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The purpose of this research was to gain insight into the anthropogenic forcing of geomorphic systems, specifically how nineteenth century land-use changes impacted watershed hydrologic, upland erosional, and sediment delivery subsystems of Southern Appalachian headwater catchments. Identification and analysis of the timing and rate of change in these subsystems, and the reestablishment of presettlement conditions, were used to address landscape sensitivity and watershed inheritance issues in a region undergoing population expansion and development.

Archival research was used to reconstruct concurrent land-use changes in the catchments of two nineteenth century water-powered mills. Changes in the physical properties of mill pond sediments including, organic content, particle size distribution, and magnetic susceptibility, were used to interpret trends in sediment source during the span of mill operation. Interpolation of augering and coring data was used to determine mill pond sediment mass and pond capacity.

Hillslope hydrologic change occurred almost immediately following land conversion. Upland erosion began with the removal of A-horizon fines, and progressed with the removal of A-horizon coarse particulates, and then B-horizon particulates. Change from one source category to another was punctuated by high flow events signifying an integration of human activity and climate in the changing of system boundary conditions.

Late nineteenth century sediment yield in Southern Appalachia was almost as high as that reported for the adjoining Piedmont although only 25 percent of highland watersheds were converted to agriculture. However, sediment delivery ratios were relatively low indicating a more complicated relationship between hillslope-channel connectivity and soil erosion. In reforested watersheds, both the hydrological and erosional subsystems reverted to presettlement conditions within a few years but may have taken up to one hundred years for sediment yield rates to return to presettlement conditions. Finally, the sediment trapped behind nineteenth century dams has served as a significant source of ecologically damaging washload to highland streams during the twentieth century.

NINETEENTH CENTURY LAND-USE, WATERSHED EROSION, AND SEDIMENT YIELD IN SOUTHERN APPALACHIA

by

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APPROVAL PAGE

This dissertation has been approved by the following committee of the Faculty of The Graduate School at The University of North Carolina at Greensboro.

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TABLE OF CONTENTS

Page

LIST OF TABLES

Page

LIST OF FIGURES

Page

CHAPTER I

INTRODUCTION

Human agency is a pervasive and frequently dominant influence on earth surface processes (Goudie 1993; Hooke 1994; James and Marcus 2006; Church 2010). Some anthropogenic land-use practices can produce significant changes in rates of soil erosion, delivery of sediment to streams, and sediment yield. However, major gaps in knowledge persist regarding these hydrogeomorphic responses to land-use, and despite decades of research there is still a basic need "to quantify the major processes responsible for the generation and transportation of sediment" (Burt and Allison 2010, 3). The nature of historical anthropogenic disturbance and its long-term impact on fluvial systems represents a critical example.

Geomorphological processes occur over a variety of spatial and temporal scales in watersheds, and current observations and quantitative data are the sum of numerous overlapping processes (Phillips 2009). It is therefore necessary to understand the full land-use and erosional histories of watersheds in order to accurately identify specific system processes and responses. Unfortunately such data are rarely available. However, archival records of historical land-use and the synchronous sediment flux contained in various sediment storage locations offer substantial opportunities for addressing this issue. This dissertation research investigates historical sediment dynamics at Bent Creek, a small but historically significant highland watershed in the Blue Ridge Mountains of North Carolina (Figure 1). The study uses methods of sediment yield reconstruction, sediment source evaluation, soil erosion modeling, archival research, and traditional surveying, to accomplish several goals. These include (1) reconstructing nineteenth century land-use in the Bent Creek watershed, (2) reconstructing nineteenth century sediment yield within the Bent Creek watershed, (3) analyzing changes in associated erosion processes and sediment sources, (4) quantifying sediment delivery to Bent Creek stream channels, and (5) assessing fine sediment in old mill dam deposits as well as its potential for future release into Bent Creek and the French Broad River. This analysis of sediment dynamics provides data critical for assessing modern sediment yields and land-use impacts on land and water resources in the rapidly populating Blue Ridge Mountains, for which few data are available (Price and Leigh 2006).

Research Background and Context

As the Holocene has progressed, the major cause of sediment flux in fluvial systems has transitioned from climate change to human activity. Change in the rate of soil erosion has been dramatic since humans adopted agriculture (Leopold 1966; Wilkinson and McElroy 2007). There are numerous interconnected factors that may increase soil erosion rates. However, change in vegetation cover, particularly the felling of woodlands to create agricultural clearings, is considered to be a primary driving force (Wilkinson and McElroy 2007).

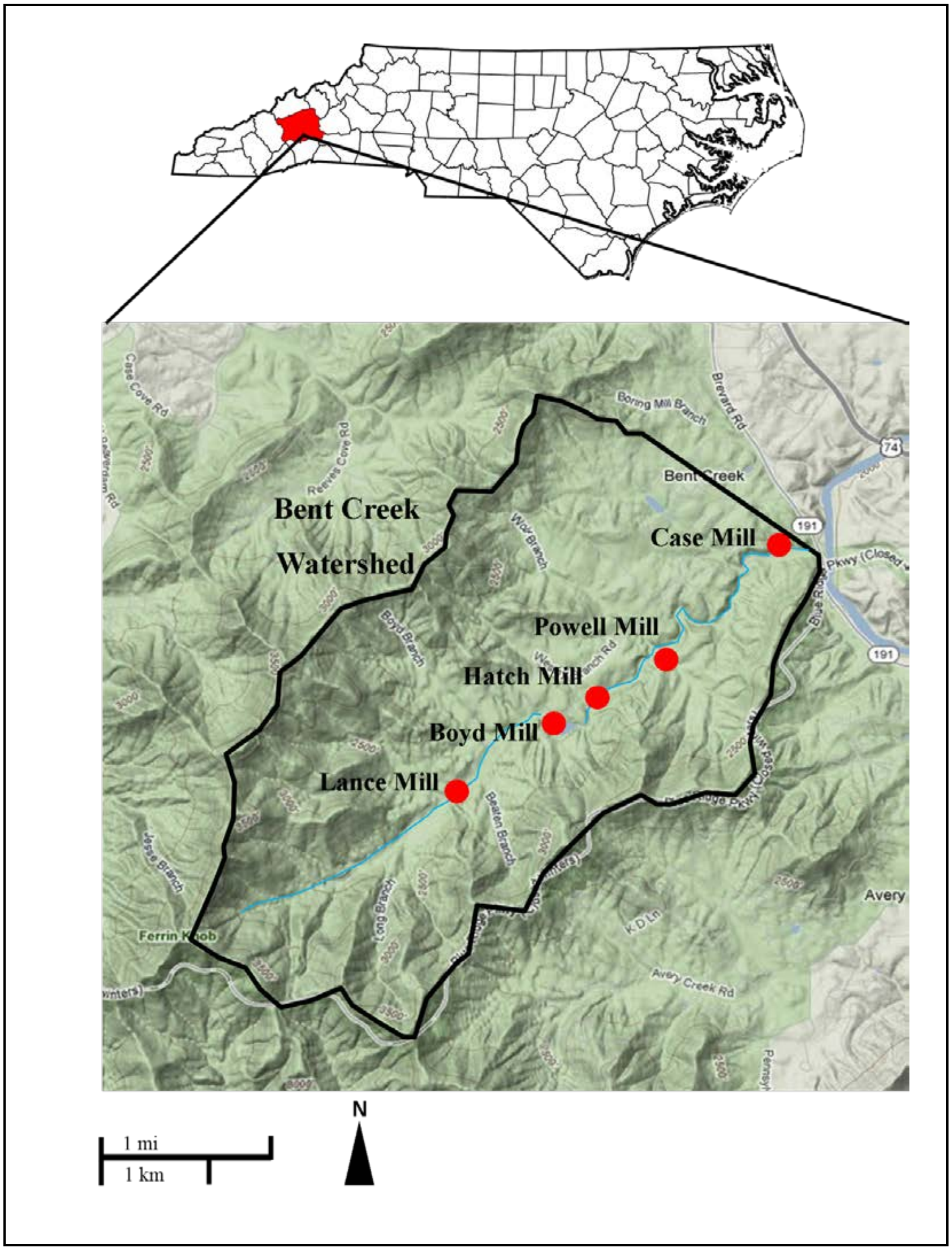

Figure 1. Bent Creek Experimental Forest, Buncombe County, North Carolina

It is estimated that a total of 640,000 km^2 of forest was cleared between the early seventeenth century and 1910 across the eastern United States (Williams 1990).

Numerous examples of changes in geomorphological processes related to human activity have been investigated and described. In humid climates (e.g., the eastern United States) changing land cover from woodland to crop production can increase erosion rates, often by an order of magnitude or more (Walling 1990). Secondly, an increase in stream-flow, due to reduced rainfall interception by plants and reduced transpirational loss of soil moisture, occurs when native vegetation is removed. Third, it has been demonstrated that in mountainous environments, logging roads increase the sediment input to fluvial systems largely through an increase in mass wasting (Eschner and Patric 1982; Swanson et al. 1982). Fourth, forest soil permeability decreases following clearance. However, it is particularly sensitive to later plowing as this destroys soil structure, and increases surface sealing, overland flow, and topsoil erosion rates. Finally, rills and gullies often develop in response to increased overland flow, both of which are problematic; agricultural land is degraded and downstream areas are inundated with sediment (Brunton and Bryan 2000; de Vente et al. 2005).

This sediment constitutes the single most important source of stream impairment in the United States (U.S.) (Environmental Protection Agency 2007). Current estimates of soil erosion and sediment input to streams tell only part of the story however, because eroded soil may be stored and later remobilized from a variety of locations in watersheds, prolonging the deleterious effects. Sediment yield values in U.S. catchments, characterized by heavy human impact, have not mirrored synchronous soil erosion rates

(Roehl 1962; Trimble 1981; Walling 1983). Rather, sediment delivery (the ratio of sediment yield to total gross erosion) has been well below unity. Scientists estimate that up to 95 percent of sediment produced by agricultural activities in the southern Piedmont region remains in catchments in a variety of transient storage forms (Trimble 1974). Research in the mid-Atlantic Piedmont indicates that large quantities of Colonial and early-American millpond sediment remain in stream valleys, and that the human impact resulting from intense agriculture and stream impoundment has been to change the hydraulic geometry of natural streams throughout the region (Walter and Merritts 2008). In summary, the previously described research indicates that the significance of current geomorphological observations is only fully realized, when placed within a comprehensive spatial and temporal framework.

The impact of initial (or even early) land-use on hydrogeomorphic processes and sediment yields during the European settlement of eastern North America requires investigation as it is poorly documented. This is particularly true in the southern Blue Ridge Mountains (Leigh and Webb 2006; Price and Leigh 2006). Euro-Americans settled the southern Blue Ridge during the early nineteenth century. These early settlers were attracted by the availability of land and large areas of virgin forest. As more people immigrated into the area throughout the century, forests were cleared for crops and pasture, and trees were logged for private and commercial purposes. Land did degrade over time and some gullies can still be seen in the reforested landscape today. However, little is known regarding the types and pace of erosion, particularly in the earliest stages of settlement when highly permeable forest soils were first exposed.

Regional research includes an evaluation of historical sedimentation rates in the Blue Ridge. A study by Leigh and Webb (2006) found sedimentation rates to be similar to those of the more heavily cultivated southern Piedmont. However, questions regarding the initial resistance of landscape subsystems to major land-use change, an important aspect of system sensitivity (Downs and Gregory 2004; Phillips 2009), having implications for modern watershed management, have yet to be addressed. Price and Leigh (2006) also observed an apparent lack of stream morphological sensitivity to moderate land-use in the Blue Ridge at the stream scale, arguing that morphological adjustment might be better addressed at the watershed scale. To-date, however, there has been insufficient geomorphic data derived from this region of time frames suitable to more definitively address such issues.

Increased soil erosion rates are not the only human impact at Bent Creek. Stream channels were impounded at a number of locations to create millponds. Water was used throughout the region to power numerous small-scale commercial enterprises (Eller 1982; Salstrom 1994; Yarnell 1998; Inscoe and McKinney 2000). Small dams constructed in the Bent Creek watershed and their associated ponds were used to generate power for a combination of gristmills, blacksmith shops, saw mills, and furniture shops (Nesbitt 1941). The sediment produced by land-use induced erosion was to a large extent trapped behind these impoundments providing a record in some cases of the first major Euro-American geomorphic impacts on relatively pristine landscapes of the Blue Ridge. Thus, these and similar deposits throughout the region constitute an important archive for studies of watershed dynamics.

Bent Creek's nineteenth century mill pond dams have since been breached or deliberately removed, and stream channel incision into intact pond sediments has occurred. In the adjoining Piedmont, mill pond deposits have been cited as significant sources of elevated fine sediment loads, as post-dam-removal stream incision remobilizes this sediment, leaving former pond-bed surfaces as terraces (Walter and Merrits 2008). Although few studies have attempted to quantify the contributions of ecologically disruptive fine sediment loading arising from pond sediment incision anywhere, they are especially lacking in the Blue Ridge Mountains.

Research Questions and Hypotheses

Reconstruction of nineteenth century land-use patterns, sediment yield, sediment sources, and soil erosion rates are necessary for gaining deeper insight into anthropogenic forcing of geomorphic systems, watershed inheritance issues and landscape sensitivity. The research questions and hypotheses posed herein are:

(1): How do early settlement sediment yields in the Blue Ridge Mountains compare to current yields and to yields documented for the adjacent Piedmont province at similar levels of settlement?

Relative to the percent of land cleared, average sediment yield values for the Blue Ridge region of North Carolina during the nineteenth century may have been higher than those estimated for the Piedmont, due to steeper slopes and lack of significant floodplain barriers to sediment delivery.

(2): How sensitive to land-use were hydrological, erosional, and sediment delivery subsystems in early settlement mountain watersheds?

Although average sediment yields may have ultimately been high in disturbed Blue Ridge watersheds, initial sediment yields could have been low due to initial system resistance to upland erosion. Permeable, coarse-grained organic-rich topsoils, which are common in the Blue Ridge Mountains, might have required advanced deterioration before major production of overland flow. This would have delayed upland erosion, sediment delivery, and sediment yield responses to initial land clearance. Thus, the channel hydrologic subsystem was likely to have been relatively sensitive to initial land clearance, responding immediately and proportionally to reduced transpiration and interception losses, whereas the upland erosional subsystem may have been relatively insensitive for some time after clearance. Although modern logging operations are critical sediment sources of mass wasting inputs currently (Swanson et al. 1982), logging is not considered to have contributed sediment during the earliest occupation of the watershed.

(3): How important have historic mill dam sites been as sources of fine, chemically active sediment in twentieth century sediment loads at Bent Creek?

Eroding Blue Ridge mill pond sediments are unlikely to have been the dominant contributor of fine particles to the overall fine sediment load of Bent Creek during the twentieth century.

Study Area

The Bent Creek watershed is located in Buncombe County, North Carolina, and is approximately 24.28 km^2 in area (Figure 1). The study area is located in the Blue Ridge Belt of the Appalachian Mountains, and the underlying geology consists of highly weathered Late Proterozoic rocks of the Ashe Metamorphic Suite, that includes; metasiltstones, metagreywackes, metaconglomerates, amphibolites, and schist (Merschat and Carter 2002). The topography is typical of the Blue Ridge Mountains, with elevations ranging from 622 m (2,040 ft.) above sea level near the outlet of the watershed to 1,122 m (3,680 ft.) above sea level near the summit of Pine Mountain in the southwestern portion of the watershed. Numerous first and second order tributary streams drain into Bent Creek from hollows throughout the watershed. Bent Creek, a third order stream, is a tributary of the French Broad River, which ultimately flows westward into Tennessee, contributing to the greater Mississippi River drainage.

Sedimentary deposits of five nineteenth century mill ponds presently exist within the Bent Creek Watershed, four of which are located on the main stem of Bent Creek. Two have been destroyed or severely impacted by the development of Lake Powhatan and its associated recreational area (Boyd and Hatch), leaving three suitable for lake-sediment-based reconstructions of sediment yields. Case Mill, located close to the confluence of Bent Creek and the French Broad River, operated continuously between 1808 and 1905, and for the first twelve years of operation (1808 to 1820) was the only impoundment in the Bent Creek catchment. From 1820 however, Case Mill pond was the final reservoir at the end of a sediment cascade as an additional four mill ponds were constructed upstream at one time or another during the nineteenth century, and for this reason, Case Mill was considered unsuitable for further investigation at this time.

Lance Mill, located on the upper main stem of Bent creek, operated between 1880 and 1910, at which time the dam was breached by flood waters. No stream impoundment ever existed upstream of Lance Mill pond. Powell Mill was constructed on the Rocky Cove Branch and operated between 1880 and 1895. No impoundment ever existed upstream of the Powell Mill pond. The sediments trapped behind Lance and Powell mill dams are therefore the direct result of sediment processes occurring in the respective catchments upstream, and for this reason, are the focus of this dissertation research.

Conditions at Bent Creek Prior to Euro-American Settlement

Human occupation of southwestern North Carolina began approximately 14,000 years before present (B.P.), and archaeological evidence of prehistoric occupation specifically in Bent Creek, from the Archaic Period (9;500 B.P.) to the Mississippian Period (300 B.P.) has been reported (Baker and Hall 1987, Snedeker et al. 1992; Noel and Ashcraft 1995). Owing to the lack of substantial floodplain formation, however, the prehistoric occupation of Bent Creek remained semi-permanent and/or transient in nature: the watershed used by Native Americans principally for hunting and gathering.

Woodland was cleared throughout the Americas by Native Americans (Butzer 1992). However, in southwestern North Carolina prehistoric clearance was largely confined to floodplains and lower terraces. Extensive archaeological and paleoecological investigations in the Little Tennessee River Valley revealed that it was only after 300

B. P. that historic period Cherokee and then Euro-Americans spread into upland areas (Delcourt et al. 1986). A later archaeological and geomorphological study at Raven Fork in southwestern North Carolina quantified changing sedimentation rates during the Holocene. Although the Cherokee engaged in corn cultivation during the late prehistoric period, the highest rates of sedimentation occurred over the last 150 years, associated with Euro-American expansion upslope (Leigh and Webb 2006). Two Cherokee families lived in the watershed between 1800 and 1838, and even at this late date, oral tradition describes the Bent Creek Cherokee as hunters, gatherers, and fishermen rather than farmers (Nesbitt 1941).

An oak-chestnut hardwood forest including species such as hemlock, buckeye, beach, hickory, shortleaf pine, chestnut, oak, ash, birch, locust, white pine, black gum, maple, and black pine, covered the Bent Creek watershed prior to Euro-American settlement (Ayres and Ash 1905; Delcourt and Delcourt 1980). The composition and structure of this early forest may have been influenced by human activity as Native Americans frequently burned woodlands to increase hunting opportunities and increase habitat for preferred fruit bearing shrubs (Denevan 1992), but there is no evidence that woodland was cleared.

In summary, the forest/vegetation conditions in Bent Creek around 1800 may not have been pristine. It is possible that some forest stand modification had occurred, principally the result of forest burning. However, there is no evidence of large scale prehistoric agriculture and it is assumed that very little woodland, if any, was cleared throughout the prehistoric period. As such, the impact on soil erosion rates would have been minimal and stream conditions relatively pristine when Euro-Americans first settled the area

CHAPTER II

LITERATURE REVIEW

This chapter provides an overview of previously conducted research considered relevant to the investigations detailed in this dissertation, ranging from the local to global scale. Beginning with an overview of the recognition of Mankind's impact as a geomorphic agent at the global scale, the discussion moves on to focus on the factors that impact hydrogeomorphic processes in catchment basins, specifically how human land-use change in watersheds modifies and alters the movement of both sediment and water from hillslope to channel, and through the fluvial system (Wohl 2006).

Studies using lake sediments and magnetic susceptibility as methods to investigate the response of watershed processes to changes in vegetation cover are reviewed, specifically research in which sediment yield is quantified, and trends in sediment source are identified.

Mankind as a Geomorphic Agent

Geographers, geologists, explorers, and others, have recognized and documented the impact of human activity on earth surface processes since the early nineteenth century (Glacken 1967; Grove 1990; Goudie 1993). Qualitative observations of conditions in the Alps and Venezuela during the first half of the nineteenth century linked local deforestation to changing fluvial conditions and fluctuating water table levels.

By the mid-nineteenth century it was generally accepted that mankind's activities on land, at least in the short term, impacted surface and near-surface processes (Goudie 2006).

The birth of the conservation movement, spurred by Marsh's *Man and Nature* (1864) in the second half of the nineteenth century, marked the onset of significant academic awareness and interest in issues such as human induced soil erosion and the human modification of hydrological processes (Shaler 1912; Gilbert 1917). However, it was Sherlock (1922) who first proposed the concept of mankind as a geomorphic agent. Land subsidence, air pollution, and altered water circulation patterns were all viewed consequent of human activity, but Sherlock argued that humans had the greatest impact on denudation rates. Sherlock's geological contemporaries were, however, reluctant to incorporate mankind into what was considered a natural science; the large spatial scale and deep temporal scale of geological processes were simply considered to be too immense to be affected in the long term by human activity (Brown 1970).

This reluctance has been shed more recently. Voluminous research and associated quantitative data collected since the mid-twentieth century has illuminated the scale and magnitude of surface material moved by humans, and it is now generally accepted that mankind is the dominant geomorphological agent, surpassing even glaciers in terms of the mass of rock and sediment moved from one location to another (Hooke 1994). Recent research on modern rates of continental erosion concludes that (1) human induced soil erosion is presently the most important surface process, (2) 20,000 gigatonnes (x 10^9) of soil have been eroded over the course of human civilization, (3) that the majority of this sediment is stored in 3rd through 6th order stream channels and, (4) that this has occurred over a very brief geological time span (Wilkinson and McElroy 2009).

In addition to increased rates of denudation and sedimentation, human activity is also considered responsible for changes in the carbon cycle (increased atmospheric carbon dioxide), significant biotic changes (species extinctions), and increased acidification of ocean waters, and that these changes are now considered "sufficiently distinct" to be viewed as a geological boundary distinguishing the Holocene Epoch from a new Anthropocene Epoch (Zalasiewicz et al. 2008). Indeed if the worst case scenario of environmental change is realized, the onset of the new Anthropocene Epoch will not only mark the end of the Holocene Epoch, but may also mark end of the Quaternary Period (Zalasiewicz et al. 2009, 6).

The Impact of Human Activity on Sediment Production

Forest Cover Removal

Change in the rate of soil erosion has been dramatic since humans adopted agriculture (Leopold 1956; Wilkinson and McElroy 2007). There are numerous interconnected factors that may result in human induced accelerated soil erosion rates, but all are rooted in the human modification of hillslope hydrology. Changing or removing hillslope vegetation cover has the greatest impact on the rates of hillslope hydrological variables including, interception, throughfall, infiltration, overland flow, perculation, throughflow, and saturated overland flow (Betson 1964; Chorley 1978; Peel 2009; Bracken 2010). It is estimated that a total of 640,000 km^2 of native forest was cleared between the early seventeenth century and 1910 across the eastern U.S. (Williams 1990), and this conversion of woodland to agricultural land-use significantly impacted the hydrogeomorphology of eastern watersheds (Trimble 1985).

In humid climates (e.g., the eastern U.S.) changing land cover from woodland to cultivation can increase soil erosion rates often by an order of magnitude or more (Walling 1990). The degradation of plowed soil moves through a series of stages and is related to the interaction of tillage and local weather patterns. In general, plowing results in a loss of soil organic content, surface compaction and surface sealing, and the destruction of natural soil aggregates, and the net effect is a reduction in infiltration rates and an increase in surface runoff and soil erosion (Bracken 2010). Rills and gullies often develop in response to increased overland flow, both of which are problematic; agricultural land is degraded and downstream areas are inundated with sediment (Brunton and Bryan 2000; de Vente et al. 2005). The rate of this enhanced soil erosion process varies with climate, geology, soil texture, and agricultural methods.

Local stream channels experience an increase in stream-flow due to increased runoff, reduced rainfall interception by plants, and reduced transpirational loss of soil moisture, when native vegetation is removed. Forest vegetation can absorb as much as 40 to 60 percent of annual precipitation and elevated stream flow has, in some circumstances, persisted for up to 30 years following logging operations in Southern Appalachian watersheds in western North Carolina (Webster et al. 1992).

Extensive research, conducted at the Coweeta Experimental Forest in Southern Appalachia, North Carolina, investigating the hydrological response to vegetation change and a variety of forest management practices, has resulted in a wealth of data regarding the variability and scale of both hillslope hydrology and sediment movement (Hibbert1967; Swank et al 1988; Webster et al. 1992; Elliot 2006). Studies indicate that changes in stream-flow, and by extension hillslope hydrology, are initiated when more than 20 percent of vegetation cover is disturbed (Bosch and Hewlett 1982; Brown et al. 2005).

Sediment production is a function of the timing of the disturbance, in terms of the quantity and intensity of subsequent precipitation, and incipient moisture conditions. A high intensity precipitation event and/or, a significantly wet period, occurring shortly after the removal of vegetation, results in higher overland flow and increased erosion rates.

Roads

Roads increase the sediment input to fluvial systems in mountainous environments largely through an increase in mass wasting (Eschner and Patric 1982; Swanson et al. 1982; Swift 1988). Soil erosion associated with roads has been found to be periodic, associated with intense rainfall events, and a function of the frequency of use (Beschta 1978). It has been demonstrated in the Pacific North-West that roads are an important source of fine sediment (Reid and Dunne 1984). There is presently evidence for more than one dirt road in both Powell and Lance Mill catchments. However, it is not possible to determine which road/s date to the nineteenth century and which may be the result of later occupation. It seems safe to assume that at least one dirt road existed in each catchment during the period of mill operations.

Forest Fire

Forest fire reduces/eliminates litter, resulting in the exposure of mineral soil and a reduction in soil organic content. If hot enough, forest fire will also create surface sealing. Consequently, for a period of time following a fire event, infiltration rates may drop and overland flow may increase, increasing the vunerability of exposed mineral soil to erosion. However, fire events result in variable hydrological responses. High temperature wild fires result in higher subsequent erosion rates than do lower temperature prescribed fires (Elliot 2006). At Coweeta, sediment production following wild fire exceeded that produced from logging and prescribed fire combined (Elliot 2006). The annual burning conducted throughout the Bent Creek watershed would not have reached the temperatures associated with wildfires and it is unlikely that fire-induced surface sealing occurred. Erosion rates following prescribed fire would more likely be related to the timing and intensity of rain events following fire events, and the timing of leaf fall.

Grazing

Stock rearing was a major component of Southern Appalachian agriculture; the typical farmer raising cattle, hogs, sheep, and goats (Nesbit 1941; Eller 1989), and prior to the Enclosure Act of 1885, all stock was released to freely graze in common land (any land not enclosed for crop production). Research in humid regions has demonstrated that the erosional impact of grazing animals can be significant. Overgrazing results in a weakening of vegetation cover that eventually leads to the exposure of mineral soil. Trampling causes soil compaction, a reduction in infiltration rates, and an increase in runoff (Evans 1997; Evans 1998). Soil thinning and gullying, may both occur, the frequency and intensity related to the density of animals in a given location (Evans 1997). Channel bank erosion can be significant where grazing animals expose and compact soil in the riparian zone (Trimble and Mendell 1995). Heathwaite et al. (1990) noted that a reversal of dominant subsurface flow to overland flow, the result of reduced infiltration rates and bulk density changes, caused moderate rainfall events to generate significant soil erosion in grazed areas.

Throughout the nineteenth century, the forest was burned annually at Bent Creek to repress the growth of woody understory and encourage herbaceous plant growth, specifically for the purpose of providing stock feed (Nesbitt 1941). The combination of reduced surface litter, exposed mineral soil, and soil compaction would have presumably resulted in an increase in the erosivity of rainsplash, a reduction in infiltration rates, and an increase in overland flow. Residents of Bent Creek provided Nesbitt with antidotal evidence of increased forest run-off during that time. It was reported that during precipitation events much erosional damage was inflicted on row crop areas by run-off generated in forest areas further upslope (Nesbitt 1941, 76).

Recovery

Hillslope hydrology, erosion rates, and stream flow are linked, and in highland watersheds, where higher hydrological and sedimentological connectivity between hillslope and stream channels predominates, disturbance of hillslopes often translates quickly to changes in stream conditions (Bracken and Croke 2007). However, research in Southern Appalachia has revealed that although linked, the recovery of fluvial and sedimentological processes operate over different temporal scales. The re-establishment of vegetation cover and the subsequent recovery of hillslopes following human disturbance can occur over just a few years. Research at Coweeta has demonstrated that once hillslopes are re-vegetated and stabilized, hydrological conditions return to a pre-disturbance state almost immediately. However, the reestablishment of pre-disturbance sediment yield levels occurs over a much longer time span as sediment stored close to or in-channel is gradually remobilized and moved downstream (Elliot 2006).

The Impact of Human Activity on Stream Sediment Characteristics

There is now a clear consensus that human activity has the potential to be a significant contributing factor in the modification of fluvial system processes occurring over various temporal and spatial scales, and a realization that the cultural history of watersheds must be considered in fluvial geomorphological studies (James and Marcus 2006). It is apparent that the "cultural overlay" of human activity on a fluvial system can be expressed in a number of ways including, changes in channel morphology (Trimble 1974; Wolman 1967; Jacobson and Coleman 1986; Leigh 2010; Price 2010; Scott et al. 2002), changes in stream chemistry (Scott et al. 2002), and variation in stream flow conditions (Hibbert 1967; Swank et al. 1988; Webster et al. 1982). The following discussion will focus on research aimed at identifying human impact on the sedimentological characteristics of Southern Appalachian streams.

Changes in hillslope hydrology and increased erosion rates at Coweeta resulted in lower organic content of channel sediments. Stream channel sediment in undisturbed Coweeta catchments typically contain between 40 and 60 percent organic material. Following logging operations, it was noted that the organic content dropped to less than 30 percent (Elliot 2006), which may play a significant role in stream ecology.

Simmons investigated the nature of sediment movement in North Carolina waterways in a decade long study, during the 1970's, and concluded that in the Blue Ridge, (1) the most important precipitation factors controlling sediment movement are the magnitude and intensity of rainfall, and antecedent precipitation conditions in the watershed, (2) suspended yield and storm flow increased concurrently during high magnitude precipitation events, and, (3) the majority of watershed sediment discharge occurred during storm run-off (Simmons 1993). This study illustrates the importance of rainfall events in the movement of sediment downstream, and any human activity that modifies stream flow will also indirectly modify in-channel sediment dynamics and characteristics. Although Simmons acknowledges the significance of land-use history as an important factor in sediment production, discussion was limited to contemporary land-use practices and did not address the known lag effect of sediment dynamics. Simmons called attention to the lack of research in North Carolina specifically addressing the impact of historical land-use changes and the possible impact of legacy sediments on contemporary stream sediment characteristics (Simmons 1993, 10).

In a later study conducted by Scott et al. (2002) in the upper Tennessee basin, a variety of geomorphological parameters at different scales were statistically evaluated in an attempt to identify which physical and/or chemical stream variables might be significantly related to current land-use conditions, and if so, at what scale. The general finding of the study was that streams in regions in which human impact was greater were found to be characterized by warmer water temperatures, high turbidity, lower nutrient content, and a finer substrate. The authors concluded that increased silt loading and turbidity were indicators of past land-use/disturbance and water temperature and chemistry related to recent land-use practices. However, a link between contemporary stream conditions and present land-use patterns was only possible at the regional scale, as streams respond to cumulative impacts and are in part influenced by past watershed disturbances.

In a more recent study, Price and Leigh attempted to link a selection of stream conditions to contemporary land-use patterns at the reach scale (Price and Leigh 2006). A number of morphological and sedimentological parameters were recorded and each channel reach categorized by the percent of adjacent forest cover. Statistical analysis found no significant relationship, at the reach scale, between any morphological characteristics recorded and adjacent percent forest cover. However, the relationship between percent forest cover category and channel bed particle size did prove significant. A fining of stream bed sediment, particularly of riffles, occurred along reaches in the more severely disturbed areas (70 to 80 percent forest cover), and the authors conclude that this sedimentological parameter may be the best indicator of “stream response to human activity” (Price and Leigh 2006, 158).

This very interesting snapshot of stream sediment characteristics in the Blue Ridge Mountains may support the concept of relatively high connectivity of hillslope and stream channel in highland watersheds; that the occurrence of finer sediment on modern day riffles in more disturbed areas is the result of increased fine sediment input from local hillslopes. Conversely, finer sediment on riffles of lower percent forested areas may be an artifact of earlier land-use patterns. If the area investigated in Price and Leigh's study is typical of the Blue Ridge Mountain region in general, then it can be assumed that much of what is presently forested was deforested during the early twentieth century (Hardin 2004). If so, then fining of stream beds occurred in the past. If stream bed riffles coarsened in areas that experienced full (or near full) reforestation, then we might assume that a remobilization of fine sediment occurred as local runoff and sediment production process changed. Consequently, the results of Price and Leigh's study may be indicative of a direct cause and effect relationship between contemporary sediment characteristics and adjacent land cover or, conversely, characterize a stream channel recovery process. In terms of stream channel sensitivity and sediment dynamics, an interesting question might be at what level of reforestation and hillslope stabilization do we first see the evacuation of fine sediment from, and coarsening of, adjacent stream reaches?

Clearly then some very interesting research aimed at linking the sediment characteristics of channels to land-use has been conducted in the Southern Appalachian region but in each case note has been made for the necessity of understanding past land-use change patterns, particularly when considering the sediment dynamics of fluvial systems. The lag time in sediment movement through fluvial systems increases the difficulty in partitioning observations in terms of those directly caused by present day conditions and those that may be artifacts (albeit modified) of earlier cultural activities.

