THESIS

POST-GLACIAL VALLEY EVOLUTION AND POST-DISTURBANCE CHANNEL RESPONSE AS A CONTEXT FOR RESTORATION, UPPER COLORADO RIVER, ROCKY MOUNTAIN NATIONAL PARK

Submitted by

Zan K. Rubin

Geosciences Department

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WE HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER OUR SUPERVISION BY ZAN K. RUBIN ENTITLED POST-GLACIAL VALLEY EVOLUTION AND POST-DISTURBANCE CHANNEL RESPONSE AS A CONTEXT FOR RESTORATION, UPPER COLORADO RIVER, ROCKY MOUNTAIN NATIONAL PARK BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE.

Committee on Graduate Work

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Brian Bledsoe

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Advisor: Ellen Wohl

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Co-Advisor: Sara Rathburn

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Department Head: Sally Sutton

ABSTRACT OF THESIS

POST-GLACIAL VALLEY EVOLUTION AND POST-DISTURBANCE CHANNEL RESPONSE AS A CONTEXT FOR RESTORATION, UPPER COLORADO RIVER, ROCKY MOUNTAIN NATIONAL PARK

In 2003 a human-caused debris flow initiated by a breach in Grand Ditch in Rocky Mountain National Park delivered ~36,000 m^3 of sediment into the Colorado River. The debris flow deposited up to ~1 m of sediment in the Lulu City wetland and major reworking of the Colorado River channel also occurred. The objectives of this study are to determine 1) how the 2003 deposit in Lulu City wetland relates to the historic range of variability in rates and processes of aggradation during the Holocene; and 2) if recovery of channel forms and processes has occurred in the Colorado River during the six years following 2003. Ground penetrating radar surveys, soil descriptions, and radiocarbon dating were used to quantify rates and processes of fill in Lulu City wetland. Channel recovery was assessed by comparing sediment transport rating curves to reference sites, monitoring changes in channel geometry, and quantifying bed material gradation. Results indicate that aggradation rates in Lulu City wetland varied through the late Holocene at periods correlated with distinct climates, and have increased approximately sixfold during the past 1-2 centuries of anthropogenic influence. Results from the Colorado River indicate channel forms and processes recovered between 2003 and 2009. Bed armoring and removal of fine sediments occurred, and channel stability persisted from 2003-2009. Results from the Lulu City wetland and impacted Colorado River can be used to guide effective restoration following the 2003 debris flow.

Zan K. Rubin
Department of Geosciences
Colorado State University
Fort Collins, CO. 80523
Summer 2010

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When it blows,

The mountain wind is boisterous,

But when it blows not,

It simply blows not.

- Ikkyu

Contents

1. Introduction

The Context of This Research

In May 2003, a breach in the Grand Ditch transbasin diversion channel initiated a debris flow in Rocky Mountain National Park that transported ~36,000 m^3 of sediment into the Upper Colorado River and deposited up to 1 m of sediment in the Lulu City wetland. Restoration of channels, riparian areas, and wetlands impacted by the debris flow is planned. This thesis contains the results of two separate yet intertwined research efforts to provide context for restoration of the Lulu City wetland and the upper Colorado River, including: 1) an assessment of post-glacial valley aggradation to quantify the historic range of variability of rates and processes of fill (quantified by assessing the range of pre-impact aggradation rates and relative contributions of processes), and 2) an assessment of channel response and recovery of the Colorado River following the debris flow. To understand the historic range of variability of disturbance and recovery, I investigated valley-bottom morphology (including channel planform) and aggradational history through a combination of aerial photography analysis, ground penetrating radar surveys, radiocarbon dating, and soil pits in the Colorado River headwaters. Channel recovery was assessed through an analysis of post-disturbance sediment transport, channel geometry, comparison with upstream reference conditions, and assessment of bankfull discharge.

This introductory chapter reviews strategies of stream restoration and provides an overview of the study site. The second chapter presents research on post-glacial valley evolution and provides historical context for the 2003 debris flow and restoration opportunities in the Lulu City wetland. The third chapter investigates post-debris flow hydrogeomorphic processes in the Colorado River upstream from the wetland and evaluates the trajectory of channel response and stability. The second and third chapters present the research objectives, hypotheses, methods, results, and discussion specific to each chapter's research emphasis. A final concluding chapter discusses opportunities for restoration.

