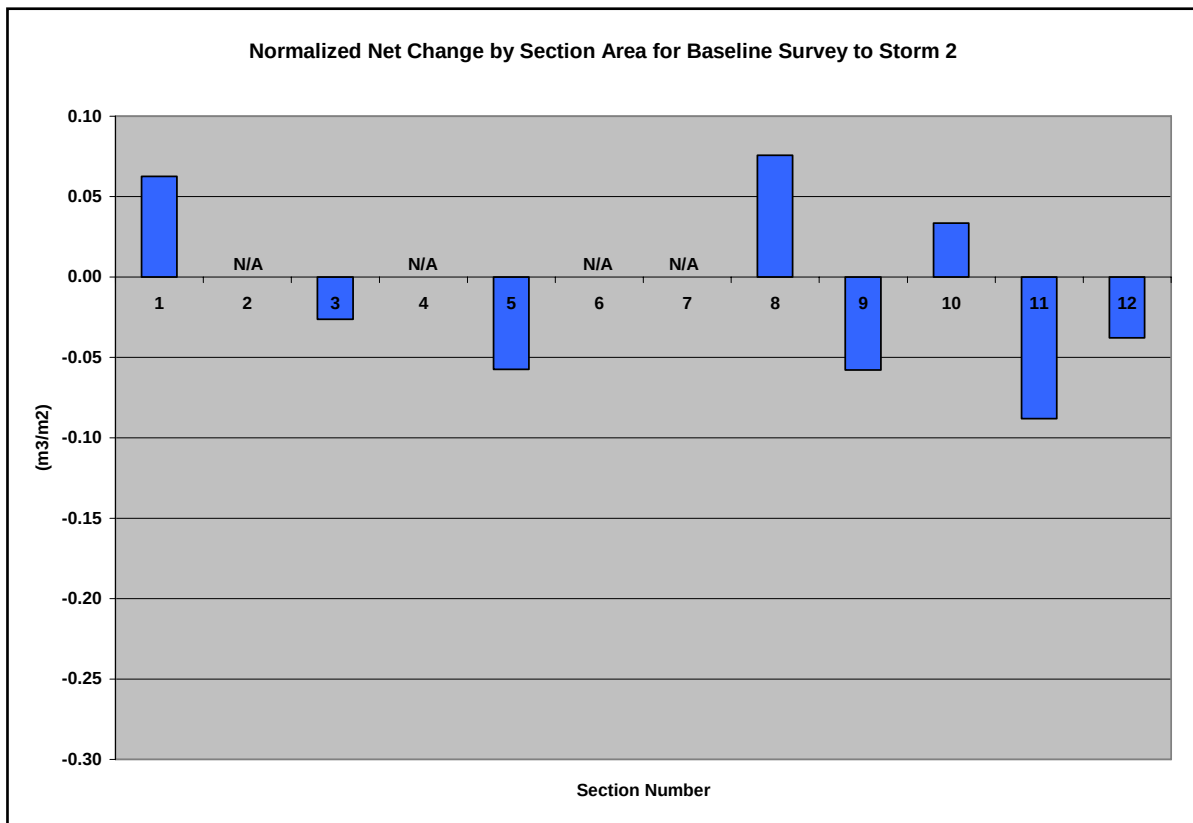
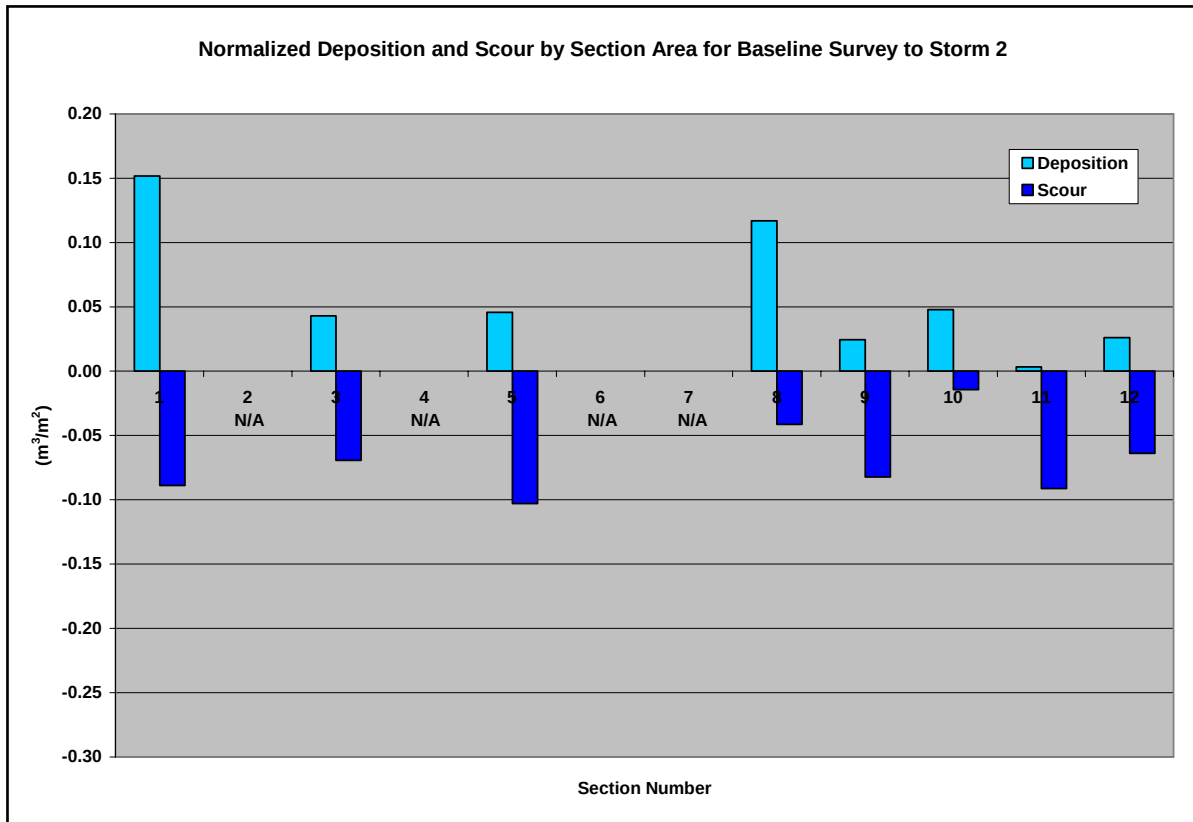
Appendix F. Valley Creek cross-section and reach analysis of change between the baseline survey in the summer of 2004 and the resurvey after the 2nd storm of September 28, 2004.

Total Scour and Deposition for Baseline to Storm 2



Total Scour and Deposition for Baseline to Storm 2





Appendix G. Calculations for the amount of sediment stored in the Valley Creek streambed within Valley Forge National Historical Park, summer 2004.

Reach ID	Volume of Maximum Scour (m ³)	% Clay and Silt (0.00045-0.063 mm)	Mass of Clay and Silt (metric tons)	% Very Fine Sand (0.063-0.075 mm)	Mass of Very Fine Sand (metric tons)	% Very Fine to Very Coarse Sand (0.075-2 mm)	Mass of Very Fine to Very Coarse Sand (metric tons)	% Very Fine to Medium Gravel (2-10 mm)	Mass of Very Fine to Medium Gravel (metric tons)	% Medium to Coarse Gravel (10-32 mm)	Mass of Medium to Coarse Gravel (metric tons)
1A	197.5	0.4	1.1	2.2	6.3	4.9	16.6	8.1	36.0	10.5	49.8
1B	185.6	2.1	5.2	4.1	11.1	12.8	40.9	26.4	110.3	27.1	120.7
1C	510.8	1.8	12.2	1.8	13.4	1.8	15.8	6.0	69.0	33.5	410.7
2A	306.5	1.2	4.9	0.0	0.0	11.3	59.6	23.6	162.8	15.4	113.3
2B	247.1	15.0	49.3	15.0	54.1	40.0	170.0	10.0	55.6	10.0	59.3
2C	121.7	15.0	24.3	15.0	26.7	40.0	83.7	10.0	27.4	10.0	29.2
3A	130.3	0.6	1.0	0.6	1.1	0.6	1.3	16.5	48.4	36.7	114.8
3B	79.9	0.6	0.6	0.6	0.7	0.6	0.8	16.5	29.7	36.7	70.4
3C	69.4	1.7	1.6	1.7	1.7	1.7	2.0	17.3	27.0	21.8	36.3
4A	363.5	15.0	72.5	15.0	79.6	40.0	250.1	10.0	81.8	10.0	87.2
4B	121.1	10.0	16.1	10.0	17.7	20.0	41.7	20.0	54.5	20.0	58.1
4C	238.0	10.0	31.7	10.0	34.8	20.0	81.9	20.0	107.1	20.0	114.3
5A	176.7	3.4	8.0	3.4	8.8	3.4	10.3	19.3	76.7	20.1	85.3
5B	404.9	0.0	0.0	0.0	0.0	0.0	0.0	4.7	42.8	14.2	138.0
5C	173.0	0.3	0.7	0.1	0.3	1.4	4.2	5.3	20.6	13.2	54.8
6A	1194.3	15.0	238.3	15.0	261.6	40.0	821.7	10.0	268.7	10.0	286.6
6B	941.7	0.9	11.3	0.1	1.4	1.9	30.8	2.6	55.1	8.7	196.6
6C	278.0	15.0	55.5	15.0	60.9	40.0	191.3	10.0	62.6	10.0	66.7
7A	178.4	15.0	35.6	15.0	39.1	40.0	122.8	10.0	40.1	10.0	42.8
7B	0.0	15.0	0.0	15.0	0.0	40.0	0.0	10.0	0.0	10.0	0.0
7C	352.7	15.0	70.4	15.0	77.2	40.0	242.6	10.0	79.3	10.0	84.6
8A	298.6	0.4	1.6	0.2	0.9	8.7	44.7	9.9	66.5	7.6	54.5
8B	144.6	0.2	0.4	0.1	0.2	2.0	5.0	3.0	9.8	11.7	40.6
8C	196.5	0.2	0.5	0.1	0.3	3.0	10.1	4.7	20.8	6.6	31.1
9A	618.6	0.8	6.6	0.2	1.8	11.4	121.3	19.3	268.6	7.3	108.4
9B	1095.5	0.7	10.2	0.1	1.6	7.4	139.4	15.6	384.5	27.5	723.0
9C	1317.6	0.3	5.3	0.3	5.8	0.3	6.8	2.0	59.3	2.0	63.2
10A	133.4	0.3	0.5	0.0	0.0	1.0	2.3	1.1	3.3	5.9	18.9
10B	232.7	1.6	5.0	0.1	0.3	8.0	32.0	11.1	58.1	17.9	100.0
10C	76.5	0.7	0.7	0.0	0.0	6.0	7.9	6.7	11.5	8.7	16.0
11A	475.8	0.8	5.1	4.8	33.3	15.5	126.8	16.1	172.4	40.6	463.6
11B	1964.1	1.2	31.3	0.4	11.5	11.0	371.6	28.9	1277.2	39.7	1871.4
11C	190.3	0.3	0.8	1.2	3.3	3.3	10.8	4.6	19.7	11.6	53.0
12A	229.5	0.5	1.5	1.5	5.0	4.0	15.8	3.7	19.1	16.5	90.9
12B	762.1	0.4	4.1	0.1	1.1	1.6	21.0	0.6	10.3	3.8	69.5
12C	275.7	0.5	1.8	0.1	0.4	29.6	140.3	21.2	131.5	7.5	49.6
Total Mass:			715.4		762.0		3244.0		3968.0		5973.2
Bulk Density Estimates Used*											
Clay and Silt				1.33	g/cm ³	(metric tons/m ³)					
Very Fine Sand				1.46	g/cm ³	(metric tons/m ³)					
Very Fine to Very Coarse Sand				1.72	g/cm ³	(metric tons/m ³)					
Very Fine to Medium Gravel				2.25	g/cm ³	(metric tons/m ³)					
Medium to Coarse Gravel				2.4	g/cm ³	(metric tons/m ³)					
Coarse Gravel to Cobbles and Boulders				2.65	g/cm ³	(metric tons/m ³)					
*Values taken from Smith and Wheatcraft (1993) Groundwater Flow, In: Handbook of Hydrology, D.R. Maidment (Ed), McGraw-Hill, New York											
	Barrel Sample Data										
	Pebble Count Data										
	Guess based on Qualitative Observations										

177

Change in the Mass of Sediment in the Streambed from Deposition.

Reach ID	Total Scour (m ³)	% Clay and Silt	Mass of Clay and Silt (metric tons)	% Very Fine Sand (0.063-	Mass of Very Fine Sand (metric tons)	% Very Fine to Very Coarse Sand (0.075-2	Mass of Very Fine to Very Coarse Sand (metric tons)	% Very Fine to Medium Gravel (2-	Mass of Very Fine to Medium Gravel (metric tons)	% Medium to Coarse Gravel (10-32 mm)	Mass of Medium to Coarse Gravel (metric tons)
		(0.00045- 0.063 mm)		0.075 mm)		mm)		mm)		tons)	
1A	36.42	1.5	0.7	1.5	0.8	1.5	0.9	11.1	9.1	15.3	13.4
1B	30.81	1.1	0.5	1.1	0.5	1.1	0.6	20.0	13.9	13.7	10.1
1C	74.62	1.2	1.2	1.2	1.3	1.2	1.5	16.7	28.0	22.6	40.5
2A	128.24	3.2	5.5	3.2	6.0	3.2	7.1	16.2	46.7	13.3	40.9
2B	153.72	15.0	30.7	15.0	33.7	40.0	105.8	10.0	34.6	10.0	36.9
2C	29.86	15.0	6.0	15.0	6.5	40.0	20.5	10.0	6.7	10.0	7.2
3A	18.57	0.0	0.0	0.0	0.0	0.0	0.0	8.6	3.6	16.3	7.3
3B	11.80	0.0	0.0	0.0	0.0	0.0	0.0	8.6	2.3	16.3	4.6
3C	10.71	0.0	0.0	0.0	0.0	0.0	0.0	24.4	5.9	15.8	4.1
4A	263.78	15.0	52.6	15.0	57.8	40.0	181.5	10.0	59.3	10.0	63.3
4B	71.65	10.0	9.5	10.0	10.5	20.0	24.6	20.0	32.2	20.0	34.4
4C	74.09	10.0	9.9	10.0	10.8	20.0	25.5	20.0	33.3	20.0	35.6
5A	56.54	4.7	3.5	4.7	3.9	4.7	4.6	20.0	25.4	30.9	41.9
5B	153.77	1.3	2.7	1.3	2.9	1.3	3.4	12.6	43.6	11.5	42.4
5C	41.83	0.3	0.2	0.1	0.1	1.5	1.1	5.7	5.4	7.6	7.6
6A	136.41	15.0	27.2	15.0	29.9	40.0	93.9	10.0	30.7	10.0	32.7
6B	30.43	1.9	0.8	0.3	0.1	2.4	1.3	2.0	1.4	9.8	7.2
6C	86.57	15.0	17.3	15.0	19.0	40.0	59.6	10.0	19.5	10.0	20.8
7A	51.08	15.0	10.2	15.0	11.2	40.0	35.1	10.0	11.5	10.0	12.3
7B	1.25	15.0	0.2	15.0	0.3	40.0	0.9	10.0	0.3	10.0	0.3
7C	182.32	15.0	36.4	15.0	39.9	40.0	125.4	10.0	41.0	10.0	43.8
8A	34.82	2.0	0.9	0.5	0.3	11.1	6.6	17.0	13.3	8.9	7.4
8B	23.16	1.5	0.5	0.2	0.1	6.8	2.7	16.2	8.4	16.8	9.3
8C	39.95	0.9	0.5	0.2	0.1	1.1	0.8	0.7	0.6	0.6	0.6
9A	109.28	1.0	1.5	0.2	0.3	9.8	18.4	13.8	33.9	8.3	21.8
9B	310.80	1.0	4.1	0.5	2.3	13.9	74.3	24.0	167.8	23.8	177.5
9C	486.07	0.3	1.9	0.3	2.1	0.3	2.5	2.0	21.9	2.0	23.3
10A	32.07	0.4	0.2	0.1	0.0	2.5	1.4	4.5	3.2	12.7	9.8
10B	61.76	0.6	0.5	0.3	0.3	1.2	1.3	5.5	7.6	26.4	39.1
10C	27.08	1.1	0.4	0.2	0.1	5.6	2.6	8.1	4.9	11.5	7.5
11A	194.86	0.8	2.1	0.3	0.9	15.8	53.0	13.4	58.8	8.9	41.6
11B	542.42	1.1	7.9	0.2	1.6	14.3	133.4	18.2	222.1	20.5	266.9
11C	91.18	1.4	1.7	0.3	0.4	18.0	28.2	27.7	56.8	25.4	55.6
12A	43.81	0.9	0.5	0.1	0.1	2.3	1.7	7.7	7.6	16.1	16.9
12B	374.21	1.0	5.0	0.3	1.6	2.5	16.1	3.0	25.3	7.5	67.4
12C	119.81	1.8	2.9	0.3	0.5	2.0	4.1	3.7	10.0	10.3	29.6
Total Mass:			245.4		245.7		1040.4		1096.9		1281.5
Bulk Density Estimates Used*											
Clay and Silt				1.33	g/cm ³	(metric tons/m ³)					
Very Fine Sand				1.46	g/cm ³	(metric tons/m ³)					
Very Fine to Very Coarse Sand				1.72	g/cm ³	(metric tons/m ³)					
Very Fine to Medium Gravel				2.25	g/cm ³	(metric tons/m ³)					
Medium to Coarse Gravel				2.4	g/cm ³	(metric tons/m ³)					
Coarse Gravel to Cobbles and Boulders				2.65	g/cm ³	(metric tons/m ³)					
*Values taken from Smith and Wheatcraft (1993) Groundwater Flow, In: Handbook of Hydrology, D.R. Maidment (Ed), McGraw-Hill, New York											

Change in the Mass of Sediment in the Streambed from Scour

Appendix I. Photographs from Valley Creek bank erosion locations identified in Figure 26.