Sediment Yield

Sediment yield is the measure of sediment exported by a stream at a specific location (outlet) over a defined period of time. Ideally, a total sediment yield value includes bed load, suspended load, and dissolved load measures. This is rarely achieved. Quantification of bedload and dissolved load transport is inherently difficult and costly, and as the majority of particulate movement through fluvial systems occurs as suspended load, investigations of contemporary sediment yields utilize suspended sediment yield values gained from monitored stream channels (Leopold 1966), limiting both the area that can be investigated and the time frame of investigation.

The study of sediment trapped in ponds/lakes/reservoirs has sometimes been used to determine trends in sediment yield through time at ungaged locations, over time scales from years to decades to millennia. In contrast to contemporary stream monitoring, limited to suspended load, deposited lake sediment includes the majority of bedload and a fraction of suspended load (Gottschalk 1964). Although imperfect, it is considered by some to be the best method to evaluate total particulate yield at the catchment scale (Leopold 1966). The ability of an artificial impoundment to retain and store suspended load is known as trapping efficiency and is discussed in more detail in the methods section.

Sediment Yield Factors

Sediment dynamics at the catchment scale are complex. Sediment production, storage, and transport occur over a variety of temporal and spatial scales, and as yet no simple relationship has been established between suspended sediment yield and any single controlling factor. Studies conducted in the first half of the twentieth century attempted to link sediment yield to topography, catchment area, climate, and vegetation cover in natural watersheds. Some general trends were identified but sediment yield values varied considerably (Leopold 1966).

Langbein and Schumm’s 1958 study illustrated a relationship between suspended sediment yield and precipitation. In arid and semi-arid areas, a low percent plant cover results in high suspended sediment yield although annual precipitation is low. As annual precipitation progressively increases and land cover changes from dessert scrub to grass and then forest, suspended sediment yields progressively decrease. A threshold is crossed however where precipitation is very high. In such areas vegetation cover cannot protect soil from excessive and high intensity rainfall events and suspended sediment yield increases once more. Langbein and Schumm’s general global trend is insufficient when studying any particular basin in detail, as it is not only the quantity of annual precipitation that influences suspended sediment yield, but how that precipitation is distributed in terms of frequency and intensity, and whether it produces a positive or negative feedback at the hillslope scale in terms of soil erosion rates.

Wolman quantified changing trends in suspended sediment yield for the Maryland Piedmont from the late 1700s to the late 1900s, arguing that the observed changes were related to changing land-use over the same period (Wolman 1967). Initial low suspended sediment yields associated with late eighteenth century native forest cover increased as forest was felled and row crop area increased. Suspended sediment yield then decreased slightly after 1930 when a portion of cropland was converted to forest and pasture. A short term spike in suspended sediment yield occurred around 1960, the result of urban/suburban expansion, but once land surfaces were covered with tarmac and concrete and essentially rendered inaccessible to rainfall and runoff, suspended sediment yield values quickly dropped. Wolman argued that this temporal variation in sediment load and stream flow was responsible for a cycle of stream channel aggradation and degradation.

An accumulation of studies of variously sized catchments indicates that, in general, suspended sediment yield values decrease as catchment area increases (Ritter et al. 1995). Opportunities for sediment storage in colluvial and alluvial deposits increase with catchment size, resulting in a decrease in net yield. The complexity of the relationship of sediment production, storage, and yield, at the basin scale, was demonstrated by Trimble in his study of sediment dynamics in the Driftless Area of Wisconsin (Trimble 1976, 1981, 1983, 2009). Heavy soil erosion prior to the 1930s resulted in a large amount of sediment stored in valley bottoms. The adoption of soil conservation practices since the 1930s and the resultant decrease in sediment production was expected to be reflected in a decrease in suspended sediment yield. However, suspended sediment yield from the Coon Creek Valley remained essentially the same between 1975 and 1993, as stored bottomland sediment was remobilized through an increase in channel bank erosion.

In a more recent study, Verstraeten and Poesen (2001) argue that the complexity of the interaction of variable temporal and spatial sediment dynamic processes negates the utility of catchment area as a "black box" parameter when considering basin wide sediment yield (Vertraeten and Poesen 2001, 139). Citing a lack of data for small catchments, and their importance in providing sediment to larger rivers, Verstraeten and Poesen focused on 26 small cultivated basins in Belgium. The authors attempted to correlate factors such as catchment area, mean slope, relief ratio, drainage density, land use, and soil texture with sediment yield (determined from catchment lake deposits). Using multiple regression analysis, catchment area was found to account for 64 percent of yield variability and most of the remaining variability was explained by catchment geomorphology, specifically the relief ratio.

This is not a new finding. Relief ratio, a measure of stream gradient, compares the straight line distance of drainage divide to outlet, to the difference in basin elevation and is used as a proxy for relief. Schumm and Hadley first demonstrated a linear relationship between relief ratio and suspended sediment yield in Colorado (1961). Verstraeten and Poesen's study indicates that a similar relationship holds for small basins emphasizing the need to consider basin size and basin geomorphology when comparing yields.

What the previously discussed studies demonstrate is the influence of climate, catchment size, geomorphology, and in-basin dynamics on the production, storage, and movement of sediment from hillslope to channel, and through the fluvial system. The complex and non-linear relationships between land-use and sediment yield, and rainfall/runoff and soil erosion, may preclude the development of a simple deterministic model of sediment yield at the human temporal scale. However, it has been suggested that such a model may yet be developed for catchments when considered over geological time (Hooke 2000).

Lake Based Sediment Yield Studies

Excellent and detailed reviews of the utility and necessary considerations of lake sediments in constructing trends in catchment sediment yield are to be found in Dearing and Foster (1986), and Foster (2010), and the following section is a brief adaptation of these previously published works.

Sediment entering and deposited within a lake/pond/reservoir is a net record of multiple processes occurring over a variety of both temporal and spatial scales. Sediment may be produced by hillslope erosion (topsoil and/or subsoil), bottomland erosion, the mobilization of in- and near-channel deposits, erosion of lake edges, and atmospheric fallout. To what extend any of these possible sediment sources (with the exception of atmospheric pollution) are represented within the sediment record may also be a function of internal catchment dynamics; the pathway and timing of sediment delivery to the stream channel. Successful investigations of lake sediments, requires the researcher to take all of these potential sediment sources into account.

Quantification of sediment yield trends over time scales spanning the Holocene (10 to 10^4 years), and recent decades has permitted researchers to reconstruct environmental change resulting from climate change (Dearing 1992), the geomorphological impact of human activity (Foster et al. 1986) and more fully explore the relative significance of both. In general, as the Holocene has progressed, the major cause of sediment flux in fluvial systems has transitioned from climate change to human activity.

Sediment Yield Research in the Blue Ridge

A review of data derived from over twenty years of studies in the eastern woodlands, including the Blue Ridge, by Patric et al. (1984) indicates that the average suspended sediment yield of an undisturbed forested basin is 4.9 metric tons per square kilometer per year (t km^{-2} y^{-1}). A study of changing sedimentation rates over a period of 111 years in the Fairfield Lake watershed in western North Carolina indicated an increase of several fold since the 1970s, and was attributed to modest suburban development that occurred during the same period in the watershed (Miller et al. 2005). It was presumed that the increase in sediment was derived entirely from hillslope disturbance in what is a highland watershed. An increase in watershed development and impervious surface area is expected to increase runoff, thereby increasing stream flow for rainfall events over the entire spectrum of precipitation intensity. It is possible that a portion of the sediment delivered to Fairfield Lake may not have been derived directly from surrounding hillslopes, but included remobilized legacy sediment, both colluvial and alluvial. Regardless, the Fairfield Lake study clearly indicates that even modest development, in areas of high relief, significantly impacts basin sediment dynamics. Unfortunately, although changes in sedimentation rates may indicate trends, they cannot be converted to sediment yield measures for the purpose of comparison.

Simmons did however report average annual suspended sediment yield values derived for the period between 1970 and 1979, for five categories of Blue Ridge basins; pristine (forested), forested with minor development, rural areas including agricultural and non-agricultural activities, rural areas dominated by agricultural land use, and urban. (Simmons 1993). Suspended sediment yield data was derived from sediment sampling at numerous USGS gauging stations across the region over the ten year period. The results are summarized in Table 1 and Figure 2, though it must be noted that these values have not been adjusted to account for other factors that are known to impact suspended sediment yield including, upstream reservoirs, construction, dirt roads, and channelization (Simmons 1993, 16), or past changes in land-use. Although located in a similar geological and geomorphological setting, basin catchment areas in Simmons study range from 14.1 km^2 to 3,449.9 km^2, significantly larger than either Rocky Cove Branch or upper Bent Creek and making comparison between the two studies problematic.

However, a number of conclusions were drawn from the ten year monitoring of water discharge and suspended sediment yield throughout the Blue Ridge that are relevant to the present study, (1) that there is a concurrent suspended sediment yield response to increasing and decreasing water discharge, (2) that the majority of stream sediment transport occurs during storm events, and (3) that, on average, 84 percent of suspended sediment comprises silts and sands and the remaining 16 percent is clay.

Table 1. Suspended Sediment Yield, Blue Ridge, 1970-1979 (Simmons 1993).

Basin	Condition 1970-1979	Area (km^2)	Annual SSY ($t\ km^{-2}$)
Beetree Creek	Pristine (Forest)	14.1	10.7
Cataloochee Creek	Pristine (Forest)	127.4	14.9
Nantahala River	Pristine (Forest)	134.4	20.1
West Fork Pigeon River	Moderate development	71.5	72.7
Davidson River	Moderate development	104.6	20.8
South Toe River	Moderate development	112.1	45.0
Linville River	Moderate development	172.7	38.1
East Fork Pigeon River	Agriculture	133.4	30.8
Cartoogechaye Creek	Agriculture	147.9	65.8
Mills River	Agriculture	172.7	34.6
French Broad River	Agriculture	175.9	65.8
Watagua River	Agriculture	238.5	48.5
Oconaluftee River	Agriculture	476.6	45.0
French Broad River	Agriculture	766.6	90.0
French Broad River	Agriculture	1750.8	83.1
West Fork Pigeon River	Agriculture and non-agriculture	143.2	9.3
Valley River	Agriculture and non-agriculture	269.4	90.0
Pigeon River	Agriculture and non-agriculture	344.5	18.7
Nantahala River	Agriculture and non-agriculture	373.0	14.2
South Fork New River	Agriculture and non-agriculture	531.0	128.1
Tuckasegee River	Agriculture and non-agriculture	898.7	100.3
Pigeon River	Agriculture and non-agriculture	906.5	65.8
Little Tennessee	Agriculture and non-agriculture	1129.2	86.5
Tuckasegee River	Agriculture and non-agriculture	1696.4	79.6
Hiwassee River	Agriculture and non-agriculture	1051.5	23.9
French Broad River	Agriculture and non-agriculture	2447.5	141.9
French Broad River	Agriculture and non-agriculture	3449.9	173.1
Swannanoa River	Urban	336.7	121.1

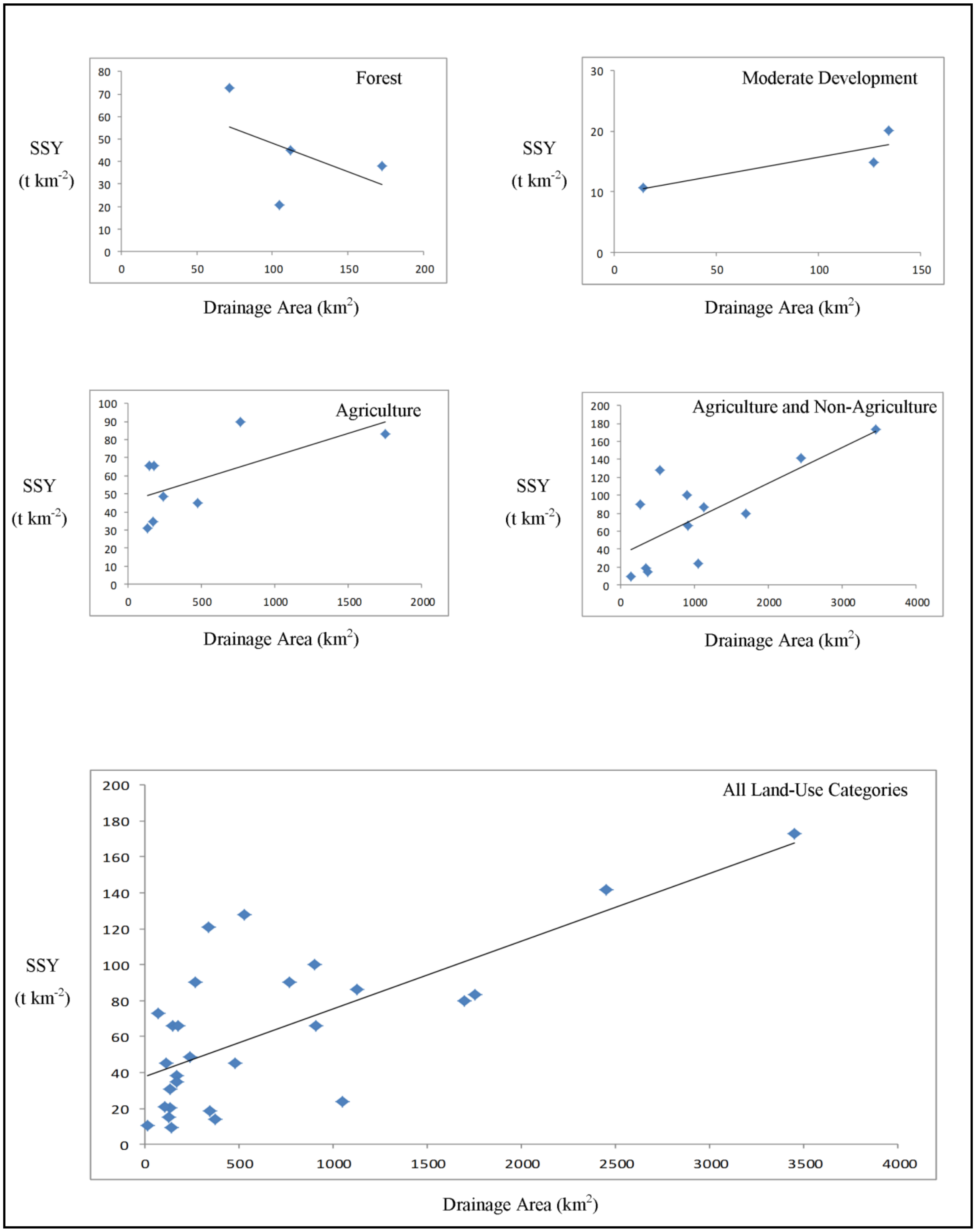

Figure 2. Suspended Sediment Yield, Blue Ridge, 1970-1979 (based on data from Simmons 1993).

However, not enough data were available to compare the impact of different land-use practices with sediment yield for the Blue Ridge region (Simmons 1993, 53).

There is a great deal of variability in suspended sediment yield for each individual land-use category. Although it was hoped that suspended sediment yield values gained from pristine catchments might provide background sediment yield values with which to compare against other basins, a number of basins characterized as agriculture and non-agriculture basins, exhibited comparable yields to forested basins.

On a regional scale it may be argued that topography is similar and climate is similar, although local precipitation can vary across the Blue Ridge, but clearly other sediment yield influencing factors must be accounted for before direct comparisons can be made simply on the basis of contemporary land-use. Additional research is required and Simmons suggests specifically targeting small low order basins to help elucidate the characteristics of headwater streams, and the importance of constructing long term records of sediment yield in order to more clearly understand trends. Finally, it should be noted that in contrast to other suspended yield studies that indicate a decrease in yield with catchment area, the data from Simmon's study, with the exception of forested basins, indicates that in the Blue Ridge, yields increase with catchment size, at least over the temporal and spatial scale of the study (Figure 2).

In a more recent and smaller study comparing observed suspended sediment yield with that generated by GIS modeling, Bolstad at al. (2006) recorded the suspended sediment yield generated by five small first and second order stream basins, over a two month period (June and July) in 2003, in the Blue Ridge of North Carolina. The basins range in catchment area from 1.32 km^2 to 16.75 km^2, and in land-use category. Table 2 summarizes the data. Only a range of suspended sediment yield values are provided by the authors; the smallest basin, Dryman Fork generating an average of 2.5 t km^{-2} yr^{-1}, and Sutton Branch, the largest basin, generating an average of 34.4 t km^{-2} yr^{-1}. Although a small data set, a strong relationship between percent forest cover and sediment yield was observed. Road density did not appear to be an influencing factor.

Table 2. Suspended Sediment Yield, 2003 (Bolstad et al. 2006).

Basin	Area (km^2)	Road density (km/km^2)	Forest (% Area)	Agriculture (% Area)	SSY (rank)
Addie Branch	5.74	0.654	100.0	0	2
Dryman Fork	1.53	4.257	100.0	0	1
Sutton Branch	1.32	1.497	72.6	26.2	5
Reed Mill	4.40	1.112	95.8	0	3
Watauga Creek	16.75	4.064	87.3	4.9	4

Note: 1 is lowest and 5 is highest suspended yield values

Only one lake based sediment yield study is available for the Blue Ridge of western North Carolina (Royall 2003). Cores taken from Deer Lake, an impoundment spanning the fifty year period between 1927 and 1977, allowed Royal to quantify the average annual sediment yield for the Wolf Branch Creek catchment, a tributary of Bent Creek. The history of land-use in the Wolf Branch Creek is very similar to both Rocky Cove and upper Bent Creeks; logging, nineteenth century farmsteads, annual forest burning and grazing, and reforestation since the early twentieth century. The average annual sediment yield of 29.7 t km^{-2} y^{-1}, over the period of record (1927 to 1977), is well above the pristine base level of 4.9 t km^{-2} yr^{-1} reported by Patric et al. (1984). Wolf

Branch Creek basin is interpreted as being in a recovery phase between 1927 and 1977, demonstrated by the continued elevation of sediment yield. The magnetic characteristics of Deer Lake sediments, used to determine trends in sediment source and sediment delivery is discussed in a later section.

Environmental Magnetism

Sediment yield, derived from lake sediments, is a net measure of sediment exiting a catchment but does not provide the researcher with insight into trends in sediment delivery and/or sediment source over time. A comparison of the magnetic characteristics of deposited sediment and catchment soils is a methodology that has proved useful in this respect.

All materials can be magnetized to some degree or other: the magnitude and specific character of magnetism of any given substance being a function of its chemical composition and structure. The magnetic classifications of naturally occurring substances, from weakest to strongest are diamagnetism, paramagnetism ferrimagnetism, and ferromagnetism. Pure iron is ferromagnetic but rarely, if ever, occurs in its pure state naturally. Rather, iron oxides and sulphides, ferrimagnetic substances, naturally occur in low concentrations in rock, soil, and sediment, and at a concentration of only 0.1 percent can mask the magnetic signature of all other types of naturally occurring magnetic minerals (diamagnetic and paramagnetic) in an environmental deposit (Lanza and Meloni 2006:89). It is the relative concentration of ferrimagnetic minerals in sediment deposits that has been used to determine trends in long term climatic studies (Robinson et al. 1995), and pollution dispersion studies (Thompson and Oldfield 1986). Identifying the relative contribution to overall magnetic susceptibility by different forms of ferrimagnetic minerals is also very informative, particularly in the study of soil formation and subsequent soil sediment dynamics.

Magnetism and Soil Erosion Studies

Ferrimagnetic minerals released through weathering of parent rock are known as primary minerals. However, it has been noted, since the mid-twentieth century, that the A-horizon of many soils demonstrate magnetic enhancement, regardless of the nature of parent material (Mullins 1977). Mullins proposed that top soil magnetic enhancement was the direct result of soil forming processes in which microbial action, in the presence of organic matter, leads to the conversion of weakly magnetic forms of iron oxide to higher magnetic forms. The resulting forms, known as secondary ferrimagnetic minerals, although microcrystalline, have been found to be associated with both the fine and coarse soil fractions (Mullins 1977; Dearing et al.1986).

In a later study, Dearing et al (1996) confirmed this mechanism for the formation of secondary ferrimagnetic minerals concluding that, (1) variation in topsoil enhancement at the regional scale is a function of the underlying geology and soil formation processes, (2) the supply of iron controls the magnitude of secondary ferrimagnetic minerals, and (3) climate is a controlling factor in the supply of iron available for conversion. Once formed, secondary ferrimagnetic minerals tend to be stable, their magnetic characteristics persisting through particulate dislocation, entrainment, transport, and deposition (Thompson and Oldfield 1986). Magnetic parameters distinguishing primary ferrimagnetic minerals from secondary ferrimagnetic minerals have been used by researchers to investigate erosion processes at the hillslope scale (Dearing et al. 1986; Royall 2001) and the catchment scale (Thomson and Morton 1979).

The variation of magnetic susceptibility values in recent sediments can be explained by one of two models. First, up-core differences reflect the changing predominance of one sediment source over a second sediment source, or secondly, fluctuations in susceptibility result from differential erosion and/or transportation of a single source. Examples of both are discussed below.

During the late 1970s, Thompson and Morton used magnetic analysis to study recent sediments deposited in Loch Lomond (Thompson and Morton 1979) in an attempt to identify trends in sediment source. Susceptibility measures were recorded for lake cores and a variety of possible sediment sources. Variation in susceptibility was linked to sediment particle size, with maxima associated with fine silts/clays and minima associated with coarser sediments, determined to be the result of differences in primary mineral concentration. The authors identified the immature soils of the catchment, containing relatively high concentrations of primary minerals, as the single source of Loch sediment and the variation in particle size/susceptibility interpreted as the result of differential erosion and transportation of surface fines, produced by land-use changes.

The magnetic mixing model has been used where changes in sediment source are believed to have occurred, particularly in catchments where A-horizon enhancement is robust and magnetically distinct from the B- and C-horizons. Stott plotted the proportion of top- and sub-soil contributions to the overall sample susceptibility and used this approach to interpret his findings from a fifty year reservoir deposit in N. W. England that was concurrent with reforestation efforts in the reservoir catchment (Stott 1986). Stott's investigations identified an up-core trend, in which secondary minerals (A-horizon) dominant in the earlier sediments were gradually replaced by primary minerals (B- and C- horizon). Rather than stabilizing hillslopes, reforestation in this catchment resulted in hillslope destabilization and gully development.

Magnetic Sediment Source Studies in the Blue Ridge

Royall's 2003 investigation of Deer Lake sediments is the single available magnetic study of reservoir deposits in the Blue Ridge of western North Carolina. Deer Lake formed when the Wolf Branch Creek sub-basin located in the Bent Creek Experimental Forest was artificially impounded between 1927 and 1977 (Royall 2003). The lake drained an area of 2.38 km^2 during a period of catchment reforestation and progressive hillslope stabilization. Royall was able to distinguish between steep upland and footslope colluviums sources, and bottomland sources on the basis of magnetic parameters. In general, upland/colluvial soils contained higher concentrations of magnetic minerals than bottomland soils. Secondly, a mixture of mineral particle size contributed to the overall susceptibility of the upland/colluvial soils, whereas the susceptibility of bottomland soils was dominated by very small magnetic grains. The magnetic parameters of Deer Lake sediment were found to be similar to those of bottomland sources. Although there are some interpretive difficulties associated with the data, this study suggests that during the period of record, bottomland sediment was remobilized as a result of channel erosion and that the sedimentological adjustment to hillslope stabilization was still in progress.

Landscape Sensitivity

The results of this dissertation will be discussed within the landscape sensitivity framework, a concept that speaks to the probability, magnitude, and rate of change occurring in any given geomorphic system in response to system disturbance, and the ability of a system to resist said change (Thomas and Allison 1993). Human activity is often considered an extrinsic factor when studying natural systems, specifically in landscape sensitivity studies. However, for the purposes of this research humans are regarded as intrinsic and cultural decisions considered a natural factor that has the capacity to change boundary conditions within any given geomorphic system.

The modified landscape sensitivity model proposed by Phillips (2009) is one in which many geomorphic concepts related to landscape change, and the framework used for evaluating geomorphic hazards, are combined and condensed into what Phillips terms the ‘four Rs’ (2009, 17); system response, system resistance, system resilience, and system recursion.

Response

The timing and rate of landscape response to a disturbance encompasses both the time between the onset of the disturbance and the onset of change, known as reaction time, and secondly, the time taken for the change to return to pre-disturbance conditions, known as relaxation time. If relaxation time exceeds the time interval between disturbance events, then the landscape will be dominated by transient forms. The transient form ratio developed by Brunsden and Thornes (1979), is modified by Philips to accommodate disturbances that occur over a period of time. Agricultural activities persisted in both Lance and Powell catchments between 1825 and 1900; a duration of 75 years. If the relaxation time, specifically how long it takes for Blue Ridge watersheds to return to pre-disturbance sediment yield levels once reforested, can be determined then it will be possible to evaluate whether contemporary landscape forms that resulted from the increase in human induced soil erosion rate are transient or persistent.

Resistance

The ability of the Lance and Powell catchments to minimize response to changes in vegetation cover is assessed in terms of strength and capacity. Soil erodibility is a measure of soil strength and Blue Ridge soils tend to be less erodibile than those of the adjoining Piedmont, a characteristic that needs to be considered when comparing Blue Ridge and Piedmont landscape responses. Secondly, the ability of a system to absorb change can be evaluated in terms of stream transport capacity, and/or hillslope/bottomland sediment storage capacity.

Resilience

A system is described as being resilient if pre-disturbance conditions are restored. For the purposes of these investigations, three sub-systems will be discussed separately in terms of their resilience following reforestation and hillslope stabilization (hillslope hydrology, soil erosion rates, and sediment yields).

Recursion

Finally, recursion requires the identification, and assessment of feedback mechanisms, whether positive or negative, on landscape response to change.

CHAPTER III

RESEARCH METHODOLOGY

Land-Use History

William A. Nesbitt compiled available archival data, oral history, and field observations in 1941, producing a nineteenth century land-use history of Bent Creek (Nesbitt 1941). Nesbitt's historical research was conducted in order to provide twentieth century foresters with a historical context to aid in interpreting twentieth century forest conditions. Although Nesbitt acknowledged the prior presence of Native Americans in the watershed, he largely assumed that all forest/vegetation modification and soil conditions noted in the early twentieth century were the result of nineteenth century Euro-American activities. Nesbitt investigated all available public records including land grants, land deeds, tax records, and Biltmore and United States Government land sale records. A watershed map illustrating lot divisions as they existed when the watershed was purchased by the United States government was created and Nesbitt provides a detailed description of land transfer for each lot beginning with the original land grants, for each lot up until the early twentieth century when Vanderbilt bought the majority of lots in the watershed. Tax records and oral history also provided information regarding the timing of land conversion, and the amount of acreage cleared, evidence of which was still clearly visible on the landscape when Nesbitt walked the property in the late 1930s. Finally, Nesbitt added the location of nineteenth century mill dams to his watershed map.

Nesbitt's discussion of Native-American lifeways and nineteenth century Euro-American lifeways is somewhat romanticized, however, his archival methodology is considered to be substantial and serves as a major source for reconstructing nineteenth century land-use in both Powell and Lance Mill catchment areas in these investigations.

Nineteenth century census data, not open to the public in 1941 and therefore unavailable to Nesbitt, were also examined (U. S. Census 1850, 1860, 1870a, 1870b, 1880). It was hoped that census data might be used to create a finer grained spatially and temporally distributed nineteenth century land-use history. Unfortunately this was not the case. The census data from outlying rural areas of Asheville were either included in the Asheville count, or identified only as 'Township No. X". It was impossible to parse Bent Creek data with the exception of the 1870 agricultural schedule. Bent Creek Township was tallied as a separate entity in 1870 providing a snapshot of agricultural activities and land-use between1869-1870 across the watershed.

Prehistoric occupation and land-use was investigated. Members of the Cherokee nation resided in the Bent Creek watershed up until their forced removal in 1838. The land-use patterns of the Cherokee and earlier Native Americans, both in the Bent Creek watershed and the Blue Ridge region in general, provide useful information regarding antecedent conditions of the watershed prior to Euro-American settlement. These data were derived from geomorphological and archaeological investigations conducted throughout the Blue Ridge region.

Sediment Yield Reconstruction

Sediments accumulating in natural lakes and artificial impoundments have been widely used to establish measures of contemporary and historical sediment yield (Trimble 1983; Foster et al. 1988; Foster et al. 1990; Royall 2003). Sediment yield reconstruction at Powell and Lance Mills was accomplished by determining mineral sediment mass adjusted for dam trap efficiency.

After identifying the location of the dam, a datum was established at each pond site and arbitrarily assigned N1000 W1000. A north-west 15 m grid was created over each pond's sediment surface and the sediment thickness at each grid intersection, and additional grid points, was determined by augering. All sediment cores were returned to the laboratory for additional analysis. A total of 25 cores was excavated at the Powell Mill pond site and a total of 19 cores was excavated at the Lance Mill pond site.

Total sediment volume in each pond was determined by interpolating sediment thickness surfaces from bank exposure and augering data using Surfer software (Golden Software, Inc. 1999). Loss-on-ignition analysis was conducted on 2 cc samples taken from mill pond strata in four channel exposures at each pond location (Dean, 1974). Each sample was heated at 100° C for one hour to remove moisture, and then heated at 550° C for one hour to combust all organic matter. Mass differences before and after each treatment were used to determine both dry bulk density (dBD) and mass of combustible organic matter for each sediment sample.

An averaged dry bulk density value for each pond site was used to convert pond sediment volumes to pond mineral masses. Each pond mineral mass was adjusted for dam trap efficiency and an average annual sediment yield calculated, expressed in metric tons per square kilometer per year (t km^{-2} y^{-1}). Of the three variables used to quantify sediment yield (i.e., sediment volume, dBD, and trap efficiency), trap efficiency is the component with the potential for highest uncertainty (Trimble and Carey 1990; Verstraeten and Poesen 2002).

Trap Efficiency

Interest and early research in reservoir trap efficiency arose in the engineering community in response to impoundment design demands. A variety of empirical models were developed in which trap efficiency was described as a function of one or more catchment/basin parameters. The earliest models related the ratio of pond capacity/watershed area (C/W), to trap efficiency (Brown 1943). This model was quickly abandoned as it does not take into account the changing sediment dynamics associated with increasing catchment area. A second criticism of the C/W model focused on its inability to account for variation in water retention time. Lake/pond sedimentation is a function of water retention time expressed as the ratio of pond capacity to inflow (C/I). The C/I ratio for two ponds, similar in every way with the exception of annual precipitation, will differ considerably.

Brune's C/I model, first published in 1953, continues to be one of the most popular methods used to calculate trap efficiency for normally ponded reservoirs. In unmonitored basins, inflow can be attained from United States Geological Survey (USGS) Annual Runoff Maps and pond capacity determined by bathymetric analysis. Brune constructed his model from data derived from 40 normally ponded reservoirs and 4 others, with catchments ranging in area from 0.09 km^2 to 478,111.8 km^2 (Brune 1953). The high frequency and wide distribution of small ponds throughout the United States prompted Heinemann's study, in which data derived from 20 farm ponds with drainage areas of less than 38.8 km^2 were used to construct a trap efficiency model (Heinemann 1981). His model also uses the C/I ratio, and resulted in a similar trending curve to that of Brune's. However, sediment yield values are less, leading Heinemann to conclude that sediment yield is sensitive to catchment area in small watersheds.

Later models increased in sophistication as they incorporated reservoir hydraulics and/ or, the effect of the sediment cascade through a series of reservoirs, into sediment yield calculations (Churchill 1948; Trimble and Bube 1990). It should be noted that only data from medium and large reservoirs were used in these later models. Secondly, these models require input data, specifically pond water velocity and/or pond discharge that is not available for nineteenth century lakes/ponds, rendering them inadequate for the purpose of the present study. Verstraeten and Poesen have more recently concentrated their efforts specifically towards increasing the accuracy of trap efficiency modeling of small ponds (Verstraeten and Poesen 2000, 2002). Again, however, the input data required is not available for nineteenth century lakes/ponds. The limited data available for nineteenth century lakes/ponds requires the use of either Brune's or Heinemann's trap efficiency model.

Pond capacity and annual inflow were reconstructed for both study sites. Pond capacity was interpolated using Surfer. Annual inflow was quantified by multiplying catchment area by the annual runoff value identified on the USGS runoff map (Gerbert et al. 1987). However, there are additional factors that influence trap efficiency including, particle size distribution, outlet location, and the non-stationary nature of trap efficiency.

Particle size distribution is related to catchment soil texture. The majority of soils in Bent Creek Forest are classified as sandy loams or loamy sands; coarse textured (Webb Soil Survey 2012). It might be expected that trap efficiency will be higher in the study ponds compared to similar ponds located in lowland catchments in which silts and clays predominate.

Outlets of small nineteenth century mill ponds were typically located at the top of the dams, drawing the highest quality water from pond surfaces. Even if density currents formed in such small ponds, a possibility during high intensity events, bed load sediment would not be lost through basal outlets.

In the Blue Ridge region, the majority of sediment is moved through the fluvial system during rainfall events (Simmons 1993). Variation in event intensity will result in trap efficiency variation. It is during high energy flows that stream bedload is transported, coarser material is entrained as suspended load, and discharge increases. Trap efficiency under these circumstances is expected to be lower. Higher trap efficiencies are expected to be associated with lower energy events. Also, as pond sedimentation progresses, capacity decreases, reducing the C/I ratio which in turn reduces trap efficiency. Although the non-stationary nature of trap efficiency is noted, presently there is no method to account for temporal variation.

