STREAMBANK STABILITY AND SEDIMENT TRACING IN VERMONT WATERWAYS

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Abstract

With over 11,000 kilometers of streams in Vermont and extensive agricultural land use sediment associated nutrient loading represents a major pollution source. To improve land and waterway management practices further understanding of sediment transport and streambank stability is desirable. Two focus areas are presented in this work; a longitudinal study conducted at two eroding stream reaches to observe streambank stability mechanics in tributaries of Lake Champlain, VT. Work was also done to evaluate the use of the radionuclide ^{10}Be as a fingerprint for suspended sediments in post glacial and temperate regions.

Assessment of streambank stability was preformed through a series of cross-sectional surveys during the 2007, 2008 and 2009 field seasons. In combination with the surveys, geotechnical properties of the streambanks were measured using insitu and laboratory methods. These included soil shear strengths, densities, gradations, erosion characteristics and tensile reinforcement from vegetation. One cross-section at each of the stream reaches was instrumented to capture the time of a streambank failure should it occur and varying hydraulic conditions. Hydraulic conditions at the two reaches were recorded, collecting ground and stream-water elevations. To capture a streambank failure event a data logging tilt switch array was used. A condensed set of geotechnical properties were then used in a slope stability computer program to determine the stability of each cross section for the range of hydraulic conditions occurring at each study reach.

Suspended sediment samples were collected from seven different sampling points located in the Lake Champlain watershed. Sampling sites were selected to represent a range of watershed characteristics; forested, agricultural, upland, lowland and impaired watersheds. Five sampling points were located in the Winooski River watershed; the remaining two were selected in an adjacent watershed to minimize geographical influences. Samples were taken during high water events when a majority of sediment is transported. To evaluate seasonal trends in sediment sources three sample sets were collected to represent a spring melt event, a summer storm event, and a fall storm event. An additional set was retrieved to observe changes in sediment sources on a daily timescale. Data collected were analyzed with respect to landuse characteristics and history of each watershed.

Rapid drawdown condition did not induce streambank failures at the study sites, because the groundwater levels in the banks followed stream water levels very closely. The low stream water level condition paired with the loss of matric suction from a rapid wetting event yielded the lowest computed factors of safety, which compared reasonably well with the recorded streambank failure event. . It is anticipated that the effects of freezing and thawing of streambank soils and ice flows in the streams, typical of humid temperate climate of Vermont, could be critical in evaluating streambanks in Vermont. Measurements of ^{10}Be concentrations in suspended sediment ranged from 0.3 to $18.7*10^8$atoms/gram. Statistical differences in concentrations could not be seen on daily or seasonal timescales. Differences in ^{10}Be concentrations showed contributing watersheds have statistically different suspended sediments, which correlate to forested and agricultural land area in the contributing watershed.

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Chapter 1: Introduction

A large portion of potable water is contained in the small percentage of fresh surface water found on the surface of the earth. Today these fresh water sources are under constant threat from accelerated pollution due to anthropocentric causes. Pollution found in our surfaces waters can be split into two separate categories, toxic and conventional pollution (Kreger, 2004). Although toxins pose immediate and serious health threats they represent only a small portion of the total pollution found in our waterway. Conventional pollution represents the larger portion of pollution found today, being defined as nutrients and biological contaminants that enter waterways. Conventional pollution includes biological oxygen demand (BOD), pathogens, ammonia, Nitrogen (N), phosphorus (P), and suspended solids (SS). Anthropocentric activity has been shown to cause increases in conventional pollution; particularly in levels of N and P (Carpenter et al, 1998). Responsible for these higher loading rates of conventional pollutants are commonly sewage treatment effluent, stormwater runoff, and non-point sources associated with agricultural and land management practices. Of both conventional and toxic pollution, P has become recognized as the largest pollutant in lakes and waterways in the US (MARC, 2007).

In most water systems phosphorus tends to act as a limiting nutrient, regulating the maximum amount of biomass that may be sustained in a given environment (Grady et al., 1980). When excess limiting nutrient is introduced into a water body micro-organism populations rapidly increase in biomass. This rapid growth is a cause for several detrimental environmental effects. Large increases in biomass accelerate eutrophication rates of the given water body. When the population of aerobic organisms are observed BOD levels exceed the rate of oxygen diffusion into the water creating anoxic conditions, potentially suffocating many larger aerobic organisms, leading to fish kills and losses in biological diversity.

Large inorganic P sources today are both point and non-point sources. Point sources of P are commonly municipal sewage and controlled storm water runoff. The most common non-point sources are active farm lands that apply phosphorous rich fertilizer and manure to fields for increased crop production. Application rates of phosphorous rich fertilizers have steadily increased since its inception in the early 1900s, due to intensive use of monocultures in efforts to produce higher yield crops. Use of fertilizers in the United States is estimated to yield P application rates of $2.7*10^{11}$kg/yr (Holtan et al., 1988).

This increase of fertilizer application coupled with phosphorous' nature to tightly bind with soil particles (Barros et al., 2005), has created P inventories in soils of long used agricultural fields. Research has shown that rill and streambank erosion from adjacent farmlands are common non-point sources contributing to suspended sediment and consequently phosphorous loading into streams and waterways (Kronovang et al., 1999). The vast majority of P in waterways is transported with alluvial sediments. The residence times of particulate phosphorus (PP) varies with the sediment deposition and removal rates for each given watershed.

Streambank erosion, scour and mass failure, have been estimated to contribute 30-80% of total sediment loading into lakes and waterways (Fox et al., 2007; Evans et al., 2006; Simon and Darby, 1999), while total sediment loading is estimated to contribute 50-90% of P loading into water bodies (Zaimes et al., 2005). Quantification of sediment transport may be measured directly through use of longitudinal surveys and erosion pins (Lawler 1999). However, such labor intensive techniques are impractical to use in large watersheds. More in-depth stability evaluations of streambanks employing geotechinal engineering principles are more suitable to examine streambank erosion processes.

Due to the large size of the Lake Champlain basin it is ideal that sediment transport contributions into the lake are known. This allows more intensive studies and restoration to be conducted in streams contributing proportionally larger sediment yields. Since this is difficult through use of direct measurement (discussed above) it is necessary to make use of a sediment fingerprinting approach. The fingerprinting method relies on selection of isotopic, chemical or physical properties with values specific to their derived source (Waling 2005). Values of these properties are compared between potential parent sources and the collected sample to provide valuable information in determination of the source material.

Two focus areas are presented in this work; a longitudinal study conducted at two eroding stream reaches was conducted to observe streambank stability mechanics of tributary waterways to Lake Champlain, VT. Work was also done to evaluate the use of the radionuclide ^{10}Be as a fingerprint for suspended sediments in post glacial and temperate regions.

The following chapter (Chapter 2) is a manuscript being prepared for submission to the *Journal of Engineering Geology* summarizing a two year study conducted at two stream reaches of North Western Vermont analyzing the stability of streambank and the material properties of the soils composing them. Chapter 3 is a manuscript prepared for submission to the *Journal of Geophysical Research Earth Surfaces* on the potential use of meteoric ^{10}Be as a fingerprint for suspended sediment in humid temperate regions, based on analysis conducted on streams with different land use characteristics in the state of Vermont. Chapter 4 summarizes the main conclusions from this thesis and future recommendations followed by the references in Chapter 5. Other relevant information such as raw data and testing protocols are organized in several appendices.

Chapter 2: Paper No. 1

Quantitative Analysis of the Stability of Vermont Streambanks

For submission to the *Journal of Engineering Geology*

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2.1 Abstract

A study investigating streambank failure mechanisms in humid temperate climate of Vermont is presented. Fourteen separate streambanks from two rivers (Winooski River and Lewis Creek) in the Lake Champlain basin were studied. The eroding portion of banks at both reaches consisted mostly of sandy silt and silty sand alluvial material. The selected reaches were located along unused pasture land with grassy vegetation. One cross section at each stream was instrumented to measure changing water levels and bank activity. Spatial and temporal data on bank cross sections, properties of streambank soils (saturated and unsaturated shear strength, root strength, erosion characteristics), and groundwater and stream levels were collected. The measured shear strengths using in-situ borehole shear tests compared reasonably well with those determined from laboratory direct shear tests. Grass root impregnation of the alluvial material was found to increase cohesive strength of the alluvial material by 1.7 to 4.5 kPa. The direct shear tests performed on bare soils and soils with roots offered a reasonable way of determining cohesion increases in streambank soils with small roots (diameter less than 1 mm). The bank top recession rates varied from 0 to 0.6 m/yr at both reaches. Sediment removal was found to range from 0 - 2.7 m^2 and 0 - 2.1 m^2 in the studied cross sections for the Winooski River and Lewis Creek reaches, respectively, over the 25 month long course of this study. Stability analysis preformed using measured properties and likely failure conditions found factors of safety ranging from 0.7 to 2.1 and 0.9 to 2.1 for the Winooski River and Lewis Creek reaches, respectively. Rapid drawdown conditions were not seen as the critical slope condition at the study sites. The low stream water level condition paired with the loss of matric suction from a rapid wetting event yielded the lowest

computed factors of safety, which compared reasonably well with the recorded streambank failure event.

2.2 Introduction

Public agencies are expending significant funds and effort to reduce sediment and phosphorus loads in streams, lakes and other water bodies. Rill erosion from farmland and streambank erosion are common non-point sources contributing to suspended sediment and phosphorous loading into streams and waterways (Kronovang et al. 1999). Phosphorus binds to soil particles tightly (Barros 2005), and is transported with suspended sediment, frequently originating from streambank erosion (Walling 1992. Streambank erosion is estimated to account for 30-80% of sediment loading into lakes and waterways (Simon 1999; Evans 2006; Fox 2007). Therefore, an in-depth understanding of the mechanisms involved in streambank erosion is essential.

In an effort to quantify streambank erosion, several direct measurement procedures have been utilized. Lawler (1999) made use of longitudinal surveys and pins to quantify sediment loading through bank erosion. Longitudinal surveys allowed the measurement of bank top retreat while the use of pins allowed measurement of toe erosion of laterally migrating streambanks. Direct techniques such as these have been found valuable in determining sediment loads in small watersheds. However, direct measurement techniques are labor intensive making their large scale use often impractical.

Often, soils in slope design are considered to be fully saturated or, dry for simplicity. Dapporto et al. (2003) and Rinaldi and Casagli (1999) argued that such simplifications are not suitable for streambank analysis and unsaturated soil properties must be considered for a more accurate analysis. Negative pore water pressures, i.e. matric suction, have long been known to increase stability of slopes (Fredlund 1985). Recent use of unsaturated soil mechanics models in evaluating streambank stability has led to reasonable results (Simon et al 2000; Rinaldi and Casagli 1999). Research conducted by Dapporto et al. (2003) and Simon et al. (2000) analyzed a number of streambanks using borehole shear testing and incorporation of unsaturated soil properties. Simon et al. (2000) found that normally stable banks often become unstable when there is a loss of negative pore water pressures.

Vegetation can contribute significantly to the stability of stream banks (e.g., Collision and Simon 2002). Typically, vegetation increases strength of soils, and therefore, slope stability in several ways. First, the demand for water by plants removes moisture from the soils and accelerates the development of matric suction in unsaturated areas (Wilson et al. 1996). Second, in addition to increasing matric suction, roots provide tensile reinforcement creating a composite soil-root material (Ennos 1990, Waldron 1977, Wu et al 1979; Pollen et al 2004). Shear strength increases caused by root additions are typically seen as an increase in soil cohesion. Several theoretically based equations have been developed to estimate cohesive additions provided by root structures based on their tensile strength and bedding plane (e.g., Waldron, 1977; Pollen, 2007). Wu et al. (1979) and De Wiel (1979) proposed a simplified equation for accounting varying angles of roots. Darby et al. (2007) incorporated the heterogeneous distribution of roots and different reinforcement levels depending on the angle of the shear plane. Although vegetation is often thought to increase the overall stability of a given slope, it can have adverse effects. For example, vegetative surcharge at the bank top increases driving forces associated with slope failure (Darby et al. 2007).

The motivation for the study presented here came from rising concerns of eutrophication of Lake Champlain, VT. To reduce nutrient loading into the lake, the States of Vermont and New York and Canadian province of Quebec are working toward reducing phosphorus levels from nonpoint sources (LCBP 1999). With over 11,000 km of waterways in Vermont, the Vermont Department of Environmental Conservation recognizes streambank erosion as one of the most important nonpoint sources of sediment and phosphorus entering streams, rivers, and lakes, and thus one of the largest contributors to the impairment of surface water quality and aquatic habitat (VTDEC 2002, NYSDEC 2002). The study presented here examined the stability and streambank failure mechanisms of two distinctly different river reaches in the State of Vermont. The focus was on understanding the processes that control streambank erosion; with special attention paid to the shear strengths of saturated and unsaturated soils and the effects of grass roots on the strength of streambank soils.

2.3 Setting

Two stream reaches were selected in northern Vermont located in Lake Champlain basin as seen in Figure 2.1. Northwestern Vermont's geology is dominated by the Green Mountains with peaks reaching over 1,400 m. Due to rapid deforestation during the 1800s, low lying floodplain areas are covered in a thick layer of historic alluvium, reaching in excess of 2 m in areas. In low lying areas, sedimentary rocks are overlain with clays and fine-grained alluvium near river channels (Doll 1970; Doolan 1996).

Seven cross sections at each stream were selected for the study on the cutbank sides of stream meanders as indicated in Figure 2.1. Abandoned farmland area of the Winooski River was chosen. Fine grained banks similar to this site are suspected to contribute greatly to sediment loading into Lake Champlain (OLOF 2008). The Winooski River basin (2,754 km^2, Figure 2.1) drains water west from the Green Mountains and discharges into the eastern side of Lake Champlain (29.6 masl). Flow in the Winooski River is varied, with low flow levels of less than 17 m^3/s, to high regulated flows exceeding 580 m^3/s (USGS 2010).

The second set of 7 sites was located in the lower reaches of the Lewis Creek watershed (210 km^2, Figure 2.1) and is nestled in the lowland areas of Vermont discharging directly into Lake Champlain (Figure 2.1). The surrounding pasture land was cleared during the 1970s and used as a gravel source prior to abandonment during the 1990s. Stream water flow in Lewis Creek varies seasonally, from less than 0.6 m^3/s during summer low periods to in excess of 57 m^3/s (USGS 2010).

2.4 Methods

2.4.1 Site Investigation and Instrumentation

Each reach was surveyed four to five times throughout the course of this study (May 2007 to December 2009). Reference pins along the reach allowed the same stream cross section to be measured repeatedly, tracking bank geometry changes, marking soil interfaces, and water levels. In addition to the cross sectional surveys, one datum survey was conducted along each reach to transfer elevation data to all of the reference pins.

At each site, investigative boreholes were augured until borehole sidewalls collapsed or soil conditions halted further auger advances. Due to limited access of the stream reaches, the subsurface investigations were limited to hand-operated equipment. Differences in soil characteristics such as color, texture, inclusions, and odor were noted for each borehole to determine soil stratification. When significant differences were observed in soil characteristics, a bulk sample was collected. Shelby tube samples were collected for subsequent strength testing using a hand-operated slide hammer type sampler. Mechanical sieve analysis (ASTM D422) tests were performed for representative bulk soil samples. In addition, hydrometer analysis (ASTM D422) and Atterberg limits (liquid and plastic limits) tests (ASTM D4318-10) were also performed on select soil samples with high fines content.

At each stream reach, one cross section was selected for instrumentation to monitor water levels and bank activity. As an example, the instrumented cross section at the Winooski River is depicted in Figure 2.2. Three groundwater wells were placed at depths of 4.3 - 4.9 m at the Winooski River instrumented site and two groundwater wells were placed at depths of 3.7 and 4.3 m at the Lewis Creek instrumented site. These allowed the water levels in the banks to be monitored, which were measured using data logging pressure transducers in conjunction with a barometric pressure transducer to compensate for changes in barometric pressure. At each reach, an additional hydraulic pressure transducer was used to record stream water levels. Due to variations in stream geology and topography, separate approaches were used to directly expose the pressure transducer to the stream water. The greater depth and high flows at the Winooski River limited access and required a non vertical well in a stable section of streambank with a zenith angle of 40˚. The shallow angled shorter streambanks at the Lewis Creek reach prevented similar instrumentation. To expose the pressure transducer directly to the stream water, a 60 cm section of screened well piping was capped at either end to house a pressure transducer then anchored to the streambed using metal pins.

Four roller ball tilt switches were imbedded into the instrumented cross sections allowing the timing of a bank failure to be captured should it occur. When moved out of plane by more than 15˚, the tilt switch registers a change in voltage. This was considered to be a significant slope movement indicating a streambank failure. The goal was to capture the water levels if a slope failure occurred between consecutive surveys. The tilt switches were monitored using a Hobo Data logger (U12-006) encased in a weatherproof box. Logging intervals were set at a two hour resolution for both tilt switch and pressure transducer systems.

2.4.2 In-Situ and Laboratory Shear Strength Testing

To quantify the shear strength properties of the soils, two testing procedures were used. In-situ tests were performed using a series of borehole shear tests (BSTs). The BST has been used successfully by other investigators in streambank evaluations (e.g. Dapporto et al. 2003; Simon et al. 2000). At each site, two BSTs were conducted at each change in soil type using a minimum of 5 confining pressures. The boreholes were first smoothed by removing a Shelby tube sample at desired depths prior to performing BSTs. Normal consolidation stresses for the tested soils ranged from 15 to 120 kPa using 15 kPa increments. Adequate time was allowed for excess pore water pressures to dissipate prior to the application of shear stresses. The BST results were also compared to the laboratory results from consolidated drained direct shear tests (DST) performed on Shelby tube samples typically retrieved at the same location of the BST. In situations when the sample quality appeared compromised from sampling disturbance, a Shelby tube sample from a nearby location on a similar soil was used for DST. The DSTs were performed using a Geo Comp ShearTrac II device in general accordance with ASTM D3080-04.

Vegetation located at each of the study sites did not include trees and was limited to approximately 90% Canadian Goldenrod (S. Candensis) and various other grass species making up the remaining vegetation. To quantify the effects of roots on the shear strength of the streambank soils, two different approaches were investigated in this study. The first was to use equation (1) proposed by Wu et al (1979), in which the cohesive addition of roots to the soil's shear strength (C_r) is related to the root area ratio (R_a , area of roots/ area of shear surface) and the root's tensile strength (T_r).

$$C_r = 1.2(T_r \bullet R_a) \tag{1}$$

Several representative Goldenrod root balls were sampled at each of the study reaches and root samples were harvested for tensile testing. Care was taken to preserve root moisture to emulate field conditions. The ends of the root sample sections were anchored into quick drying epoxy molds, and allowed to fully harden. The samples and the epoxy anchors were then transferred to a tensile testing machine where they were loaded until the root material ruptured. The rupture force for each root was then divided by the cross sectional area of each root sample to determine its tensile strength. Root area ratios were measured by recording the volume of roots found in field root-impregnated soil samples measuring 2.5 cm in height and 7.3 cm in diameter.