1.1 River restoration in the United States

Restoration of rivers, streams, and wetlands has received an increasing level of interest and funding in recent decades. This trend will likely continue as the need for, and recognized value of, ecosystem services such as clean drinking water and fish habitat continue to grow throughout the world [*Bernhardt et al.*, 2005]. Recent assessments suggest many rivers are currently in physically and/or biologically impaired conditions. In the United States, 42% of wadeable streams were deemed to be of "poor" biological condition [*Paulsen et al.*, 2008]. Freshwater ecosystems represent ~0.01% of global area, but account for more than 9% of all known species [*Balian et al.*, 2008]. These freshwater ecosystems and the species they support are disproportionately threatened compared to terrestrial and marine ecosystems in the United States [*Ricciardi and Rasmussen*, 1999] as well as worldwide [*Vie et al.*, 2009]. As protection and restoration efforts increase, restoration efforts are under increasing scrutiny to ensure maximum efficacy.

In the last decade, a great deal of attention has been paid to assessing what goals restoration can hope to accomplish and what methods of restoration are actually effective. River restoration can have varied targets and can occur on many spatial and temporal scales. Most commonly, "restoration" refers to reach-scale projects to improve water quality, instream habitat, bank stability, fish passage, or riparian vegetation [*Kondolf*, 1996; *Bernhardt et al.*, 2005]. An increasing number of restoration projects, however, are larger scale efforts to implement environmental flows [*Poff et al.*, 1997; 2009], remove dams [*Bednarek*, 2001; *Hart and Poff*, 2002], or target landscape causes of riverine degradation. Large, high profile examples of watershed-scale restoration include wetland restoration for flood abatement and water quality improvement throughout the Mississippi River basin [*Zedler*, 2003], restoration of floodplain connectivity and wetlands in the Kissimmee River [*Dahm et al.*, 2006], and water allocation and levee setbacks in the San Francisco Bay Delta [*Doyle and Drew*, 2008]. Many have argued that the watershed scale is the most appropriate for effective restoration because restoration of a watershed addresses the root causes of degradation rather than treating a single expression of a commonly fundamental problem [*Williams et al.*, 1997; *National Research Council*, 1999; *Wohl et al.*, 2005]. Case studies such as Redwood Creek, where channel stability was enhanced downstream without addressing sediment inputs upstream, suggest the absurdity of reach-scale treatments when upstream causes of degradation are not addressed [*Ziemer*, 1997].

Because it is not always feasible to achieve restoration on the watershed scale, a growing number of restoration practitioners and scholars also argue for the importance of process-based restoration targets [*Wohl et al.*, 2005; *Kondolf*, 2006; *Kondolf et al.*, 2006]. Process-based restoration seeks to re-establish the functions and trajectory of landscape evolution to which native species are adapted. That is, process-based restoration is a pragmatic way of targeting the varied (and commonly unknown) habitat needs of *all* native species. Because in most cases it is infeasible to quantify the natural spatial and temporal variability of biological organisms or systems, process-based restoration instead seeks to recover physical functions and therefore to benefit native species. The process-based approach to restoration acknowledges the dynamic quality of landscapes by allowing variability and disturbance (a natural part of all systems) at reasonable levels, while permitting riverine landscapes to evolve and adapt to physical and biological processes of their watersheds. The discussion herein follows the definition of disturbance offered by Resh et al. [1988], as discrete events outside the normal range of frequency, intensity, and severity that disrupt ecosystem habitat, community, or population structure and change resources or the physical environment. In the context of the Lulu City wetland and Colorado River restoration, it becomes important to not only identify disturbance events, but to distinguish altered disturbance regimes, so that the magnitude and frequency of non-human-induced disturbances such as floods, fires, droughts, and debris flows to which ecosystems are adapted are differentiated from more extreme events, often human-caused, beyond the frequency or intensity present in the historic range of variability. For the purposes of restoration planning, it is insufficient to describe an event as a disturbance; we must also investigate whether the event is fundamentally different in severity or frequency from the natural system. (The magnitude, frequency, and duration of a specific process such as stream flows or debris flows prior to intensive human resource use in an area define what will hereafter be referred to as the historic range of variability for that process.) This distinction is fundamental to the research focus of this thesis, which seeks to determine whether the disturbance regime of the upper Colorado River has been significantly altered by humans during the past two centuries and thus establish a longer temporal context for setting restoration goals following a recent human-induced disturbance.