Although Heinemann argues that Brune’s model may overestimate trap efficiency in the case of small catchments, the relatively coarse texture of Bent Creek soils favors the use of Brune’s model as the model envelope considers sediment source texture (Figure 3).

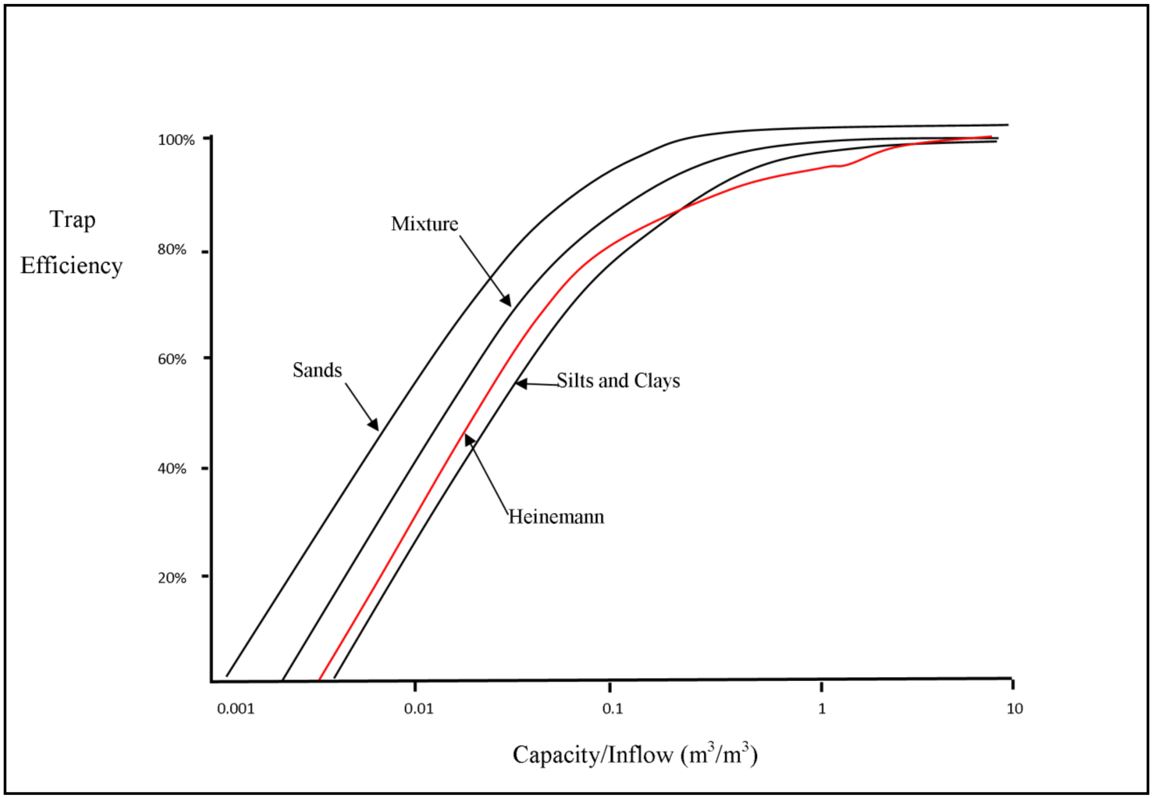

Figure 3. Brune’s and Heinemann’s Trap Efficiency Models.

The outer envelope (coarse sediment) of Brune's trap efficiency model is expressed by the following equation (Harbor et al. 1997):

$$\textbf{Where } C/I < 0.02$$
$$\textbf{Trap Efficiency (\%)} = 128 - (6.59\ |\ln C/I|^{1.52})$$

Sediment Source

Field Methods

Four stream bank exposures within each of the two study ponds were excavated and described in terms of Munsell color, field texture, and sedimentary structure. Volume magnetic susceptibility (k_{lf}) was measured at 1 cm intervals in all eight channel profiles, and 10 cm^3 sub-samples were taken at 2 cm intervals from each profile for more detailed laboratory-based mineral magnetic measurements. Volume susceptibility was measured in the field using the Bartington MS2K sensor designed for stratigraphic sections. Bulk samples were collected from each field recognized stratum for laboratory analyses of particle size and organic matter content.

For the purpose of identifying sediment source, the catchment area of each pond was delineated and soil pits excavated in both bottomland and hillslope locations. Bottomland was characterized by low gradient, overbank sandy deposits adjacent to stream channels. Hill slopes were sub-divided into gentle-slope (less than 30 percent slope) and steep-slope categories (greater than 30 percent slope), and all were characterized by stoney sandy loams and loamy sand soils (Webb Soil Survey 2012). A total of 15 pits was excavated in the Powell Mill catchment, and a total of 14 pits was excavated in the Lance Mill catchment. Volume susceptibility was recorded at 1 cm intervals down profile in each soil pit, and each profile was sub-sampled using 10 cm^3 pots at 2 cm intervals for laboratory-based magnetic analysis.

Laboratory Methods

All 10 cm^3 pots were returned to the laboratory and air dried. Mass specific susceptibility (X^{lf}), and frequency dependent susceptibility (k^{fd}), were determined for all 10 cm^3 magnetic pot samples using the Bartington MS2B sensor. Saturation isothermal remnant magnetization (SIRM) was measured for subsamples by placing each 10 cm^3 pot in a 1 tesla magnetic field and recording remnant magnetism in a Molspin minispin fluxgate magnetometer. Trends in each magnetic parameter were plotted for all soil pits and selected channel profiles.

Mass adjusted susceptibility (X_{lf}) measures the concentration of magnetic minerals within a given sample. Frequency dependent susceptibility (k_{fd}) is a measure of the proportion of a magnetic signature that can be ascribed to superparamagnetic grains (SP), also known as secondary grains. A k_{df} value between 2 and 10 percent indicates a mixture of SP grains and non-SP grains, and when k_{fd} > 10 percent almost all the magnetic signal is likely derived from SP grains. Saturated Isothermal Remnant Magnetism (SIRM) in contrast, does not measure the magnetism produced by SP grains but instead measures the concentration of primary grains; magnetic minerals derived directly from the weathering of bedrock. Being able to distinguish primary from secondary grains is important as soil development processes is one way in which SP grains can be produced, and soil A-horizons often exhibit elevated susceptibility values and/or k_{fd} values owing to the magnetic enhancement produced by SP grain concentrations.

The deepest channel profile of each mill pond deposit was selected for sediment source analysis. Particle size analysis of bulk samples collected from Profile1 at Powell Mill and Profile 1 at Lance Mill was conducted using the hydrometer method. The sand component of each sample was later hand sieved using standard 2 mm, 0.5 mm, 0.25 mm, and 0.125 mm brass laboratory sieves. The combination of data derived from hydrometer and sieving resulted in seven categories of grain particle size; clay (<3.9µm), fine silt (3.9-62.5µm), coarse silt/very fine sand (62.5-125µm), fine sand (125-250µm), medium sand (0.25-0.5 mm), coarse sand (0.5-1 mm), and very coarse sand (1-2 mm).

Sediment Delivery

Mass failures, although dominant sediment sources in some western U.S. mountainous environments, are less common in the southern Blue Ridge (Eschner and Patric, 1982). Thus in the absence of stratigraphic indicators of catastrophic events, more gradual surficial erosion is a better explanation for sediment yield rates. Estimates of gross surficial erosion synchronous with pond ages were determined using the Universal Soil Loss Equation (USLE) (USDA 1978). USLE is determined thus:

$$\mathbf{A = R \times K \times LS \times CP}$$

Where:

A = annual soil loss ($t\ km^{-2}\ y^{-1}$)

R = rainfall erosivity factor ($MJ\ mm\ ha^{-1}\ h^{-1}\ yr^{-1}$)

K = soil erodibility factor (t ha h ha^{-1} MJ^{-1} mm^{-1})

LS = topography factor (dimensionless)

C = cropping and management factor (dimensionless)

P = conservation practices factor (dimensionless)

USLE, an empirical model designed to predict long term rill and inter-rill erosion rates of disturbed slopes, does not include evaluations of sediment produced by gullying, stream bank erosion, or mass movement. USLE was calculated using the ArcGIS raster calculator, and required the construction of three thematic raster layers. The watershed was delineated and extracted from a mosaic of five LiDAR tiles (FMIS 2012). Slope length and gradient were combined (topographic factor) and derived from the extracted catchment using the Mitasova equation to produce an LS factor raster layer (Mitasova et al. 1996). A map of the spatial distribution of soil erodibility values for the study area was downloaded (Webb Soil Survey 2012), digitized, and converted to raster format to produce a K factor raster layer. Finally, Nesbitt's description of the location of cleared areas, row crop rotation, and plow techniques were used to derive C and P values from standard tables (USDA 1978, GaSWCC 2000). These values were combined, digitized and converted to produce a CP raster layer. The rainfall erosivity constant (R) for the study area was derived from published USGS maps (Gerbert et al. 1987). The three thematic layers (SL, K, and CP) and constant R were combined in ArcGIS raster calculator to produce an USLE layer. The channel network was removed resulting in a final raster layer in which USLE values were calculated per grid cell located on catchment slopes. Gross annual soil loss was obtained by totaling grid cell values. Sediment yield divided by gross annual soil loss gives the sediment delivery ratio.

Fine Sediment Remobilization

Large volumes of fine grained sediment degrade stream habitat in highland regions. Abandoned nineteenth century mills and their associated pond sediments are ubiquitous throughout Southern Appalachia. It is of interest to determine if remobilization of pond sediment has been a significant source of fine sediment in upland areas since the abandonment of water power. An average percent value of fine silt and clay was derived from particle size analysis conducted on bulk sediment collected from the deepest profile at each pond location.

Channel cross-section surveys of reaches of incised pond sediment were used to determine the volume of pond deposit evacuated at each study site. This volume was multiplied by the averaged dry bulk density to obtain mineral mass. Mineral mass was multiplied by the fine silt/clay percentage and divided by the number of years since dam failure, providing an average medium-term estimate of wash-load export.

CHAPTER IV

RESULTS

The results of the field, laboratory, and archival investigations are presented in this chapter. The two mill ponds and their respective catchments are detailed separately. The framework of the two individual pond discussions is the same in that each begins with a description of nineteenth century land-use, followed by a sediment yield analysis, a sediment source analysis, USLE soil erosion modeling, and finally an estimate of the fine particulate mass of pond sediment that has been evacuated as wash-load is presented.

Archival Research

William A. Nesbitt compiled a history of the Euro-American settlement of the Bent Creek Experimental Forest in 1941 with two goals in mind: to provide a contextual tool for foresters to use when interpreting early twentieth century forest conditions; and secondly, as a window on regional rural nineteenth century life. Nesbitt's methods and sources are outlined in Chapter 3, and as they are considered reliable, the following section is largely a summary of Nesbitt's publication (Nesbitt 1941), beginning with a general description of nineteenth century land-use in Bent Creek as a whole, and then moving on to a detailed description of land-use in the two mill pond catchments.

Nineteenth century United States census data, not available to Nesbitt in 1941, were also researched. Unfortunately, for most census years, surrounding rural areas were aggregated with the Asheville record, and it was therefore impossible to isolate Bent Creek data. The single exception was 1870, in which data were recorded at the township level. The 1870 agricultural schedule provides a snapshot of rural life in the Bent Creek watershed as a whole.

In 1870, 13 percent of Bent Creek watershed was described as improved land (Table 3), which included all land under cultivation, fallow fields, orchards, and areas cleared for grazing. The majority of the land in the watershed however (83 percent) was classified as woodland, and the remaining 4 percent described as unimproved (abandoned fields and woodland). The relative proportions of different land-use in the Lance Mill Catchment at the end of the nineteenth century was almost identical to Bent Creek as a whole, with 13 percent described as "cleared" and the remaining 87 percent described as "woodland". Powell Mill catchment varied in that a larger portion (i.e., 35 percent) was described as "cleared" at the end of the nineteenth century (Nesbitt 1941). Across the Bent Creek watershed in 1870, corn was the dominant row crop, followed by wheat and small grains such as rye, and oats. Sheep and swine were the preferred stock.

Nineteenth Century Settlement of Bent Creek

The original land grant, encompassing most of the Bent Creek watershed was granted to Abraham Randals in February 1800. Settlement of the area began almost immediately and it is estimated that between 1795 and 1900 approximately 104 homesteads were established in the watershed. During the first half of the nineteenth century forest was cleared for cultivation and home/farm construction, but not harvested for commercial purposes. According to Nesbitt, the best timber was removed from many lots during the farm building phase. The practice of land cultivation throughout Bent Creek was similar. First, forest trees were girdled three years in advance of plowing. During this three year period roots rotted, branches and bark dropped, and eventually logs fell to the ground. Logs not retained and used for domestic purposes, were burned. Bent Creek inhabitants used a bull-tongue plow and a three year crop rotation of corn, wheat or rye, then fallow. According to Nesbitt, nineteenth century soil conservation practices were evident in 1941. Most farmers engaged in contour plowing, and some built check dams, diversion ditches, placed brush in gullies, and terraced hillslopes.

Stock raising was very important in this region, providing household meat and surplus for market sale. The 1870 agricultural census for Bent Creek details both the annual total (1879-1880) crop and stock production of 126 homesteads (U. S. Census 1870). The average farm earned $56.00 from hog sales, the 2005 equivalent of $798.00 (Economic History Services 2005).

Until the enclosure act of 1885 all stock was released to graze throughout the watershed between May and October. To increase grazing opportunities for hogs, sheep, cattle, and goats, the woods were burned annually during the winter months. According to Nesbitt, annual burning would likely have resulted in a reduction of soil chemical and humus content, which in turn increased soil erodibility, although no surficial evidence of forest erosion was noted in 1941. However, anecdotal evidence indicates that increased runoff from such managed woodland increased soil erosion in downslope fields.

Table 3. Bent Creek 1870 Agricultural Census.

Item	**Amount/Value**		**Item**	**Amount/Value**
Improved land	2,356 acres (13%)		Wool	1,442 lbs
Woodland	14,353 acres (83%)		Peas and Beans	71 bushels
Unimproved land	558 acres (4%)		Irish Potatoes	1,396 bushels
			Sweet Potatoes	375 bushels
Horses	101		Orchard	868 dollars
Mules and asses	52		Butter	8,215 lbs
Milk cows	192		Cheese	150 lbs
Working oxen	46		Hay	77 tons
Other cattle	209		Grass	30 bushels
Sheep	1,172		Flax	33 lbs
Swine	1,182		Molasses	1,016 gallons
			Bee Wax	129 lbs
Winter wheat	985 bushels		Bee Honey	536 lbs
Rye	1,789 bushels		Forest Products	307 dollars
Corn	15,180 bushels		Home Manufacture	2,620 dollars
Oats	2,058 bushels		Stock sold/slaughtered	7,070 dollars
Barley	48 bushels			
Buckwheat	106 bushels			
Tobacco	1,661 bushels			

The practice of land cultivation throughout Bent Creek was similar. First, forest trees were girdled three years in advance of plowing. During this three year period roots rotted, branches and bark dropped, and eventually logs fell to the ground. Logs not retained and used for domestic purposes, were burned. Bent Creek inhabitants used a bull-tongue plow and a three year crop rotation of corn, wheat or rye, then fallow. According to Nesbitt, nineteenth century soil conservation practices were evident in 1941. Most farmers engaged in contour plowing, and some built check dams, diversion ditches, placed brush in gullies, and terraced hillslopes.

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The demand for lumber increased after the Civil War and it was during the second half of the nineteenth century that some remaining forested areas became the focus of intense, if selective, logging operations. A variety of forest products including fuelwood, poles, posts, pine tar, charcoal, shingles/shakes, and sawed timber were produced in Bent Creek for the Asheville market.

Nineteenth Century Land-Use in the Powell Mill Catchment

The total planar area of the Powell Mill catchment is 1.7 km^2, and seven lots are located within the catchment area (Figure 4). Four lots remained largely wooded throughout the nineteenth century (lots, 2, 3, 4, and 5), but larger portions of lots 6, 7, and 8 were cleared and used for cultivation at different times during the century (Table 4). Ninety- two acres (0.4 km^2), predominantly along ridgetops, were cleared prior to the Civil War and the remaining 63.7 acres (0.2 km^2), located on lower and gentler sloping areas, were cleared between 1865 and 1890.

Both the location and timing of land clearance is relevant to this investigation. The location of cleared land, more specifically, the degree of connectedness between cleared land and stream channels has a direct impact on stream sediment yield. Sedimentation from soil erosion, in some cases, may only be transported to lower slopes to be stored for variable periods of time. The timing of land clearance, specifically in relation to the functioning period of Powell Mill is also significant. With the exception of the 26.5 acres cleared in lot 6 in 1890, cultivation was initiated prior to the construction of Powell Mill. The sediments trapped behind the dam do not therefore represent the earliest record of disturbance (with the exception of lot 6), but instead provide a 15 year window into ongoing sediment delivery and yield processes in the catchment.

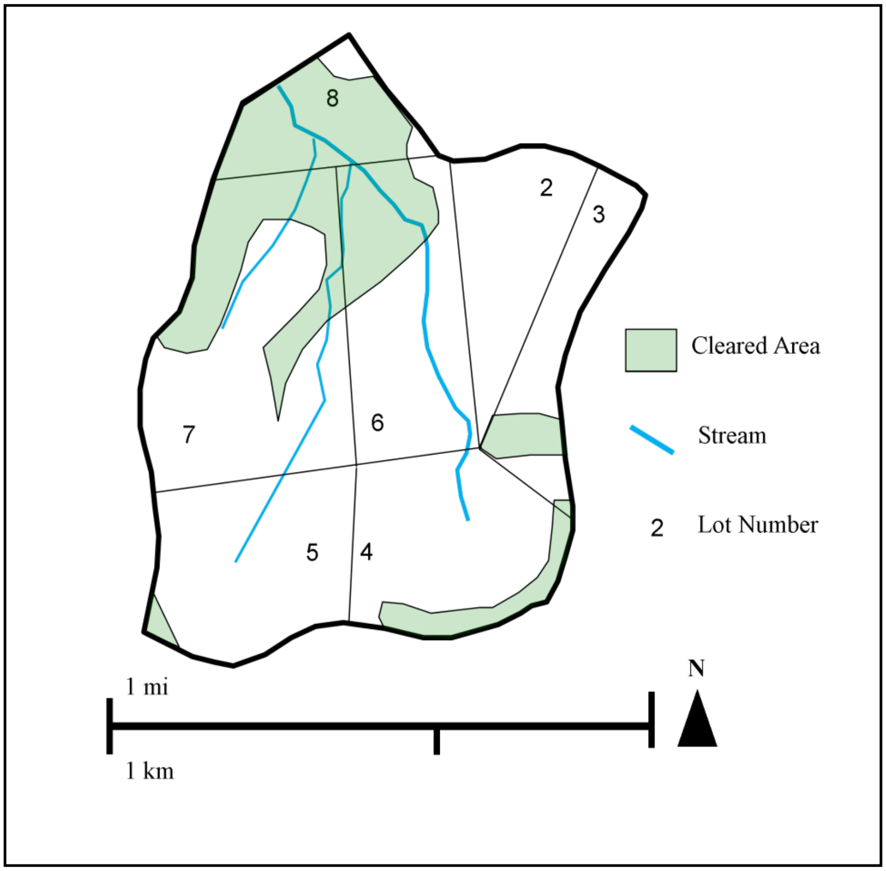

Figure 4. Nineteenth Century Land-Use, Powell Mill Catchment.

Table 4. Cleared Acreage, Powell Mill Catchment.

Lot	Acres Cleared	Date	Comments
2	0	n/a	n/a
3	32.6	1825	n/a
4	13.5	1840	n/a
5	6	1825	n/a
6	26.5	1890	n/a
7	52	1825	n/a
8	37.2	1865	n/a
TOTAL	**167.8**		

Powell Mill Pond Sediment Yield Analysis

Sediment Mass

Figure 5 illustrates the location of the nineteenth century dam, contemporary channel, extracted cores, and four channel profiles at the Powell Mill pond site. Evidence of pond sedimentation was present in 16 of the 25 cores extracted at the site. The remaining nine cores exhibited normal soil profile characteristics and were considered to be external to the pond. The true depth of each core was recorded by inserting a solid measuring tape into the core void, and the length of each core then adjusted to compensate for compression. The 1880 pre-pond surface was identified in the 16 pond cores, and mill pond sediment depth determined. Pond sediment depth ranged from 0.33 m to 1.18 m. The pond sediment depth, noted in each of the four channel profiles excavated, was also included in the sediment volume analysis. Table 5 details pond sediment depth at all core and channel profile locations.

Pond sediment was characterized by alternating horizontal layers of unconsolidated sediment ranging in particle size from silt/clay through coarse sand (Figure 6). The nature of the 1880 pre-pond surface varied across the study area and included, channel gravel, dark colored over-bank deposited sand containing plant macrofossils, and highly oxidized orange silty sand, each representing a distinct pre-pond depositional environment.

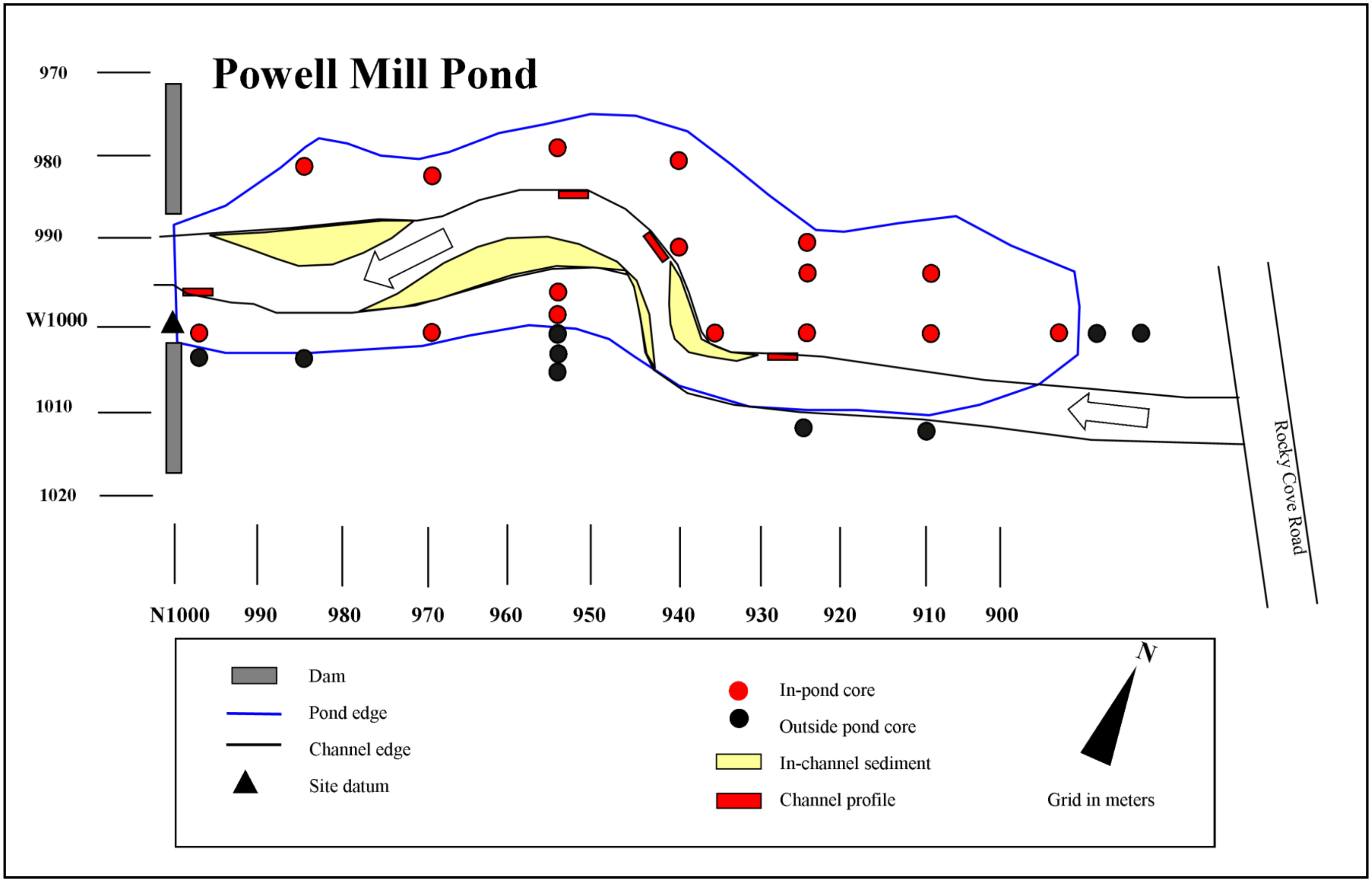

Figure 5. Powell Mill Site Map.

Table 5. Powell Mill Pond Sediment Depths.

Description	North	West	Sediment depth (m)*	Pond Deposit
Core 1	995	1000	n/a	No
Core 2	995	1002	n/a	No
Core 3	995	1004	n/a	No
Core 4	995	998	0.72	Yes
Core 5	955	996	0.85	Yes
Core 6	936	1000	0.79	Yes
Core 7	925	1000	1.02	Yes
Core 8	910	1000	0.75	Yes
Core 9	895	1000	0.69	Yes
Core 10	885	1000	n/a	No
Core 11	910	992.5	n/a	No
Core 12	940	990	0.67	Yes
Core 13	940	980	0.98	Yes
Core 14	955	977	0.87	Yes
Core 15	970	985	1.12	Yes
Core 16	985	980	1.18	Yes
Core 17	970	1000	0.47	Yes
Core 18	985	1003	n/a	No
Core 19	890	1000	0.33	Yes
Core 20	925	993	0.63	Yes
Core 21	910	1011.5	n/a	No
Core 22	925	1011	n/a	No
Core 23	998	1004	n/a	No
Core 24	998	1000	1.00	Yes
Core 25	925	991	0.83	Yes
Profile 1	996	998	1.91	Yes
Profile 2	955	984	1.12	Yes
Profile 3	942	990	0.61	Yes
Profile 4	926	1002	0.57	Yes

* adjusted for core compression

Figure 6. Pond Sediment, Profile 1, Powell Mill.

The first step in determining the location of the edge of the pond was by using core data. The furthest upstream evidence of pond sediment occurred at a surface elevation of 1.38 m above datum. The elevation of the top of the dam, as evidenceby dam remains on either hillslope, is 1.40 m above site datum, supporting core evidence. It is unlikely that a longitudinal gradient existed across the surface of such a small pond and therefore, the core determined elevation of 1.38 m, in conjunction with non-pond core locations was used to determine the location of the pond edge.

Pond sediment depth at each core and channel profile location, in addition to numerous pond edge grid points (zero depth) comprised the input database for the Golden Software Surfer program. An isopach map, illustrated in Figure 7, was produced in Surfer from which pond sediment volume was calculated. The volume provided by Surfer includes the non-mineral sediment component including water and organic material in addition to the mineral component and must therefore be adjusted using the dry bulk density to attain a measure of the total mineral mass. Table 6 details the averaged dry bulk density used for the Powell Mill site. The total mineral mass of pond sediment impounded at Powell Mill is given by:

$$\mathbf{M = V_{ps} \times dBD}$$

$$\mathbf{= (1{,}218 \times 10^6)\ cm^3 \times 0.91 g\ cm^{-3}}$$

$$\mathbf{= 1{,}108 \times 10^6\ g}$$

$$\mathbf{= 1{,}108\ metric\ tons\ (mt)}$$

where:

Vps = volume of pond sediment (cm^3)

dBD = dry bulk density (g cm^{-3})

M = mineral mass (mt)

Trap Efficiency

Not all sediment moving through a fluvial system is trapped behind an impoundment. It is expected that almost 100 percent of bedload is retained whereas a portion of suspended load is retained, as rates of suspended load deposition are a function of water residence time, particulate settling velocity, and pond hydraulics. The portion of suspended sediment retained by an impoundment is defined as trap efficiency and is expressed as a percentage. A full discussion of the variety of trap efficiency models is presented in Chapter 3. The capacity/watershed area model is considered inadequate (Brown 1943), and models requiring unavailable input data cannot be applied (Trimble and Bube 1990, Verstreaten and Poesen 2002). The upper envelope of Brune's capacity/inflow model is used to determine the trap efficiency of both Powell and Lance Mill dams.

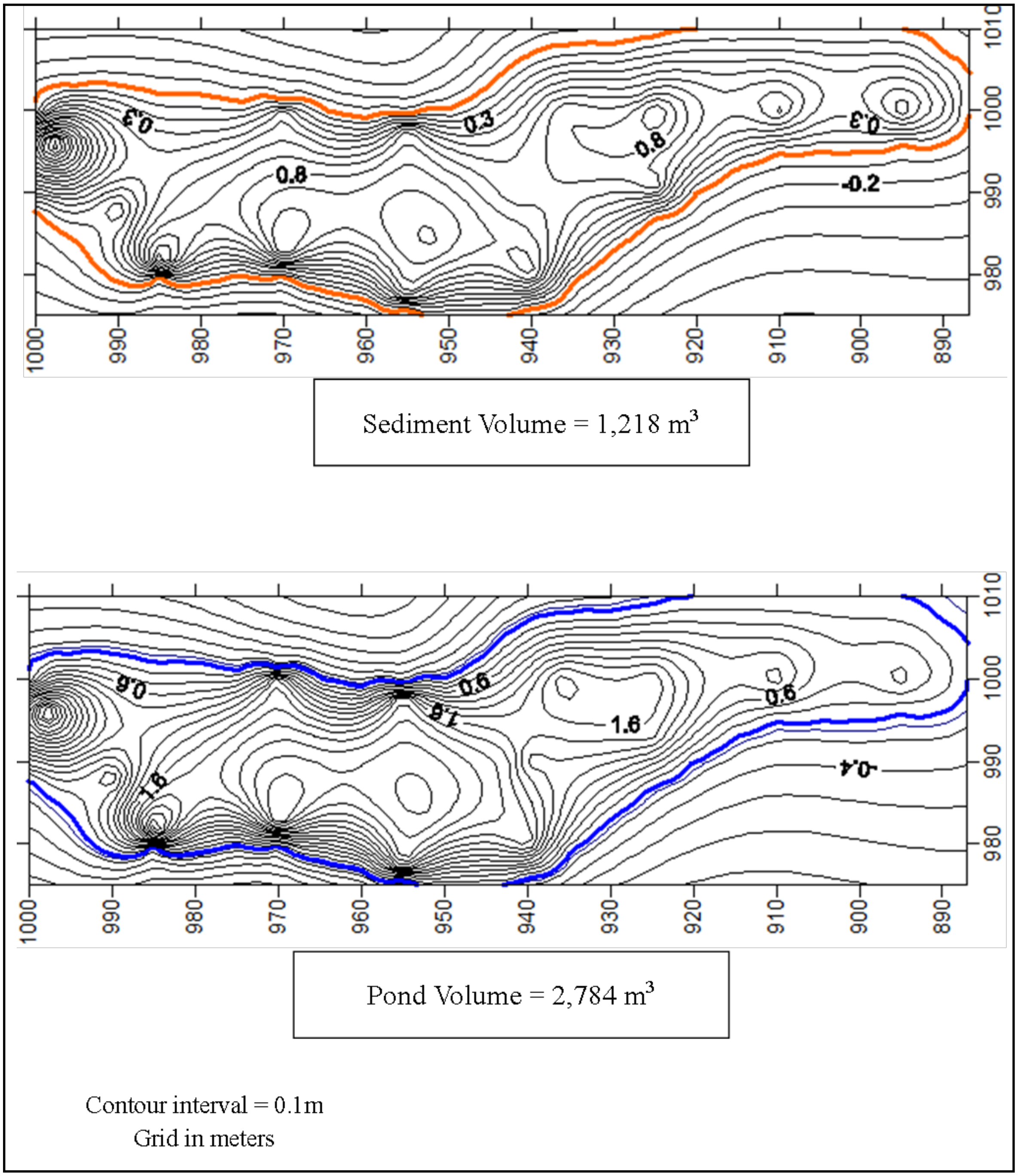

Figure 7. Sediment and Pond Depths, Powell Mill.

Table 6. Average Dry Bulk Density, Powell Mill.

	Profile 1	Profile 2	Profile 3	Profile 4
Horizon	**dBD(g cm^{-3})**	**dBD(g cm^{-3})**	**dBD(g cm^{-3})**	**dBD(g cm^{-3})**
1	0.97	1.06	1.18	1.08
2	0.93	0.99	0.91	0.99
3	0.85	0.63	0.91	0.99
4	0.98	0.79	0.62	1.14
5	0.62	0.68	0.90	1.10
6	0.68	0.76	0.88	1.08
7	0.92	0.69	1.13	1.12
8	0.93	0.81	0.89	0.63
9	0.62	0.85	1.00	1.06
10	0.60	1.05	1.19	
11	0.79	0.78	1.30	
12	0.74	1.00		
13	0.50	0.73		
14	0.67	0.64		
15	0.61	0.70		
16	0.60	1.13		
17	0.64	1.14		
18	0.66	1.27		
19	0.72	0.85		
AVERAGE	**0.74**	**0.87**	**0.99**	**1.02**
Site Average = 0.91 g cm^{-3}				

Pond Capacity

The pond capacity and annual inflow must both be quantified for use in Brune's Mill pond edge, also delineates the maximum elevation of the pond surface. Table 7 details the total depth of both sediment and water for all pond core locations and channel profiles. Total depth at each core and channel profile location, in addition to numerous pond edge grid points (zero depth) comprised the input database for the Golden Software Surfer program. Figure 7 illustrates the isopach map interpolated by Surfer and the total pond volume calculated.

