STREAM CHANNEL INCISION OF THE BLUFF'S PARCEL TRIBUTARY, DELAWARE: SEDIMENT PRODUCTION CAUSED BY RECENT LAND USE CHANGES IN DELAWARE'S COASTAL PLAIN

by

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ABSTRACT

This study illustrates the use of dendrogeomorphic analyses of tree roots for determining time-averaged, channel incision rates at the Bluff's Parcel Tributary, a Strahler second order stream located in the Coastal Plain of Delaware. A combination of both macroscopic and microscopic analysis of the cellular structure of roots from three trees are used to determine the year of exposure (i.e., the onset of erosion) and subsequent rates of incision in the channel. Results indicate that incision rates vary from 0.019 m yr^{-1} to 0.022 m yr^{-1} and suggest that the channel has been incising for approximately 50 years. The volume of sediment removed during this period is approximately 744 m^3, or an average of 14.9 m^3 yr^{-1} of sediment delivered to Blackbird Creek since the onset of erosion. Analysis of land use land cover change observed in aerial photographs from A.D. 1937 to A.D. 1992 indicates a coincidence of increased urbanization in the watershed at the onset of incision. The results illustrate how minor amounts of urbanization in the uplands of a watershed can have significant impacts on small streams. Given the density of similarly sized tributaries undergoing an analogous channel response throughout the Blackbird Creek watershed, the sediment load contribution of these incising tributaries has the potential to negatively impact ecologically sensitive estuarine tidal environments.

Chapter 1

INTRODUCTION

The interconnected nature of the earth, when coupled with a globalized human society, results in landscape manipulations that often sum to large-scale environmental impacts over time (Syvitski and Kettner, 2011). For example, many observed 19th and 20th century land cover/land use changes, especially where forests are converted to a mixed agricultural and urban environment, result in increased surface runoff and channelization of flows (Wolman, 1967; Wolman and Schick, 1967; Leopold, 1973; Hollis, 1975; Booth, 1990; Pizzuto et al., 2000). Such changes in the surface hydrology often result in a period of channel adjustment for transport-limited systems, manifested in unstable banks, incised and enlarged channels, and/or increased sediment loads. All of these effects can prove detrimental to the existing ecosystem through habitat transformation (Wolman, 1967; Hollis, 1975; Booth, 1990; Pizzuto et al., 2000). While our understanding of the types of channel response is well documented, the onset and rates of change are not always well understood in many settings.

In this thesis, geomorphic, hydrologic, sedimentologic, and dendrochronologic data are collected and used to evaluate the onset and rate of stream-channel incision in the Bluff's Parcel Tributary of the Blackbird Creek, Delaware. Geomorphic properties of the channel provided insights as to the nature of the channel adjustment. The hydrologic properties observed at the site proved useful in an assessment of channel erosion capability and causality. Sedimentologic characteristics of the channel bed and the floodplain proved useful in assessing channel movement and the relationship between the channel and the floodplain. Finally, a novel dendrogeomorphic analysis of exposed roots in the channel provided a means of quantifying the onset and rate of channel incision. The results provide insight into the likely causality of incision (i.e., the effects of deforestation and other anthropogenic alterations to the watershed) and the volume and flux of sediment delivered to the Blackbird Creek estuary over time. On a regional scale, the similarity of the Bluff's Parcel Tributary to other tributaries in same and adjacent watersheds provides an analog for evaluating poorly understood rates of sediment flux in the coastal uplands of Delaware. On a broader scale, this thesis adds to the relatively few dendrochronologic studies that use root-exposure period to evaluate channel incision rates over time.

Chapter 2

STUDY AREA

The Bluffs Parcel Tributary of Blackbird Creek is located on the Blackbird Creek within the Delaware National Estuarine Research Reserve (DNERR), Townsend, DE, which is within the broader Atlantic Coastal Plain Geologic Province (39°23'33.86"N, 75°38'21.35"W; Figure 1). The tributary is a freshwater channel with a headwater elevation of 14 m AMSL. The tributary flows a total of 559 m before joining the Blackbird Creek at sea level. Thin mud beds and oxidized poorly sorted siliciclastic gravels and sands can be observed in the channel walls and along the bed of the tributary. The floor of the channel is often covered with sand and gravel with no obvious upstream source. As the channel approaches mean sea level the bed material rests on a resistant bluish clay typical of tributaries in the area and indicative the Calvert Formation (Fletcher III, 1988; Fletcher III et al., 1992). Blackbird Creek is a sub-estuary that flows into the much larger Delaware Bay estuary.

The surficial geology at the site is mapped as the Pleistocene aged Columbia Formation and Lynch Heights Formation (Jordan, 1964; Groot and Jordan 1999; Ramsey, 2005). The dominant terrestrial lithofacies in these formation are unconsolidated fluvial silts, sands, and gravels deposited in discontinuous layers in valleys formed during Pleistocene Glaciations (i.e., the modern day topography is primarily the result of the late Pleistocene drainage networks) (Jordan, 1964; Groot and Jordan 1999; Ramsey, 2005). The sand and gravel sized clasts present throughout the Columbia Formation are predominantly quartz (Jordan, 1964; Ramsey, 2005).

Paleoenvironment investigations of the Delmarva Peninsula indicate a warming and wetting trend since the last glacial maximum, 14,000 yr BP, to the present. Sirkin et al. (1977) identified two major pollen assemblages and inferred the presence of two major climatic regimes since 14,000 yr BP. At the last glacial maximum the pollen assemblage suggests a very cold taiga to tundra like environment shifting to a slightly warmer taiga environment by 10,000 yr BP. Isolated stands of pine, spruce, and birch dominate the landscape with the introduction of alder hemlock and shrubs as the climate warmed, transitioning the landscape to a heavy forest cover (Sirkin et al., 1977). Modern climatic conditions resulted from a gentle warming trend since 10,000 BP. The warming produced a land cover transition from coniferous forests to deciduous forests with oak, hickory, birch, cypress, and pine dominating the pollen assemblages (Sirkin et al., 1977). The Bluff's Parcel Tributary watershed likely remained a forested landscape for approximately 10,000 years.

Although the precise history of the land use in the Bluff's Parcel Tributary is unknown, the onset of European settlement in the 17th century resulted in the beginning of significant shifts from forested to agricultural lands regionally (Matlack, 1997). Land cover land use studies in the region suggest that by A.D. 1850 old growth forest accounted for less than 5% of the land cover in the area with 65% engaged in active agriculture and 25% pasture or secondary forest (Benitez and Fisher, 2004). The regional shifts suggest that the Bluff's Parcel Tributary transformed from a heavily forested region during pre-European settlement to a zone with a maximum of 30% forested land post- European settlement.

Fluctuations in sedimentation rates for watersheds on the Delmarva Peninsula correspond to shifts in land use and land cover, indicating that denudation rates increased during the transition from forested lands to agricultural lands (Cooper, 1995; Benitez and Fisher, 2004). However, after A.D. 1850 the land use/land cover for the area stabilized, and as a result the sedimentation rates declined to a rate approximately halfway between pre-European settlement and the maximum post-European settlement rate (Cooper, 1995). Since the 1850s the amount of land under agricultural production has fluctuated slightly with a steady decline in lands actively farmed since A.D. 1900 (Matlack, 1997). The forested areas preferentially exist in rough terrain like that found in the small valleys with first and second Strahler order tributaries (Strahler, 1957) to Blackbird Creek due to ease of accessibility (i.e., difficulties farming, harvesting lumber or building on uneven terrain when flat terrain dominates the region.). As of A.D. 2002, agricultural (36.1%) and urban lands (13.2%) comprise 50% of the Blackbird Creek watershed with the other 50% composed of landscapes dominated by deciduous forest, wetlands, and water (HydroQual, 2006).

Chapter 3

METHODS

3.1 Benchmarks

Four permanent brass benchmarks were installed at the study area (Figure 2). The Delaware Department of Natural Resources and Environmental Control (DNREC) provided centimeter-accurate coordinates for these benchmarks using a real time kinematic (RTK) global positioning system (GPS). The benchmarks facilitated the transformation of the local coordinates utilized in the onsite surveys (longitudinal profile and cross sections) into Delaware State Plane coordinates.

3.2 Longitudinal Profile

Longitudinal profile surveys followed the channel thalweg, or the deepest part of the channel in areas of no flow for the channel length. The survey was completed using a TOPCON GTS-302 total station with linear distance accuracy of 0.003 m and an electronic angle measurement accuracy of $1.45*10^{-5}$ radians (0.00083 degrees). All ground surveys were conducted using the GTS-302. Field survey datasets contain horizontal and vertical errors of less than 0.10 m and 0.05 m, respectively. The Bluff's Parcel Tributary main channel longitudinal survey began at the confluence of the channel and Blackbird Creek and ended at the highest discernible channelized flow path in the headwaters. The tributaries to the Bluff's Parcel Tributary were surveyed in a similar fashion, upward from the main channel. Points recorded for the longitudinal profiles were spaced to capture topographic slope breaks and characterize macro scale bed features (typical spacing about 1m), such as pools and runs.

3.3 Topographic Profiles

Topographic profiles (i.e., cross sectional topography) of the valley slopes, floodplains/abandoned terraces, and the active channel were measured perpendicular to the channel centerline at 36 locations (Figure 2). Elevation data were collected every 10 cm to obtain a detailed topographic profile, valley cross section, that well represents the channel bed and bank-full elevation. Beyond the active channel a horizontal spacing of 1 m to 5 m was implemented to capture significant breaks in slope and the general topography of the adjacent floodplain, terraces, and valley walls.

3.4 Floodplain Cores

Sediment cores collected along the valley floor adjacent to the active channel were used to evaluate the depositional and/or erosional history of the channel. A three inch bucket auger was used to extract the sediment cores. The core was catalogued as it was removed from the auger head. The top 2 cm was removed as this material was determined to be material dislodged by the extraction of the previous core and the insertion of the auger head to collect the next segment. The outer material was scraped away from the core with a cross cutting motion to avoid contamination from frictional drag of surrounding sediment. The wet color of the sediment was determined through the use of a Munsell color chart. The dominant sediment size and the size of anomalous large clasts were recorded. Qualitative field determinations of relative silt and clay percentages were determined through standard field textural analyses (Shepard, 1954; Goudie, 1981).

3.5 Stage Monitoring

HOBO pressure transducers were used to assess the stage height (water depth) at two locations (cross sections 19 and 21; Figure 2). Absolute pressure was recorded from pressure transducers placed in pools while a third pressure transducer, attached to a nearby tree, recorded the local atmospheric pressure. The pressure transducers collected pressure readings every 15 minutes for 128 days. The pressure readings were converted to water depths using the following equation.

$$D_{water} = (P_{water} - P_{air}) / (g * \varrho_{water}) \qquad (1)$$

D = Depth in meters

P = Pressure in Pa

g = Acceleration due to gravity 9.81 m^2 s^{-1}

ϱ= Density kg m^{-3}

3.6 Discharge

To provide a means of determining stage heights through hydraulic modeling discharge was calculated using the relationship;

$$Q = A * V \qquad (2)$$

Q = Discharge

A = Area of cross sectional flow

V = Mean water velocity

The cross sectional area of flow and the velocity of the flow were measured to determine the discharge for a particular stage height. The velocity was recorded at 10 cm increments across the channel using a Global Water FP111 flow prober with a detection range of 0.09 m s^{-1} to 6.06 m s^{-1}. The Global Water FP111 recorded the velocity at a depth of two thirds of the total water depth from the free surface to obtain an average flow velocity (Julien, 2010). The discharge for each 10 cm wide polygon was calculated and summed to get the total average discharge for the cross section.

3.7 Modeled Discharge

The field measurements of discharge and stage were used to calibrate HEC-RAS 4.1 modeled water surfaces. HEC-RAS 4.1 is a flow modeling software package produced by the U.S. Army Corps of Engineers. HEC-RAS 4.1 solves continuity, energy, and flow resistance equations to produce water stage and velocity estimates for a cross section, the parameters are then solved for the upstream cross section based on the results of the downstream cross section producing what is known as step-backwater surface model (Sarhadi et al., 2012). The water surface models determined the stage levels along the length of the channel. Due to the influence of anthropogenic disturbance in the watershed, rainfall-runoff models of the watershed were avoided in favor of a hydraulic geometry modeling approach. Land use/land cover and topography do not accurately reflect the drainage networks constructed by municipal and private landowners negating the feasibility of accurate rainfall-runoff models (e.g., road side ditches, residential drainage systems, and residential dewatering networks). HEC-RAS 4.1 has successfully modeled extreme events based on geometry rather than rainfall-runoff models for small flashy ephemeral channels, similar to Bluff’s Parcel Tributary (Conesa-Garcia et al., 2010).