Erosion Location 1 (November 1, 2003)



Erosion Location 2 (November 1, 2003)



Erosion Location 3 (November 8, 2003)



Erosion Location 4A (November 8, 2003)



Erosion Location 5 (November 8, 2003)



Erosion Location 6 (December 13, 2003)



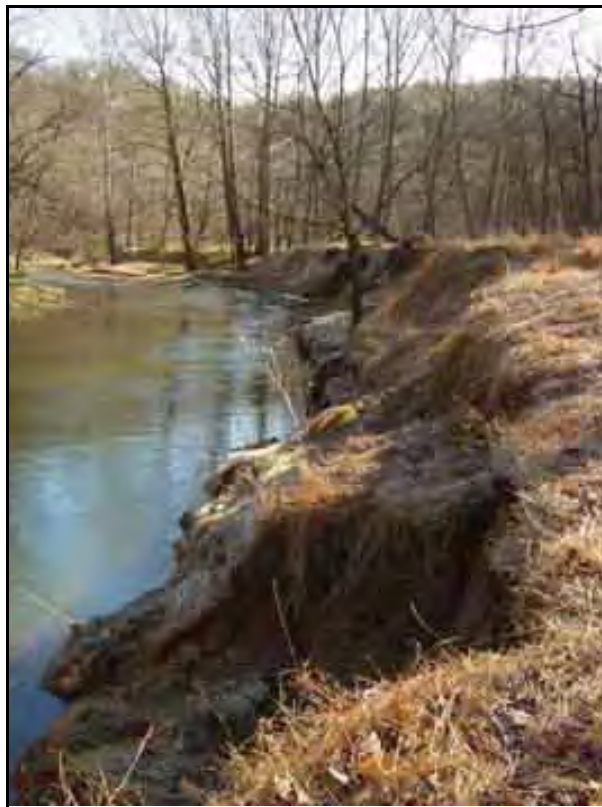
Erosion Location 7 (December 13, 2003)



Erosion Location 8 (December 13, 2003)



Erosion Location 9 (December 13, 2003)



Erosion Location 10 (December 13, 2003)



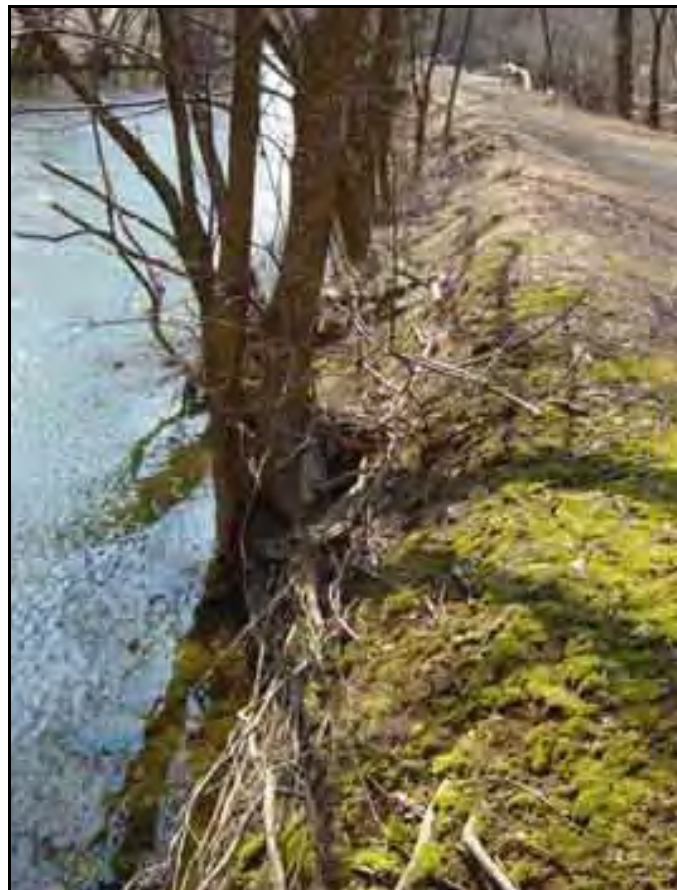
Erosion Location 11 (December 13, 2003)



Erosion Location 12 (December 13, 2003)



Erosion Location 13 (December 13, 2003)



Erosion Location 14 (December 20, 2003)



Erosion Location 15 December 20, 2003)



Erosion Location 16 (December 20, 2003)



Erosion Location 17 (December 20, 2003)



Erosion Location 18 (December 20, 2003)



Erosion Location 19 (December 20, 2003)



Erosion Location 20 (December 20, 2003)



Erosion Location 21 (December 20, 2003)



Erosion Location 22 (February 20, 2004)



Erosion Location 23 (February 20, 2004)



Erosion Location 24 (February 20, 2004)



Erosion Location 25 (February 20, 2004)



Erosion Location 26 (February 20, 2004)



Erosion Location 27 (February 20, 2004)



Erosion Location 28 (February 20, 2004)



Erosion Location 29 (February 20, 2004)



Erosion Location 30 (April 3, 2004)



Erosion Location 31 (April 3, 2004)



Erosion Location 32 (April 3, 2004)



Erosion Location 33 (April 3, 2004)



Erosion Location 34 (April 3, 2004)



Erosion Location 35 (April 4, 2004)



Erosion Location 36 (April 4, 2004)

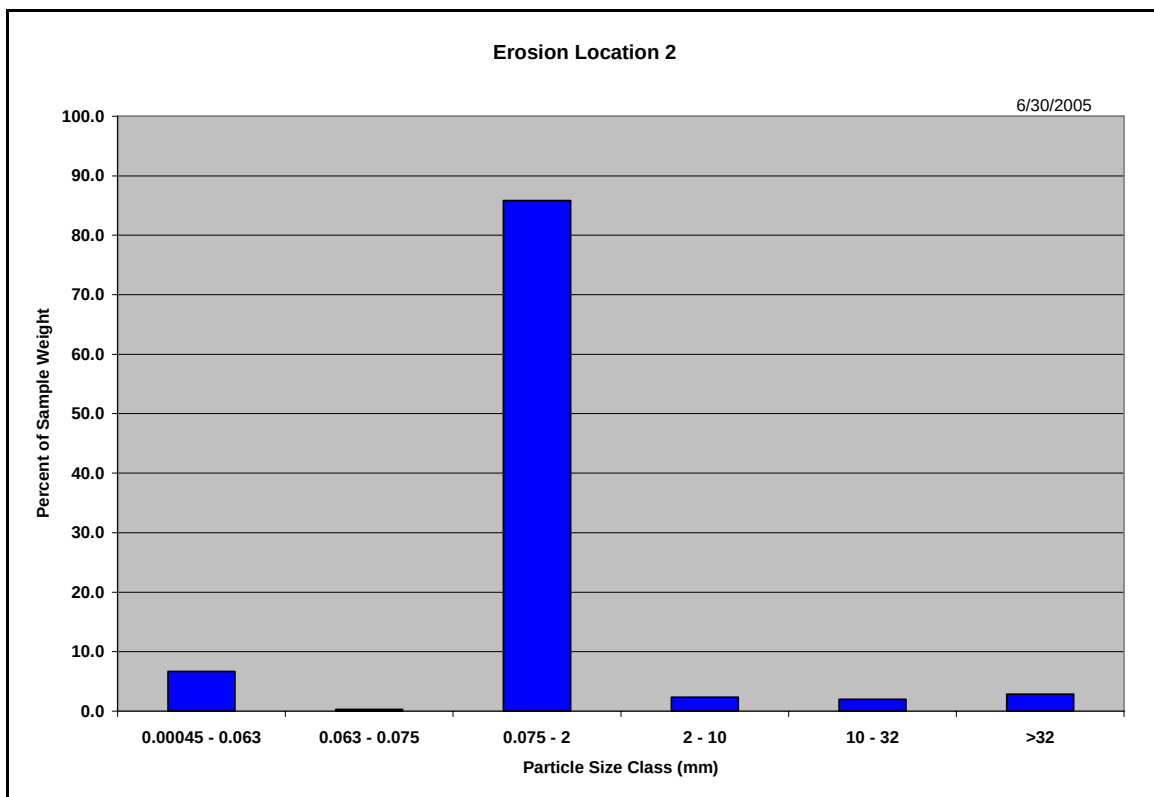
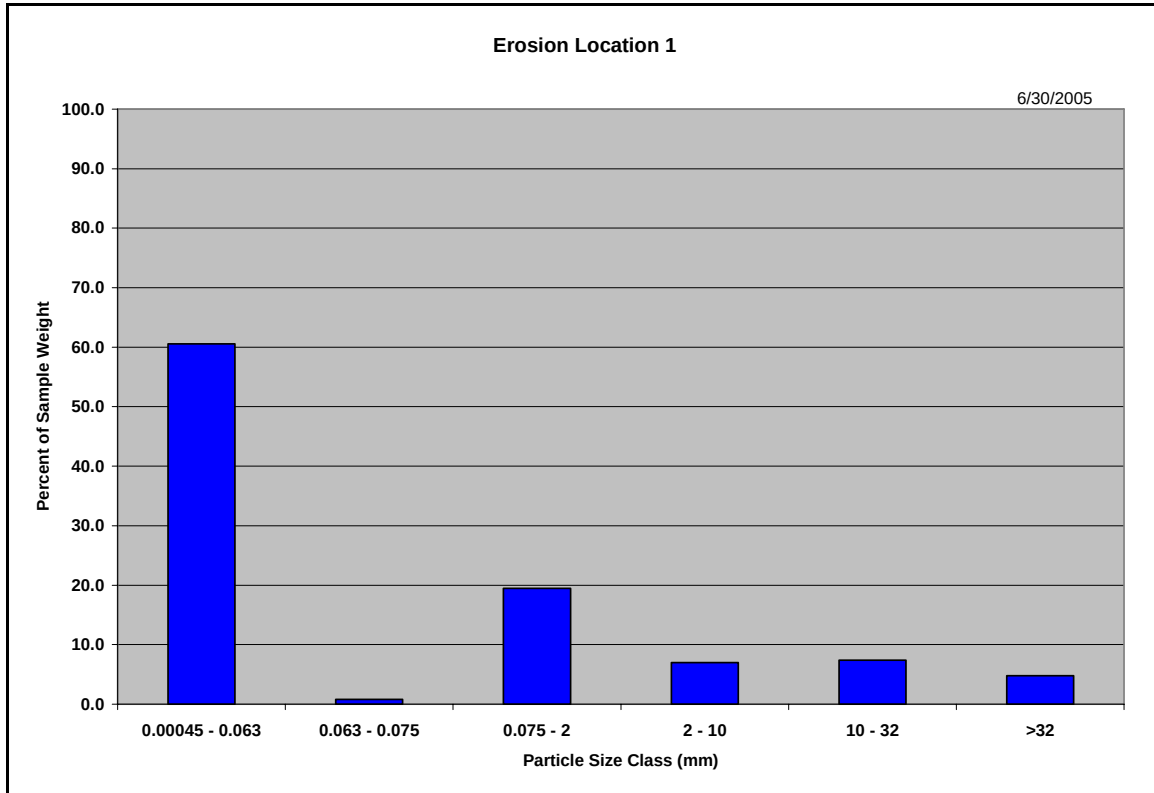


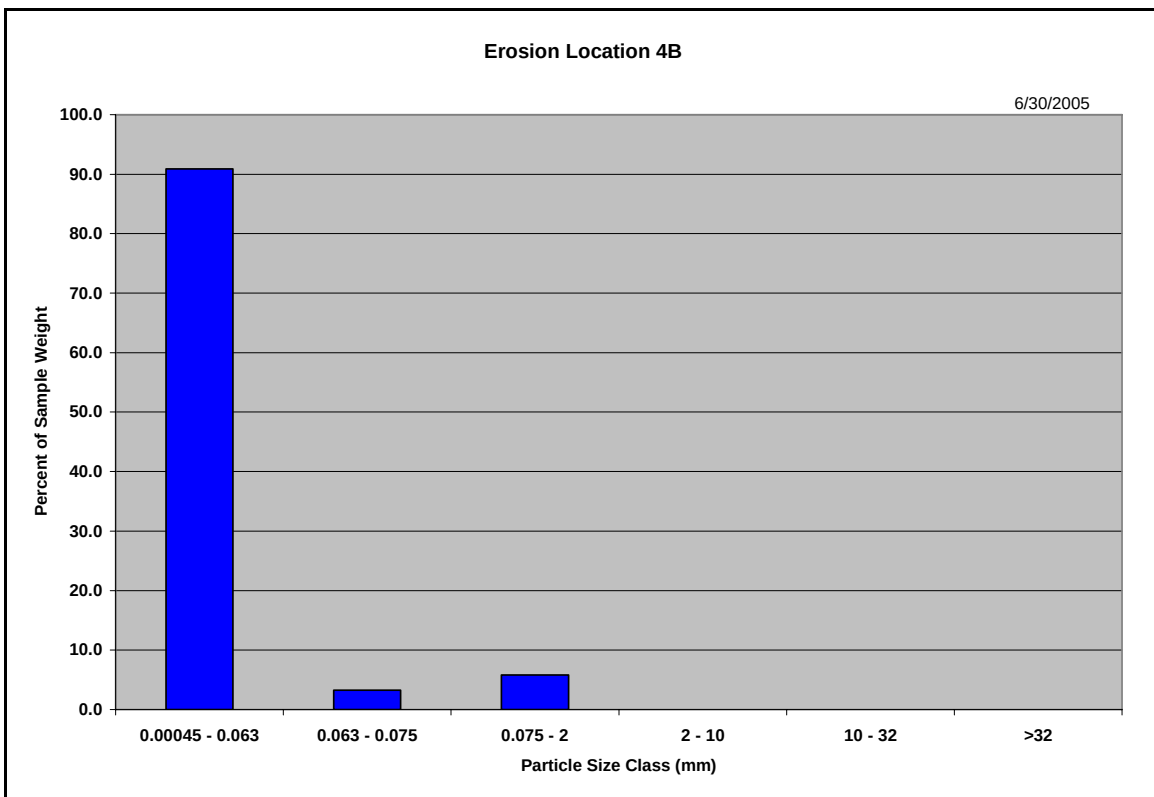
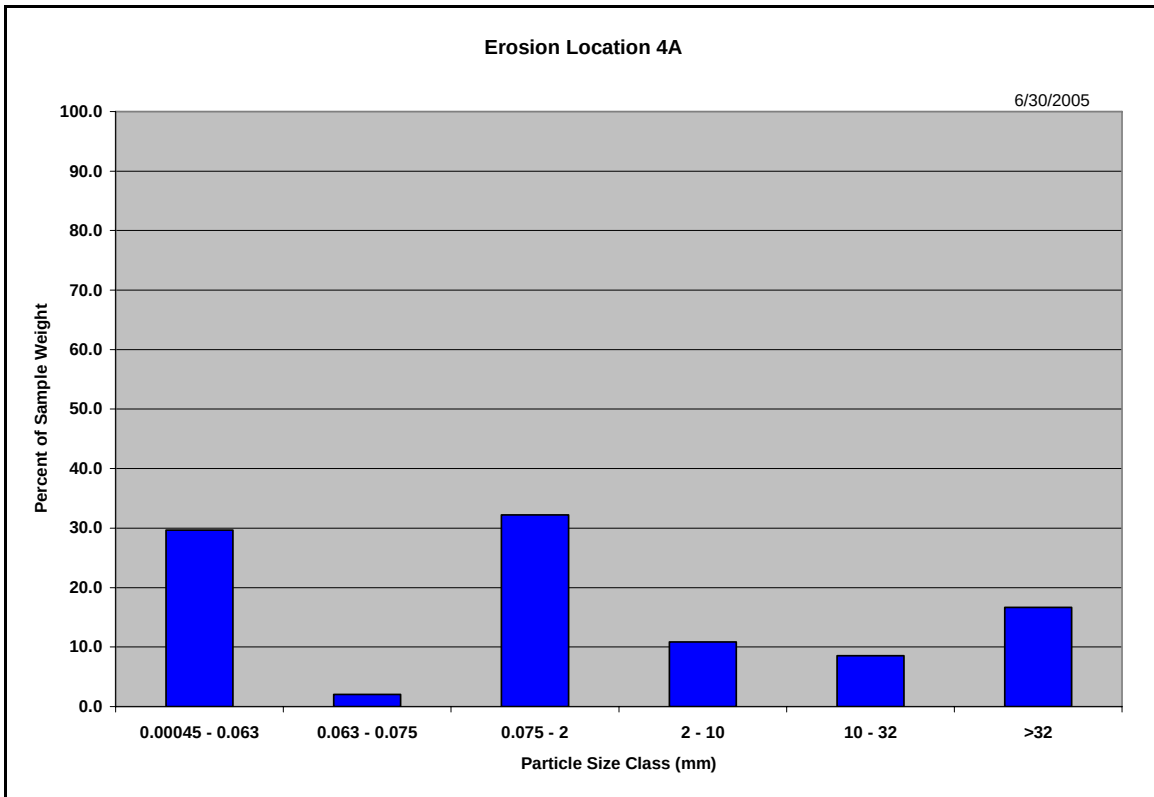
Erosion Location 37 (April 4, 2004)

