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Urban Stream Channel Geomorphology: Investigating the Short-Term Channel Stability and Bed-Material Transportation within a Rehabilitated Urban Stream Reach in DeKalb County, Georgia

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URBAN STREAM CHANNEL GEOMORPHOLOGY: INVESTIGATING THE SHORT-TERM CHANNEL STABILITY

AND BED-MATERIAL TRANSPORTATION WITHIN A REHABILITATED URBAN STREAM REACH IN DEKALB

COUNTY, GEORGIA

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Under the Direction of Jordan A. Clayton

ABSTRACT

Rivers and streams are sensitive to alterations in their watersheds and one of the greatest disturbances is from urban development. An urban stream channel in the Atlanta metropolitan area in the Georgia Piedmont was studied to establish the nature of adjustment the channel form was experiencing. This study compared a degraded channel with a channel influenced by stabilization efforts in the same stream reach, in order to investigate the behavior of channel adjustments towards a greater stability. Measurements of the short-term changes in channel cross-sectional area and bed-material volume, following a series of threshold flow events, were taken in the reach and the variation in bed sediment texture was also investigated. Results showed that channel banks were stable compared to more mobile beds and that urban effects continued to dictate sedimentation. Rehabilitation measures were aggrading channels in their reaches and were likely perpetuating the instability of upstream channels.

INDEX WORDS: Urban stream, Urban stream restoration, Urbanizing watersheds, Bed-material move-
             ment in unstable channels

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1   INTRODUCTION

As rural populations dwindle at the expense of increasingly urbanizing populations it is expected that by 2025 85% of the U.S. population will be considered urban (United Nations, 2012). Between 2000 and 2008 the southern U.S. experienced the largest regional population increase in the nation (11.5 million) according to the 2009 U.S. census (O'Driscoll et al., 2009). Typically the urbanization of watersheds is associated with a multitude of alterations in the hydraulic regime of stream channels and associated channel instabilities which will affect the maintenance of aquatic habitats (Wolman, 1967; Rose and Peters, 2001; Leopold et al., 2005; Chin, 2006). The term 'stability', in terms of stream channels, implies that a channel form is essentially constant or temporarily balanced under current conditions (Henshaw and Booth, 2000; Niezgoda and Johnson, 2005). Rivers and streams that have been modified by human intervention will undergo progressive channel modifications towards greater stability over a much shorter time-span compared to modifications related to more natural disturbances. This makes urban streams ideal settings for studying the balance between channel sediments changes and channel morphology alterations as these stream channels develop into more stable forms (Simon, 1989).

The normal adjustment of degraded urban streams are frequently cut short by additional human intervention in the form of channel stabilization or stream restoration measures to limit property damage, control unpredictable flows or rehabilitate lost ecological settings (Niezgoda and Johnson, 2005; Bernhardt and Palmer, 2007). Practices such as stream restoration have notoriously been linked to a dearth of sufficient monitoring data needed to assess the degree of post-project effectiveness, and thus restoration efforts can conceivably also contribute towards further channel degradation. A common approach in understanding the propensity towards channel stability, particularly in urban reaches, is through channel cross-section evaluation as channel areas are sensitive and quick to adjust to

flow and sediment imbalances (Henshaw and Booth, 2000). Reach instability can include incision of the channel bed, bank erosion or failure, and an increased sediment transportation competency. Many of these cases of instability are communicated by comparisons of temporal and spatial channel cross-sectional change and others by channel bed-material sediment investigations. Grain size changes are important for many reasons including the inhibition of a channel equilibrium geometry, influences on sediment transport capacity, implications for biological communities, and because changes in grain size distributions represent a degree of freedom in channel responses to channel disturbance (Doyle and Shields, 2000). The fundamental cause for bed material change, other than just increased high flows, would be the sediment supply derived from watershed development contributions.

This purpose of this study was to evaluate the dominant processes taking place in a stream channel affected by watershed urbanization, and to assess the current stability of the reach through inspection of changes in channel areas and the movement trends of bed sediments. In addition this research explores whether reach-scale stream restoration practices are likely having a positive or negative feedback on an existing degraded stream system.

1.1   Purpose of the Study and Thesis Question

The current research investigates whether the short-term adjustments in stream channel volume in conjunction with bed sediment transportation could, after a series of threshold flow events, be utilized to assess the stability of a restored reach in an urbanizing watershed. This premise is based on comparing a channel reach in a degraded stream, where watershed-scale anthropogenic disturbances continue to exert their indirect control, to a channel reach in the same stream that has been influenced by reach-scale anthropogenic stabilization efforts such as stream restoration. Quantification of channel capacity modifications (by cross sectional comparison) and an analysis of bed-material transportation, should indicate that there is either a direct relation to post-restoration

stabilization efforts on the stream channel or that the same channel is still largely adjusting to watershed urbanization.

A 'stable' morphology would imply that the channel form no longer undergoes progressive adjustments, such as with bed and bank erosion, and it is essentially in a state of dynamic equilibrium (Wolman, 1967; Schumm, 1977; Henshaw and Booth, 2000; Rakovan and Renwick, 2011). Stream channels which have, for example, historically been destabilized as a result of increased impervious surface cover following watershed urbanization, will over a period of some years have adjusted their channel form to a state where there is neither a propensity towards aggradation nor degradation (Church, 2006). It may take decades for urban rivers and streams to restabilize (Ruhlman and Nutter, 1999; Chin, 2006), and unless there is sufficient prior knowledge of pre-disturbance channel conditions, predicting required time-periods for increased stability becomes improbable. Reaches adjusting to variable external controls will attain what is known as a quasi-equilibrium state in their channel geometry and hydraulic processes (Knighton, 1998; Leopold et al., 2005; Annable et al., 2012). In many cases it has been possible to frame these newly equilibrated channel hydraulic geometries and bedload characteristics in terms of stages in a channel evolution model (CEM) for incised channels developed by Schumm et al. (1984) and modified by Simon (1989, 1994) (Simon, 1989; Doyle and Shields, 2000; Mukundan et al., 2011). Given enough time and space to adjust (Niezgoda and Johnson, 2005), degraded urban channels can be analyzed based on stage classification thus permitting certain predictions on the long-term responses associated with channel sediment and discharge dynamics.

Work by Annable et al. (2012) postulates that even with the profuse and rapid urbanization of watersheds currently taking place, there are still too few studies that expand on our knowledge of urban channel stability in terms of a quasi-equilibrium condition. Bledsoe and Watson (2001) admitted that measured data of urban influences on stream channel form are lacking, which means that our understanding of what constitutes a dynamically stable urban channel has the potential to be expanded

upon. The current study on a restored reach in Snapfinger Creek in DeKalb County, Georgia, aims to identify the current state of stability at a reach-scale and to apply these findings as a prediction relating to a larger spatial- and temporal scale for this urban stream. It should be noted that this study is not intended as an unequivocal evaluation of the success and failures of restoration efforts at Snapfinger Creek, but is rather a study of the nature of channel topography adjustments in a unique setting where both urban and restoration dynamics are at play.

1.2   Background on Urban Streams and Stream Rehabilitation

Urban stream channels differ from streams flowing through less impacted landscapes because they are affected by a unique set of watershed impacts and both physical and cultural constraints. Stream channels found in cities drain low-permeability watersheds that in turn produce flashy hydrographs and reduced baseflow conditions (Rose and Peters, 2001; O'Driscoll et al., 2010). Impervious surface coverage regularly accompanies watershed development and transmits the larger volumes of runoff even during ordinary precipitation events. The receiving stream channels become greatly enlarged as their ecosystems become increasingly degraded by diminished water quality conditions and the removal of riparian vegetation (Wolman, 1967; Leopold et al., 2005; Violin et al., 2011).

The impacts of urbanization on streams typically follow an evolution of alteration phases or stages in characteristic channel morphologies (Simon, 1989; Doyle and Shields, 2000). Initial construction and urban expansion produces sedimentation of drainages with large quantities of sand and associated stream channelization. With completion of construction, sediment sources are decreased as the amount and efficiency of runoff is increased as channel beds and banks begin to degrade as streams become incised (Wolman, 1967). Over time the material contributed by channel enlargement causes downstream sediment accumulation in the form of aggrading channels. Frequent and higher

flows tend to selectively remove finer grains from a generally increasingly coarse channel bed and, because of a reduction in stream power aided by coarse sediments, the reach approaches a quasi-equilibrium condition as a more dynamic form of channel stability (Simon, 1989; Chin, 2006; Annable et al., 2012). As each developing watershed is unique pertaining to the degree and rate at which urbanizing is taking place (in addition to many other factors), urban stream channel responses will vary both spatially and temporally in achieving a more stable form.

1.3   Site Selection and Description

Snapfinger Creek has its watershed in the headwaters of the Upper Ocmulgee river basin located in north central Georgia (Figure 1.1). This 4th order stream (Eco-South Inc., 2007) feeds into the Ocmulgee River basin which ultimately forms the Altamaha River towards the Atlantic coastline to the southeast. The total watershed area covers approximately 100 km^2 (U.S.EPA, 2010) and it is underlain by Southern Piedmont-Blue Ridge province geologies of the late Proterozoic and early Paleozoic Atlanta Group including the Clairmont, Wahoo Creek, and Clarkston Formations, together consisting largely of gneisses, schists and amphibolites (McConnell and Abrams, 1984). The watershed drained by Snapfinger Creek and its two main tributaries (Indian Creek and Barbashela Creek) lies entirely within DeKalb County and comprises approximately 38% urban land use (Trawick, 2009) with largely sub-urban residential and light industrial developments. According to the U.S. EPA 2010 watershed assessment report for the Upper Ocmulgee, Snapfinger Creek was listed as 'impaired' due to high pathogen and low stream biota counts and in 2000 it was listed as having high counts of heavy metals (U.S.EPA, 2010). The urban nature of this stream is further demonstrated by its flashy flow response to rainfall events.

In August 2009, the Snapfinger Creek Mitigation Bank (SCMB) was completed on a reach in the lower third of the Snapfinger Creek watershed. The roughly 62.7 hectare restoration site is located ±19 km east of the city of Atlanta and lies between US 12 Covington Highway and Interstate I-20 outside

of the metropolitan perimeter (Figure 1.2). The property is bordered to the south by the I-20 overpass at

which point the interpolated drainage area of Snapfinger Creek is 81.8 km^2 (Carter et al., 1986).

Mitigation efforts sought to restore lost forested, bottomland hardwood wetlands habitats and

impacted stream functions to this former golf course (Eco-South Inc., 2007; U.S.FWS, 2012). Primary

objectives in restoring the Snapfinger Creek reach were to stabilize the largely eroding banks along the

reach by implementation of around 630 linear meters of both traditional and bio-engineering features

which included rock vanes, root-wads, geotextiles and log-revetments (Eco-South Inc., 2007). Many of

the bank-engineering functions, such as the establishment of riparian vegetation and the prevention of

excessive bank erosion, were compromised by the occurrence of a large flood event in September of

2009 soon after project completion.

Major Drainage Basins in Georgia and
the location of DeKalb County
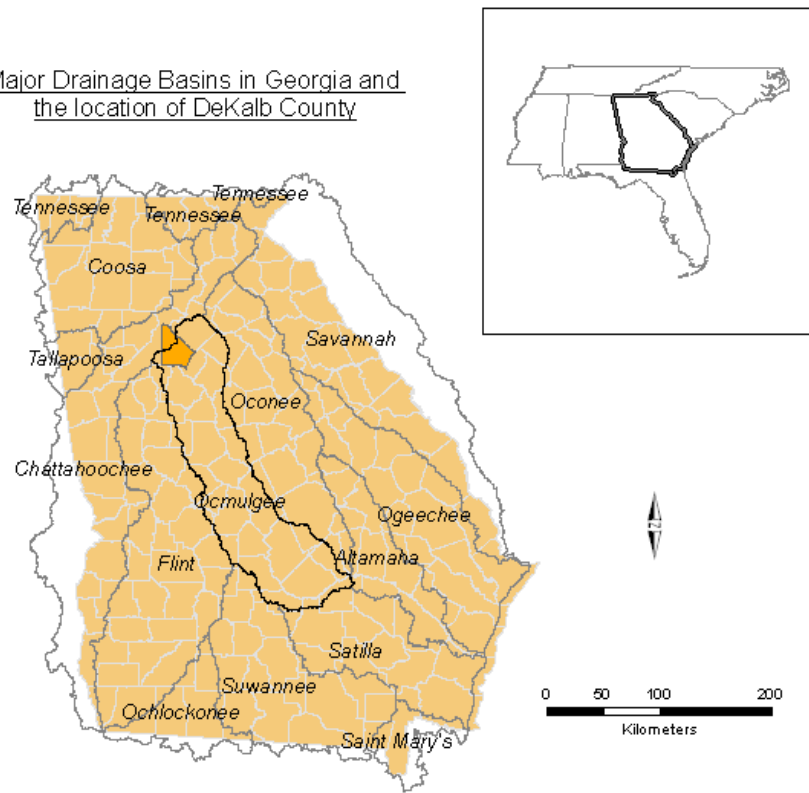
Location of Snapfinger Creek within the Upper Ocmulgee basin
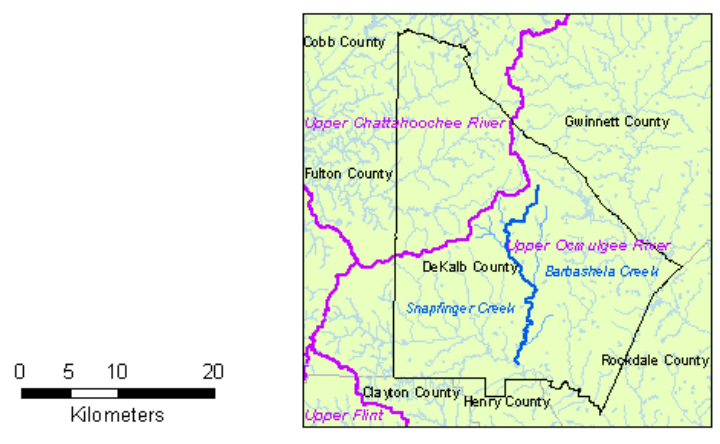
Figure 1.1 – Study location in the state of Georgia
Location of Snapfinger Creek within the Upper Ocmulgee watershed in DeKalb County, Georgia.

Figure 1.2 – Map of the study reach
Satellite image of the study reach and the three channel sites. The yellow boundary demarks the mitigation bank property and the numbered orange lines denote the approximate cross-section setup for each site (2010 orthoimagery courtesy of U.S. Geological Survey).

Snapfinger Creek comprises largely sandy channel material with very apparent ripple bed-forms covering the channel bed. Sand dominated bed-material regularly becomes fully mobilized over a broad range of flows as it moves in the form of sand sheets and suspended material. Channels characterized by bed sediment which moves as mixed loads are known as transitional channels. An abundant supply of sand tends promote bed instabilities by increasing bed–material mobility and the accompanied migration of bed-forms (Church, 2002, 2006).

Three channel locations were investigated to study the sediment transportation potential in this restored reach. The study design incorporated a comparison of restored with non-restored portions of the same urban stream. It should be noted that the term 'restored', in this study, is used to refer to reaches on which mitigation intervention has been practiced and does not indicate the absolute stability of those sections of Snapfinger Creek. Two experimental sites known as the North Experimental Site (NES) and the South Experimental Site (SES) would examine the channel adjustments taking place near the middle and lower reaches in the mitigation bank respectively. Upstream of the restoration site, reaches were unaffected by direct stabilization efforts and were therefore suited as a control for alterations due to intervention downstream. The Control Site (CS) was located ±120 m upstream of the property boundary where the predominant influence on channel dynamics would be from urbanization rather than from restoration efforts (Figure 1.2).

Two criteria were used for selecting study sites and these were based on the field observations conducted before the study commencement. The first requirement was that sites had a relatively straight channel section in order to limit the influence of geomorphic effects which may have complicated the interpretation of perceived stability observations (O'Driscoll et al., 2009). Any geomorphic flow hydrology controls would also have obscured the effects of urban-induced processes with more natural processes of channel alteration (Henshaw and Booth, 2000). The second requirement was to avoid channels with any anthropogenic constrictions such as overpasses and to limit inclusion of

excessive bank-protection engineering. By meeting these requirements each survey channel would likely not conform to the conventional reach study length of 20-50 channel widths and a cross-sectional spacing of two to five channel widths as used by other field investigators (Kondolf and Micheli, 1995). Actual sites for this study amounted to shorter reach lengths and cross-section spacing for field measurements (Figure 1.2).