HEC-RAS 4.1 modeled discharges for average and extreme precipitation events to determine the stage and flooding extent produced by peak flows. Surveyed cross sections of the main channel provided the inputs for the channel geometry. Field measurements and estimates from channels with similar geometries determined the input parameters to run the subcritical steady flow simulation. Comparison of the Bluff's Parcel Tributary to channels of a similar geometry and hydrology in the region provided a means to estimate the value of the roughness coefficient, Manning's n (Pizzuto et al., 2000; unpublished data). A range of values for the channel roughness coefficient were modeled from 0.05 to 0.06 while the overbank roughness was determined to be 0.08 (Pizzuto et al., 2000; unpublished data; Brunner and CEIWR-HEC, 2010). The channel roughness coefficient selected to model flows was 0.053 as this value produced a stage level of 0.19 m with a discharge of 0.04 $m^3 s^{-1}$ which match field observations. Minimal geometric change between cross sections in conjunction with the subcritical nature of the flows and negligible flow loss dictated the use of gradual contraction and expansion coefficients, 0.1 and 0.3 respectively (Brunner and CEIWR-HEC, 2010).

Field measurement of water surfaces and discharges constrained the initial conditions used to model the flow of average precipitation events. For extreme events, average bed slope, a proxy for the normal depth slope, at the first cross section sets the boundary conditions (Brunner and CEIWR-HEC, 2010). Field measurements of flow depth based on rack lines and erosional features in the channel walls provided a means of estimating the stage level associated with extreme events. Water surface profiles based on the field data were compared to the water surface profiles modeled by various discharge values to estimate the volumetric flow rate of extreme events. The resulting average and extreme discharge values determined the stage height throughout the system at cross sections lacking direct or indirect field measurements providing a more complete picture of the system hydraulics.

3.8 Characteristics of the Bed Material

The distribution of clasts sizes within the Bluff's Parcel Tributary was derived from pebble counts of the bed (Wolman, 1954). The pebble counts were completed throughout the tributary to allow for correlation of grain size distributions with specific surveyed cross sections. Each pebble count consisted of at least 207 clasts, the minimum sample size necessary to provide a sample mean within 10% of the population mean at a 95% confidence level (Hey and Thorne, 1983). A single operator conducted all pebble counts to minimize the variation in clast selection bias. A 0.25 m^2 archaeological survey grid with 0.1 m × 0.1 m grid lines placed on the channel bed ensured a spatially uniform unbiased selection of grains (Kondolf, 1997). A finger blindly inserted into the water at the intersection of each grid line ensured that the unbiased selection of the first clast encountered, limited only by the sensitivity and manipulative ability of the operator's fingers. A survey began with the placement of the grid at the downstream end of the sample area moving perpendicular to flow to cover the channel width before moving upstream. Moving from downstream to upstream and replacing measured clasts in situ removed the potential to measure a clast more than once or overly disturb the survey site. 36 clasts were selected and measured with each grid placement. The process was repeated until the site clast count reached at least 207. Clast size was determined via the smallest opening through which it fit in a standard gravelometer (Hey and Thorne, 1983). The standardization of this procedure minimized operator error and bias increasing the potential that any observed differences in bed material size distribution among sample sites resulted from actual variations in the bed material.

3.9 Bed Mobility

The threshold of incipient motion was calculated for different water stage heights to enable evaluation of the conditions under which bed materials may mobilize. A grain may mobilize at a specific water height if the calculated Shields stress parameter surpasses a critical Shields stress, 0.045 (Yalin and Karahan, 1979). This value represents an average of a large data set that removes biases related to defining incipient motion that plagued previous studies (Buffington and Montgomery, 1997). This value is appropriate for rough turbulent flows denoted by Reynolds numbers greater than 70 (Yalin and Karahan, 1979). However, if the threshold for incipient motion is surpassed, then the particle only has the potential to move, it may not actually move because basal shear stress fluctuates due to upstream conditions. (Shields, 1936; Yalin and Karahan, 1979; Buffington and Montgomery, 1997; Behesti and Ataie-Ashtiani, 2008)

$$\tau_* = \frac{\tau_0}{(\rho_s - \rho_m) * g * d_s} \qquad (3)$$

τ_* = Shields parameter

ρ_s = Density of the grain; 2660 kg m^{-3} as bed material is dominantly Quartz.

ρ_m = Density of the fluid; 998 kg m^{-3} as temperature is assumed to be 10 °C

g = Acceleration due to gravity; 9.81 m^2 s^{-1}

d_s = Grain diameter

τ_0 = Basal shear stress

$$\tau_0 = \rho_m * g * S * R \quad (4)$$

S = Slope of the bed in the direction of flow; 0.0227

R = Hydraulic radius

$$R = \frac{A}{P} \quad (5)$$

A = Cross sectional area of flow

P = Wetted perimeter

$$Re_* = \frac{d_s * u_*}{\nu_m} \quad (6)$$

Re_* = Grain shear Reynolds number

d_s = Grain diameter

ν_m = Kinematic viscosity of the fluid; $1.0*10^{-6}$ m^2 s^{-1}

u_* = Shear velocity

$$u_* = \sqrt{g * S * R}$$

The above methods only reveal that a clast is experiencing the conditions under which it may move, but does not indicate how quickly it actually moves. Therefore, it gives no indication as to the sediment transport rate. Also the analysis uses an idealized rectangular channel cross section representative of the average width of the incised channel, 3.40 m, and not calculated for each cross section. From a physics perspective, the Shields diagram assumes a spherical, uniform grain size, which is not true for most stream beds. Also, the density of the particles is assumed to be constant, which is reasonable if the bed material is dominated by a particular lithology. Despite the above limitations the Shields parameter is an established means of determining if the threshold of incipient motion has been surpassed and motion is possible. (Shields, 1936; Yalin and Karahan, 1979; Buffington and Montgomery, 1997; Behesti and Ataie-Ashtiani, 2008)

3.10 Erosion Rates Calculated from Roots

Because the study period of this thesis was limited to less than 1 year, the use of traditional methods (scour chains, cross section surveys) that require significant temporal resolution were not available. Therefore, this study relied on a dendrochronological technique based on root exposure typically applied to stream channels and hillslopes to calculate erosion rates (e.g., Gärtner et al., 2001; Malik, 2008; Bodoque et al., 2011; Stoffel et al., 2012; Stoffel and Wilford, 2012) and channel migration rates (lateral or headward) (e.g., Malik and Matyja, 2008; Hitz et al., 2008a; Vandekerckhove et al., 2001). The inexpensive technique involves the sampling of exposed roots along the channel and determining the years of exposure based on anatomical changes in the cellular structure of the root. It provides decades of record depending on the age of the trees yet requires a single trip into the field making it an attractive alternative to traditional erosion rate calculation methods.

3.11 Biological Background of Exposed Root Analysis

Gärtner et al. (2001) identified anatomical cellular changes of exposed roots that provide a proxy record of the timing of exhumation. Evaluating the exhumation record of exposed roots in conjunction with the distance between the root and the ground surface allows for localized land surface elevation fluctuations to be assessed (e.g., Gärtner et al., 2001; Bodoque et al., 2005; Hitz et al., 2008a; Malik, 2008; Malik and Matyja, 2008; Bodoque et al., 2011; Corona et al., 2011). In the simplest terms the cellular structure of the new growth of an exposed root changes from a root structure to a stem-like structure. The cellular response is possible because the new growth cells, secondary xylem, change function based on the environment in which they reside (Lebedenko, 1962 cited in Fayle, 1968). The transformation of the secondary xylem is possible because of the similar anatomical composition of roots and stems (i.e., wood, vascular cambium, and bark) (Shigo, 1986). The anatomical signals that indicate root exposure are changes in: cell size, cell wall thickness, cell formation/distribution, the presence of discernible latewood/earlywood, growth ring width, growth ring symmetry, ray density, and scars (Gärtner et al., 2001)(Figure 3). Not all species react to exposure the same way making exposure identification difficult. For example, some species show changes in all categories while others do not. Deciduous trees have complex cell structures and while more difficult to use than conifers are still viable candidates for determining the timing of root exposure (Gärtner et al., 2001; Hitz et al., 2008b). The key is that there is a change that occurs and it is observable at the cellular level.

3.12 Rapid Versus Gradual Exposure

The rate of exhumation is an important factor that impacts the nature of the cellular changes that occur. In terms of cellular response exhumation is either sudden (event driven) or gradual (e.g., diffusive processes driven) (Gärtner et al., 2001). Sudden exhumation results in a distinct cellular change, typically a more than 60% decline in the vascular cell size coupled with an increase in the number of cells in earlywood (Gärtner et al., 2001). The sudden presence of a clearly discernible latewood, depending on the species, and the differences in cellular arrangement (ring porous versus diffuse porous) associated with latewood also indicate exposure, as buried roots lack these structures (Gärtner et al., 2001).

Conversely, a group of annual rings that gradationally shift from root to stem structures indicates a gradual exhumation (Gärtner et al., 2001). Observed indicators typically include a slight decrease in cell size and an increasing number of cells present in the earlywood of the next annual ring (Gärtner et al., 2001). The gradual exhumation changes the earlywood with subtle shifts in cellular structure (decrease in size and increase in number) that eventually manifest as a discernible earlywood and late wood growth period (Gärtner et al., 2001). As with rapidly exposed roots, the first earlywood growth ring to show approximately a 60% reduction in cell size when compared to the root structure indicates full exposure and not simply a near-the-surface presence (Gärtner et al., 2001). The near-the-surface presence can be difficult to identify as cellular changes begin when the root is buried by less than 0.03 m of soil (Corona et al., 2011). Erosional events often drive sediment transport processes, thus the channel roots should display characteristics of rapid exhumation in theory simplifying the identification of the year of exposure (Corona et al., 2011).

3.13 Corrasion Scars

Corrasion scars are event-driven indicators of exposure. Scars are formed when an object impacts a root with enough force to damage the cambium. Corrasion scars are easily visible as color variations in the woody tissue composed of dead cambium cells. The discoloration occurs as the damaged cells transition into a form more resistant to decay resulting in their demise (Shigo, 1986). The visibility is enhanced as annual rings continue to grow around the dead cambium producing a pronounced scar (Shigo, 1986; Hupp and Bornette, 2003). The corrasion scars indicate that the root was exposed at or near the surface as they require an impact to initiate the transformation of the cambium cells, which is not possible when the root is buried.

3.14 Root Sample Selection

Roots used to calculate channel incision rates must meet several selection criteria. Channel incision must expose the root, not channel widening, bend migration, or other erosional processes. A suitable site must therefore display no signs of erosional processes other than the one of interest. Sediment cores of the valley floor adjacent to the channel in conjunction with the morphologic assessment can rule out the possibility of channel migration. The root must be living at the time of sample collection or the researcher risks calculating an erroneous erosion rate as the amount of eroded material no longer corresponds to the time recorded by the root. Ideal roots extend out into the channel with living ends buried in the soil (Malik and Matyja, 2008). Thicker roots tend to be older roots and should be selected where long term erosion rates are desired (McAuliffe et al., 2006; Malik and Matyja, 2008). Some researchers caution against the selection of older roots due to the possibility of re-burial complicating the analysis (Bodoque et al., 2011). However, the very reason old roots should be pursued is because they may reveal the presence of a complicated history of exposure and burial, indicating erosion and aggradation of the channel. Finally, the selection of multiple roots distributed along the length of the channel reveals the channel-wide history rather than a localized history of a single site. The evolutionary history of the channel is validated by the presence of a similar pattern among different root sample sites (Malik and Mayja, 2008).

Following sample site and specimen selection the details of the orientation and the geometry of the root with respect to the channel are recorded. For a horizontal or oblique root the section of root closest to the channel centerline was sampled, as it should be the first part of the root exposed by incision and mitigates the impact of slight channel widening if present (Vandekerckhove et al., 2001). For vertical roots the top and bottom of the exposed section of the root was sampled. Vertical roots longer than 0.30 m are ideal as the spatial distance will correlate to a temporal gap between years of exposure if exhumation was gradual (Malik, 2006). Vertical roots were of particular importance as they provide evidence for or against incision. The vertical distance from the sample location to the channel floor was recorded for the incision rate calculation. For horizontal roots the distance from the top of the root to the channel floor and the bottom root to the channel floor were recorded for use in the erosion rate equation. For vertical roots the distance from the observation surface to the channel floor was recorded. Finally, the width of the root sample selected needs to be large enough to allow for two pieces to be obtained from the sample: one for macroscopic and one for microscopic analysis.

3.15 Root Analysis

Roots were analyzed in the lab macroscopically and microscopically. The dried and sanded root cross sections eased ring and corrasion scar identification. A comparison of two different surfaces of the same root screened for anomalies in the growth pattern (e.g., missing rings and wedged rings) (Malik and Matyja, 2008). The presence of corrasion scars, eccentric ring growth, and/or bending rays signaled the year of exposure at the macroscopic scale (Gärtner et al., 2001). Microscopic analysis confirmed the exact year of exposure. As Malik and Matyja (2008) observed that the year of exposure was successfully identified at the macroscopic level for two-thirds of their samples. Thin sections were created using a sledge microtome and analyzed at a variety of magnifications to precisely identify the ring in which the characteristic anatomical changes indicative of exposure existed.