The second method of examining the contribution of the roots to the soil strength employed DSTs on relatively undisturbed Shelby tube soil specimens with and without roots collected at both reaches. At each reach, a minimum of three rootless soil samples were collected from depths of up to 0.45 m in vertical (zenith angle 0˚) boreholes. A minimum of three soil samples with roots were collected from boreholes drilled at zenith angles of 0˚ (vertical), 45˚, and 90˚ (horizontal). For each sample a consolidated drained DST was performed, using normal stresses ranging between 14 and 48 kPa. A shear stroke of 13 mm was selected to allow mobilization of the roots' tensile strength. The measured failure shear stress was used to determine the soil's friction angle (φ') and cohesion (c'). Samples containing roots were tested in the same manner.

Sections of the alluvium layers at both sites were often above the water table necessitating determination of unsaturated soil friction angle (φ^b). To examine the effects of matric suction on soil strength a series of tensiometer measurements, DSTs and BSTs were conducted on bare alluvial soils. Matric suction of the soil at the time of testing was measured using an Infield 7 data logger attached to a T4 tensiometer. The suction measurements were made every 15 s until the readings stabilized. The difference between the measured cohesions of the BST and DST was taken to be the apparent cohesion added by matric suction. This value was used to calculate the unsaturated friction angle (φ^b).

2.4.3 Erosion Rates

Scour parameters of the soil were determined using a non-vertical jet erosion test (JET). A pair of JETs was performed at each reach on the alluvial material at the instrumented site. Flat sections of streambank material were chosen for the testing to provide a good seal. Tests were run for 30 minutes using 1 min intervals initially and then increasing to 2 min intervals as the scour depth approached the equilibrium depth. Data collected were used to determine the soil's critical shear stress (t_c) and erosion rate (k_r).

2.5 Results

Streambanks along the Winooski River reach range from 2.3-3.3 m above the low water level and are primarily composed of fluvial silts and sands. The Lewis Creek reach contains streambanks from 2.1-3.2 m above the low stream water level. The streambed is composed of blue clay typical of the Lake Champlain basin. An upper soil of silty sand ranged from 0.5 to 2m in thickness with a narrow (0.6m) cobble layer confined between the clay and sand layers.

2.5.1 Soils

The collected data on the alluvial streambank soils; index properties (density, Atterberg limits, gradation, and classification) and shear strength properties are summarized in Table 2.1.

Streambank soils along the Winooski Reach were fairly homogenous for each site and consisted of sandy silts and silty fine sands for the entire depth of borehole investigations. Bulk densities of these soils were found to range between 1.8 and 1.9 Mg/m^3. The strength properties c’ and φ’ ranged from 0 to 3.6 kPa and 29.0° to 41.1°, respectively.

Streambank soils along the Lewis Creek reach consisted of sandy silts over a thin cobble layer with a clay streambed. Bulk densities of the sandy soils varied from 1.7 to 1.9 Mg/m^3. The strength properties c’ and φ’ ranged from 0 to 1.0 kPa and 32.2° to 42.6°, respectively.

A comparison between measured strengths of the upper alluvial soils determined using the BSTs and DSTs (Figure 2.3) show similar values of the effective friction angle ($\varphi^{'}$). It is to be noted that BST in unsaturated soils provides apparent cohesion (c_a), whereas consolidated drained DST provides effective cohesion (c’). The non-systemic differences and similar range in values measured using BST and DST allowed results from both tests to be used interchangeably, and estimate φ^b.

Measurements of tensile rupture force of S. Candensis roots are plotted against diameter (Figure 2.4) showing the increase in rupture force for increasing root size. The root tensile strength was calculated as the rupture force divided by the root cross sectional area. Tensile strengths are plotted against root diameters in Figure 2.4. The average measured root tensile strength is 46.8 MPa.

The soil shear strength increases from roots was also quantified using a series of DSTs preformed on bare and root impregnated soil samples. Subsets of these samples were derived from the 3 zenith sampling angles in the alluvium layer to characterize anisotropy associated with tensile root reinforcement. Roots were typically smaller than 1 mm in diameter and visual inspection showed random orientation of roots within the collected soil samples. The failure shear stresses and normal stresses for the samples with roots are plotted in Figures 2.5a and 2.5b for different zenith angles. This figure may be used to evaluate the effects of the failure plane direction on the observed strength of root-soil matrix. Although the data displayed some possible dependence, no specific trend was observed or the inherent anisotropy overpowered any dependence on the direction of the failure plane with respect to the roots. Therefore, a comparison between the DST data sets from all samples with roots (all zenith angles) and the samples without roots is made in Figures 2.5c and 2.5d for the two reaches. Linear regressions performed on the data with and without roots display a clear increase in cohesion (c_r) contributed by the roots. The increase in strength is 1.7 and 4.5 kPa for the Lewis Creek and Winooski River alluvial soils, respectively.

2.5.2 Water Conditions

Water conditions for the sites varied significantly with flows varying over two orders of magnitude at each site. Water levels along the Winooski River reach varied by approximately 4.0 m at the instrumented site over the observed sampling period from November 2007 to June 2009. Similar fluctuations were observed at the Lewis Creek reach with water levels varying from 1.0 m to 2.8 m below instrumented site bank top elevation. The groundwater elevation minus the stream level elevation is plotted for two well locations. A positive number means that the stream level was lower than the groundwater elevation indicating a rapid drawdown type condition. As seen, although the groundwater table went below the stream level by as much as 0.8 m, the groundwater level was less than 0.105m above the stream level during the period plotted in Figure 2.6. During the entire study period, the groundwater table was never above 0.3m above the stream level. A similar trend in the groundwater and stream level response was observed for Lewis Creek when ground water levels were above the clay layer. Ground water levels at the Lewis Creek remained at or above the clay layer because of the low permeability clay.

2.5.3 Bank Erosion and Stability

2.5.3.1 Cross Sectional

Cross sectional surveys tracked streambank morphology throughout the course of this study. The bank top crests at the sites along the Winooski River reach retreated ranging from 0 to 1.3 m and with an average of 0.43 m (n=7). The total sediment area removed at the seven sections ranged from 0 to 2.7 m^2 for the bank heights ranging from1.8 to 3.8 m. Average sediment removal rates for the course of this study varied from 0 to 0.6 m^2/yr at the Winooski River reach. Bank top retreat at the Winooski River instrumented site was 1.3 m. Tilt switch monitoring revealed the possibility of a mass failure event occurring on January 10, 2008 coinciding with a mid-winter snow melt event. Visual observations of failures along this reach indicated they were generally steep rotational or slab failures. No tension cracks were observed along this reach. Evidence of sapping induced failure events were observed adjacent to a stand of recently planted riparian trees, but not at the studied site.

Repeated surveys could not be conducted at one of the Lewis Creek sites as the bank top receded by at least 3.1 m during the 2007 winter months removing the survey reference pins. The remainder of the Lewis Creek sites showed bank top retreat of 0 to 1.3 m with an average of 0.41 m. No bank top retreat was noted at the Lewis Creek instrumented site. The total sediment area removed at the Lewis Creek sites were 0 to 2.1 m^2. Average sediment removal rates over the course of the study ranged from 0 to 0.6 m^2/yr for the Lewis Creek reach. Failures along this reach were noted as primarily slab failures with some observable tension cracks prior to failure. In areas of finer alluvial soil, rotational failures were also observed.

2.5.3.2 Scour Erosion Characteristics

Alluvial soils' erosion properties were measured using a pair of JETs at the instrumented site at each of the study reaches. At the Winooski River reach, the measured critical shear stress measurements estimated t_c to be 7.5 Pa and 5.0 Pa. At the Lewis creek, the measured t_c was 4.5 Pa and 4.9 Pa. Averaged t_c values were used to calculate the erosion coefficient k_d of the alluvial soils found to be 0.040 and 0.046 cm^3/N-s for the Winooski River and Lewis Creek reaches, respectively.

2.6 Analysis and Discussion

2.6.1 Materials

The upper alluvial soil layers, comprising the majority of the streambanks on both reaches, were predominantly sandy silts and silty sands with densities ranging between 1.7 to 1.9 Mg/m^3 and 1.6 to 1.8 Mg/m^3 for the Winooski River and Lewis Creek reaches, respectively. The Lewis Creek sites had cobble and clay layers under the coarse layer. The differences were observed below the upper soil layer; however, the observed failure and erosion did not involve the lower soil layers.

The shear strength measurements were also generally consistent at all the sections for a given reach. The BST results compared quite well with the DST results (Figure 2.3) giving credence to the strength measurements. The slightly higher values of effective friction angle φ' obtained from the direct shear tests may be attributed to sample compaction during Shelby tube sampling and the difficulties associated with cleaning BST sample sites. The effective cohesions (c') based on DST were generally small (less than 3.5 kPa) for both reaches except at one location where it was measured to be 9 kPa; this was considered an outlier. The apparent cohesions (c_a) based on BST ranged from 0 to 12 kPa. Using the BST and DST data, the unsaturated friction angle (φ^b) was calculated to be 16.5^o to 22.6^o (average of 21.9^o for Winooski River and 19.6^o for Lewis Creek) at the four locations where suction measurements were available to calculated φ^b. In the subsequent slope stability analysis, the measured strength parameters (c' based on DST and $\varphi^{'}$ average of BST and DST) at the particular site were used in the stability analysis. If φ^b was not available for a given site, the above mentioned average values were used.

The slope stability analysis (discussed later) required the density and strength properties of the cobble layer and the clay layer at the Lewis Creek reach. The c' were estimated to be 0 and 40 kPa for the gravel and the clay layers, respectively, and φ' were estimated to be 45° and 18°, respectively. Their bulk densities were estimated to be 2.1 and 1.9 Mg/m^3, respectively. The specific values for these properties of the gravel and clay layer were relatively unimportant because the observed failure surfaces did not pass through these layers.

Figures 2.4a and b present data from the tensile tests conducted on the roots from the Winooski sites. As expected, the tensile rupture load increased with the root diameter, but the rupture strength (rupture force divided by root cross sectional area) remained relatively constant and averaged 46.8 MPa. To estimate the cohesion addition (C_r) using equation (1), representative soil samples with roots were collected. The root area ratios of these sampled ranged from 0.003 to 0.014, which would predict C_r of 190 to 770 kPa. These values are two orders of magnitude higher than the measured C_r values from DST (discussed later) and are unrealistically high. This could be because equation (1) assumes that all roots fail in a tensile manner. This is not realistic assumption as some roots could be pulled out at stresses lower than their tensile strengths (Pollen, 2007). It is difficult to accurately measure the size of small roots (such as at the studied sites) and some roots may be lost during sampling. In addition, determining dead versus live roots and their respective contributions is difficult. For these reasons, the C_r estimates based on tensile strength tests were not used in the subsequent analysis.

The alternate method of using DSTs on bare soils and soil samples with roots provide more reliable results (Figure 2.5). Although the data displayed some possible dependence on the failure plane orientation (Figures 2.5a and b), no specific trend was observed. It is possible the inherent anisotropy overpowers any dependence on the direction of the failure plane with respect to the roots. Therefore, it was assumed that for the studied sites, the root reinforcement is isotropic and homogenous within the rooted soil zone. Figures 2.5c and d indicated C_r to be about 4.5 kPa and 1.7 kPa for Winooski River and Lewis Creek reaches, respectively. These values were used in the subsequent slope stability analysis.

The measured erosion properties were quite similar at both reaches. Based on the numbers mentioned above, the streambank soils were considered to be moderately erodible.

2.6.2 Water Conditions

Rapid drawdown events provide the least stable slope conditions, but had minimal occurrence along the study reaches. The groundwater measurement for well 3 at the Winooski River instrumented site, shown in Figure 2.6, was made more than 4 m inside the instrumented bank. The water level difference between the groundwater and stream level at any given time was less than 75 cm. However, when that happened, the groundwater level was actually below the stream level (negative values in Figure 2.6), which is generally a stable condition in comparison to rapid drawdown type situation.

Figure 2.6 showed that the groundwater was never higher than the stream water by greater than 0.3m (positive values in Figure 2.6). Therefore, it was concluded that the banks, if failed, were not due to rapid drawdown conditions.

It is to be noted that the study sites were specifically selected such that they did not have large vegetation, only grasses. Evidence of sapping failures (sand boils) was not seen at any of the study sites. However, evidence of sapping was observed at sites other than the study sites similar to the Winooski instrumented site. These sites had trees with trunks up to 15 cm dbh with canopies draining water on the banks. Sapping failures are similar to a rapid drawdown situation, where ground water flows within the streambank create localized areas of high water pressure (Bras et al. 2002). This may be caused by concentration of precipitation at the bank's surface. As sand boils were only present along the reach with trees adjacent to the streambank, it is suggested that canopies from the trees may concentrate precipitation resulting in preferential ground water flow paths and localized bank instability. At this time, this is only based on visual observations; and a more detailed study would be necessary for more definitive conclusions.

With relatively high bulk densities observed in the field, rapid wetting events are considered a likely source of streambank failures at the studied sites. Simon et al. (2000) observed that a common cause of streambank failures is a decrease or loss of matric suction in the soil pores. When soils become saturated there is an associated loss in matric suction. If this is accompanied with a rise in stream water levels, the hydraulic pressure from the stream provides supporting force to the weakened streambank.

However, if the stream water does not swell, the banks may become unstable. With the small differences between measured bulk and saturated densities, rainfall or snowmelt may quickly dissipate any matric suction found in the streambanks, making this a likely failure mode. This is particularly relevant in humid temperate climates such as that in Vermont. This is supported by the bank failure captured on January 10, 2008 during a winter snow melt event at the Winooski River instrumented site. Therefore, the loss in matric suction was considered one of the variables in the slope stability analysis discussed next.

2.6.3 Stability Analysis

Stability analysis of each surveyed streambank was conducted using the GeoStudios SLOPE/W, version 2007, software package, which is based on the limit equilibrium method for slope stability. Analysis was performed using three separate sets of conditions: (1) low stream water level, (2) high stream water level; and (3) low stream water level with rapid wetting of streambank soil (e.g. from rain event or snow melt). Since the rapid drawdown condition was shown to be not relevant for the study sites, that type of analysis was not conducted.

For the first two types of analysis, c’ and φ' were assigned to soils below the groundwater table. For the soils above the groundwater table, φ^b was used in the analysis. A linear capillary distribution was assumed above the groundwater table. The program then calculates the apparent cohesion. The upper 0.5 m of the soil at all sites was considered a zone with roots. An added cohesion (C_r of 4.5 kPa for Winooski River and 1.7 kPa for Lewis Creek, as discussed earlier) was used for this layer. The third type of analysis was similar, except that the entire soil layer was assumed saturated and effective strength parameters were used along with the saturated unit weight. Note that the stream water level was still considered at the lowest level.

As an example, the three analyses conducted for the Winooski instrumented site are shown in Figure 2.7 using the cross section measured prior to the tilt switches indicating a possible failure event. The figures include the computed minimum factors of safety (FOS) and associated critical failure surfaces for each case. The high water and rapid wetting cases resulted in FOS smaller than 1.0 indicating failure. As expected, the rapid wetting case yielded the lowest factor of safety. This site indeed failed, as recorded by the tilt switches. However, the last measured cross section before that event was 2 months prior. During that time, the stream water level was at an intermediate stage below the base of the observed failure surface. SLOPE/W predicted a corresponding FOS of 1.05 (Figure 2.7d). It is hypothesized that the rapid wetting event could have also contributed to the failure, because it happened during a heavy snow melt period.

The above set of slope stability analyses was repeated without considering added strength from roots as a parametric study. For the cases where the critical failure surfaces originated at the top of the bank, the FOS decreased by about 6%, indicating the importance of the relatively small root zone (45 cm deep) found in the streambanks of this study. At other sites with shorter streambanks or deeper root zone, the influence of added strength from roots would be more significant.

FOS for all other 13 sites were also computed for all three loading cases and for all measured cross sections. For all sites, the low stream water level analysis yielded FOS greater than 1.0. FOS determined using the high stream water situation ranged from 0.9 to 1.9 for the Lewis Creek sites and 0.7 to 2.6 for Winooski River sites, while FOS in the rapid wetting case ranged from 0.9 to 1.6 and 0.8 to 2.1 for the Lewis Creek and Winooski River reaches, respectively, for the rapid wetting case.

Figure 2.8 summarizes computed FOS on a bank height versus bank slope plot for the two reaches for the rapid wetting case. This case was chosen for the illustration because it was determined to be the most severe case. The FOS numbers were divided into three ratings, stable (FOS > 1.2), marginally stable (1.2 > FOS > 1.0), and unstable (FOS < 1.0). These charts were developed to assess if there was any correlation between computed FOS and the slope characteristics (height and angle). Figure 2.8 does not reveal any specific boundary among the three stability ratings.

The cross section data were used to compute the sediment removal amounts. Figure 2.9 is in a format similar to Figure 2.8, except material lost is presented instead of FOS. For each site, multiple cross sections were available. Although the height stays the same, slope angles change as the material is lost. While considering a set of two consecutive cross sections, the area between the two cross sections was computed to be sediment removal and the associated slope angle was determined from the first of the two cross sections. The sediment removal amounts were divided into three ratings; low (< 0.3

m^3), moderate (0.3 – 1.0 m^3) and high (> 1.0 m^3). No specific boundary lines are evident in Figure 2.9.

Finally, Figure 2.10 presents a comparison between sediment removal amounts and computed FOS in Figures 2.10a and b. Figures 2.10c and d are similar to Figures 2.10a and b, but the sediment removal is divided by the bank height as an attempt to normalize the soil loss and its possible dependence on how high the banks are.

The analysis presented in Figure 2.7 for the Winooski instrumented site indicated that it is possible to predict the streambank stability. However, when all sites were considered, no specific trends could be found between computed FOS and sediment removal analysis. There could be multiple reasons for the disagreement. First, rotational failure surfaces were examined in SLOPE/W; however, not all observed bank movements involved rotational failures, especially at the Lewis Creek sites. Also, significant ice movement takes place in Vermont streams during winter, especially in Winooski River. Also, the frost depths are estimated to be up to 2 m. The silty soils encountered at the study sites are prone to frost and formation of ice lenses. The possible impacts of freezing and thawing of the soils, formation of ice lenses as well as moving ice packs through streams was not included in the analysis.

2.7 Conclusions

The changes in streambank geometry, ground water levels, and stream water levels over a two year period at several cutbank sites along two reaches, each located in a separate watershed were studied. Both sets of study sites were located in northern

Vermont, with similar alluvial soils composing the streambanks. Stream flows found at each site were dissimilar with the Winooski River reach having flows of about a magnitude larger than the Lewis Creek reach. Despite the differences in the stream characteristics (e.g. flow, watershed area) very similar erosion rates were measured in this study.

This study supported the findings by Pollen (2002), Wu et al. (1979) and Darby et al. (2007) that root impregnation increases soil's shear strength. The direct shear tests performed on bare and with roots streambank soil samples offered a reasonable way of determining the cohesion increase of streambank soils with small roots (diameter less than 1 mm). For the studied sites, the slope stability factors of safety would have been under predicted by 6%, if the increased strength from the roots was not considered within the root zone that was about 45 cm deep. At other sites with deeper root zone, the influence of added strength from roots would be more significant.