The Control Site (CS) reach was chosen based on (i) its proximity to the mitigation site but and (ii) that it exhibited the typical channel morphology of a degraded urban stream. This channel exhibited deeply incised channel depths (±2.51 m), fairly narrow channel widths (±12.9 m), and significant tilted and fallen trees. The eastern banks were well vegetated and primarily composed of sand deposits that were likely derived from historic meander alluvium. In contrast, the western banks were taller and composed of cohesive, red ultisols with steep bank failures. Along these banks it was common to find severely undercut tree roots with large trees essentially suspended above the outer channel. This site typified an urban stream channel that was not yet adjusted to frequent high flows and had experienced significant vertical incision with bank failures. Bed sediments were mostly fine to coarse sands and silts and characteristic features in this reach included sand/silt bed-forms which seemed to aggrade down channel.

The North Experimental Site (NES) was situated near the midpoint of the stream mitigation property (Figure 1.2) and it represented a reach that was directly downstream of the majority of bank engineering practices in the reach. The channel was fairly shallow (±1.86 m) and broad (±14.9 m) compared to the CS dimensions, and bank material consisted mainly of non-cohesive sands with well vegetated banks. This site had some notable features which included: (i) a coir-fiber log protecting almost the entire length of the left bank toe, (ii) that it was immediately downstream of a channel step in the form of rock weir, (iii) an in-stream tree as a result of prior bank collapse, and (iv) two large channel bars related to thalweg meandering.

At approximately 85 m north of the I-20 overpass towards the southern end of the mitigation property, the SES constituted the most downstream culmination of possible mitigation effects on channel dimensions and bed composition. This channel reach was shallower (±1.8 m) and broader (±16.1 m) than both upstream sites and some bank stabilization features such as log revetments, remnant bank rip-rap and a few geotextile bank coverings were present. Relatively few flow obstacles existed in this channel compared to the other study sites and riparian vegetation was generally well established except for a clearing along the upper-most part of the reach. All the study sites had beds with clearly developed ripples comprising the largely sandy bed-material surface and rip rapped portions of the banks in all three sites were unavoidable. Bed surface compositions also maintained shifting gravel clusters (surface material >4.0 mm) which were particularly apparent in both experimental sites.

1.4   Literature Review

Doyle and Shields (2000) produced a study to develop a modified version of the Channel Evolution Model (CEM) based on the inclusion of qualitative predictions of bed textural changes which incising rural channels experience as they progress through the geomorphic evolution as described by Schumm et al. (1984) and later revised by Simon (1989, 1994). In their study three reaches in eastern Mississippi were chosen for the sake of comparison with a study done on the same reaches a decade before and the current study attempted to replicate these previous study procedures. It was found that the prediction of longitudinal grain size distribution did not follow the conventional down-stream fining trends observed by others, and the dominant factor in in the development of grain size distributions was rather attributed to the sediment sizes, quantities, and their source locations within the watershed. Although grain size plays a larger role than previously appreciated in the evaluation of incised channels, too many variables make this approach more complicated in its simple implementation.

Numerous contemporary papers are centered around evaluating the effectiveness of stream rehabilitation projects, often supplementing for the general lack of existing post-project monitoring data (Bernhardt et al., 2005). One such study by Buchanan et al. (2012) investigates a suite of geomorphic parameters in order to identify the success of project objectives in central New York State, two years after rehabilitation efforts. It was found that the restored reach experienced excessive overall degradation, especially in the upper reach, and aggradation at the bottom of the reach likely resulting from local scour higher up. Low bed and bank stability throughout the reach may have been attributed to 'hard' engineering structures such as cross- and bank vanes, which promoted accelerated incision of scour pools and inadvertently deflected high flows onto banks. The resulting short-term channel instability did not, however, undermine the outlook for long-term success but rather emphasized the importance of accounting for sediment transport and watershed-scale stressors.

A study by Miller and Kochel (2010) evaluates 26 stream mitigation sites in North Carolina, many of which have suffered from large post-project adjustments in channel capacity over a timespan of one to six years since project completion. By examining channel dimension changes through time, the authors investigated the short-term stability and the long-term likelihood of equilibrated channel conditions. In many of the examined reaches there was a re-organization of channel form, configuration, and slope in the form of localized amounts of scour and fill. Changes in channel capacities were particularly related to increases in slope, bed grain size and project age and in this study the time required for channels to reach equilibrium exceeded the monitoring period. The recovery of highly dynamic channels was deemed near impossible to instigate save for properly addressing three influential parameters, namely excess shear stress (e.g. flashy urban channels and high gradient streams), sediment supply (e.g. historic land-use changes upstream), and bank erodibility (the degree of bank material cohesiveness).

2   METHODS

2.1   Channel Cross-Section Analysis

Cross-sectional measurements were used to determine the changes that were occurring in channel areas and were taken using auto-level surveys at seven transects with a spacing of 10 m (permitting there were no major obstacles) along the length of three 60 m reaches. The transect spacing was determined from an initial inspection of the NES reach channel width, which helped establish that cross-sectional spacing should be at least 8 m apart which would equal approximately one-half of the channel width. To measure each transect, a stake was set on either side of the channel which was spanned by a surveying tape across the entire width of the channel starting from the left bank side. An auto-level was positioned on either bank to clearly sight both stakes on opposing banks of the transect. The entire length of the measuring tape, spanning each transect, needed to be visible without obstruction. To maintain a consistency in measurements, each completed cross-section was calibrated by checking the instrument's elevation against a site benchmark location (BM). Benchmarks were commonly chosen to be the tops of adjacent stakes or other more permanent features such as trees or signage postings. A stadia rod was used to measure the changes in elevation across the cross-section and elevation readings are compared to a predetermined datum (the top of the left bank stake in this case). Two persons were responsible for conducting these measurements, with one at the surveying station and the other walking each cross-section with the stadia rod taking depth measurements. The person walking along the channel transect decided at what intervals and thus at what resolution readings were taken at various locations in the channel. To ensure that transect monuments could withstand overbank flows so that future measurements could be taken, staked locations were reinforced with rebar rods. GPS coordinates were collected for all auto-level surveying sites so that the approximate locations could again be found for future measurements.

Any potential changes in channel area would depend on the threshold for entrainment of bed- and bank-material imposed by stream channel flow. Consequently, this study was constructed around a period of flow events that were effective in moving channel sediments to a measurable degree (this is described in greater detail below). The terminology used in the study describes 'pre-flood' and 'post-flood' measurements in association with initial channel conditions and those conditions representing a period of effective flow events, respectively. To calculate the amount of change in cross-sectional areas for each transect, an area calculation was performed in a spreadsheet whereby the channel depth was set to bank scour lines representing some high flow stand in the NES channel. The use of a scour line to represent the cross-section area was considered more representative than using a determined bankfull flow as it is well known that bankfull stages are difficult to estimate based on specific return intervals in urban environments (Annable et al., 2012). The flashy hydrology of urban streams makes determining a bankfull-flow recurrence interval for these channels less reliable than for channels with less variable flows (Shields Jr et al., 2003). The scour lines in the NES measured 1.92 m in channel depth and the wetted channel perimeter at this stage was thought to be representative of pertinent changes in channel form, as bank vegetation above this line appeared more established. The water surface height at this stage was used as the datum for calculating cross-sectional area changes. As no major tributaries entered the study reach, a continuity of steady, uniform flow through the reach was assumed with a discharge (Q) that was relatively constant for each site. Appropriate bank heights for the remaining reach cross-sections were estimated using the continuity equation in Equation 1, where these heights were approximated from resulting areas (A) using the calculated velocity (v) and a uniform discharge value (Q). The calculations utilized to establish cross-sectional areas were:

$$Q = vA \tag{1}$$

$$v = (kR^{2/3} S^{1/2})/n \tag{2}$$

where Q = flow discharge (m^3/s), v = flow velocity (m/s), A = the channel area of the wetted perimeter (m^2), k = 1 $m^{1/3}$/s (for SI), R = hydraulic radius, S = channel slope, and n = Manning's roughness value. Initial calculations required determining the flow velocity (v) for the NES using the Manning equation (Equation 2) and this value was established by: (i) using the measured channel slope (S = ±0.001), (ii) calculating the hydraulic radius (R) relating to the bank scour height where A = 26.1 m^2 (R = 1.4 m), and (iii) evaluating an appropriate Manning's roughness value (n) for this channel based on known roughness coefficients (from various sources) for typical sand-bed, Piedmont channels. As bed-material was primarily sand in all channels, the value for n was 0.039, 0.035 and 0.04 for the NES, SES and CS respectively and variations in roughness were attributed mainly to the amount of channel debris and flow obstacles. Bed-forms and bank roughness were however not considered in this study. The resulting flow velocity of 1.0 m/s, together with the known channel area (A) for the NES, was used in Equation 1 to give a discharge of ±26.0 m^3/s.

The flow velocities in the SES and CS could not be calculated using Equation 2 as for the NES, because R remained unknown, and hereby their velocities required approximation in reference to 1.0 m/s (velocity for NES). These approximations utilized known channels slopes (SES = 4.0 × 10^{-4}; CS = ±0.001) and appropriate roughness values (see above). Resulting velocities were 1.1 m/s for the SES and 0.9 m/s for the CS and by rearrangement of Equation 1 and the use of a uniform discharge (Q), their areas equated 23.6 m^2 and 28.8 m^2 respectively. The final step included designating the representative bank heights by fitting the calculated area values to the channel cross-section geometry plots. Average bank heights in the NES, SES and CS (i.e. heights representative of the scour line) were approximately 2.0 m, 1.9 m, and 2.6 m respectively.

2.2   Sediment Volume

Alterations in individual cross-sectional areas ultimately related to degradation and aggradation

of channel beds and banks, therefore the quantity of bed sediment which was mobilized could be

approximated by calculating the volumetric mass balance (Buchanan et al., 2012). The difference in

channel cross-sectional area was multiplied by half the distance to both adjacent upstream and

downstream transect pins to calculate a volume in cubic meters of bed material sediment moving

through or stored within each reach (Terrio et al., 1997; Martin and Church, 2006; Fraley et al., 2009). In

this study the sediment transport by suspension was not considered as important as bedload

transportation. The major interest was in monitoring adjustments channel form, and bedload is

attributed to bed and bank changes (Church, 2006). Bedload transport estimates for the duration of the

study period would be extended to predict an annual sediment budget for the reach. These volumetric

results were also compared to estimates for bed-material transportation for similar watershed sizes in

the physiographic region.

2.3   Grain-size Distribution

Sediment samples were taken from selected bed locations within each reach to determine any

changes in bed textures which may have accompanied alterations in channel topography after a series

of effective discharge events. For each of the reaches (two experimental and one control), a set of bed

sediment samples were taken comprising of two sand samples and two gravel samples which were

representative of the subsurface and the bed surface/ pavement sediments respectively. Both samples

types had been collected from locations within the stream channel that were characteristic of the

specific type of grain size sample based on field observations (e.g. channel bar or thalweg) and these

sample locations were marked for future comparative sample collection. This meant that both sand and

gravel samples in each reach were from subjective location choices but were consistent with cross-

sectional transect lines. Pebble counts (surface gravels) and volumetric (subsurface) samples were considered separately, because one was more descriptive of the flow competency whereas the other is more telling of the proportion of grain sizes and changes in bed texture.

Bed-material composition samples, with a grain size generally ≤ 2 mm, were collected using a cylinder-type sampler to extract a volume of subsurface sediments to a shallow depth of 5 cm. This depth was assumed to represent the 'active' bed-material layer and would not include significant historic sediments. Sampling was conducted using a 7.62 cm aluminium pipe which was worked into the channel bed. To retrieve the sample, the top of the open pipe was sealed with a mechanical pipe plug and the sediment was extracted by holding the base of the pipe closed using a small shovel inserted into the bed underneath the pipe. Whether samples were collected within a stream flow or on an exposed bar, this technique prevented significant sample losses upon extraction. The samples were transferred into labeled, quart-sized bags and returned to Georgia State University for laboratory grain-size analysis. Samples were dry-sieved using a Rotap sieve shaker at standard half-phi (½ φ) interval mesh sizes and the grain-size percentiles of D_{16}, D_{50} and D_{84} as well as the grain-size distributions were determined for all three study sites.

Gravel- or pavement samples with a diameter ≥ 2 mm were examined on site using a modified Wolman (1954) and Edwards & Glyson (1999) method. This method involved a random sampling technique within a predetermined channel bed area. A pebble count of 50-100 samples was taken within a fixed 1.2 m^2 (60 cm × 60 cm) grid plot whereby each sample was assessed for size in the field using a ½ φ unit class gravelometer.

The chosen locations for gravel and sand sample pairs were intended to best present the variation in grain-size and sediment texture within the reach. The representative grain size distribution of gravel (pavement) and sand (subsurface) for each reach was taken to be the average of each sample pair. This however meant that individual samples were still maintained separately (i.e. they were not

mixed) and their size distributions were measured separately in order to fully interpret bed texture dynamics. A statistical analysis of the resulting bed-material size distributions (a) between sites and (b) between survey dates for the same sites was conducted to scrutinize between sampling results. The significance in the difference in averaged grain sizes was assessed using both parametric and non-parametric tests because of the asymmetry in some bed sample distributions. Both the two-tailed t-test for unequal variances and the Mann-Whitney U Test were utilized for this purpose.

2.4   Stream Stage and Water Surface Slope

The closest operational stream gage to the study reach was ±8 km upstream from the NES (USGS 02203950 near Redan Rd.). For stream stage predictions further downstream a custom measuring staff was permanently installed in the upper part of NES within the channel and was monitored by taking readings over the duration of the study period. A rudimentary stream stage correlation between the USGS gage and the stage within the NES needed to be ascertained to provide continuous stage data for remotely monitoring flow stages. The base of this staff was set to the current water surface level (the datum) at the time of installation when the stage at USGS gauging station read 0.75 m. This stage approximated near base-level flow in Snapfinger Creek for that time of year.

Eight points were initially used to set up the correlation curve between the study reach and the active stream gauge upstream (reach-gauge correlation) and the highest flow measured 0.98 m at the USGS station. Only using these low flows would not have sufficed for this study, particularly due to the interest in sediment transportation at higher stages. To account for larger flows occurring in the study reach, an additional correlation was set up using the above USGS gauge and a second operational gauge (USGS 02203560) which was located ±3 km downstream of the study site (between-gauge correlation). Because there were no major tributaries entering between the study reach and this southern gauge site, it was considered practical to use the regression curve for between-gauge correlation and translate this
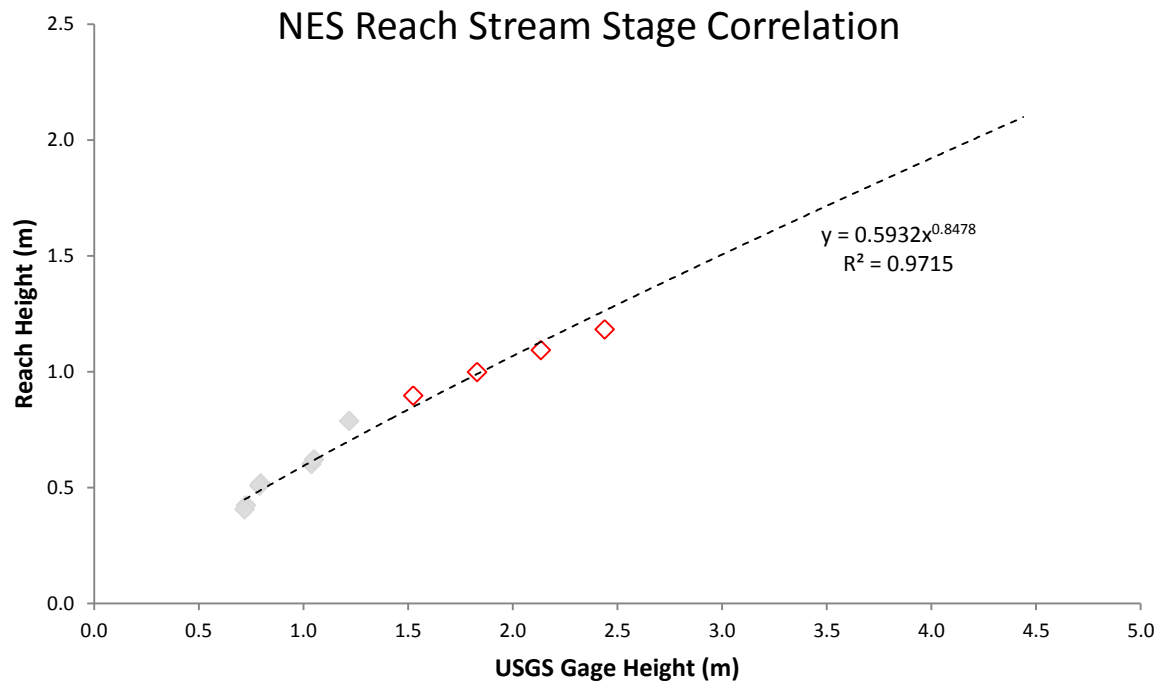
Figure 1.3 – Reach flow stage determination
Stage correlation for NES with a curve based on incorporating between-gauge correlations. Grey points represent the original staff readings and the red outlined points are translated from downstream USGS gauge site.

 curve onto the gauge-reach data plot. This new curve (Figure 1.3) provided a means of extrapolating

higher flows within certain reservations but at a suitable accuracy (r^2 = 0.97).