The foundation of process-based restoration is to understand what the natural forms and functions of a watershed were and can be, given imposed climatological, ecological, and geological conditions, as well as land-use constraints. Failure to appropriately assess the historic variability of a system, or to appropriately define contemporary flow and sediment dynamics, has resulted in several well-documented restoration failures such as Cuneo and Uvas Creeks in California, where restoration activities attempted to impose meandering channels in locations where watershed conditions suggested braided or unstable planforms [*Kondolf*, 2006], and Whitemarsh Run in Maryland [*Soar and Thorne*, 2000], where a channel was designed without the capacity to transport the inflowing sediment load. Innumerable other restoration projects have not achieved any broad ecological benefit because restoration attempted to impose forms that were inappropriate or unsustainable given present climate, land-use, and watershed conditions [*Wohl et al.*, 2005].

The foundation of process-based restoration rests in accurately assessing process targets such as upstream/downstream, channel/floodplain, and surface/groundwater connectivity [*Wohl et al.*, 2005]. In the case of river restoration, knowledge of process can be 1) extrapolated from theoretical or empirical knowledge of river process-form interactions in general, 2) based on historical records from the site to be restored, or 3) based on extrapolation from nearby, less impacted, reference sites. The tools used to investigate historical physical processes are typically limited. Aerial photos, discharge and sediment gage records, specific gage analysis, surveys, and dating modern deposits with dendrochronology are the most common tools to provide a historical context for restoration [*Soar and Thorne*, 2000; *National Resource Conservation Service*, 2007; *Watson et al.*, 2007]. Typically, the aforementioned methods are capable of categorizing impacts to channel form and process for a time-scale on the order of 10^1 years. Given the short time-periods available for “historical” investigations, restoration targets are commonly established to mimic forms immediately preceding a recent impact. More likely, periods of 10^2 to 10^3 years are necessary to understand the natural disturbance regime and historic range of variability in processes [*Turner et al.*, 1993]. By acknowledging a range of historic forms and processes, we gain insight into the potential for a system to recover from anthropogenic impacts.

Once an appropriate context for restoration has been established through assessment of historic processes, reference reaches, and/or theoretical inference, a variety of restoration procedures may be recommended based on the current condition of the upstream channel, watershed land-use, and climate. Restoration treatments are often active alterations of stream form and process, such as channel reconfiguration, instream structures, riparian planting, bank stabilization, grade control, and grazing exclosures [*Allen and Leech*, 1997; *Bentrup and Hoag*, 1998; *Wohl et al.*, 2005]. Channel restoration may also be passive, with targets such as reforestation, modified flow regulation, changes in land-use, or land-cover, and changes in groundwater withdrawals to restore water-table depths [*Kondolf and Curry*, 1986; *Poff et al.*, 1997; *Webb et al.*, 1999; *Wohl et al.*, 2005]. Humans have sought to manage rivers for societal benefit for millennia. River restoration emerges from that tradition, and commonly rethinks and seeks to undo harm from prior management decisions and attitudes.

1.2 Post-disturbance channel recovery

Ecological disturbances are important processes that eliminate organisms, destroy habitat for certain species, and create opportunity for others [*Pickett and White*, 1985; *Benda et al.*, 2004]. Landscape stability devoid of disturbances is a concept to be viewed suspiciously, and should be carefully avoided in the context of restoration planning. Schumm and Lichty [1965] suggest that steady-state conditions are never present at the watershed scale or at long time spans. That is, disturbance is a relativistic concept that varies according to the spatial and temporal scales of the observer [*Rykiel*, 1985]. At scales relevant to land managers and restorationists, however, a more functional view of disturbance is necessary.

Geomorphologists distinguish between transient and persistent features of landforms. A 100-year-flood, for example, can cause substantial deposition. The flood deposits are transient if subsequent smaller flows remove the deposits and restore the original configuration of the channel and floodplain prior to the next 100-year flood. The deposits are persistent if they last until the next 100-year flood. This concept offers a potential tool for discerning the threshold between normal disturbance events and altered disturbance regimes marked by unusually severe or frequent disturbances. Brundsen and Thornes [1979] differentiate transient and persistent features with a transient-form ratio (TFr).

$$TFr = \frac{mean\ relaxation\ time}{mean\ recurrence\ time\ of\ events}, \qquad 1.1$$

where a ratio greater than 1 suggests there will be no steady-state, stable forms. Brundsen and Thornes suggested this ratio as a measure of sensitivity of a landscape to internal and external change. Similarly, this ratio can be applied to organisms, communities, or particular processes within a system [*Phillips*, 1995]. I use the transient-form ratio as a framework for viewing the impact of the 2003 debris flow in the Lulu City wetland. The transient-form ratio is also applied qualitatively, as a framework for viewing channel recovery of the 2003 debris flow.