The slope stability analysis presented here supported the findings by Simon et al. (2000) that the loss of matric suction may lead to bank instabilities. The low stream water level condition paired with the loss of matric suction from a rapid wetting event yielded the lowest computed factor of safety, which compared reasonably well with the recorded streambank failure event.

The consideration that bank failures occur due to rapid drawdown events following high river stage when confining pressures are reduced (Thorne, 1982; Lawlwer et al. 1997) is appropriate; however, the streambanks at the study sites did not experience severe drawdown conditions.

Although the recorded streambank failure could be modeled reasonably well using the slope stability computer program SLOPE/W, no specific correlation could be found among slope height, slope angle, computed factor of safety and sediment removal amounts, quantities that would be expected to be somewhat related. It is anticipated that the effects of freezing and thawing of streambank soils and ice flows in the streams, that were not considered in the analysis might have contributed to the lack of correlation among these quantities.

2.8 Acknowledgments

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2.9 Resources

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2.10 Figures

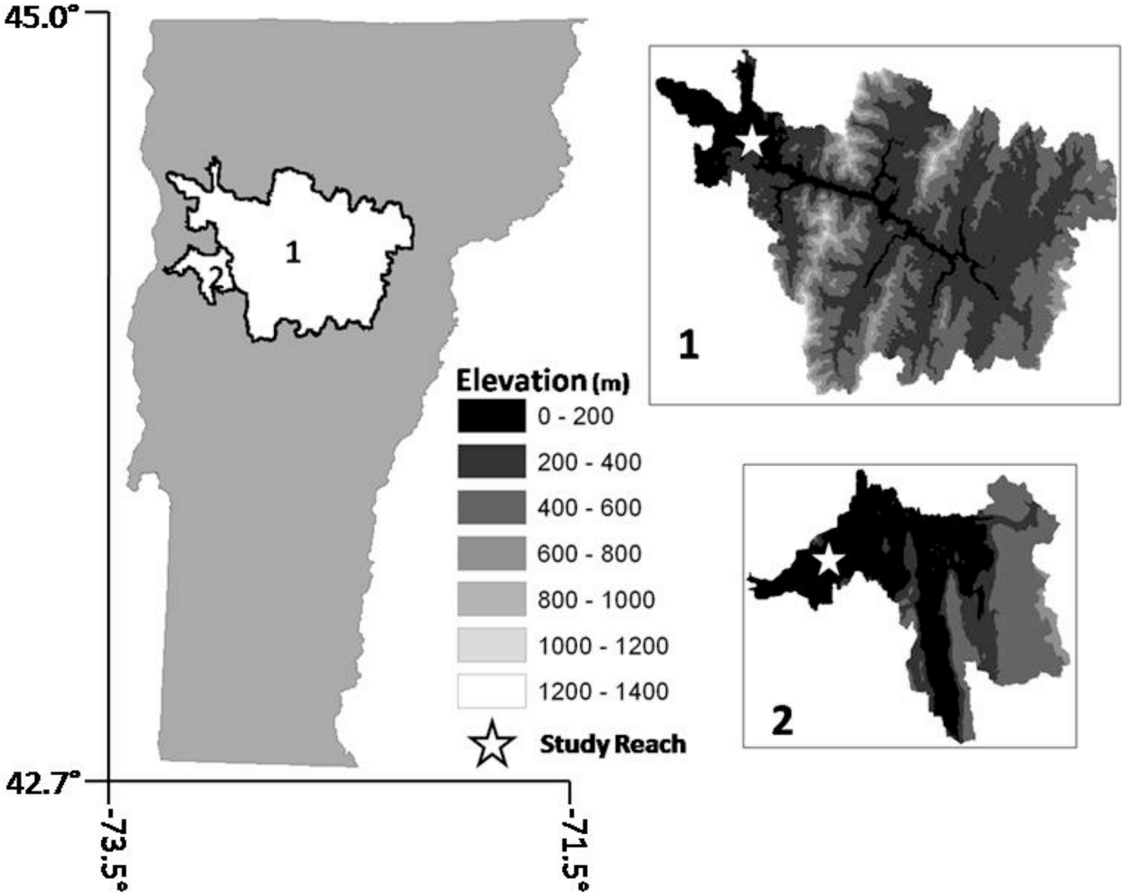

Figure 2.1. Study basins in relation to the state of Vermont including local elevations.

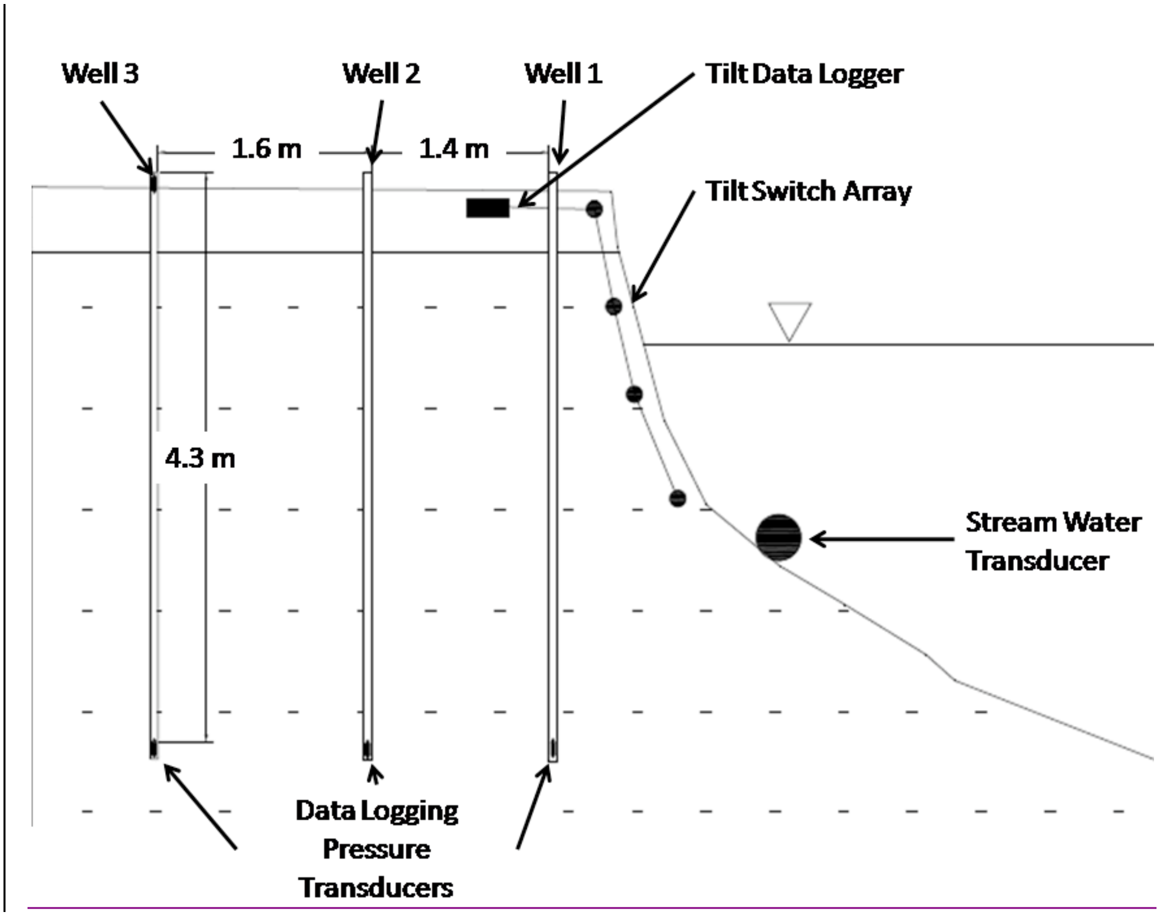

Figure 2.2. Typical instrumented site, showing the Winooski River instrumented site for the Bank geometry surveyed in October,2008 with the stream water transducer system used at the Lewis Creek reach

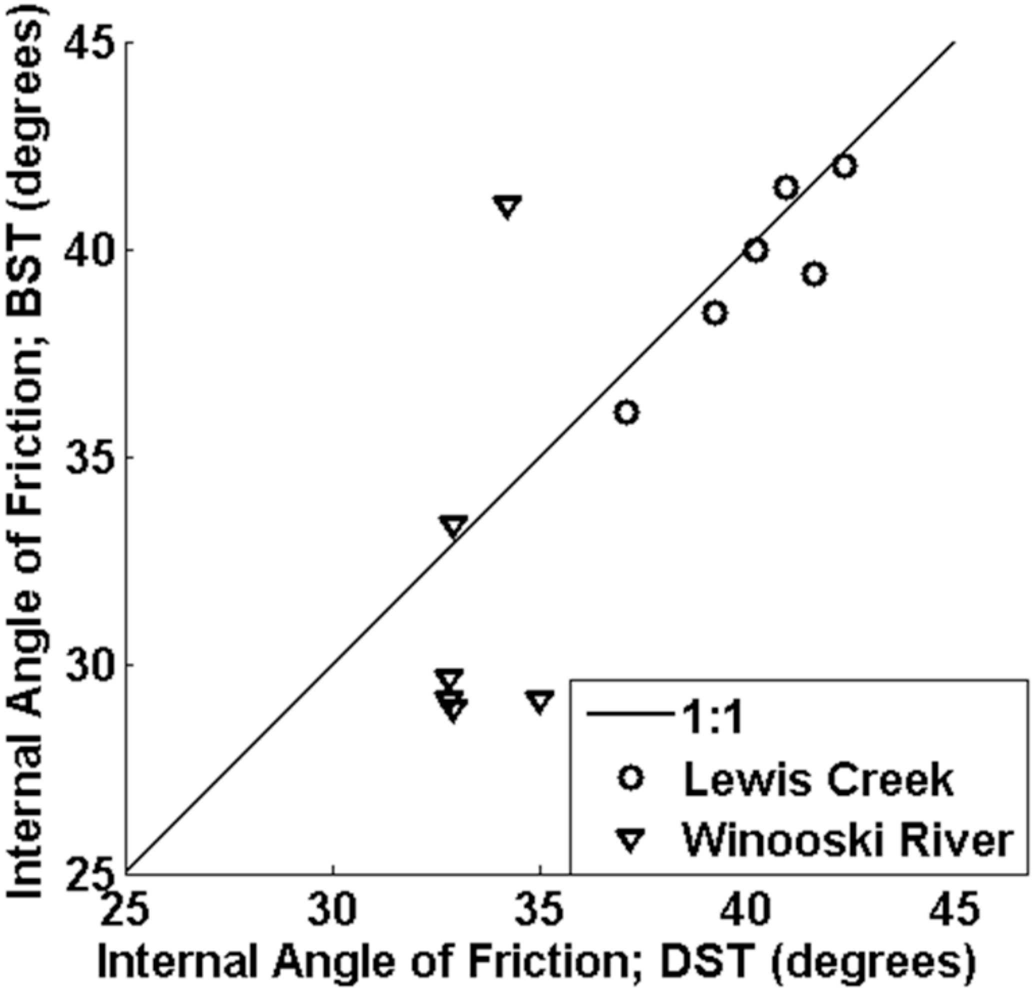

Figure 2.3. Comparison of effective friction angle

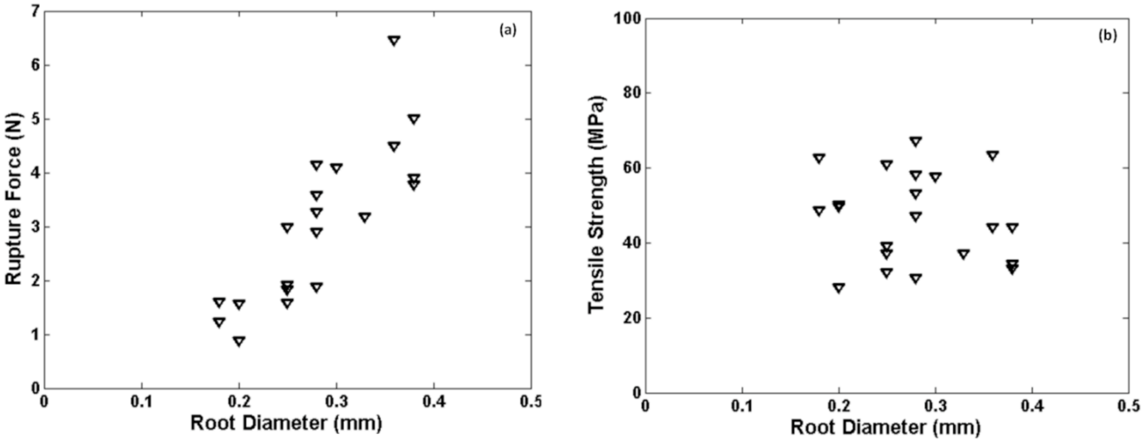

Figure 2.4. Results of the tensile testing on S. Candensis roots (a) tensile rupture force versus root diameter and (b) tensile root strength versus root diameter.

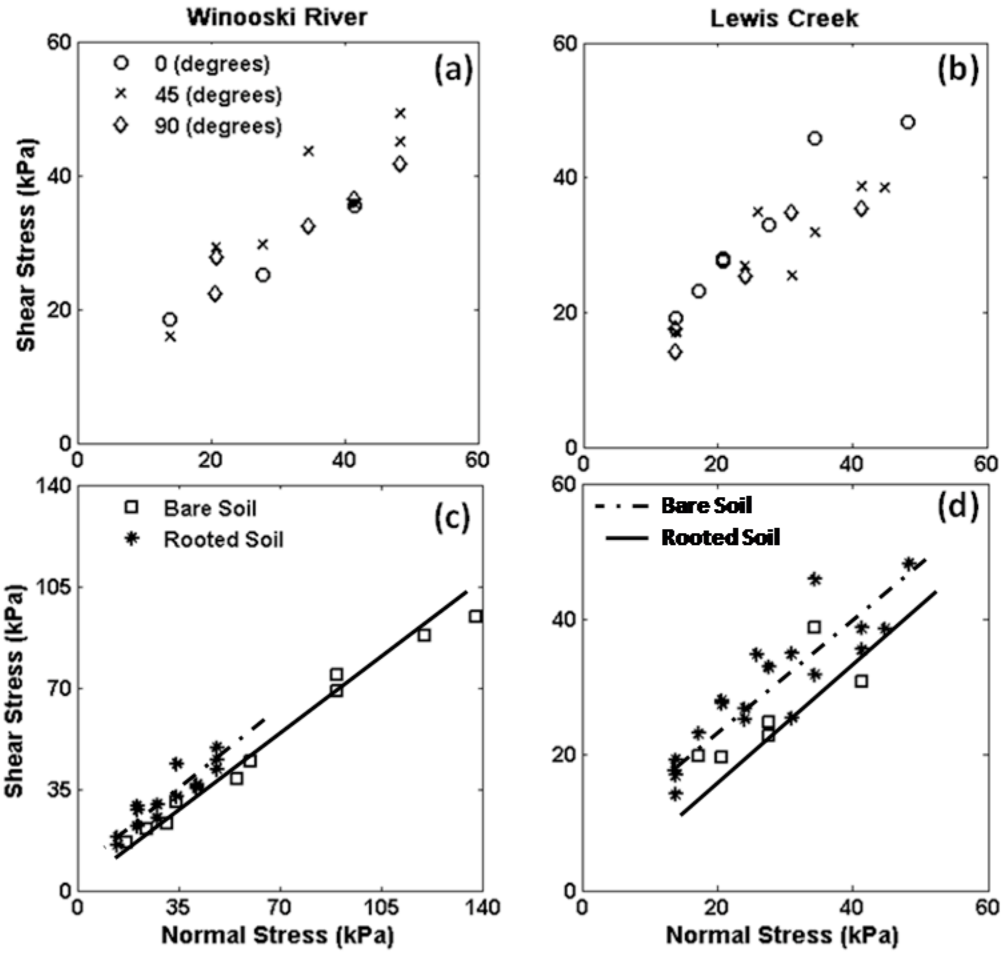

Figure 2.5. Measured root reinforcement (a) root impregnated samples at the Winooski River site for all zenith angles, (b) root impregnated samples at the Winooski River site for all zenith angles, (c) all root impregnated samples at the Winooski River site versus bare samples from the Winooski River instrumented site, and (d) all root impregnated samples at the Lewis Creek site versus bare samples collected from the Lewis Creek instrumented site

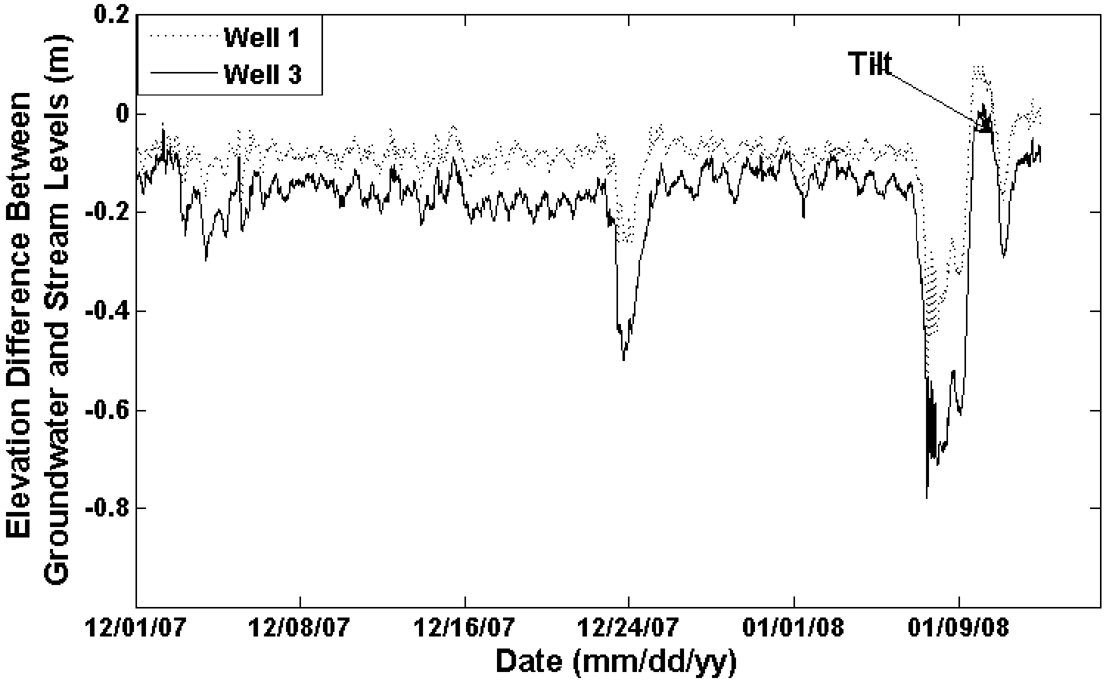

Figure 2.6. Example water levels at the Winooski instrumented site between December 1, 2007 to January 13, 2008; the groundwater elevation minus the stream water elevation is plotted; the measured failure event as registered by the tilt switches occurred on January 10, 2008 at 9:00 am

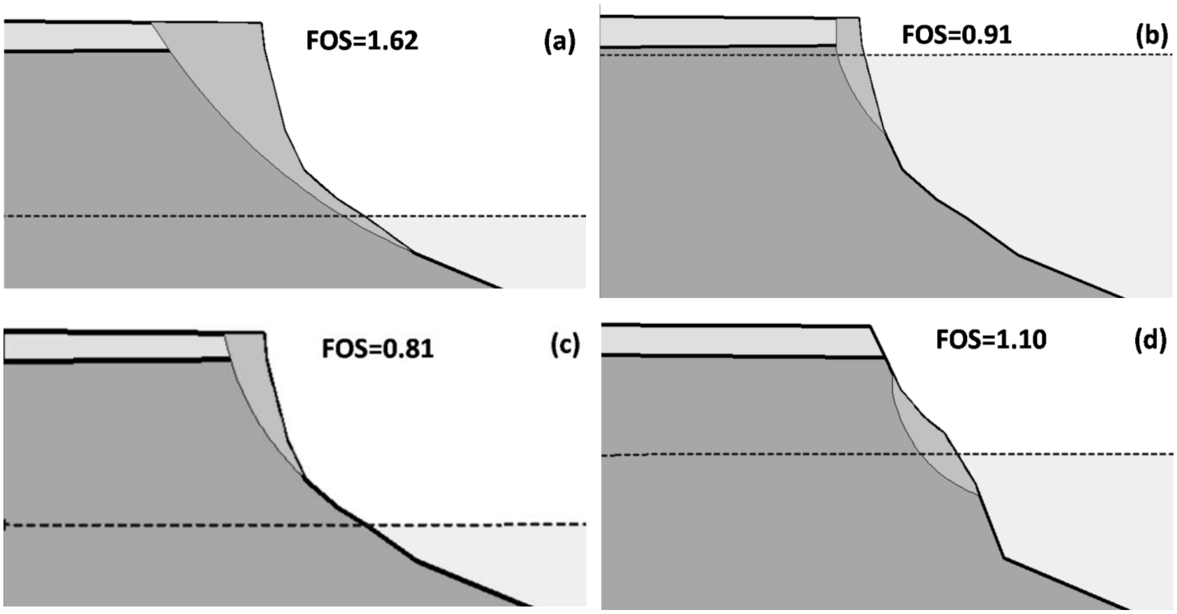

Figure 2.7. Slope stability analysis examples for the Winooski instrumented site for (a) low stream water level condition, (b) high stream water level condition, (c) rapid wetting low water condition, (d) assumed failure associated with tilt switch even of January 10, 2008.