Because the study was interested in examining the movement of bed-material through

respective reaches, the critical threshold for entrainment of a largely sand-sized bed needed to be

established. This meant that the range of flows capable of fully mobilizing grain sizes of medium to

coarse sands (0.2 - 2.0 mm) through the reach needed to be calculated. Diagrams by Kuhnle (1993) and

Frings (2008) were used to empirically support the necessary critical shear stress (τ_{cr}) for Snapfinger

Creek as calculated here by the Shields equation:

$$\tau_{cr} = \tau^* \times (\rho_s - \rho)gD_{50} \tag{3}$$

where ρ_s = density of the solid (2,650 kg/m^3 for quartz predominance), ρ = density of water (1,000 kg/m^3), g = gravity (9.81 m/s^2), D_{50} = median subsurface grain size, and τ^* = Shields dimensionless shear stress (a value of 0.04 was used). A critical shear stress value greater than 0.5 N/m^2 was required to overcome the boundary shear stress of bed-material with D_{50} of 0.7 mm (median grain size based on pre-flood grain-size distribution measurements). This estimation was in agreement, although slightly greater than those supported by the above authors (0.3 - 0.4 N/m^2 for similar D_{50}). One possible explanation is that uniform bed sediments, as in this study, are entrained more selectively and at higher critical values than are sediment mixtures for a similar D_{50} (Church, 2006).

A conservative boundary shear stress (τ_0) needed to be established for an effective flow stage that would initiate the mobilization of bed-material load. The boundary shear stress was calculated for the channel dimensions of the reach using the following equation:

$$\tau_0 = \rho gRS \tag{4}$$

where ρ = density of the fluid (1,000 kg/m^3), R = hydraulic radius, and S = water surface slope. Measurements of the water surface slope were conducted at low flow and subsequent to cross-sectional field measurements of the pre-flood channel topography. A total station instrument was used to establish the slope along the middle of the channel across the approximate length of each reach (i.e. ±60 m). Such measurements gave a general idea of the channel grade in each site.

2.5   Effective Stream Discharge

Effective flow events were those flows that measured between 0.3 m and 1.92 m at the NES during the study period from September 2011 to January 2012. Because of the flashy nature of this stream and the short duration of the rising and falling limb during precipitation events, only stages above a selected discharge of 3.1 m^3/s (or a 0.7 m stage in NES) were considered threshold or effective events. These were considered events which were capable of mobilizing the full range of grain sizes

present in the active layer of the bed-material load. At this discharge the sandy subsurface material in all three sites would be mobilized based on above threshold shear stress calculations for the three sites (τ_{cr} for D_{50} subsurface was 0.3 - 0.5 N/m^2). Most of the surface gravels, however, would have required flows at higher threshold stages that where only possible at stages nearer 25.2 m^3/s (τ_{cr} for D_{50} gravel surface material of 14.0 mm was approximated at 10.0 N/m^2 using Equation 3). Continuity of flow was again assumed for the reach because no major tributaries enter between individual study sites and thus the effective discharge was roughly equal in all sites. The inundated channel area at this stage was translated to individual sites using the continuity equation (Equation 1). By the time the cross-sectional resurvey was taken in January 2012, there had been a total of 11 effective flow events through the reach. It should be noted that the SES had experienced one less effective flow event than the other two sites due to discontinuity in successive field data collection.

2.6   Rapid Geomorphic Assessment

Since the practice of restoration may itself be considered a disturbance (Chin, 2006; Unghire et al., 2011; Violin et al., 2011) the contribution of watershed based sediments has the potential to be more localized in this site. A rapid geomorphic assessment protocol was used to evaluate the potential sediment contribution by existing in-stream structures in the mitigation bank reaches. This assessment was performed by a coordinated rating of each structure's effectiveness in performing its intended task in the reach (Miller and Kochel, 2010; Buchanan et al., 2012). A subjective field-based survey was conducted of the most significant bank engineering practices along the entire restored reach (±585 m) to account for likely locations of degradation and aggradation exclusive to the experimental sites. The assessment protocol that was used was based on one used by Brown (2000) in his study on urban stream restoration practices, which itself is a protocol similar to the USEPA Rapid Bioassessment Protocol (Barbour et al., 1999) and others like it. The standard protocol evaluates (i) the performance of

structural restoration practices, (ii) the enhancement of aquatic habitat and (iii) the health of riparian vegetation along the stream banks. For the current study, however, only the 'structural integrity' and the 'effectiveness/ functionality' of bank installations were assessed for the Snapfinger Creek mitigation site because the potential contributions of bank material from restored reaches and their associated tributaries were of particular interest.

The survey sheet was based on a pre-determined set of criteria used to assess the following: (a) the percentage of engineering feature intactness; (b) the amount of dislocation of practice materials; (c) the degree of unintended erosion and deposition caused by the practice; (d) whether or not the practice was serving its intended purpose; (e) the likelihood of the practice acting as a source of sediments to the downstream channel. In an attempt to reduce the subjectivity of this assessment, a two-person team was utilized to base the scoring criteria on their best judgment. The assessment had been conducted three months following the final channel resurveys in 2012.

3   RESULTS

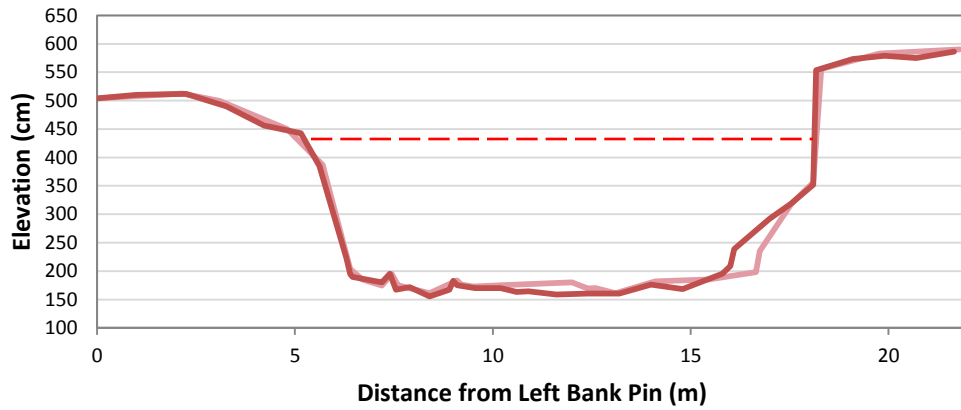### 3.1   Channel Cross-section Analysis

Channel cross-section changes over time were based on the increase or decrease in total area, which for this study meant that degradation received positive values (due to channel expansion) and aggradation received negative values (due to channel contraction). To calculate the change in channel area, the same datum line used for the pre-flood was also used for post-flood measurements (Figure 3.1, Figure 3.3, and Figure 3.5). This method diverged from the conventional use of the top of the pin as a datum, and the results were for the most part in good agreement with the study method used. Both the absolute (|scour + fill|) and the net change in channel area were calculated to identify the degree of alteration and the dominant transportation processes of bed sediments respectively taking place in each cross-section (Schoonover et al., 2007; Miller and Kochel, 2010; Buchanan et al., 2012). Pre-and post-flood cross sectional comparisons showed that each reach exhibited a dissimilar total amount of change, which meant that different processes were predominant in each reach (Table 1 and Figure 3.7). The largest amount of change experienced at any cross-section was 5.1 % (1.4 m^2) and the smallest amount of change was usually due to a balance of erosion and deposition and thus zero. Total changes (i.e. the amount of scour and fill) exhibited in all cross-sections for each site were significantly different between the control and the experimental sites (Table C). Changes between both experimental sites were however not statistically significant.

The average of the net changes experienced in all transects revealed that the two experimental reaches displayed a largely aggradational trend in channel modification (NES = -0.7 % or -0.2 m^2, SES = -1.0 % or -0.2 m^2) compared to the CS which had greater degradational channel characteristics (+1.7 % or +0.5 m^2) (Table 1). A definite pattern of upstream degradation becoming progressively more aggradational downstream was visible when looking at the average changes from CS through SES in Figure 3.7.

Control - Section 1
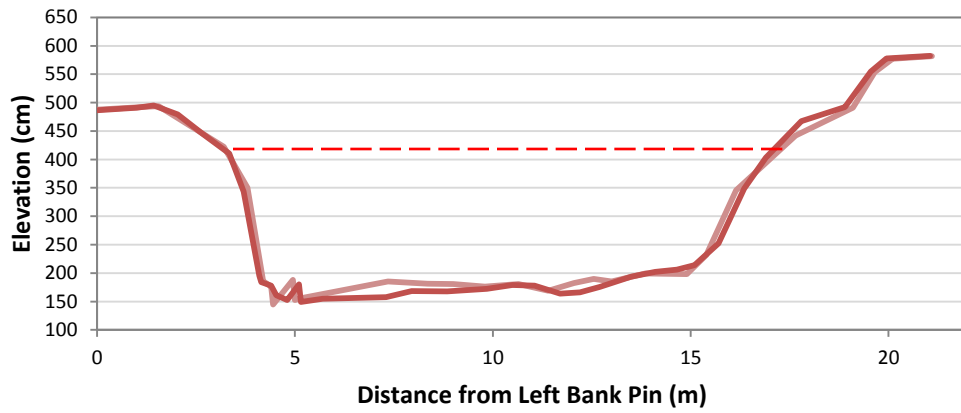
Control - Section 2

Control - Section 3
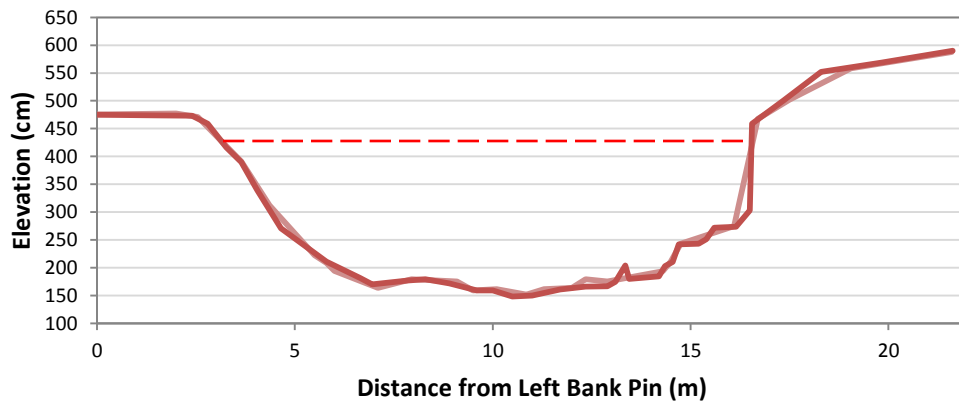
Pre Flood — Post Flood

Control - Section 4
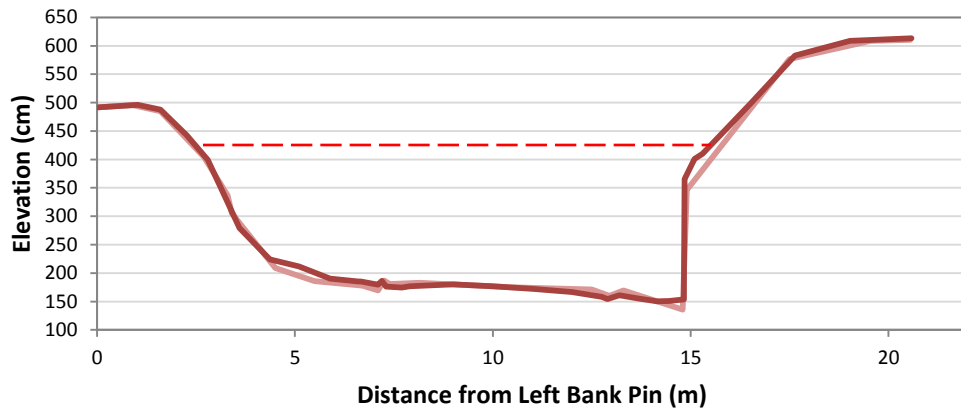
Control - Section 5
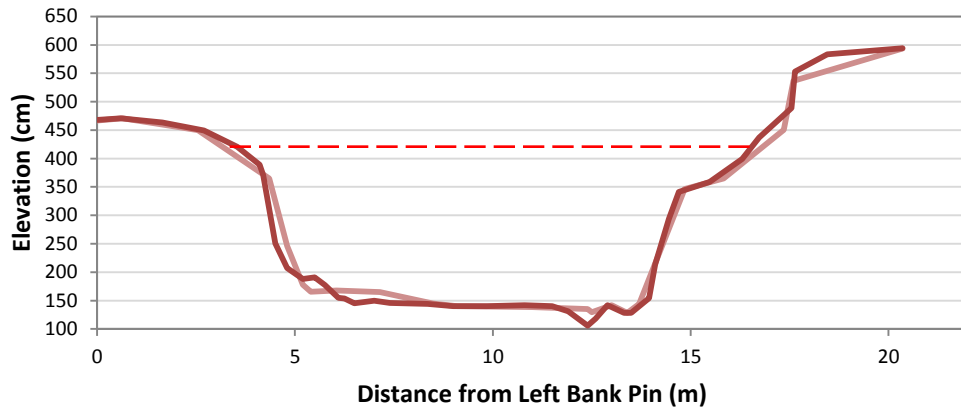
Control - Section 6
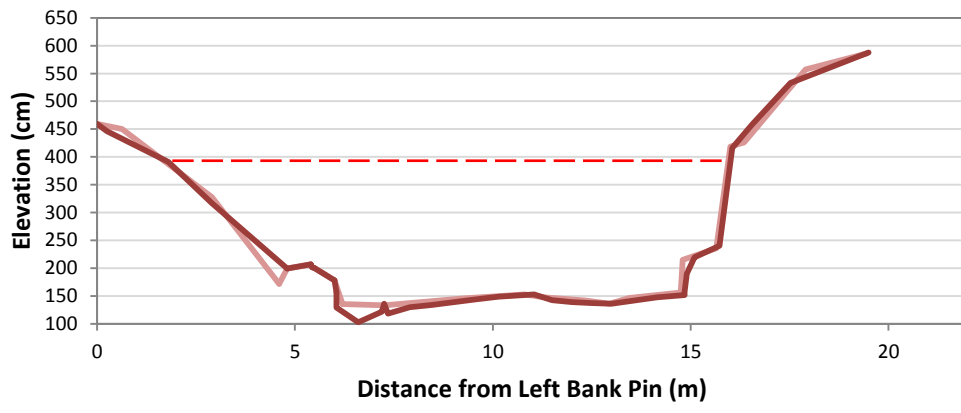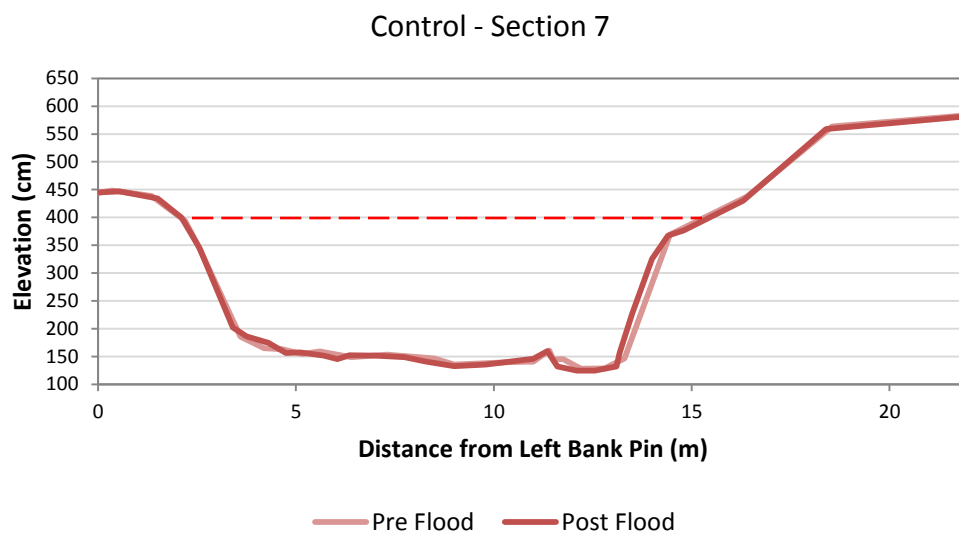
Figure 3.1 – Control Site cross-sectional analysis
Cross-sectional plots of pre- and post-flood channels in the CS. The red, dashed line denotes the high flow mark used for the area calculation.
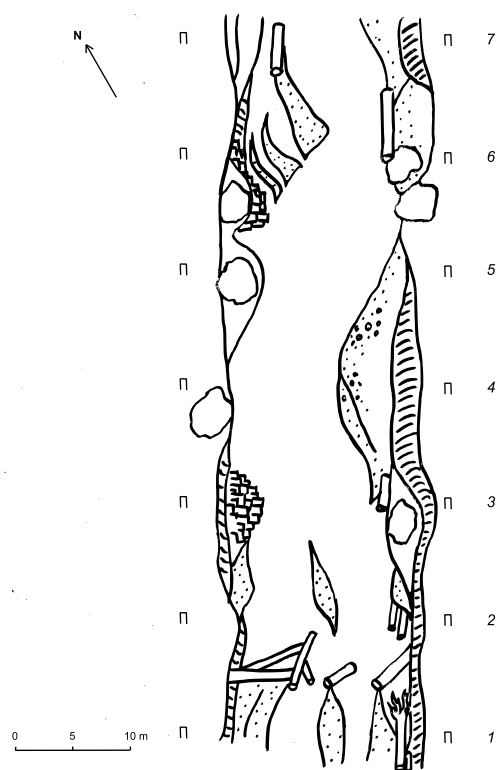
Figure 3.2 – Control Site sketch
Interpretation of the CS channel with locations of cross-section transects numbered in the upstream direction.