1.3 Research overview

The objective of this research is to investigate the historic range of variability in hydrogeomorphic processes and provide context for restoration of a riverine environment affected by a human–caused debris flow in Rocky Mountain National Park, Colorado during 2003. To investigate the historic range of variability over a time scale of 10^2 to 10^3 years, analysis of aerial photography, ground penetrating radar surveys, radiocarbon dating, and soil descriptions were conducted in a portion of the Colorado River headwaters known as the Lulu City wetland. In addition, I quantified post-debris flow processes and assessed the geomorphic stability and trajectory of the impacted Colorado River since 2003. To investigate current conditions, I monitored flow, sediment transport, bed particle size distribution, and channel cross sections at selected locations between the entry point of the debris flow and the upstream end of the wetland (Figure 2.1).

2. Study Area

The study area is the headwaters of the Colorado River on the west side of Rocky Mountain National Park, with particular focus on the Lulu City wetland and the ~29 km^2 upstream (Figure 2.1). The watershed is bounded by the Never Summer Mountains on the west, La Poudre Pass on the Continental Divide to the north, and the Front Range of the Rocky Mountains to the east. The Never Summer Mountains consist primarily of Oligocene granitic magmas, and the Front Range consists primarily of Proterozoic biotite schist with some Oligocene rhyolitic lava flows and tuff [*Braddock and Cole*, 1990]. The elevation of the watershed ranges from ~2830 m (9300 ft) at the Lulu City wetland, to 3944 m (12,940 ft) at Mount Richthofen.

Pleistocene glaciers in the Colorado River Valley extended ~ 24 km from the Continental Divide to Grand Lake [*Meierding*, 1980] and thus completely covered the study area. Although little work has been done in the upper Colorado River valley to define the chronology of glacial retreat, an estimated age of 14,000 yr BP is suggested as the end of valley glaciation throughout the Front Range in northern Colorado (R. Madole, pers. comm., 2009).