3.16 Erosion Rate Calculation

Calculating erosion rates (E_{ra}) from roots required the thickness of the eroded soil layer (E_r) and the number of years since the exposure ($NRex$).

$$E_{ra} = E_r / NRex \qquad (7)$$

For roots oriented vertically or almost vertically, E_r was assumed to be the straight line distance between the sample location and the ground surface directly below the channel side of the root. Horizontally oriented roots provided some complexity to calculating E_r. Corona et al. (2011) showed that the simplest statistically reliable method for calculating E_r is:

$$E_r = E_x - (Gr1) + \frac{(B1+B2)}{2} + \varepsilon \qquad (8)$$

Where E_x is the distance measured in the field between the top of the root and the ground surface, $Gr1$ is the subsequent growth on the upper side of the root, $B1$ is the thickness of the bark on the upper side of the root, and $B2$ is the thickness of the bark on the lower side of the root. Equation 8 accounts for the growth that the root experiences after exposure but assumes that axial shifting of the root core is negligible (Corona et al., 2011). The last term, ε, is the error term associated with the depth at which the root begins to show anatomical signs of exposure while still buried, which was assumed to be 0.03 m (Corona et al., 2011).

Chapter 4

RESULTS

4.1 Channel Geometry

The longitudinal data show that the total length of the main channel, as measured along the center line, is 558.6 m and the straight line axial valley distance is 457.7 m. These measurements yield a sinuosity of 1.22 (Figure 2). The concave longitudinal profile has a mean channel slope of 0.0227 (Figure 4). Separating the channel at the inflection point, 290 m from the channel mouth, yields two mean channel slopes, 0.0185 for the lower half and 0.0304 for the upper half of the tributary (Figure 4). The unchannelized valley floor has a mean slope of 0.022.

Channel geometry data indicate an average channel width of 3.00 m with a standard deviation of 1.26 m and a range of 0.90 m to 6.09 m. The average bank height is 0.69 m with a standard deviation of 0.44 m. However, the range of bank heights runs from almost unchannelized flows at 0.02 m near the confluence with Blackbird Creek to 1.69 m near large trees and steep slopes of the adjacent valley (Figure 5). Bank height increases towards the middle of the channel length and decreases towards either end (Figure 4).

4.2 Bed Material

Pebble counts along the length of the stream show that the grain size of bed materials decreases downstream (Figure 6). The grouping of coarser samples of the bed material distributions were located upstream of cross section 7 which has an average channel slope of 0.0304. The two fine-grained, bed-material samples were located downstream of cross section 7, which has an average channel slope of 0.0185. The D50s for bed material above cross section 7 range from 18.5 mm to 31.5 mm, while D50s for bed material below cross section 7 range from 2.1 mm to 5.3 mm. The D84s for bed material above cross section 7 range from 37.5 mm to 68.0 mm, while D84s for bed material below cross section 7 range from 11.0 mm to 12.6 mm. The Shields stress analysis of an idealized average channel cross section results in surpassing the threshold of incipient motion at water depths of 0.13 m for the maximum of the D50 range and 0.27 m for the maximum of the D84 range (Table 1).

4.3 Stage Monitoring

The HOBO pressure transducers recorded the stage height for 128 days from April 14, 2011, until August 19, 2011, showing average variations of 0.12 m over the course of a 24 hour period (Figure 7). The average daily maximum stage height is 0.19 m, which corresponds to a discharge of approximately 0.04 $m^3 s^{-1}$ according to field measurement for discharge at that stage. The maximum stage height recorded is 0.55 m and HEC-RAS modeling of the channel indicates that this flow has a modeled discharge of 0.84 $m^3 s^{-1}$. Field observations after Hurricane Irene, August 28th 2011, indicate that it produced a stage of 0.45 m in the channel at the site of HOBO 2 where bankfull is 1.0 m. Hurricane Irene produced the fourth greatest peak discharge in 56 years of stream flow monitoring of the Blackbird Creek, stream into which the Bluff's Parcel Tributary flows (United States Geological Survey, 2012). This means that any stage in the Bluff's Parcel Tributary above 0.45 m is an extreme event.

4.4 Cores

Five cores of unconsolidated sediment were analyzed over the length of the channel (Figure 8). Core 1 was retrieved to a depth of 0.14 m. The upper 0.04 m were composed of very dark brown (7.5YR 2.5/2) organic fragments followed by 0.10 m of dark brown (7.5YR 3/3) low plasticity, silty sand. The core was rejected at a depth of 0.14 m by a root mass. (Figure 9)

Core 2 was retrieved to a depth of 0.84 m. The upper 0.01 m were very dark brown (7.5YR 2.5/2) organic fragments. From 0.01 m to 0.10 m was a light brown (7.5YR 6/4) silty sand with a low plasticity. From 0.10 m to 0.17 m was a yellow brown (10YR 5/8) high plasticity, clayey silt with rounded gravel clasts intermixed. From 0.17 m to 0.20 m was a gravel layer with a yellow brown (10YR 5/8) clayey silt matrix. From 0.20 m to 0.38 m was a high plasticity yellow brown (10YR 5/6) silty sand layer with rounded gravels and spotted red (2.5 YR 4/8) discolorations 2 mm to 4 mm in diameter. From 0.38 m to 0.40 m was a reddish yellow (5YR 6/8) low plasticity, fine to coarse sand layer. From 0.40 m to 0.60 m was a yellowish red (5YR 5/8) high plasticity, silty sand matrix with rounded gravel clasts. From 0.60 m to 0.84 m was a white (5YR 8/1) high plasticity, clay layer with red (2.5 YR 4/8) mottling, which was the current material of the stream bed at the core location. The core ends at 0.84 m because penetration of the clay and gravel below was not possible (Figure 9).

Core 3 was retrieved to a depth of 1.51 m. From 0.00 m to 0.10 m was a very dark brown (7.5YR 2.5/2) low plasticity, organic and medium to coarse sand. From 0.10 m to 0.20 m was a yellow brown (10YR 5/8) low plasticity, silty sand with a medium to coarse sand fraction. From 0.20 m to 0.30 m was a brown (7.5YR 4/4) moderate plasticity, silty sand with a fine to coarse sand fraction. From 0.30 m to 0.42 m was a pinkish white (7.5YR 8/2) high plasticity, clay layer with less than 5% sand grains. From 0.42 m to 0.60 m was a yellow (10YR 7/8) non-plastic, medium to fine clean sand. From 0.60 m to 0.84 m was a dark gray (7.5YR 4/1) high plasticity, silty clay. From 0.84 m to 1.08 m was a gray (7.5YR 5/1) moderate plasticity, sandy clay with rounded gravels, sand and rounded gravel content increase with depth. From 1.08 m to 1.51 m was a non-plastic reddish yellow (7.5YR 6/8) sand with rounded gravels. The core ends at 1.51 m because penetration of the gravel below was not possible (Figure 9).

Core 4 was retrieved to a depth of 1.64 m. From 0.00 m to 0.06 m was a very dark brown (7.5YR 2.5/2) moderate plasticity, organic-rich clay layer. From 0.06 m to 0.16 m was a yellow brown (10YR 5/8) moderate plasticity, silty clay with rounded pebbles. From 0.16 m to 0.24 m was a gray (7.5YR 5/1) moderate plasticity, silty clay. From 0.24 m to 0.34 m was a reddish yellow (7.5YR 6/8) non-plastic, fine to coarse clean sand. From 0.34 m to 0.40 m was a gray (7.5YR 5/1) moderate plasticity, sand-silt-clay. From 0.40 m to 0.60 m was a gray (7.5YR 6/1) high plasticity, clay with less than 10% coarse sand grains and red (2.5 YR 4/8) spotted 2 mm to 4 mm in diameter spread throughout. From 0.60 m to 0.62 m was a gray (7.5YR 6/1) low plasticity, silty sand layer with red (2.5 YR 4/8) spotting 2mm to 4 mm in diameter. From 0.62 m to 0.66 m was a gray (7.5YR 6/1) low plasticity, silty sand. From 0.66 m to 0.90 m was a gray (7.5YR 5/1) moderate plasticity, sandy silt. From 0.90 m to 1.23 m was a gray (7.5YR 5/1) non-plastic, fine to coarse sand matrix surrounding rounded pebbles and some mm scale red banding. From 1.23 m to 1.25 m were rounded gravels with no matrix. From 1.25 m to 1.30 m was a gray (7.5YR 5/1) low plasticity, sandy silt with rounded pebbles. From 1.30 m to 1.64 m was a gray (7.5YR 5/1) high plasticity, sandy clay with rounded gravels. The core ends at 1.64 m as the saturation level of the material inhibited successful core retrieval at greater depths (Figure 9).

Core 5 was retrieved to a depth of 2.20 m. No organic layer was developed. From 0.00 m to 0.20 m was a brown (7.5YR 4/2) moderate plasticity, silty clay. At 0.20 m a gray (7.5YR 6/1) high plasticity, clay begins and extends at least to 2.20 m in depth. Variations within the layer consisted of the presence or absence of minor amounts, less than 5%, of sand, rounded pebbles, and rounded gravels consisting. The core ends at 2.20 m because that was the maximum operable length of the bucket auger (Figure 9).

Several rounded pebble to gravel sized siliciclastic clasts were encountered during the coring similar to those found in the bed material during the pebble counts. The color, grain-size, and plasticity data in cores 1 through 5 coincide with the field-map descriptions of unconsolidated fluvial silts, sands, and gravels deposited in discontinuous layers of the Columbia and Scotts Corner formations (Jordan, 1964; Groot and Jordan 1999; Ramsey, 2005). The lower elevation core 6 is dominated by a gray clay indicative of the Calvert formation (Ramsey, 2005).

4.5 Roots

Three trees along the length of the channel were suitably located to provide incision rates based on exposure ages. See Figure 8 for tree root locations and Tables 2 and 3 exposure data. The first tree (MT1) was located in a channel bend while the second and third (MT2 and MT3) were located in straight reaches. The trees were spaced out along the length of the channel to allow for the collection of a spatially averaged incision rate. MT1 and MT2 had vertically oriented roots, while MT3 had a horizontally oriented root. The range of exposure was between 12 years and 50 years.

The bottom of the vertical roots yield low incision rates of 0.002 m yr^{-1}, while the top of each of the vertical roots and the horizontal root yield incision rates of 0.018 m yr^{-1} to 0.023 m yr^{-1}, an order of magnitude greater.

Chapter 5

DISCUSSION

Two major components of the channel geometry indicate that incision is a dominant channel forming mechanism: 1) the slope of the longitudinal profile and 2) the progression of the cross sectional channel form along the length of the main flow path. First, the longitudinal profile data indicate that the channel-bed slope is steeper than the slope of the adjacent valley floor/floodplain in the upper reaches and only assumes a similar slope at the mouth. This concave profile form suggests that the channel has abandoned the floodplain, a likely result of channel incision (Figure 4). Second, growth in channel depth as compared to width suggests incision (Booth, 1990). Bank heights at the midpoint of the channel fail to produce bankfull stages even during extreme events such as Hurricane Irene, August 28th 2011, which indicates that floodplain aggradation cannot explain the geometry of the channel cross sections (Booth, 1990).

The ability of flows to move material through the system is a prerequisite for incision. The hydrologic results indicate that stages greater than 0.27 m in the channel have the ability to transport the maximum D84 and that stages greater than 0.13 m for the period of record surpass the threshold of incipient motion for the maximum of the D50. This means that at least half of the bed material is mobile during average events, 0.19 m stage, and that a majority of the bed material is mobile during extreme events, 0.45 m stage. The cores of the valley floor indicate that the channel incised through non-uniform massive deposits of poorly to well sorted sands, silts, and clays (Figure

9), material finer than the D50 maximum, creating a physical setting in which incision can take place (i.e., the transport capacity is greater than the sediment supply). The Shields stress analysis does not account for the cohesiveness of the sediment. However, the existence of the channel in its current condition indicates that basal shear stress of the flow has overcome the cohesion of the underlying bed material, a qualitative assessment supported by the quantitative analysis of incision rates calculated from the exposed roots.

The tree roots collected for this study show cellular characteristics indicative of aerial exposure in the Bluff's Parcel Tributary. When incision is the dominant process, roots parallel to the slope of the bank are exposed from the top down and the anatomical changes observed in the roots record this process. Because the vertical roots sampled at the Bluff's Parcel Tributary show variations in exposure ages along the length of the roots, incision is likely the dominant channel forming process (Table 2). Coupling of the annual growth-ring data from the sampled roots with their elevation above the active channel bed allows for accurate measurement of the timing of exposure, in years, and the depth of eroded material at each location. These data suggest that Bluff's Parcel Tributary is incising at a rate between 0.018 m yr^{-1} and 0.023 m yr^{-1}. The differences in rates observed vertically suggest that there is little lateral migration or widening, which would result in near-simultaneous exposure ages along the length of a vertically oriented root. The root sample data suggest that incision began approximately 43 to 54 years ago (Table 3) between A.D. 1958 and A.D. 1969.