N Experimental - Section 1
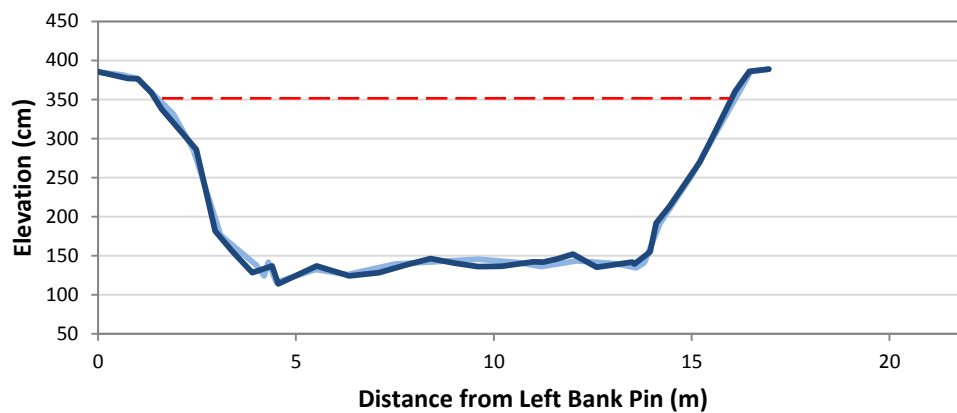
N Experimental - Section 2
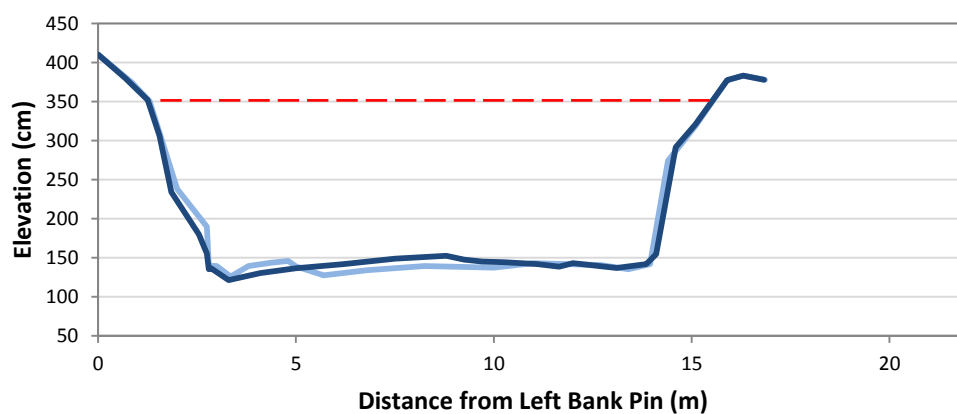
N Experimental - Section 3
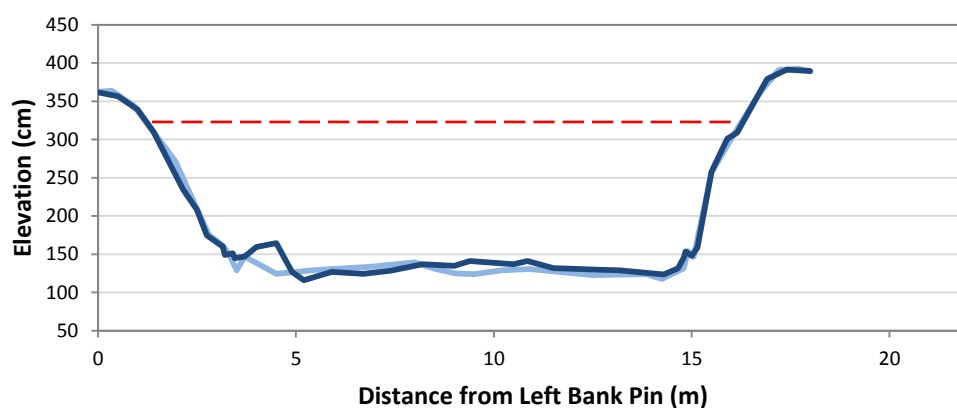
Pre Flood   Post Flood

N Experimental - Section 4
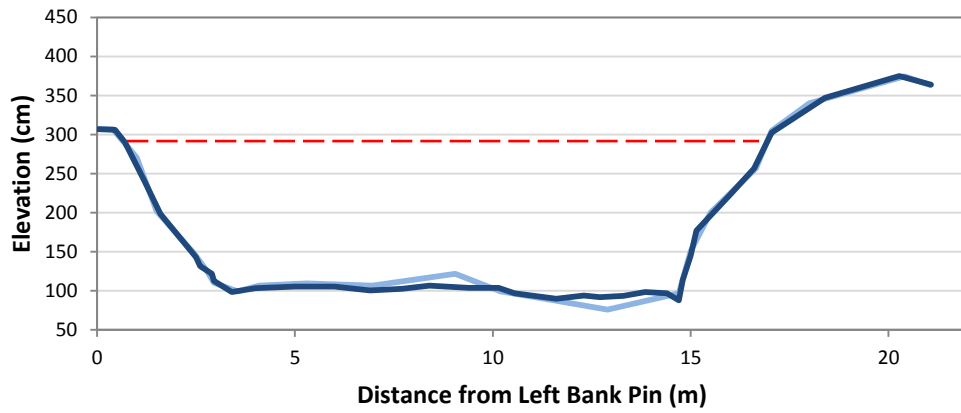
N Experimental - Section 5

N Experimental - Section 6
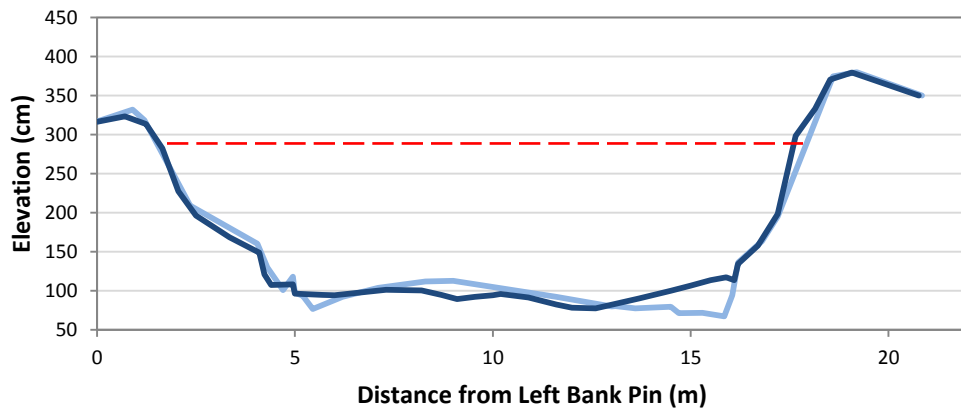
Pre Flood   Post Flood
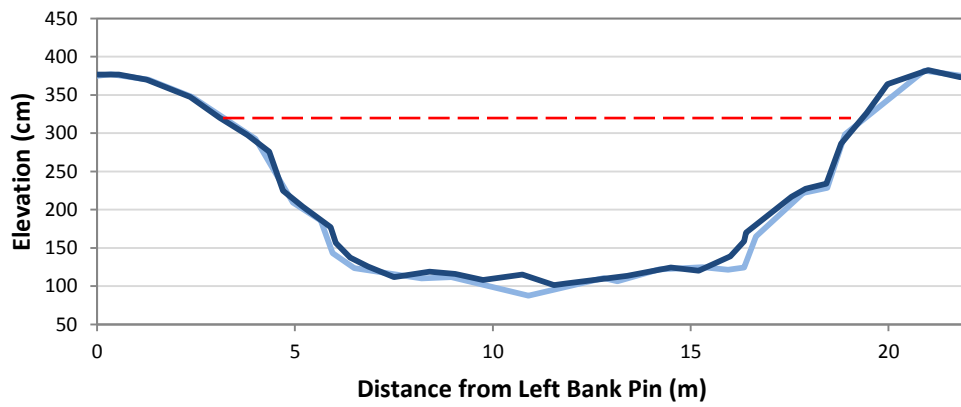
N Experimental - Section 7
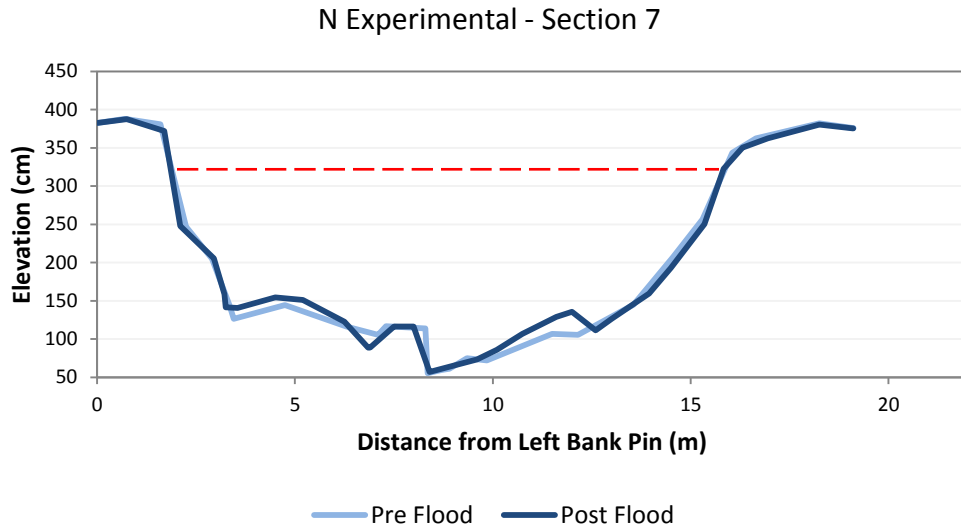
Figure 3.3 – North Experimental Site cross-sectional analysis
Cross-sectional plots of pre- and post-flood channels in the NES. The red, dashed line denotes the high flow mark used for the area calculation.

Figure 3.4 – North Experimental Site sketch
Interpretation of the NES channel with locations of cross-section transects numbered in the upstream direction.

S Experimental - Section 1
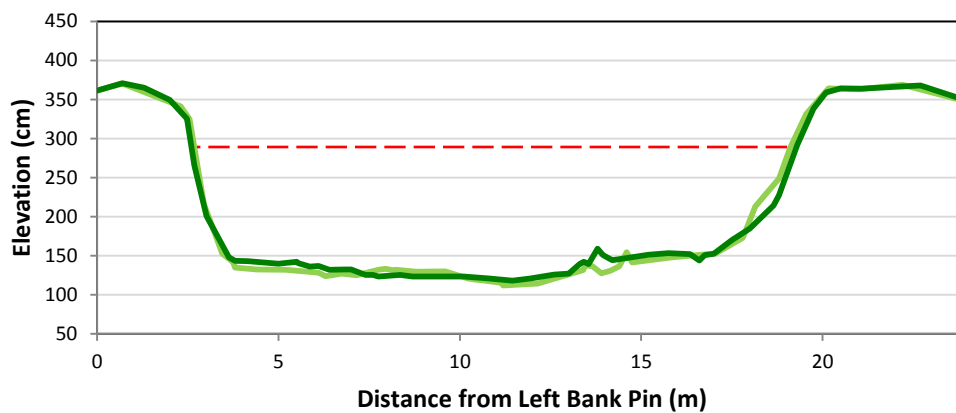
S Experimental - Section 2
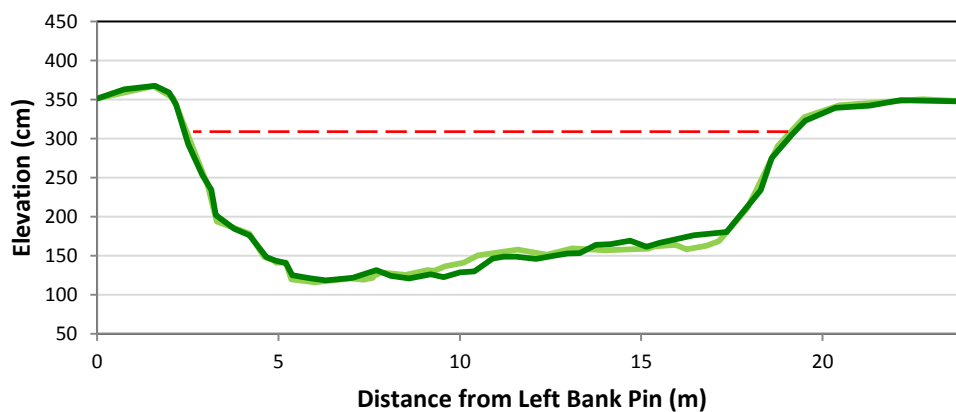
S Experimental - Section 3
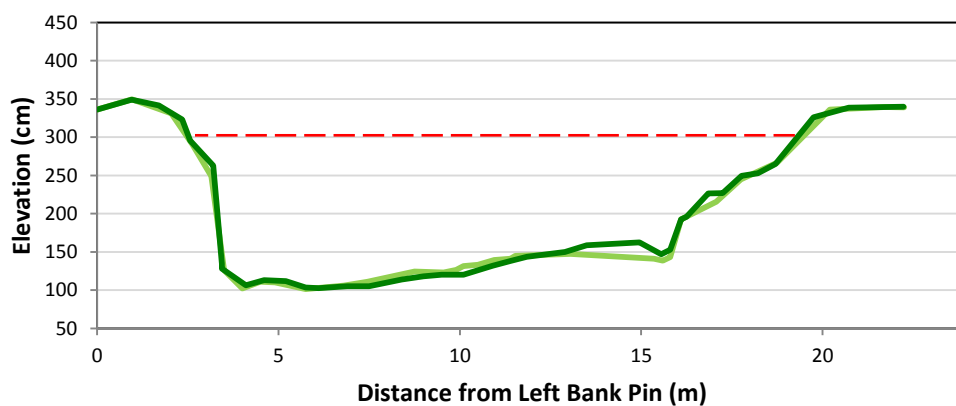
Pre Flood　Post Flood