Annual Inflow

Annual inflow to the pond is quantified by multiplying the catchment area by the USGS average annual runoff value for the Bent Creek catchment (Gerbert et al. 1987).

$$\mathbf{I = R_{AA} \times A_c}$$
$$\mathbf{= 0.46\ m \times 1{,}755{,}867\ m^2}$$
$$\mathbf{= 807{,}699\ m^3}$$

where:

I = annual inflow (m^3)

R_{AA} = average annual runoff (m)

A_c = catchment area (m^2)

Thus, the capacity/inflow ratio is:

$$\mathbf{2{,}784\ m^3/807{,}699\ m^3 = 0.003}$$

Quantification of trap efficiency along the upper envelope of Brune's model can be mathematically expressed as (Harbor et al. 1997):

$$\mathbf{TE_{ue} = 124 - (6.59 \times l\ lnC/I\ l^{1.52})}$$

$$\mathbf{= 124 - (6.59 \times l\ ln0.003\ l^{1.52})}$$

$$\mathbf{= 28\ \%}$$

where:

TE_{ue} = upper envelope trap efficiency value (%)

Sediment Yield

Sediment yield is expressed in metric tons, per square kilometer, per year (t km^{-2} y^{-1}). Using a trap efficiency of 28 percent over a period of 15 years, average annual sediment yield of the Rocky Cove Branch sub-basin between 1880 and 1895 is:

$$\mathbf{SY_{AA} = \frac{(M * TE) / A_c}{T}}$$

$$\mathbf{= \frac{(1{,}108 * 28\ \%) / 1.7\ km^2}{15\ years}}$$

$$= 155\ t\ km^{-2}\ y^{-1}$$

Where:

SY_{AA} = average annual sediment yield (t km^{-2} y^{-1})

M = mineral mass (mt)

TE = trap efficiency (%)

A_c = catchment area (km^2)

T = time (y)

Table 7. Sediment and Water Depths at Core and Channel Profile Locations.

Description	**North**	**West**	**Sediment Depth(m)**	**1880 Surface**	**Pond surface**	**Total Depth (m)**
				elevation(m)*	elevation(m)*	
Core 4	955	998	0.72	-0.66	1.38	2.04
Core 5	955	995	0.85	-0.83	1.38	2.21
Core 6	936	1000	0.79	-0.53	1.38	1.91
Core 7	925	1000	1.02	-0.38	1.38	1.76
Core 8	910	1000	0.75	0.26	1.38	1.12
Core 9	895	1000	0.69	0.69	1.38	0.69
Core 12	940	990	0.67	0.28	1.38	1.10
Core 13	940	980	0.98	-0.60	1.38	1.98
Core 14	955	977.5	0.87	-0.87	1.38	2.25
Core 15	970	982.5	1.12	-1.47	1.38	2.85
Core 16	985	981	1.18	-1.83	1.38	3.21
Core 17	970	1000	0.47	-0.25	1.38	1.63
Core 19	890	1000	0.33	1.05	1.38	0.33
Core 20	925	993	0.63	-0.10	1.38	1.48
Core 24	998	1000	1.00	0.00	1.38	2.38
Core 25	925	991	0.83	0.42	1.38	0.96
Profile 1	998	996	1.90	-2.11	1.38	3.49
Profile 2	952	984	1.12	-1.23	1.38	2.61
Profile 3	942	990	0.61	-0.47	1.38	1.85
Profile 4	927	1002	0.57	0.07	1.38	1.31

* elevation relative to arbitrary site datum

Powell Mill Pond Sediment Source Analysis

Before investigating mill pond sediment deposits for evidence of trends in sediment source, it must first be established that (1) bottomland sediment is magnetically distinct from slope sediment, and (2) that topsoil and subsoil can be distinguished from one another in the Mill pond catchment. A total of fifteen soil pits were excavated upstream of Powell Mill pond; four in bottomland over-bank deposits, six in gentle-sloping areas, and five in steep-slope areas (Table 8 and Figure 8).

Table 8. Location of Soil Pits Excavated in Powell Mill Catchment**.**

No.	Easting*	Northing*	Description	Geology
1	354608	3927733	steep slope	Metasiltstone
2	354626	3927734	steep slope	Metasiltstone
3	354032	3927454	steep slope	Metagraywacke
4	354076	3927476	steep slope	Metagraywacke
5	353684	3928329	steep slope	Schist
6	353686	3928324	bottomland	Metagraywacke
7	354369	3927609	gentle slope	Metagraywacke
8	354158	3927785	gentle slope	Metagraywacke
9	354048	3928302	bottomland	Metasiltstone
10	353968	3928336	bottomland	Metagraywacke
11	353861	3928466	bottomland	Schist
12	353968	3928302	gentle slope	Metagraywacke
13	353924	3928301	gentle slope	Metagraywacke
14	353961	3928212	gentle slope	Metagraywacke
15	354060	3928216	gentle slope	Metagraywacke

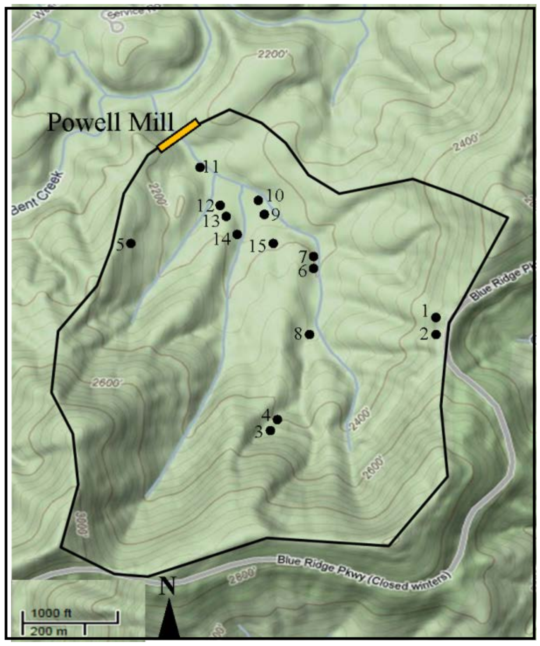

Figure 8. Soil Pit Locations, Powell Mill Catchment.

The majority of pits were excavated within the metagraywacke geological unit as it dominates surface catchment geology. However, pits were also excavated in minority geological units (metasiltstone and schist). Each pit was excavated to a depth between 30 cm and 40 cm below surface, exposing both A- and upper B-horizons, and sampled at 2cm intervals using 10 cm^3 magnetic analysis collection pots. Table 9 details the conditions of the fifteen soil pits. Some evidence of soil degradation was noted during excavation, particularly at pit 5 where the A-horizon had been removed. Limited A-horizon development was noted at all bottomland locations, where a slight darkening of overbank sediment occurred to a depth of approximately 15 cm below the surface. Two pits (14 and 15) were located in the area used as a Conservation Camp in the 1930's, and finally, the upper horizon of pit 8 was observed to be a plow zone.

Mass Adjusted Susceptibility

Mass adjusted ("specific") susceptibility (X_{lf}), frequency dependent susceptibility (k_{fd}), and SIRM are illustrated in Figures 9, 10, and 11. Overall, there is little evidence of a difference in X_{lf} values in the A-horizon compared to the B-horizon (Figure 9). Pit 11, located in overbank sediment, exhibiting very weak A-horizon development, is the single exception. To further investigate whether X_{lf} increased or decreased up profile for all profiles or any particular profiles, the ratio of average X_{lf} values of A- and B-horizons for each soil pit were plotted (Figure 12). A ratio greater than unity indicates higher average values in the A-horizon and a ratios less than unity indicates higher average values in the B-horizon. All three pit categories range from below to above unity. No clear pattern emerges. The X_{lf} ratio plot does not indicate either a clear increase or decrease in X_{lf} up-profile for any the three soil pit categories. Mass adjusted susceptibility was also averaged for each soil pit and plotted in terms of geographic location to determine if X_{lf} value ranges varied with topography (Figure 13). Steep slope soil pits do not demonstrate a similar group trend across the catchment (Figure 9). However, some similarities can be detected at the hill slope scale. Pits 1 and 2, both located in the metasiltstone unit, have very similar trending X_{lf} profiles, and similar X_{lf} ranges. Pits 3 and 4, both located in the metagraywacke unit also resemble one another in terms of overall X_{lf} trend and range values. It seems apparent then that geology plays a role in X_{lf} trending and intensity in the steep-slope portions of Powell Mill catchment.

Table 9. Soil Pit Conditions, Powell Mill Catchment.

Pit	Surface	Humus	A-horizon	Total Depth	Comment
1	steep slope	0-2cm	2-15cm	30cm	very stoney
2	steep slope	0-5cm	5-20cm	30cm	very stoney
3	steep slope	0-2cm	2-15cm	25cm	very stoney
4	steep slope	0-2cm	2-15cm	30cm	very stoney
5	steep slope	0-2cm	2-10cm	30cm	very stoney
6	bottomland	0-10cm	n/a	30cm	no A-horizon development
7	gentle slope	0-5cm	5-10cm	37cm	very stoney
8	gentle slope	0-4cm	4-20cm	30cm	plow zone
9	bottomland	0-2cm	2-14cm	25cm	weak A-horizon development
10	bottomland	0-3cm	3-23cm	21cm	weak A-horizon development: lag at 21cm
11	bottomland	0-4cm	4-23cm	20cm	weak A-horizon development: lag at 23cm
12	gentle slope	0-5cm	5-10cm	30cm	truncated/eroded A-horizon?
13	gentle slope	0-5cm	5-15cm	28cm	truncated/eroded A-horizon?
14	gentle slope	0-5cm	5-20cm	28cm	CCC camp area
15	gentle slope	0-3cm	3-20cm	28cm	CCC camp area

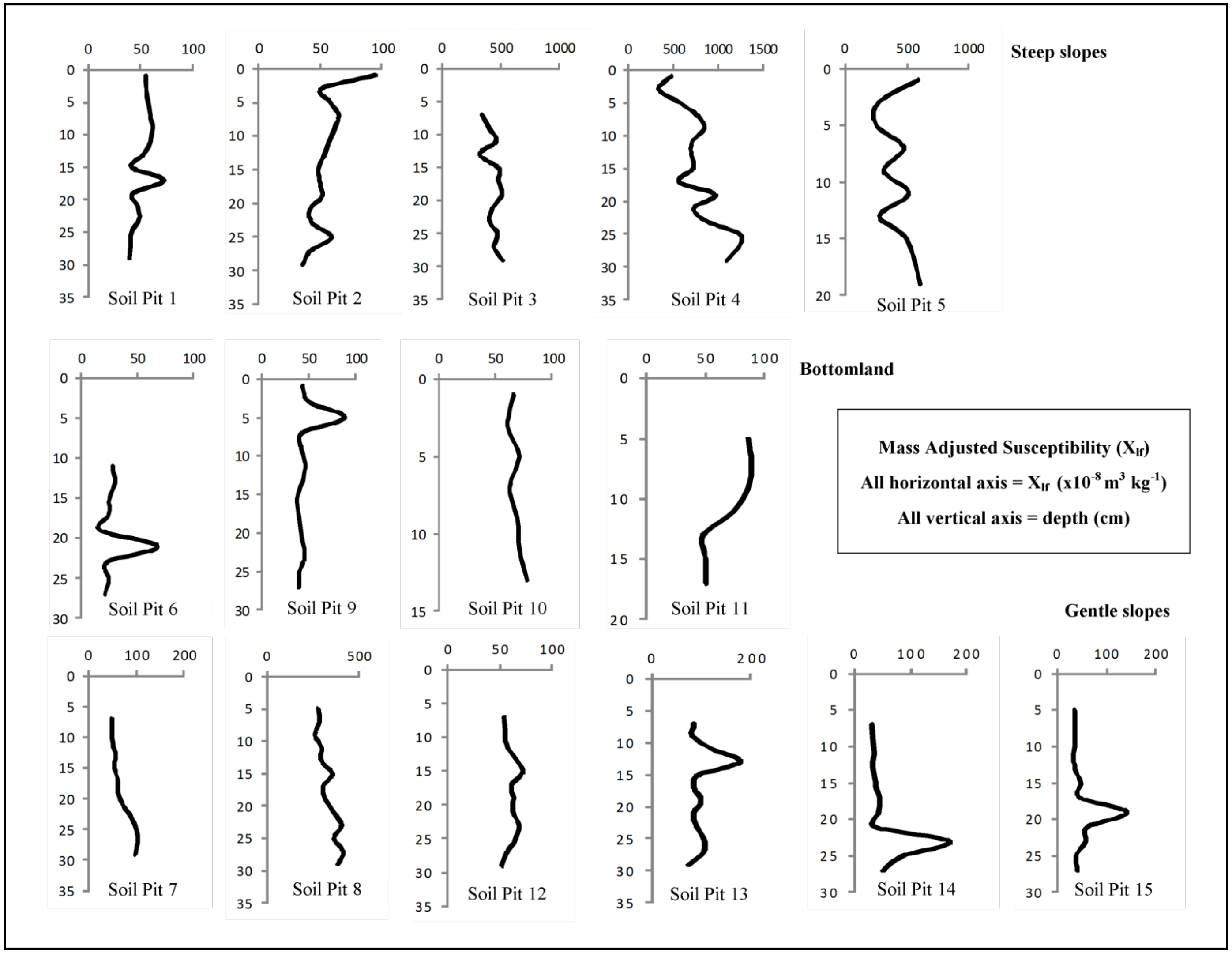

Figure 9. Mass Adjusted Susceptibility, Soil Pits, Powell Mill Catchment

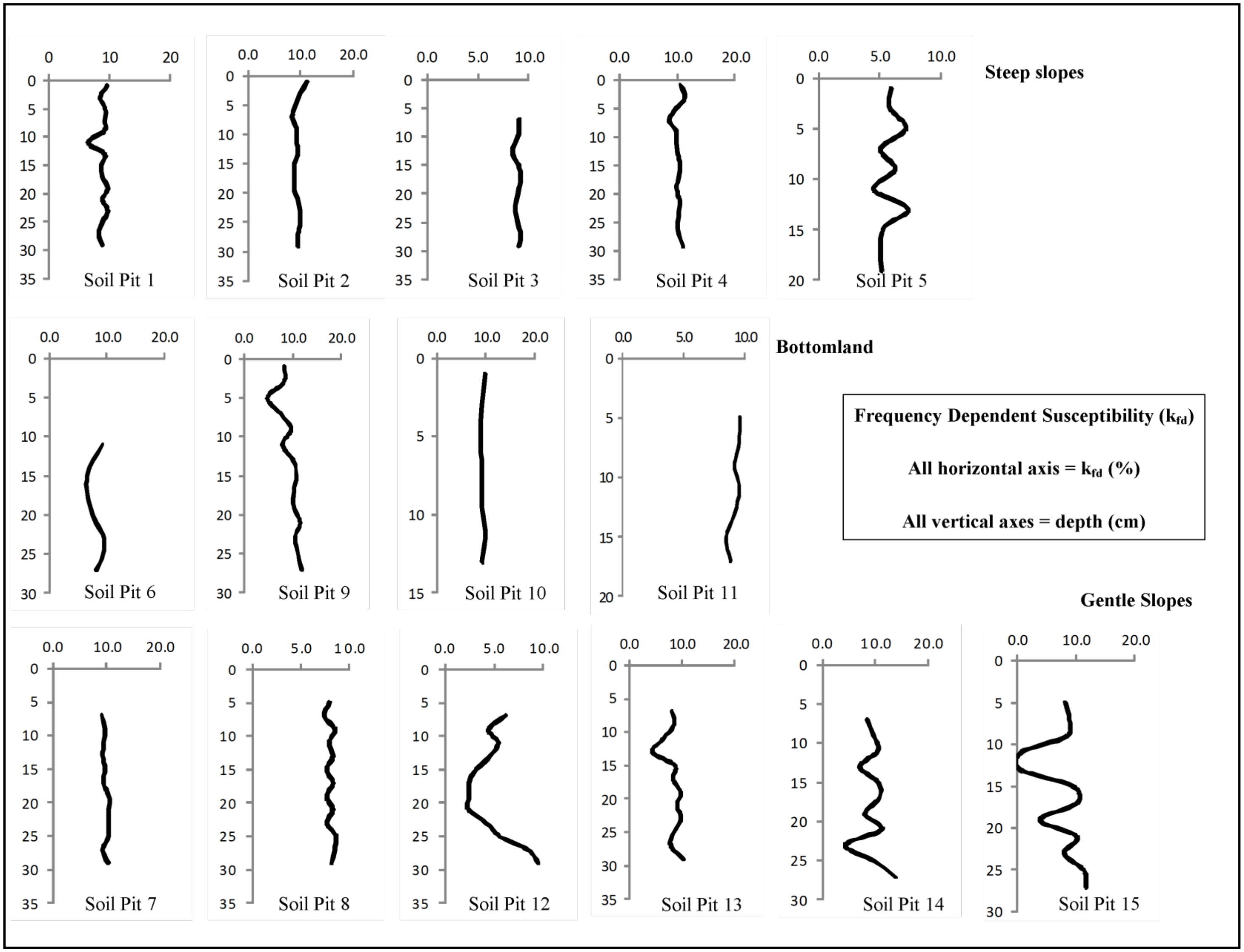

Figure 10. Frequency Dependent Susceptibility, Soil Pits, Powell Mill Catchment.

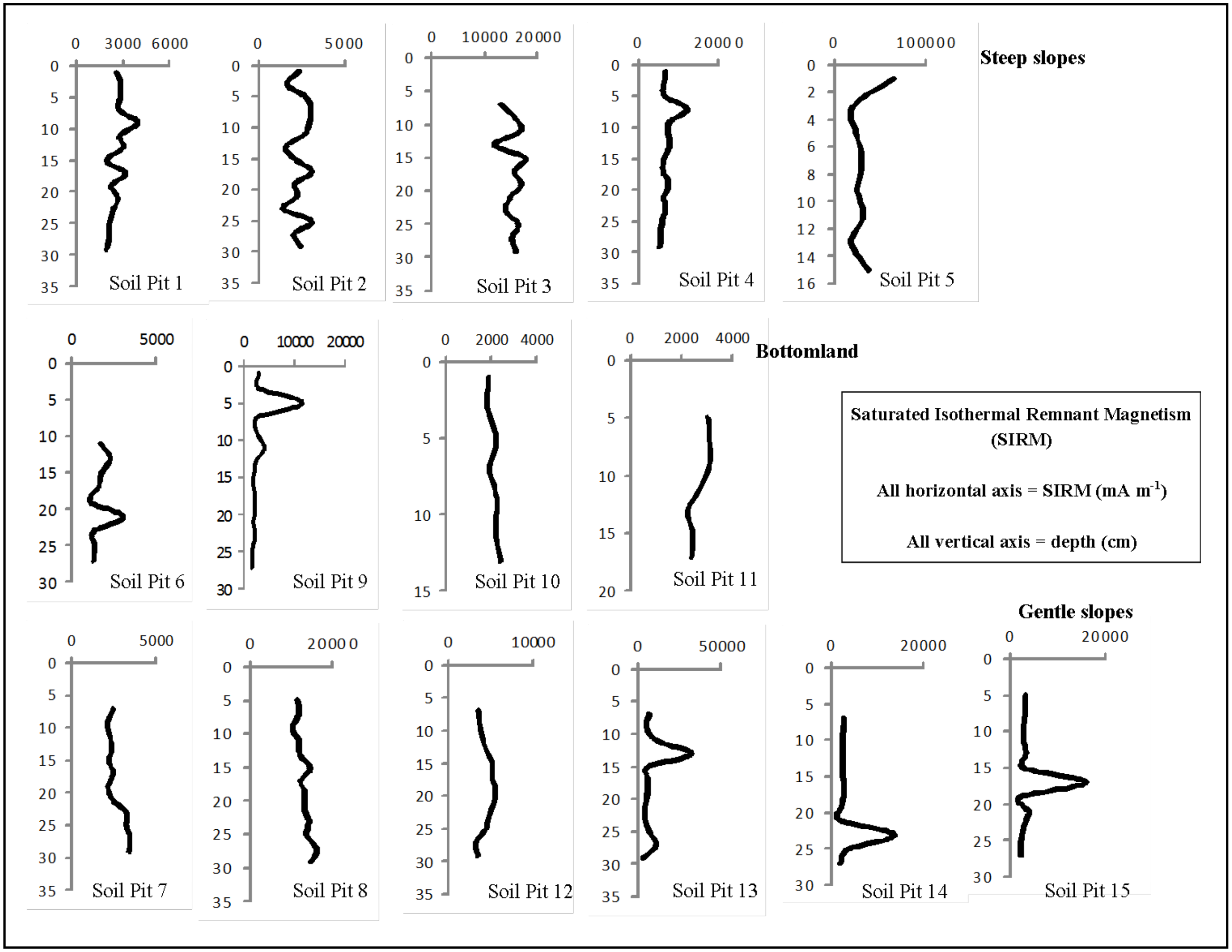

Figure 11. Saturated Isothermal Remnant Magnetism, Soil Pits, Powell Mill Catchment

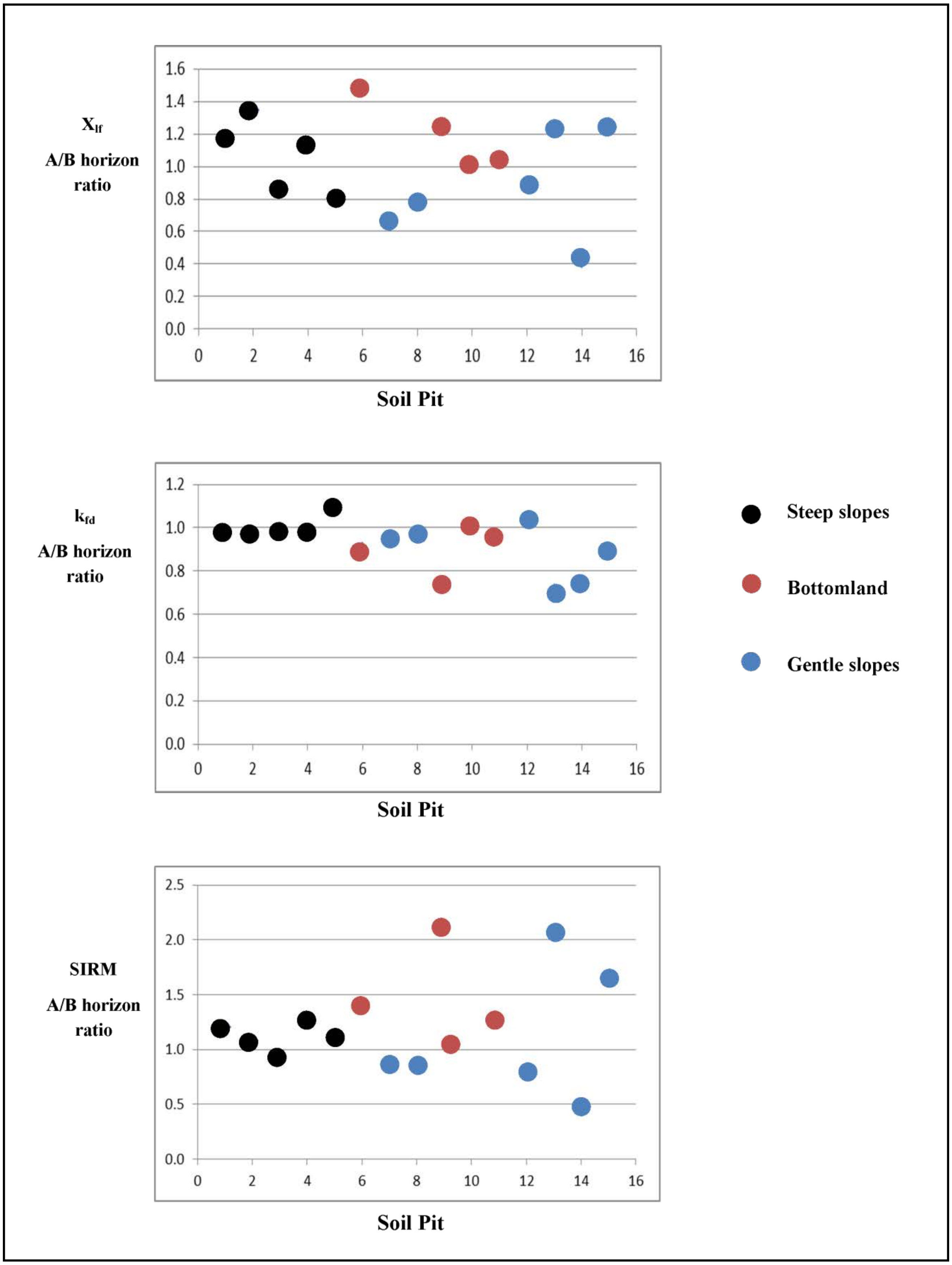

Figure 12. Average A-horizon/ Average B-horizon Magnetic Ratios, Powell Mill.

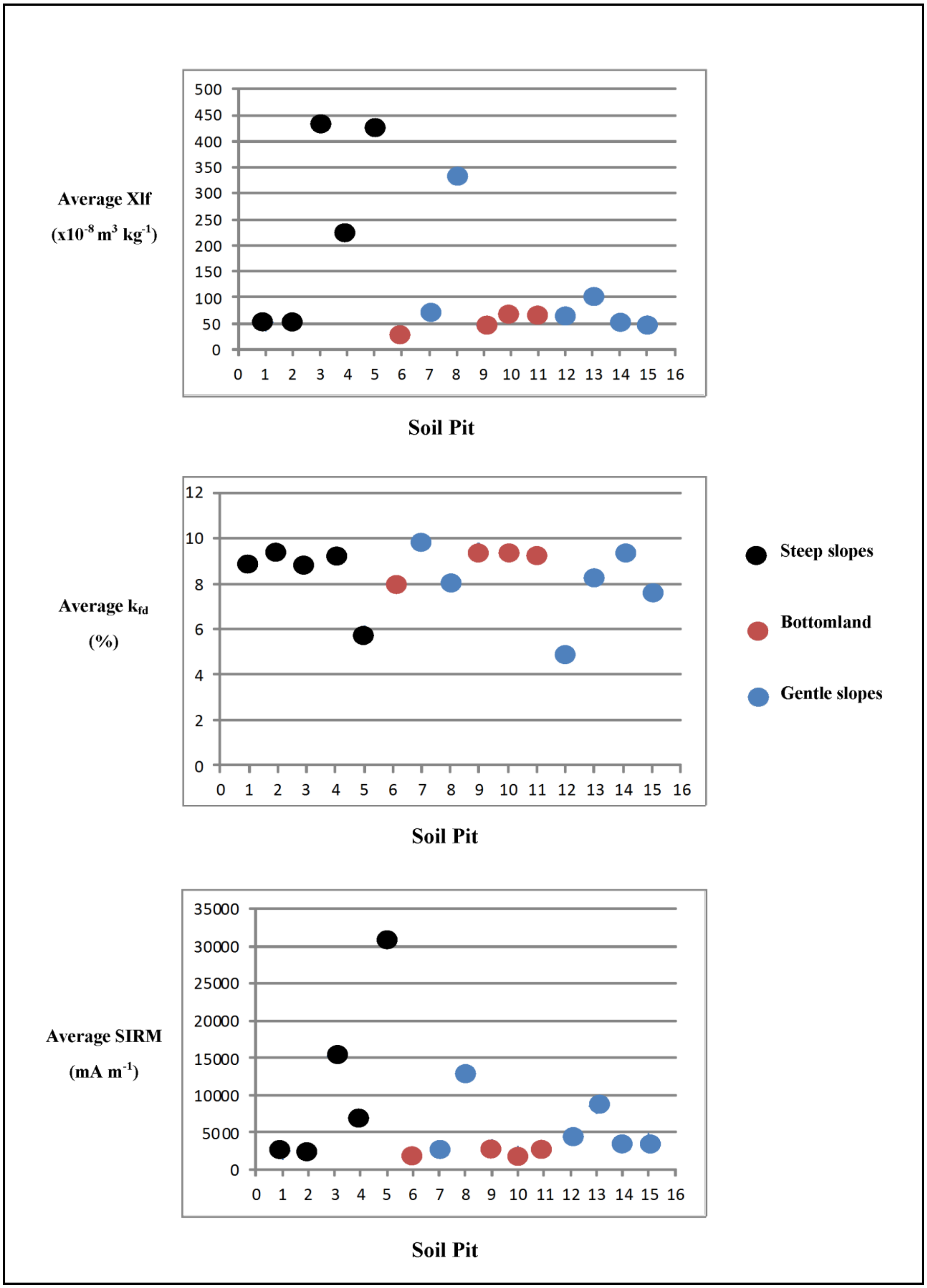

Figure 13. Averaged Magnetic Parameters, Soil Pits, Powell Mill.

Gentle slope X_{lf} values are all relatively low, but there is no common trend across profiles (Figure 9). As with the steep-slope profiles, the gentle-slope profiles do not exhibit a consistent group character, but trends and value ranges are similar in profiles located in close proximity. Pits 14 and 15, approximately 30 m apart, demonstrate almost identical X_{lf} profiles. Pits 12 and 13, 20 m apart also trend in a similar manner. As with steep-slope profiles, it seems that very local conditions play an important role in determining X_{lf} trends and value ranges in gentle- sloping locations of the catchment. In general, X_{lf} values are slightly higher in steep-slope locations, particularly in those located in the dominant metagreywacke unit, than those located in gentle-sloping areas.

Bottomland soil pits exhibit consistently low X_{lf} values, but do not demonstrate similarities in trend. Bottomland averages ranged between 29 – 69 ($x10^{-8}$ m^3 kg^{-1}). However, two steep-slope pits (1 and 2) and three gentle-slope pits (12, 14, and 15) also average in this range.

Frequency Dependent Susceptibility

Profile plots of frequency dependent susceptibility (k_{fd}) are illustrated in Figure 10. As with X_{lf}, there is no evidence of a general increasing trend in k_{fd} from the B-horizon to the A-horizon. In some pits k_{fd} appears to decrease slightly up profile (e.g., pit 7, 9, 13, and 14). The majority of averaged A- and B-horizon k_{fd} ratios are very close to unity indicating that superparamagnetic (SP) mineral concentration is very similar in the A- and upper B-horizons (Figure 12). The three exceptions are pits 9 (bottomland), 13, and 14 (gentle slopes), where higher k_{fd} values are found in the B-horizon.

Four of the five steep-slope pits (1, 2, 3, and 4), exhibit similar trends, in that k_{fd} values range between 8 - 10 percent, do not widely fluctuate down profile, and in each case, the relatively high k_{fd} values extend down into the upper B-horizon. These data suggest that SP grains are not confined to the A-horizon. The remaining steep-slope pit (pit 5) located on the schist unit differs from the previous four. Frequency dependent values fluctuate more widely and range lower, between 4 - 8 percent. The soil at this location was severely degraded and it is possible that the difference noted at pit 5 is related to the removal of a higher concentration of SP grains through erosive processes. Although mass adjusted susceptibility was consistently low in all four bottomland pit profiles, k_{fd} is relatively high, ranging between 7 - 11 percent.

More variability is noted across the gentle-sloped profiles in general. Frequency dependent values range between 2 - 14 percent. Again, there is more similarity where pits are located close to one another. For example, pits 14 and 15 exhibit almost identical trending k_{fd} profiles. Both fluctuate widely and extend down into the upper B-horizon. Although the X_{lf} profiles of pits 12 and 13 are very similar, their respective k_{fd} profiles differ, although again each fluctuates quite widely and extends down into the B-horizon. Less fluctuation is noted in pits 7 and 8. The plot of averaged k_{fd} values for each profile is illustrated in Figure 13. Frequency dependent susceptibility is relatively high across the entire watershed and extends from the A-horizon into the upper B-horizon. As such k_{fd} cannot be used to distinguish between topsoil and subsoil, or distinguish between bottomland and slopes. Variation in k_{fd} in millpond sediment is therefore more likely to be a function of flow competency.

Saturated Isothermal Remnant Magnetism

SIRM profile plots are illustrated in Figure 11. The steep-slope plots are consistent with X_{lf} plots in that very high SIRM values are noted in pits 3, 4, and 5, indicating higher concentrations of magnetic minerals. SIRM is highest in the degraded soil profile of pit 5. According to Nesbitt (1941), pit 5 is located in an area that was cultivated. It is possible that as soil erosion progressed, lower portions of the soil profile became exposed to plow action, resulting in an increase in primary mineral concentration, and a lower concentration of SP grains: relatively lower concentrations of SP grains are indicated by the lowest average k_{fd} value of 6 for the catchment. Lower SIRM values are noted in pits 1 and 2, consistent with X_{lf}

All bottomland profiles demonstrate low SIRM, consistent with relatively low $X_{lf.}$ Finally, with the exception of single anomalies in pits 13, 14, and 15, SIRM values tend to increase slightly or remain stable down-profile in each of the gentle-sloping profiles. Overall, SIRM values range quite widely (2,000 - 40,000 mA m^{-1}). Averaged SIRM values are plotted in Figure 13. As with X_{lf}, bottomland profiles are consistently low, but are not exclusively low. The three steep-slope pits located in the dominant metagreywacke exhibit generally higher SIRM values than the gentle-sloping pits. Pit 5 is unique in its very high average SIRM value and low k_{fd} value.