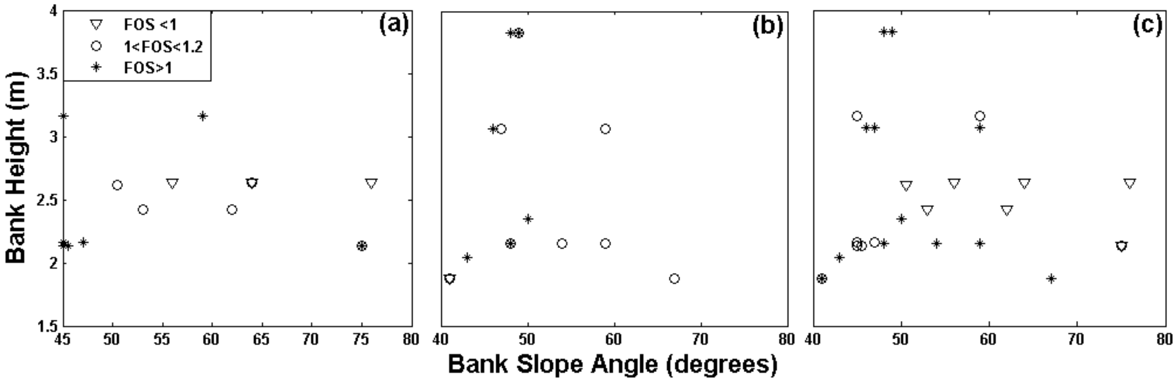

Figure 2.8. Bank height versus bank angle plot categorized by FOS values for the (a) Winooski River sites, (b) Lewis Creek sites, and (c) all sites

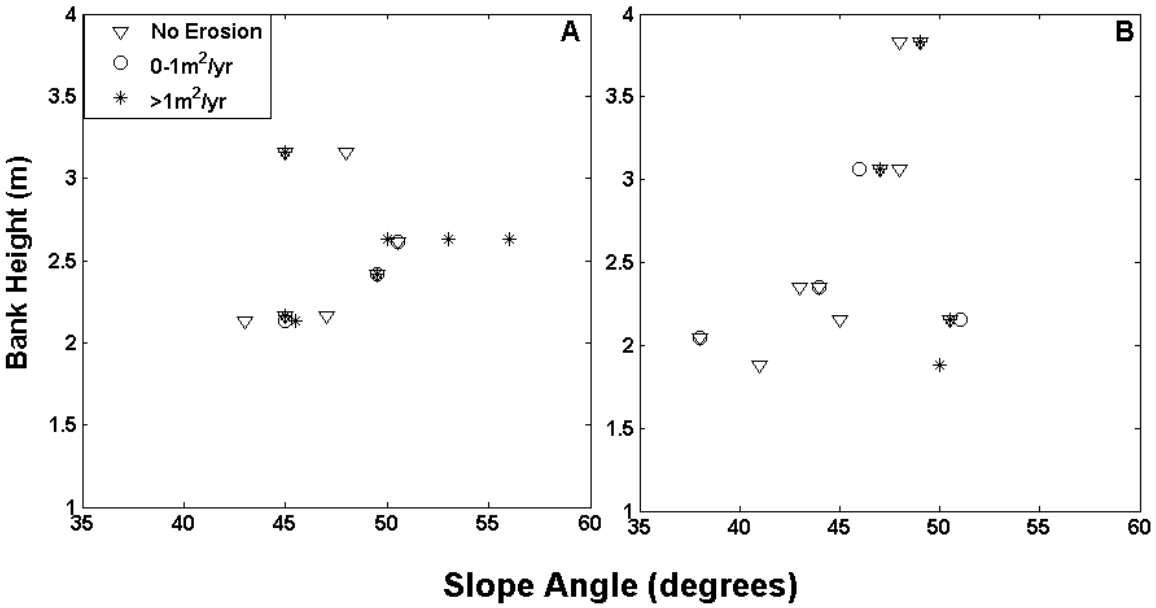

Figure 2.9. Bank height versus bank angle plot categorized by total sediment removal for the (a) Winooski River sites, and (b) Lewis Creek sites

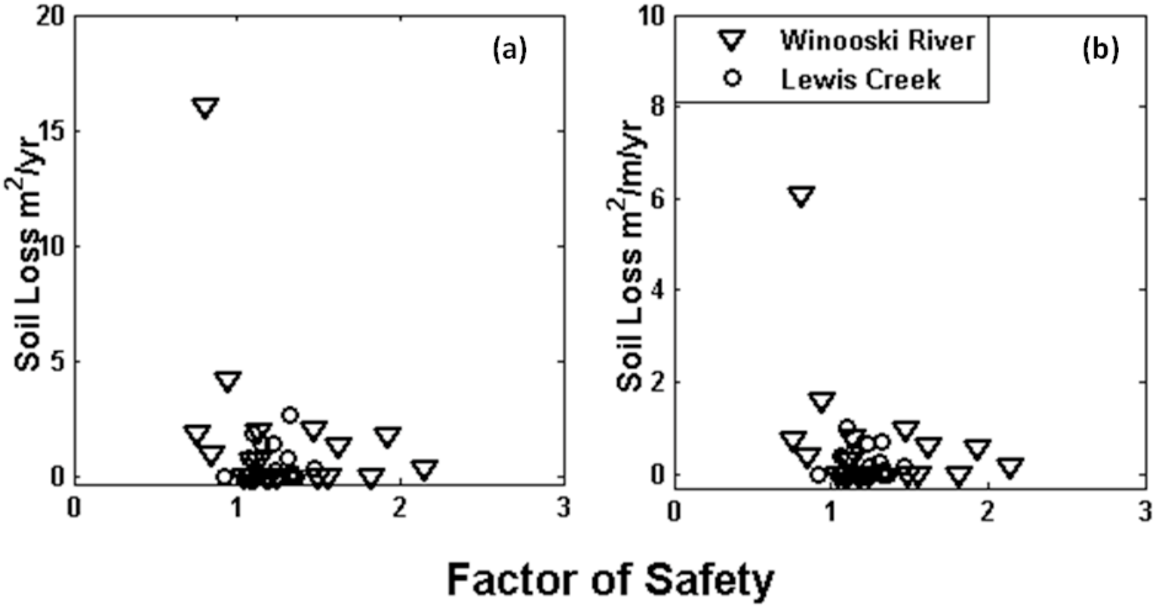

Figure 2.10. FOS versus average sediment removal rates (a) Sediment removal rate (b) sediment removal normalized by bank height

2.10 Tables

Table 2.1. Summary of soil data collected for both river reaches

(a) Winooski River

Site No.	G^1 (%)	S^2 (%)	M^3 (%)	C^4 (%)	LL^5 (%)	PL^6 (%)	Soil Type	ρ_{sat} (Mg/m^3)	ρ (Mg/m^3)	P_d (Mg/m^3)	ψ (kPa)	c' (kPa)	ϕ' DST (deg)	c_a (kPa)	ϕ' BST (deg)	ϕ_b (deg)	ϕ'_{AVG} (deg)
1	3	46	47	4	19	NP	ML	1.88	1.85	1.74	--	--	--	0*	35.1	--	32.9
1	--	--	--	--	--	--	--	1.83	--	1.66	--	--	--	1	32.4	--	32.9
1	--	--	--	--	--	--	--	--	--	--	--	--	--	0*	33.2	--	32.9
1	--	--	--	--	--	--	--	--	--	--	--	--	--	6	29.6	--	32.9
1	--	--	--	--	--	--	--	--	--	--	--	--	--	1	34.4	--	32.9
2	0	46	52	2	27	NP	ML	1.86	1.83	1.76	--	--	--	2	38.3	--	38.9
2	1	48	50	1	29	NP	ML	1.93	1.88	1.84	--	--	--	0	39.5	--	38.9
2	0	45	53	2	23	NP	ML	--	--	--	--	--	--	4	38.1	--	38.9
2	--	--	--	--	--	--	--	--	--	--	--	--	--	0*	39.7	--	38.9
3	3	45	51	1	--	NP	ML	--	--	--	--	0	35	--	--	--	35.0
3	--	--	--	--	--	--	--	--	--	--	--	0.8	34.2	--	--	--	35.0
3	0	46	51	3	--	NP	ML	1.88	--	1.68	--	--	--	1	41.1	--	35.0
3	--	--	--	--	--	--	--	2.03	--	1.91	--	--	--	1	29.2	--	35.0
3	2	38	56	4	--	NP	--	--	--	--	--	--	--	3	41.1	--	35.0
3	--	--	--	--	--	--	--	--	--	--	--	--	--	3	29.6	--	35.0
4	3	75	20	2	--	NP	SW-SM	1.81	1.78	1.72	--	--	--	5	36.3	--	36.6
4	--	--	--	--	--	--	--	--	--	--	--	--	--	7	36.9	--	36.6
5	--	--	--	--	--	--	--	--	--	--	--	--	--	2	32.6	--	34.8
5	5	73	22	0	20	NP	SW-SM	--	--	--	--	--	--	4	34.2	--	34.8
5	--	--	--	--	--	--	--	--	--	--	--	--	--	0*	37.6	--	34.8
6	--	--	--	--	--	--	--	--	--	--	--	--	--	1	32.6	--	33.6
6	--	--	--	--	--	--	--	--	--	--	--	--	--	0	33.6	--	33.6
6	--	--	--	--	--	--	--	--	--	--	--	--	--	1	34.6	--	33.6
7	0	90	9	1	--	NP	SM	1.99	--	1.87	--	3.6	32.9	--	32.9	--	33.6
7	--	--	--	--	--	--	--	--	--	--	--	9	32.8	--	32.8	--	31.7
7	--	--	--	--	--	--	--	--	--	--	--	--	--	3	29.7	--	31.7
7	--	--	--	--	--	--	--	--	--	--	--	--	--	3	34.4	--	31.7
7	0	87	11	2	--	NP	SW-SM	1.89	1.86	1.77	--	--	--	11	29.0	--	31.7
7	--	--	--	--	--	--	--	--	--	--	--	--	--	6	29.2	--	31.7
7	--	--	--	--	--	--	--	--	--	--	14	--	--	6	33.4	22.6	31.7
7	--	--	--	--	--	--	--	--	--	--	20	--	--	9	31.8	21.2	31.7

(b) Lewis Creek

Site No.	G^{1} (%)	S^{2} (%)	M^{3} (%)	C^{4} (%)	LL^{5} (%)	PL^{6} (%)	Soil Type	ρ_{sat} (Mg/m^{3})	ρ (Mg/m^{3})	P_{d} (Mg/m^{3})	ψ (kPa)	c' (kPa)	ϕ' DST (deg)	c_{a} (kPa)	ϕ' BST (deg)	ϕ_{b} (deg)	ϕ'_{AVG} (deg)
1	0	73	27	0	26	NP^{7}	SM	1.82	1.79	1.63	--	--	--	4	34.3	--	35.4
1	--	--	--	--	--	--	--	--	--	--	--	--	--	0	36.5	--	35.4
2	--	--	--	--	--	--	--	--	--	--	--	0*	41.6	--	--	--	39.5
2	--	--	--	--	--	--	--	--	--	--	--	--	--	4	38.0	--	39.5
2	--	--	--	--	--	--	--	--	--	--	--	--	--	0*	39.0	--	39.5
2	0	79	20	1	22	NP	SM	1.74	1.71	1.57	--	--	--	0	39.4	--	39.5
3	--	--	--	--	--	--	--	--	--	--	--	0*	42.3	--	--	--	39.5
3	--	--	--	--	--	--	--	--	--	--	--	--	--	0	38.5	--	39.5
3	6	70	21	3	--	NP	--	--	--	--	--	--	--	0*	32.2	--	39.5
3	2	70	28	0	--	NP	--	--	--	--	--	--	--	1	42.6	--	39.5
3	--	--	--	--	--	--	--	--	--	--	--	--	--	4	42.0	--	39.5
4	--	--	--	--	--	--	--	--	--	--	--	--	--	1	36.6	--	39.3
4	--	--	--	--	--	--	--	--	--	--	--	--	--	0*	39.4	--	39.3
4	--	--	--	--	--	--	--	--	--	--	--	--	--	2	39.8	--	39.3
4	--	--	--	--	--	--	--	--	--	--	--	--	--	2	41.4	--	39.3
4	--	--	--	--	--	--	--	--	--	--	--	--	--	0	39.4	--	39.3
5	2	73	23	2	--	NP	SW-SM	1.84	1.79	1.68	--	1.45	39.2	--	--	--	40.7
5	--	--	--	--	--	--	--	--	--	--	--	--	--	1	41.8	--	40.7
5	--	--	--	--	--	--	--	--	--	--	--	--	--	12	38.5	--	40.7
5	--	--	--	--	--	--	--	--	--	--	--	--	--	0*	40.7	--	40.7
5	--	--	--	--	--	--	--	--	--	--	--	--	--	0	42.0	--	40.7
5	--	--	--	--	--	--	--	--	--	--	--	--	--	0*	42.0	--	40.7
6	--	--	--	--	--	--	--	--	--	--	--	0.1	40.2	--	--	--	38.2
6	5	70	22	3	--	NP	SM	1.77	1.74	1.56	--	0.9	37.1	--	--	--	38.2
6	--	--	--	--	--	--	--	--	--	--	--	--	--	0*	40.3	--	38.2
6	0	81	18	1	--	NP	SW-SM	1.84	1.81	1.73	--	--	--	1	38.2	--	38.2
6	--	--	--	--	--	--	--	--	--	--	--	--	--	0*	40.0	--	38.2
6	--	--	--	--	--	--	--	--	--	--	19	--	--	0*	36.1	16.5	38.2
6	--	--	--	--	--	--	--	--	--	--	8	--	--	2	35.8	22.7	38.2
7	0	76	24	0	--	NP	SM	--	--	--	--	0*	40.9	--	40.9	--	40.4
7	--	--	--	--	--	--	--	--	--	--	--	--	--	6	39.9	--	40.4
7	--	--	--	--	--	--	--	1.75	1.71	1.60	--	--	--	0	41.5	--	40.4
7	--	--	--	--	--	--	--	--	--	--	--	--	--	6	39.3	--	40.4

G – gravel, S- sand, M – silt, C – clay (< 2μ), LL- liquid limit, PL- plastic limit, NP- non-plastic, ρ_{sat}- saturated density, ρ - bulk density, ρ_d - dry density, ψ- matric suction, c'- effective cohesion, ϕ' DST- effective friction angle determined using DST, c_a- apparent cohesion, ϕ' BST- effective friction angle determined using BST, ϕ_b - unsaturated friction angle, ϕ'_{AVG}- averaged effective friction angle for material, --: not available

Chapter 3: Journal Article 2

Meteoric ^{10}Be adhered to suspended sediment: transport dynamics in a large New England watershed

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3.1 Abstract

To assess the utility of meteoric ^{10}Be as a tracer of sediment source in humid, temperate, previously glaciated terrain, we collected samples of suspended sediment (n= 22), streambank material (n= 6), and agricultural soils (n= 2). Suspended sediment was collected during spring, summer, and fall storm events from 7 catchments (20 to 2754 km^2) each of which had different land-use characteristics and elevation distributions. For each sample, we measured meteoric ^{10}Be concentration in two suspended sediment grain-size fractions (43 or 53 to 125 μm and 125 to 500 μm). Measured concentrations of meteoric ^{10}Be ranged over an order of magnitude from 0.362 to 18.7 $*10^8$ atoms/g. There were no significant temporal trends in meteoric ^{10}Be concentrations at daily or seasonal timescales. Meteoric ^{10}Be concentrations in the different grain sizes were positively correlated (R^2=0.70). Fine-grain fractions contained higher meteoric ^{10}Be concentrations on average and in 19 of the 30 samples. Suspended sediment from lowland catchments had meteoric ^{10}Be concentrations similar to those collected from adjacent lowland agricultural soils and streambank material. Samples from forested, high-elevation catchments contained the highest meteoric ^{10}Be concentrations. The relationship between meteoric ^{10}Be concentration, land use, and topography suggests that meteoric ^{10}Be can be used for tracing the source of suspended sediment.

3.2 Introduction

Suspended sediment is an important transportation medium for contaminants and nutrients in fluvial systems [Warren et al. 2003; Walling 2005] and is the most common pollutant of U.S. water bodies [MARC 2009]. Streambank erosion processes are estimated to contribute 30-80% of total sediment loading into lakes and waterways [Evans et al. 2006; Fox et al. 2007]; sheet flow and rill erosion off of fields account for the remainder. Traditional methods of sediment source determination, longitudinal surveys and sediment mass troughs [Sutherland and Bryan 1989; Lawler et al. 1999], are time intensive and cost prohibitive for all but the smallest watersheds. If sediment removal cannot be measured directly, "finger printing" approaches can be used to identify the dominant sediment sources [Walling 2005].