S Experimental - Section 4
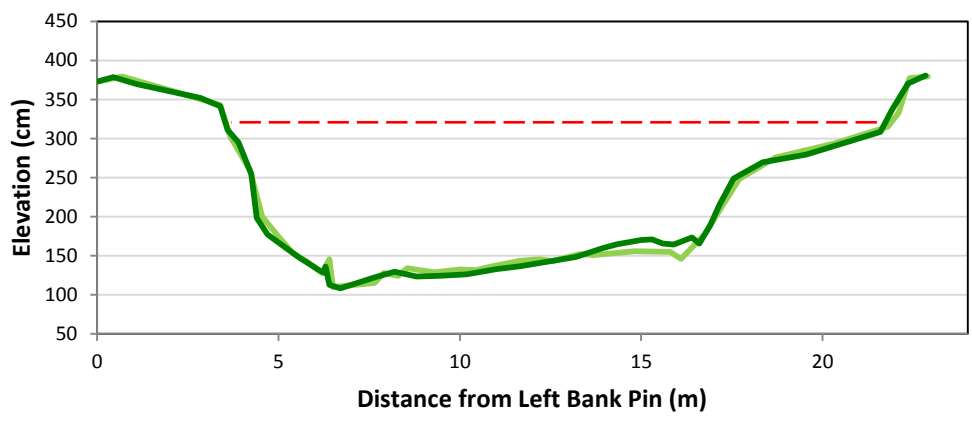
S Experimental - Section 5

S Experimental - Section 6
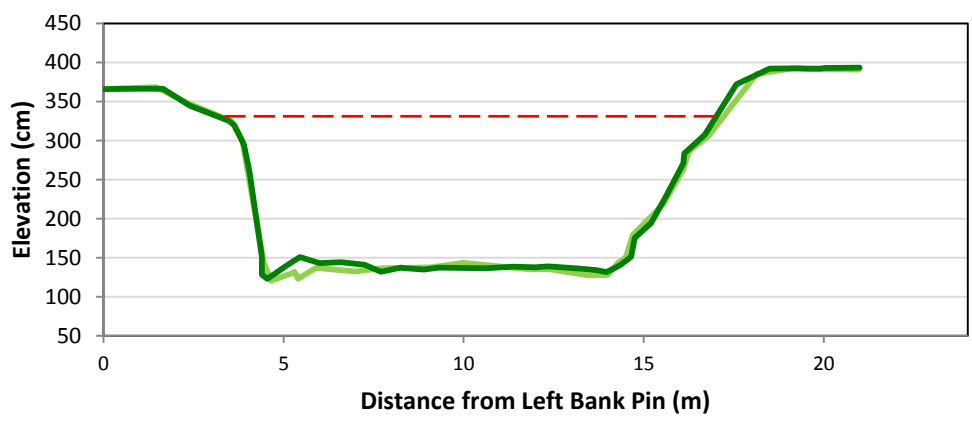
Pre Flood — Post Flood
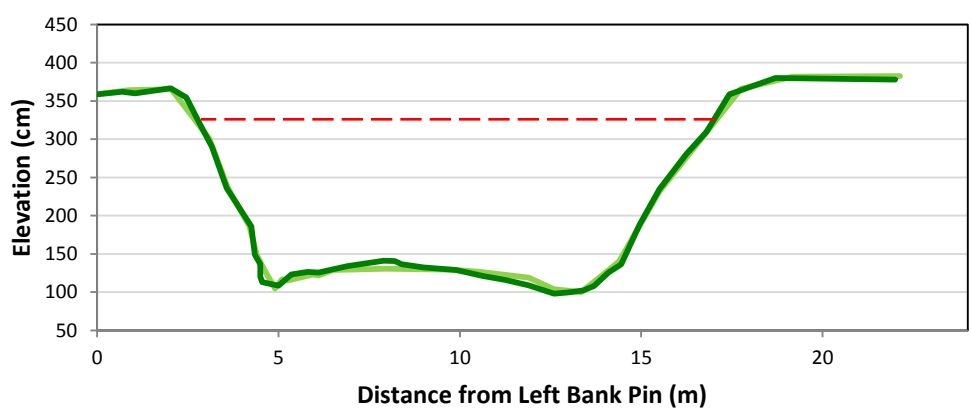
S Experimental - Section 7
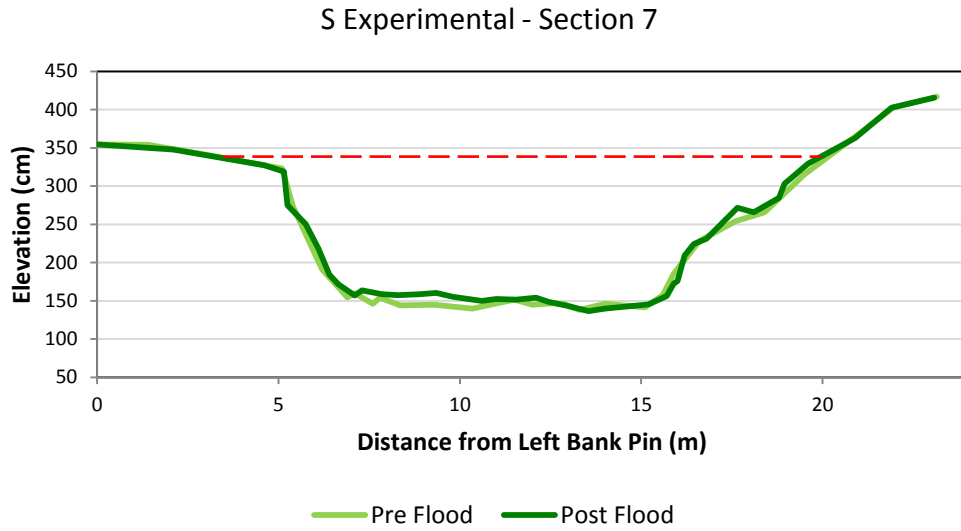
Figure 3.5 – South Experimental Site cross-sectional analysis
Cross-sectional plots of pre- and post-flood channels in the SES. The red, dashed line denotes the high flow mark used for the area calculation.
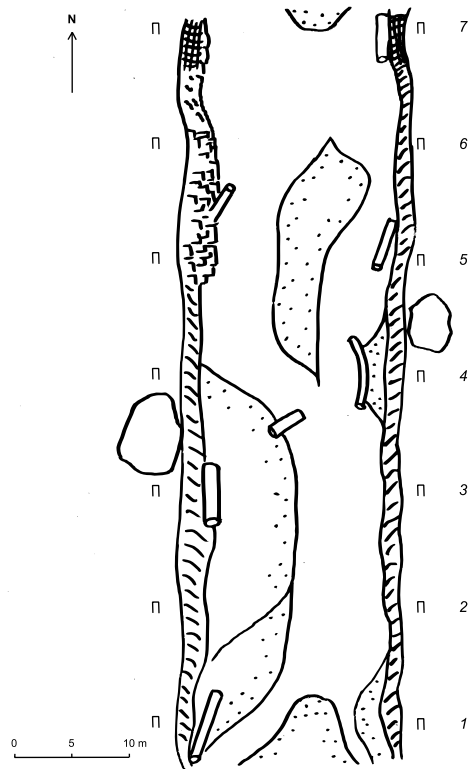
Figure 3.6 – South Experimental Site sketch
Interpretation of the SES channel with locations of cross-section transects numbered in the upstream direction.

Table 1 – Results from the cross-sectional resurvey analysis

Changes in channel cross-sectional area and channel volume for the study reach representing the total amount of scour and fill per cross-section as positive and negative values respectively. The post-flood channel dimension for each transect was used as the baseline for area change calculations. For channel volumes each cross-section represents a segment of the channel length. Positive and negative values represent the total amount of sediment eroded and deposited respectively.

| Site	Pin No.	Distance (m)	Segment Length (m)	Reference Height (m)	Pre-flood Channel Area (m²)	Area Change at Reference Stage (m²)	Area Change (%)	Absolute Value of Change (m²)	Absolute Value of Change (%)		Net Volume Change (m³)	Absolute Volume Change (m³)	Dominant Process
NES	1	0.0	10.0	2.18	26.0	0.05	0.2%	0.05	0.2%		0.55	0.55	degradation
	2	10.0	9.20	2.16	26.2	0.05	0.2%	0.05	0.2%		0.48	0.48	degradation
	3	18.3	10.0	2.01	25.6	-0.41	-1.6%	0.41	1.6%		-4.12	4.12	aggradation
	4	30.0	10.9	1.89	26.2	0.13	0.5%	0.13	0.5%		1.44	1.44	degradation
	5	40.0	10.0	1.60	25.9	0.20	0.8%	0.20	0.8%		1.98	1.98	degradation
	6	50.0	10.0	2.14	26.7	-1.09	-4.1%	1.09	4.1%		-10.9	10.9	aggradation
	7	60.0	10.0	2.20	25.1	-0.24	-1.0%	0.24	1.0%		-2.41	2.41	aggradation
				reach mean net change		*-0.19*	*-0.7%*	*0.31*	*1.2%*	net	*-13.00*	*21.90*	
SES	1	0.0	10.0	1.67	23.9	-0.24	-1.0%	0.24	1.0%		-2.43	2.43	aggradation
	2	10.0	9.10	1.67	23.6	0.00	0.0%	0.00	0.0%		0.00	0.00	-
	3	18.2	10.0	1.76	24.1	-0.38	-1.6%	0.38	1.6%		-3.76	3.76	aggradation
	4	30.0	10.9	1.84	23.7	0.01	0.0%	0.01	0.0%		0.12	0.12	-
	5	40.0	10.0	2.03	23.2	-0.33	-1.4%	0.33	1.4%		-3.29	3.29	aggradation
	6	50.0	9.40	2.09	23.8	0.05	0.2%	0.05	0.2%		0.51	0.51	degradation
	7	58.7	9.40	1.95	22.9	-0.77	-3.4%	0.77	3.4%		-7.25	7.25	aggradation
				reach mean net change		*-0.24*	*-1.0%*	*0.26*	*1.1%*	net	*-16.10*	*17.36*	
CS	1	0.0	10.0	2.43	27.3	1.39	5.1%	1.39	5.1%		13.9	13.9	degradation
	2	10.0	10.0	2.57	28.8	0.16	0.5%	0.16	0.5%		1.55	1.55	degradation
	3	20.0	10.0	2.55	27.6	0.23	0.8%	0.23	0.8%		2.33	2.33	degradation
	4	30.0	10.0	2.60	27.6	-0.07	-0.2%	0.07	0.2%		-0.67	0.67	aggradation
	5	40.0	10.5	2.73	27.4	0.80	2.9%	0.80	2.9%		8.41	8.41	degradation
	6	51.0	11.0	2.47	28.8	0.54	1.9%	0.54	1.9%		5.99	5.99	degradation
	7	62.0	10.5	2.54	27.6	0.19	0.7%	0.19	0.7%		2.00	2.00	degradation
				reach mean net change		*0.46*	*1.7%*	*0.48*	*1.7%*	net	*33.47*	*34.82*	

Total net change   4.38 m³
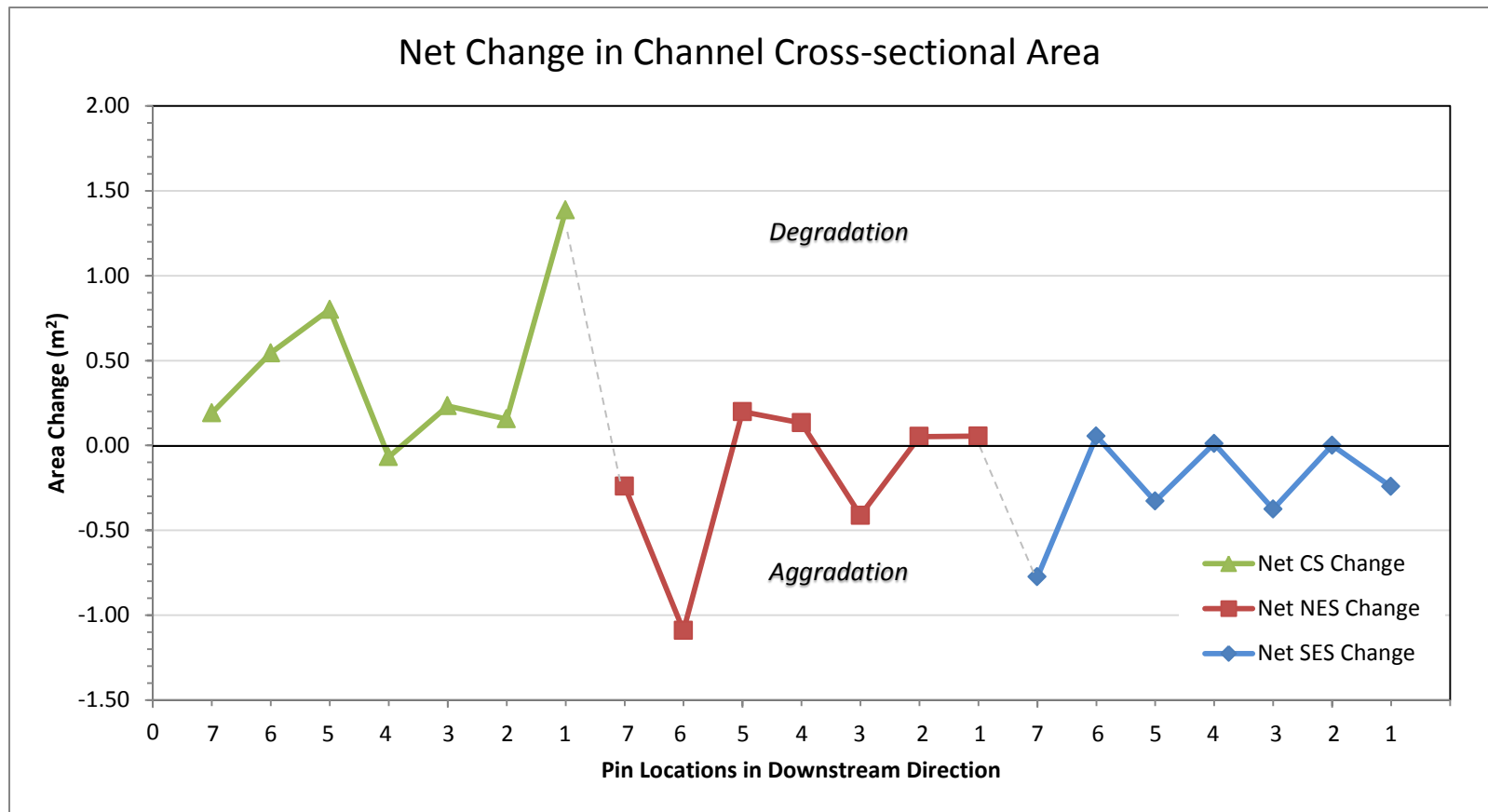
Figure 3.7 – Plot of channel area alterations
Changes in Cross-sectional geometry associated with the amount of scour (degradation) and fill (aggradation) experienced in each reach from the upstream to the downstream sites per transect pin in each site. Distances between pins and sites are not shown here.
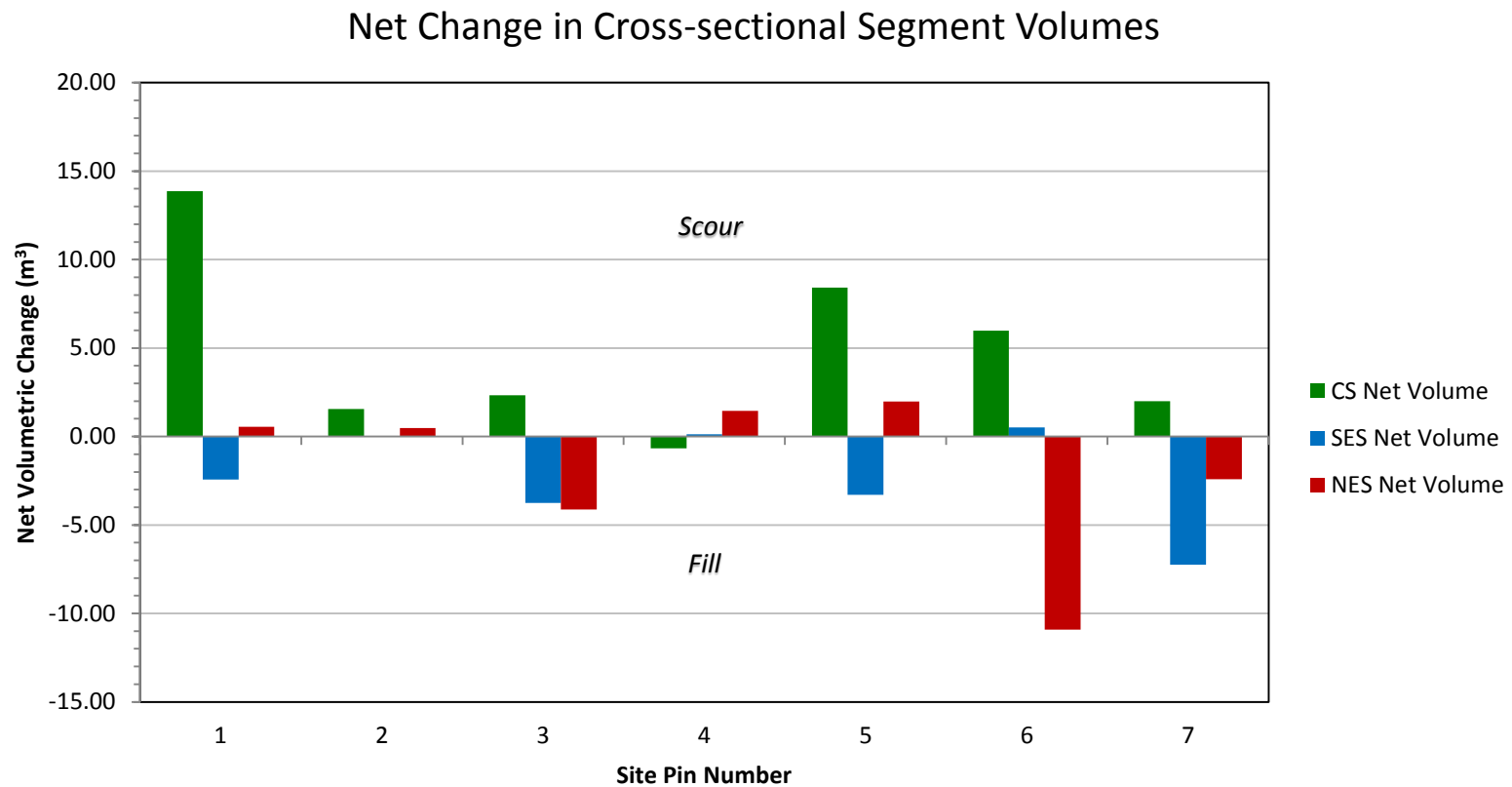
Figure 3.8 – Plot of volumetric channel changes per cross-sectional segment
Results showing the volumetric sediment gains and losses for each channel in the study reach. Positive values indicate a bed-material loss and negative values denote bed-material accumulations.