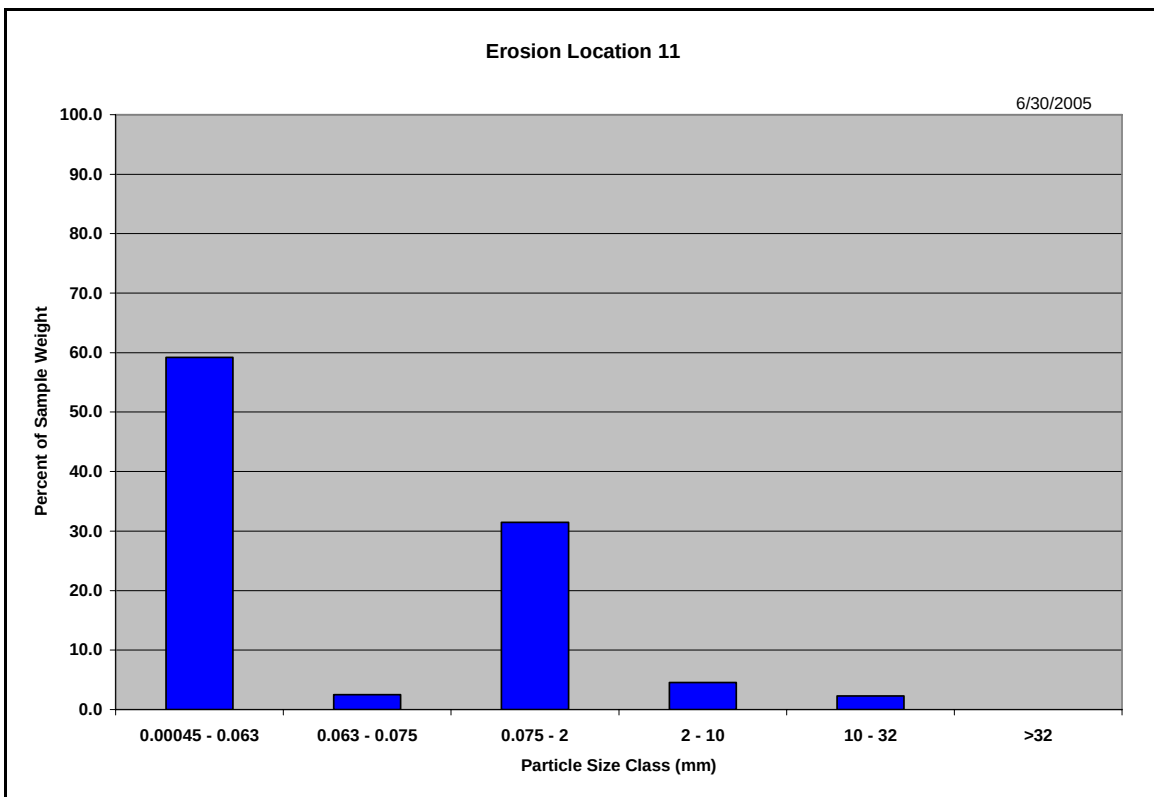
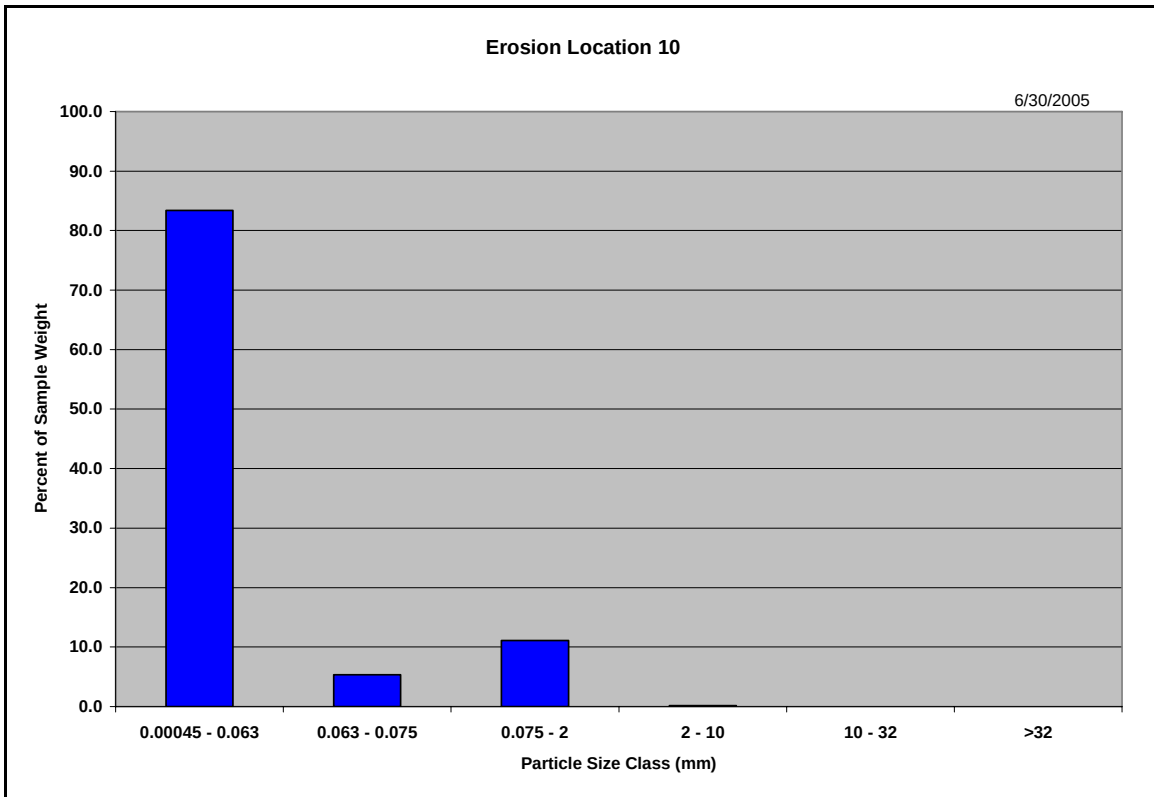


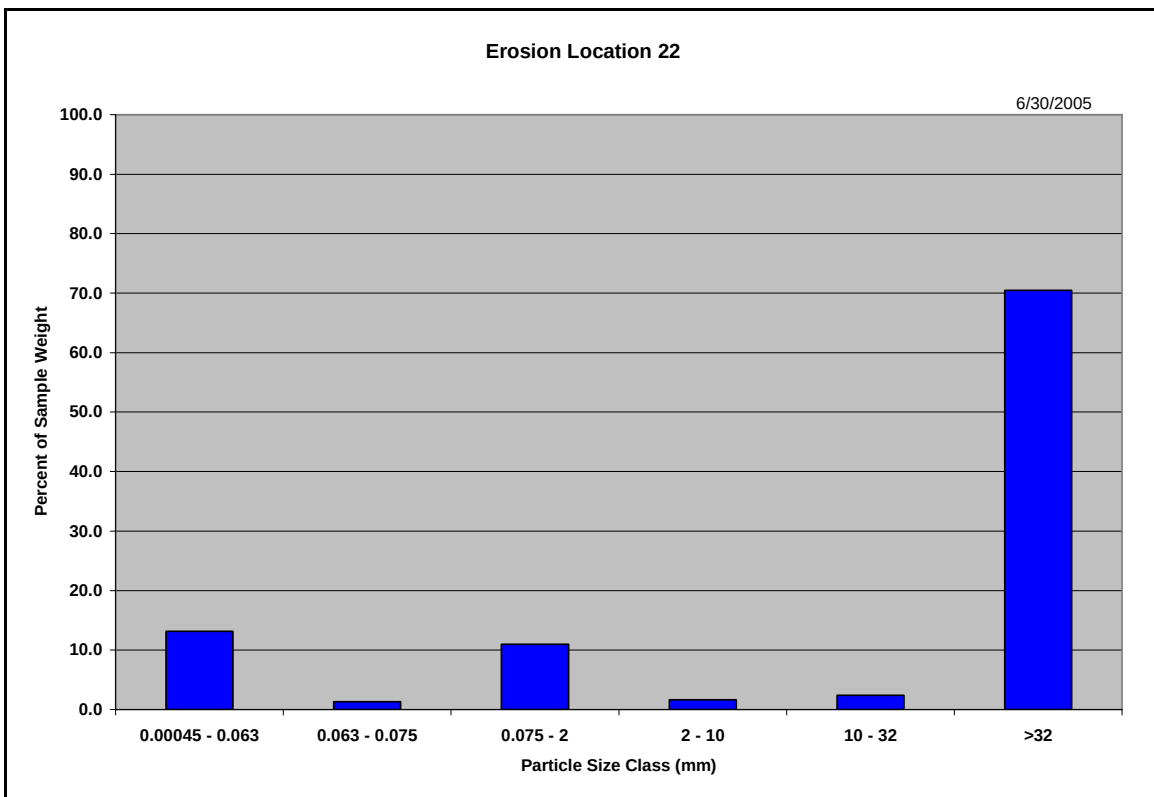
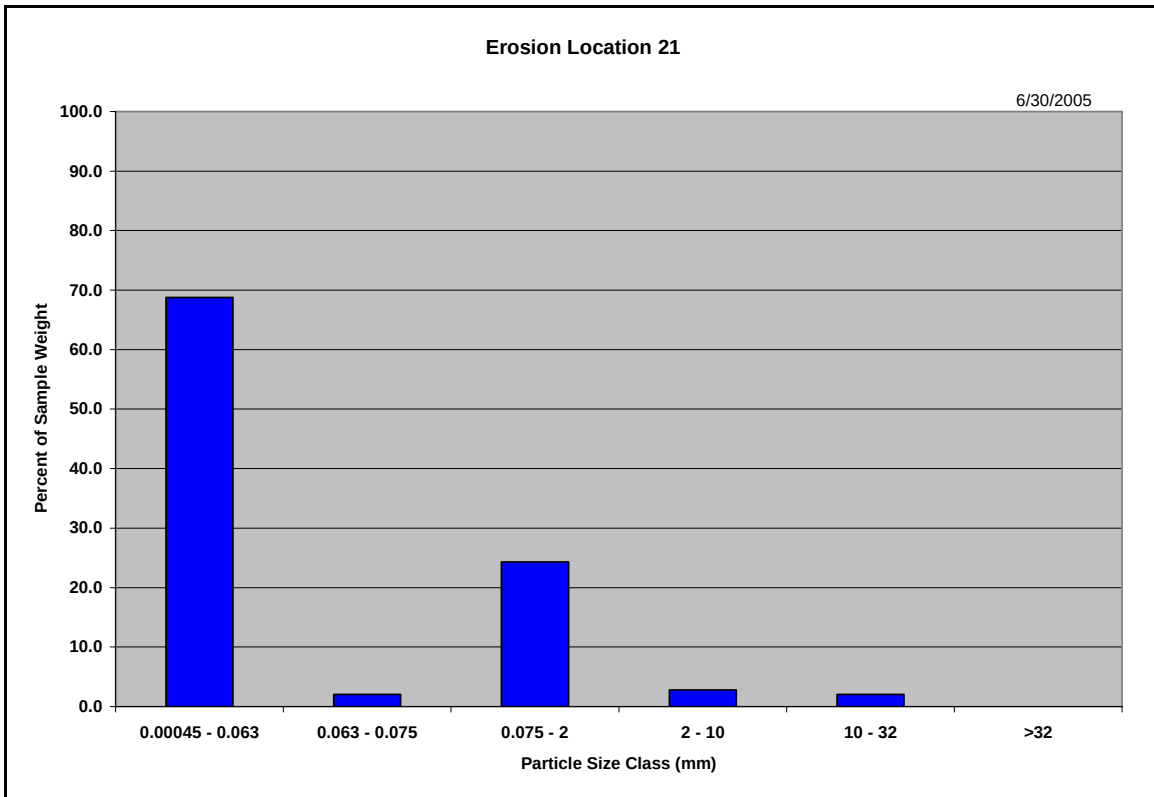
Erosion Location 38 (April 4, 2004)

Appendix J. Particle size distributions of bank material at the 10 Valley Creek bankline survey locations on June 30, 2005.