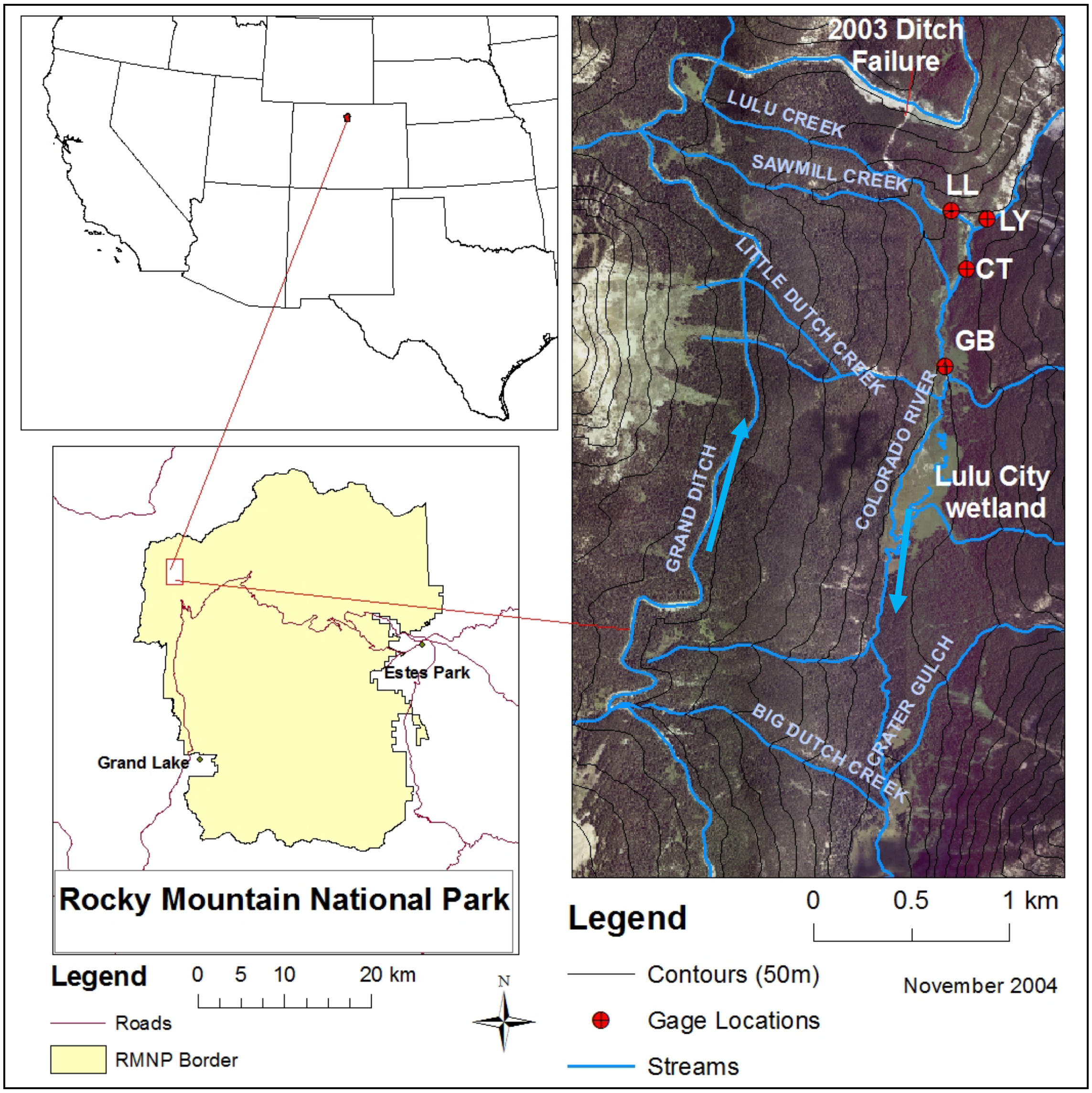

Figure 2.1. The project area is the upper Colorado River in northern Colorado on the west side of Rocky Mountain National Park, USA. Blue arrows indicate direction of water flow. Tributaries that flow into the Colorado River are diverted out of the basin to the north by the Grand Ditch (northward pointing blue arrow). Stream gage locations are indicated with corresponding abbreviations: LL is lower Lulu Creek, LY is Colorado River at Little Yellowstone, CT is Colorado River at Crooked Tree, GB is Colorado River at Gravel Beach. The coordinates of the Lulu City wetland are ~40.45 N, 105.83 W.

Holocene climate records have been investigated in the Rockies through correlations of pollen and insects. Post-glacial warming occurred from ~14,000- 11,000 yr BP [*Doerner*, 2007]. The Younger Dryas cooling interrupted the warming from ~11,000- 10,000 yr BP, causing glaciers to advance and tree line to shift downward by as much as 120 m [*Short*, 1985; *Menounos and Reasoner*, 1997; *Doerner*, 2007]. The middle Holocene Altithermal was categorized by warmer and wetter conditions ~9,000-4,500 yr BP [*Elias*, 1985; *Fall*, 1985; 1997]. Cooler and drier conditions persisted from ~4,000 to 2,000 yr BP and created another small-scale advance of alpine glaciers known as the Neoglacial [*Fall*, 1997]. The last 2000 years have been generally similar to the modern climate [*Vierling*, 1998], although cooler and more severe temperatures were present during the Little Ice Age from ~700-100 yr BP [*Fall*, 1985; *Doerner*, 2007]. The Medieval Optimum (~1050-750 yr BP) is not specifically identified in local climate reconstructions, but has been documented in North America and throughout the world as a warm period [*Mann et al.*, 2009].

More recently, as inferred from tree-ring reconstructions of climate, significant variation in precipitation has occurred over the past centuries. An extended drought in the late 1800's-early 1900's was more severe than any others in the past 600 years [*Woodhouse and Lukas*, 2006; *Www.Treeflow.Info/Upco/Coloradogranby.Html*, 2010]. An extended wet period of the early-mid 1900's was similarly unique in the 600-year record. This period of abundant precipitation has been identified in several other paleoclimate reconstructions including one for Lee's Ferry in northern Arizona [*Stockton and Jacoby*, 1976], and has been identified throughout the western United States and the Great Plains [*Fye et al.*, 2003]. Despite those decadal extremes of the 20th century, inferred precipitation appears to be generally consistent in the upper Colorado basin over the past six centuries (Figure 2.2).