The magnetic data derived from soil pits in the Powell Mill catchment allow the following statements to be made. First, although there is evidence of relatively high concentrations of SP grains across the catchment (i.e., k_{fd} values generally greater than 6 percent), A-horizon susceptibility is not appreciably higher than upper B-horizon susceptibility. Sandy bottomland over-bank deposits consistently demonstrate low X_{lf} and low SIRM. However, as some other soil profiles also measure in a similar X_{lf} and SIRM range, these parameters may only be used as a general guide when using X_{lf} ranges to determine sediment source. Geology does impact the magnetic characteristics of catchment soils. The minority metasiltstone unit generates soils with lower X_{lf} and SIRM, but steep-slope soils in the dominant metagreywacke unit typically exhibit higher X_{lf} and SIRM ranges than do soils located in bottomland areas. Finally, the lower kfd values noted in the heavily degraded soil of pit 5 (≤ 6 %) suggests that as soil erosion progresses, exposing the lower B-horizon, the proportion and influence of primary mineral grains increases, and the proportion of SP grains decrease.

Soil Texture and Organic Content

Table 10 detail soil types in the Powell Mill catchment. The cleared and cultivated areas of the catchment coincide with Evard-Cowee soils (Ewc, Ewd, and Ewe) described as stoney sandy loams (Web Soil Survey 2012) and their textural characteristics are detailed in Table 11. Sand and silt both decrease in proportion down profile (13.2 percent and 10.7 percent respectively) as clay increases (29.3 percent). The largest down profile decrease however is in organic content where there is an 84 percent reduction below a depth of 20 cm. It should be noted that this large reduction in organic matter content below 20 cm depth, occurs in all soils across the catchment. Sheet wash erosion of hillslope A-horizons might then be expected to deliver relatively high concentrations of organic matter to the stream channels compared to lower portions of the soil column.

Table 10. Soil Types, Powell Mill Catchment.

Map Unit Symbol	Map Unit Name	Catchment %
AcD	Ashe-Cleveland-Rock outcrop complex, 15 to 30 percent slopes, very stony	1.60%
ArE	Ashe-Cleveland-Rock outcrop complex, 30 to 50 percent slopes, very bouldery	2.60%
EdD	Edneyville-Chestnut complex, 15 to 30 percent slopes, stony	3.90%
EdE	Edneyville-Chestnut complex, 30 to 50 percent slopes, stony	13.30%
EdF	Edneyville-Chestnut complex, 50 to 95 percent slopes, stony	16.80%
EwC	Evard-Cowee complex, 8 to 15 percent slopes, stony	2.70%
EwD	Evard-Cowee complex, 15 to 30 percent slopes, stony	13.70%
EwE	Evard-Cowee complex, 30 to 50 percent slopes, stony	12.20%
PwD	Porters-Unaka complex, 15 to 30 percent slopes, stony	0.00%
PwE	Porters-Unaka complex, 30 to 50 percent slopes, stony	2.70%
PxF	Porters-Unaka complex, 50 to 95 percent slopes, rocky	7.70%
TaC	Tate loam, 8 to 15 percent slopes	1.60%
TaD	Tate loam, 15 to 30 percent slopes	7.20%
TkD	Tate loam, 15 to 30 percent slopes, very stony	4.90%
TpE	Toecane-Tusquitee complex, 30 to 50 percent slopes, very bouldery	8.80%
Ud	Udorthents, loamy	0.30%
Totals for Area of Catchment		100

Table 11. Textural Characteristics of Evard-Cowee Soils.

Depth (cm)		**Ewc**	**Ewd**	**Ewe**
0 - 20	% organic	2.8	2.8	2.8
	% sand	40.1	40.1	40.1
	% silt	37.3	37.3	37.3
	% clay	22.6	22.6	22.6
20 - 40	% organic	0.5	0.5	0.5
	% sand	34.8	34.8	34.8
	% silt	33.2	33.2	33.2
	% clay	32.0	32.0	32.0

Sediment Source Model for Powell Catchment

The following sediment source model has been derived using the magnetic data derived from catchment soil pits, and soil survey descriptions (Table 12). Bottomland soils are characterized by low X_{lf} and low SIRM values. As some slope soils exhibited similar X_{lf} and SIRM value ranges, these parameters must be used cautiously but may indicate bottomland sediment sources. Magnetic data from gentle-sloping areas are difficult to parse from bottomland sources, but steep-slopes generally exhibit higher X_{lf}, values.

Percent organic content can be used to distinguish between material eroded from the A-horizon and material eroded from lower in the soil profile, as percent organic content of A-horizons across the watershed are significantly higher than in the B-horizon. Finally, a distinction can be made between sediment derived from the A-/upper B-horizon and material derived from the lower B-horizon. The lower B-horizon is characterized by very high SIRM values and relatively low k_{fd} values.

Table 12. Sediment Source Model, Powell Mill Catchment.

Geographic Location	**Steep Slopes**	**Gentle Slopes**	**Bottomland**
	X_{lf}: > 150	N/A	X_{lf}: < 100
Soil Column	**A-Horizon/upper B-Horizon**		**lower B-Horizon**
	high organic content (A-horizon)		low organic content
	SIRM: < 20,000		SIRM: > 20,000
	kfd: ≤ 6		kfd: ≥ 6

Characteristics of Profile 1

Analysis of Profile 1 included a detailed field description of sedimentation, the collection of bulk samples from profile strata, particle size analysis of each stratum, and the total sedimentary deposit sub-sampled using 10 cm^3 pots at 2 cm intervals for detailed laboratory magnetic analysis.

Mill pond sediment was 2 m thick and characterized by alternating horizontal strata of varying texture and color (Figure 14). A detailed description of color and field determined texture is provided in Table 13 and the results of particle size analysis are illustrated in Figures 15 and 16. Overall, there is a fining of sediment texture down profile. The upper strata are relatively sandy whereas silt is the dominant particle size in the lower strata, particularly between 87 cm and 200 cm below surface. The change from sand to silt dominated strata occurs at approximately 87 cm below surface.

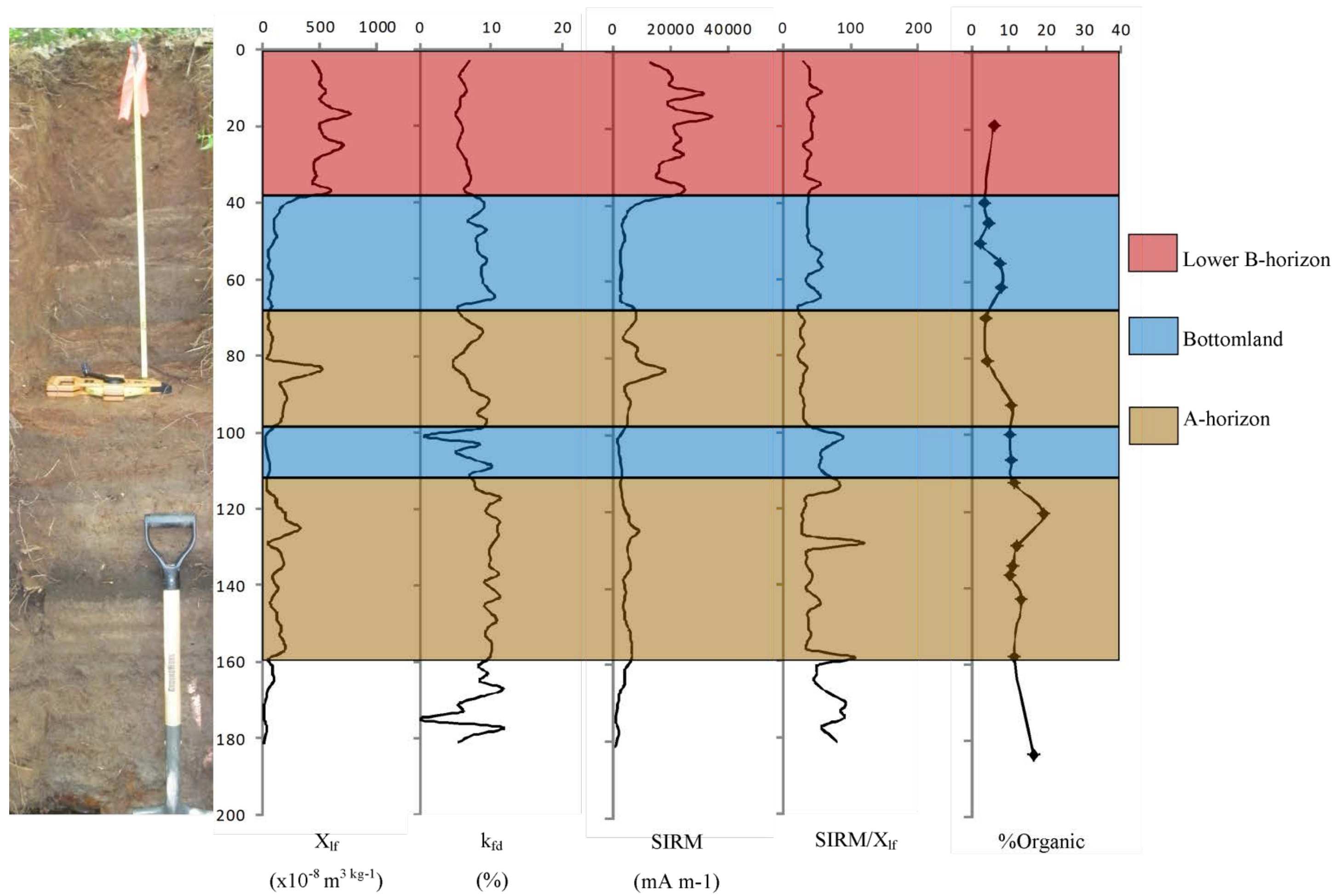

Figure 14. Powell Mill, Profile 1: Magnetic Characteristics and Organic Content.

Table 13. Powell Mill, Profile 1, Strata Texture and Color.

Stratum	Depth (cm)	Color	Texture
1	0-38	7.5YR 3/3 dark brown	silty medium sand
2	38-41	10YR 3/6 dark yellowish brown and 10YR 6/4 light yellowish brown	silty medium sand
3	41-48	7.5YR 3/3 dark brown	silty medium sand
4	48-52	10YR 4/6 dark yellowish brown	medium sand
5	52-58	10YR 3/4 dark yellowish brown	silty fine sand
6	58-65	10YR 3/2 very dark grayish brown	silty fine sand
7	65-74	10YR 3/6 dark yellowish brown	silty medium sand
8	74-87	7.5YR 3/4 dark brown	silty medium sand
9	87-97	10YR 3/3 dark brown	silty fine sand
10	97-103	10YR 3/4 dark yellowish brown	silt
11	103-110	7.5YR 3/4 dark brown	silt
12	110-115	10YR 3/6 dark yellowish brown	silt
13	115-126	10YR 2/1 black	silt
14	126-132	10YR 3/2 very dark grayish brown	silt
15	132-136	10YR 3/2 very dark grayish brown	silt
16	136-137	10YR 4/4 dark yellowish brown	silt
17	137-149	7.5YR 3/3 dark brown	silt
18	149-167	10YR 3/3 dark brown	silt
19	167-200	10YR 4/3 brown	silt

Organic content is consistently high between 200 cm and 92 cm below surface (10 – 16 percent) with a peak at 120.5 cm below surface (19 percent). However, organic content is consistently lower in the upper portion of the profile, between 92 cm below surface and the surface (2.5 – 5.9 percent) with a low peak occurring between 61 and 55 cm below surface (7.9 percent).

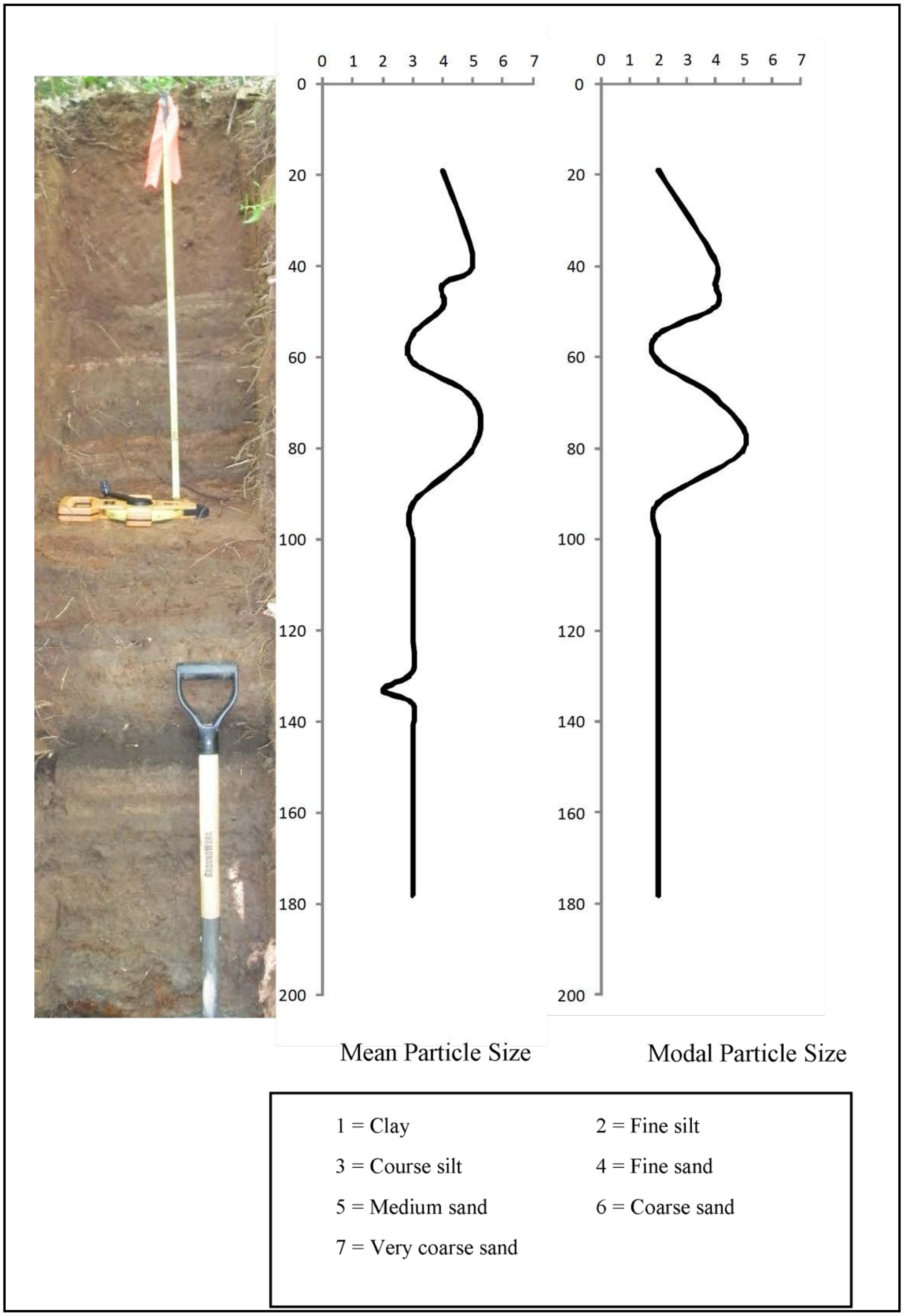

Figure 15. Powell Mill, Profile 1, Particle Size Distribution.

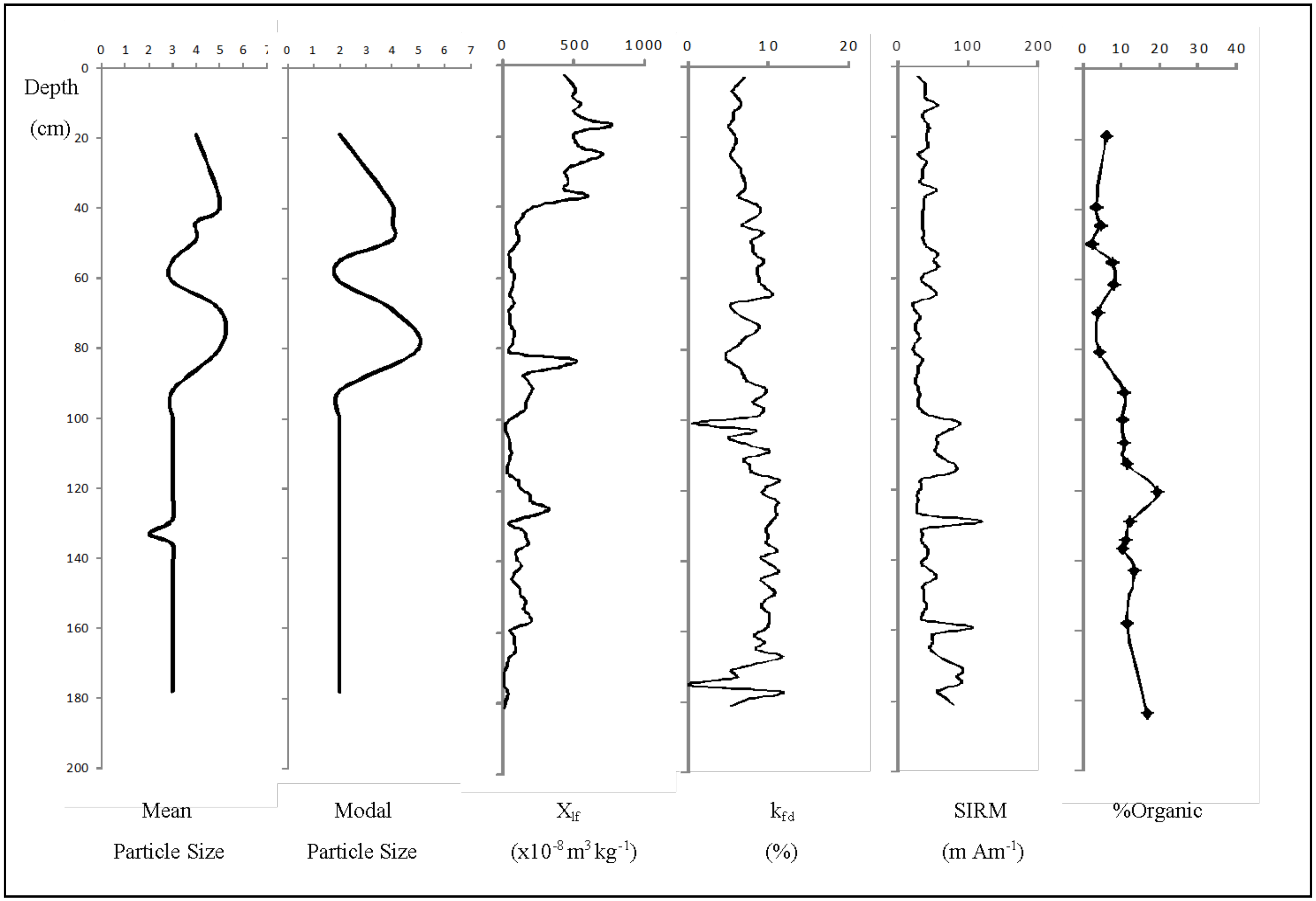

Figure 16. Powell Mill, Profile 1: Particle Size Distribution and Magnetic Parameters

Overall, particle size does not appear to be a controlling factor in changing trends in magnetism up-profile. There is a coarsening of sediment and a corresponding increase in X_{lf} and SIRM at approximately 82 cm, but this is not repeated at the top of the profile where X_{lf} and SIRM increase considerably, yet particle size does not increase. Five zones were delineated based on averaged values of X_{lf}, k_{fd}, SIRM, and percent organic content (Table 14 and Figure 14).

Table 14. Powell Mill, Profile 1, Averaged Parameters.

Zone	Depth (cm)	X_{lf}	k_{fd}	SIRM	% Organic
1	0 – 39	520	6.2	21098	4.7
2	41 – 65	88	8.7	3620	5.6
3	67 – 97	265	7.1	5758	6.3
4	99 - 115	45	7.0	2838	10.7
5	117 - 160	145	10.1	4689	13.0

The lowest 40 cm of profile 1 was saturated and highly mottled, conditions unsuitable for the preservation of magnetic minerals, and this portion of profile 1 is therefore not considered in the following analysis. Zone five, extending from 160 cm up to 117 cm below surface was characterized by high k_{fd}, moderate SIRM and X_{lf}, and high organic matter content. Secondly, although somewhat mixed, there was more tendency for X_{lf} to increase as k_{fd} increased, indicating that SP grain concentration trends with overall susceptibility in the fine grained sediment between 160 cm and 117 cm below surface. This is consistent with erosion of fine particulates from topsoil on catchment hillslopes.

Zone four extending from 115 cm up to 99 cm below surface is characterized by very low X_{lf}, low-moderate k_{fd}, low SIRM, and high organic content. Silt remains the dominant particle size but decreases up-profile, and sand increases. As with zone five, X_{lf} and k_{fd} trend similarly. The very low X_{lf} and SIRM values, in addition to up-profile particle size increase may indicate that bottomland sources are contributing to the sediment load possibly the result of a series of high flow events.

Zone three, extending from 97 cm up to 67 cm below surface was characterized by moderate X_{lf}, low-moderate k_{fd} and SIRM, and a decrease in percent organic content. Here, as X_{lf} increases, k_{fd} decreases indicating that SP grain concentration is not related to increases in overall susceptibility. Considering the increase in X_{lf} and SIRM together with a coarsening of sediment texture (sands) may suggest that this section of the profile represents continued sheet erosion of the coarser hillslope fraction.

Zone 2, extending from 65 cm up to 41 cm below surface, is characterized by low X_{lf}, low SIRM, relatively high k_{fd}, and relatively low-medium percent organic content. Particle size analysis indicates a coarsening of sediment from fine to medium sands up-profile. The characteristics of this zone are similar to those of bottomland over-bank deposits, possibly representing a series of high flow events.

Zone 1, extending from 39 cm up to the surface, was characterized by consistently high X_{lf}, low k_{fd}, very high SIRM values, and low percent organic content, indicating a lower B-horizon sediment source. Mean particle size decreases slightly although there is a broad overall particle size distribution in this stratum.

In summary, magnetic characteristics of Powell Mill pond sediment indicate changes in sediment source over the 15 year period of record. Without absolute dating of pond sediment the observed changes may only be discussed in terms of a sequence of change between 1880 and 1895. The earliest sediment delivered to Powell Mill in 1880 comprised silt and clay eroded from A-horizons (zone 5). As erosion progressed and fines were selectively removed, coarser particulates were exposed to erosion, and pond texture coarsened (zone 3). Periods of high energy flow events may be represented by zones 4 and 2 during which channel sediment was moved through the pond. Finally, a transition from A-/ upper B-horizon derived material to lower B-horizon derived material occurs at 41 cm (zone1), characterized by higher X_{lf}/SIRM values and lower k_{fd} values. Lacking absolute dating what can be said is that after 1880 but shortly before 1895, soil erosion had progressed in some portions of the watershed to such a degree that lower B-horizon material was being introduced to the stream channel.

Soil Erosion Modeling

Gross surficial soil erosion was calculated using GIS as described in Chapter 3. Figure 17 illustrates the resulting calculation of USLE in GIS. Total gross erosion (i.e., addition of all grid cell values) for the entire catchment area is 1,496 t km^{-2} y^{-1}. Sediment delivery ratio describes the portion of gross eroded sediment that is delivered to stream channels, and is derived using the following:

$$\textbf{SDR} = \frac{\textbf{Sediment Yield}}{\textbf{Gross Erosion}} \times 100\%$$

$$= \frac{155 \text{ t km}^{-2} \text{ y}^{-1}}{1{,}496 \text{ t km}^{-2} \text{ y}^{-1}} \times 100\%$$

$$= 10.3\ \%$$

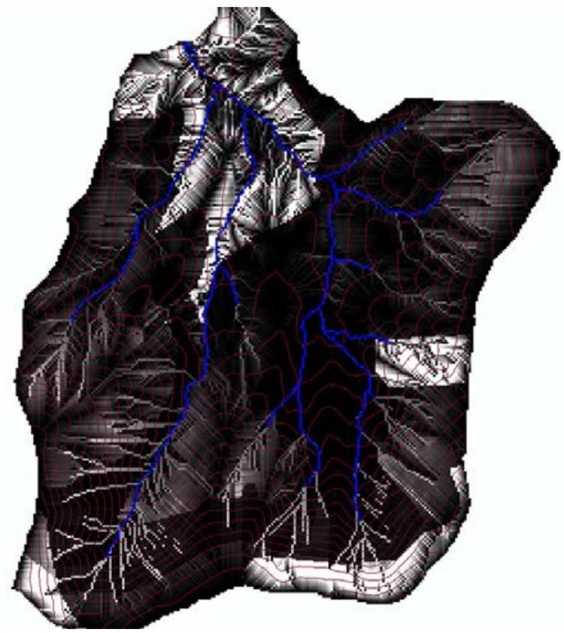

Figure 17. Powell Mill Catchment: USLE Calculated in GIS.

A 10.3 percent sediment delivery ratio may seem low for a low-order highland stream. There are, however some considerations particular to this type of terrain and land-use. The large portion of the catchment that remained woodland also coincides with the coarsest soil types containing approximately 70 percent sand. It is expected that erosion rates were lower in wooded areas compared to cultivated areas, but much of the dislodged coarse material may have been re-deposited downslope, remaining as stored sediment across the catchment. Secondly, the majority of reported sediment yield ratios are based on suspended sediment yield measures. It is possible that the trap efficiency used for Powell is an overestimate, resulting in an underrepresentation o f finer particulates and sediment yield. This will be discussed further in the following chapter.

Nineteenth Century Land-Use in the Lance Mill Catchment

The general land-use history of the Lance Mill catchment is similar to that of the Powell Mill catchment. However, there are some interesting differences between the two catchments. First, a significantly smaller portion of the Lance catchment was cleared for cultivation (13 percent compared to 35 percent). Secondly, a significant portion was commercially logged during the functioning period of Lance Mill. Finally, a much higher proportion of land was converted to cultivation either at the same time or slightly later than the construction date of Lance Mill.

The planar area of the Lance catchment is 9.1 km^2 (Figure 18). Table 15 details nineteenth century land use per lot. A total of 291.6 acres (1.2 km^2), was cleared, 178.6 acres (0.7 km^2) prior to the construction of the dam, and the remaining 113 acres (0.5 km^2) concurrent or later than dam construction. Four lots (65, 66, 67, and 68) were commercially logged specifically for the Lance sawmill. Russel P. Lance, the owner and operator of Lance Mill was one of three Bent Creek residents interviewed by Nesbitt (Nesbitt 1941:4). Lance reported that he cut an annual average of 50,000 board feet log scale of Yellow Poplar from the Long Branch and Chestnut Cove area (Lots 65 and 66) over a period of thirty years (the period of mill operation). With the exception of acreage located at Billy Cove Gap and Hickory Top, cleared area in the Lance catchment occurs at relatively lower elevations around stream bottoms possibly increasing connectedness between slope and stream. In addition to being a record of ongoing erosion and sediment delivery process in the Lance catchment, the sediments trapped behind the Lance dam may also be expected to record the earliest record of erosion and delivery processes associated with late nineteenth century clearing of 113 acres and logging in Chestnut Cove and Long Branch.

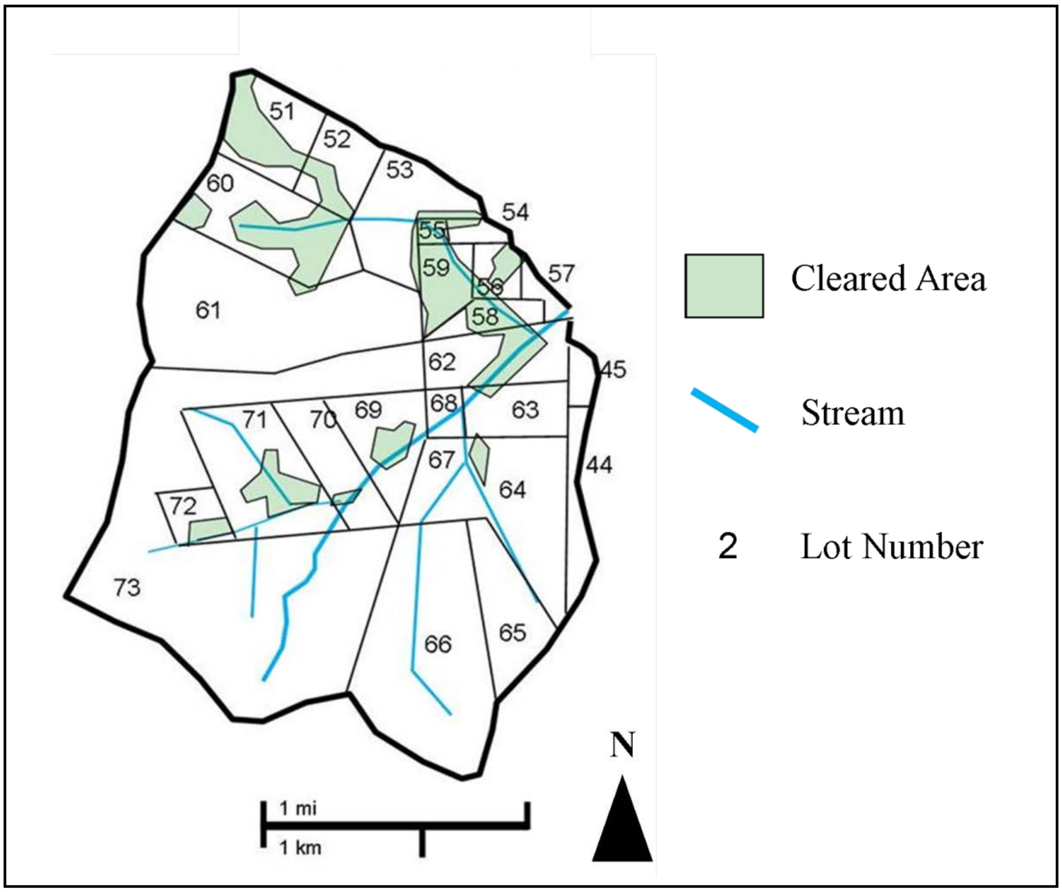

Figure 18. Nineteenth Century Land-Use, Lance Catchment.

Lance Mill Pond Sediment Yield Analysis

Sediment Mass

The location of the nineteenth century dam, modern channel, extracted cores, and four channel profiles at the Lance Mill pond site are illustrated in Figure 19

Table 15. Cleared Acreage, Lance Mill Catchment.

Plot	Acres Cleared	Date	Comments
50	0	n/a	n/a
51	27	1870	n/a
52	15.5	1866	n/a
53	0	n/a	logged
54	14.2	1880	orchard; sheet erosion
55	3.8	1880	orchard
56	10.8	1880	orchard; terracing; ditching
57	0	n/a	n/a
58	16.8	1890	orchard; sheet erosion
59	33.6	1850	orchard; erosion scars
60	52	1865	orchard; erosion scars
61	0	n/a	stock range
62	21.3	1890	orchard; sheet erosion
63	7.7	1890	sheet erosion
64	8.5	1890	orchard; sheet erosion
65	0	n/a	logged
66	0	n/a	logged
67	0	n/a	logged
68	0	n/a	stock rang and logged
69	29.9	1880	orchard; sheet erosion
70	3.4	1862	n/a
71	35.2	1865	orchard; sheet erosion
72	8.5	1870	n/a
73	3.4	1850	n/a
TOTAL	**291.6**		

Evidence of pond sedimentation was present in 16 of the 19 cores extracted at the site, and the remaining three cores exhibited normal soil profile characteristics and were considered to be outside the pond area (Table 16). Core depth was adjusted to compensate for compression. The 1880 surface was identified in the 16 pond cores and the depth of pondsediment determined, which ranged from 0.34 m to 1.80 m. The pre-pond surface was also identified in each of the four channel profiles and these data are included in the sediment volume analysis. All core and channel profile sediment depths (adjusted for compression) are detailed in Table 16.

Pond sediment was characterized by alternating horizontal layers of unconsolidated sediments. The 1880 pre-pond surface varied across the study area and included, channel gravel, dark sand containing plant macrofossils, and highly oxidized orange silty sand, representing a variety of pre-pond depositional environments. The highest surface elevation at which pond sedimentation occurred was at 0.95 m above site datum. Unlike Powell Mill there was no evidence of dam remnants to use as an elevation check. The pond edge was determined using the elevation of negative cores (outside pond), location of constraining bedrock, and the elevation of positive cores (pond sediment).

Pond sediment depth at each core and channel profile location, in addition to numerous pond edge grid points (zero depth) comprised the input database for the Goldenware Surfer program. An isopach map, illustrated in Figure 20, was produced in Surfer from which pond sediment volume was calculated. The volume provided by Surfer includes the non-mineral sediment component such as water and organic material in addition to the mineral component, and must therefore be adjusted.

Table 16. Lance Mill Pond Sediment Depths.