Although the average incision rates obtained from the top of the vertical roots and the horizontal root agree, the rates calculated from the bottom of vertical roots are an order of magnitude smaller. Malik (2006) collected multiple samples from a single root and reconstructed multiple events for horizontal roots but the distance the exposure signal can travel along the root remained undefined. Thus, the lower incision rates derived from the bottom of vertical roots at the channel bed may result from the exposure signal traveling along the root. This would cause buried sections of the root to begin anatomical changes at depths greater than the 0.03 m, the established depth at which horizontal roots begin to show evidence of exposure (Corona et al., 2011). The exposure signal may travel a greater distance along a vertical root attached to the channel bottom due to mechanical and environmental stress exposure related to channel flows and impacts of mobile sediment. This conclusion requires more research to determine validity, as vertical roots have primarily been used to quantify lateral bank movement and headward erosion in gullies (Vandekerckhove et al., 2001), which would yield contemporaneous exposure ages along the length of the root

There are three common causes of channel incision in the literature: base-level lowering, adjustment to rapid deposition, or changes in hydrology. The Bluff's Parcel Tributary base level is the eustatic sea level, which is currently rising (Cronin, 1981). Anthropogenically stimulated sedimentation events may result in significant aggradation that forces incision and expansion of the channel (Wolman and Schick, 1967; Magilligan and Stamp, 1997; Colosimo and Wilcock, 2007; Walter and Merritts, 2008). However, the sediment cores and map of the surface geology indicate that the incision is into unconsolidated material of the Pleistocene Columbia Formation or Scotts Corner Formation deposits. The catalyst responsible for the observed channel incision of the Bluff's Parcel Tributary is likely a recent hydrologic change.

Although the forcing behind hydrologic changes at the study site are not fully understood, they are likely due to anthropogenic manipulations of the Bluff's Parcel Tributary watershed. Common anthropogenic alterations of the landscape observed in the watershed are impervious surfaces creation, drainage network extension through ditching and interflow interceptors, and agricultural removal of overland flow roughness elements. While the subdued topography and the buried drainage networks make identifying the extent of watershed alterations difficult, the channel condition is indicative of an anthropogenically induced response (Wolman, 1967; Hollis, 1975; Booth and Henshaw, 2001; Gurnell et al., 2007). If as little as 20% of the basin is impacted by these alterations, a tenfold increase in the peak discharge for 1 year flooding events may result (Hollis, 1975). Increased peak discharge results in an increase of flow depth in a confined channel. As flow depth increases, basal shear stress increases, which is a good proxy for erosive power. Therefore, the incision is the result of an increase in the erosivity of the flow, likely due to anthropogenic land uses.

The findings of this study are applicable to other similar-order streams in geologically, climatically, and physiographically similar regions that are undergoing similar anthropogenic manipulations. Anthropogenic influences on the landscape often trigger rapid, and sometimes unprecedented, responses upon crossing a quasi-equilibrium threshold; my results suggest that these unchannelized valleys incise rapidly upon crossing that threshold (Wolman, 1967; Booth, 1990; Pizzuto et al, 2000). The scale of anthropogenic changes in these catchments belies their significance, because the minor perturbations of the Bluff's Parcel Tributary lead to rapid significant changes as the channel adjusts to a new quasi-equilibrium state

(Booth and Henshaw, 2001). If adjacent channels behave similarly, then contributions of material from the beds of all the incising tributaries may have a significant impact on the ecological health of the Blackbird Creek and potentially even a localized impact on Delaware Bay. As an example, roughly 14 ha compose the Bluff's Parcel Tributary watershed. Applying the average soil loss for agricultural lands in Delaware (4.4 metric ton yr^{-1} ha^{-1} [USDA/NRCS National Resources Inventory, 2007]) as a worst case land use scenario results in landscape lowering processes removing approximately 61 metric tons of soil from the watershed per year. The main channel of the Bluff's Parcel Tributary comprises 0.168 ha of that watershed and taking the volume of material missing in the incised channel (744 m^3) and the maximum channel formation time (54 years), then the tributary loses 22 metric tons of material every year. Thus, a minimum 26% of the soil loss in the Bluff's Parcel Tributary watershed comes from 1.2% of the total area every year, but only for the past half century. Applying the soil loss percentage to other incising tributaries throughout the Blackbird Creek watershed suggests that the 13.2% urbanized upland areas (Hydroqual, 2006) likely contribute a significant sediment load to Blackbird Creek. Future research should focus on applying these findings to the Blackbird Creek watershed, in order to quantify soil loss and sediment load contributions for the entire watershed.

Figures and Table

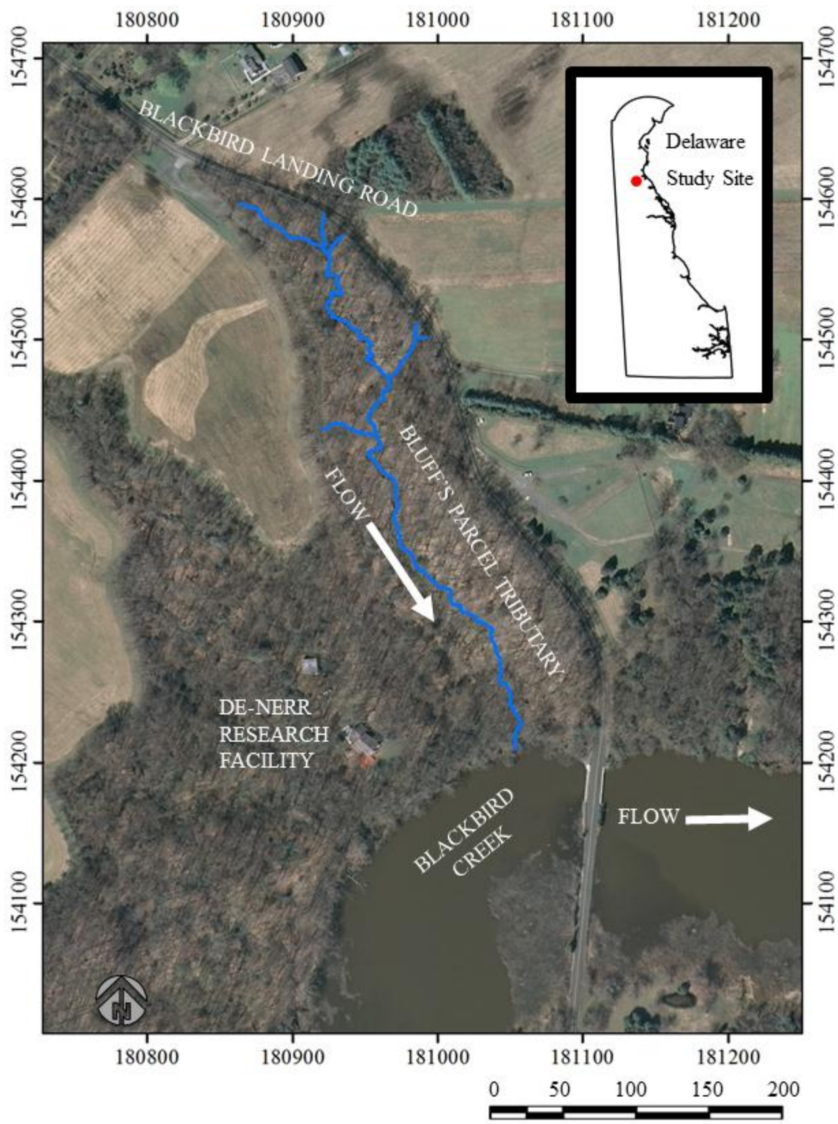

Figure 1: High Resolution Orthoimage of the Bluff's Parcel Tributary (blue) to Blackbird Creek (2010 Orthoimage courtesy of United States Geological Survey).

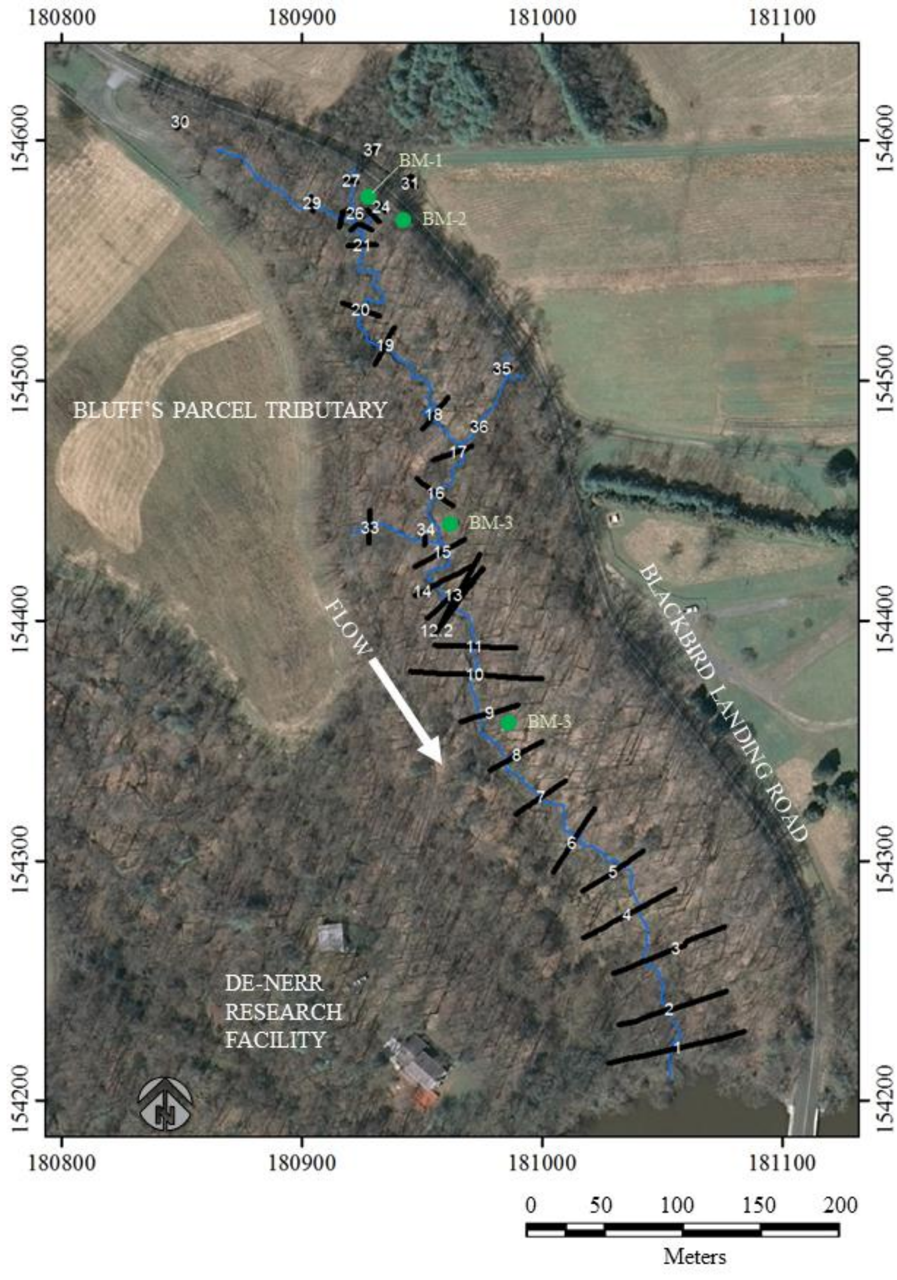

Figure 2: Benchmark locations (green) and valley cross section location, orientation, and extent (black) (2010 Orthoimage courtesy of United States Geological Survey).

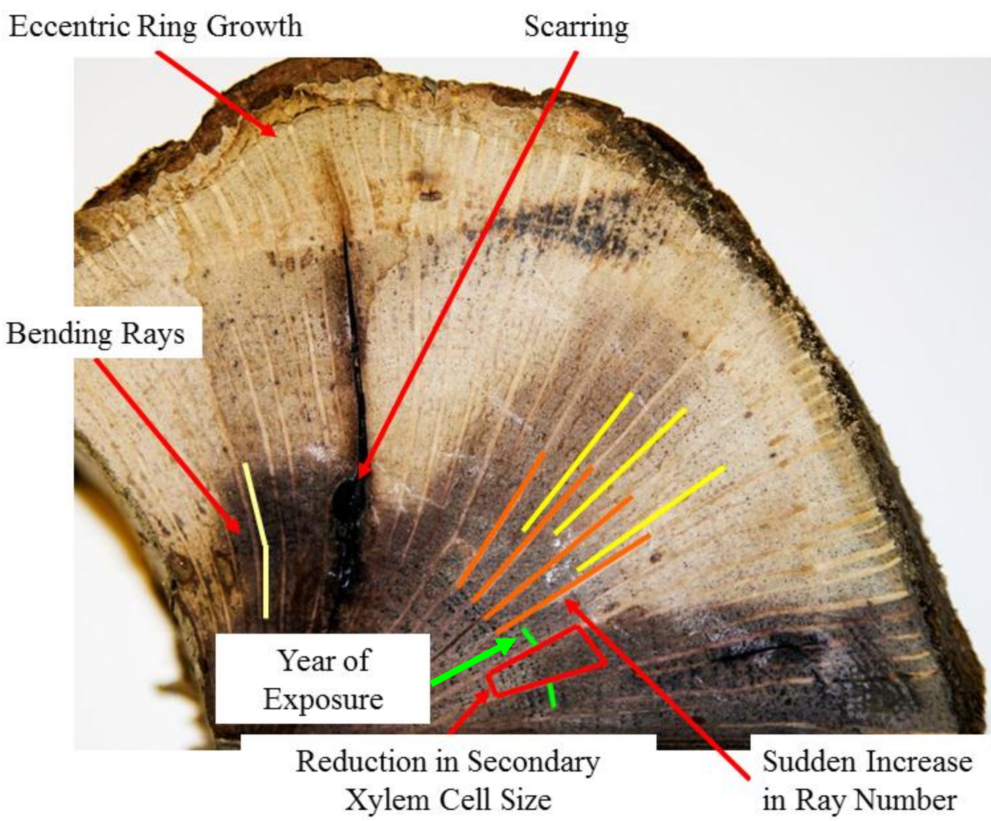

Figure 3: Macroscopic view of root illustrating structures that identify exposure.