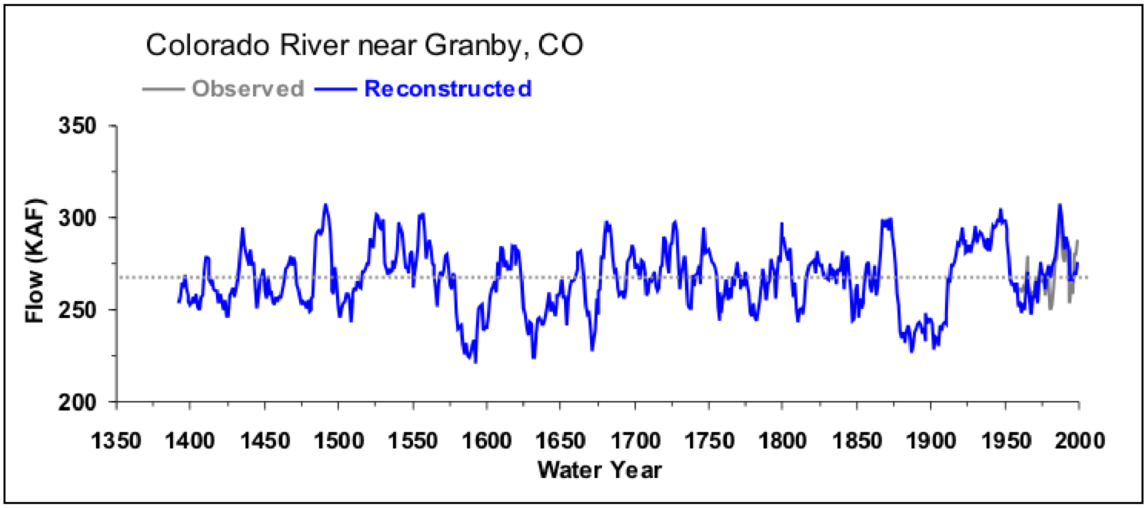

Figure 2.2. 10-year running average of streamflow reconstructed from tree-ring records. The dashed line is the mean annual flow of the period of record for the Granby gage (1951-1999). Image from www.treeflow.info/upco/coloradogranby.html

The Colorado River at the Lulu City wetland is a 3rd order stream in the Strahler [1952] classification. Channel slope in the wetland is ~0.9%, while upstream the pool-riffle Colorado River slope is generally 2-3%. Tributaries such as Lulu Creek are typically step-pool channels with slopes of up to 20%. Hydrology is snowmelt dominated, with annual peaks typically occurring in late May and early June. Over 80% of annual runoff occurs during the early summer melt period of May, June, and July [*Woods*, 2000]. Annual precipitation is estimated at 107 cm [*Capesius and Stephens*, 2010], with ~84% as snow at the nearby Lake Irene SNOTEL station (CO05J10S, elevation 3260 m) [*Westbrook et al.*, 2006].

Vegetation in wide portions of the valley bottom along the upper Colorado River is a mix of riparian shrublands dominated by willow (*Salix monticola*, *S. geyeriana*, *S. drummondiana*), dry meadows with *Deschampsia cespitosa* and *Calamagrostis canadensis*, and peat-accumulating fens dominated by willow (*Salix planifolia*) and *Carex* *aquatilis*. Hillslope vegetation is dominated by Engelmann spruce (*Picea engelmannii*), lodgepole pine (*Pinus contorta*), and subalpine fir (*Abies lasiocarpa*) [*Woods*, 2000; *Westbrook et al.*, 2006]. Willow communities throughout Rocky Mountain National Park have been in drastic decline in recent decades, likely a result of multiple stressors including browsing pressure from increased moose and elk populations [*Hess*, 1993; *Kaczynski et al.*, 2010].

2.1 Impacts of the Grand Ditch

The Grand Ditch water diversion was constructed in stages from 1890- 1936, first with hand laborers and later with machinery [*Woods*, 2000]. The Grand Ditch captures tributary runoff from the Never Summer Mountains and diverts water from the Colorado basin, over the Continental Divide to Long Draw Reservoir and the Cache la Poudre watershed. The Grand Ditch impacts the upper Colorado River in two primary ways: water withdrawal and sediment input.

Water diversion from Grand Ditch has pronounced effects on the downstream hydrology that include less total flow volume, a shortened period of elevated flows, and rapid fluctuations in discharge [*Woods*, 2000; *Rubin et al.*, 2010]. Although the Grand Ditch captures runoff from approximately the upper 50% of the watershed, peak runoff exceeds Grand Ditch capacity in most years, and peak flows are thus reduced by less than 50%. Receding limb flows, however, driven by late-season snowmelt at high altitude areas, are almost completely captured by the Grand Ditch, shortening and reducing the recession [*Woods*, 2000]. The flow reduction changes sediment transport capacity and lowers the water table, which contribute to conjunctive impacts to willow and other riparian plant communities [*Woods and Cooper*, 2005], benthic invertebrate abundance [*Clayton and Westbrook*, 2008], and beaver that are dependent on the aforementioned vegetation types and channel processes [*Collen and Gibson*, 2000].