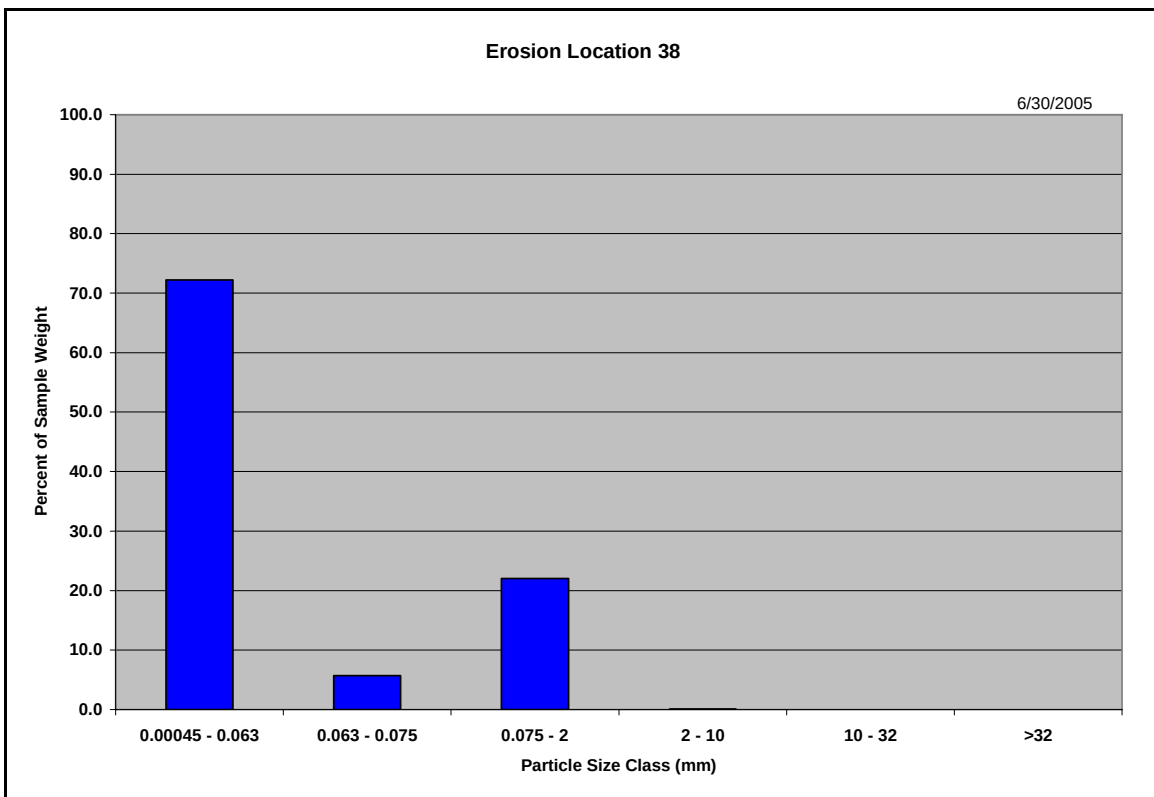
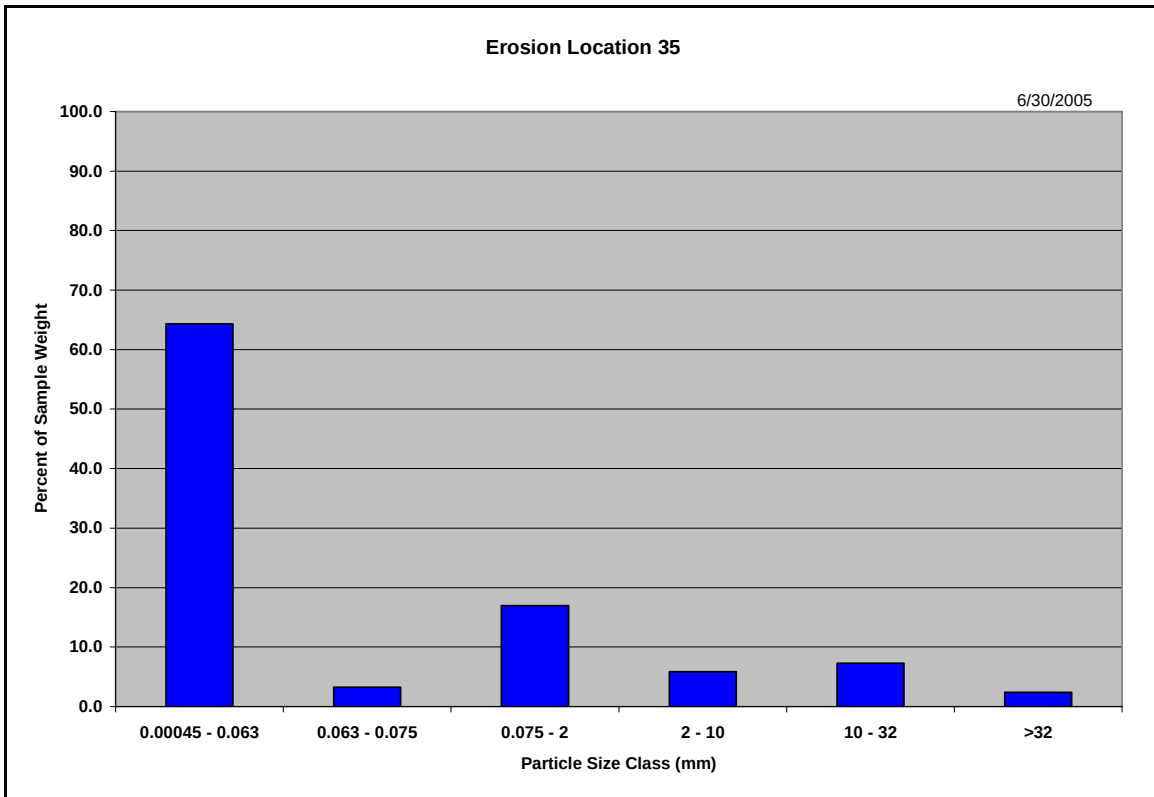


Table J1. Particle size distribution of bank material at erosion location 1 on June 30, 2005.

Particle Size Class (mm)	Mass (g) ¹	Percentage of Total Mass
0.00045–0.063	3445.042	60.5
0.063–0.075	45.000	0.8
0.075–2	1108.0	19.5
2–10	399.6	7.0
10–32	422.1	7.4
>32	271.6	4.8

¹ Mass (g): Particle sizes within the 0.00045 – 0.075 range were measured to an accuracy of 0.001g and particle sizes > 0.075 were measured to an accuracy of 0.1g.

Table J2. Particle size distribution of bank material at erosion location 2 on June 30, 2005.

Particle Size Class (mm)	Mass (g) ¹	Percentage of Total Mass
0.00045–0.063	0.000	6.7
0.063–0.075	6.593	0.3
0.075–2	1883.1	85.8
2–10	51.5	2.3
10–32	44.2	2.0
>32	62.6	2.9

¹ Mass (g): Particle sizes within the 0.00045 – 0.075 range were measured to an accuracy of 0.001g and particle sizes > 0.075 were measured to an accuracy of 0.1g.

Table J3. Particle size distribution of bank material at erosion location 4A on June 30, 2005.

Particle Size Class (mm)	Mass (g) ¹	Percentage of Total Mass
0.00045–0.063	784.960	29.6
0.063–0.075	54.700	2.1
0.075–2	853.7	32.2
2–10	287.7	10.9
10–32	226.8	8.6
>32	441.7	16.7

¹ Mass (g): Particle sizes within the 0.00045–0.075 range were measured to an accuracy of 0.001g and particle sizes > 0.075 were measured to an accuracy of 0.1g.

Table J4. Particle size distribution of bank material at erosion location 4B on June 30, 2005.

Particle Size Class (mm)	Mass (g) ¹	Percentage of Total Mass
0.00045–0.063	996.266	90.9
0.063–0.075	35.673	3.3
0.075–2	63.8	5.8
2–10	0.0	0.0
10–32	0.0	0.0
>32	0.0	0.0

¹ Mass (g): Particle sizes within the 0.00045 – 0.075 range were measured to an accuracy of 0.001g and particle sizes > 0.075 were measured to an accuracy of 0.1g.

Table J5. Particle size distribution of bank material at erosion location 10 on June 30, 2005.

Particle Size Class (mm)	Mass (g) ¹	Percentage of Total Mass
0.00045–0.063	6264.262	83.4
0.063–0.075	402.300	5.4
0.075–2	834.2	11.1
2–10	10.8	0.1
10–32	0.0	0.0
>32	0.0	0.0

¹ Mass (g): Particle sizes within the 0.00045 – 0.075 range were measured to an accuracy of 0.001g and particle sizes > 0.075 were measured to an accuracy of 0.1g.

Table J6. Particle size distribution of bank material at erosion location 11 on June 30, 2005.

Particle Size Class (mm)	Mass (g) ¹	Percentage of Total Mass
0.00045–0.063	1028.794	59.2
0.063–0.075	43.300	2.5
0.075–2	547.5	31.5
2–10	78.7	4.5
10–32	39.9	2.3
>32	0.0	0.0

¹ Mass (g): Particle sizes within the 0.00045 – 0.075 range were measured to an accuracy of 0.001g and particle sizes > 0.075 were measured to an accuracy of 0.1g.

Table J7. Particle size distribution of bank material at erosion location 21 on June 30, 2005.

Particle Size Class (mm)	Mass (g) ¹	Percentage of Total Mass
0.00045–0.063	2898.450	68.8
0.063–0.075	87.500	2.1
0.075–2	1025.7	24.3
2–10	117.3	2.8
10–32	86.8	2.1
>32	0.0	0.0

¹ Mass (g): Particle sizes within the 0.00045 – 0.075 range were measured to an accuracy of 0.001g and particle sizes > 0.075 were measured to an accuracy of 0.1g.

Table J8. Particle size distribution of bank material at erosion location 22 on June 30, 2005.

Particle Size Class (mm)	Mass (g) ¹	Percentage of Total Mass
0.00045–0.063	464.646	13.2
0.063–0.075	46.200	1.3
0.075–2	387.4	11.0
2–10	58.7	1.7
10–32	85.3	2.4
>32	2486.0	70.5

¹ Mass (g): Particle sizes within the 0.00045 – 0.075 range were measured to an accuracy of 0.001g and particle sizes > 0.075 were measured to an accuracy of 0.1g.

Table J9. Particle size distribution of bank material at erosion location 35 on June 30, 2005.

Particle Size Class (mm)	Mass (g) ¹	Percentage of Total Mass
0.00045–0.063	3260.664	64.3
0.063–0.075	163.800	3.2
0.075–2	859.4	17.0
2–10	296.7	5.9
10–32	368.1	7.3
>32	119.8	2.4

¹ Mass (g): Particle sizes within the 0.00045 – 0.075 range were measured to an accuracy of 0.001g and particle sizes > 0.075 were measured to an accuracy of 0.1g.

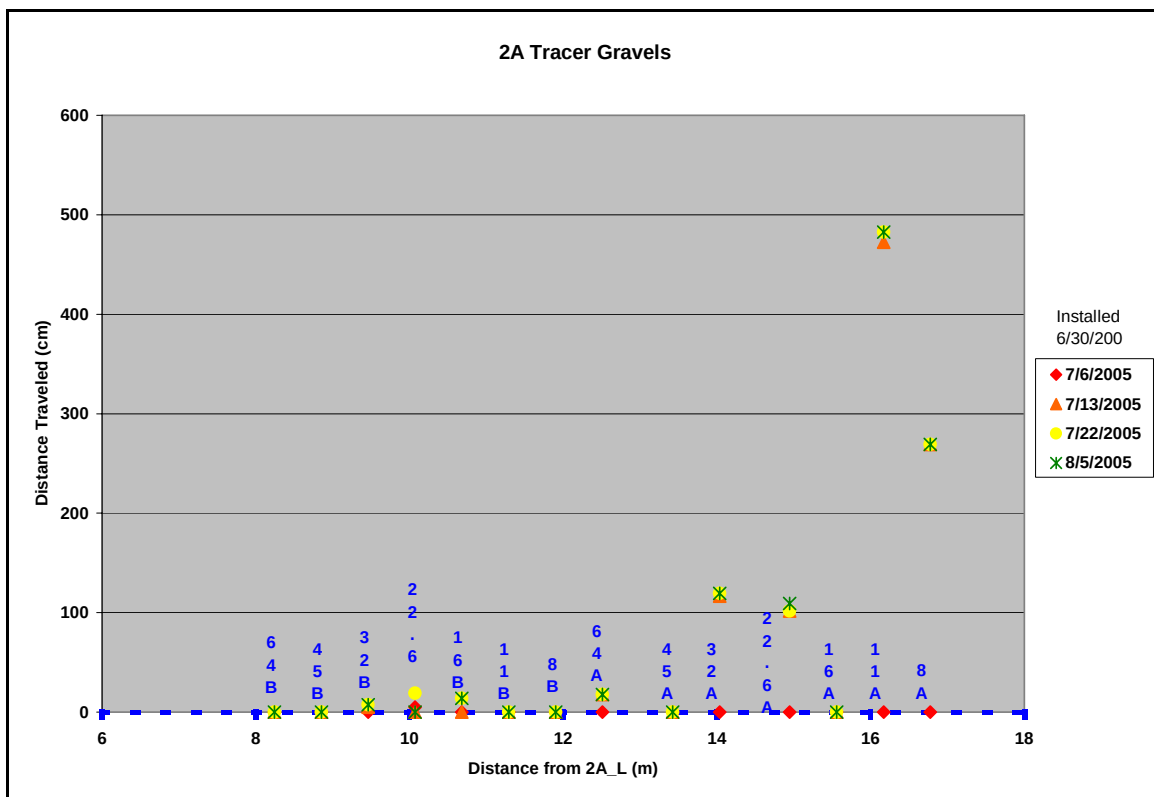
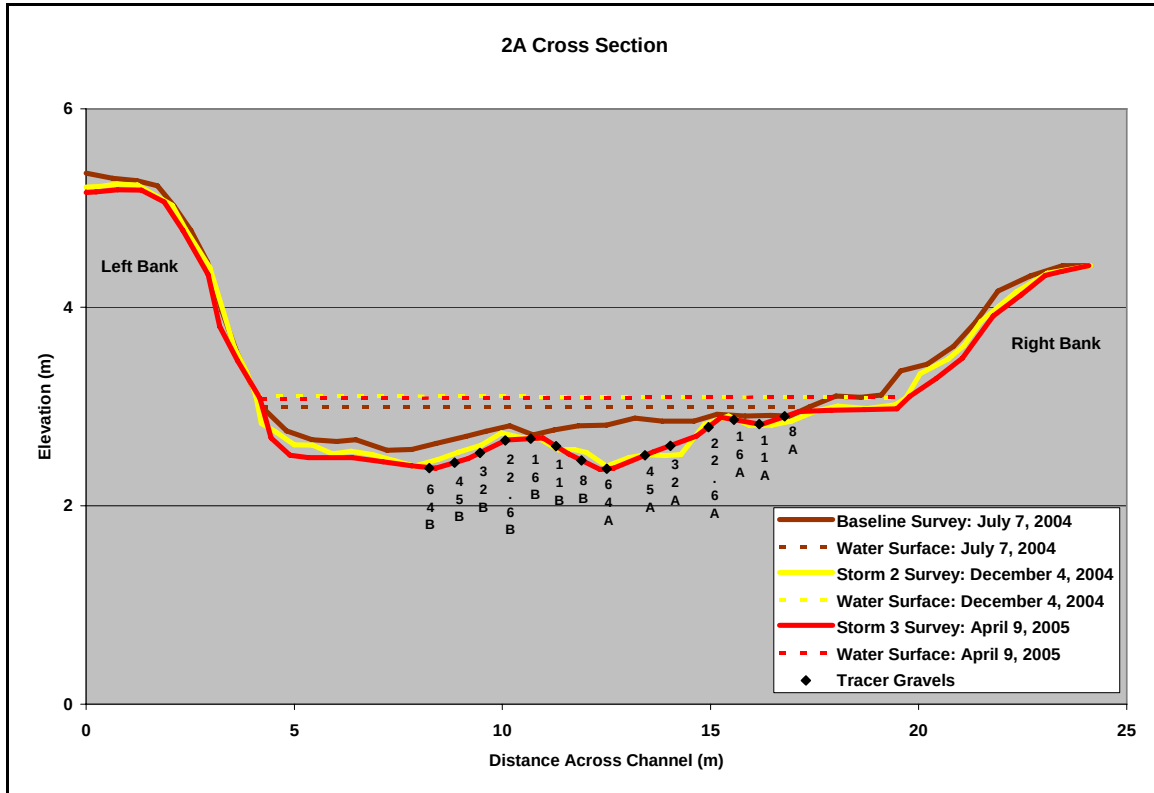
Table J10. Particle size distribution of bank material at erosion location 38 on June 30, 2005.