Description	North	West	Sediment depth (m)*	Pond Deposit
Core 1	1000	1000	1.45	Yes
Core 2	995	1000	0.99	Yes
Core 3	1005	1000	1.80	Yes
Core 4	995	1015	1.04	Yes
Core 5	990	1015	1.07	Yes
Core 6	986	1015	0.34	Yes
Core 7	990	1030	1.78	Yes
Core 8	985	1030	n/a	No
Core 9	988	1030	0.74	Yes
Core 10	992	1049	0.85	Yes
Core 11	993	1050	0.83	No
Core 12	987	1058	0.68	Yes
Core 13	988	1059	0.87	Yes
Core 14	983	1055	1.41	Yes
Core 15	979	1071	n/a	No
Core 16	975	1068	0.76	Yes
Core 17	976	1069	0.80	Yes
Core 18	982	1066	0.64	Yes
Core 19	983	1067	0.64	Yes
Profile 1	1001	1014	1.10	Yes
Profile 2	991	1033	1.00	Yes
Profile 3	990	1046	0.83	Yes
Profile 4	975	1062	0.62	Yes

* adjusted for core compression

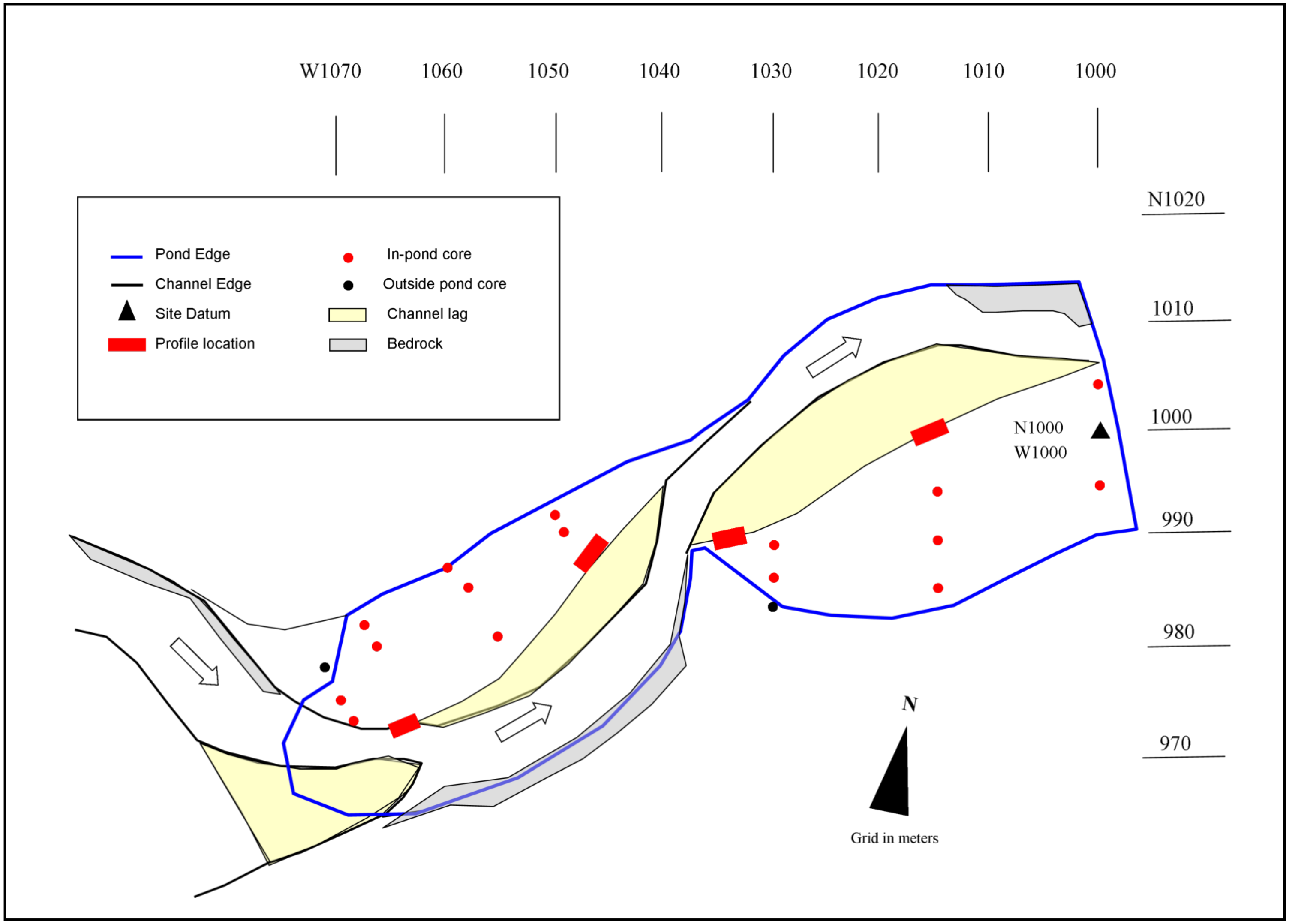

Figure 19. Lance Mill Site Map.

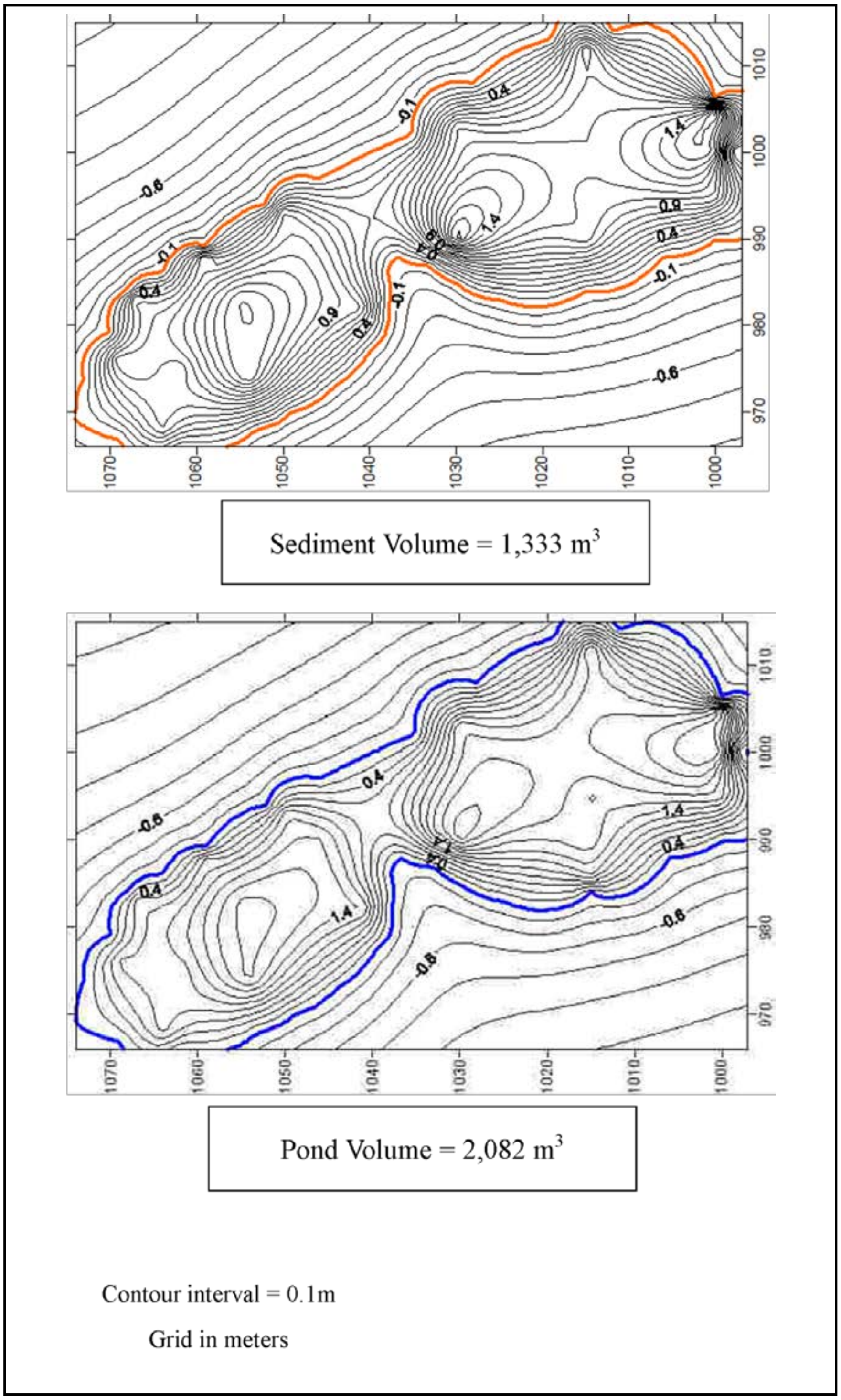

Figure 20. Sediment and Pond Depths, Lance Mill.

Table 17 details the averaged dry bulk density used for the Lance Mill site. The dry bulk density was averaged for each channel profile and then averaged for the site giving a value of 0.84 g cm^{-3}.

Table 17. Dry Bulk Density, Lance Mill

	Profile 1	**Profile 2**	**Profile 3**	**Profile 4**
Horizon	**dBD(g cm^{-3})**	**dBD(g cm^{-3})**	**dBD(g cm^{-3})**	**dBD(g cm^{-3})**
1	1.38	0.69	0.98	0.81
2	1.07	0.82	0.72	0.69
3	1.28	0.97	0.55	1.11
4	0.43	0.69	0.53	1.12
5	0.99	0.62	0.96	1.21
6	0.68	0.60		0.72
7	0.65	0.61		1.01
8	1.36	0.55		1.11
9		0.63		
10		0.63		
11		0.83		
12		0.75		
13		0.62		
14		0.45		
AVERAGE	**0.98**	**0.68**	**0.75**	**0.97**
Site Average = 0.84 g cm^{-3}				

The total mineral mass of pond sediment impounded at Lance Mill, is given by:

$$\mathbf{M = V_{ps} \times dBD}$$

$$\mathbf{= (1{,}333 \times 10^6)\ cm^3 \times 0.84\ g\ cm^{-3}}$$

$$\mathbf{= 1{,}121 \times 10^6\ g}$$

$$\mathbf{= 1{,}121\ metric\ tons\ (mt)}$$

where:

Vps = volume of pond sediment (cm^3)

dBD = dry bulk density (g cm^{-3})

M = mass (mt)

Trap Efficiency

Both pond capacity and annual inflow were calculated using the methods described above in the Powell Mill section. Table 18 details the total depth of both sediment and water for all pond core locations and channel profiles at Lance. A pond capacity of 2,082 m^3 was determined using Golden Surfer software (Figure 20). Annual inflow, quantified by multiplying the catchment area by the USGS average annual runoff value for the Bent Creek catchment (Gerbert et al. 1987) was also determined:

$$\mathbf{I = R_{AA} \times A_c}$$

$$\mathbf{= 0.46\ m \times 9{,}100{,}000\ m^2}$$

$$\mathbf{= 4{,}186{,}000\ m^3}$$

where:

I = annual inflow (m^3)

R_{AA} = average annual runoff (m)

A_c = catchment area (m^2)

Thus, the capacity/inflow ratio is:

$$\mathbf{2{,}082\ m^3/4{,}186{,}000\ m^3 = 0.0005}$$

Table 18. Sediment and Water Depths at Core and Channel Profile Locations**.**

Description	**North**	**West**	**1880 Surface**	**Pond surface**	**Total Depth (m)**
			elevation(m)*	elevation(m)*	
Core 1	1000	1000	-1.45	0.95	2.40
Core 2	995	1000	-0.74	0.95	1.70
Core 3	1005	1000	-1.6	0.95	2.55
Core 4	995	1015	-0.62	0.95	1.57
Core 5	990	1015	-0.69	0.95	1.72
Core 6	986	1015	0.31	0.95	1.26
Core 7	990	1030	-1.32	0.95	2.27
Core 9	985	1030	-0.1	0.95	1.05
Core 10	992	1049	-0.29	0.95	1.24
Core 11	993	1050	-0.19	0.95	1.14
Core 12	987	1058	0	0.95	0.95
Core 13	988	1059	0.1	0.95	0.85
Core 14	983	1055	-0.89	0.95	1.84
Core 15	979	1071	0.95	0.95	0.83
Core 16	975	1068	0.12	0.95	0.85
Core 17	976	1069	0.1	0.95	0.78
Core 18	982	1066	0.17	0.95	0.71
Core 19	983	1067	0.24	0.95	2.04
Profile 1	1001	1014	-0.72	0.95	1.79
Profile 2	991	1033	-0.84	0.95	1.41
Profile 3	990	1046	-0.46	0.95	0.86
Profile 4	975	1062	0.09	0.95	2.04

* elevation relative to arbitrary site datum

This very low C/I ratio is outside Brune's Trap Efficiency model and cannot be used to calculate trap efficiency. Lance Mill pond was similar in size to Powell Mill pond but served as the outlet of a much larger catchment; 9.1 km^2 compared to 1.7 km^2. Annual inflow at Lance is five times greater than at Powell: 4,186,000 m^3 compared to 807,699 m^3. The result is water retention time is much lower at Lance compared to Powell, reducing the amount of time for particle settling and deposition. Low water retention time results in increased turbulence and an increased likelihood of particle re-suspension and erosion. The ability of Lance Mill pond to trap silt and clay sized material was very poor and it can be assumed that only a very small fraction of the suspended load is represented in existing mill pond deposits.

Minimum Sediment Yield

Although trap efficiency cannot be determined for Lance pond, a minimum sediment yield over the period of record can be calculated:

$$\mathbf{SY_{AA}} = \frac{(\mathbf{M} * \mathbf{TE})}{\mathbf{T}} / \mathbf{A_c}$$

$$= \frac{(1{,}121\ \mathbf{t} * 100\%)}{30\ \mathbf{years}} / 9.1\ \mathbf{km^2}$$

$$= 4.1\ \mathbf{t\ km^{-2}\ y^{-1}}$$

where:

SY_{AA} = average annual sediment yield (t km-2 y-1)

M = mineral mass (t)

A_c = catchment area (km^2)

T = time (y)

TE = Trap efficiency (%)

Lance Mill Pond Sediment Source Analysis

A total of 14 soil pits was excavated in the Lance Mill pond catchment; five in bottomland sediments (overbank deposits), four on steep slopes, and five on gentle slopes (Figure 21 and Table 19). The geology varies more than at Powell Mill catchment in that the schist unit makes up a greater proportion of surface geology and the catchment contains slivers of an amphibolite unit. However, metagraywacke remains the dominant unit, followed by schist, metasiltstone, and amphibolite. Pits were excavated in all geological units.

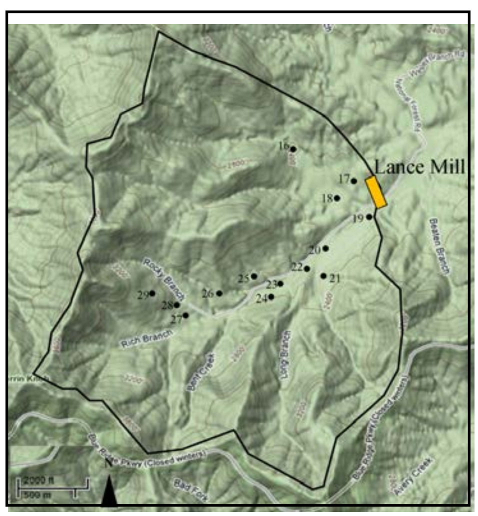

Figure 21. Soil Pit Locations, Lance Mill Catchment.

Table 19. Location of Soil Pits Excavated in Lance Mill Catchment.

No.	Easting*	Northing*	Description	Geology
16	350535	3927522	steep slope	Metagraywacke
17	351025	39227118	gentle slope	Schist
18	351004	3927063	bottomland	Schist
19	351062	3926812	bottomland	Metagraywacke
20	350806	3926392	gentle slope	Schist
21	350829	3926374	steep slope	Schist
22	350563	3926389	bottomland	Metagraywacke
23	350422	3926231	bottomland	Metagraywacke
24	350316	3926185	bottomland	Schist
25	350316	3926216	steep slope	Schist
26	349736	3925995	gentle slope	Amphibolite
27	349699	3925932	gentle slope	Metagraywacke
28	349562	3925992	gentle slope	Metasiltstone
29	349462	3926000	steep slope	Metasiltstone

All pits were excavated to a depth between 30 cm and 40 cm with the exception of pits 27 and 28 (24 cm), both located in very stoney soils. The conditions noted in each pit are detailed in Table 20. Very weak A-horizon development occurred in three of the five bottomland locations and the A-horizon was absent in pits 18 and 19. The A-horizon had been completely removed at the gently-sloping location of pit 17, and a positively identified plow zone was noted at the gently-sloping location of pit 26.

Mass Adjusted Susceptibility

Figure 22 illustrates the X_{lf} profiles for all Lance Mill catchment soil pits. All four steep-slope pits exhibit a declining up-profile trend in X_{lf}, although located in three different geological units; there is no evidence of higher X_{lf} values in the A-horizon compared to the B-horizon. Mass adjusted susceptibility values, in the steep-slope pits range from 98 - 355 ($x10^{-8}$ m^3 kg^{-1}), although the majority of measures are greater than

100 ($x10^{-8}$ m^3 kg^{-1}).

Table 20. Soil Pit Conditions, Lance Mill Catchment.

Pit	Surface	Humus	A-horizon	Total Depth	Comment
16	steep slope	0-4cm	4-20cm	30cm	very stoney
17	gentle slope	0-5cm	n/a	30cm	degraded-no A horizon
18	bottomland	0-3cm	n/a	38cm	overbank sands
19	bottomland	0-4cm	n/a	20cm	overbank sands
20	gentle slope	0-4cm	4-19cm	40cm	stoney
21	steep slope	0-2cm	2-16cm	30	stoney
22	bottomland	0-5cm	5-20cm	35	overbank sands-weak A-horizon
23	bottomland	0-2cm	2-7cm	30	overbank sands-weak A-horizon
24	bottomland	0-5cm	5-20cm	30	overbank sands-weak A-horizon
25	steep slope	0-5cm	5-10cm	22	very stoney
26	gentle slope	0-5cm	5-15cm	28	plow zone?
27	gentle slope	0-3cm	3-16cm	24	stoney at 24 cm
28	gentle slope	0-2cm	2-9cm	24	stoney at 24 cm
29	steep slope	0-2cm	2-11cm	25	very stoney

The bottomland pits are all similar in that X_{lf} values are all less than 100 ($x10^{-8}$ m^3 kg^{-1}). Four of the 5 bottomland pits (18, 22, 23, and 24) appear to exhibit increasing X_{lf} up-profile.

Pit 28, located on gentle-slopes in the metasiltstone unit ranged low, just as pits 1 and 2, also located in metasiltstone, in the Powell catchment. Overall, there is no evidence of a common X_{lf} trend across the gentle sloping pits; three pits (20, 26, and 28) demonstrate very limited variation up-profile, whereas pits 17 and 27 vary more widely up-profile.

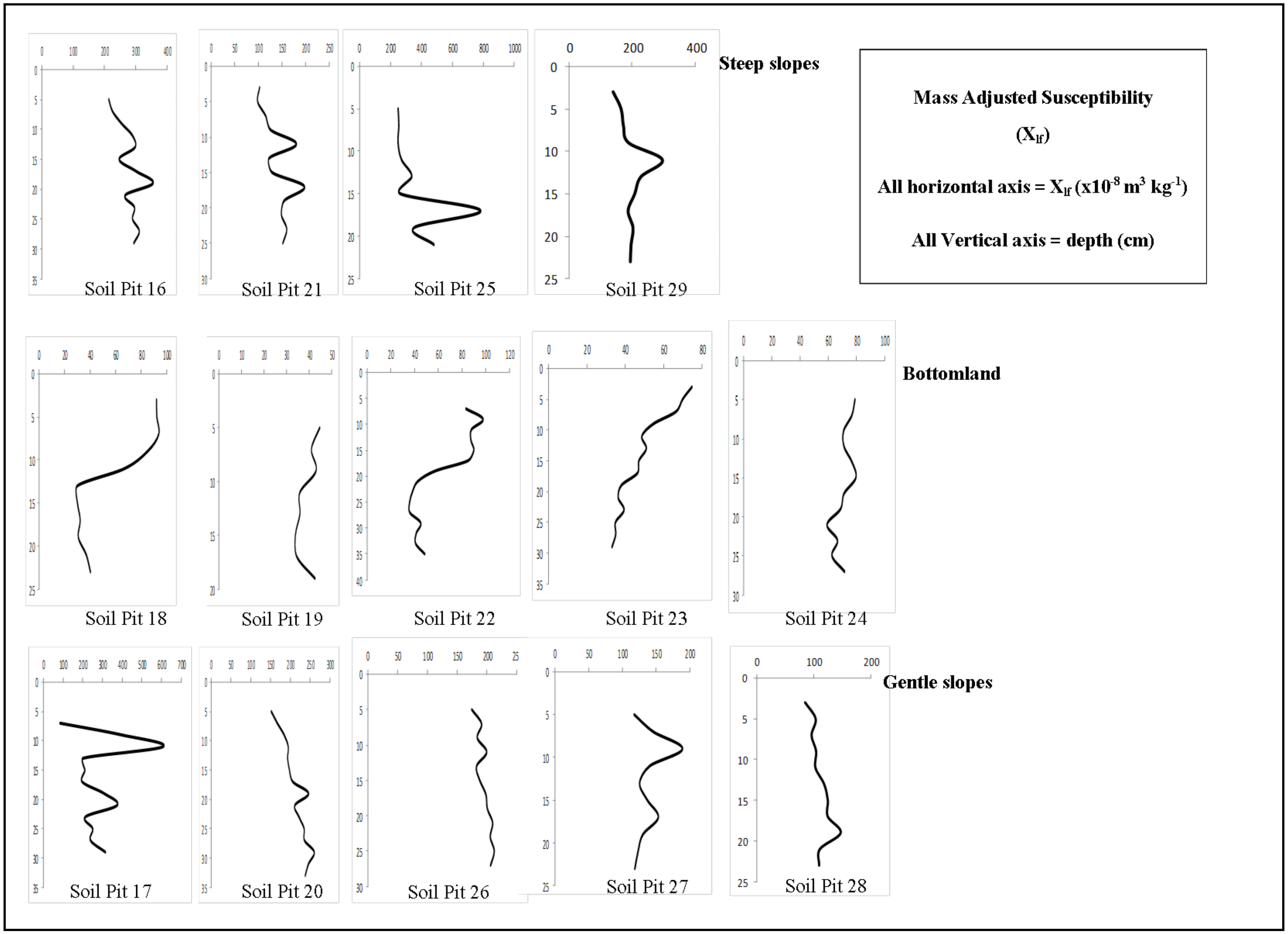

Figure 22. Mass Adjusted Susceptibility, Soil Pits, Lance Mill Catchment.

As with steep-slopes and bottomland profiles, there is no evidence of changing trends in X_{lf} at the boundary between the A- and B-horizon, and gentle-sloping areas cannot be distinguished from steeper-slopes using X_{lf}.

Averaged whole profile X_{lf} values do indicate a clear division between bottomland deposits and slope soils (Figure 23). All five bottomland profiles do however average below 100 ($x10^{-8}$ m^3 kg^{-1}). The steep- and gentle-sloping soils are mixed, but all average above bottomland values. It is possible therefore to use low X_{lf} values more confidently, in the Lance Mill pond sediments, to distinguish between bottomland and slope soils using $X_{lf.}$ Finally, Figure 24 illustrates the ratio of averaged A- and B-horizon X_{lf} values for each soil pit confirming that only bottomland soils consistently exhibit higher X_{lf} values in the A-horizon compared to the B-horizon.

Frequency Dependent Susceptibility

The frequency dependent susceptibility profiles are detailed in Figure 25. The very high values noted in pit 16 suggest contamination. There was evidence of logging roads in the vicinity of pit 16 and it is possible that metal fragments have been incorporated into the soil. Pits 29 and 21, although located on different geological units, are very similar in profile; little variation up-profile from the B- to A-horizon, and relatively high k_{fd} values. Although pit 25 is located in the same geological unit as pit 21, k_{fd} values are less and vary more widely. The k_{fd} profiles of bottomland pits demonstrate consistency. There is little variation up-profile, and even where there is no evidence of A-horizon development, k_{fd} values are relatively high.

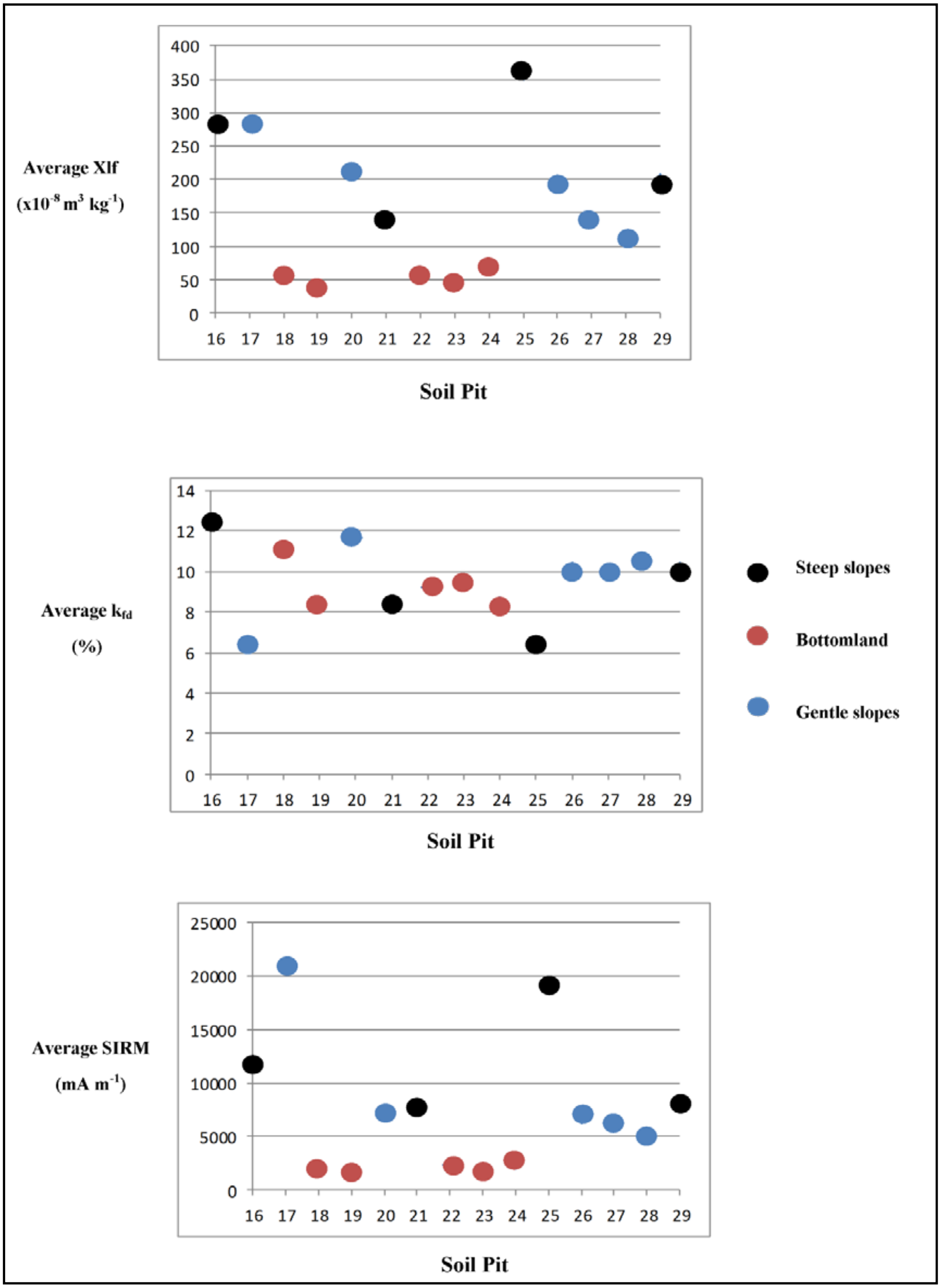

Figure 23. Averaged Magnetic Parameters, Soil Pits, Lance Mill.

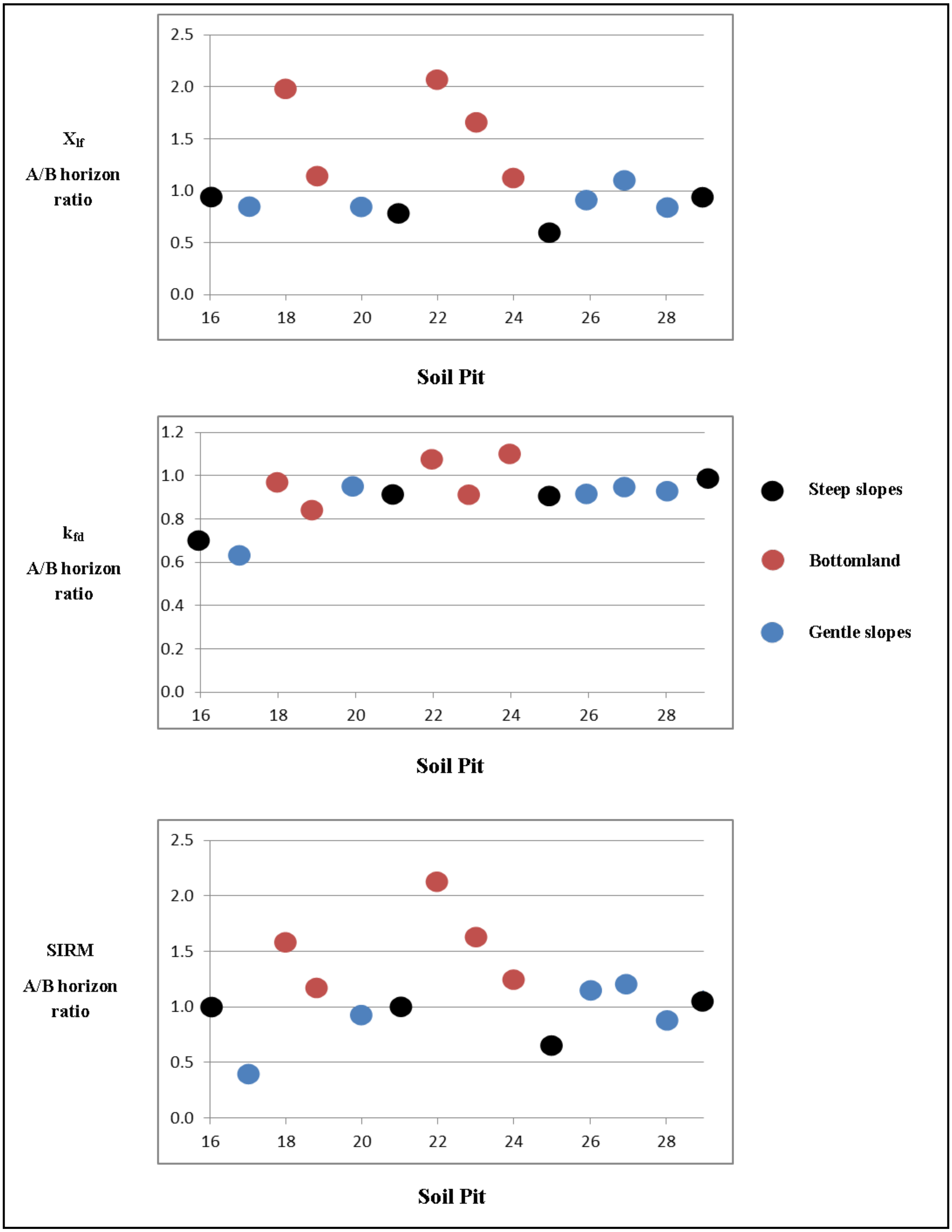

Figure 24. Average A-horizon/Average B-horizon Magnetic Ratios, Lance Mill.

A similar pattern is observed across profiles of gentle-sloping areas; little variation up-profile and relatively high k_{fd} values. Pit 17, a degraded soil, is the single exception where k_{fd} values fluctuate widely, and in some cases could not be plotted as calculations of k_{fd} resulted in negative values. Measurements were repeated but with the same results. Problems continued with samples from this local when taking SIRM measurements, and is discussed below. Average whole values indicate that k_{fd} is not useful in determining sediment source of Lance Mill pond sediment. The A- B-horizon k_{fd} ratio does not present any meaningful pattern either (Figure 24).

Saturation Isothermal Remnant Magnetism

SIRM profiles are illustrated in Figure 26. Steep-slope profiles range between from 5802 – 40,000 ($x10^{-8}$ m^3 kg^{-1}), whereas, SIRM values are consistently lower in bottomland profiles, all plotting below 2,600 ($x10^{-8}$ m^3 kg^{-1}). Four of the five gentle-sloping profiles range between 5,000 and 7,000 ($x10^{-8}$ m^3 kg^{-1}). Pit 17 proved troublesome in that some samples overloaded the molespin. However, the remaining samples exhibited very high SIRM and relatively low k_{fd}. The soil at this location was degraded and the magnetic data is similar to that at pit 5 in Powell catchment where the exposure of lower B-horizon material affected magnetism.

Only bottomland soils consistently demonstrate higher SIRM measures in the A-horizon compared to B-Horizon (Figure 24). The lowest SIRM values are observed in pit 29, located on the metasilstone, consistent with a relatively low X_{lf} profile soil is characterized by lower k_{fd} and high SIRM and X_{lf} values.