The most visible impact of the Grand Ditch is the repeated occurrence of breaches or failures along the Ditch, and subsequent debris flows that have caused increased sediment loads down Lulu Creek and adjacent channels, resulting in extensive aggradation in the Lulu City wetland. Aerial photos dating back to 1937 (Appendix A) show evidence of Grand Ditch-initiated debris flows and gully erosion as well as debris flow and splay deposits in the Lulu City wetland [*Rathburn and Rubin*, 2009]. This suggests an elevated sediment and disturbance regime that has persisted for at least 70 years. The specific mechanisms of debris flow initiation at the Grand Ditch are not known. In the Lulu City wetland the Ditch-related sediment inputs changed the meandering single thread channel (visible in the 1937 air photo) to a bifurcated zone of deposition at the head of the wetland. The 2003 debris flow deposited up to ~ 1 m of sand and gravel in the wetland. There was no *a priori* assumption about pre-Grand Ditch debris flow frequency, but the appearance of debris flow deposits on sequential air photos suggests that frequency likely increased following ditch construction. The 2003 breach resulted in a lawsuit between Rocky Mountain National Park and the Grand Ditch operators that led to a settlement out of court which will subsequently fund restoration efforts. In order to provide a context for the 2003 debris flow and subsequent restoration planning, this study investigated pre-Grand Ditch processes and aggradational history of the Lulu City wetland.

2.2 19th and 20th century history of the upper Colorado River basin

Human impacts to the upper Colorado River basin follow a pattern similar to many parts of the central Rocky Mountains including water diversion, mining, and beaver trapping [*Wohl*, 2001]. Development of the "Lulu City" mining town just upstream of the wetland occurred the 1880's. Lulu City, now a one-hour walk from the nearest road, reached a population of several hundred people during its brief existence, possessing a post-office, hotel, and even a "red light district" of two cabins [*Buchholtz*, 1983; *Kaye*, 1983; *Brown*, 2003]. In addition to disruption of valley-bottom sediments for placer mining, and associated downstream increases in sediment yield, inhabitants of the mining area started fires and likely created localized deforestation that may have destabilized hillslopes and further exacerbated sediment yields to the valley bottom [*Wohl*, 2001].

When beaver are present along a river, their dams can help to slow the passage of seasonal flood peaks, increase the extent of overbank flooding and groundwater recharge [*Westbrook et al.*, 2006] and retain sediment [*Butler and Malanson*, 2005; *Westbrook et al.*, 2010]. Beaver present in the vicinity of Lulu City were likely removed within the decades immediately preceding the existence of Lulu City [*Wohl*, 2001]; any recovery of beaver populations following initial trapping in the 1820s was likely decimated during the existence of Lulu City. Beaver populations subsequently began to recover, but during the latter 20th century a drastic decline in beaver populations throughout Rocky Mountain National Park reduced an estimated Colorado River Valley population from 600 beavers in 1940 to 5% that amount (0 in the Lulu City wetland or anywhere upstream of the Colorado River Trailhead) by 1999 [*Packard*, 1947; *Mitchell et al.*, 1999]. Some, if not most, of this decline may be associated with increasing elk populations and heavy grazing pressure [*Hess*, 1993] that reduce or eliminate woody riparian plants on which both beaver and elk feed, and which influence stream bank stability, overbank roughness, and thus sediment transport in channels and overbank environments. Beaver populations prior to European settlement and trapping were likely even higher than the 1940 levels, although specific estimates for the Colorado River are not available [*Seton*, 1953; *Wohl*, 2001; *Westbrook et al.*, 2006]. In aerial photos of Lulu City wetland (Appendix A), no new beaver-dammed ponds appear after 1969, although the resolution is poor in the earlier photos and the ponds that are present may be several decades older than 1969.

The cumulative effect of historical changes during the past two centuries has thus likely been to increase sediment yields to the valley bottom along the upper Colorado River and to alter the manner in which sediment is transported or retained in the valley bottom by changing flow volumes, removing beaver populations, and altering valley-bottom vegetation communities. Furthermore, the legacy of the 2003 debris flow and previous impacts may facilitate future instability if triggered by heavy rainfall or high streamflow.

3. Aggradational History of Lulu City Wetland

3.1 Introduction: post-glacial history of alpine and subalpine valleys in the central Rocky Mountains

Understanding landscape history is a critical step towards understanding ecosystem functions. Geomorphic forms and processes such as alluvial fans, flood plains, and abandoned channels dictate the fundamental physical attributes of ecosystem habitat [*Swanson et al.*, 1988]. Near-surface deposits also influence many geomorphic and biogeochemical processes [*Leopold et al.*, 2009]. Despite the ecological significance, no comprehensive effort to describe variability in post-glacial processes of valley fill has been conducted in the Rocky Mountain National Park region.