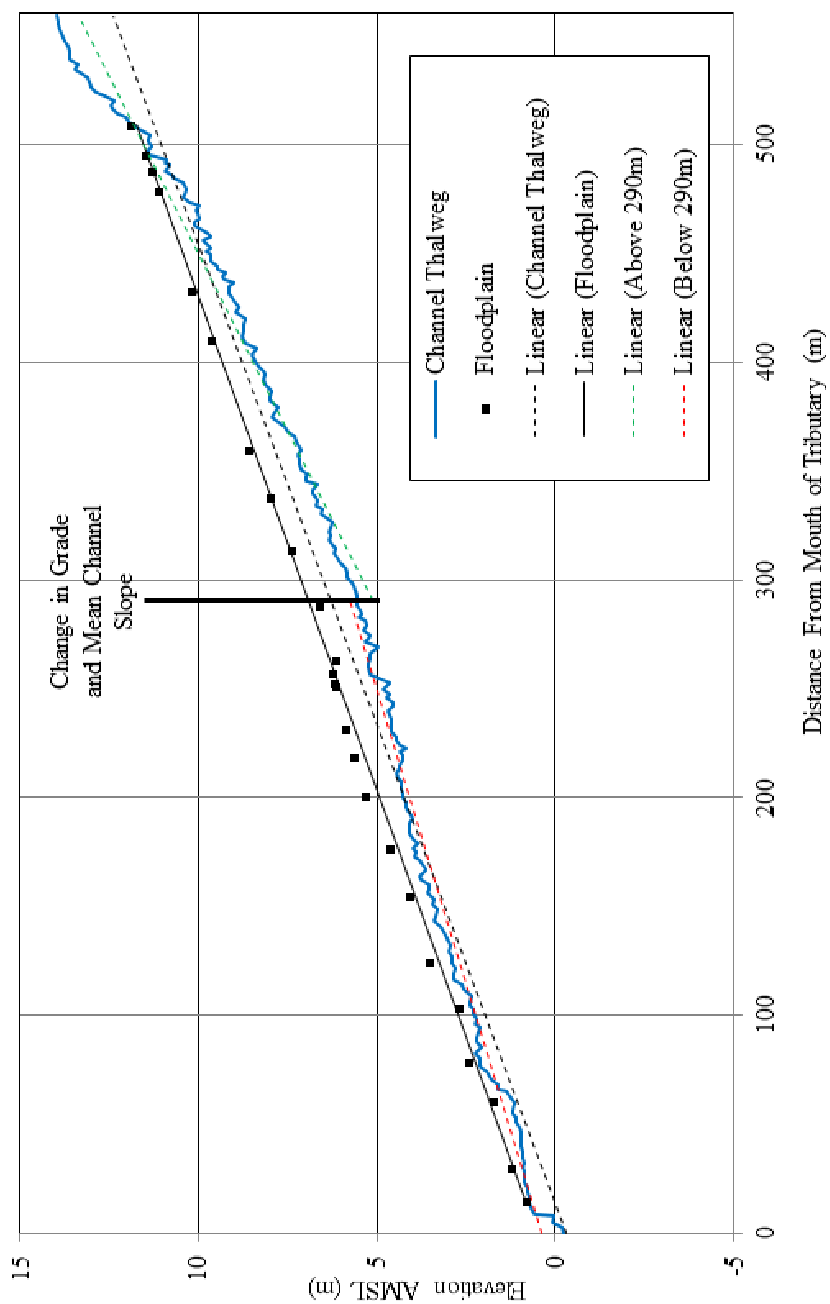

Figure 4: Bluff's Parcel Tributary channel thalweg and floodplain/valley floor longitudinal profiles. All mean slopes are determined from linear regressions.

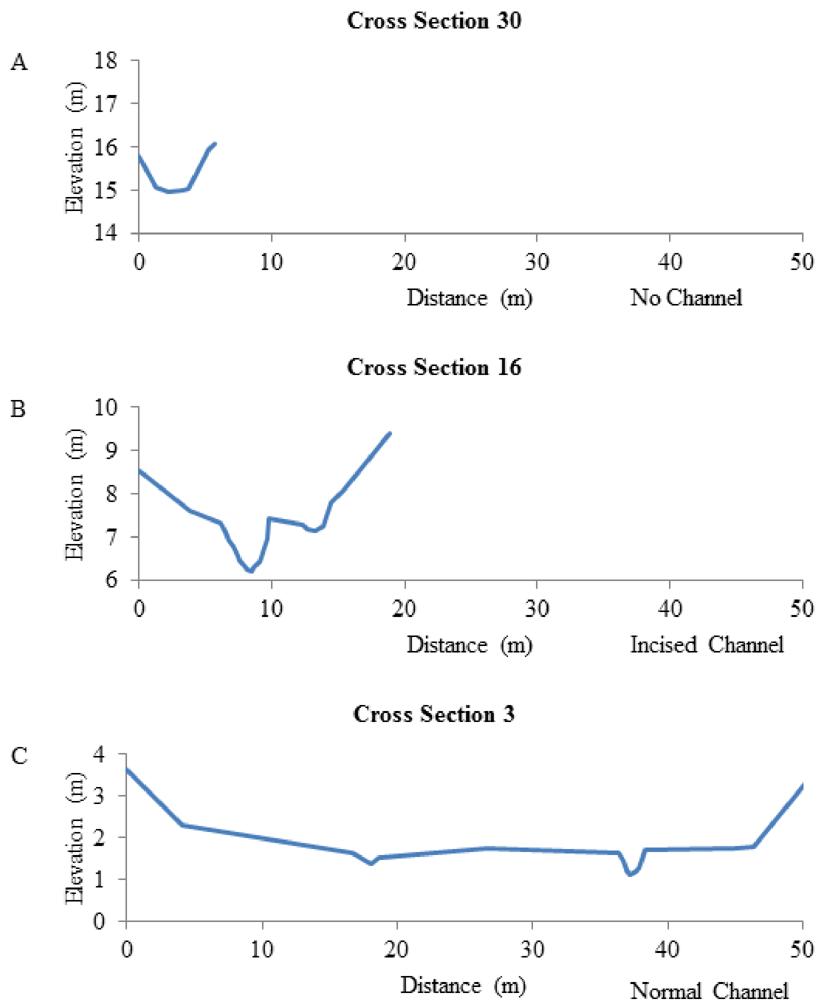

Figure 5: Cross section evolution upstream (A) to downstream (C).

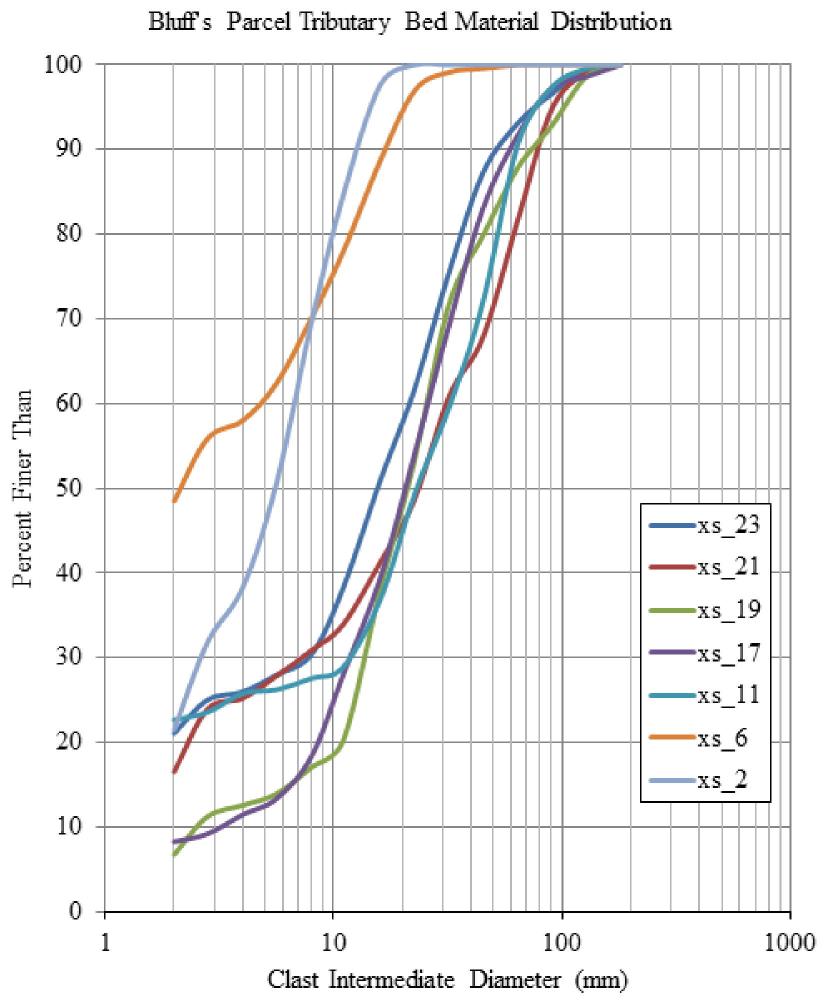

Figure 6: Grain size distributions for the bed material of Bluff's Parcel Tributary. Location indicated by cross section ID, ID numbers decrease in the downstream direction. Distributions fine downstream.

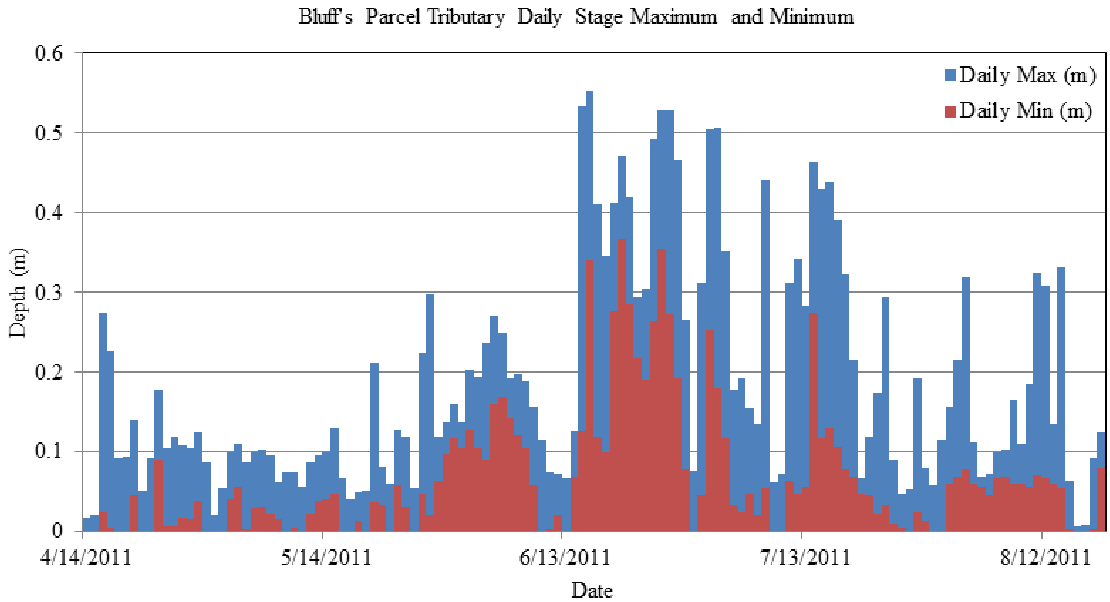

Figure 7: Water stage calculated from onsite HOBO pressure transducer data.