A finger printing approach to sediment sourcing relies on the selection of a set of isotopic, chemical, or physical properties with values specific to sediment derived from different source types or areas [Walling 2005]. Comparisons of these properties are made between potential sediment sources and suspended sediment. Suspended sediment tracers have included color [Udelhoven and Symader 1995], heavy metals [Charlesworth and Lees 2001], magnetic properties [Oldfield et al. 1979; Caicheon 1993; Slattery et al. 1995; Charlesworth and Lees 2001], and geochemical and trace elements [Horowitz and Elrick 1987]. Short lived radio isotopes have been investigated for their sediment tracing abilities including ^{137}Cs ($t_{1/2}$ = 30.1 years), ^{210}Pb ($t_{1/2}$ = 22.3 years) and ^{7}Be ($t_{1/2}$ =0.15 years) [Bonniwell et al. 1999, Walling and Woodward 1992; Wallbrink and Murray 1993; Walling et al. 1995].

The long-lived atmospheric radioisotope, meteoric ^{10}Be (half life, 1.36 Ma; Nishiizumi et al. 2007) has seen only scant use in sediment fingerprinting [Vallet-Silver et al. 1986; Helz and Valette-Silver 1992; Reusser and Bierman 2010]. Recently, interest in meteoric ^{10}Be as a sediment tracer for timescales from decades (Reusser and Bierman 2010) to millina (Jungers et al. 2009) has increased, catalyzed by both advances in accelerator mass spectrometery (AMS) and preparation chemistry [Stone 1998] allowing meteoric ^{10}Be content of very small samples to be well quantified [Willenbring and Blanckenburg 2010].

Meteoric ^{10}Be is formed by cosmic-ray spallation of oxygen and nitrogen atoms in the Earth's stratosphere [Lal and Peters, 1967]. Atoms formed in this process bind rapidly to aerosols and undergo atmospheric mixing. The atmospheric residence time of meteoric ^{10}Be is about a year and the isotope is delivered to Earth's surface both by precipitation and dry fall [Beer et al. 1984; Heikkilä et al. 2008a]. Precipitation fall out rates of meteoric ^{10}Be are proportional to rain fall [Graham et al. 2003]. Upon reaching Earth's surface, meteoric ^{10}Be rapidly sorbs to sediments [Raisbeck et al. 1979; Brown et al. 1986], with soil to water partitioning coefficients of 10^5- 10^6 [Brown et al. 1986; Brown et al. 1988; You et al. 1989] at pH > 4.0. This high partitioning coefficient allows for the assumption that meteoric ^{10}Be is transported with the sediment phase [Brown et al. 1986]. As the accumulation and removal of sediment bound meteoric ^{10}Be in the hilly humid terrain of New England is rapid there is inconsequential loss of ^{10}Be to radio-decay.

In this paper, we report the first systematic measurement of meteoric ^{10}Be in suspended sediment collected from a humid, temperate, previously-glaciated catchment. We find that the concentration of meteoric ^{10}Be in suspended sediment collected from seven sites in northern Vermont during storm flows does not vary systematically with time, is correlated between different grain sizes, and differs with landscape metrics. These findings suggest that measurements of meteoric ^{10}Be in fluvial sediment have the potential to assist scientists and land managers in tracing the origin of sediment moving through river systems.

3.3 Setting

Samples in this study were collected from 7 diverse watersheds draining northwestern Vermont, U.S.A. (Figure 3.1). Study area geology is dominated by the schistose Green Mountains with peaks reaching over 1400 m. In the uplands, deglaciation of Laurentide Ice Sheet left behind glacial till over bedrock on which shallow soils have developed. In the lowlands, ice-contact sand and gravel deposits line valley walls with silt-rich, glacial lake deposits found in many valleys. To the west of the Green Mountains, the lowlands are underlain by sedimentary rocks with by fertile, fine-grain alluvium near river channels [Doll 1970; Doolan 1996].

The mountainous topography strongly influences mean annual precipitation and thus the flux of meteoric ^{10}Be to different parts of the study area. Deposition of primary meteoric^{10}Be scales positively with the mean annual precipitation (Heikkila et al. 2007). Precipitation in the study area varies from less than 91 cm/y in lowland areas to greater than 173 cm/y in the uplands [Daly and Weisburg 1997]. The differences in precipitation would lead to a maximum of a 2.5 fold increase in primary meteoric ^{10}Be deposition rate between the lowest and highest elevations in this study. Primary meteoric ^{10}Be deposition rates at similar latitudes (36-48^{o}) range from ~2.5 * 10^{6} atoms atoms/(cm^{2}*y) on mountain peaks in the Alps to ~1.0 * 10^6 atoms/(cm^2*y) in the lowland study areas of New Zealand [Graham et al. 2003; Heikkilä et al. 2008b].

Land use in the study area has varied over time. Forests of Vermont were rapidly cleared in the 1700s and early 1800s coinciding with European settlement [Wessels 1997]. Agriculture peaked with an estimated 1.7 million sheep walking the state's slopes during the 1840's. Rapid migration to the west diminished Vermont's population in the 1850s and marked the beginning of land abandonment, reforestation, and agricultural decline in rural New England [Wessels 1997]. Today, upland areas are heavily forested, with agriculture and urban areas concentrated in the lowlands [Albers 2000]. Land use change during the past several decades has increased urbanization in the lowland areas with an increase of forested areas in the uplands as trees replaced agricultural land [Hackett 2009].

Legacy sediments [Walter and Merritts 2008], the result of colonial clearcutting and agriculture, are present along most channels, particularly in the lowland areas of larger Vermont watersheds. Most Vermont streams experienced a period of rapid aggradation coinciding with upland deforestation during the 1800s [Jennings et al. 2003]. Cutbanks along mainstem lowland rivers in the eastern United States, such as the lower Winooski, can exhibit more than 4 m of historic sediments [Bierman et al. 1997], comprising much of the exposed streambank sediment cropping out and eroding today.

Waterways in Vermont range from steep cascades in the uplands to low gradient alluvial rivers in the lowlands (Figure 3.1). Upland streams in the study include the Dog

River (139 km^2) and the Browns River (38 km^2). Allen Brook (83 km^2) and the urban watershed of Potash Brook (20 km^2) are lowland streams. Some streams in Vermont span large elevation gradients; Mill Brook (41 km^2) was selected because its narrow watershed draws drains upland and lowland sources. High order streams such as the Winooski River at Colchester (2754 km^2) and the Winooski River at Duxbury (1334 km^2) incorporate a diversity of landuse and elevation. Sediments from all of the sites we sampled are eventually deposited in Lake Champlain where sediment and sediment-carried pollutants such as phosphorus have been a long-term land-management concern [Meals and Budd 1998].

3.4 Methods

We selected 7 sampling sites to capture various types of watersheds draining northwestern Vermont into Lake Champlain; 5 sites were within the Winooski River watershed and two are in close proximity (Figure 3.1). Specific sampling locations were selected for ease of access, allowing us to collect multiple suspended samples during a single storm event. Contributing watersheds, many of which are nested, were delineated for the sampling points using ArcGIS™ with a publicly available 10 m digital elevation model smoothed specifically for hydrological use [VCGI 2006]. Maximum, minimum, and mean elevations were determined for each sub-watershed using the Arc GIS software package. Land cover data were extracted from the publicly available 30 m 2001 National Land Cover Dataset for each watershed [U.S. Geological Survey 2003]. Land cover was integrated into four categories; forested, grassland and agricultural, surface water and wetlands, and urban (Table 3.1).

Soil samples (n=6) were collected to analyze meteoric ^{10}Be concentrations from potential sediment sources. Streambank samples were collected from eroding stream banks in all but the Potash Brook watershed. Streambank samples were collected immediately upstream of the suspended sediment sampling location. We sampled agricultural fields (n=2) one upstream both the Allen Brook and Mill Brook sample locations. Small subsamples representing the agricultural field soils were collected and amalgamated into a single representative sample for each of the agricultural fields.

Suspended sediment sampling (n=22) was conducted during high flow events throughout a 10-month period in 2008. We sampled during high flow events, when the closest gauging indicated a 90th percentile event, as most suspended sediment transport occurs during these periods of high discharge. Suspended sediment samples were taken using a stack of ASTM standard sieves suspended sub-horizontally with the aid of an attached drag net (Figure 3.2). Samples were collected simultaneously in four grain size fractions; 43 or 53 to 73µm, 73 to 125µm, 125 to 250µm, and 250 to 500µm. Samples were taken at each stream for three high flow events; spring melt, a summer storm, and a fall storm. Samples were collected from 0 to 1m below the surface of the water at the thawleg of the sample stream. To collect the minimum sample size of 0.5g sampling time varied from 30 min to over 3 hours including a periodic removal of the collected material. An additional sample set (n= 5) was taken at the mouth of the Winooski River during the spring melt (2, April 2008 to 11, April 2008) to determine temporal variability in meteoric ^{10}Be concentrations on a shorter timescale. Samples collected in the field were combined into two sediment fractions, fine (43/53-125 µm) and coarse (125 µm- 500 µm), amalgamating all material collected from each grain size sub fraction. Sample fractions were pulverized in a SPEX shatter box prior to ^{10}Be extraction.

Meteoric ^{10}Be was extracted from pulverized samples at the University of Vermont's cosmogenic nuclide extraction laboratory. Samples, including one full process blank for each batch of 15 unknowns, were prepared in batches of 16 following a modification of the flux fusion method presented by Stone [1998]. Up to 0.5 g of finely milled material was mixed with KHF and $NaSO_4$ along with ~300 ug of Be- carrier (SPEX brand). The mixture was fused in a Pt crucible for several minutes until the melt had cleared. After cooling, the crucible containing the solidified fusion cake was rapidly submerged into a Teflon beaker containing Milli-Q water (18.2 Mohm) and allowed to leach overnight. Excess K was removed by $HClO_3$ precipitation and BeOH precipitated as the hydroxide. The hydroxide was burned to BeO, mixed with an equimolar amount of Nb metal powder, and loaded into stainless steel cathodes for AMS analysis at the Center for Accelerator Mass Spectrometry, Livermore National Laboratory.

Beryllium isotopic ratios were measured using multiple interrogations of each target along with post-AMS ion stripping to reduce boron isobaric interference. Analyses of each target were repeated between 2 and 4 times until the precision of each measurement was 3% or better (μ=1.9±0.4%). Three secondary standards were run repeatedly to verify linearity of the AMS. Results were normalized to KNSTD3110 with an assumed ^{10}Be/^{9}Be ratio of $2.85 * 10^{-12}$ [Nishiizumi et al. 2007]. Standard-corrected isotopic ratios ranged widely from $956 * 10^{-15}$ to $46,600 * 10^{-15}$. We made a blank correction by subtracting the average of the process blanks run with the four batches of samples (n=4, μ =17.2±1.6 * 10^{-15}) from each sample ratio. Because these samples contained so much ^{10}Be, the average ratio was high (n= 60, μ= 6630* 10^{-15}), and the resulting blank correction is inconsequential.

Concentration variations of meteoric ^{10}Be were analyzed with respect to sample type, grain size, collection date, source watershed, and watershed characteristics. Grain sized dependence of meteoric ^{10}Be were assessed using Wilcox signed-ranks test. Performing a series of Wilcox signed-ranks test assessed temporal trends in meteoric 10Be concentrations. These tests provided a statistical measure of the differences in meteoric ^{10}Be concentrations in sediment collected during spring, fall, and summer high flow events.

A series of one way ANOVAs were performed to determine the relationship of meteoric ^{10}Be in suspended sediment samples and the landscape scale variables including land use characteristics and mean watershed elevation. Additionally, interaction effects between land use and mean elevation were analyzed using a series of one way ANOVAs.

3.5 Results

Samples collected from Vermont rivers, fields, and cut banks contain significant concentrations of meteoric ^{10}Be, 0.57 to 18.7 x 10^8 atoms/g (n=60, Table 3.3). These concentrations vary more than an order of magnitude and the resulting distribution is strongly skewed with a long tail toward higher concentrations (Figure 3.3). Meteoric ^{10}Be concentrations in the suspended sediments of the Browns River and Dog River are up to an order of magnitude higher than measured meteoric ^{10}Be concentrations in samples from other streams (Figure 3.5). Concentrations of meteoric ^{10}Be in streambank soils ranged from 0.36±0.01 to 2.80±0.05*10^{8}atoms/g (n=12). The lowest concentration of meteoric ^{10}Be was found in the streambank material collected adjacent to the Winooski River, Duxbury sample site (0.36±0.01 atoms/g). Soil samples collected from agricultural fields had meteoric ^{10}Be concentrations ranging from 0.71±0.02 to 1.62±0.03*10^{8}atoms/g (n=4) from Mill Brook and Allen Brook sites, respectively.

The measured concentration of meteoric ^{10}Be in coarse and fine sediment is correlated (r^2=0.70, Figure 3.5); however, meteoric ^{10}Be concentrations in many samples differ depending on grain size. In 19 of the 30 samples, the fine fraction contains more meteoric ^{10}Be than the coarse fraction. A one way series of Wilcox sign rank tests using coarse and fine fractions reveals significant differences between 5 of the stream pairings with a 95% confidence interval (Table 3.2). On average, the fine sediment fractions collected in this study contains a higher concentration ($p<0.05$) of meteoric ^{10}Be (μ= 3.04±4.03*10^{8} atoms/g, n=30, 1σ) than the coarse fraction sediment samples (μ= 2.18±2.53*10^{8} atoms/g, n=30, 1σ).

Meteoric ^{10}Be concentrations in suspended sediment appear to be consistent over both daily and seasonal timescales. Samples collected from the Winooski River, Colchester (2754 km^{2}) show no systemic difference in measured concentrations of meteoric ^{10}Be over 10 days during the spring melt event (Figure 3.6). Concentrations for each stream were compared across seasons using a non parametric Wilcox rank sum test, revealing no detectable changes in meteoric ^{10}Be concentration ($p>0.05$).

All streambank samples collected for this study have lower concentrations of meteoric ^{10}Be than suspended sediment samples from the same stream. This discrepancy is most pronounced in the Browns River watershed where concentration of meteoric ^{10}Be in suspended sediment from the watershed is up to 6 times higher than associated streambank sediments taken near the suspended sediment sampling site (figure 3.7). Utilizing a one way ANOVA showed concentration of meteoric ^{10}Be in suspended sediment ($\mu=3.2\pm3.8$, 1σ) was significantly elevated over concentrations measured in bank materials ($p<0.05$, $\mu=2.51\pm0.98$, 1σ)

Concentrations of meteoric ^{10}Be in suspended sediment samples are related to water shed elevation and landcover. The unique landcover relationships of of Vermont were incorporated using a series of one-way ANOVAs showing that the mean elevation of the watersheds sampled is significantly correlated with the land cover properties ($p<0.01$). Using a multivariate ANOVA only the mean elevation was shown to significantly affect the observed concentrations of meteoric ^{10}Be in suspended sediments ($p<0.05$). Crossed effects (mean elevation*forested and mean elevation*agriculture) were better predictors of meteoric ^{10}Be than any of the three parameters individually ($p<0.01$).

3.6 Discussion

Data collected in this study suggest that the concentration of meteoric ^{10}Be associated with suspended sediment has the potential to identify sediment sources and thus become a useful sediment fingerprinting tool. Specifically, the high concentration of meteoric ^{10}Be in these suspended sediment samples makes measurement simple, rapid, and precise. The lack of temporal trends over both seasonal and weekly timescales indicates suspended sediment is well homogenized by fluvial transport and that any short-term changes in sediment sourcing are not detectable at the scale of watersheds we sampled (20 to 2754 km^2). The lack of pronounced grain size control on meteoric ^{10}Be concentration diminishes the importance of varying parent material. Most importantly, the systematic differences we measured in meteoric ^{10}Be concentration between watersheds and the relationship of these concentrations to landscape metrics indicates the utility of meteoric ^{10}Be as a sediment tracer.

The concentration of meteoric ^{10}Be in suspended sediment from Vermont varies greatly and in general, is quite high. Globally, measured meteoric ^{10}Be concentrations in soil profiles, the ultimate source of fluvial sediment, vary from less than 10^7 atoms/g, where erosion is rapid or the samples were collected at depths of meters below the surface, to greater than $2*10^9$ atoms/g [Graly et. al., in review; n =93]. Data collected in studies on fluvial sediments show concentrations of ^{10}Be sediments ranging from $9.3*10^7$ to $1.0*10^9$ atoms/g [Brown et al. 1988; Reusser and Bierman 2010]. Suspended sediments in this study show a range of meteoric ^{10}Be concentrations, from $0.36*10^8$ atoms/g in lowland streambank sediments to concentrations of $18.7*10^8$ atoms/g in suspended sediments from upland sources. Meteoric ^{10}Be concentrations observed in this are far higher than those collected in rapidly eroding sediments collected in the Waipaoa River, New Zealand (0.14 to 1.46 $*10^7$ atoms/g; [Reusser and Bierman 2010].

The relatively high concentration of meteoric ^{10}Be measured in suspended sediment collected from high elevation watersheds, such as the Browns River, is likely the result of five factors: shallow subsurface hydrology, large amounts of organic matter, orographic precipitation gradients, minimal erosion since European settlement, and glacial processes. Shallow, low-permeability upland soils directly overlie compacted till and bedrock, hindering deep vertical transport of meteoric ^{10}Be after fall out. This limited vertical mobility of water likely increases near-surface concentrations of ^{10}Be. Similarly, the forest soils that dominate the uplands are capped by thick A/O horizons rich in organic material known to concentrate meteoric ^{10}Be on clay particles cation exchange sites (Jungers et al. 2009, Maejima 2005). Upper elevations in the Browns River watershed receive more than 173 cm/year of precipitation increasing the flux of meteoric ^{10}Be to about twice that of lowland areas we studied [Daly and Weisburg 1997, Graly et al. 2010 in review]. Because uplands in Vermont experienced less intensive land use than lowlands, the depth of soil erosion, and consequent loss of meteoric ^{10}Be in the uppermost soil horizons is likely less than in lowland sites resulting in higher concentrations of meteoric ^{10}Be in material being eroded and supplied to streams today removed.

More speculative is the possibility that unconsolidated material at high elevations contained a higher concentration of ^{10}Be when it was deposited and that it has been exposed to meteoric ^{10}Be fallout for longer than lowland material. Deglaciation of mountainous northern New England proceeded both by thinning [Bierman et al. 1999] and marginal stagnation zone retreat [Koteff and Pessell 1981]; thus, summits were exposed before lowlands, perhaps by several thousand years. In situ cosmogenic nuclide measurements are consistent with this sequential exposure and indicate that last glacial maximum ice did not entirely remove nuclides produced during the last interglacial at both Mt. Katahdin in Maine and on Mt. Washington in New Hampshire (Bierman et al. 2000). As glacial sediments, specifically the till which is the parent material for upland soils, are primarily derived locally, incomplete erosion of till exposed during the last interglacial would result in upland-derived fluvial sediments have a greater meteoric 10Be concentration than low-land sediments.