Aggradation in the SES was largely exhibited by lateral channel bar development in the upper reaches (pin 5-7) and to some degree in the lower reach (pin 1). An interesting feature in this site was the development of point bar along the right bank through transects of pin 3 to pin 4 (Figure 3.5 and Figure 3.6), as sediment from the mid-channel was generally eroded. In the NES aggradation was dominant mainly because of deposition in the upper reaches (pin 6 and 7) and occurrence of a log in mid reach (pin 3). The overall net change indicated channel narrowing, but excluding these above mentioned features would have made this channel degradational (Table 1). The pin 7 transect was essentially taken across a scour pool, where an influx of sand developed left and right bank point bars. The rock weir above this site was redirecting the flow towards the left bank, which although not measured in this study, had been severely undercut and eroded in the past. A probable legacy of this was that a prominent lower bank aggradation was taking place on the right banks along the pin 6 transect (Figure 3.6). In the remainder of the site there was a degree of thalweg migration as the channel meandered filling in previous thalweg locations and redistributing channel bar sediments (pin 2-6).

For the most part the CS experienced predominant channel erosion over the duration of the study period. As with the NES, there was a migration of the thalweg channel as meandering tended to scour new low-flow channels and degrade exiting channel bars (Figure 3.1). The resurvey of these channel banks along precisely the same transect line was complicated by the presence of tree roots, overhanging banks, and persistent vegetation cover. The comparative measurements of changes in bank dimension were therefore adjusted in the spreadsheet calculations to compensate for any anomalous bank adjustments. Bank aggradation did however take place along the left bank above a log in the channel along the pin 6 transect of and on the right bank along the pin 2 transect. The largest erosion took place below a channel debris constriction upstream of the pin 1 transect causing the removal of mid-channel bars (Figure 3.1and Figure 3.2).

The sum of the absolute changes for all transects in each reach, demonstrated that the total amount of both scour and fill relating to the alteration in each reach was different (Table 1). Statistical results from comparing these changes between individual sites were not considered significant ($p > 0.05$ for $\alpha = 0.05$ using Mann-Whitney test and two-tailed t-test) (Table C). When all three reaches were compared, the CS represented the largest amount of absolute change (1.7 % see Table 1), the NES experienced a moderate amount of change (1.2 %) and the SES exhibited the least amount of change (1.1 %). Average changes in the CS almost culminated to as much as the average changes of both experimental sites together (Table 1), but this does not directly indicate the CS as the sediment source. As demonstrated by the NES and SES channels, the measure of absolute change lends a greater understanding of the true amount of actual bed movement through each site and although the SES demonstrated the greatest degree of aggradation, the NES experienced considerably more bed mobility. These changes may also be translated into the relative amount of instability which exists in this channel (see Schoonover et al. (2007)).

Channel shape also warranted inspection following resurveying of channel sections, and in many cases these shapes could be attributed to possible stages according to the channel evolution model (CEM) for incising rivers (Simon, 1994). In this model, the channel morphology of a degraded stream progresses through six stages as it adjusts to imposed disturbances such as urbanization (Simon, 1989; Doyle and Shields, 2000; Niezgoda and Johnson, 2005). Stage I includes the premodified, unaltered channel form and as construction commences, the watershed becomes a significant sediment source as stream channels become channelized during Stage II. As the watershed becomes developed and impervious surface cover causes increased runoff during precipitation events, stream channels become incised (Stage III) and consequent bank failures cause channels to widen (Stage IV). The channel bed begins to aggrade with continued widening in Stage V, and channels ultimately reach a quasi-equilibrium form when bank heights are reduced sufficiently to allow for floodplain deposition during Stage VI.

Not enough time had accumulated for any of the channel dimensions to change significantly, especially since bed erosion and deposition was more prevalent than bank involvement and so channels were thought to represent their current stage in evolution. The CS had an entrenched, trapezoidal shape confined by its steeply incised banks and resembled a Stage III or IV. Riparian vegetation was set very high relative to the flow line and the upper right banks were frequently vertical in this channel. The NES also appeared trapezoidal in shape but bank angles were gentler compared to the CS banks with fallen riparian vegetation becoming established on the lower bank line (Figure 3.3 and Figure 3.4). This site was subjected predominantly to degradation of the channel bed but the magnitude of deposition concurrently occurring classified this site as aggradational and therefore qualifying it as a Stage V channel. The lower and characteristically aggradational SES had low bank heights, had more rounded channel dimensions with a pronounced convex bank shape particularly for the right banks. The SES, according to the CEM, would likely represent a late Stage V channel.

3.2   Sediment Volume

The total volume of sediment moving through each reach was estimated using the cumulative or net change in channel area as discussed above. Between the three sites there was a visible aggradational development in the downstream direction culminating in the SES channel (Figure 3.8). The total change in volume for the study was 4.4 m^3 of bed-material, which was representative of a net degradation (Table 1). While the SES had experienced one less effective flow event, the results albeit indicated that more loss of bed-material could be accounted for in the CS than could be balanced as influx into both study sites together. However, a sediment budget approach cannot be considered absolute in this instance because the surveyed reaches are not directly connected and the fate of sediments can only be loosely inferred. This implies that sediments are additionally stored in reaches between or beyond individual study sites. What these results do afford is an understanding of the

balance of scour and fill in all three reaches. Cumulative volumes of 13.0 m^3 and 16.1 m^3 were being

deposited in the NES and SES channels respectively and the CS experienced a net removal of 33.5 m^3 of

bed-material from its channel. This also makes the latter site with the most net change as would be

expected from the cross-section results. Because the segment volumes were calculated using the cross-

section areas, the patterns observed in the area change plots are repeated for the volumetric trends

(Figure 3.7 and Figure 3.8). The NES showed variations between degradation and aggradation, and

although it experienced a lower amount of aggradation than the SES, it generally shows a larger

absolute change in volume compared to that site (NES = 21.9 m^3 versus SES = 17.4 m^3).

Table 2 - Channel sediment volume densities
Bulk density estimates calculated using channel segment volumetric changes (method based on densities used by Fraley et al. (2009)).

grain size	density (g/cm^3)	kg/m^3	average sample representation
clay/silt	1.3	1330	0.1%
fine sand	1.5	1460	6.6%
med/coarse sand	1.7	1720	86.4%
fine gravel	2.3	2250	6.8%
medium gravel	2.4	2400	0.2%
	CS	NES	SES
sediment volume (m^3)	33.5	-13.0	-16.1
sediment mass (t)	58.3	-22.6	-28.0
net change for all sites (t)	7.6		

3.3   Grain-size Analysis

3.3.1   Bed-material Subsurface

The grain size distribution of bed-material samples for all three sites were generally uni-modal, moderately well to poorly sorted compositions of medium to coarse sand and fine gravel with typical D_{50} values ranging from 0.43 mm to 1.03 mm. Overall the resulting changes in grain size distributions within and between sites during the study period were not deemed statistically significant by Mann-Whitney tests or two-tailed t-tests ($p > 0.05$ for $\alpha = 0.05$) (Table C). For this study it was expected that bed sediments would be significantly different in the mitigation site compared to upstream locations due to observed bank erosion caused by bank engineering. The similarity between pre- and post-flood sample distributions points towards a common sediment source further upstream. Channel processes at work in the upper Snapfinger Creek watershed are still providing large sources of sand-sized bed load material, which is moving for the most part downstream as pulses with each high-flow event in the form of bed-forms (Knighton, 1998). The high proportion of sand in the channel bed implies that this material is likely frequently mobilized (Schoonover et al., 2007). Another expected result was that the sites in the lower reaches would experience a bed fining as upstream channels became more coarse grained. The results show no indication of this because the channel morphology controls in this reach are largely affected by bed processes such as the reworking of sand in the form of scour and fill.

All three channels had median grain sizes which did not shift significantly from that of coarse sand, but minor trends in distributions were noticeable. Pre- and post-flood grain-size distributions for the NES remained largely identical even though the latter was a larger sample quantity (Figure 3.9 and Figure A) with median D_{50} grain sizes not changing from around 0.7 mm (0.5 ϕ). The bed-material of the SES was not as univariant as it generally coarsened from a D_{50} of 0.5 mm to 0.7 mm. The reverse could be said for the CS, whose bed generally became less coarse as D_{50} went from 0.7 mm to 0.5 mm. It is clear from Figure 3.9 that both these sites have exchanged their distribution shapes for their pre- versus

post D_{50}, D_{16} and D_{84} samples. This reinforces the understanding that the same sediment is has been moving through the study reach from likely sources in the upper watershed and that mitigation activities have had little impact on contributing sediment to the study reach.

Certain observations were made over the course of sampling that may relate to sediment sources and morphological characteristics such as slope or bed-forms. As mentioned above, all sites had well developed ripple bed-forms but the CS had bed features not occurring downstream. These were mid-channel sediment bars which looked like sand 'tongues', distinct from the surrounding bed surface composition. Subsequent observations of these features confirmed that they were migrating downstream through the CS reach. Such bed-forms were particular to this site and did not appear to occur downstream in the restoration site.

Individual samples for each site corresponded to locations of aggraded thalweg channels, degraded channel bars and aggraded bars in the post-flood channel setting. The bed-material that was ostensibly representative of the dominant active bed layer, had a distribution of D_{16} = 0.3 mm, D_{50} = 0.5 mm, and D_{84}=0.9 mm. This deduction was based on the identification of characteristic sediments which tended to (i) fill previous thalweg channels and (ii) become removed from existing channel bars. An example of channel in-fill was shown by post-flood samples NES1 and SES2 (Table B) and previous channel bars were represented by pre-flood samples NES2 and CS1 (Table B). Average distributions which outline this trend are the curves for pre-flood SES and post-flood CS bed sediments as in Figure 3.9. This observation was not validated statistically by any correlation and was concluded only by inference based on grain-size analysis location features. Two of the four samples taken from the NES had poor sorting and generally had much larger D_{84} sizes (±2.5 mm) compared to those of the SES and CS sites. One sample in particular was a poorly sorted and weakly bimodal sediment mixture (Figure A).

CS Grain-size Distributions

NES Grain-size Distributions
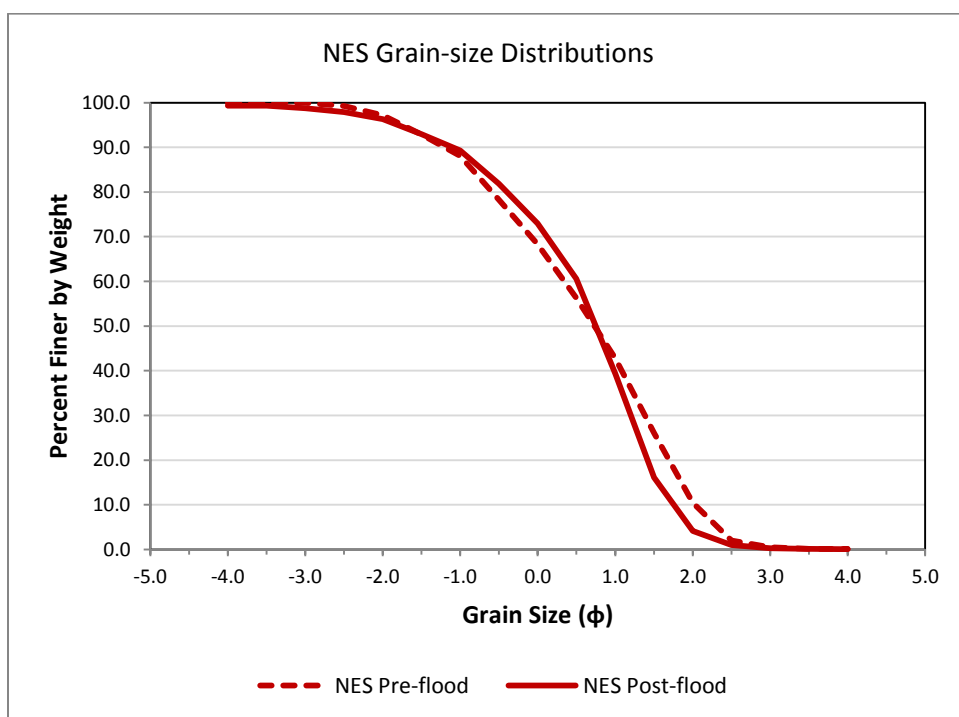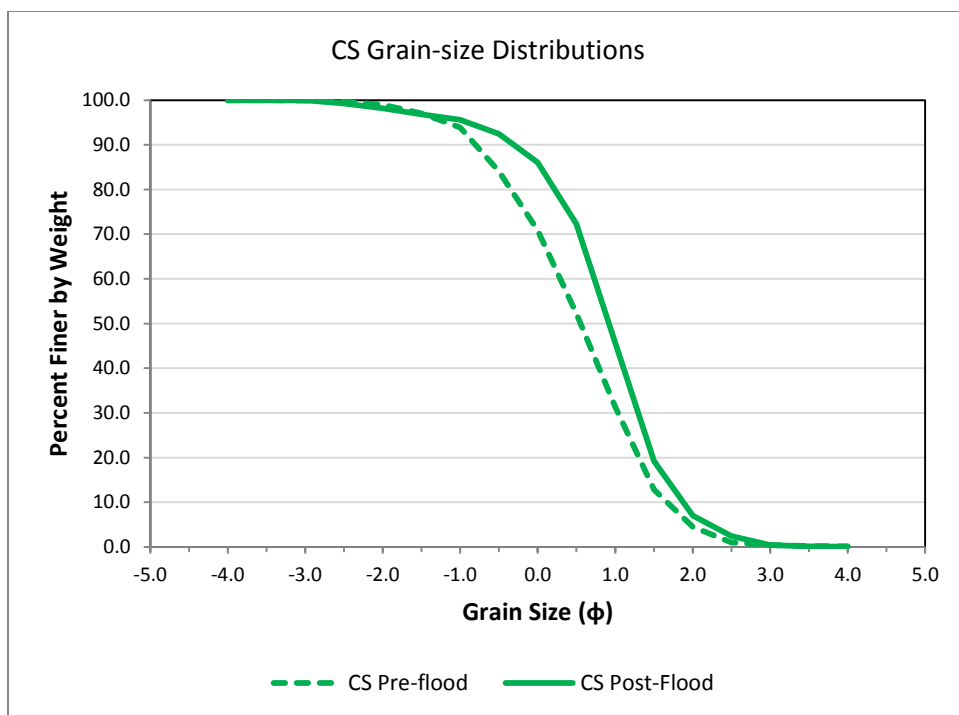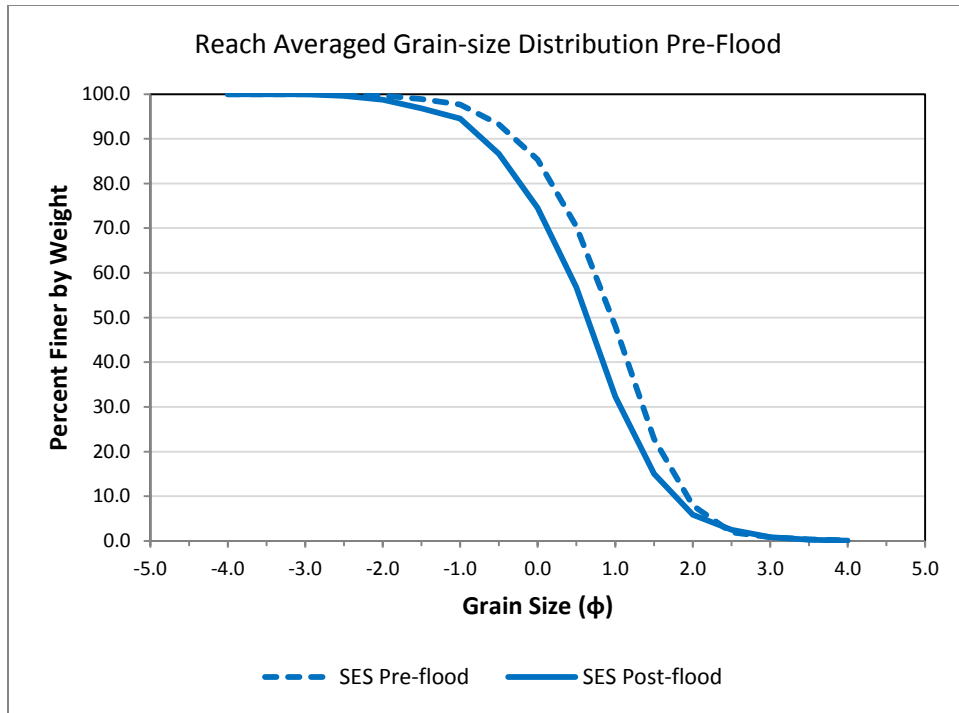
Figure 3.9 – Grain-size distribution plots
Graphical representation of the change in the averaged grain-size distribution for each site over a series of effective discharge events.