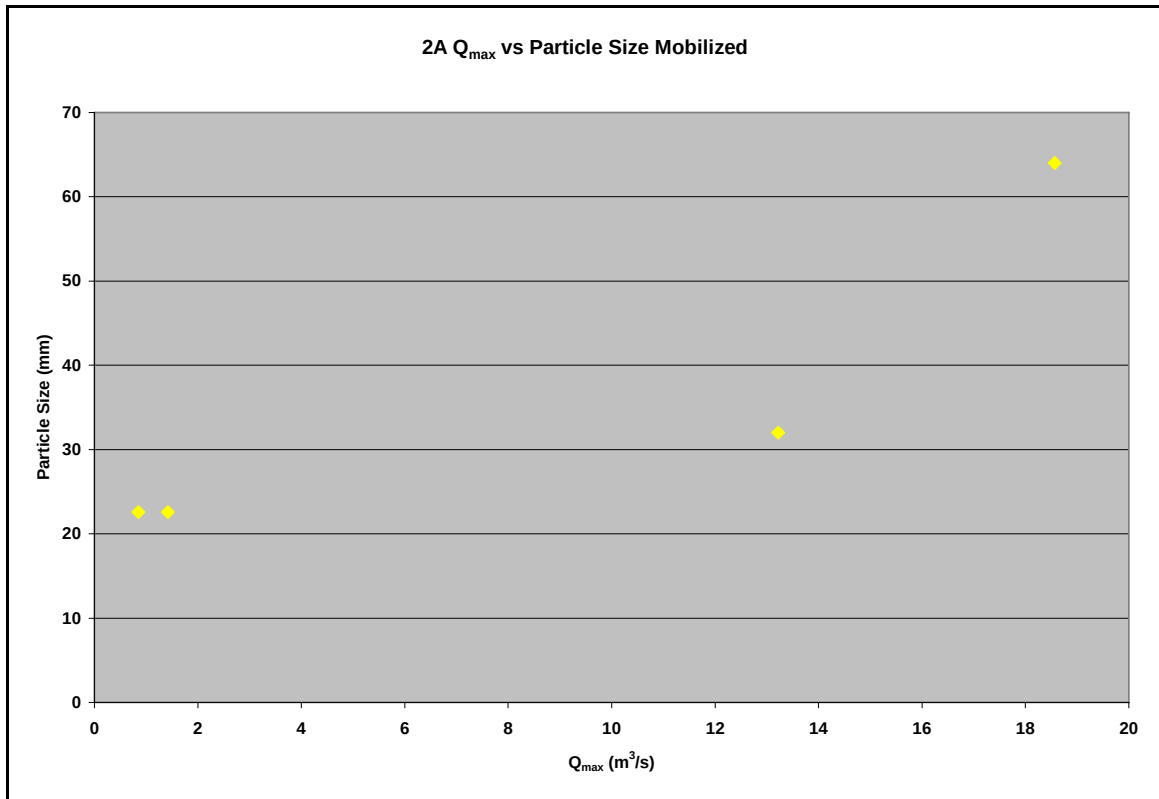
Particle Size Class (mm)	Mass (g) ¹	Percentage of Total Mass
0.00045–0.063	505.886	72.2
0.063–0.075	40.000	5.7
0.075–2	154.1	22.0
2–10	0.5	0.1
10–32	0.0	0.0
>32	0.0	0.0

¹ Mass (g): Particle sizes within the 0.00045–0.075 range were measured to an accuracy of 0.001g and particle sizes > 0.075 were measured to an accuracy of 0.1g.

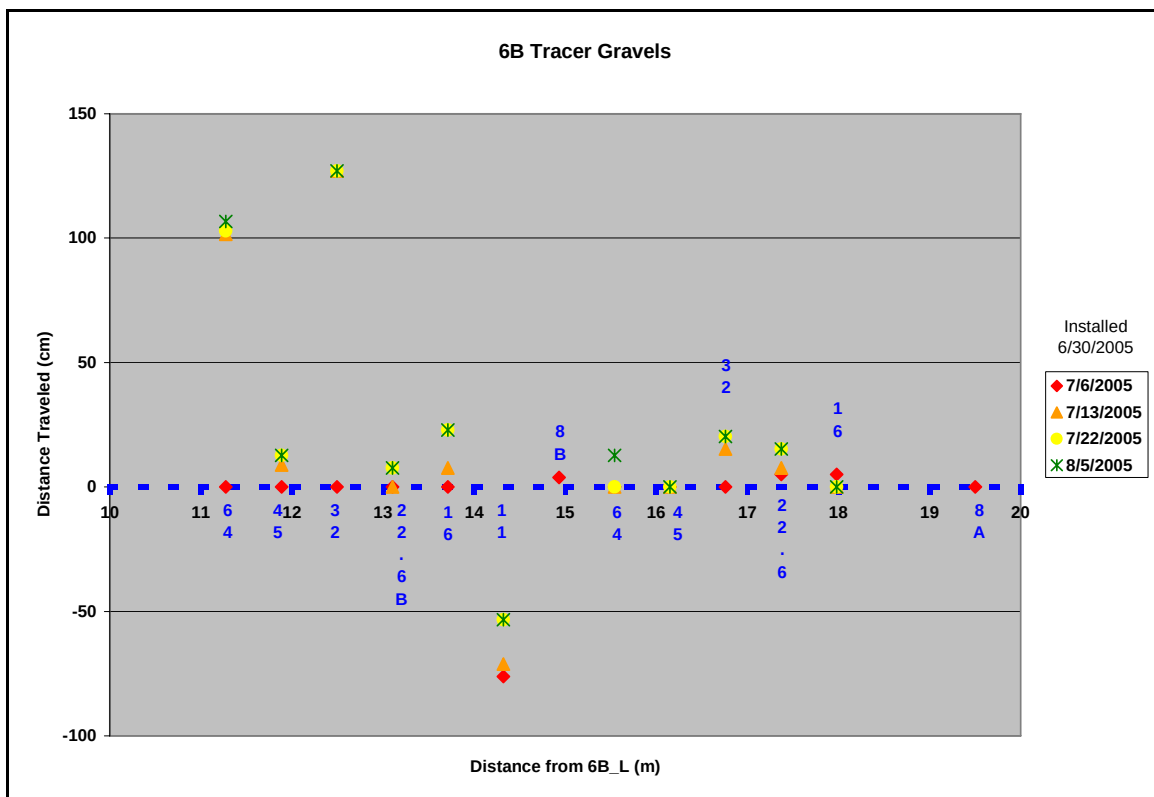
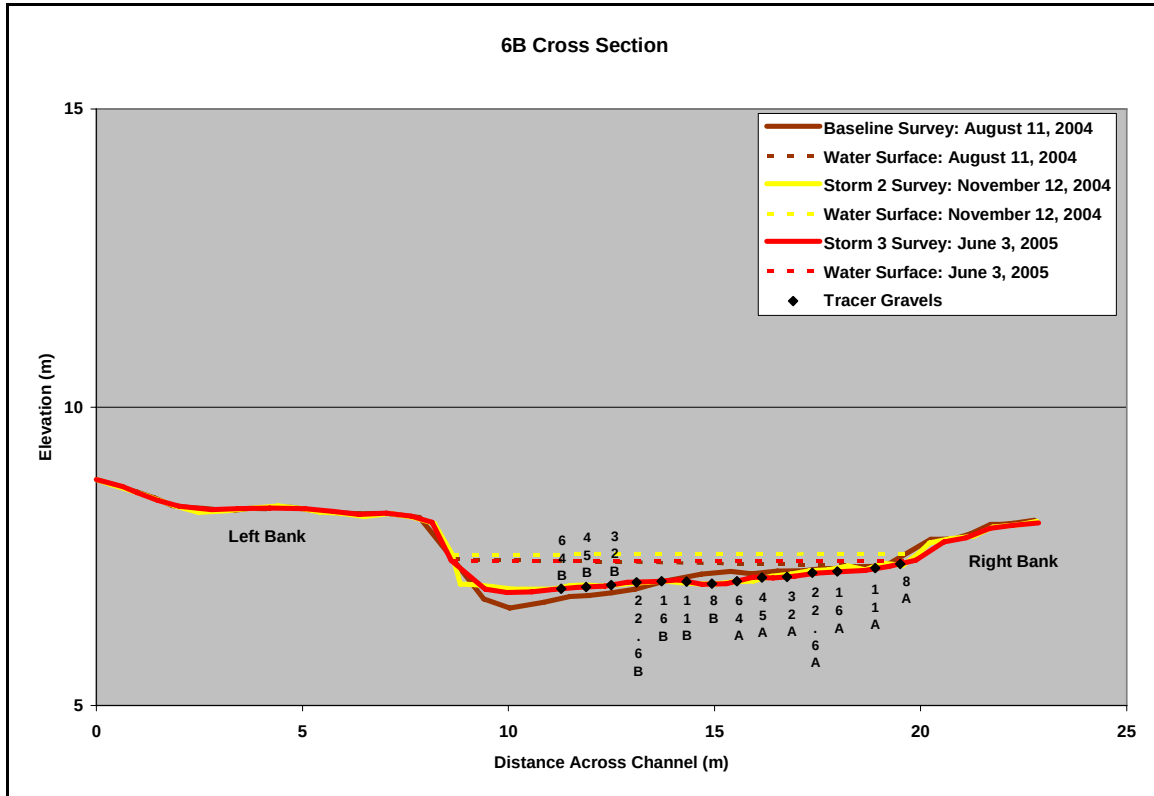
Appendix K. Tracer gravel data for Valley Creek cross-sections.

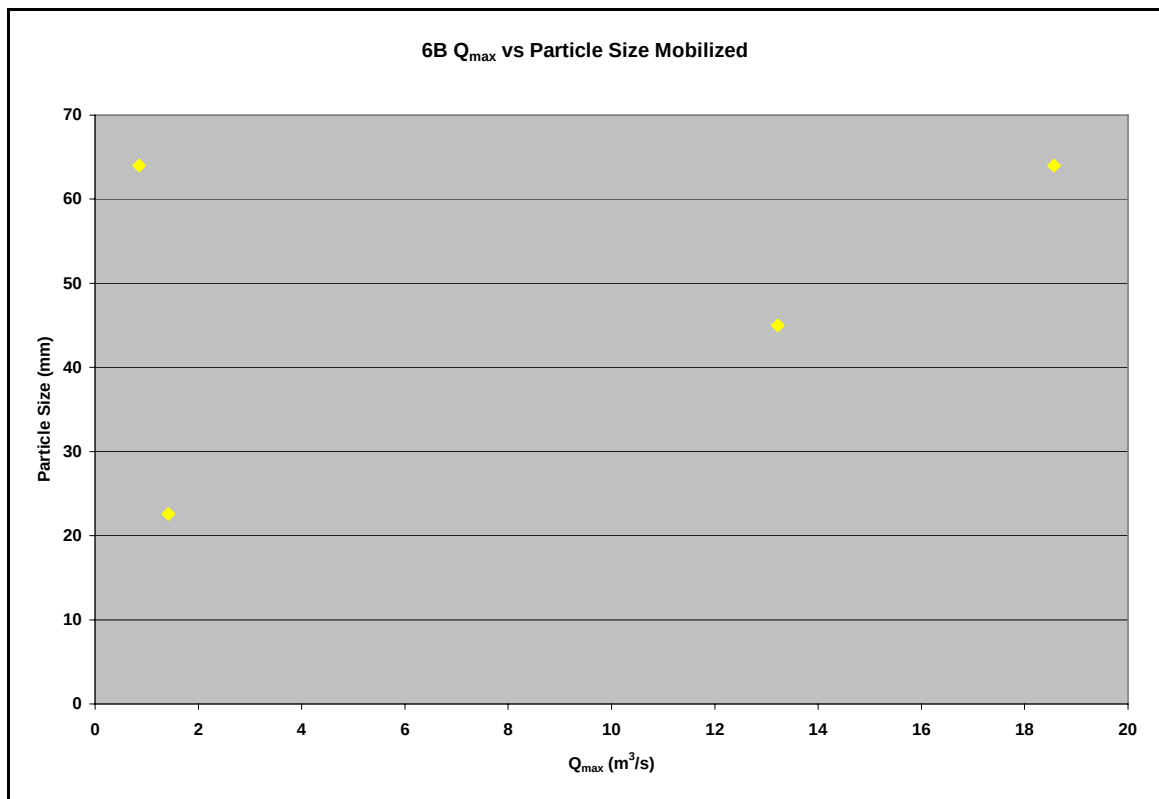
Cross-Section 2A



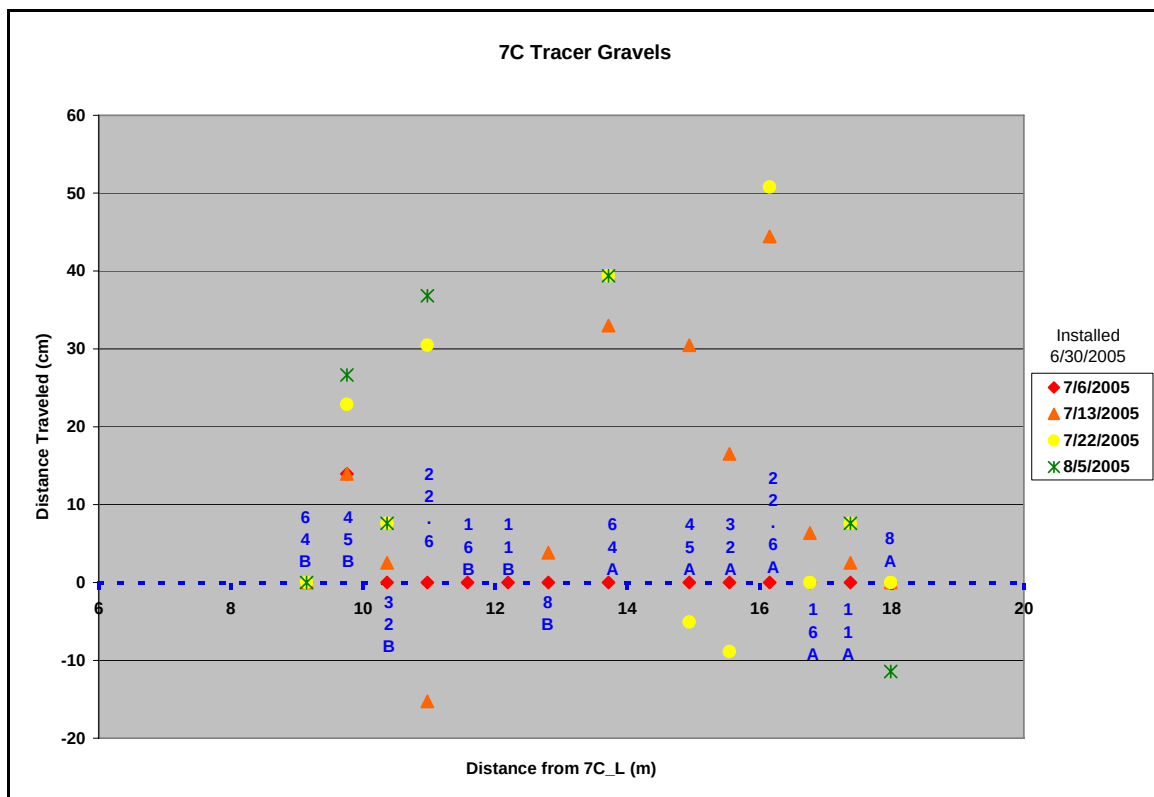
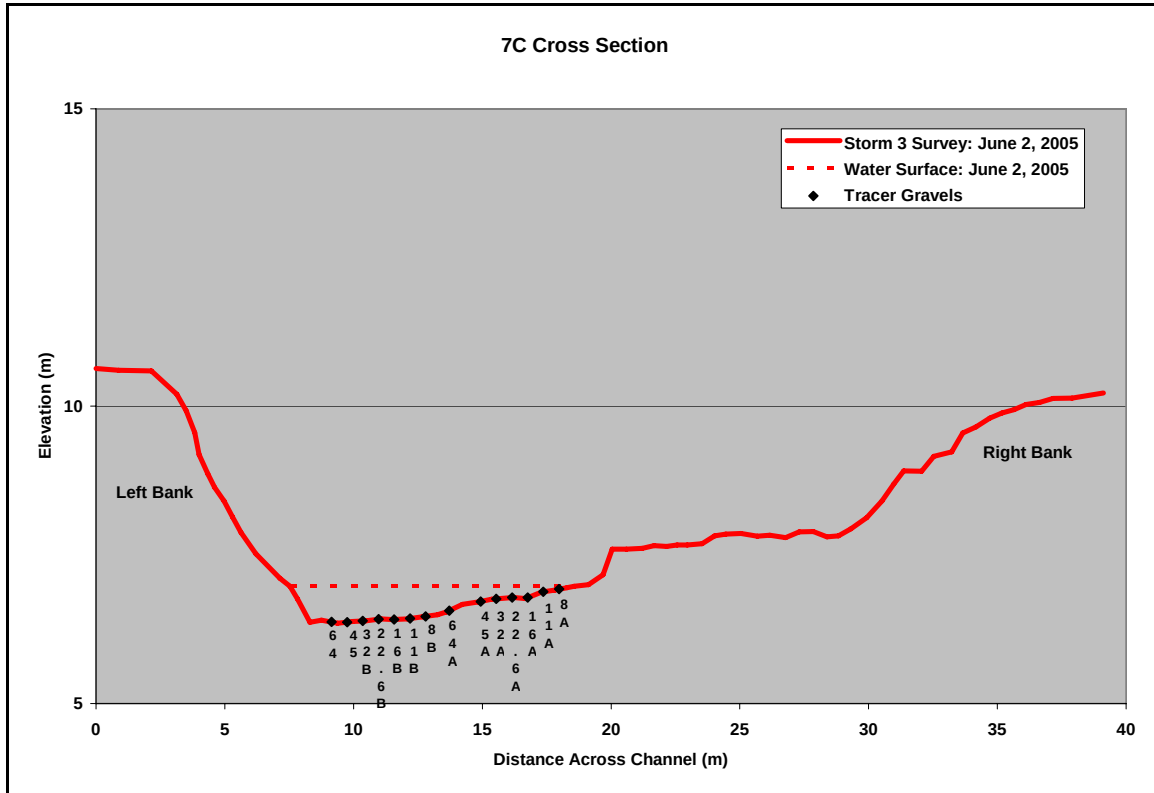