Grain size affects ^{10}Be concentration in our sample set but the offset between finer and coarser grain sizes in not consistent. In 19 out of 30 paired samples, fine sediment collected had higher concentrations of meteoric ^{10}Be than coarse sediment. On average, the fine sediment fraction had higher concentrations than the coarse sediment fraction ($p<0.05$) consistent with differences in specific sediment surface area. However, in 11 samples, coarse fractions contained more meteoric ^{10}Be than fine fractions suggesting for these samples that sediment source difference were more important than grain size in controlling meteoric ^{10}Be concentration. Coarse fraction suspended sediment taken from the Winooski River, Colchester site (the largest catchment) during the spring flood had higher average concentration of meteoric ^{10}Be than the fine sediment fraction from the same site set ($p<0.05$, $n= 10$). It is possible that in these spring flood samples, coarse material is preferentially sourced from the high elevation watersheds, where suspended sediment of both grain sizes has high concentrations of meteoric ^{10}Be.

The disparity in meteoric ^{10}Be concentrations between streambank samples (lower concentration) and suspended load carried by the same stream (higher concentration) likely reflects of landscape history. Most streams in Vermont are deeply incised into post-settlement alluvium. This alluvium, which currently makes up many exposed and failing channel banks, was deposited rapidly coinciding with clearing of New England slopes for farming in the 1700 and 1800s. Our stream bank samples suggest that these "legacy sediments" [Walter and Merrits 2008] contain relatively low concentrations of meteoric ^{10}Be, consistent with deep gully erosion and alluvial fan deposition noted widely in both literature of the time [Marsh 1882] and through geologic investigation [Jennings et al. 2003]. Suspended sediment moving through watersheds today is an admixture of legacy sediment derived from failing banks, soil lost from shallow erosion of agricultural fields, and material sourced from stable vegetated areas of the catchment.

The wide difference in meteoric ^{10}Be concentration between forested upland watersheds and urban/agricultural lowland watersheds allows us to partition the source of suspended sediment entering Lake Champlain. Samples collected from the Winooski River, Colchester site represent the sediments entering into Lake Champlain, while sediments from the Browns River and Allen Brook are taken to represent upland and lowland sources respectively. A simplified mixing model can be solved with basin-averaged concentrations of meteoric ^{10}Be.

Where C_a=average concentration of meteoric ^{10}Be entering Lake Champlain (2.1-10^8 atoms/g), C_l= concentration of meteoric ^{10}Be in lowland suspended sediments (0.8-10^8 atoms/g), C_u= concentration of meteoric ^{10}Be in upland suspended sediments (10.1-10^8 atoms/g); X_l and X_u represent the proportion of each end member. Using suspended sediment averaged concentration from the Browns River and Winooski River, Colchester to represent an upland watershed and concentrations entering into Lake Champlain respectively, we calculate the upland sediment contributions using both Allen Brook and Potash Brook as representative concentrations lowland watersheds. By setting the value of X_a to 1 and solving the equation it results show approximately 14% of sediment entering into lake Champlain is coming from upland sediment and lowland sources produce approximately 35% more suspended sediment than upland sources. Due to the variability of meteoric ^{10}Be in the samples collected these suggest that there is sediment removal from all of the watersheds in our study area.

The mixing calculation we performed suggests that upland areas in the study region contribute proportionally less sediment than lowland areas. If we designate uplands as all the land area above 238 meters asl, the elevation of the sample station on the Browns River watershed, then the Winooski watershed is 19% upland and 81% lowland.

The meteoric ^{10}Be concentration we measured in our samples is related to landscape-scale variability at the watershed scale. Percent agricultural land showed a strong inverse relationship to the meteoric ^{10}Be concentration in suspended sediment with lesser correlation to other land use types. This finding is consistent with other research suggesting agricultural areas are hotspots for sediment removal [Owens et al. 1999]. In many cases, mass flux from agricultural areas provides enough sediment to overpower meteoric ^{10}Be signals from other sources. Data also suggest thresholds are important; meteoric ^{10}Be concentrations are greater if 80% or more of the watershed is forested (figure 3.8.). Forested area is strongly correlated with the mean elevation of watershed basins (r^2=0.94, N=7). Similar threshold effects have been observed in sediment delivery rates as effective impervious area in a watershed rises above 10% [Booth and Jackson, 1997].

Our work builds upon earlier meteoric ^{10}Be studies of fluvial sediment conducted in different geomorphic and hydrologic settings and thus extends the applicability of the technique to very different terrains. For example, Brown et al.'s [1988] measurements of meteoric ^{10}Be in sediment from numerous unglaciated mid Atlantic watersheds allowed them to calculate erosion indices and thus identify watersheds that were eroding rapidly at a landscape scale. Conversely, Reusser and Bierman [2010] used meteoric ^{10}Be concentrations in fluvial sediment to trace the impact of a point source of sediment as material from a large mass movement was transported downstream. Here, we have shown that meteoric ^{10}Be concentrations in suspended sediment effectively fingerprint material coming from high-elevation, forested watersheds, further extending the applicability of this isotopic system for land management.

3.7 Conclusions

We find that suspended sediment collected during storm events from 7 humid, temperate, previously glaciated watersheds contains high concentrations of meteoric

^{10}Be. Measured concentrations are independent of time but vary systematically with landscape scale metrics including landuse and topography. Although meteoric ^{10}Be concentrations are on average higher in fine grain size fractions than in coarser sediment, the difference is neither large nor consistent and the concentration of meteoric ^{10}Be in finer and coarser suspended sediment samples is linearly related. Together, these findings suggest that measurements of meteoric ^{10}Be will, along with other chemical and isotopic tracers, increase the ability of scientists and land mangers to identify suspended sediment sources and quantify sediment fluxes from different parts of the landscape.

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3.10 Figure Captions

Figure 3.1. Shaded relief map of the study area showing elevation characteristics in 200 m contours. Watersheds are delineated. Stars represent sampling location for each watershed. Inset shows location of Winooski River watershed in Vermont.

Figure 3.2. Suspended sediment sampling equipment. A. In-stream suspended sediment sampler consists of a set of standard sieves with an attached dragnet. B. Sampler is suspended semi-horizontally in stream flow to collect sediment. The first two screens were used to remove larger debris protecting the following five sieves (500 microns, 250 microns, 125 microns, 73 microns and 43/53 microns). The final sieve is in place to reduce impact on the smallest collecting sieve at the start of sampling.

Figure 3.3. Histograms of meteoric ^{10}Be concentrations from suspended sediment, streambanks, and agricultural fields taken during this study (n = 30). A. Fine fraction (43/53 -125µm). B. Coarse fraction (125-500µm).

Figure 3.4. Bar chart showing meteoric ^{10}Be concentration of suspended sediment samples by sample date, concentrations of meteoric ^{10}Be separated by grain size fraction, coarse (125-500µm, white) and fine (43/53-125µm, black), and sampled watershed.

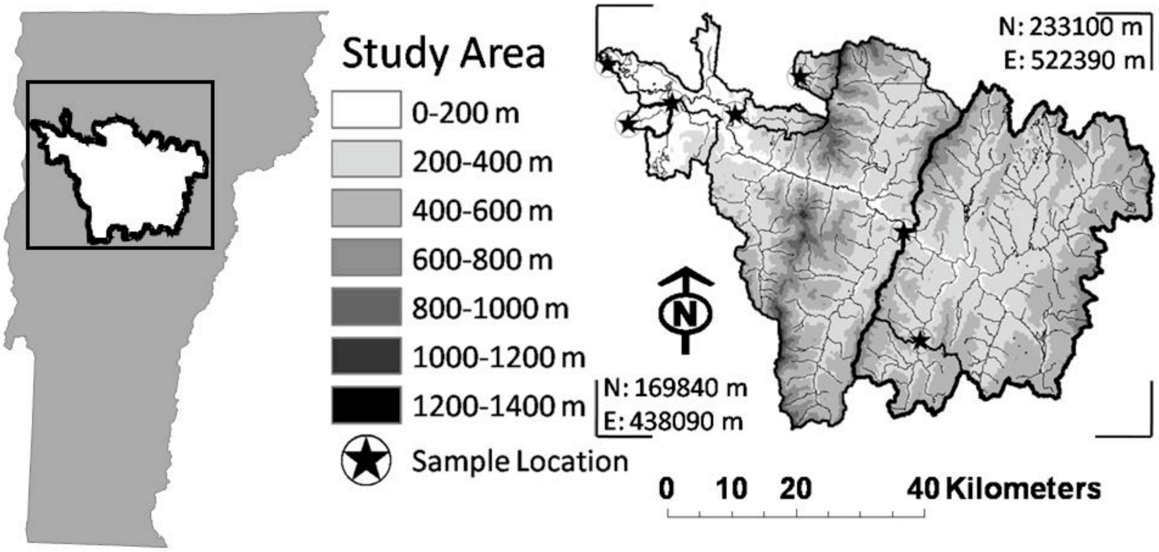
Figure 3.5. Meteoric ^{10}Be concentrations of coarse and fine sediment fractions are positively correlated (R^2=0.70) considering all study samples. The value of R^2 is reduced to 0.31 when samples with concentrations greater than $3*10^8$ are removed.

Figure 3.6. Five suspended sediment samples taken over a 10-day period during the spring melt, high flow event at the Winooski River, Colchester sampling location show no trend over time. Coarse (125-500 µm, white) and fine (43/53 -125 µm, black) sediment fractions.

Figure 3.7. Measured meteoric ^{10}Be concentration of all samples taken considered by sediment source and grain size fraction. Bolded data points represent the mean value for each set.

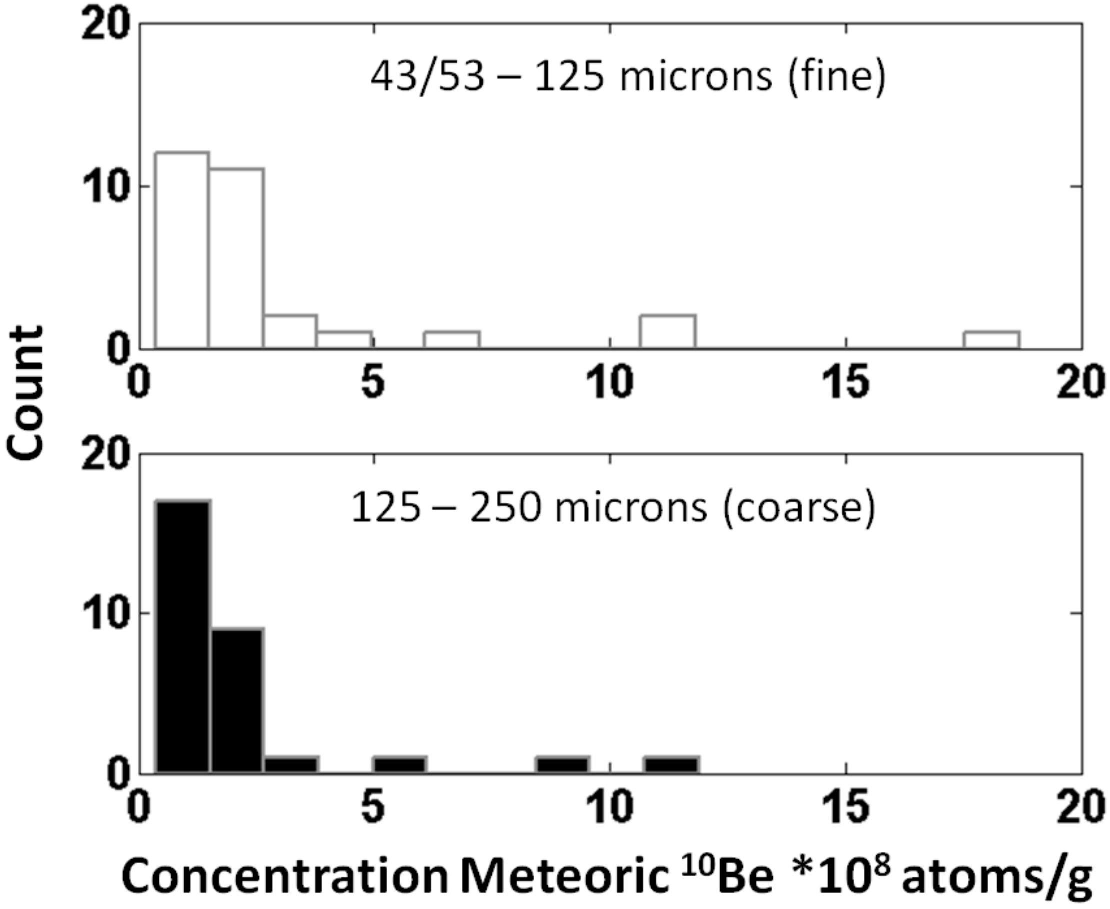
Figure 3.8. Measured meteoric ^{10}Be concentrations in fluvial suspended sediment are related to catchments forested area

3.11 Figures



Borg et al., Figure 3.1.

Borg et al., Figure 3.2.



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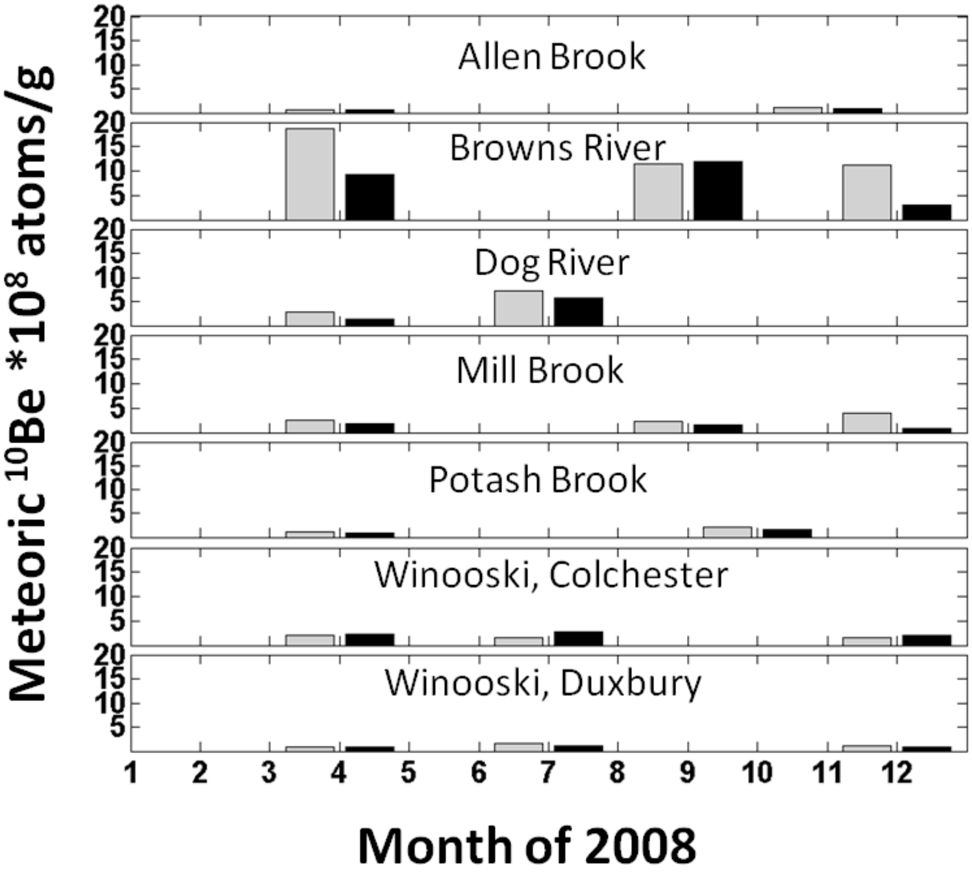

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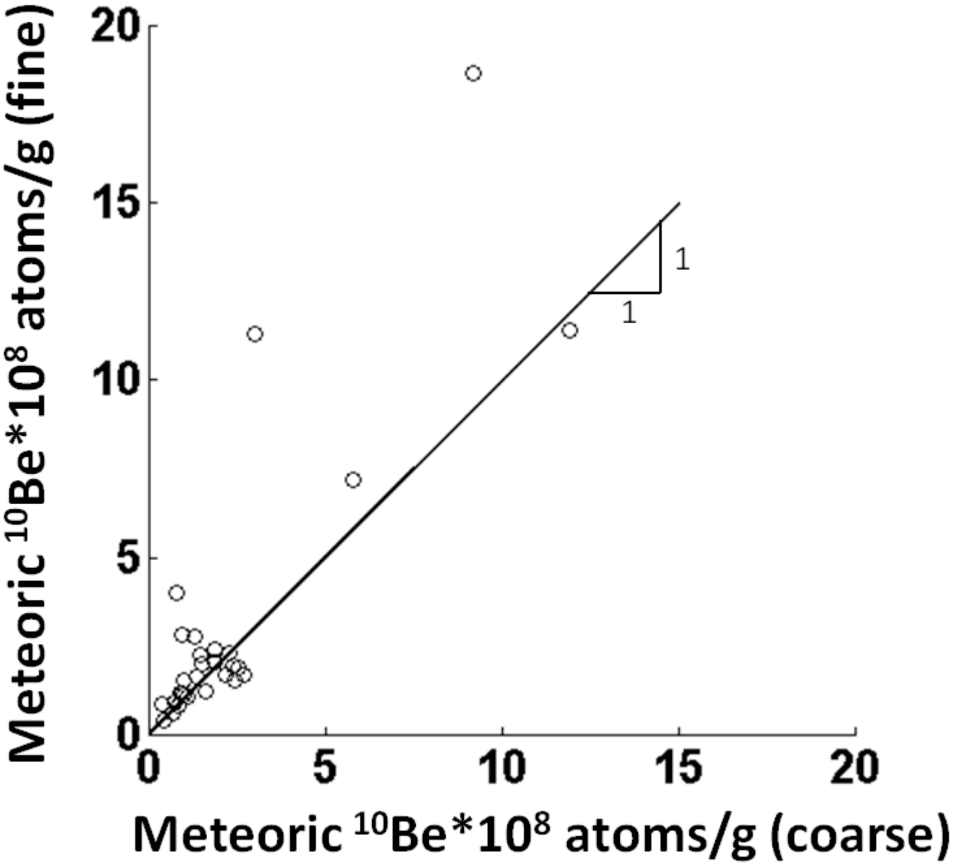