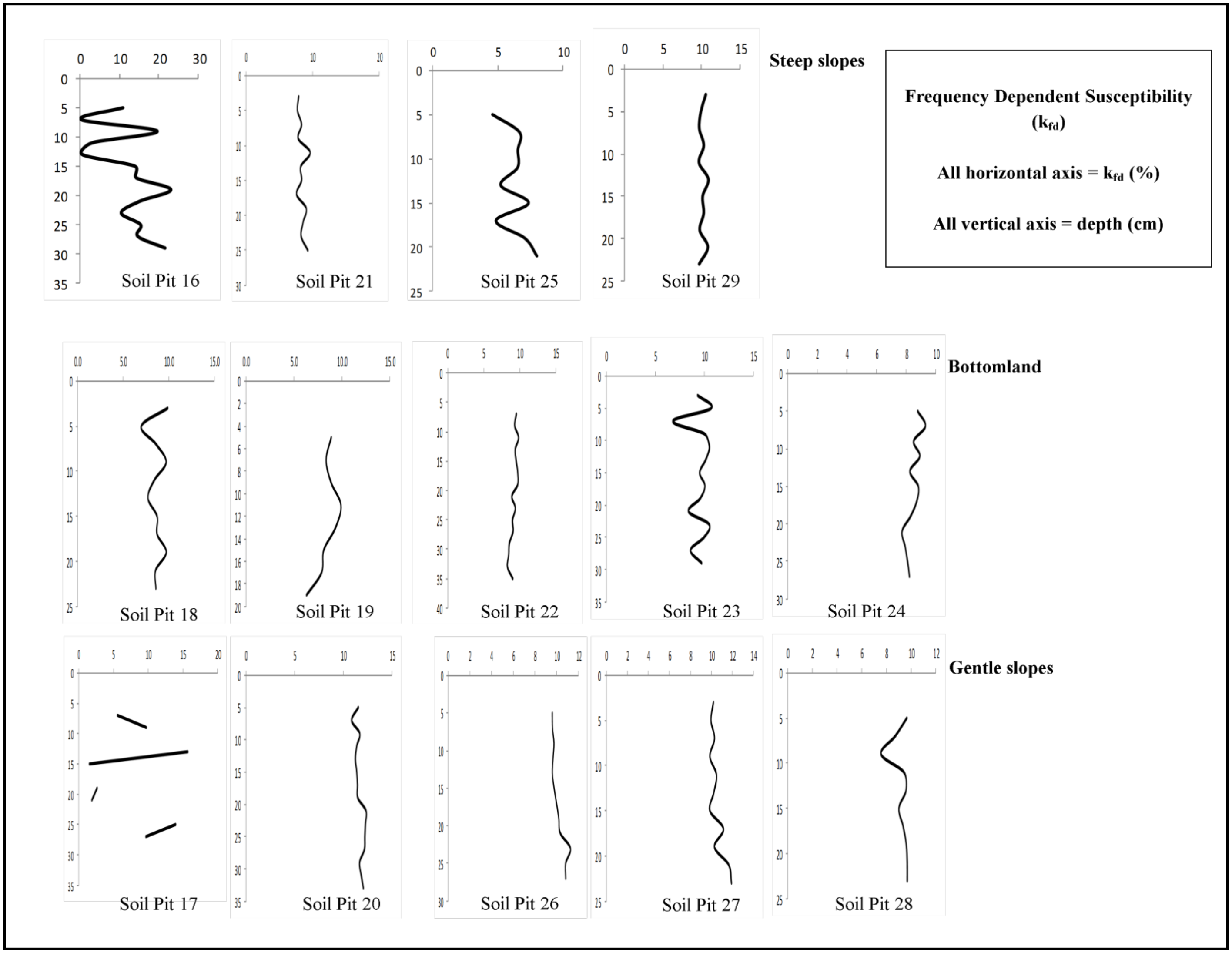

Figure 25. Frequency Dependent Susceptibility, Soil Pits, Lance Mill Catchment.

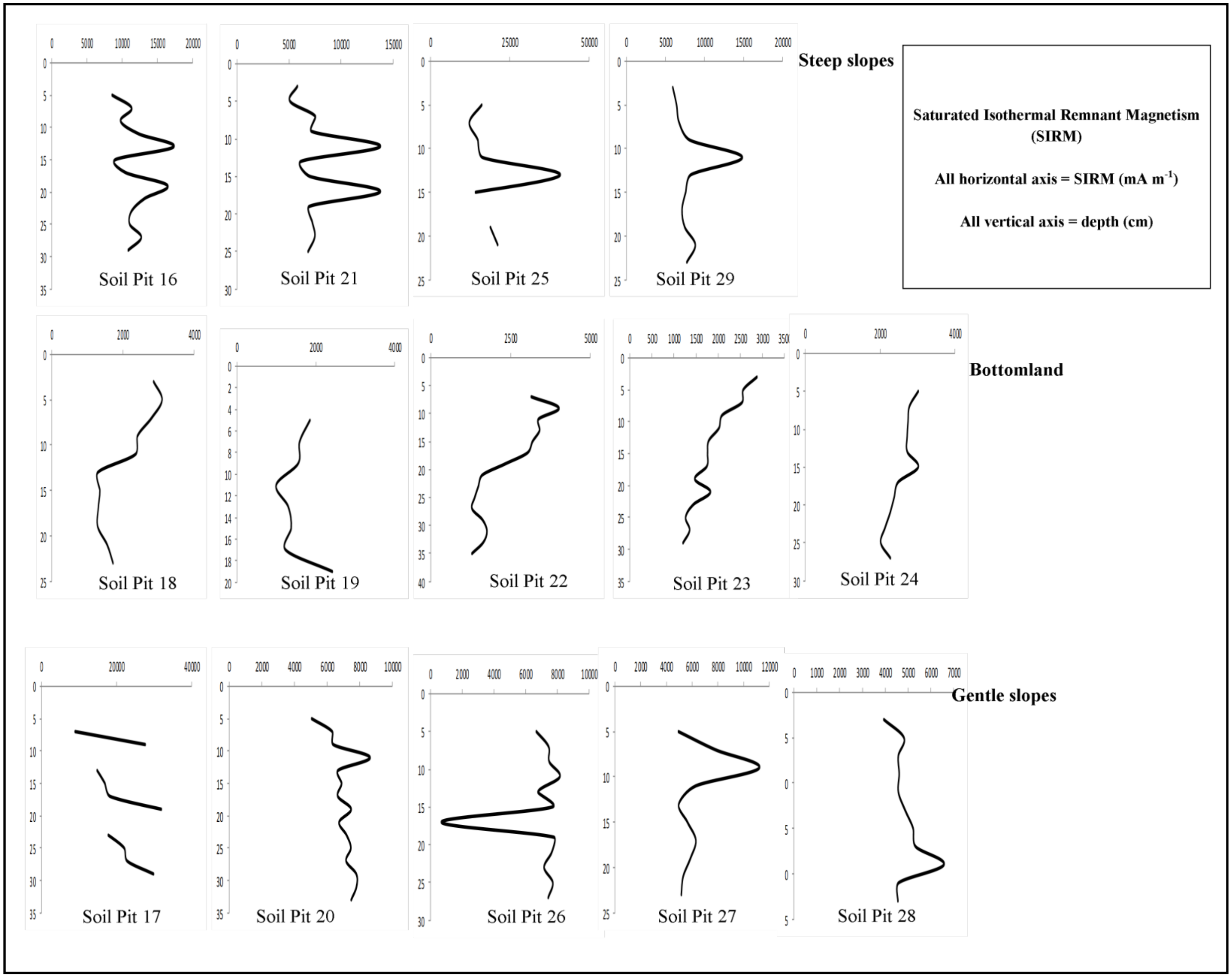

Figure 26. Saturated Isothermal Remnant Magnetism, Soil Pits, Lance Mill Catchment.

Averaged SIRM values are plotted in Figure 23. Only the bottomland pits can be separated out, all averaging below 2,600 ($x10^{-8}$ m^3 kg^{-1}).

In summary, the general statements regarding the magnetic characteristics of soils in the Powell Mill catchment apply also to the Lance Mill catchment. Geology plays a role on the slopes of the catchment. The minority metasiltstone unit produces soils with relatively lower concentrations of magnetic minerals. Superparamagnetic minerals occur in relatively high proportions throughout the watershed, regardless of location, and extend into the upper B-horizon. Low X_{lf} and low SIRM values characterize bottomland deposits and may be used to distinguish mill pond sediment in terms of slope or bottomland origin.

Soil Texture and Organic Content

Soil types cleared and used for cultivation in the Lance catchment are much more varied than at Powell. Table 21 details the physical characteristics of the most commonly occurring soils in the catchment (Web soil Survey 2012). Despite the increase in soil type variation, textural changes down profile echo those of Powell catchment. The clay proportion increases slightly while organic content decreases dramatically down-profile. Therefore, erosion of A-horizons might be expected to deliver relatively high concentrations of organic matter compared to B-horizons.

Sediment Source Model for Lance Catchment

The following sediment source model has been derived by combining soil magnetic data and physical properties for the Lance Mill catchment (Table 22). The model is similar to that produced for Powell but with a few differences. Bottomland soils are consistently characterized by low X_{lf} and low SIRM values in the Lance catchment, and slopes (gentle and steep) consistently exhibit higher X_{lf} and SIRM values.

Table 21. Textural Characteristics of Dominant Lance Mill Catchment Soils.

Depth (cm)		**EdF**	**TpE**	**ArF**	**EwE**	**EdE**	**ArE**
		18%	**11%**	**9%**	**9%**	**8%**	**7%**
0 - 20	% organic	2.8	10.0	2.8	2.8	2.8	2.8
	% sand	68.4	43.8	66.1	40.1	68.4	66.1
	% silt	19.4	40.2	19.2	37.3	19.4	19.2
	% clay	12.2	16.0	14.7	22.6	12.2	14.7
20 -40	% organic	0.5	0.5	0.5	0.5	0.5	0.5
	% sand	70.1	43.0	64.4	34.8	70.1	64.4
	% silt	16.4	39.5	18.6	33.2	16.4	18.6
	% clay	13.5	17.5	17.0	32.0	13.5	17.0

Table 22. Sediment Source Model, Lance Mill Catchment.

Geographic Location	**Steep Slopes**	**Gentle Slopes**	**Bottomland**
	X_{lf}: > 100	X_{lf}: >100	X_{lf}: < 100
	SIRM: > 6,000	SIRM: 5,000-7,000	SIRM: < 2,600
Soil Column	**A-Horizon/upper B-Horizon**		**lower B-Horizon**
	high organic content (A-horizon)		low organic content
	kfd: ≤ 6		kfd: ≥ 6

Mass adjusted susceptibility can be used with more confidence to distinguish between slope and bottomland sources. There are overlaps between gentle and steep slope parameters making it impossible to distinguish between the two. Relatively high percent organic content indicates an A-horizon source. The data from pit 17 suggests that lower-B horizon material is characterized by high SIRM values, relatively low k_{fd}, and low organic content.

Characteristics of Profile 1

Detailed analysis of profile 1 included a field description of sedimentation, the collection of bulk samples from field recognized strata, particle size analysis of each stratum, and 2 cm interval sub-sampling using 10 cm^3 magnetic sampling pots for detailed laboratory magnetic analysis.

Mill pond sediment at profile 1 was 1.06 m thick and characterized by alternating horizontal strata of varying texture and color (Figure 27). A detailed description of color and field determined texture is provided in Table 23 and the results of particle size analysis illustrated in Figure 28. In contrast to the assumption that only relatively coarse bedload might be present at Lance pond, fine silt and clay sized particles were noted throughout the profile. The clay proportion of all six strata ranged from 6 to 10 percent. Fine silt was identified in 5 of the 6 strata and ranged in proportion from 8.8 to 48.8 percent, and is the dominant particulate in strata 3 and 4. Very coarse sand only occurs in the lower strata 4 and 7 (0.4 and 1.0 percent respectively).

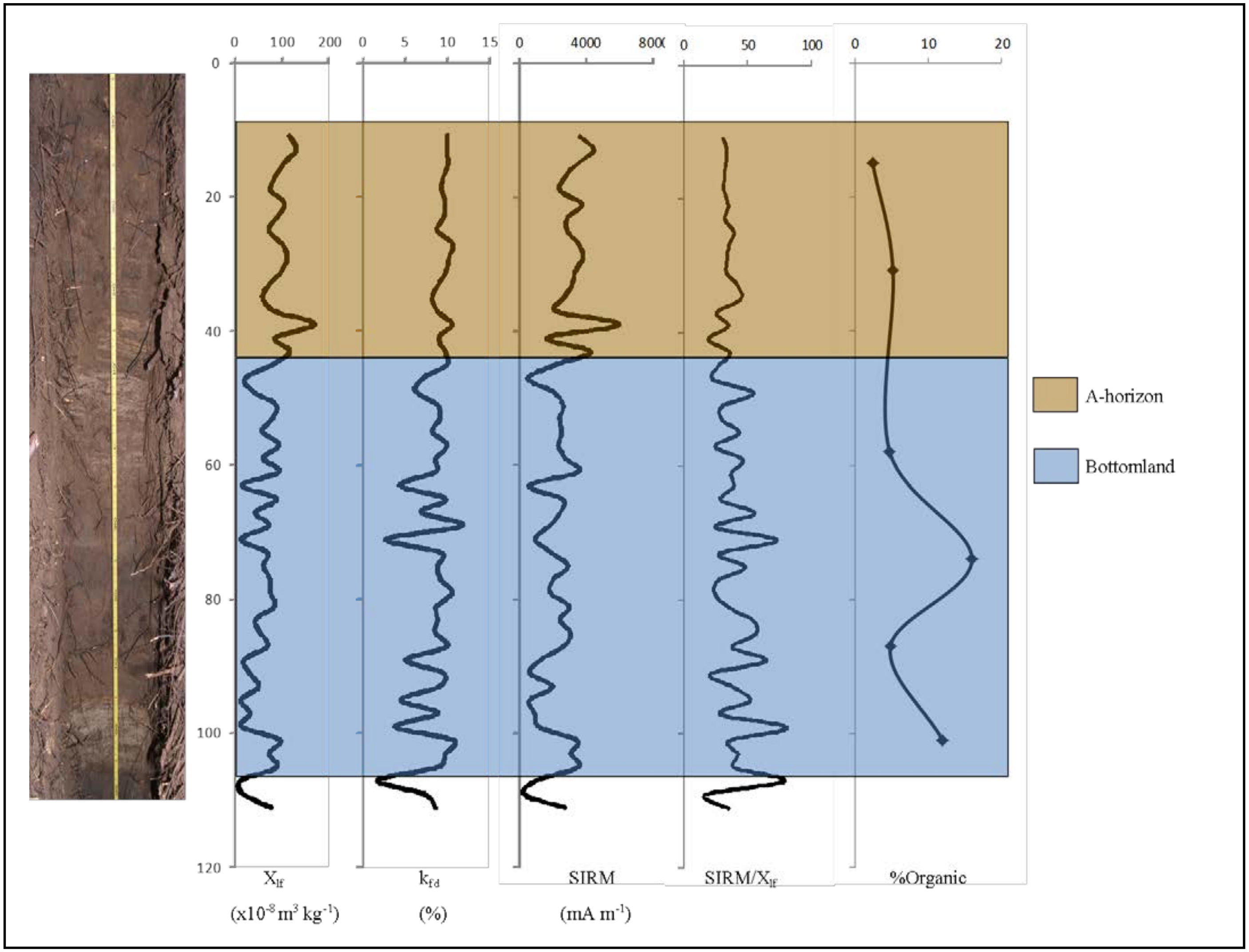

Figure 27. Lance Mill, Profile 1, Magnetic Characteristics and Organic Content.

However, coarse sand is more widely distributed; identified in strata 4, 5, 6, and 7, and ranged in proportion from 0.6 to 3 percent. Although Lance Mill pond may have trapped a relatively low proportion of suspended load, the sedimentary strata of profile 1 do vary in their textural composition.

Table 23. Lance Mill, Profile 1, Strata Texture and Color.

Stratum	Depth (cm)	Color	Texture
1	0-10	slump/wash: not sampled	n/a
2	10-20	7.5YR 3/4	silty fine sand
3	20-21	10YR 3/6: not sampled	medium sand
4	21-41	10YR 4/6	silty fine sand
5	41-68	10YR 3/4	silty medium sand
6	68-80	7.5YR 3/4	silty fine sand
7	80-95	10YR 4/4	silty fine sand
8	95-106	10YR 3/6	silty medium sand

Beginning at the base of profile 1, strata 7 and 6 exhibit a similar textural composition. Each is dominated by medium and fine sands, but the trend is a fining of sediment up-profile. Silt increases in strata 6 as sand decreases. Stratum 5 represents an abrupt change. Silt disappears and the relative proportions of medium and fine sand increases. A second abrupt change is represented by both strata 4 and 3: fine sand, silt, and clay all increase. The sediment fines up-profile as both clay and fine silt slightly increase in portion in strata 3. However, this second fining up sequence is topped by the relatively coarse stratum 1 deposit in which clay and silt decreases and sand increases.

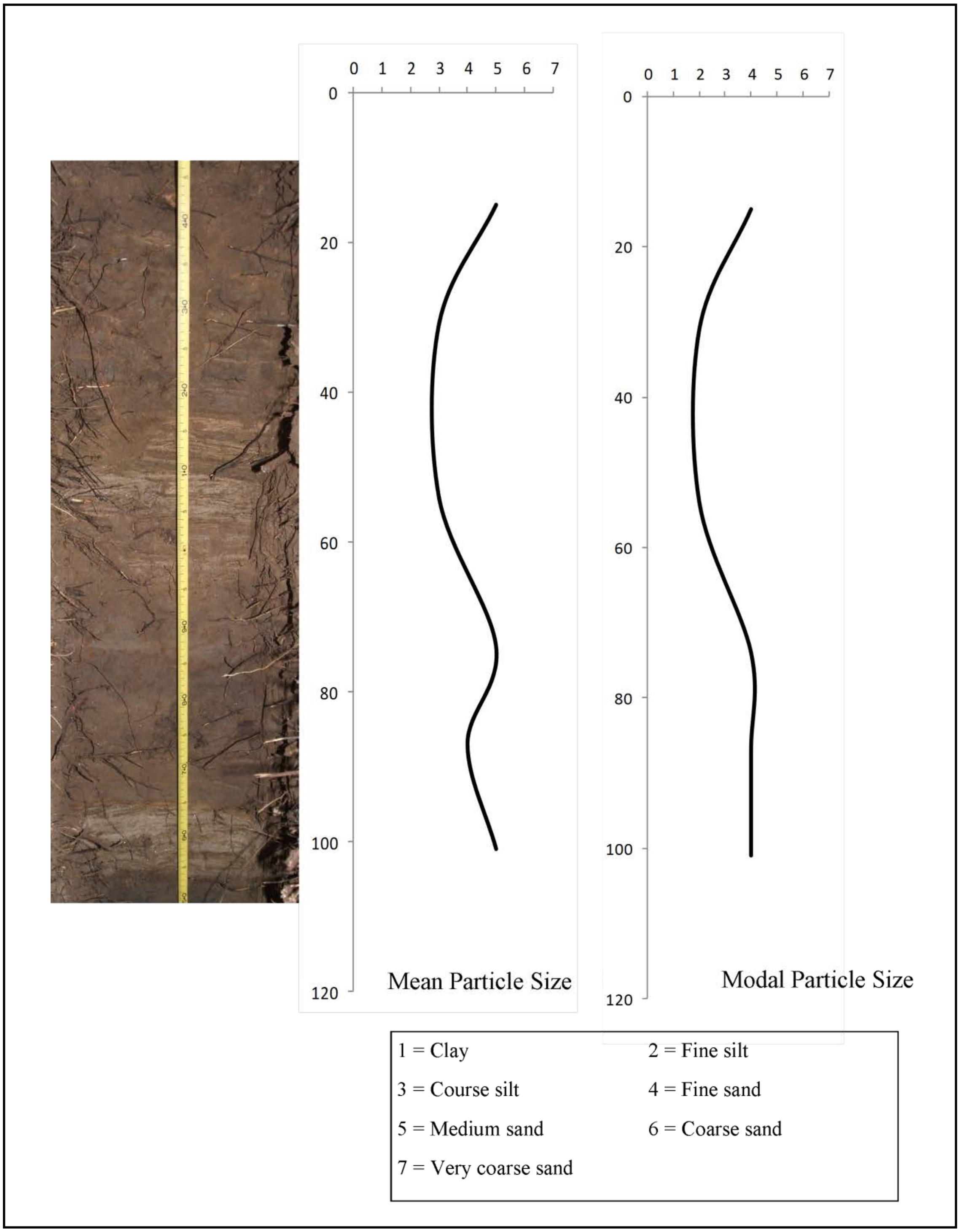

Figure 28. Lance Mill, Profile 1, Particle Size Distribution.

The magnetic parameters of profile 1 and percent organic matter are illustrated in Figure 27, and Figure 29 illustrates the trend in mean and modal particle size with magnetic parameters. As with Powell, particle size does not appear to be a controlling influence in magnetic trends. Bottomland soil pits in Lance catchment exhibited low X_{lf} and SIRM values, and the magnetic parameters of profile 1 do not exceed bottomland X_{lf} and SIRM values between 106 and 43 cm below surface. It is only in the top 33 cm (10 – 43 cm below surface) that higher X_{lf} and SIRM values occur in the profile. It should also be noted that in contrast to Powell Mill, X_{lf} and k_{fd} trend similarly throughout the profile indicating that increases in overall susceptibility are a function of an increase in SP grain concentration. This relationship was only noted in the bottom silt dominated strata at Powell Mill.

Approximately 29 cm of the pre-pond surface, comprised of overbank sediment, was also sampled in the course of field investigations (between 108 and 137 cm below surface). The value ranges of X_{lf} and SIRM in the pre-pond deposits are similar to those of the pond sediment above in that they are consistently within the ranges noted for contemporary bottomland deposits.

The magnetic character of pond sediment changes at approximately 41 cm below surface. Profile maxima in the upper 43 cm of pond sediment, exceed bottomland value ranges for both X_{lf} and SIRM, indicating a change in sediment source from bottomland to hillslope occurs at approximately 41 cm below surface. Although k_{fd} may not be used to distinguish between bottomland and slope sediment sources, the k_{fd} profile is interesting in that a change in trend is also noted at approximately 41 cm below surface.

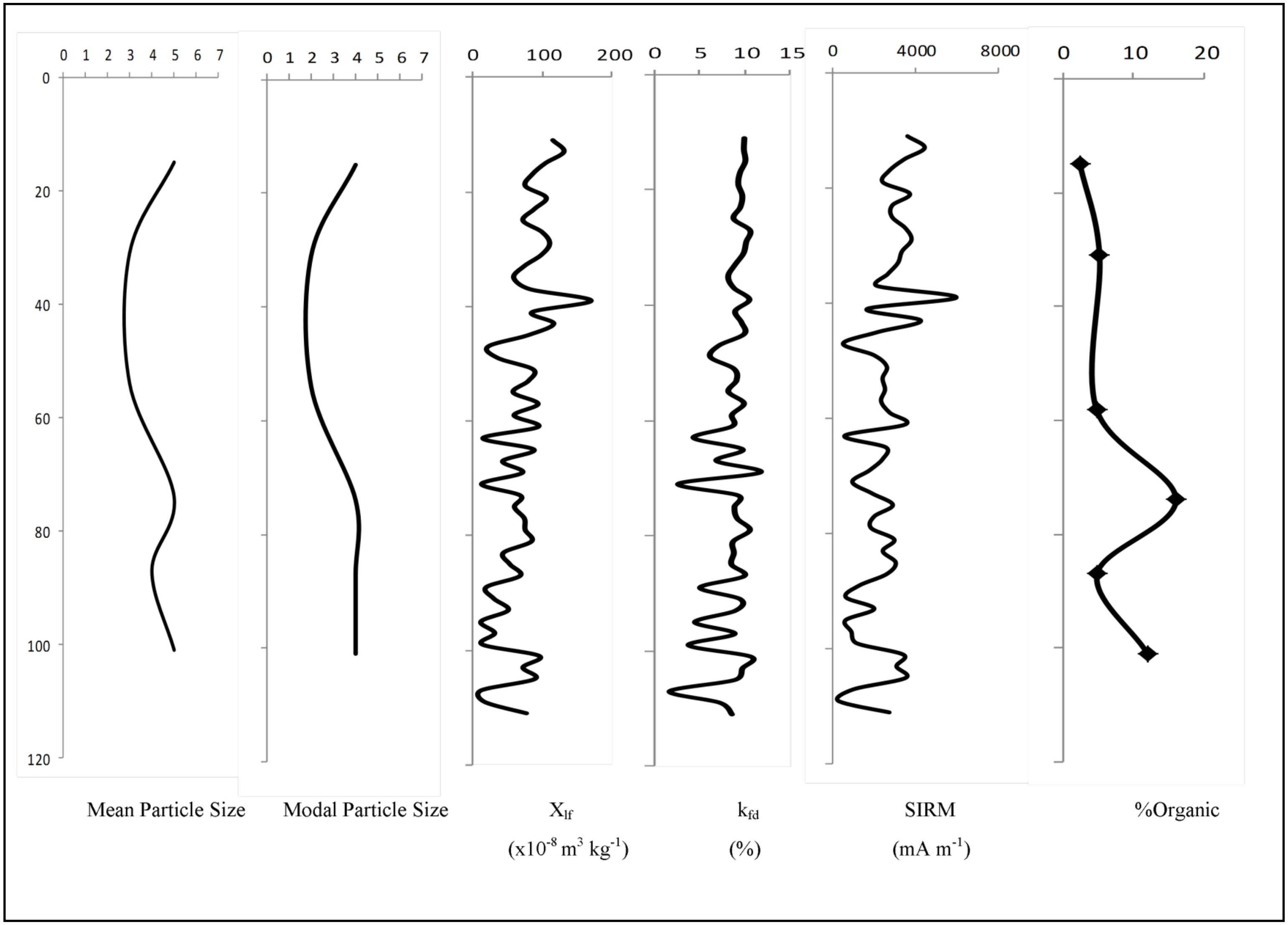

Figure 29. Lance Mill, Profile 1: Particle Size Distribution and Magnetic Parameters.

Below this depth, k_{fd} values vary considerably with four minima of 4 percent or lower. Low k_{fd} values were noted in degraded soils of the watershed but were associated with very high SIRM values. This is not the case in profile 1. Fluctuations in k_{fd} are interpreted as representing variations in flow competency.

Seven magnetically defined zones were delineated in profile 1 (Table 24). Zone seven, located at the base of the profile, a deposit of fine grained sand, was characterized by low X_{lf}, high k_{fd}, low- moderate SIRM, and high organic content. Zone seven may represent a series of high flow events during which bottomland sediment was moved through the pond.

All parameter averages decrease in zone six. The texture of this zone is slightly finer than zone seven but sand is the dominant particle size. A large increase in organic content accompanied by slight increases in X_{lf}, k_{fd}, and SIRM characterize the sandy zone 5, which is in turn replaced by a zone characterized by very low X_{lf}, SIRM, and low k_{fd}. Very dark colored sands containing plant macrofossils were observed at the base of mill pond sediments in the smaller Powell catchment, and interpreted as representing water - logged (boggy) bottoms. This type of environment would result in very low susceptibility values as a result of reducing conditions and it may be that zones 6 and 4 represent the erosion and transportation of sediment from water-logged environments. Zones 3, 2, and 1 see a continued increase in X_{lf}, k_{fd}, and SIRM, as hillslope derived sediment increasingly influences the magnetic signature of profile 1.

Table 24. Lance Mill, Profile, 1, Averaged Parameters.

Zone	Depth (cm)	X_{lf}	k_{fd}	SIRM	% Organic
1	0 - 37	93	9.5	3208	3.83
2	39 - 51	86	8.8	2752	3.83
3	53 - 61	78	8.9	2727	4.78
4	63 - 73	50	7.5	1721	n/a
5	75 - 81	74	9.4	2452	16
6	83 - 99	37	7.6	1653	4.9
7	101 - 105	86	9.8	3356	12

The pulsed character of all magnetic profiles testifies to the importance of precipitation events in both erosional processes and sediment movement within stream channels. Monthly precipitation records are available from 1895 for Southern Appalachia (ESRL 2012), corresponding with the second half of Lance Mill's operational span. The monthly precipitation totals from 1895 to 1910 are graphed in Figure 30, and average monthly totals over the fifteen year period of record detailed in Figure 31. Precipitation occurred all year round with a monthly average of 4.58 inches (11.6 cm) between 1895 and 1910. Thunderstorm activity may explain the increase noted during summer months.

Without absolute sediment dating it is impossible to correlate the precipitation record with the sedimentary record of Lance Mill pond. However, the precipitation record indicates that the highest monthly precipitation total occurred during the fall of 1901, possibly the result of tropical storm activity.

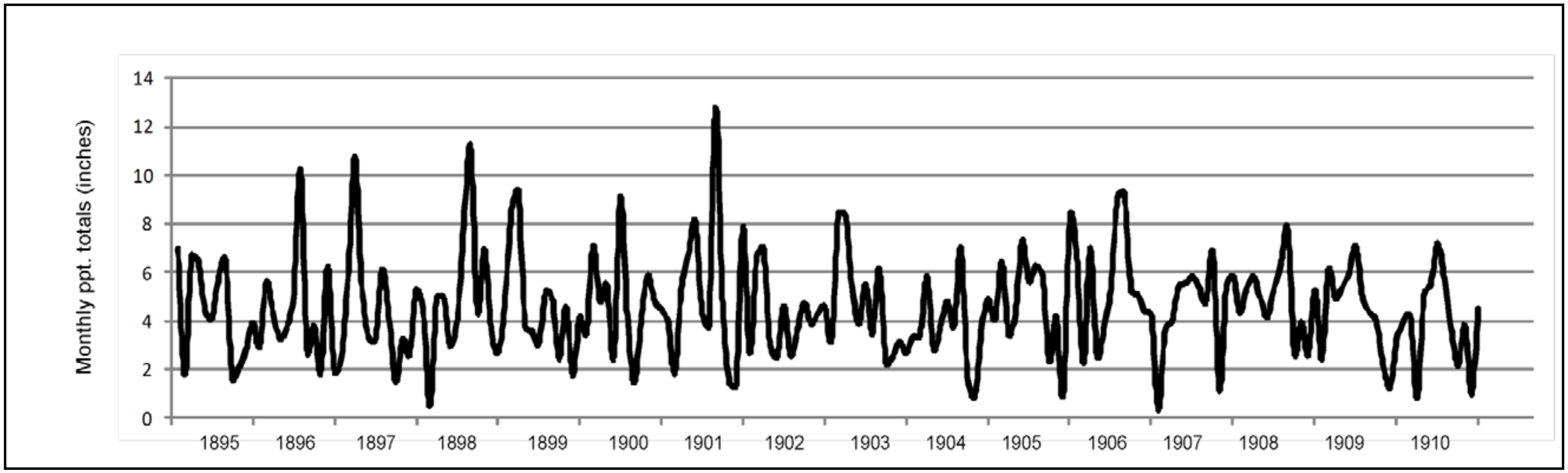

Figure 30. Monthly Precipitation Totals, 1895-1910, Southern Appalachia.

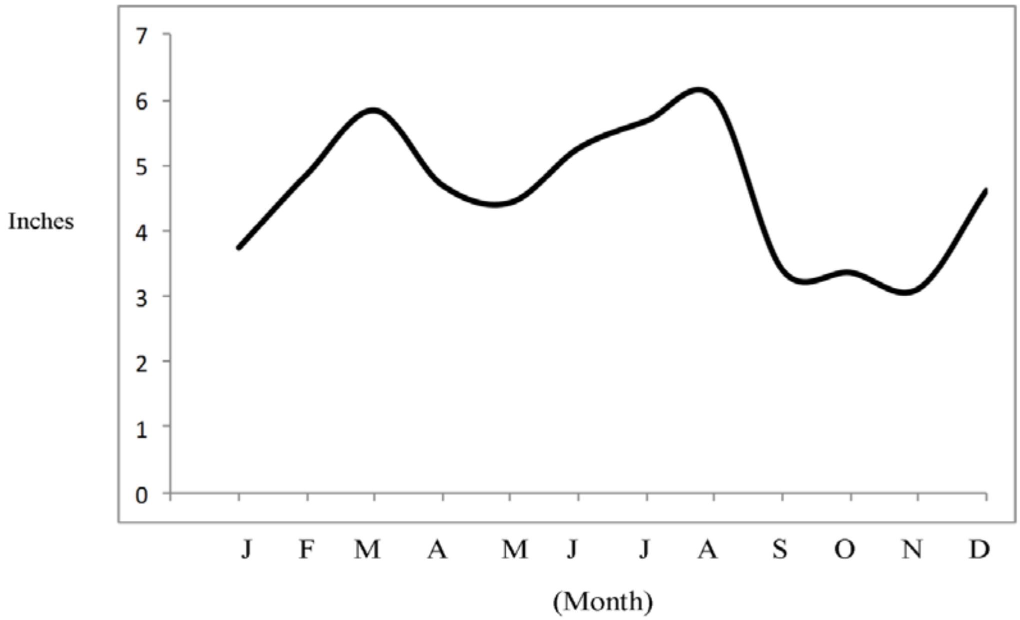

Figure 31. Monthly Average Precipitation, 1895-1910. Southern Applachia.

The magnetic profile exhibits a distinct maximum in X_{lf}, SIRM, and k_{fd}, and corresponding low X_{lf}/SIRM ratio, at a depth of 39 cm, a depth that corresponds with the top of Stratum 2. It is possible that this magnetic maximum may have been the result of the 1901 fall precipitation maximum. According to the sediment source model, the magnetic parameters at 39cm are indicative of a bottomland sediment source. However, following this magnetic maximum, magnetic parameters suggest a change to hillslope source up profile.

In summary, the averaged magnetic data indicate a general increase in susceptibility over time associated with an increase in SP grain influence. However, the range of magnetic parameters do not exceed bottomland values until approximately 41 cm after which both SIRM and X_{lf} values correspond with hillslope soil values. The susceptibility maximum at 39 cm is indicative of a major precipitation event, possibly the wet fall of 1901, after which hillslope sources predominate in the mill pond record.

Soil Erosion Modeling

Gross surficial soil erosion was calculated using GIS as described in Chapter 3. Figure 32 illustrates the calculation of USLE per grid cell in GIS for the Lance catchment. The surface volume (i.e., addition of all grid cell values) for the entire catchment area is 622 t km^{-2} y^{-1}.