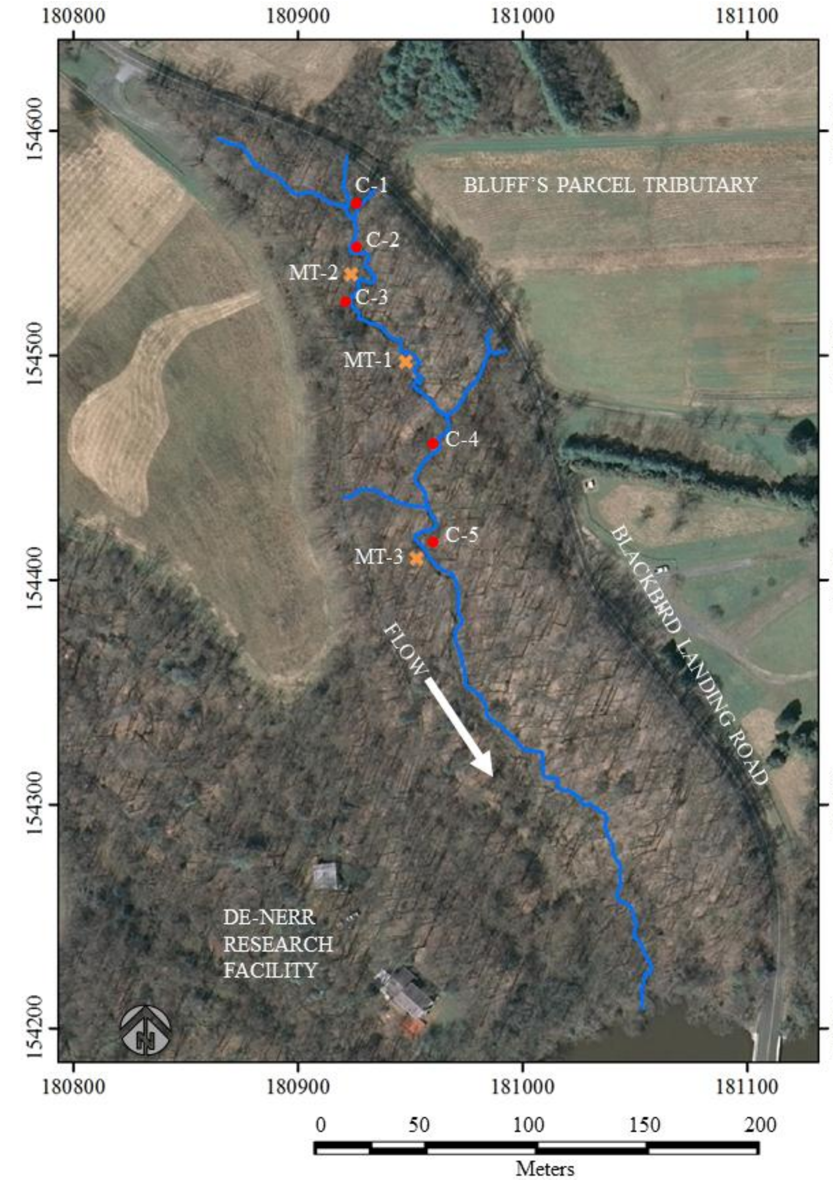

Figure 8: Plan-view of Bluff's Parcel Tributary with core locations (red circles). Tree-root sample locations (orange crosses) (2010 Orthoimage courtesy of United States Geological Survey).

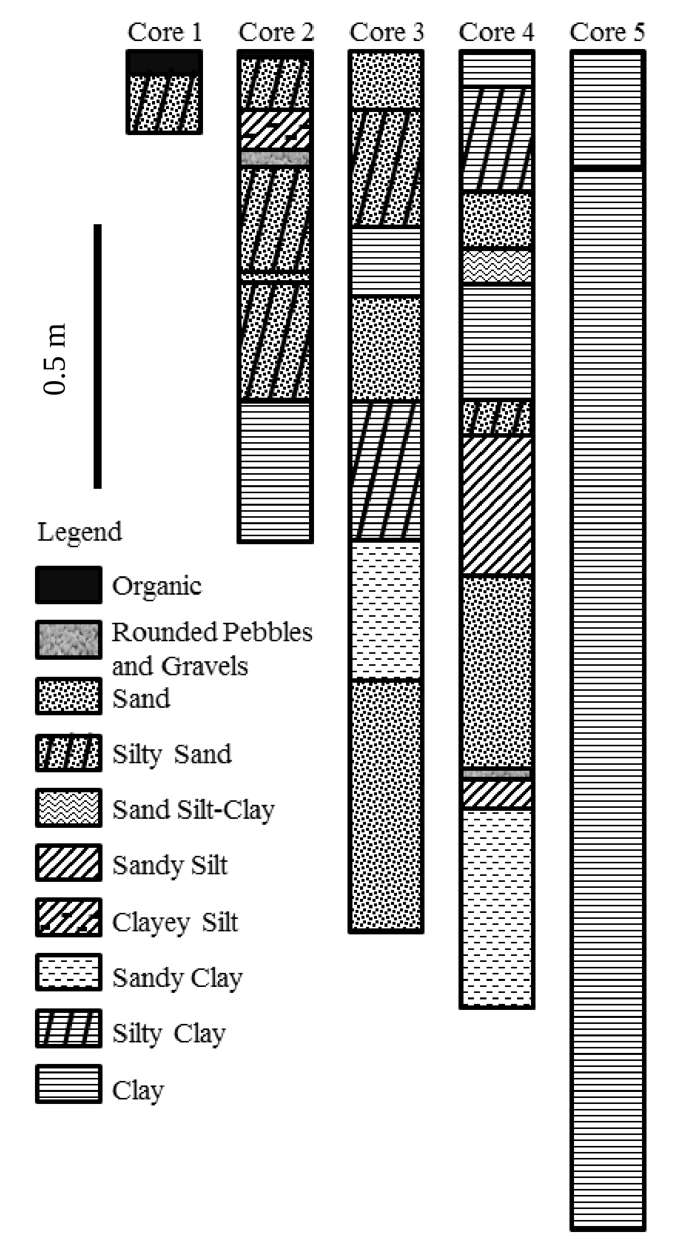

Figure 9: Logs of bucket auger cores collected adjacent to the active channel. Cores displayed in progression from upstream to downstream but do not overlap stratigraphically.

		τ_{*c} = 0.045	Shields parameter	Shields parameter
Cross Section	Particle Size in Percent Finer	Grain Size (mm)	Depth = 0.13 m; R = 0.12 m	Depth = 0.29 m; R = 0.23 m
2	D16	1.4E+00	1.30	2.30
	D50	5.3E+00	0.33	0.59
	D84	1.1E+01	0.16	0.29
6	D16	3.5E-04	-	-
	D50	2.1E+00	0.85	1.50
	D84	1.3E+01	0.14	0.25
11	D16	6.6E-01	2.70	4.77
	D50	3.1E+01	0.06	0.10
	D84	4.4E+01	0.04	0.07
17	D16	5.7E+00	0.31	0.56
	D50	2.2E+01	0.08	0.14
	D84	4.5E+01	0.04	0.07
19	D16	6.0E+00	0.30	0.53
	D50	2.4E+01	0.07	0.13
	D84	4.9E+01	0.04	0.06
21	D16	1.5E+00	1.17	2.08
	D50	2.3E+01	0.08	0.13
	D84	6.8E+01	0.03	0.05
23	D16	8.5E-01	2.10	3.72
	D50	1.9E+01	0.10	0.17
	D84	3.7E+01	0.05	0.08

Table 1: Calculated values of the Shields Parameter at an idealized cross section. Particle Size of the D16, D50, and D84 were determined using a logarithmic regression through the grain size distributions produced by the pebble counts. The D16 at cross section 6 is erroneously small due to this procedure and the results were removed.

Root ID	Years Of Exposure	Eroded Sediment (m)	Incision Rate (m yr^{-1})	Root Orientation
MT_1_Bot	27	0.08	0.003	Vertical
MT_1_Top	50	1.1	0.022	Vertical
MT_2_1_Bot	12	0.05	0.004	Vertical
MT_2_1_Top	25	0.48	0.019	Vertical
MT_3_1	44	0.97	0.022	Horizontal

Table 2: Results of the macro and microscopic analysis of the exposure age of the roots and associated findings.

Root ID	Height of bank at location (m)	Incision Rate (m yr^{-1})	Years to Complete Incision
MT_1	1.198	0.022	54
MT_2_1	0.948	0.019	50
MT_3_1	0.94	0.022	43

Table 3: Estimates of the time it took to form the channel from incision rates

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Appendix A

BLACKBIRD CREEK MONITORING PROJECT

The Delaware National Estuarine Research Reserve (DNERR), the property managers of the Bluff's Parcel Tributary, was concerned about channel erosion onsite and looking for possible methods of mitigation. This provided the impetus for this thesis and the investigation into channel erosion of the coastal bluffs. The findings of this work were utilized in the creation of a channel restoration design plan that would fulfill the DNERR goals of stewardship of the estuarine environment. The following report outlines the synthesis of the erosional characteristics of the Bluff's Parcel Tributary and includes detailed engineering design plans for the mitigation of the erosion.

BLACKBIRD CREEK MONITORING PROJECT

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PROJECT SUMMARY

This report presents stream-flow data, observed sediment fluxes, engineering designs, and long-term monitoring suggestions for the Bluff's Parcel Tributary on the Blackbird Creek Reserve, Delaware. The project evolved from a desire of DNREC and University of Delaware partners to mitigate observed erosion of the tributary that threatens infrastructure and impedes DNREC's obligation to stewardship of the Reserve. The project is hinged on an assumed, but undocumented, increase in discharge in the tributary as a result of land-use and land-cover changes over the last few centuries, which is amplified by increased by flows from road networks and ditches. We provide discharge estimates from stream-depth data collected at two locations along the tributary over a 6-month period between March and September of 2011. The pressure-transducer derived depth proxies were calibrated using field observations of flow and cross sectional area to derive an average discharge for this period of 1.4 ft^3s^{-1}. Our original proposal included measurement of sediment flux at the site, anticipating significant lateral movement of the channel in recent decades. However, sediment cores in terraces adjacent to the active channel suggest predominantly vertical incision. The coring effort was redirected to engineering support.

Our topographic surveys of the channel thalweg and bankfull elevations, suggest a convex thalweg profile indicative of recent incision from discharges that exceed the natural capacity of the channel. Our proposed restoration design suggests a partial filling of an approximately 1000 ft reach of the tributary. This filled reach has 23 pools in fills where grain-size distributions were determined by hydrologic modeling, to produce a stable pseudo-natural channel slope.

SETTING

The Bluff's Parcel Tributary of Blackbird Creek is located on the Blackbird Creek Delaware National Estuarine Research Reserve in Townsend, DE within the Atlantic Coastal Plain Geologic Province (39°23'33.86"N, 75°38'21.35"W; Figure 1). The tributary is a freshwater channel with a headwater elevation of 48 feet amsl, and flows 1830 feet where it joins the Blackbird Creek at sea level (see Figure 2 for longitudinal profile). The basal geology at the site has been mapped as part of the Quaternary aged Columbia Formation (Groot and Jordan 1999; Jordan, 1964; Ward and Groot 1957). The dominant terrestrial lithofacies in this formation are fluvially derived silt and gravel sands deposited in valleys formed during Pleistocene Glaciations (i.e., the topography present is primarily the result of the late Illinoian and the late Wisconsinan drainage networks). Thin mud beds and oxidized poorly sorted gravels and sands can be observed in the channel walls and along the bed of the tributary. The floor of the channel is often covered with sand and gravel lags derived from the adjacent channel walls. As the channel elevation approaches mean sea level, it reaches erosionally resistant bluish clay, which is typical of tributaries in nearby areas (see Fletcher, 1988 and Fletcher et al., 1992). Note that the aforementioned clay unit may be a pre-Pleistocene layer as it is found under the other Quaternary deposits of the Atlantic Coast.

PROBLEM

DNREC and University of Delaware researchers, working at the Blackbird Creek Reserve, have observed active erosion along road embankments adjacent to the Bluff's Parcel Tributary and knickpoint migrations in the headwaters of the stream near the reserve entrance. The amount of observed erosion adjacent to the road is qualitative, but has visibly undermined the embankment by several feet in recent decades. Data regarding the knickpoint migration in the headwater area (Stotts, 2011) indicates 0.3 ft of headward and vertical incision on an annual basis (between 2009 and 2011). These rates of observed erosion raise concerns regarding the long-term stability of this channel with regard to local infrastructure and the long-term stewardship plan of the NERR property on which the channel is located.

Although there are no historical data regarding pre-anthropogenic discharges at the study site, substantial land-use and land cover changes, and alterations to natural flow by roads and residential development drive modern discharges that exceed the capacity of the channel. Contributing drainage area is difficult to define because of captured flows from nearby ditches and residential drains, coupled with disconnected drainages from upstream roads that often flood during heavy rainfall events. Calibrated data from pressure transducers that operational in the spring and summer of 2011 indicate that normal (average) discharges in the stream are approximately 1.4 ft^3s^{-1} with a maximum discharge of 20 ft^3s^{-1} on August 28, 2011 following Hurricane Irene. Irene produced the third largest discharge recorded in the last 56 years by the nearby Blackbird Creek hydrograph. However, we also note that during several field visits in the summer of 2010 and 2011, the channel was nearly dry and flow velocities were inadequate to measure with a flow meter. Indicative of similar agriculture and suburban areas along the Mid Atlantic coast, discharges in the Bluff's Parcel Tributary are extreme, with flashy responses that are larger than would be expected under pre-anthropogenic forested conditions.