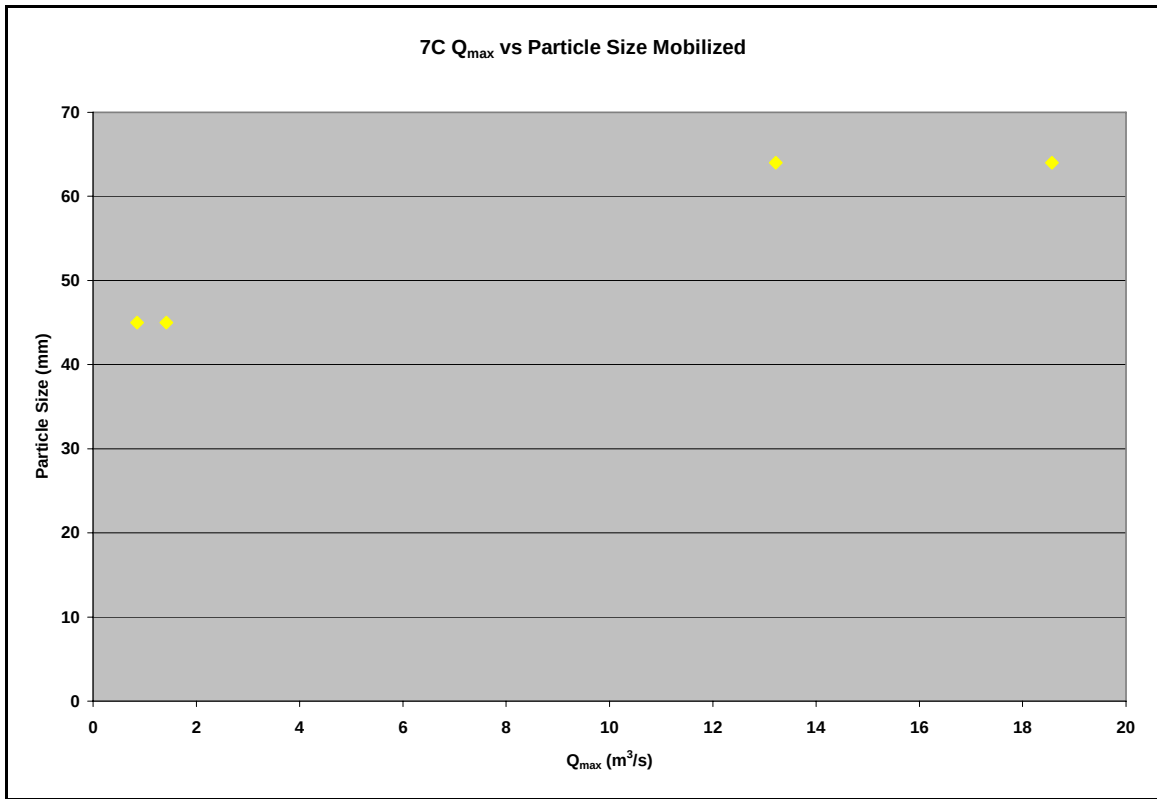
Cross-Section 6B



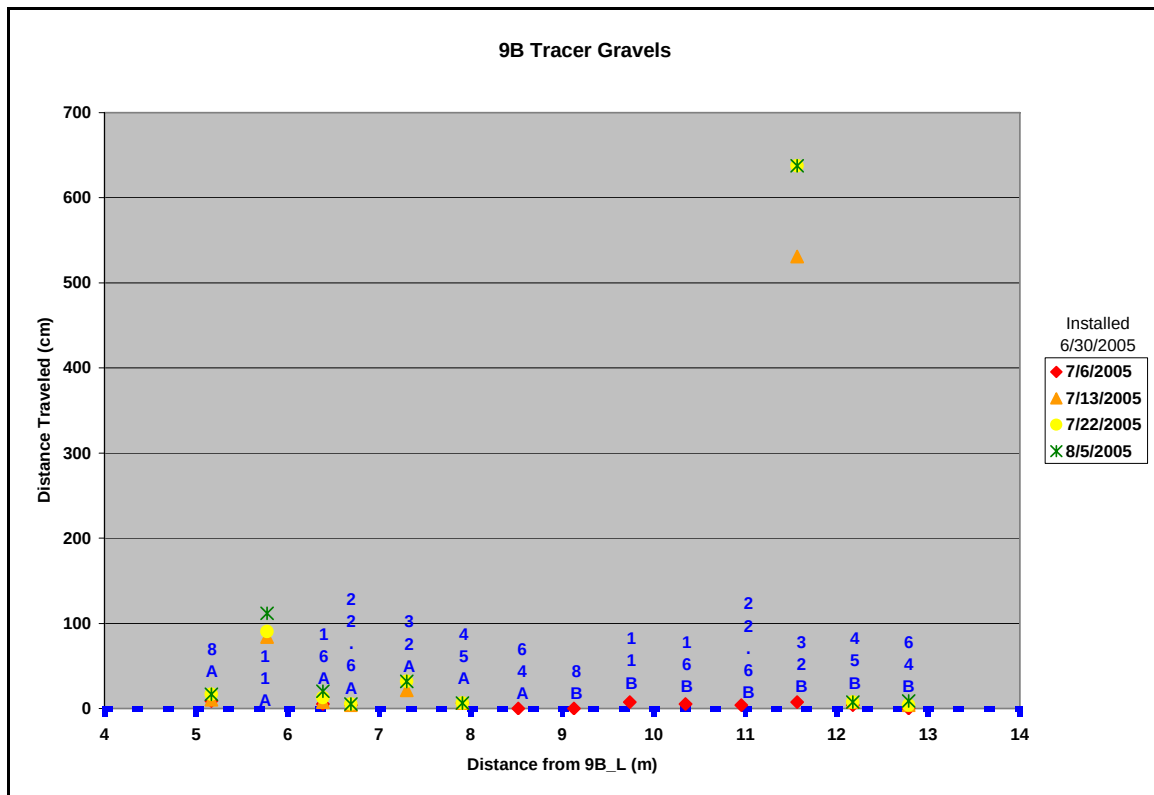
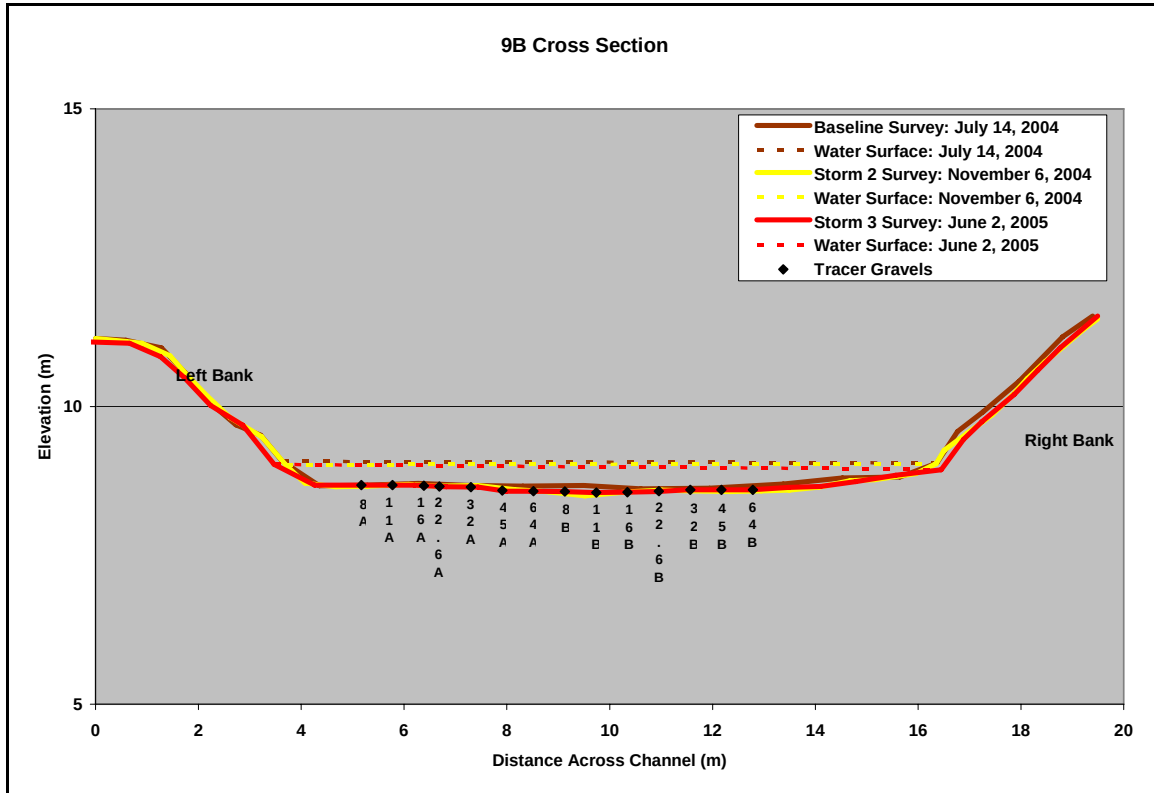