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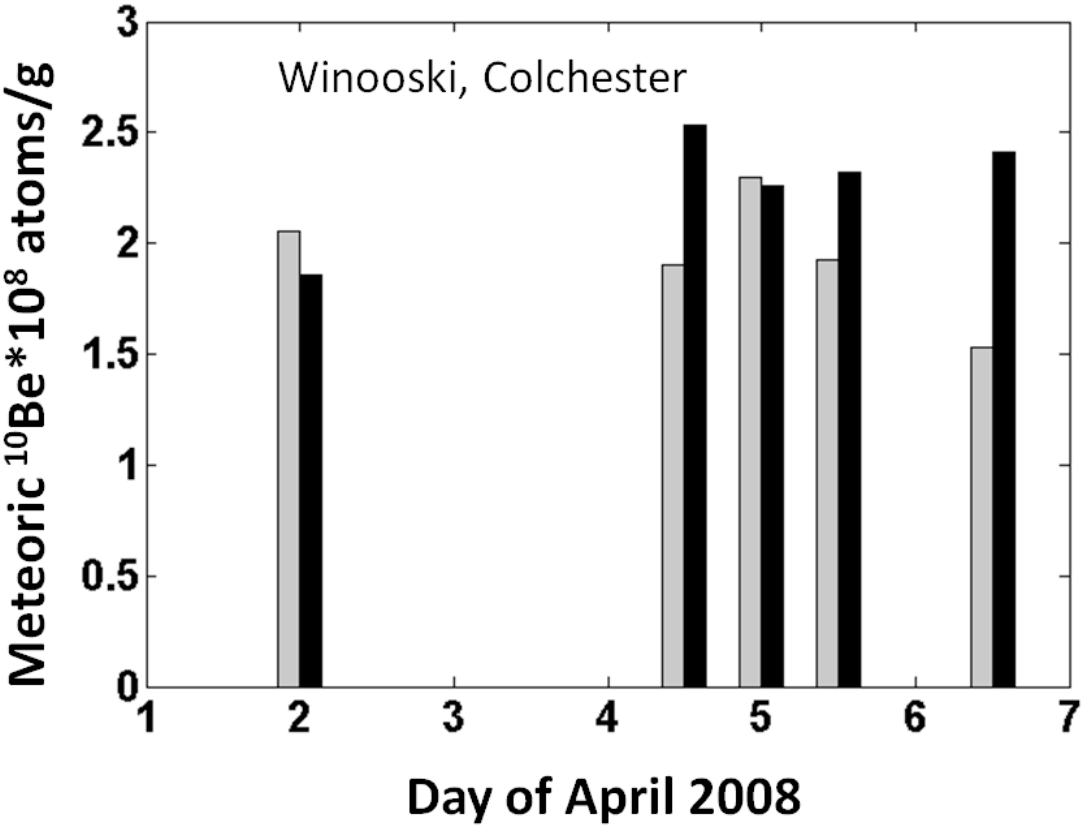
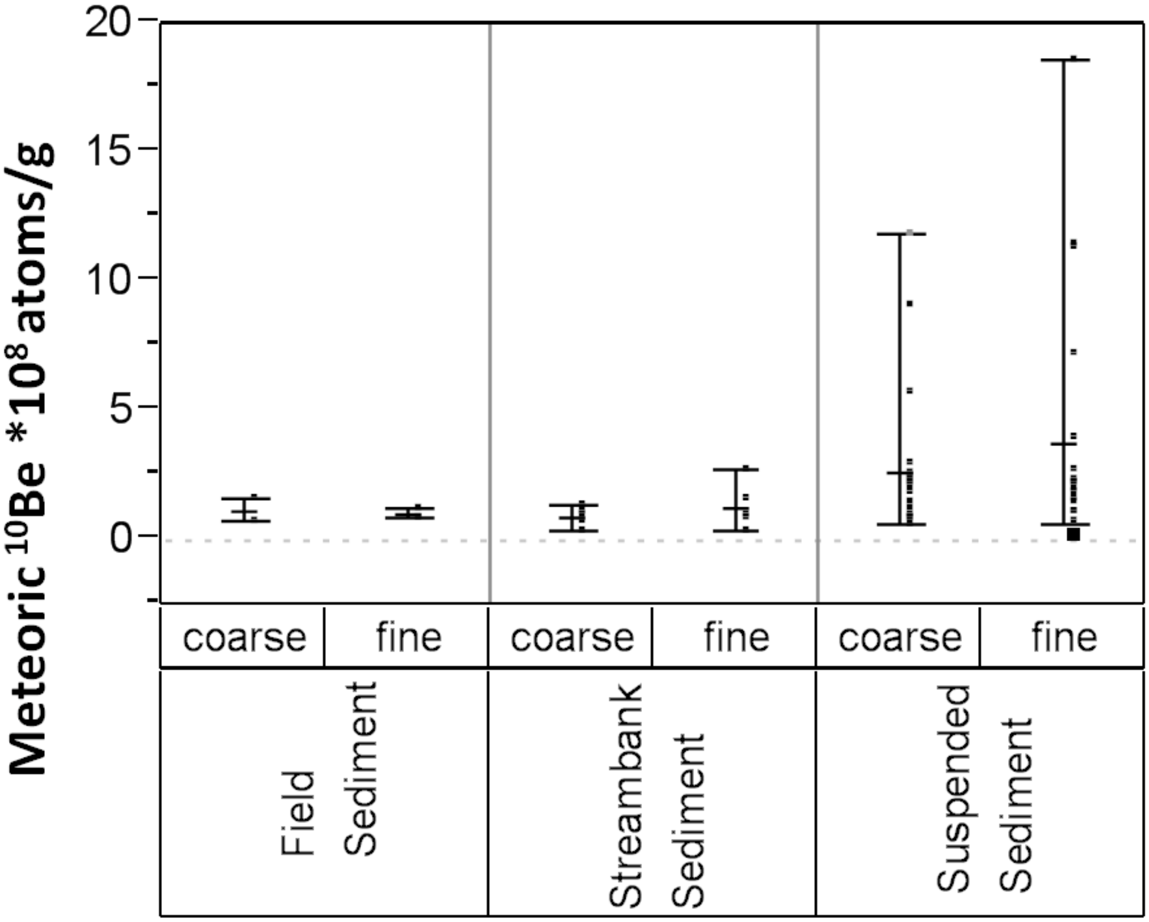
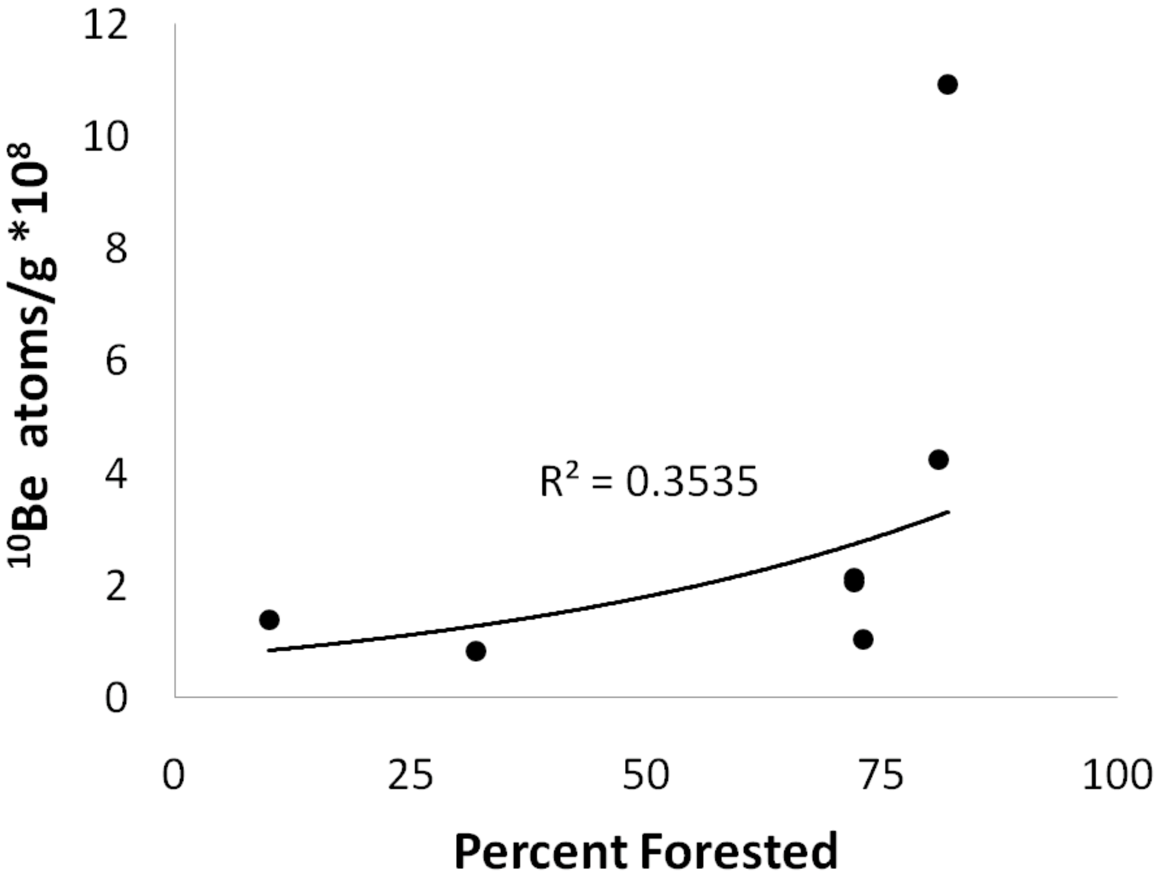


Borg et al., Figure 3.6.



Borg et al., Figure 3.7.



Borg et al., Figure 3.8.

3.12 Tables

Table 3.1. Sampled Watershed Characteristics

	Basin Area	Location[a]		Elevation(m)			Land Cover (%)			
Stream	km^2	Northing (m)	Easting (m)	Maximum Elevation	Mean Elevation	Minimum Elevation	Forested	Agricultural	Urban	Wetland
Dog River	139	486733	180299	882	521	216	81	9	7	3
Allen Brook	83	449481	219388	357	199	61	32	34	22	12
Potash Brook	20	443026	216473	142	87	24	10	27	56	7
Winooski Colchester	2754	439915	225259	1139	397	29	72	12	9	7
Winooski Duxbury	1334	486733	203119	786	459	130	73	12	8	7
Mill Brook	41	459294	217452	1135	350	87	72	10	9	9
Browns River	38	468532	223275	1330	511	238	82	3	7	8

[a] NAD 1983 Vermont State Plane [b] 2001 National Land Cover Database

Table 3.2. Results of one way ANOVAs comparing meteoric ^{10}Be in suspended sediment samples

	Browns River	Dog River	Mill Brook	Potash Brook	Winooski River, Colchester	Winooski River, Duxbury
Allen Brook	0.77	-	0.88	-	0.44	0.003
Browns River		0.90	0.33	0.93	0.72	0.83
Dog River			0.92	0.2	0.79	0.13
Mill Brook				0.89	0.16	0.70
Potash Brook					0.59	0.06
Winooski River Colchester						0.04

Table 3.3. Sample table

Watershed	Sample Date	Sample Type[a]	Sediment Fraction (μm)	10Be Concentration $*10^8$ Atoms/g		
Allen Brook	4/7/2008	Field	125-250	1.62	+/-	0.03
Allen Brook	4/7/2008	Field	53-125	1.20	+/-	0.02
Allen Brook	4/7/2008	Streambank	53-125	0.91	+/-	0.02
Allen Brook	4/7/2008	Streambank	125-250	0.70	+/-	0.02
Allen Brook	4/1/2008	Suspended Sediment	53-125	0.36	+/-	0.01
Allen Brook	4/1/2008	Suspended Sediment	125-250	0.43	+/-	0.01
Allen Brook	11/16/2008	Suspended Sediment	53-125	1.06	+/-	0.02
Allen Brook	11/16/2008	Suspended Sediment	125-250	1.08	+/-	0.02
Browns River	4/18/2008	Streambank	53-125	1.61	+/-	0.03
Browns River	4/18/2008	Streambank	125-250	1.34	+/-	0.03
Browns River	4/18/2008	Suspended Sediment	53-125	2.8	+/-	0.0
Browns River	4/18/2008	Suspended Sediment	125-250	0.95	+/-	0.02
Browns River	9/9/2008	Suspended Sediment	53-125	0.9	+/-	0.0
Browns River	9/9/2008	Suspended Sediment	125-250	0.7	+/-	0.0
Browns River	12/16/2008	Suspended Sediment	53-125	0.9	+/-	0.0
Browns River	12/16/2008	Suspended Sediment	125-250	0.38	+/-	0.01
Dog River	4/9/2008	Streambank	53-125	2.76	+/-	0.05
Dog River	4/9/2008	Streambank	125-250	1.29	+/-	0.03
Dog River	4/9/2008	Suspended Sediment	53-125	0.80	+/-	0.01
Dog River	4/9/2008	Suspended Sediment	125-250	0.82	+/-	0.02
Dog River	7/21/2008	Suspended Sediment	43-125	2.05	+/-	0.04
Dog River	7/21/2008	Suspended Sediment	125-250	1.86	+/-	0.04
Mill Brook	4/1/2008	Field	53-125	18.69	+/-	0.28
Mill Brook	4/1/2008	Field	125-250	9.18	+/-	0.14
Mill Brook	4/1/2008	Streambank	53-125	2.41	+/-	0.04
Mill Brook	4/1/2008	Streambank	125-250	1.84	+/-	0.03
Mill Brook	4/1/2008	Suspended Sediment	53-125	0.57	+/-	0.01
Mill Brook	4/1/2008	Suspended Sediment	125-250	0.66	+/-	0.01
Mill Brook	9/9/2008	Suspended Sediment	53-125	1.17	+/-	0.02
Mill Brook	9/9/2008	Suspended Sediment	125-250	0.88	+/-	0.02
Mill Brook	12/10/2008	Suspended Sediment	53-125	1.90	+/-	0.04
Mill Brook	12/12/2008	Suspended Sediment	125-250	2.53	+/-	0.05
Potash Brook	4/1/2008	Suspended Sediment	53-125	2.30	+/-	0.03
Potash Brook	4/1/2008	Suspended Sediment	125-250	2.26	+/-	0.04
Potash Brook	10/15/2008	Suspended Sediment	53-125	1.92	+/-	0.03
Potash Brook	10/15/2008	Suspended Sediment	125-250	2.38	+/-	0.04
Winooski, Colchester	4/7/2008	Streambank	53-125	1.53	+/-	0.02
Winooski, Colchester	4/7/2008	Streambank	125-250	2.42	+/-	0.04
Winooski, Colchester	4/2/2008	Suspended Sediment	53-125	1.66	+/-	0.03
Winooski, Colchester	4/2/2008	Suspended Sediment	125-250	2.67	+/-	0.04
Winooski, Colchester	4/7/2008	Suspended Sediment	53-125	1.69	+/-	0.03
Winooski, Colchester	4/7/2008	Suspended Sediment	125-250	2.16	+/-	0.03
Winooski, Colchester	4/8/2008	Suspended Sediment	53-125	1.50	+/-	0.02
Winooski, Colchester	4/8/2008	Suspended Sediment	125-250	1.00	+/-	0.02
Winooski, Colchester	4/9/2008	Suspended Sediment	53-125	1.10	+/-	0.02
Winooski, Colchester	4/9/2008	Suspended Sediment	125-250	0.97	+/-	0.02
Winooski, Colchester	4/11/2008	Suspended Sediment	53-125	7.21	+/-	0.10
Winooski, Colchester	4/11/2008	Suspended Sediment	125-250	5.76	+/-	0.08
Winooski, Colchester	7/24/2008	Suspended Sediment	43-125	2.00	+/-	0.03
Winooski, Colchester	7/24/2008	Suspended Sediment	125-250	1.51	+/-	0.03
Winooski, Colchester	12/16/2008	Suspended Sediment	53-125	2.23	+/-	0.05

Winooski, Colchester	12/16/2008	Suspended Sediment	125-250	1.45	+/-	0.03
Winooski, Duxbury	4/10/2008	Streambank	53-125	4.02	+/-	0.12
Winooski, Duxbury	4/10/2008	Streambank	125-250	0.79	+/-	0.01
Winooski, Duxbury	4/10/2008	Suspended Sediment	125-250	1.14	+/-	0.02
Winooski, Duxbury	4/10/2008	Suspended Sediment	53-125	0.93	+/-	0.01
Winooski, Duxbury	7/21/2008	Suspended Sediment	43-125	11.44	+/-	0.14
Winooski, Duxbury	7/21/2008	Suspended Sediment	125-250	11.89	+/-	0.12
Winooski, Duxbury	12/16/2008	Suspended Sediment	53-125	11.32	+/-	0.17
Winooski, Duxbury	12/16/2008	Suspended Sediment	125-250	3.01	+/-	0.04

[a] Sample types. Field- amalgamated sample from surface of agricultural field. Streambank- taken from 3 levels of the exposed cutbanks and amalgamated. Suspended Sediment- collected using in stream suspended sediment sampling device (figure 3.2) during high flow event

Chapter 4: Conclusions

With over 11,000 kilometers of streams in Vermont and extensive agricultural land use sediment associated nutrient loading represents a major pollution source. To improve land and waterway management practices further understanding of sediment transport and streambank stability is desirable. Two focus areas were presented in this work; a longitudinal study at two eroding stream reaches was conducted to observe streambank stability mechanisms of tributary waterways to Lake Champlain, VT, and evaluation of the use of the radionuclide $_{10}$Be as a fingerprint for suspended sediments in post glacial and temperate regions.

4.1 Streambank Stability Conclusions

A total of 14 different streambanks from the Winooski River and Lewis Creek located in north western Vermont were selected for this study. A series of cross sectional studies and a combination of in-situ and laboratory testing were performed to characterize the selected streambanks. Data loggers, pressure transducers and tilt switches were deployed to measure groundwater and stream water levels and monitor bank activity to aid in analysis of streambanks. Information collected was then used to determine the geotechnical stability of the studied streambanks and the material removal rates for each site. The following are the main conclusions from this study.

1. The results of laboratory direct shear tests and in-situ borehole shear tests conducted on the streambank silty sand and sandy silt soils at the study sites yielded reasonably similar results.

2. This study supported the findings by Pollen (2002), Wu et al. (1979) and Darby et al. (2007) that root impregnation increases a soil's shear strength. The direct shear tests performed on bare and with roots streambank soil samples offered a reasonable way of determining the cohesion increase of streambank soils with small roots (diameter less than 1 mm).
3. The rapid drawdown events are generally expected to cause bank failures. However, the streambanks at the study sites did not experience severe drawdown conditions because significant drawdown conditions did not generate. The groundwater level was within 60 cm of the stream water levels at all times.
4. This slope stability analysis supported the findings by Simon et al. (2000) that the loss of matric suction may lead to bank instabilities. The low stream water level condition paired with the loss of matric suction from a rapid wetting event yielded the lowest computed factor safety, which compared reasonably well with the recorded streambank failure event.
5. Although the recorded streambank failure could be modeled reasonably well using the slope stability computer program SLOPE/W, no specific correlation could be found among slope height, slope angle, computed factor of safety and sediment removal amounts, quantities that would be expected to be somewhat related. It is anticipated that the effects of

freezing and thawing of streambank soils and ice flows in the streams, which were not considered in the analysis, might have contributed to the lack of correlation among these quantities.

4.2 Sediment Tracing Conclusions

During the field season of 2008 suspended sediment samples were collected from 7 sampling locations in the Lake Champlain basin. Sample sites were selected to compare differences in varying watershed and landuse characteristics common to the Vermont. Suspended sediment was collected during three high flow events at the sample locations to determine the temporal variability of meteoric $_{10}$Be. The following are the main conclusions from this study.

1. The suspended sediment collected during storm events from 7 humid, temperate, previously glaciated watersheds contained high concentrations of meteoric $_{10}$Be.
2. Measured concentrations meteoric $_{10}$Be were independent of time but varied systematically with landscape scale metrics including landuse and topography.
3. Although meteoric $_{10}$Be concentrations were on average higher in fine grain size fractions than in coarser sediment, the difference was neither large nor consistent and the concentration of meteoric $_{10}$Be in finer and coarser suspended sediment samples was linearly related. Together, these findings suggest that measurements of meteoric $_{10}$Be will, along with other chemical and isotopic tracers, increase the ability of scientists and land mangers to

identify suspended sediment sources and quantify sediment fluxes from different parts of the landscape.