Field observations of the current channel of the Bluff's Parcel Tributary suggests little lateral movement outside of bends, and that the dominant nature of erosion in recent decades has been manifested as vertical incision into the underlying terrain. Comparison of the thalweg and bankfull elevations along the 1830 ft-long reach shows a concave profile form that has resulted from lowering of the thalweg, between 600 ft and 1600 ft (Figure 2). Materials excavated from channel wall deposits and cores collected from adjacent terraces are Pleistocene age deposits and suggest: 1) the pre-historic channel moved more freely laterally and took millennia to erode the current valley, and 2) the increased modern discharges promote incision of the channel that is mostly vertical. There are five first order channels that flow into the tributary that are not directly part of the study. Three of these channels show signs of recent erosive activity in the form of incision, knickpoint retreat, and undercut banks. Like the main tributary, the cause of the recent incision is likely land-use and land-cover changes and hydrology that is controlled by routing water over impervious surfaces that increase discharges beyond the natural capacity of this channel.

PROJECT GOALS

1. Stabilize the stream by reducing vertical incision and headward erosion of knickpoints, which decreases the threat to existing infrastructure (roads).

2. Provide vertical stability, without compromising the existing horizontal stability of the channel, to promote a channel morphology that provides a pseudo-natural landscape in equilibrium with current discharges.

3. Increase bed roughness elements (gravels and cobbles) to reduce flow velocities and facilitate settling of fine particles. Reducing flow velocities will also decrease sediment flux into Blackbird Creek.

4. Increase storage capacity in pools and in an active hyporheic zone. This increased

capacity improves stream ecology with increases in nutrient transfer rates, dissolved organic carbon uptake, and nitrification.

DESIGN

Concept

The designs presented herein provide channel stability through the re-creation of a pseudo-natural channel slope (Figure 2) with pool and riffle sequences that meet the maximum hydrologic conditions observed at the site in 2011 (Figures 3 and 4). As stated before, the channel is not designed to approach a pre-anthropogenic configuration because the hydrology and geology of the system have changed fundamentally as a result of human modifications of the landscape over the last few centuries. Instead, the channel is designed to provide vertical and horizontal stability by decreasing the mean flow velocity. This is accomplished by introducing roughness elements, which increase turbulence and drag forces. Increased turbulence results in increased instantaneous velocities in directions other than the mean flow direction. The roughness elements for this project are large-scale bed forms (pools and riffles) and large clasts. Large clasts will increase the overall roughness of the bed at any one section, while the bed forms will act as roughness elements for the entire channel.

The grain-size distributions for the fill materials presented in Figures 3 and 4 are based on pebble counts in the current channel (Hay and Thorn, 1983), calculation of Shield's Parameter (Julien, 2010), and hydrologic modeling in HEC-RAS. All grain-size and modeling data are available online at http://gis.geog.udel.edu/DNREC/Blackbird. The grain-size data presented in Figures 3 and 4 allows for self-organization within the bed to avoid pushing the stream laterally while also remaining stable under normal storm events to prevent further incision of the underlying terrain.

Slope

The average grade of the new channel is based on the longitudinal profile of the thalweg and bankfull elevations. The bankfull elevation suggests that the natural channel migrated across the valley floor on millennial timescales activating approximately the top foot of material. The application of geomorphic principles suggests that the grade of the bed is determined to be most stable if it is semi-parallel to the bankfull terrace elevations. The grade of the bankfull terraces hinges at 950 ft, hence the change in grade depicted in the channel design construction plans (Figure 2).

Pool/Riffle Substrate

The scale and placement of the pools and riffles are dictated by the constraints and parameters of the channel geometry (Leopold and Wolman, 1957). The size of the pools is primarily determined by the size of the larger pools present in the system as revealed in the longitudinal profile of the thalweg. The elevation of the bed at various locations often restricted the size of the pools resulting in pools of varying dimensions ranging from 0.4 ft to 1 ft in depth and 15 ft to 30 ft in length. The spacing of the pools is dictated by the width of the channel and the location of the channel bends. Leopold and Wolman (1957) indicate that pools are spaced approximately 5 to 7 channel widths in natural systems. The channel design used that principle as a foundation to determine the number and spacing of the pools, while adjusting for the channel geometry to avoid placing riffles in the channel bends. The result is a design that contains 23 pools over 1000 ft.

IMPLEMENTATION

Based on the average channel width, the proposed design requires 448 cubic yards of fill materials. Given the geology of Delaware, the fill materials will need to be imported from adjacent sates. To accommodate uncertainties in the availability of different grain-sizes, we provide appropriate ranges of materials that are sufficient to meet project expectations (Figures 3 and 4).

The construction of the channel bed should have a minimal impact on the local environment as the site has excellent accessibility (see staging areas and stockpile areas in Figure 2). Potential stockpile areas can be accessed via the private access to the Reserve and Blackbird Landing Road on the eastern side of the site. The potential stockpile areas will need minimal alteration to allow for the marshaling of materials as the areas depicted are flat areas above the stream with little under story and few larger trees (Figure 2). The transfer of material from the stockpiles to the stream can be accomplished with a small front-end loader, which can navigate between the large trees located on the site. In areas a vehicle cannot easily reach it may be possible to construct gravity fed shoots from plywood.

LONG-TERM MONITORING

1. Annual surveys of key cross sections (Figure 5) provide estimates for yearly sediment fluxes.

2. In conjunction with 1 (above), monitoring the movement of painted clasts at several cross sections provides a mechanism for evaluating annual and event scale sediment flux.

3. Annual surveys of the channel thalweg profile will provide an estimate of the effectiveness of the design in mitigating vertical incision of the underlying terrain.

4. Annual pebble counts at key-cross sections provide insights regarding the appropriateness of the grain-size distribution prescribed for the fill.

5. Periodic terrestrial LIDAR scans of the headwaters will allow for volumetric assessments of slope movements and embankment stability.

SUGGESTIONS

The culvert located near station 1600 should be assessed for stability as storm events are undermining the road at the culvert outlet, as seen in the formation of a hole extending 3 to 6 feet from the culvert outlet back towards the road. This under cutting is aided by the hydraulic head created as water ponds at the culvert intake on the North side of Blackbird Creek Landing Road. We recommend that DNREC encourage DELDOT to stabilize this area within the right-of-way of Blackbird Landing Road before implementing any changes to the channel.

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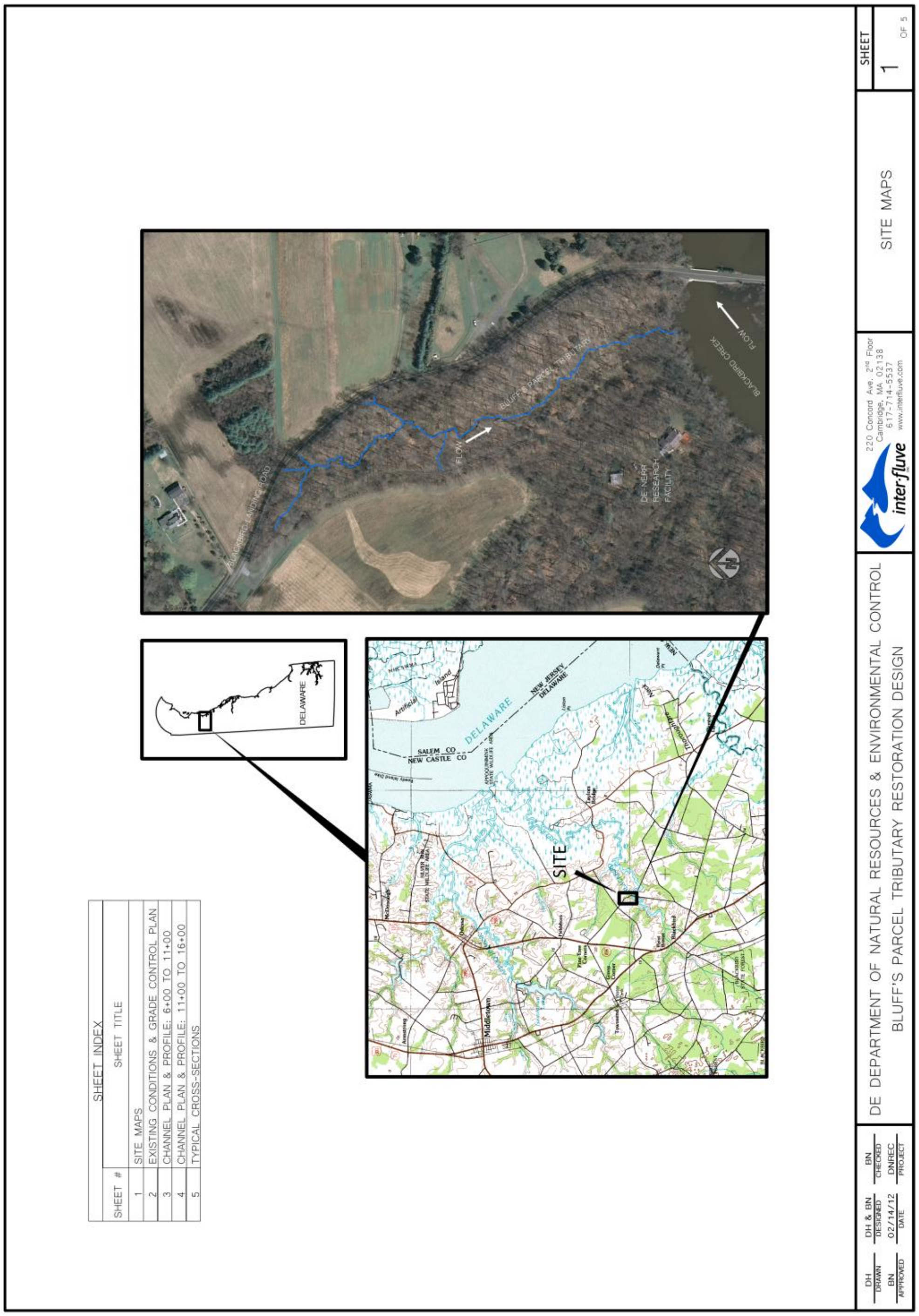

Figure A.1: Site maps displaying the state of Delaware and the location of the Bluff's Parcel study site.

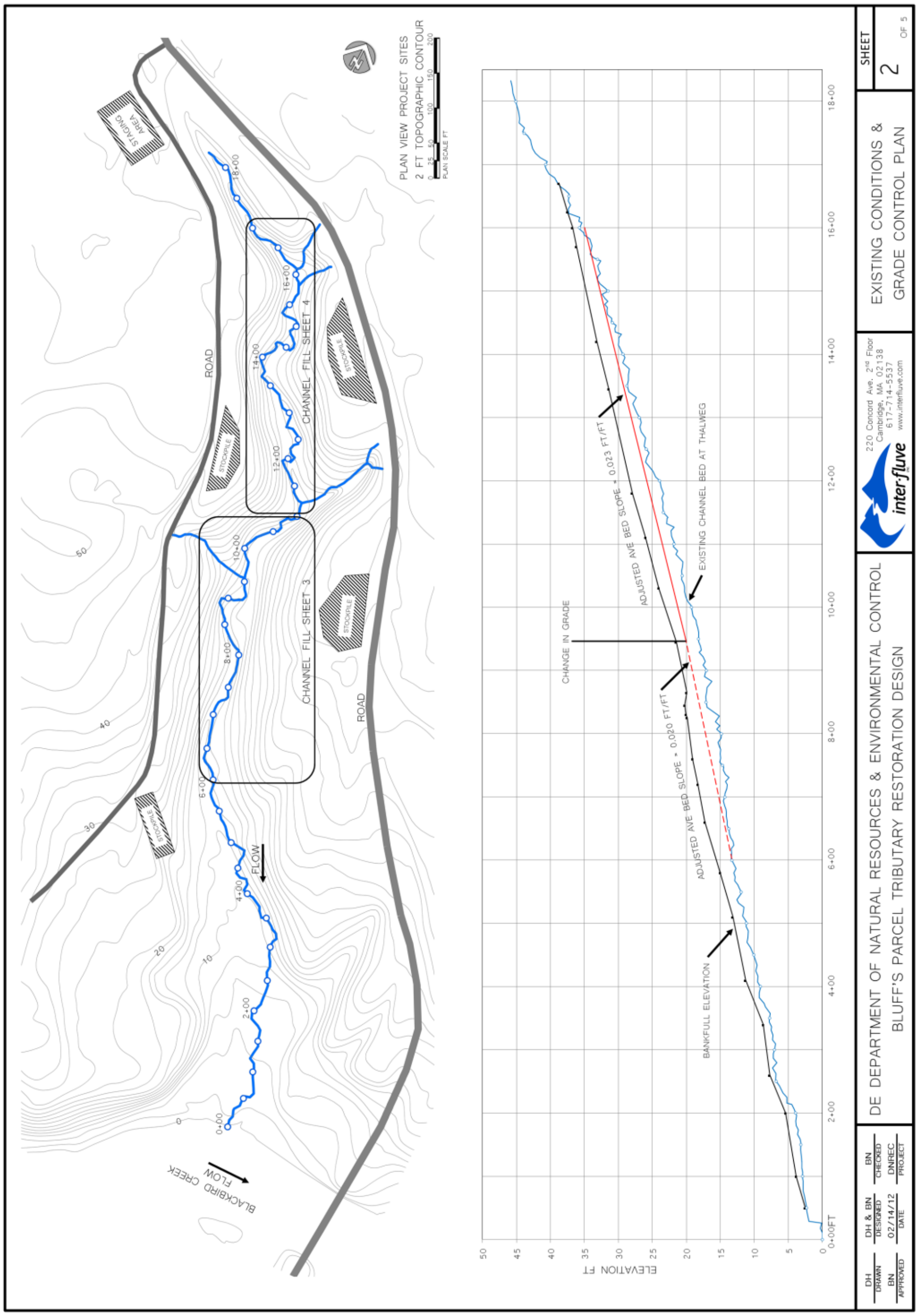

Figure A.2: Existing conditions and grade-control plans.