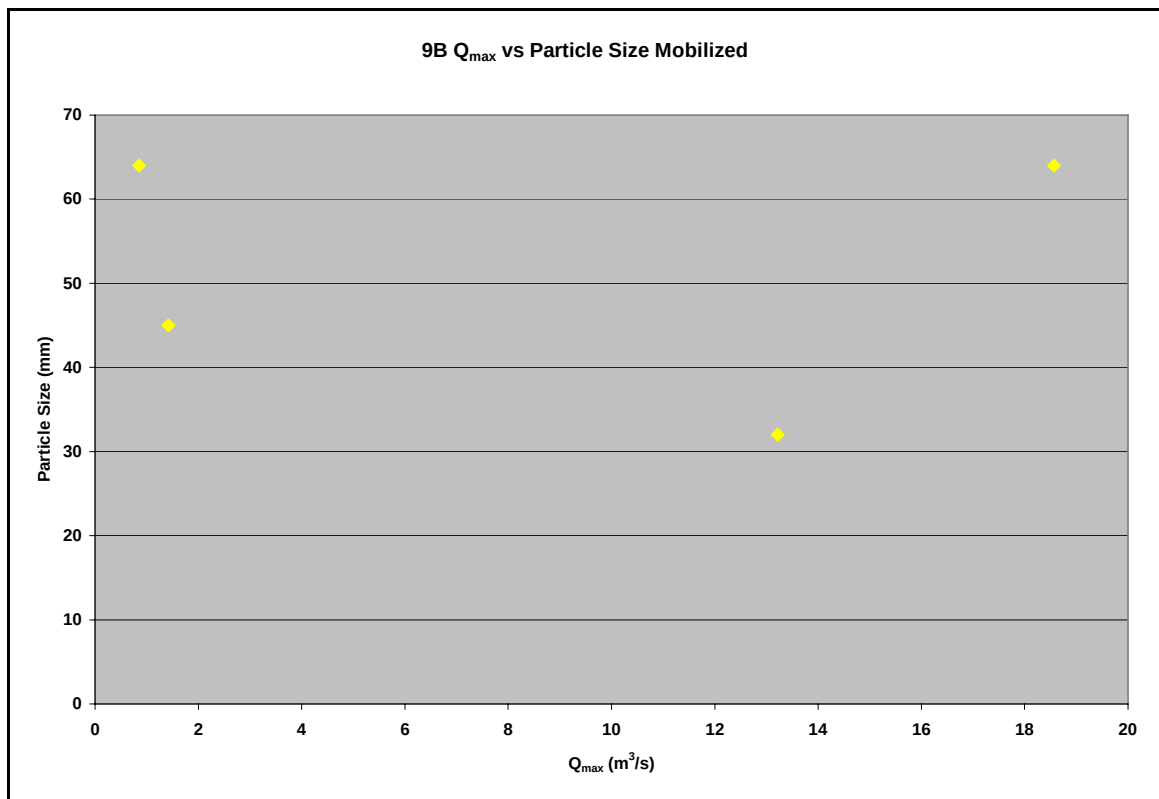
Cross-Section 7C



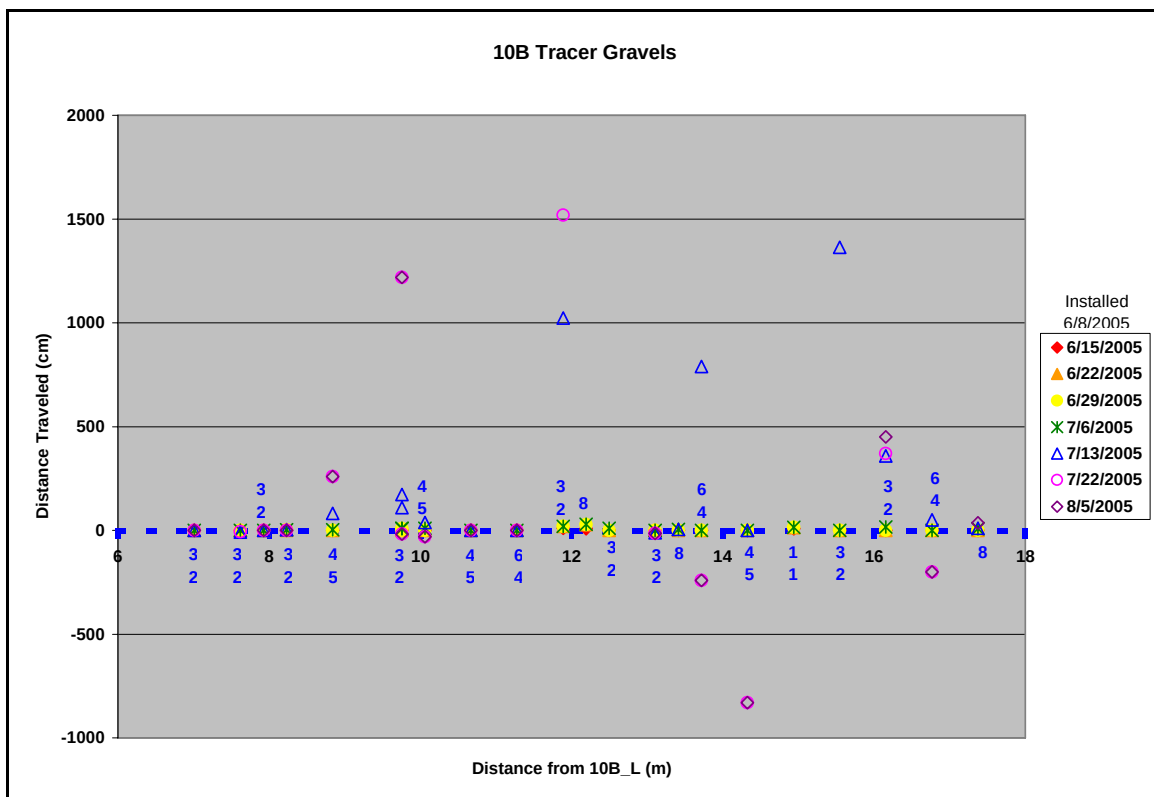
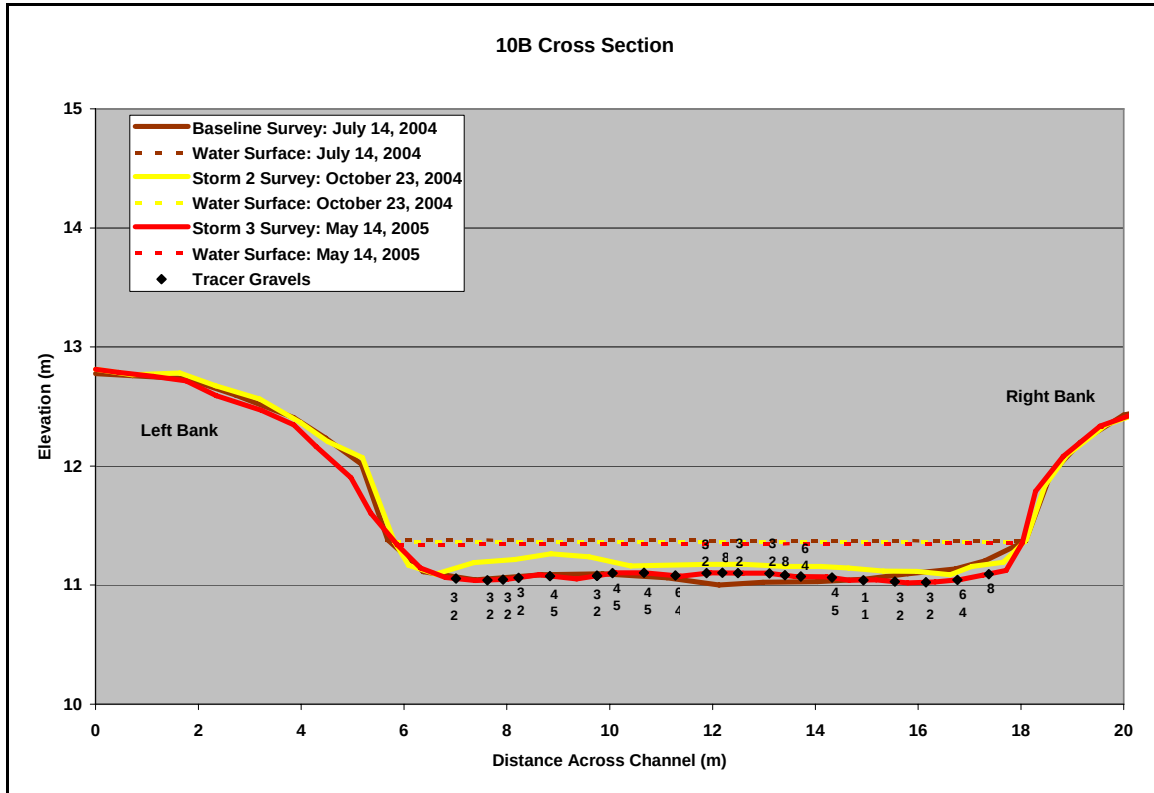


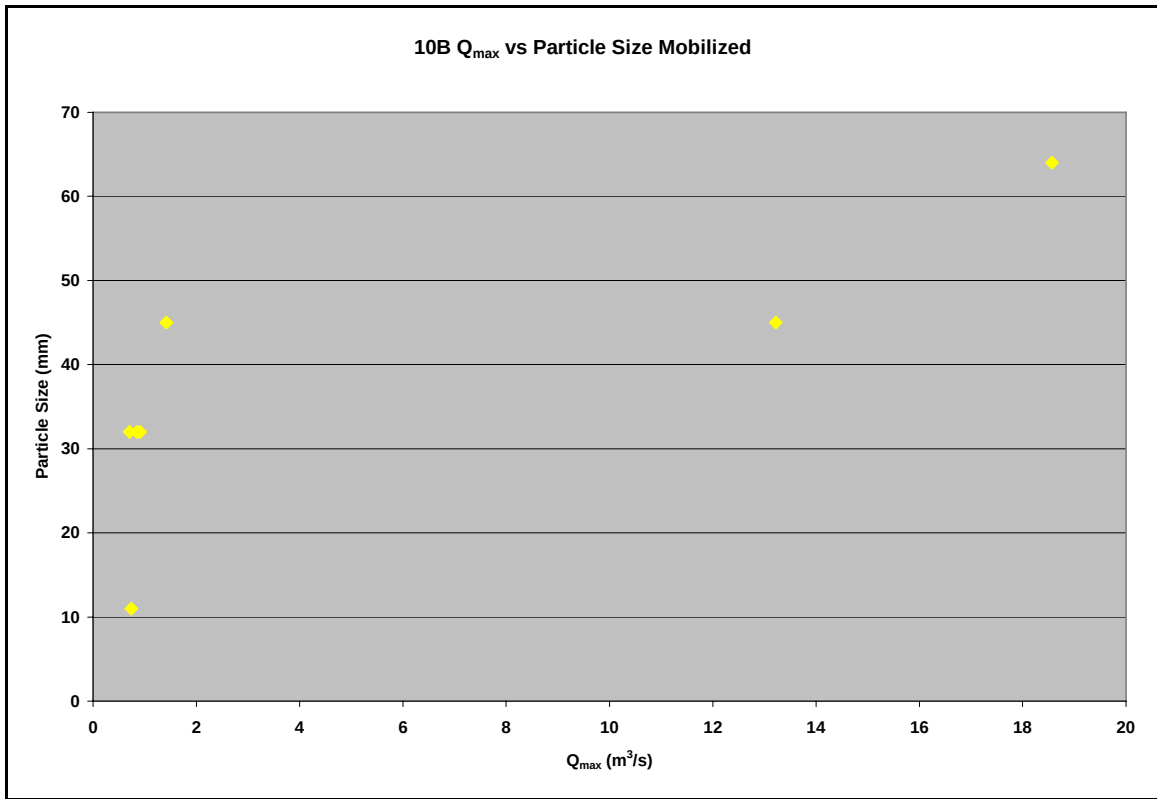
Cross-Section 9B



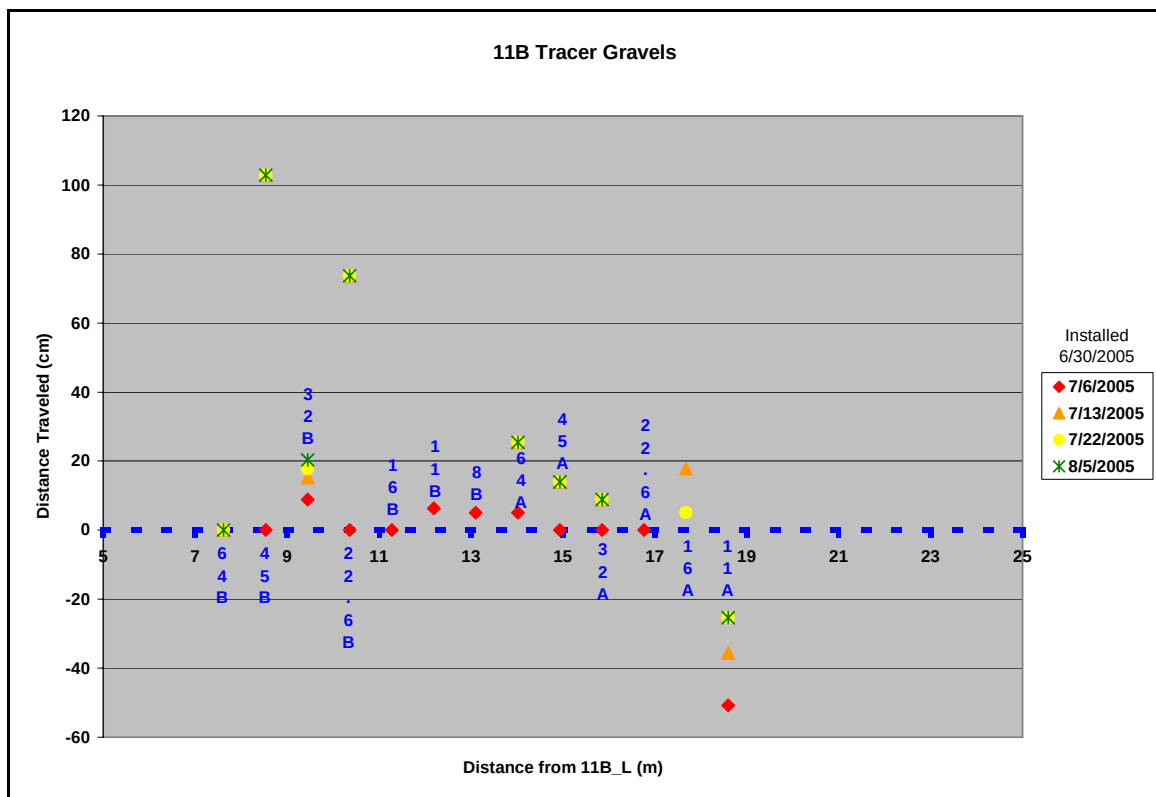


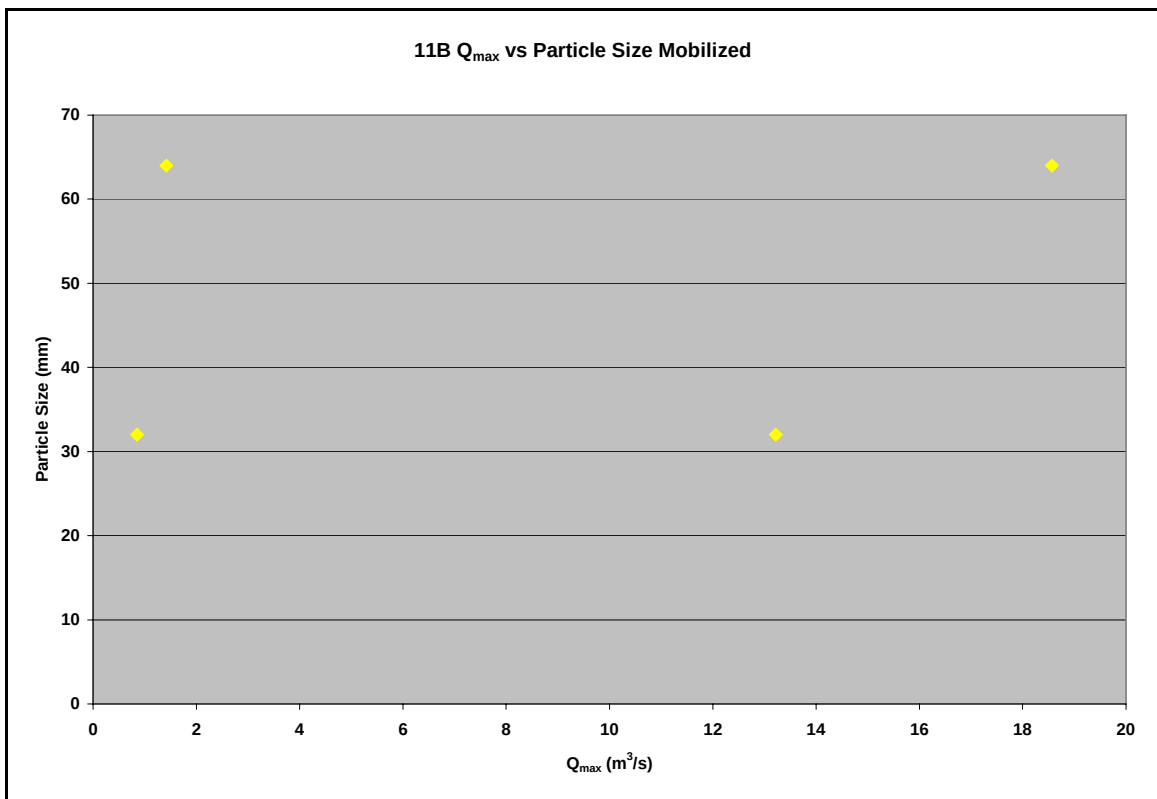
Cross-Section 10B



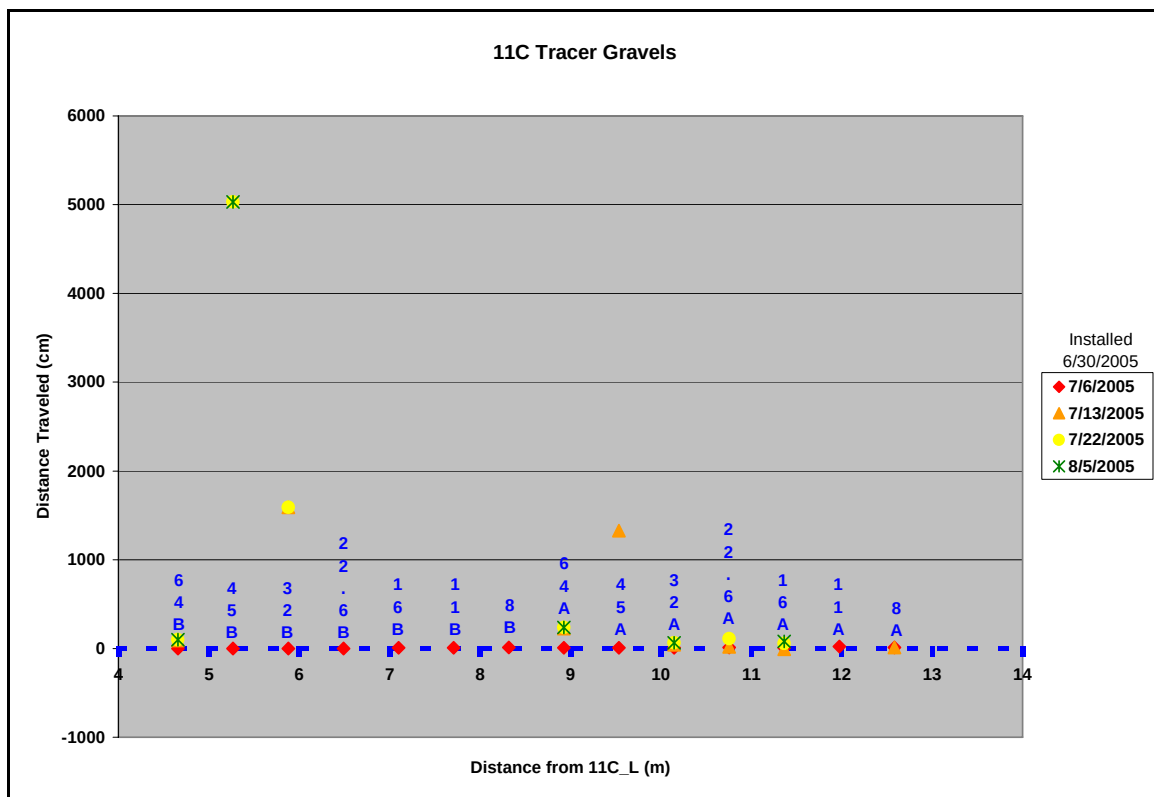
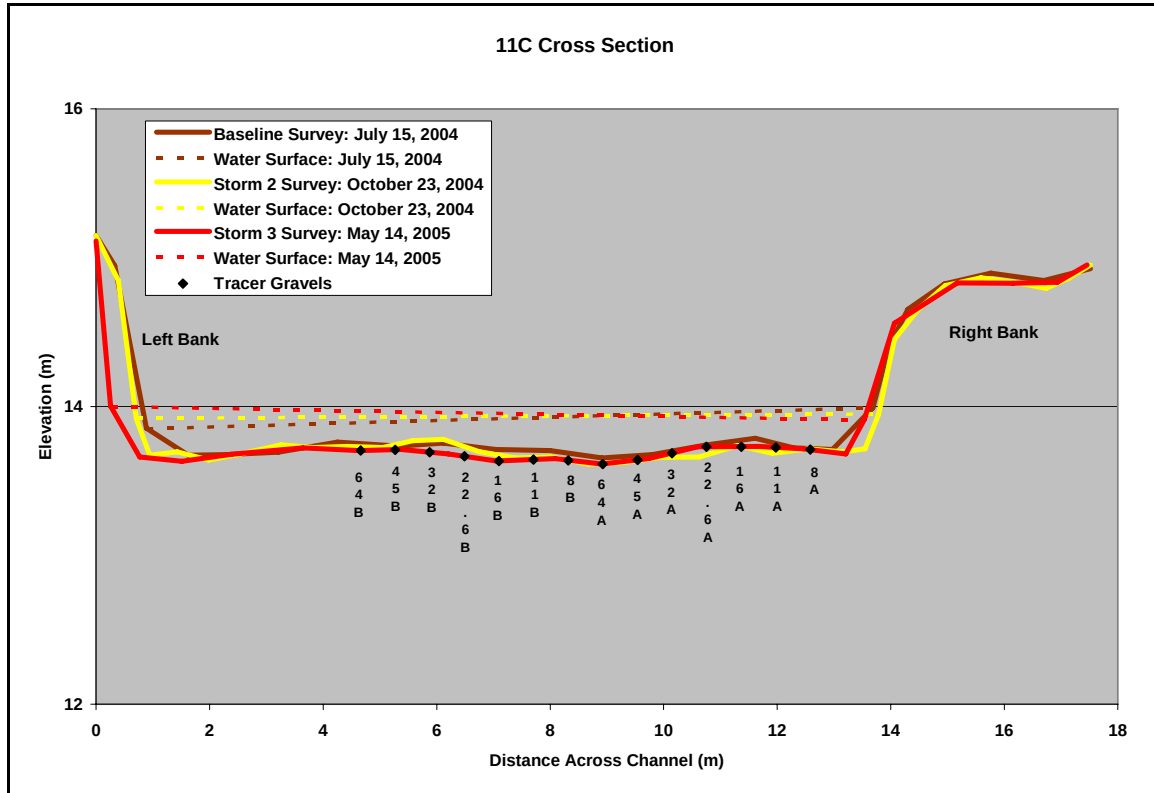