Chapter 5: Resources

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Chapter 6: Appendices

6.1 BST Protocol

Borehole Shear Test (BST)

Purpose

The use of this test is to measure soil's internal friction angle and apparent cohesion in-situ.

Equipment

- BST shear test apparatus, with accessories (shear head, pumps, CO_2, screw driver, allen keys)
- Level
- Shelby tube sampler and tubes
- Soil auger (2.75 in [7cm] in diameter or larger)

Procedure

1) Borehole
    a. Place tarpaulin cloth with a cutout over the desired borehole location. This facilitates easy clean up of the site
    b. Drill a 2.75 in (7cm) diameter or larger hole using auger, emptying soil onto an area of the tarpaulin.
    c. Remove a Shelby tube sample at the desired depth BST. If a 2.75 in (7cm) soil auger is used the Shelby tube sample is not necessary, but stay consistent for all tests run.
2) BST set up
    a. Take the base plate of the BST apparatus (Figure 6.1) and place it center over the borehole. Using the level check, level of the base plate.
    b. If the base plate is not level, remove the plate and add soil around the borehole until the plate is level. Make sure the soil contacts the entire underside of the base plate. This will insure that the base plate remains level throughout the test.
    c. Assemble the shear head (Figure 6.2) and pull rod assembly. Make sure the rod length will be at least 8 in (21cm) above the top of the borehole.

    d. Place the shear head and pull rod assembly into the borehole making sure it reaches the appropriate depth and slide through the base plate assembly and torque arm collet.
    e. Bring the shear head and pull rod assembly at least 1 in (25 mm) from the bottom of the borehole. This provides an even contact with the borehole walls where there is no residual soil from the boring process. Then tighten the torque arm collet with the arm placed between the worm gear stanchions.
    f. Attach the shear head pressure hose to the appropriate pressure source; either the hand pump or CO_2 pump (Figure 6.3a &21b).
3) Testing
    a. Apply the initial confining pressure using the appropriate pressure source.
    b. Allow adequate time for pore water pressure dissipation. 30 min for sands and up to 90 min for clays is usually required.
    c. Check the confining pressure gauge and note it prior to beginning the pull. Pull the shear head using the base plate crank arm at a rate of 1 Hz, and pay attention to the shear stress gauge on the base plate. Continue cranking until the shear stress remains constant for 40 crank arm rotations and record as the shear stress at failure.
    d. Increase the confining pressure on the soil and allow the pore water pressures to dissipate. 10 min minimum for sands and upwards of 60 min for clays. Then repeat the previous step for 5 increasing confining pressures.
        i. If there is a noticeable drop off in the increased shear strength the most probable cause is the excess pore water pressures and therefore the consolidation times should be increased.
    e. Plot results on a normal stress versus shear stress plot to obtain the soil's internal friction angle and the apparent cohesion for the soil.

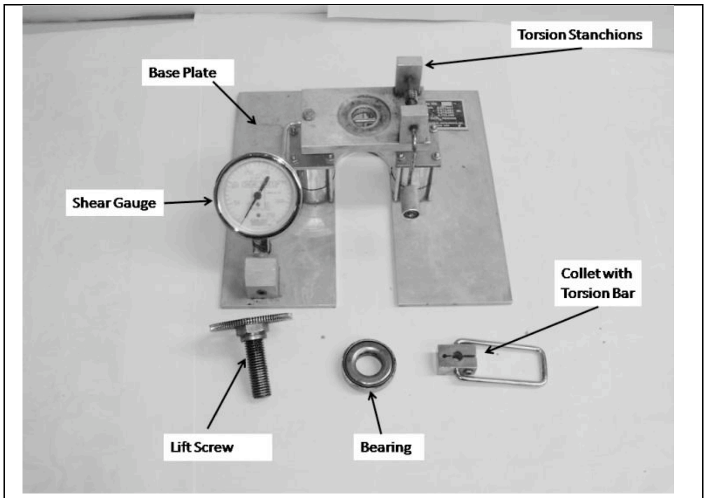

Figure 6.1. BST base plate and components

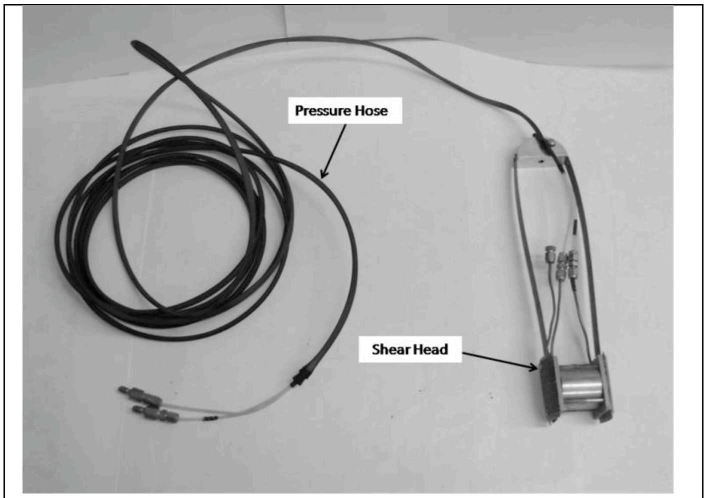

Figure 6.2. Shear head and pressure hose

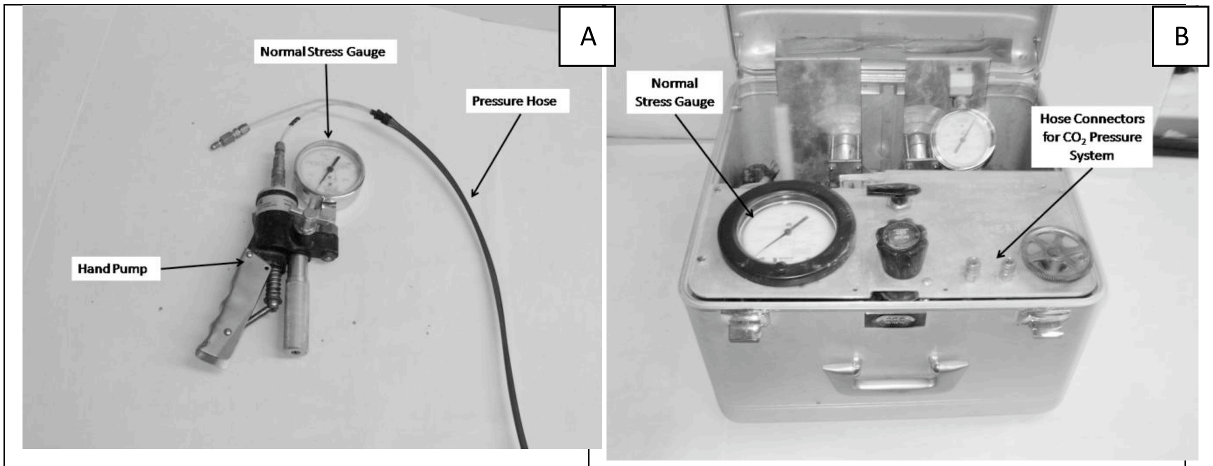

Figure 6.3 a&b. Pressure sources for normal stress

6.2 Cross-Section Survey Protocol

Cross sectional survey procedure

Purpose

The purpose of this procedure is to allow easy repeated cross sectional surveys of a streambank study site. This procedure is done using a total station survey equipment and strategically placed survey pins.

Equipment

- Center punch
- Hammer
- Iron/rebar pins
- Measuring tape
- Total station, prism, and rod

Procedure

1) Pins
    a. Select an appropriate cross section for repeated surveys and insert two rebar pins to define the cross section a pin close to the top of the bank (p_c) and one far away (p_f) to a depth of at least 18 in(Figure 6.4). Make sure the entire cross section can be measured with the total station set up on p_c and that p_c is sufficiently distanced from the top of the bank and it will not be removed by bank failure.
    b. Dimple each of the pins using the center punch. These are the reference points for the cross section.
2) Survey
    a. Set up the total station centered over the dimple on p_c. Back sight to p_f and set the horizontal angle to 0 degrees then lock the total station horizontal angle.
    b. Take a shot at the top of p_f and directly in front at ground level.
    c. Unlock the total station and rotate to a horizontal angle of 180 degrees then locking at this angle for the remainder of the survey.
    d. Take a shot at the top of the bank and at every notable gradient change along the cross section. Make sure to take a shot at the stream water level at the time of the survey. Continue across stream or as far as the water will allow.

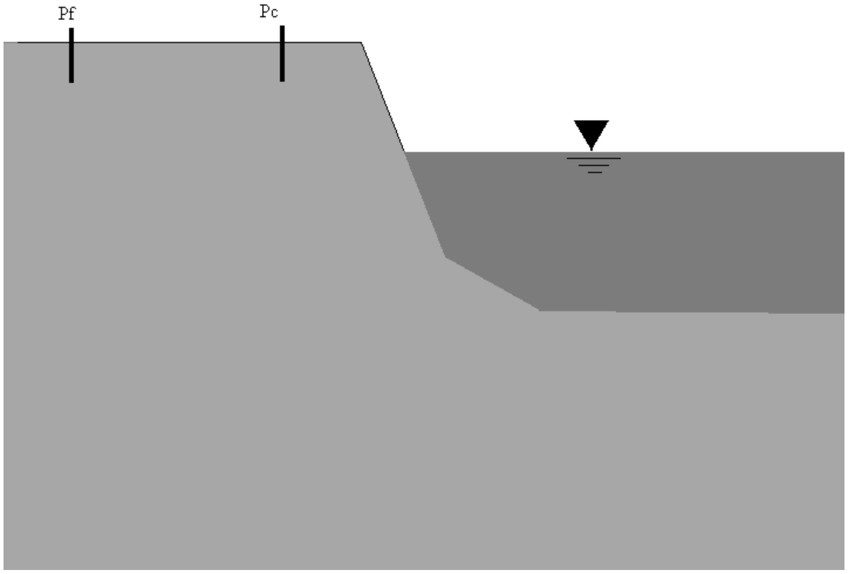

Figure 6.4. Schematic of a survey cross-section

6.3 JET Protocol

Jet Erosion Test (JET) Procedure

Purpose

This test is used to estimate soil's erosion rate and critical shear stress in-situ.

Equipment

- Non-horizontal field jet erosion apparatus (Figure 6.5)
- Garden hosing
- Portable pumping unit

Preparation

- The test location should consist of a relatively flat section of sediment. Care should be taken to select a site with minimal pieces of larger aggregate to avoid damaging the insertion ring(Figure 6.6).
- Attach JET head unit to the supply, and effluent hoses. Connect the supply hose to the pump unit at this time. The effluent hose should be connected to the high side of the surface being tested.
- Adjust the tank bezel so the jet orifice is obscured by the restrictor plate and the depth to the soil surface can be measured (Figure 6.7).

Procedure

- Measure the distance to the soil surface prior to testing.
- Insert ring
- Hook up jet head and hoses
- Take zero reading
- Turn on the pump unit
- Flood the scour tank and set head pressure using needle valve located at input of water to the scour tank; use 0.5 psi to 5 psi for the head setting, 0.5 psi for fine grained dispersive soils and up to 5 psi for clayey materials resistant to scour.
- Turn bezel to initiate scour of the soil
- Apply scour jet to the soil for a period of 1 minute then turn bezel back and take a reading of scour depth and current pressure, repeating this step 15 times
- Apply scour jet to the soil for a period of 2 minutes and take scour depth reading. Repeat a minimum of 8 times ideally until the equilibrium depth of scour is reached (i.e. no further scour)

    - Changes in flow path distance through the soil may necessitate changes to the needle valve to maintain pressure
    - Highly erodible soils may not allow all measurements to be made as the soil may no longer keep the ring stable
- Use ASTM standard (D5852-95) to calculate the critical shear stress and erosion rate of the soil

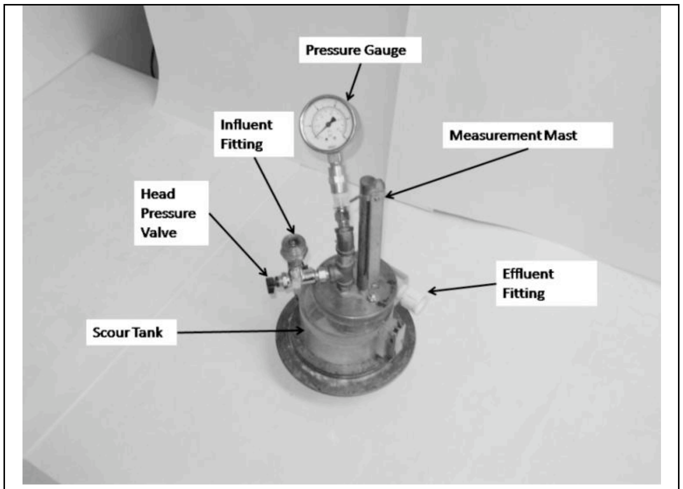

Figure 6.5. JET assembly

Figure 6.6. JET insertion ring

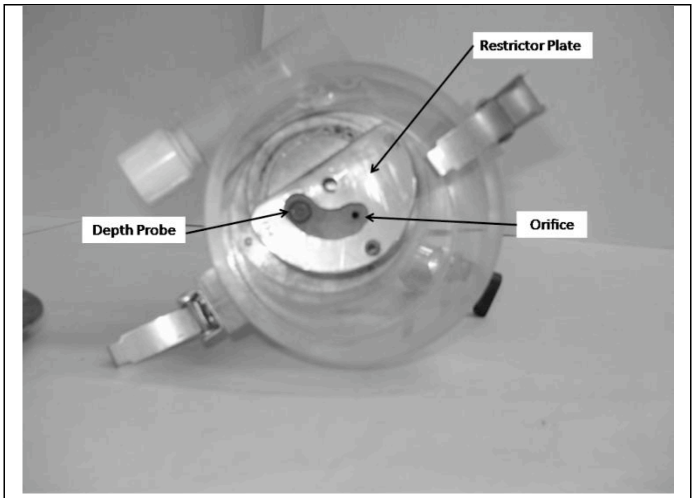

Figure 6.7. Bottom view of the JET apparatus

6.4 Matric Suction Protocol

Negative soil pore-pressure (matric suction) Measurements

Purpose

This procedure is done to measure the negative pore water pressures in the soil for a given time. This can be conducted in conjunction with a BST to correct for the apparent cohesion in the soil due to the presence of negative pore water pressure.

Equipment

- Soil auger
- Soil sampler (Shelby tube or similar)
- Infield T5 laboratory tensiometer and compatible data logger
- Stop watch

Procedure

- Auger to desired sample depth
- Collect undisturbed sample using a Shelby tube or similar device
- Insert the T5 tensiometer and begin data monitoring (Make sure the sample is not exposed to water for accurate measurement. If the data logger is being collected in a continuous file skip the following step)
- Record the pore-water pressure reading every 15 seconds until the readings stabilize for 6 minutes
- Plot collected data. The asymptote of the data collected is used as the pore water pressure for the sample collected.

Figure 6.8. Tensiometer data logger and moisture probe system

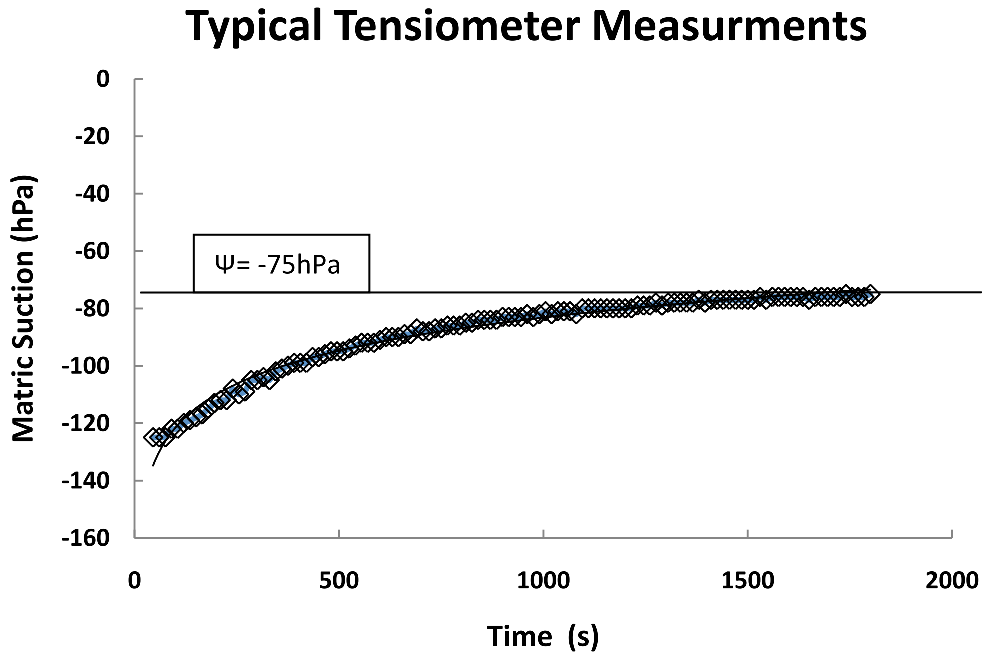

Figure 6.9. Display of matric suction calculation

6.5 Rooted DST Protocol

Rooted sample collection and DST preparation

Purpose

A set of direct shear tests on rooted samples allows determination of roots' addition to soil's cohesive strengths.

Equipment

- Direct shear apparatus
- Protractor and plumb bob
- Sample trimming ring
- Saran wrap
- Shelby tube extruder
- Shelby tube sampler
- Snap blade utility knife

Procedure

1) Sample collection
    a. Sample as would be done when taking a Shelby tube sample on a bare soil. Make sure it is a new or re-sharpened Shelby tube for minimized resistance from roots in the sample zone. Works better for fine grained soils, coarse material will increase sampling disturbance greatly.
    b. To collect non vertical root samples use a protractor and plumb bob to set sample at the proper angle and advance the tube in without using the slid hammer. Check the sampling angle frequently during sampling to insure it remains at the proper angle.
    c. Remove the Shelby tube and sample from the sampling device and pack the open end of the Shelby tube with saran wrap to prevent movement of the sample inside of the Shelby tube and minimize water loss from the roots during transport. Cap the tube and wrap in saran wrap to preserve the sample at field moister.
2) Sample preparation
    a. Remove sample packing and place into sample extruder.
    b. Extrude sample until an undisturbed portion of the sample is at the top of the extruder.
    c. Using the snap type utility knife fully extend carefully cut through the sample using the top of the extruding ring as a guide. Then advance at

    least 1 in (25 mm) using the sample trimming ring as a height gauge. If the soil sample is disturbed in this section trim again and repeat extrusion.

    d. Press the sample extruding ring into the top of the extruded sample and use the bottom of the ring as a guide. Trim the top again to match the ring height.

3) Sample testing
    a. Place the trimmed sample into the DST apparatus.
    b. Increase the shear stroke to a minimum of 0.5 in (12.5 mm) to allow full mobilization of the root strength.
    c. Use shear rate for the soil type collected according to ASTM standard D3080-98 for direct shear testing of a consolidated drained sample.