3.3.2 Pebble Counts

Each of the sites was represented by two pebble samples, which were averaged to give the

median D_{16}, D_{50} and D_{84} grain sizes. Resampling took place at a slightly higher stream stage compared to

pre-flood sampling and this may have caused coarser gravels to become preferentially more exposed.

Although the resulting changes in all three sites were not significant ($p > 0.05$ for $\alpha = 0.05$ using Mann-

Whitney and t-test) (Table C), the experimental reaches both had a greater proportion of coarse surface

material relative to the control site. The NES had the coarsest surface gravels both before and after

floods (Figure 3.10), with samples generally becoming more variable to a degree (i.e. both coarser and

finer), while keeping D_{50} unchanged. This coarseness of gravels corresponds to the fact that this site also

had the coarsest D_{84} for the grain-size analysis, therefore implying a local gravel source to the reach. The

CS experienced a coarsening of all three grain size fractions. There was little significant gravel

representation in this channel and the bed roughness seemed to be dominated instead by bed-forms

such as ripples.
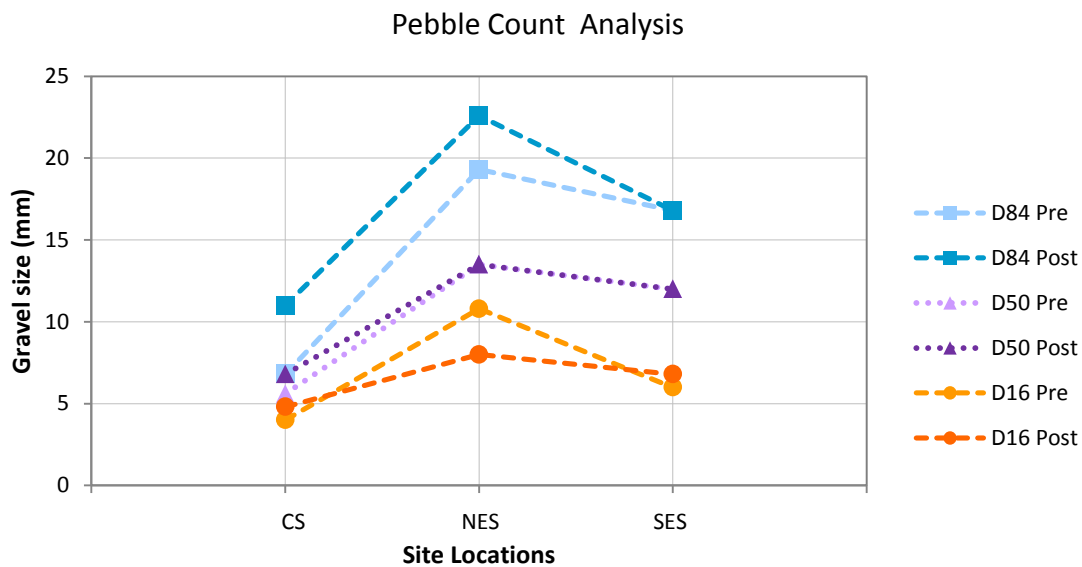
Figure 3.10 – Channel bed surface gravel analysis
Pebble count results showing the surface bed-material changes as measured by pre- and post-flood
samples in each site. The horizontal axis represents the relative downstream site locations and the
vertical axis shows gravel caliber.

3.4   Rapid Geomorphic Assessment

The results from this analysis proved that the 'hard' engineering practices (Kondolf, 1996) such

as riprap, rock vanes and weirs remained largely intact, whereas the more environmentally based

bioengineering features tended to have become severely impacted by high flows (with the exception of

rootwads). Out of the 15 practices evaluated (11 were omitted from this analysis) three experienced

significant dislocation and eight were impacted only slightly (Table 3). Those practices that were

significantly impacted certainly did not prove effective, nor did three additional practices that

experienced little dislocation. Because the vast majority of bank protection had been removed or

damaged by high waters, banks looked to be particularly susceptible to further erosion and would act as

potential sources of sediment supply to the channel. The northern half of the mitigation bank had

experienced more engineering and intervention than the southern half, and therefore this should have

been reflected in the sediment accumulation of downstream sites.

Table 3 - Rapid Geomorphic Assessment (RGA) results for the Snapfinger Creek Mitigation Bank
Assessment locations were labeled according to their position north or south of the road bisecting the restoration property (Snapfinger Woods Dr.) and were numbered in relation to their position downstream of the northern property boundary (Note: a map of these locations was not produced due to the greater importance of other methods used in the study and the more trivial nature of these results).

Code	Length	Practice	Type	% Intact	Dislocation	Erosion	Deposition	Effectiveness	Sediment Source
N1	5m	Log Vane	Flow Deflection	75-100	None	Moderate	Slight	No	sand/gravel
N2	20m	Rootwad	Bank Protection	75-100	Slight	Slight	None	Yes	sand/gravel
N3	10-12m	Rock Vane	Flow Deflection	75-100	None	Moderate	Slight	Yes	gravel
N4	15m	Log Revetment	Bank Protection	10-25	Significant	Slight	None	No	sand
N5	2x15m	Rootwad	Bank Protection	75-100	Slight	Moderate	Slight	Yes/No	sand/gravel
N6	25-30m	Coir Fiber Log	Bank Stabilization	10-25	Significant	Moderate	None	No	sand
N7	10-15m	Log Revetment	Bank Protection	0-10	Significant	Significant	Moderate	No	sand/silt/clay
N8	3-5m	Rock Vortex Weir	Grade Control	75-100	None	Significant	Moderate	Yes	sand/silt/clay
N9	50m	Coir Fiber Log	Bank Stabilization	75-100	Slight	Slight	Slight	Yes	all
S1	12-15m	Rootwad	Bank Protection	75-100	None	Moderate	Moderate	No	sand
S2	6-7m	Gravel Weir	Grade Control	75-100	Slight	Significant	Moderate	Yes	sand/gravel
S3	20m	Geotextile	Bank Stabilization	50-75	Slight	Significant	Slight	Yes	sand/gravel
S4	10-15m	Log Vane	Flow Deflection	75-100	Slight	Moderate	Moderate	Yes	sand/gravel
S5	20-25m	Rootwad	Bank Protection	75-100	Slight	Slight	None	Yes	silt/clay
S6	5-6m	Rock Revetment	Bank Protection	75-100	Slight	Slight	Significant	No	sand

4   DISCUSSION

A significant contrast of channel fill versus channel scour predominated cross-sectional changes in the experimental sites versus the control site. Short-term observations did not directly identify instabilities such as bank erosion, but did provide sufficient evidence of continued bed-material mobility which was suggestive of continued channel bed instability. The dominant degree of degradation occurring in the CS could be indicative of the headward migration of channel erosion, which may have been exacerbated by the mitigation banking activities downstream providing a sediment sink. A considerable sediment influx into the middle reaches (e.g. near the NES) would have likely produced downstream channel area contraction simultaneous to upstream channel expansion (Miller and Kochel, 2010). The stabilization of engineered banks within the mitigation site has perceivably been at the expense of propagating the same instability outside of this property.

The lowered sediment transportation in the SES was caused by gentler channel slopes with increasing bed elevation as the channel became choked with bed sediments. Upstream of this site, the CS is possibly deprived of sediment supply resulting in a propensity of bed scour. The CS banks are largely stable due to the cohesive nature of the cutbank sediments, but the channel bed continues to experience notable mobility. To the same degree (i.e. based on the absolute channel changes) both the NES and SES showed a great deal of bed reconfiguration with thalweg channels being filled and channel bars being relocated. This re-mobilization of bed-material consequently has a negative effect on benthic habitats and therefore impacts the maintenance of important aquatic habitats. The primary indicator of bed instability is the tendency of continuous bed-material movement within a channel. This is usually apparent as areas of excessive scour and fill, general channel down cutting or transient mid-channel bars such as what has been observed in Snapfinger Creek (Buchanan et al., 2012).

By establishing the amount of effective flows that have affected Snapfinger Creek over the study period and inspecting the duration of individual peak discharge events, it was possible to quantify the sediment transportation rate. Calculations showed that for the 11 events with discharges greater than 2.3 m^3/s, an average flux of ±0.4 m^3 of bed-material load per storm event had been moved through the entire study reach. On average there are 30 'effective' events affecting the reach on any given year, based on 2010-2012 USGS 15-minute discharge data for gauge station 02203590 (due to data availability at this gauge site). Each relevant flow event duration over the study period lasted on average around 11 hours, and it was speculated that a similar duration might apply to the past years' events. This resulted in a calculation of the total estimated volume of sediment flux through the reach which was 11.2 m^3/year (or 0.03 m^3/day). A bulk density approach was also used that was based on work by Fraley et al. (2009) for estimates of stream channel sediment mass storage. Such a conversion was necessary for comparison to regional rating curves, which frequently use mass per time to describe bedload transportation. Because the samples were not significantly different from each other, the bulk density parameters were averaged following Table 2. A calculated net amount of ±7.6 metric tons (t) of material had moved through or been removed from the reach over the duration of the study, and this rate was otherwise estimated to equate ±19.4 t/year (or ±0.1 t/day). If each site were to be compared separately, the transportation rate would increase from 0.2 to 0.4 t/day for both aggradation and degradation. These values were compared to other estimates based on studies conducted on drainage basins in the southeast, with a similar basin size to Snapfinger Creek. Work done by the USGS in the North Carolina (N.C.) Piedmont Province (Hazell and Huffman, 2011) estimated that bedload transport for a stream of comparable drainage area was 2.2 - 3.6 t/day for flows of 0.8 to 1.9 m^3/s. Another USGS study reported bedload transportation rates of 4.0×10^{-3} - 5.1 t/day for flows between 1.1 and 15.5 m^3/s for a stream in the N.C. Blue Ridge Province (Oblinger, 2003). A study on an urbanizing Piedmont watershed in Maryland estimated bedload transportation of 900 and 2,080 t/year (using two different transportation

formulas) for discharges ranging from 0.57 to 22.7 m^3/s (Yorke and Herb, 1978). Based on these

comparisons Snapfinger Creek is no longer experiencing the mass sediment fluxes associated with early

stages of watershed urban development, nor is it passing enough sediment through its reaches to

replicate less disturbed conditions (Wolman, 1967). These studies, however, only contribute loosely to

credible transportation boundaries for results in this study, because of factors distinguishing separate

watersheds such as topography, predominant land-cover, soil types and geology, and climatic conditions

amongst others. Significant error may be introduced by such simplistic method as cross-section survey

being translated into erosion and deposition volumes. Because we are not accounting for the

compromise of scour and fill during the survey period, the bed-material transportation rate may be an

underestimation of the actual rate (Lane et al., 1995; Church, 2006).

     The results from the sediment budget analysis indicate that the removal of sediments from the

upstream CS has only to an extent been balanced by the accumulation in the experimental reaches.

Because no major tributaries are thought to contribute significant sediment loads within the study

reach, an assumption of a balanced sediment discharge budget between all three sites could be loosely

applied (although sediment passing completely through the reach went largely unaccounted for).

Accumulation of bed-material within the experimental reaches did not account for the total loss of

sediments upstream of the mitigation site, as the sediment transportation rate for these was far less

than that of the latter. It was estimated that ±0.2 t/day was delivered into the NES and SES separately

and ±0.4 t/day was removed from the CS alone. This meant that within the ±500 m of stream length

separating the CS and NES, approximately 36 tons of sediment had either become stored as floodplain

alluvium or point bar deposits as it entered the mitigation site or it had passed through undetected. The

residence times of such sediment deposits should thus be considered when estimating the actual

sediment flux through a stream reach (Knighton, 1998), as this clearly becomes important when

evaluating sediment budgets. Between the two experimental reaches, which were ±700 m apart, an

estimated 5.4 tons of bed-material had been supplied to the SES. This equated only 9 % of the total load removed from the CS and implied that sediment production within the entire midsection of the mitigation site had decreased considerably.

A general coarsening of bed-material load would have the effect of protecting a reach from high flows (Buchanan et al., 2012), which are frequent in urban settings. Channel substrate was however coarser than what would have been predicted in these loamy clay rich Piedmont soils (Schoonover et al., 2007), and sufficient energy is required to mobilize these sediments. This energy has been made available by the flashy flows r associated with precipitation events. The current sandy bed sediments are the result of decades-long watershed urbanization possibly even combined with soil erosion dating back to pre-urban agricultural settings in the watershed. Such legacy sediments are common in many southern Piedmont streams (Ruhlman and Nutter, 1999; Schoonover et al., 2007; Mukundan et al., 2011) and it is well known that large sediment supplies in channels have the potential to undermine any rehabilitation efforts of degraded stream channels (Miller and Kochel, 2010).

Transient mid-channel bars and the occurrence of scour and fill sequences all indicate that the channel bed itself is in an unstable state. The general lack of gravel together with the continuous mobility of the current bed-material size fraction and development of channels bars, are not conducive to fish spawning and benthic invertebrate habitats, thereby degrading the potential channel aquatic ecology (Levell and Chang, 2008). Based on work by Leopold and Wolman (1957), in a figure relating channel style and bed material supply, the current reach slope and discharge range correctly classify this channel as a low sinuous sand-bed channel (Church, 2002). Downstream aggradation is the result of an abundant bed material supply from the watershed, and if the channel banks are stabilized by riparian vegetation then lateral adjustments are no longer possible. In such a case the channel will continue to steepen and incise to keep up with increased sediments from upstream (Simon, 1989).

Stream bank stability based on visual interpretation is 'moderately' to 'completely unstable' in the CS channel due to (a) excessive bank erosion and undercutting, (b) abundant and fairly recently exposed tree roots, (c) lack of waterline perennial vegetation, and (d) common tree falls in the channel (Henshaw and Booth, 2000). Degradation is still a problem in this site as bed material previously stored in the channel continues being removed (Rakovan and Renwick, 2011). It is also suspected that bank erosion may not have ceased although it was not identified in this short-term study.