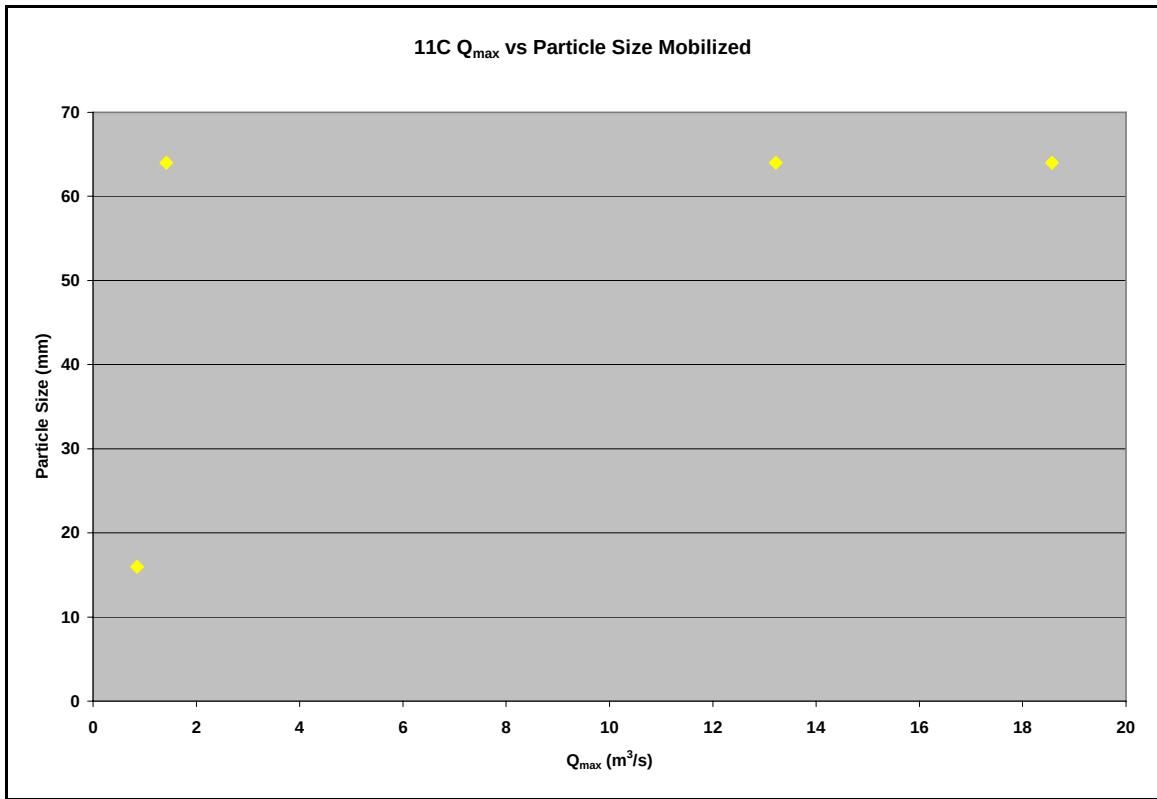
Cross-Section 11B



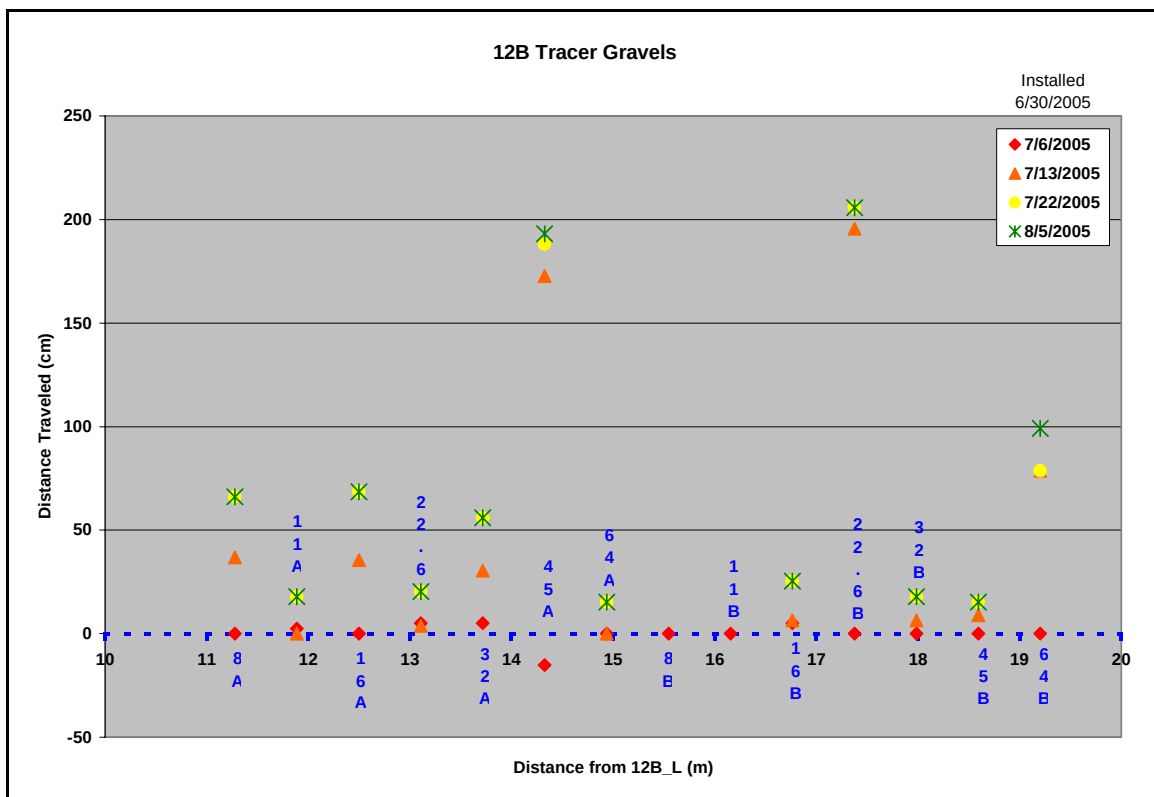
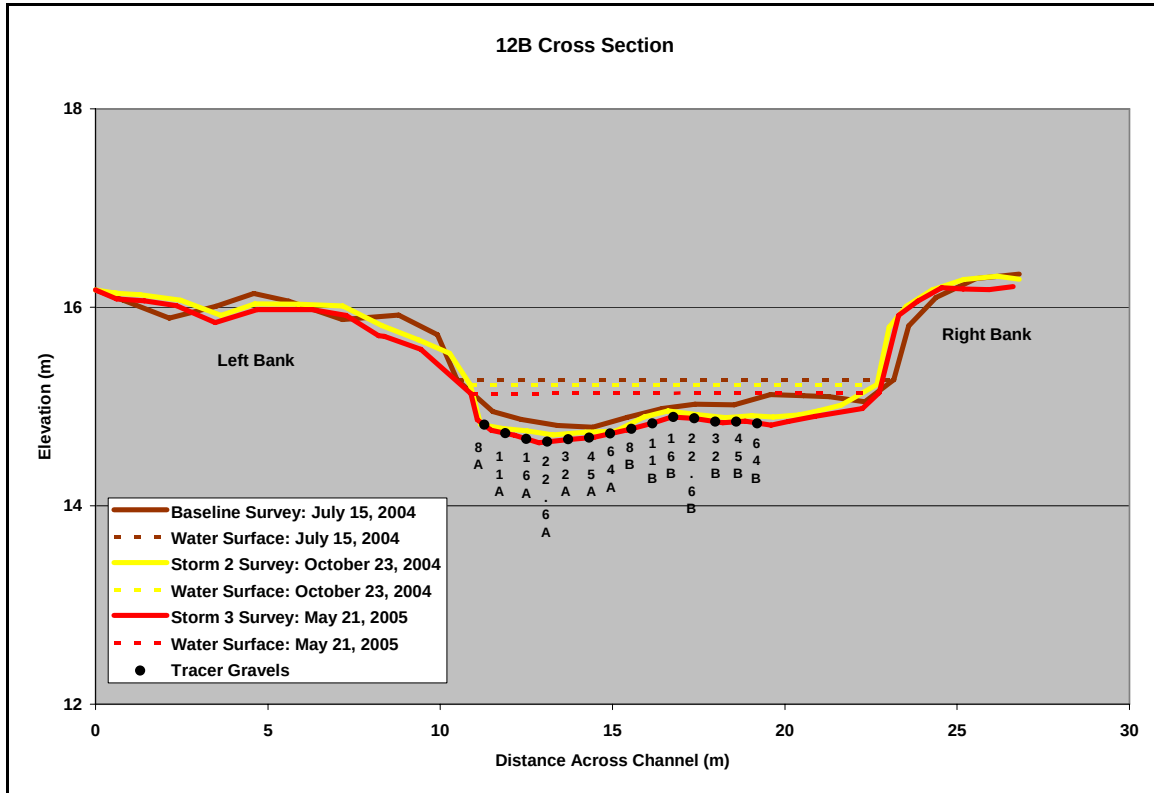


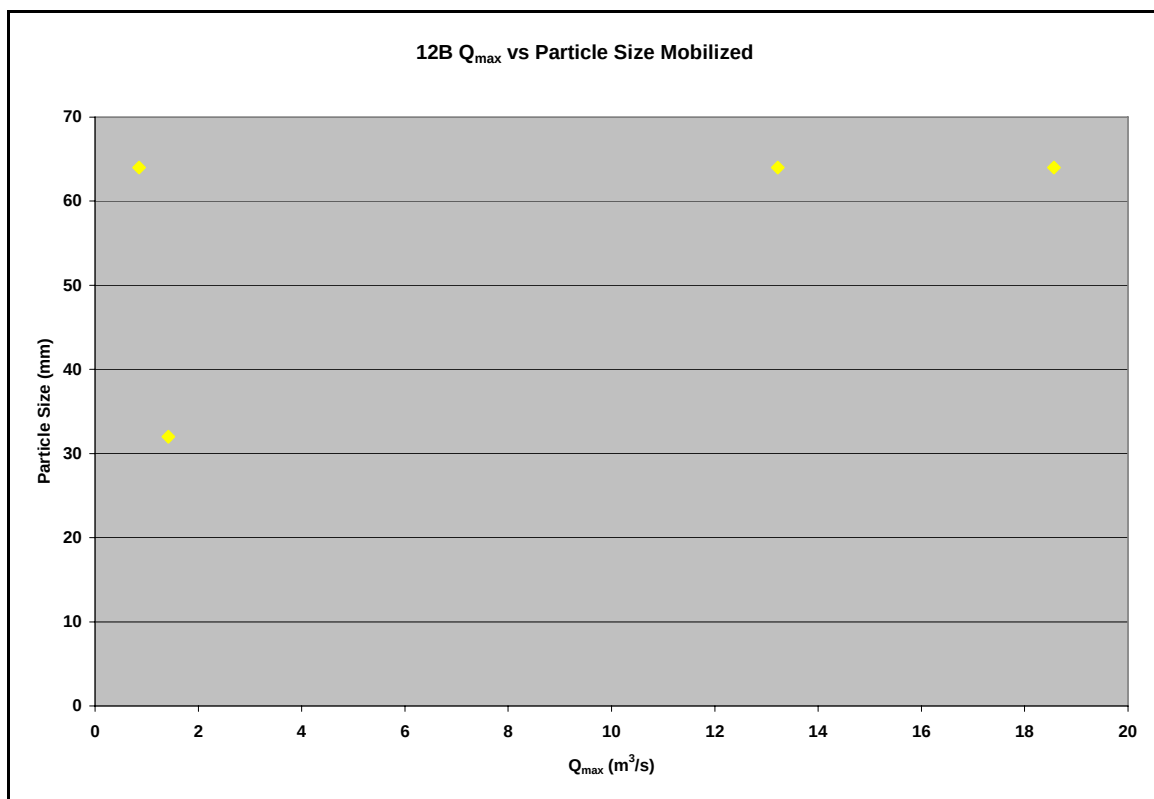
Cross-Section 11C





Cross-Section 12B





Appendix L. Statistical comparison of successive pebble counts.

In order to test the particle size distributions of the two successive pebble counts, a paired-sample t-test (parametric) and Wilcoxon signed ranks test (non-parametric) were conducted for the four cross-sections (11B, C; 12 A, B) where fining appears to coincide with net scour. The null hypothesis for the t-test is that the means of the 2004 and 2005 pebble count data are equal and the null hypothesis for the Wilcoxon signed ranks test is that the medians of the 2004 and 2005 data are equal. The null hypotheses were rejected for p-values less than 0.05, indicating that the changes in mean and median particle size are statistically significant.

Among the four cross-sections that became finer (11B-12B) between the 2004 and 2005 sampling period, only the results at 11B were found not to be statistically significant. Results for that site from the t-test and Wilcoxon signed-ranks test had p-values greater than 0.05 and the null hypotheses were accepted. Cross-sections 11C and 12B had p-values less than 0.05 for both statistical tests. The null hypotheses were rejected and the differences between the 2004 and 2005 pebble counts were found to be statistically significant. Cross-section 12A had a p-value less than 0.05 for the t-test and greater than 0.05 for the Wilcoxon signed-ranks test. The pebble count histogram for cross-section 12A (Appendix E) suggests that the data are normally distributed. If this is the case, then the parametric t-test provides a better indication of the significance of the data. The null hypothesis was rejected and the change in particle size was found to be statistically significant. The particle size distribution fining in conjunction with net streambed scour remains to be explained for cross-sections 11C-12B. Repeated pebble counts and cross-section surveys conducted on shorter sampling intervals would provide more detail on the changes in these upstream reaches.

As the nation's primary conservation agency, the Department of the Interior has responsibility for most of our nationally owned public land and natural resources. This includes fostering sound use of our land and water resources; protecting our fish, wildlife, and biological diversity; preserving the environmental and cultural values of our national parks and historical places; and providing for the enjoyment of life through outdoor recreation. The department assesses our energy and mineral resources and works to ensure that their development is in the best interests of all our people by encouraging stewardship and citizen participation in their care. The department also has a major responsibility for American Indian reservation communities and for people who live in island territories under U.S. administration.

National Park Service
U.S. Department of the Interior



Northeast Region

Natural Resource Stewardship and Science
200 Chestnut Street
Philadelphia, Pennsylvania 19106-2878

<http://www.nps.gov/nero/science/>