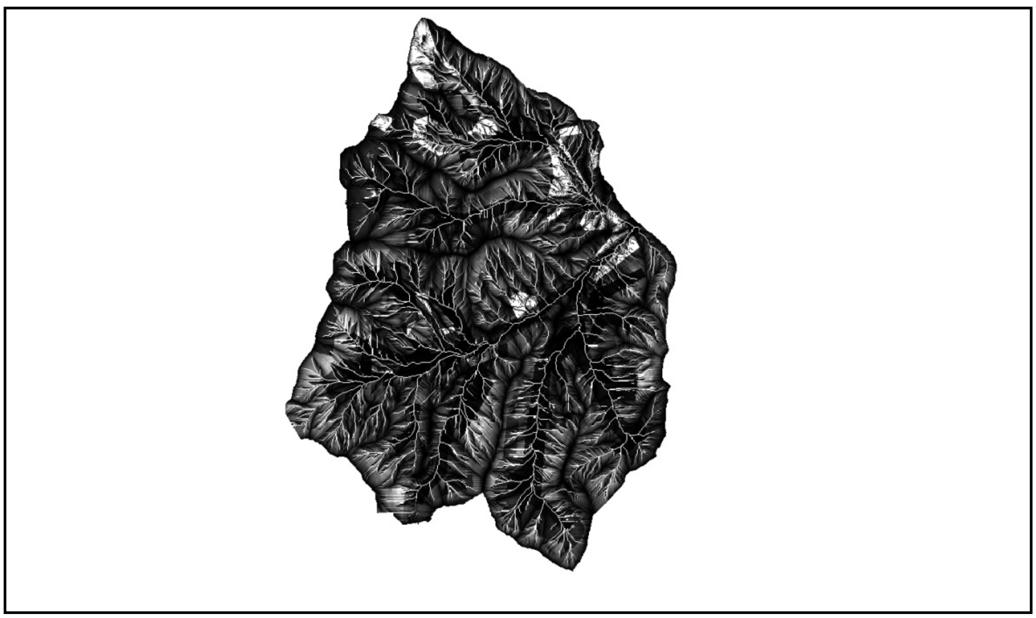

Figure 32. Lance Mill Catchment: USLE Calculated in GIS.

A minimum sediment delivery ratio can be derived for Lance Mill using the following:

$$\mathbf{SDR = \frac{Sediment\ Yield}{Gross\ Erosion} \times 100\%}$$

$$\mathbf{= \frac{4.1\ t\ km^{-2}\ y^{-1}}{622\ t\ km^{-2}\ y^{-1}} \times 100}$$

$$\mathbf{= 0.65\ \%}$$

Mill Ponds as Sources of Fine Sediment

Channel cross section profiles were used at each pond site to determine the volume of sediment evacuated since each millpond has been abandoned. A total of 865.5 m^3 of mill pond sediment has been eroded at Powell Mill as a result of channel incision, and channel bank erosion remains active. This volume was converted to mineral mass by multiplying by dry bulk density:

$$\mathbf{(865.5 \times 10^6\ cm^3) \times 0.91\ g\ cm^{-3} = 787.6\ mt}$$

An average percent value of fine silt and clay content for mill pond sediment was derived by averaging the results of particle size analysis of profile 1 (Table 25), and used to determine the mass of evacuated fine silt and clay:

$$\mathbf{787.6\ mt \times (58.2/100) = 458\ mt}$$

Powell Mill was abandoned in 1895, and the field work was conducted during 2011, spanning a total of 116 years. Therefore the medium-term average for wash-load export at Powell Mill is:

$$458 \text{ mt} / 116 \text{ years} = 3.9 \text{ mt y}^{-1}$$

The same procedure was used for Lance Mill where fine silt/clay makes up 27 percent of the total 921.6 m^3 of mill pond sediment that has been removed between 1910 and 2011.

$$(921.6 \times 10^6 \text{ cm}^3) \times 0.84 \text{ g cm}^{-3} = 774 \text{ mt}$$

$$774 \text{ mt} \times (100/27) = 209 \text{ mt}$$

$$209 \text{ mt} / 101 \text{ years} = 2.1 \text{ mt y}^{-1}$$

Table 25. Proportion of Fine Silt and Clay.

	POWELL	LANCE
Horizon	**% fine siltclayy**	
Profile 1		
1	37.8	14.8
2	19.8	58.8
3	30.4	50
4	35.2	6
5	67.8	19
6	54.4	13.4
7	22.4	
8	23.4	
9	49.8	
10	71.4	
11	69	
12	85	
13	73.6	
14	75.8	
15	79	
16	75.6	
17	68.2	
18	75.8	
19	91.4	
Average	**58.20%**	**27%**

CHAPTER V

DISCUSSION AND CONCLUSSIONS

The following chapter begins with individual discussions of the three research questionsposed at the outset of this research, followed by some general conclusions.

How do early settlement sediment yields in the Blue Ridge Mountains compare to current yields and to yields documented for the adjacent Piedmont at similar levels of settlement?

Sediment yields derived for a variety of streams in the Blue Ridge and Piedmont are detailed in Table 26 and illustrated in Figure 33. It should be noted that from the current study, only Powell Mill pond is considered as trap efficiency could not be ascertained for Lance Mill. Recent research conducted by Bolstad et al. (2006) indicates that suspended sediment yield of reforested small headwater streams is very low (2.5 t km^{-2} y^{-1}). The Dryman Fork catchment is comparable in drainage area to Powell and considered to represent pre-European settlement conditions of small headwater streams. Although presently forested, the land-use history of Dryman Fork is not known. There are however, few areas of Southern Appalachia that were not impacted by nineteenth and early twentieth century agricultural and/or logging operations, and so for the purpose of this discussion it is assumed that Dryman Fork represents a once partially devegetated watershed that has since been revegetated, although the scope of disturbance is not known.

There are few published reports of small drainage sediment yields from the Blue Ridge in general and none that date to the late nineteenth century. Data derived from Powell Mill indicate that by the end of the nineteenth century sediment yield values of small headwater stream catchments, were 62 times greater than prior to Euro-American settlement.

Table 26. Comparative Blue Ridge and Piedmont Stream Sediment Yields.

Location	Date	Land-use	Drainage area	Sediment yield
			(km^2)	($t\ km^{-2}\ y^{-1}$)
BLUE RIDGE				
Powell Mill	1880-1895	Agriculture	1.7	155
Deer Lake[1]	1927-1977	Forest	2.38	29.7
Sutton Branch[2]	2006	Mixed	1.32	34.4
Dryman Fork[2]	2006	Forest	1.53	2.5
Addie Branch[2]	2006	Forest	5.74	3.0
PIEDMONT[3]				
Pre-Agriculture	n/a	Forest	n/a	10
Late 19th century	n/a	Agriculture	n/a	208
Early 20th century	n/a	Mixed	n/a	104

[1]Royall 2003: [2]Bolstad et al. 2006: [3]Wolman 1967

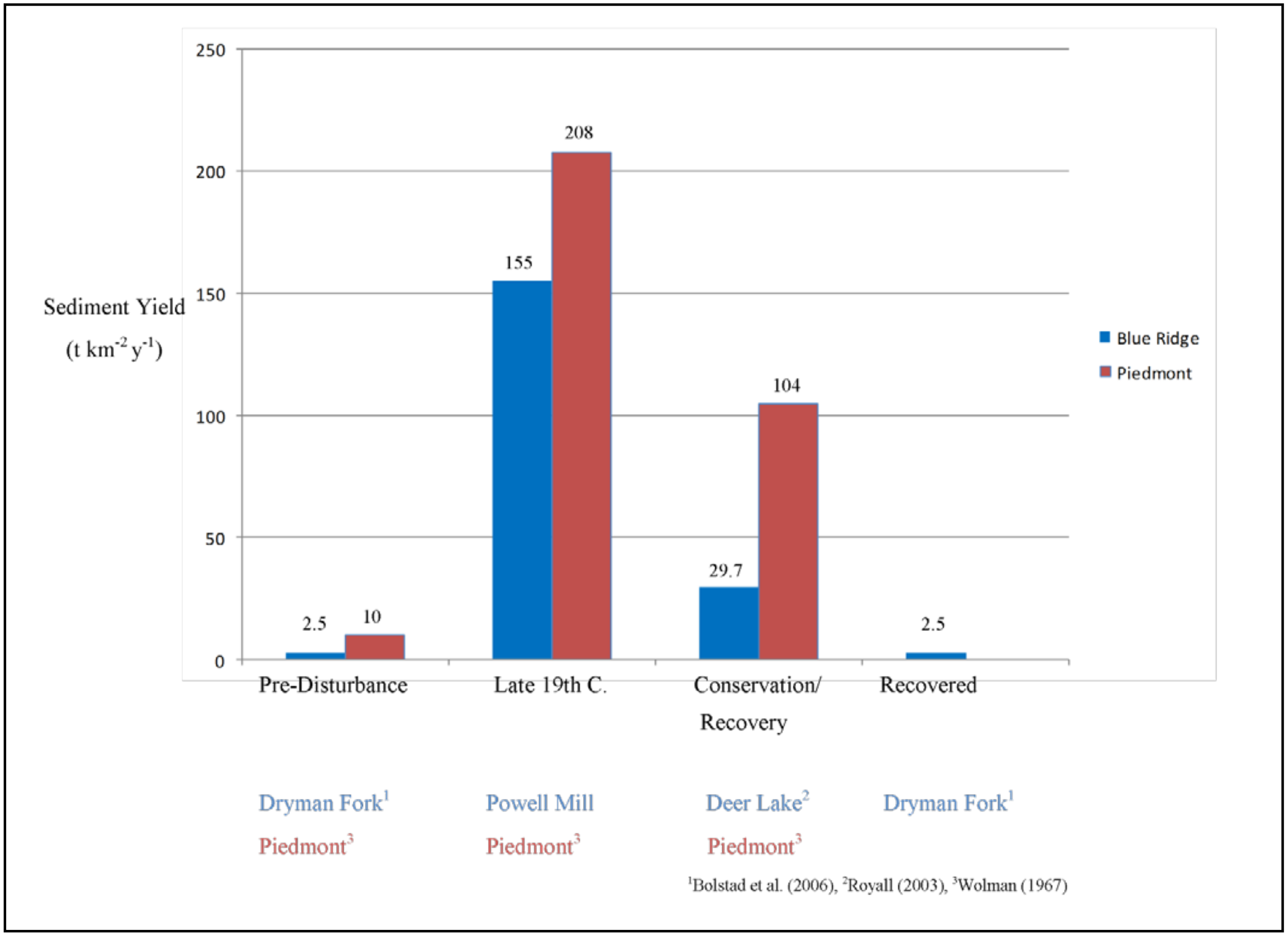

Figure 33. Blue Ridge and Piedmont Stream Sediment Yields.

Reported increases in the Piedmont over the same period are quite similar to the Blue Ridge. However, there is a considerable difference in the percentage of drainage cleared for agriculture in the Blue Ridge compared to the Piedmont.

By the late nineteenth century, close to 100 percent of Piedmont drainages had been converted to farmland. Very little original forest cover remained. In contrast, only 35 percent of the Powell Mill catchment was cleared. Blue Ridge drainages were subject to lower rates of land conversion and home to more permeable coarse soils, but steeper slopes and fewer opportunities for sediment storage resulted in high suspended sediment yield values. The trajectory of increased sediment yield in the Blue Ridge suggests that if land clearance in the Blue Ridge had expanded across entire watersheds as had occurred on the Piedmont, sediment yields would have been substantially greater than those of the Piedmont, supporting the stated hypothesis.

The recovery phase of small Blue Ridge headwater catchments is well illustrated at Deer Lake, also a tributary of Bent Creek. Deer Lake catchment land-use history, geology, climate, and relief are all very similar to Powell Mill. The investigations at Deer Lake indicate that bottomland sediment storage occurred during the nineteenth century and that the remobilization of this legacy sediment following the stabilization of catchment slopes resulted in elevated sediment yields throughout the first half of the twentieth century. The Deer Lake average annual sediment yield of 29.7 t km^{-2} y^{-1} from 1927 through 1977 although elevated is an 81 percent reduction compared to the late nineteenth century Powell Mill sediment yield value.

This finding concurs with research conducted at Coweeta, where it has been demonstrated that hillslope hydrology quickly reverts to pre-disturbance conditions following hillslope stabilization (revegetation). In areas where there is a return to almost zero surface runoff following reforestation we might only expect hillslope sediment to be delivered to the stream channel in cases of mass wastage (or in still active gullies). Elevated suspended yield rates at Deer Lake speak to the remobilization of stored bottomland deposits, depicting a lag time between hillslope hydrology recovery and stream sediment dynamics recovery.

Numerous small headwater catchments are still farmed in the Blue Ridge. Sutton Branch is comparable in size to Powell Mill (1.32 km^2), however, less drainage area is used for agriculture than Powell Mill (26.2 percent of drainage area), and is in pasture rather than row crop production. The contemporary sediment yield of 34 t km^{-2} y^{-1} of Sutton Branch is approximately one quarter of that for late nineteenth century Powell Mill. The overall percent of cleared land and differences in agricultural land-use practices may have a considerable impact on the variability of suspended sediment yields in the Blue Ridge.

The practice of conservation techniques, forest regrowth and reduction in cropland on the Piedmont also resulted in a suspended sediment yield decline during the twentieth century. However, a direct comparison of twentieth century Blue Ridge and Piedmont sediment yields is difficult owing to differences in percent drainage clearance, agricultural practices, soil types, geology, and land-use history. Although data available for the Piedmont indicates a sediment yield reduction of half (208 t km^{-2} y^{-1} to 104 t km^{-2}

y^{-1}), during the first half of the twentieth century, these data cannot be directly compared to Deer Lake. To date there is no published sediment yield data for stabilized and revegetated Piedmont drainages.

What can be stated is that the remobilization of 19th- and early 20th-century legacy sediment stored in floodplain or bottomland locations, following the stabilization of hillslopes, extends the period of elevated suspended yield in both the Piedmont and the Blue Ridge, and the low sediment delivery ratio derived from GIS modeling at Powell indicates that a substantial portion of eroded soil may remain stored in Blue Ridge catchments.

If a substantial amount of eroded material was stored on hillslopes and never conveyed to stream channels the increased hillslope (colluvial) storage would result in a decrease in bottomland storage, thereby reducing the availability of sediment for later remobilization. This statement contradicts what is generally acknowledged regarding high slope-channel connectivity in highland watersheds, but is crucial in terms of landscape sensitivity.

It is possible (likely) that GIS generated gross erosion rates are an overestimate and as a consequence, sediment delivery ratios an underestimate. Contemporary Blue Ridge sediment delivery ratios have been found to range from 6 to 36 percent (Simmons 1993). It should be noted that all sediment delivery ratios for the Blue Ridge use USLE to estimate gross rill-interill erosion, where increased slope gradients may reduced the accuracy of predicted erosion rates. However, even a sediment delivery ratio of 36 percent still requires that a substantial portion of eroded sediment be retained in the watershed. The ability of a watershed to absorb change in the form of sediment storage is a component of system resistance and is discussed further in a later section.

The physical properties of Blue Ridge soils may also play a role in reducing slope-channel connectivity. The majority of Blue Ridge soils are coarse and higher energy surface flows are required to entrain and mobilize grains. Any reduction in flow energy will result in deposition. Piedmont soils, in contrast, contain much higher proportions of clay, are less permeable, generate increased runoff when vegetation is removed, and catchments are characterized by large bottomland deposits. Lower soil erodibility values in the Blue Ridge are also a component of system resistance and are discussed further in a later section.

The habit of clearing and using ridge tops in the Blue Ridge must also be considered in terms of hillslope-channel connectivity. Throughflow and related saturation overland flow are often the dominant processes of stormflow generation in Appalachia and the Piedmont, generally resulting in overland flow adjacent to stream channels. Ridge top areas of the Blue Ridge are spatially disjointed from typical overland flow generation. Soil degradation and surface sealing is required to have occurred in order to entrain and transport soil from ridge tops, whereas cleared areas closer to channels would also have been subject to typical overland flow production in addition to increased overland flow produced as a result of soil degradation. Secondly, areas of woodland often existed between cleared ridge tops and stream channels increasing the likelihood of redeposition of eroded material downslope. However, if high rates of bottomland deposition did occur, then initial rates of sediment evacuation must have been high following hillslope restabilization.

How sensitive to land-use were hydrological, erosional, and sediment delivery subsystems in early mountain watersheds?

The following discussion of the sensitivity of Powell and Lance watershed geomorphic subsystems is framed by Phillip's modified landscape sensitivity model (2009), in which system changes are examined in terms of response, resistance, resilience, and recursion.

Response

Response speaks to the timing and rate of geomorphic response to change, and includes two components. The first is reaction time, the timing of the initial response, following the onset of system disturbance, and secondly, relaxation describes the time the system requires to recover from the disturbance.

Reaction Time

The hypothesis relating to the initial hydrological response states that an initial resistance to upland soil erosion coupled with a reduction in transpiration rates, would have resulted in higher than average stream flows able to erode and transport bottomland sediment at a greater rate than that of upland sheet erosion. Both Lance and Powell mills were constructed after land clearance had been initiated in their respective catchments and the mill deposits represent a window into on-going hydrogeomorphic processes rather than to initial watershed response.

However, although both mill dams were constructed in 1880 and clearance had occurred prior to 1880 in both catchments, sediment data from the two mill ponds differ. The early deposits of both ponds contained relatively high percent organic content, a characteristic of A-horizon upland soils. However, only the lower sediments of Powell Mill demonstrated magnetic characteristics of upland soil A-horizons. The entrainment and transportation of hillslope A-horizon fines was underway in Powell catchment by 1880. Coarser A-horizon material and then lower B-horizon material appear up-profile, punctuated by high flow events.

A similar response did occur in the Lance catchment but not until approximately 1900. Again, the change from bottomland to upslope derived material in the Lance mill is separated by a high flow event. The time lag in the appearance of A-horizon material in Lance Mill deposits may be a function of percent cleared area, as only 13 percent of Lance was cleared compared to 35 percent at Powell. However, evidence from both ponds clearly indicates a coupling of the progression of human induced erosion and climatic factors.

The hydrologic reaction time was less than upland soil erosion time. Bottomland erosion in the Lance catchment speaks to increased stream capacity although cleared land only accounted for 13 percent of the catchment. Changes in streamflow at Coweeta only occurred when more than 20 percent of vegetation cover was removed. The difference between late nineteenth century evidence and contemporary evidence may be in the nature of the remaining woodland: natural at Coweeta compared to historically managed.

Relaxation Time

Contemporary research indicates that once hillslopes are stabilized hillslope hydrology returns to predisturbance conditions in a little as one year. However, sediment yield relaxation time lags behind hydrologic relaxation time. The onset of agriculture (disturbance) occurred in both watersheds around 1825 and continued until approximately 1900. If we accept the ergodic reasoning presented in the first section (figure 33); that Dryman Fork represents pre-disturbance and possibly recovered conditions, Deer Lake represents twentieth century recovery conditions, and Powell Mill represents late nineteenth century conditions, the time required for a small headwater watershed to return to pre-disturbance sediment yield rates is approximately100 years:

Onset of agriculture...	~1825
Slope stabilization…	~1900
Return to predisturbance SY rates	~2000

The ecological significance of this lag in sediment yield relaxation time may be significant for a variety of reasons: increased washload is known to be detrimental to highland fish and invertebrate habitat; increased turbidity increases the cost of producing safe drinking water; and the possible adverse ecological and health issues associated with the remobilization of potential contaminants especially to areas downstream of historic mining operations (e.g., arsenic and mercury).

Once both hydrological and sediment yield relaxation has occurred will any evidence of nineteenth century agricultural activity remain in the watershed? A sediment delivery ratio of 10.3 percent at Powell Mill indicates that landform changes must have occurred in the watershed in response to increased nineteenth century soil erosion rates possibly in the form of increased colluvial deposits and in-channel deposits. If these landforms continue to exist in the watershed 100 years following slope stabilization, are they permanent or transient? And do they continue to operate as sediment sources?

The relaxation/duration ratio (RDR) (Phillips 2009) is a modification of the transient form ratio (TFR) (Brunsden and Thornes 1979). A TFR >1 is indicative of a landscape in which the time between disturbances is less than relaxation time, and as a result, that landscape is dominated by transient landscape forms. If however, TFR <1, sufficient relaxation time has passed before the following disturbance. Such a landscape is dominated by permanent landforms. Philips's modification of TFR simply allows the researcher to use the same logic but apply to a disturbance that occurs over a period of time. If we assume that soil erosion (however limited) was initiated in 1825, and continued until slope stabilization in 1900, then the duration of the disturbance is 75 years, and assume a relaxation time of 100 years, then:

$$\mathbf{RDR = R_i/\Delta t_i}$$
$$\mathbf{= 100\ years/75\ years}$$
$$\mathbf{= 1.33}$$

where:

Ri = relaxation time

Δt_i = duration of event

An RDR>1 indicates that landforms that occurred as a result of elevated soil erosion rates may have been considered transient for as long as elevated soil erosion rates continued. Blue Ridge headland catchments in which elevated soil erosion rates are ongoing can be considered to be dominated by transient forms, and stored sediment may be expected to serve as a sediment source.

However, in a fully reforested catchment such as Powell, where sufficient relaxation time has passed without additional disturbance, remaining landforms may now be considered permanent rather than transient, and less likely to serve as sediment sources. Examples may include colluvial deposits, stabilized mill pond sediment, bottomland deposits, and possible stream channel modifications.

Resistance

Resistance is defined as the ability of a system to avoid or minimize responses to disturbance, and can be addressed in terms of strength and/or capacity (Phillips, 2009). Soil erodibility is a measure of strength. Sandy soils, typical of the steep slopes in both catchments are typified by low erodibility values as permeability tends to be high reducing runoff, and higher energy flows are required to entrain and transport larger grains. However, loamy soils (i.e., soil with higher silt content) more commonly located on lower slopes in both catchments are more erodible. Therefore resistance to soil erosion would have varied spatially across catchments. As the majority of Blue Ridge soils are coarse grained and more permeable than those in the Piedmont, the overall resistance to soil erosion would be expected to be higher in the Blue Ridge than in the Piedmont.

The capacity of a system to absorb change is also a measure of resistance. The behavior of the sediment delivery sub-system in the Powell Mill basin exemplifies system resistance. The low sediment delivery ratio calculated for the Powell Mill catchment indicates that the majority of eroded sediment was not conveyed to stream channels but redeposited downslope. The sediment delivery ratio calculated in GIS may be lower than in reality, the calculation skewed by steep slopes, but indicates that the watershed was able to absorb some of the change imposed by nineteenth century land-use change. However, in contrast to the higher resistance of Blue Ridge soils to erosion compared to the Piedmont, the ability of the Blue Ridge to absorb change in the form of sediment storage is expected to be less than that of the Piedmont.

Resilience

Resilience is a measure of a landscape's ability to recover toward pre-disturbance conditions, and in this situation the concept must be discussed in terms of hydrological, soil stability, and sediment dynamics. Although not the focus of this research, it has been demonstrated that when eastern woodlands are reforested, both hillslope hydrology and soil stability recover very quickly, often in just a few years, and it is assumed that this was also the case for both Lance and Powell catchments. However, as shown above, a return to pre-disturbance sediment yield values takes longer, possibly up to one hundred years (or longer), two orders of magnitude difference. Evidence from Deer Lake may indicate that sediment yield rates do not decline linearly but that sediment yield rates decline quite drastically once slope stabilization occurs, and then decay more slowly over time.

Recursion

Recursion addresses the possibility that once a change has been initiated either negative or positive feedback mechanisms may occur. Changes in geomorphic systems are rarely linear, usually the result of feedback mechanisms. Although not the focus of these investigations, it is very likely that positive feedback played a role in elevated soil erosion rates at Bent Creek. Once vegetation is removed, soil sealing occurs when clay sized particles are washed by rain into pores between larger grains. The result is a decrease in infiltration and corresponding increase in runoff, which in turn entrains more particles, increasing rates of erosion.

How important have historic mill dam sites been as sources of fine, chemically active sediment in twentieth century loads at Bent Creek?

The Bent Creek Experimental Forest is approximately 25.5 km^2, and a total of five mill dams were constructed in the watershed during the nineteenth century (i.e., Case, Boyd, Hatch, Lance, and Powell) representing a mill pond density of one pond per 6.4 km^2. Bent Creek was not atypical and although there are few if any material remains left today to indicate the ubiquity of nineteenth century water powered mills throughout Southern Appalachia, it can be reasonably assumed that the pond density data of Bent Creek is representative of the Blue Ridge region in general. The abandonment of water power and the decay of log-crib dams resulted in stream incision and the remobilization of pond sediment. As stream incision progressed during the early twentieth century, did pond sediment remobilization result in increased fine sediment loads at Bent Creek?

There are two separate considerations here. First, quantifying the textural composition of pond sediment is vital. Clearly, if pond sediment is relatively coarse then it cannot serve as a fine sediment source. Secondly, the rate of sediment evacuation influences the impact of mill ponds as sediment sources. A relatively fast evacuation rate may have a greater impact on water quality in the short term but allow water quality to rebound quickly, whereas a relatively slow rate may have a limited impact in the short term but a greater impact over the long term as water and benthic habitat quality remains depressed over a longer period of time and negative impact accumulates. Powell and Lance mill ponds demonstrated variation in both these regards.

Rate of Sediment Evacuation

Powell and Lance mill ponds were similar in size and volume but varied in terms of drainage area. Powell Mill pond served as the outlet of a 1.7 km^2 drainage area and Lance Mill pond served as an outlet of a 9.1 km^2 drainage area. Consequently, stream discharge at Lance is greater than at Powell for the same precipitation event and may explain the difference in channel width and bank stability noted at the two sites.

The banks of Rocky Cove Branch, through Powell pond, are characterized by bank undercutting and slumping (Figure 34). Bank erosion is on-going and the stream banks are unstable along the mill pond reach. No other area of bank instability was noted upstream of the mill pond. In contrast, the Bent Creek channel is not only wider through the Lance Mill pond, but channel banks are heavily vegetated and show no evidence of current erosion (Figure 34).

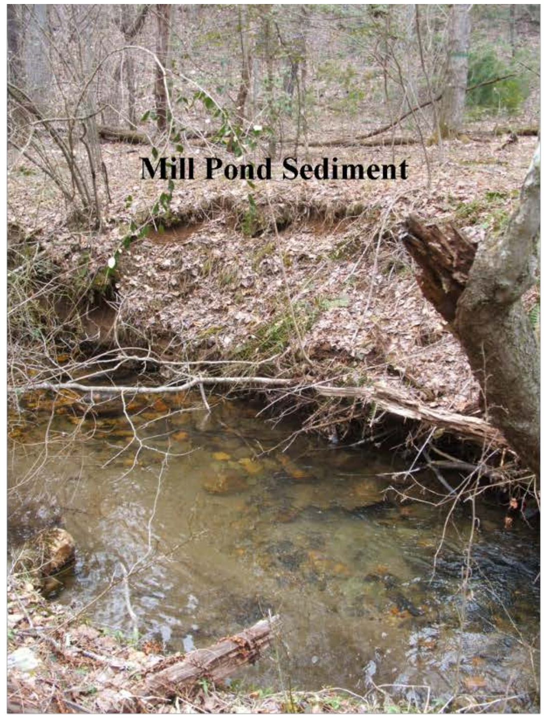

Figure 34. Channel Bank Stability at Powell (top) and Lance (bottom) Mills.

Slightly less mineral mass has been removed from Lance Mill pond, compared to Powell Mill pond (774 mt and 787 mt respectively). However, channel bank conditions suggest that sediment evacuation occurred relatively faster at Lance compared to Powell. These different rates of evacuation are believed to be principally a function of catchment discharge.

Pond Sediment Texture

Catchment area controls pond inflow which impacts dam trap efficiency which in turn influences overall pond sediment texture. Higher trap efficiency rates at Powell (small catchment area), resulted in a relatively high silt and clay content (58.2 percent). In contrast, the very low trap efficiency of the Lance dam (high catchment area) resulted in a relatively low proportion of silt and clay (27 percent).

Powell and Lance are two of five nineteenth century mill ponds constructed in Bent Creek. Boyd, Hatch, and Case mills were all located downstream on the main stem of Bent Creek (larger catchment areas) and each operated over a longer time span than either Lance or Powell. An averaged mill pond mineral mass derived from Powell and Lance data will serve as a minimum mineral mass for each of the other three nineteenth century ponds in the watershed.

Total mineral mass deposited at Powell mill over a period of fifteen years equals 1,108 mt, and the total mineral mass deposited at Lance over a twenty year period equals 1,121 mt: an average mineral mass of 1,114 mt. Therefore, a minimum nineteenth century mineral mass trapped behind pond dams equals 5,570 mt, and a significant portion of this sediment has been evacuated since the abandonment of water power.

Brief field observations at Case and Hatch mills indicated that post-dam stream incision had also occurred at these two locations (Boyd Mill deposits lie beneath Powhatan Lake and are therefore inaccessible).

A total of 774 mt of sediment has been removed at Powell (i.e., 70 percent) and a total of 787 mt of sediment has been removed at Lance (i.e., 70 percent). If we assume a similar rate of evacuated mass throughout the watershed then:

$$\textbf{Total evacuated nineteenth century sediment} = \frac{\textbf{5,570 mt}}{\textbf{1}} \times \frac{\textbf{70}}{\textbf{100}}$$

$$= \textbf{3,899 mt}$$

Twenty-seven percent of the Lance mill deposit comprised clay and silt sized particles and 58 percent of Powell Mill comprised clay and silt: an average of 42 percent. Therefore:

$$\textbf{Minimum clay and silt released into Bent Creek} = \frac{\textbf{3,899 mt}}{\textbf{1}} \times \frac{\textbf{42}}{\textbf{100}}$$

$$= \textbf{1,637 mt}$$

If this sediment were released into Bent Creek over a relatively short period of time, for example 20 years, the annual fine sediment loading would have been:

$$\frac{\textbf{1,637 mt}}{\textbf{20 years}} = \textbf{82 mt per year}$$

If released over fifty years, then:

$$\frac{\mathbf{1{,}627\ mt}}{\mathbf{50\ years}} = \mathbf{32\ mt\ per\ year}$$

A minimum early twentieth century fine sediment load at Bent Creek derived solely from evacuating millponds may have ranged from 32 – 82 mt per year. Sediment yield data derived from investigations at Deer Lake indicated that an average annual sediment yield of 29.7 t km^{-2} y^{-1}, was generated by the 2.38 km^2 Wolf Branch catchment between 1927 and 1977 (Royall 2003). The higher trap efficiency of Deer Lake reservoir (compared to nineteenth century mill dams) suggests that half the sediment yield may be assumed to be clay and silt. Therefore, the recovering Wolf Branch catchment may have been generating 14.8 t km^{-2} y^{-1} clay and silt, between 1927 and 1977.

The Wolf Branch catchment comprises approximately 10 percent of the Bent Creek Watershed. If we extrapolate the clay and silt sediment yield rates derived from Wolf Branch across the Bent Creek watershed, then 148.0 t km^{-2} y^{-1} of silt and clay may have been generated in the Bent Creek watershed between 1927 and 1977. The increase in fine particulates solely from evacuating millponds during this period would have increased the total by 22 to 55 percent, depending on the rate of evacuation. Nineteenth century mill ponds clearly then served as significant sources of fine particulates during the first half of the twentieth century prolonging the recovery of stream channels and water quality even in watersheds where reforestation was encouraged and hillslope stability aggressively pursued.

Conclusions

With only a 35 percent land conversion from woodland to row crop production in Powell Mill catchment, sediment yield may have increased from 2 to 3 t km^{-2} y^{-1} up to 155 t km^{-2} y^{-1} by the end of the nineteenth century. Although lower than contemporary Piedmont values, it is safe to assume that had land conversion rates been similar to those of the Piedmont, sediment yield values in the Blue Ridge would have surpassed those of the Piedmont.

The initial hydrologic response, increased stream flow, first resulted in the remobilization of stored bottomland sediment. Once initiated, hillslope erosion progressed by first removing A-horizon fines, then coarser A-horizon particulates, and finally lower B-horizon material; the rate of this progression a function of watershed size and percent cleared land. High energy/intensity precipitation events forced changes in the erosional system and there is a clear coupling of human-induced soil erosion and climate in the sediment record of both mill ponds. This is significant in light of projected climate change. If the frequency of high intensity precipitation events increase as predicted then the boundaries of upland soil erosional systems will change and sediment yields will likely increase, particularly in cleared areas.

A low sediment delivery ratio for nineteenth century Powell Mill, indicates that a substantial portion of eroded soil remained in low order headwater catchments suggesting that there may be differences in hillslope-channel connectivity between high velocity mass movement events such as landslides and human-induced soil erosion. If allowed to fully reforest, Blue Ridge watersheds may reestablish pre-settlement erosional and sediment yield conditions within approximately 100 years and any remaining landforms resulting from nineteenth century land-use will become persistent. However, unlike the Bent Creek Experimental Forest, many Blue Ridge catchments contain a variety of land uses and sediment yield values continue to be elevated. In such watersheds pre-disturbance conditions have not been reestablished and landforms may be considered transient.

Mill pond sediments are essentially a form of bottomland deposit and as such have been partially evacuated from low order basins with stream channels incision: the rate of evacuation a function of stream flow and competency. During the first half of the twentieth century Blue Ridge washload was substantially increased by erosion of mill pond sediments and relatively high volumes of silts and clays moved downstream into higher order stream channels. However, a portion of mill pond sediment does remain in low order stream channels although the rate of evacuation has decreased considerably, most evacuation now only occurring during high intensity precipitation events. As such, increases in high intensity precipitation frequency (projected climate change) may result in increased evacuation rates, remobilizing fines and possible associated contaminants.

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