The 'breaking-in' of the project site by a large storm event in its early completion stage in 2009 may have contributed to the currently more stable bank conditions in the experimental site (Buchanan et al., 2012). Although bank vegetation had been largely discouraged by the excessive removal of geotextiles by high flow, the remaining bank features have provided additional hydraulic roughness elements to dissipate high flow energies. These non-cohesive sandy banks were not a significant source of continued sediment supply to the reach, as grain-size analysis shows. The main source of sediment is the channel bed itself and the likely continuing upstream erosion taking place in the watershed. Sediment storage and mobilization was estimated only within the time resolution of this study, and therefore long-term predictions of transportation rates may be more or less than those estimated (Martin and Church, 2006)

In terms of the CEM the three sites would be designated a Stage IV (degradational) for the CS, a late Stage V (aggradational) for the SES, and a Stage IV (threshold) or V for the NES. These designations are for the most part superficial but nonetheless applicable to an incised reached that is adjusting to more stable channel morphologies. This is still very much the case for this study reach in Snapfinger Creek. It is predicted that the study reach as a whole, will with time approach the wider and shallower channel morphology currently demonstrated by the SES channel. In this particular site the channel has evolved through later instabilities caused by accumulations of excessive channel deposits.

5   CONCLUSION

The outlook of channel restabilization in this reach is dependent on too many factors for a confident prediction to be made. Because this project was undertaken without any baseline data of pre-development or pre-restoration conditions, it was difficult to assess whether current conditions were convergent of divergent from a more stable channel form. Urban channels have been shown to eventually restabilize after disturbance given enough time and space (Niezgoda and Johnson, 2005). Intervention in the form of bank mitigation or stream rehabilitation may not necessarily hasten restabilization, but will in some cases augment existing channel instabilities by displacing these elsewhere in the same reach (Henshaw and Booth, 2000; Chin and Gregory, 2005).

The restoration efforts have effectively reduced the stream power of this urban stream reach and have produced a reduction in sediment transport capacity and channel bed slope. Contrary to RGA results, no significant addition of sediments was sourced from impacted mitigation practices. Rather, the bulk of the sediment is still being supplied by highly mobile bed sediments in upper reaches. The mitigation site is currently liable to initiate greater upstream erosion by the continued accumulation of extensive volumes of sediment within its channels. While the implication of this study was not to examine the effectiveness of stream restoration techniques, several observations were made that would warrant further research. These include the possibility that reach-scale restoration efforts in urban settings have the potential to augment existing channel instability in adjacent reaches. The choice of restoration techniques and the appropriateness of the extensive use of bio-engineering in urban stream channels is additionally a worthwhile investigation.

Due to the fact that measurements could not always be taken on consecutive days in some cases and the occurrence of unpredictable high flows between measurement and sampling events, the results from this study become more suggestive regarding observations in a highly dynamic environment. Additional approaches such as discharge and sediment transport measurements may have

improved the accuracy of estimated flow velocities and annual bedload transportation yields. A longer period between cross-section resurveys would likely have rendered a greater understanding of the true trend for each channel adjustment as the current trends are possibly shorter-term adjustments. Sediment yield estimates were not convincingly comparable to existing sediment transport data because (i) many estimates measure suspended sediment loads, (ii) these studies are not contemporary regarding current anthropogenic watershed influences, and (iii) studies in this particular region are sparse. Regardless of these obvious shortcomings, the current study provides valuable information in a dynamic setting of the anthropogenic influences on stream channel morphology. Such influences are expected to increase in the future as we continue to modify and expand our urban environments and the groundwork developed by the current study and studies like it, will further our understanding in managing urban stream degradation.

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APPENDICES

Appendix A
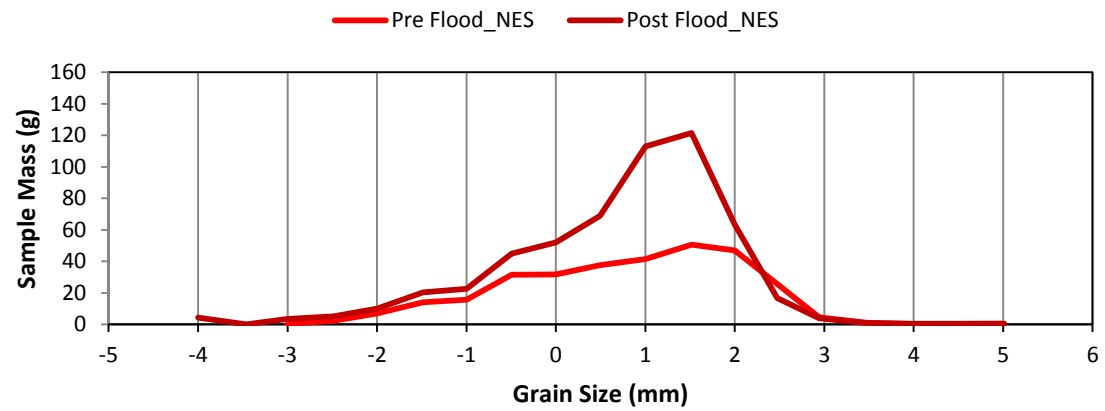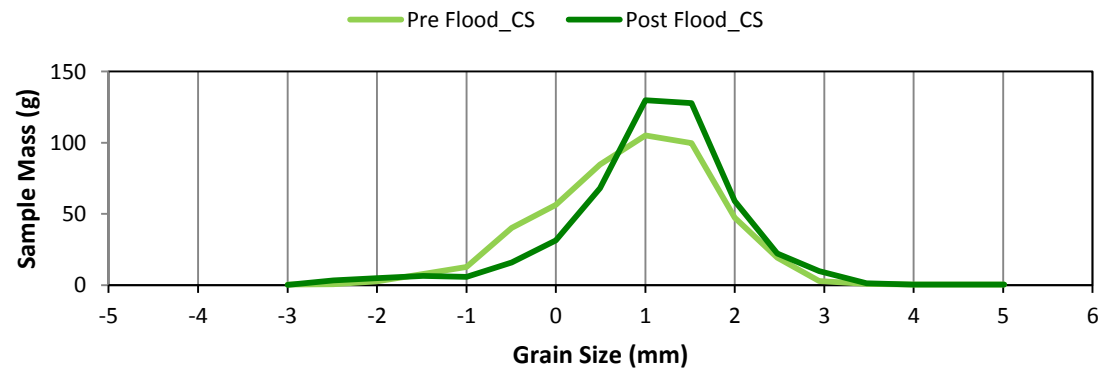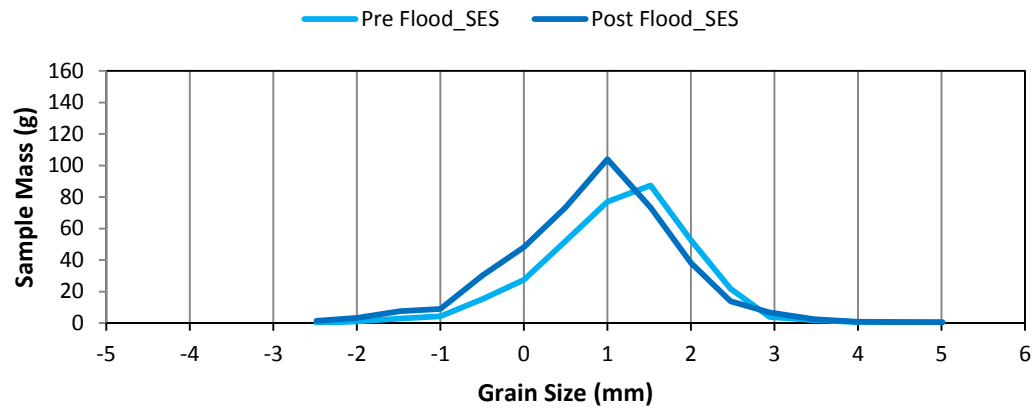
Figure A - Sample mass grain-size distribution
Grain-size distribution by sample weight per channel site.

Appendix B

Table B1 - Pre-flood sample analysis
Grain-size analysis data of pre-flood subsurface.

Sieve Diameter (ϕ)	Grain Size Diameter (mm)	Percent Finer by Site Sample								
		NES1	NES2	Avg. for NES	SES1	SES2	Avg. for SES	CS1	CS2	Avg. for CS
-4.0	16.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
-3.5	11.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
-3.0	8.0	99.9	100.0	100.0	100.0	100.0	100.0	99.9	99.8	99.9
-2.5	5.6	98.6	100.0	99.3	100.0	100.0	100.0	99.9	99.5	99.7
-2.0	4.0	94.6	99.8	97.2	99.6	99.8	99.7	99.7	98.2	99.0
-1.5	2.8	86.7	99.0	92.9	98.7	99.1	98.9	98.7	95.3	97.0
-1.0	2.0	78.3	97.8	88.1	97.4	97.9	97.7	97.1	90.6	93.9
-0.5	1.41	62.5	94.1	78.3	92.4	94.1	93.3	91.9	76.3	84.1
0.0	1.0	48.8	87.8	68.3	83.8	86.9	85.4	83.5	58.3	70.9
0.5	0.71	35.8	76.7	56.3	68.2	72.5	70.4	68.2	36.4	52.3
1.0	0.5	24.8	60.7	42.7	43.2	52.9	48.0	44.7	17.8	31.3
1.5	0.35	14.6	37.5	26.1	16.4	29.2	22.8	19.1	6.5	12.8
2.0	0.25	6.4	14.6	10.5	4.8	11.1	8.0	6.4	2.5	4.5
2.5	0.18	1.6	2.3	2.0	1.3	2.5	1.9	1.0	1.0	1.0
3.0	0.13	0.5	0.5	0.5	0.7	1.0	0.9	0.3	0.5	0.4
3.5	0.09	0.2	0.2	0.2	0.4	0.3	0.3	0.2	0.2	0.2
4.0	0.063	0.1	0.1	0.1	0.2	0.1	0.2	0.1	0.1	0.1
	D_{84} (mm)	2.5	0.9	*1.7*	1.0	0.9	*1.0*	1.0	1.7	*1.4*
	D_{50} (mm)	1.0	0.4	*0.7*	0.5	0.5	*0.5*	0.5	0.9	*0.7*
	D_{16} (mm)	0.4	0.3	*0.3*	0.3	0.3	*0.3*	0.3	0.5	*0.4*

Table B2 - Post-flood sample analysis
Grain-size analysis data of post-flood subsurface.

Sieve Diameter (φ)	Grain Size Diameter (mm)	Percent Finer by Site Sample								
		NES1	NES2	Avg. for NES	SES1	SES2	Avg. for SES	CS1	CS2	Avg. for CS
-4.0	16.0	100.0	98.6	99.3	100.0	100.0	100.0	100.0	100.0	100.0
-3.5	11.0	100.0	98.6	99.3	100.0	100.0	100.0	100.0	100.0	100.0
-3.0	8.0	100.0	97.5	98.8	100.0	100.0	100.0	99.9	100.0	99.9
-2.5	5.6	99.8	96.0	97.9	99.3	100.0	99.6	98.5	99.9	99.2
-2.0	4.0	99.8	92.8	96.3	97.6	100.0	98.8	96.8	99.6	98.2
-1.5	2.8	99.5	86.4	93.0	93.7	100.0	96.8	95.2	98.5	96.8
-1.0	2.0	99.2	79.4	89.3	89.1	99.9	94.5	94.2	97.0	95.6
-0.5	1.41	97.8	66.0	81.9	74.5	98.9	86.7	92.7	92.2	92.4
0.0	1.0	93.2	52.8	73.0	55.9	93.2	74.6	89.4	82.8	86.1
0.5	0.71	81.7	39.4	60.6	38.1	75.4	56.8	79.3	65.3	72.3
1.0	0.5	54.0	24.6	39.3	23.7	40.8	32.3	52.0	39.2	45.6
1.5	0.35	21.3	10.9	16.1	14.7	15.4	15.1	20.0	18.3	19.2
2.0	0.25	5.2	3.0	4.1	7.2	4.6	5.9	5.6	8.4	7.0
2.5	0.18	1.2	0.8	1.0	3.5	1.5	2.5	1.9	3.0	2.5
3.0	0.13	0.2	0.3	0.3	1.3	0.5	0.9	0.4	0.5	0.4
3.5	0.09	0.0	0.2	0.1	0.4	0.1	0.3	0.1	0.2	0.1
4.0	0.063	0.0	0.1	0.1	0.1	0.0	0.1	0.1	0.1	0.1
	D_{84} (mm)	0.8	2.5	*1.6*	1.8	0.8	*1.3*	0.8	1.0	*0.9*
	D_{50} (mm)	0.5	0.9	*0.7*	0.9	0.5	*0.7*	0.5	0.6	*0.5*
	D_{16} (mm)	0.3	0.4	*0.4*	0.4	0.4	*0.4*	0.3	0.3	*0.3*

Table B3 - Pre-flood pebble count analysis
Pebble count data for pre-flood surface gravel samples.

Grain Size Diameter (mm)	Pebble Sample Counts								
	NES_A	NES_B	Avg. for NES	SES_A	SES_B	Avg. for SES	CS_A	CS_B	Avg. for CS
128	0	0	0	0	0	0	0	0	0
90	1	0	0.5	0	0	0	0	0	0
64	1	0	0.5	0	0	0	0	0	0
45	1	3	2	0	3	1.5	0	0	0
32	8	3	5.5	0	6	3	0	0	0
22.6	18	4	11	2	11	6.5	0	0	0
16	18	17	17.5	5	18	11.5	2	5	3.5
11	11	20	15.5	15	17	16	6	4	5
8	13	15	14	19	13	16	14	17	15.5
5.6	6	8	7	19	3	11	17	20	18.5
4	1	4	2.5	7	2	4.5	6	9	7.5
2.8	0	6	3	4	1	2.5	6	5	5.5
2	2	1	1.5	1	0	0.5	1	1	1

D_{84} (mm)	22.6	16	**19.3**	11	22.6	**16.8**	8	5.6	**6.8**
D_{50} (mm)	16	11	**13.5**	8	16	**12**	5.6	5.6	**5.6**
D_{16} (mm)	16	5.6	**10.8**	4	8	**6**	4	4	**4**

Table B4 - Post-flood pebble count analysis
Pebble count data for post-flood surface gravel samples.

Grain Size Diameter (mm)	Pebble Sample Counts								
	NES_A	NES_B	Avg. for NES	SES_A	SES_B	Avg. for SES	CS_A	CS_B	Avg. for CS
128	2	0	1	0	0	0	0	0	0
90	1	0	0.5	0	0	0	0	0	0
64	1	0	0.5	0	1	0.5	0	0	0
45	2	0	1	1	4	2.5	0	1	1
32	6	6	6	1	7	4	1	0	0.5
22.6	15	14	14.5	1	10	5.5	2	1	1.5
16	15	15	15	7	24	15.5	7	3	5
11	23	25	24	19	18	18.5	18	10	14
8	11	13	12	28	15	21.5	19	20	19.5
5.6	6	7	6.5	20	5	12.5	20	25	22.5
4	0	0	0	1	0	1	8	12	10
2.8	0	0	0	0	0	0	0	2	1
2	0	0	0	0	0	0	0	0	0

D_{84} (mm)	22.6	22.6	**22.6**	11	22.6	**16.8**	11	11	**11**
D_{50} (mm)	16	11	**13.5**	8	16	**12**	8	5.6	**6.8**
D_{16} (mm)	8	8	**8**	5.6	8	**6.8**	5.6	4	**4.8**

Appendix C

Table C1 - Statistical analysis of cross-section resurvey results
Testing the statistical significance of the net and absolute changes in channel area between sites using two methods of analysis.

	Net scour and fill			Absolute area changes		
	NES and SES	**NES and CS**	**SES and CS**	**NES and SES**	**NES and CS**	**SES and CS**
	$p = 0.38^a$	$p = 0.02^a$	$p = 0.006^a$	$p = 0.71^a$	$p = 0.46^a$	$p = 0.38^a$
	$p = 0.82^b$	$p = 0.04^b$	$p = 0.02^b$	$p = 0.78^b$	$p = 0.49^b$	$p = 0.31^b$

-

[a] Mann-Whitney u test

[b] two-tailed paired t-test

$\alpha < 0.05$

Table C2 - Statistical analysis of sediment sampling results
Testing the statistical significance changes in sediment character for pre- and post-flood samples.

	Grain-size analysis			Pebble-count analysis		
	Pre- versus post-flood			*Pre- versus post-flood*		
	CS	**NES**	**SES**	**CS**	**NES**	**SES**
	$p = 1.00^a$	$p = 0.34^a$	$p = 0.62^a$	$p = 0.61^a$	$p = 0.55^a$	$p = 0.92^a$
	$p = 0.93^b$	$p = 0.02^b$	$p = 0.20^b$	$p = 0.13^b$	$p = 0.97^b$	$p = 0.35^b$

-

[a] Mann-Whitney u test

[b] two-tailed paired t-test

$\alpha < 0.05$