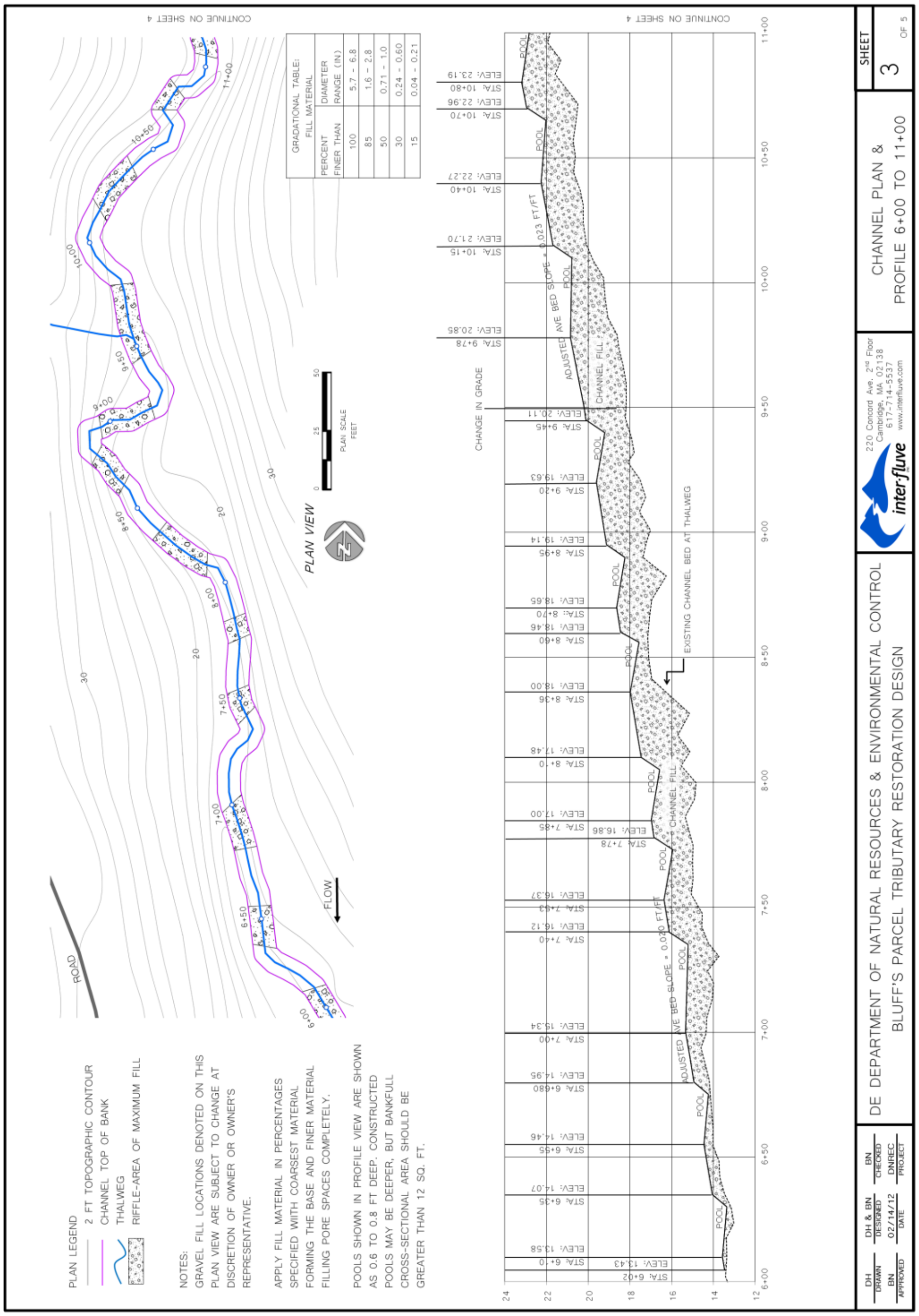

Figure A.3: Channel plan and profile between 600 ft and 1100 ft.

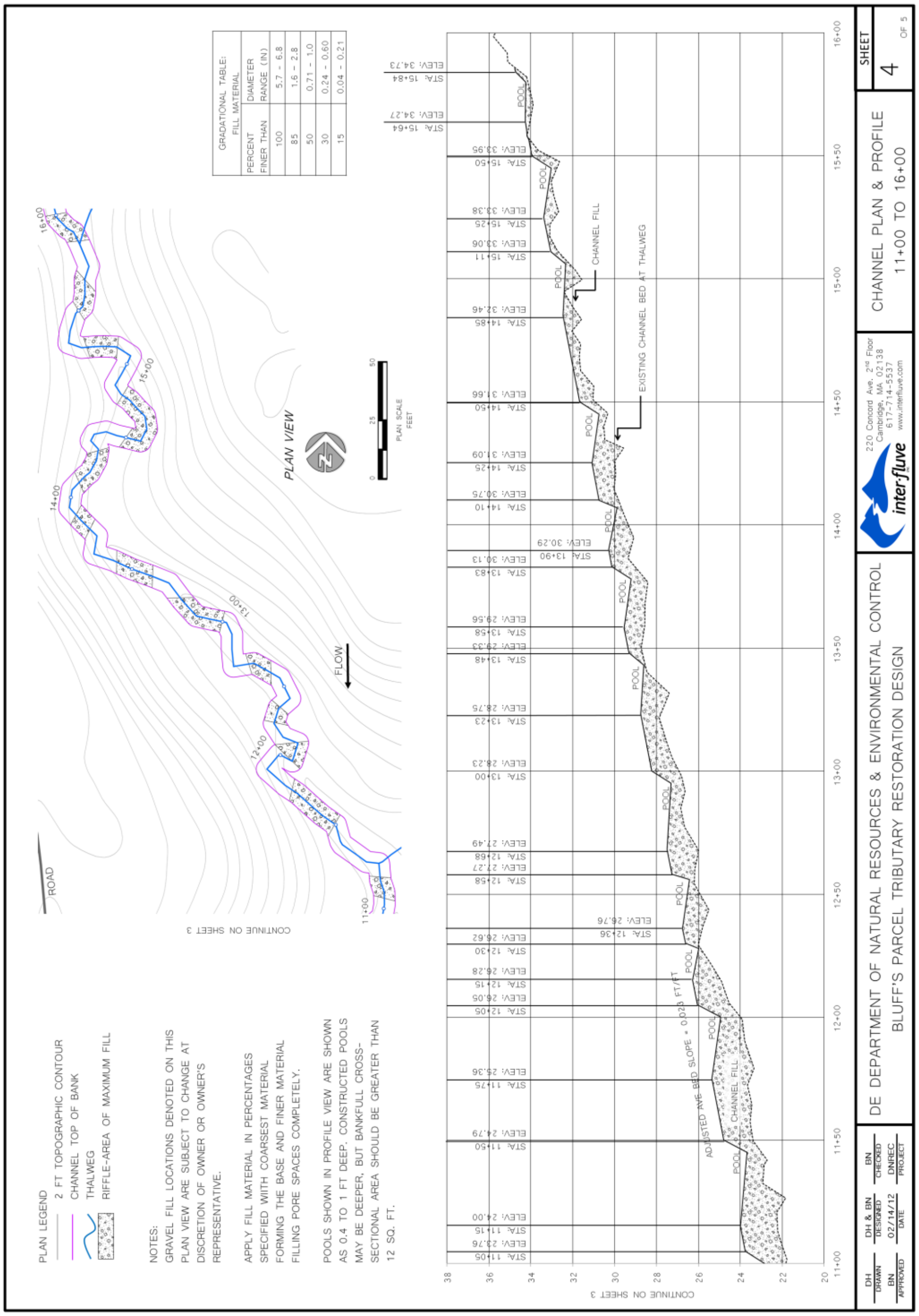

Figure A.4: Chanel plan and profile between 1100 ft and 1600 ft.

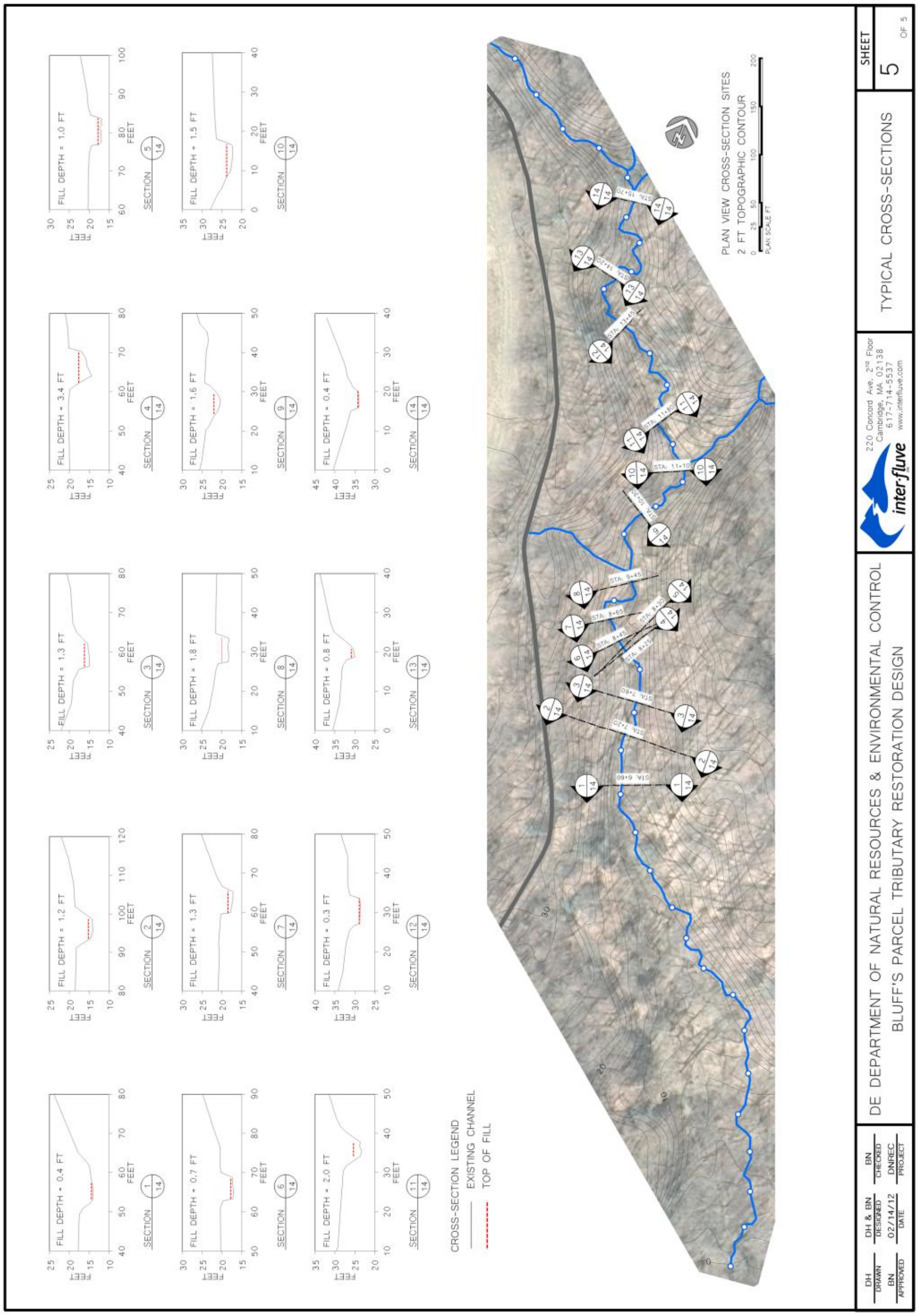

Figure A.5: Typical cross sections.