Several relevant case studies investigating valley fill have been conducted in Rocky Mountain National Park and surrounding regions. In the higher elevation (~3470 m) alpine environment east of the Continental Divide at Niwot Ridge, a thin veneer of soil (~2.5 m) overlying a thicker sequence (~10 m) of coarse periglacial deposits and regolith was identified with seismic reflection and ground penetrating radar surveys [*Leopold et al.*, 2009]. Similarly, in Beaver Meadows (elevation ~2520 m) on the east side of Rocky Mountain National Park, limited shallow augering revealed 1-2 m of fine-grained organic-rich sediment underlain by cobbles and boulders of unknown thickness [*Graf*, 1997]. In a tributary valley of the Colorado River ~16 km downstream of the current study site, stratigraphic and seismic reflection studies of Big Meadows (elevation 2865 m) identified ~45 m of till overlain by ~2 m of peat with few layers of fine sediment [*Shuter*, 1988; *Cooper*, 1990]. In the Colorado River valley ~8 km downstream of the study site, a groundwater well constructed in 1953 at Holzworth Ranch (now in Rocky Mountain National Park) consisted of 0.3-0.6 m of topsoil underlain by ~19 m of fine gravel and sand. The well “bottomed out” at 19.2 m, providing an estimated minimum depth to bedrock [*Colorado Water Conservation Board*, 1953]. Seismic surveys at unknown locations in the Kawuneeche Valley of the Colorado River (8-20 km downstream of the study site) estimate bedrock at 15-122 m [*Braddock and Cole*, 1990]. Several investigations have also been conducted at La Poudre Pass, a col on the Continental Divide (elevation 3100 m) at the head of the Colorado River ~5 km up-valley from the study site. Peat (~1.7 m thick) was described overlying glacial gravely sand deposits (estimated at 10 m thick from roadcut exposures). An accelerator mass spectrometry radiocarbon date of a thin layer of organic sediments over the glacial gravel was dated as ~11,165 yr BP (J. Doerner, unpublished report, 2005). Aggradation rates from seven dates in the profile by Doerner range from 1.0 to 1.7 cm/100 yr back to 6750 yr BP, with higher rates of 1.6 to 2.7 cm/100 yr from 6750 to 11,165 yr BP. It is unknown how total thicknesses and processes of fill at those sites compare to the Lulu City wetland, but differences in topography and lithology between these sites and the wetland make it unlikely that the other sites have received as much post-glacial colluvial sediment contributed by either natural- or human-induced debris flows as has the Lulu City wetland.

Given the limited site-specific assessments of the range of variability for depths to bedrock and processes of fill in the vicinity of Rocky Mountain National Park, this research seeks to provide insight into post-glacial valley processes in a previously unstudied portion of the upper Colorado River valley. To provide context for the 2003 debris flow, this research seeks to quantify the historic range of variability of aggradation rates and mechanisms of aggradation at the Lulu City wetland during the Holocene. Two end-member scenarios were hypothesized as follows (Figure 3.1):

> H1) Valley fill is predominantly coarse, deposited during and shortly after deglaciation, with little accumulation since glacial retreat ~14,000 years ago [*Madole*, 1980; R. Madole, pers. comm., 2009]. Valley configuration in this scenario can be considered in a state of equilibrium, wherein post-glacial sediment inputs are not stored in the wetland, but transported downstream.
>
> H1A) Valley fill is composed of fluvial and hillslope inputs deposited continuously since deglaciation. This scenario represents a trajectory of aggradation wherein sediment inputs to the valley are preserved in the wide, low gradient Lulu City wetland.

Within hypothesis H1A, four scenarios were proposed:

> H1A-1) Rates of post-glacial deposition did not change significantly during the Holocene.
>
> H1A-2) Rates are variable at intervals that correlate with Holocene climatic variability (Altithermal, Medieval Optimum, Little Ice Age, or other regionally documented periods of climatic variation). This suggests the historic range of variability of aggradation rates is significant relative to recent (post Little Ice Age) variability, and driven by known climatic variation.

H1A-3) Rates did not change significantly during the Holocene, but a substantial increase in aggradation rates occurred since construction of Grand Ditch. This suggests that modern anthropogenic inputs have altered the rate of deposition beyond what has occurred in the historical range of variability, and may suggest a fundamentally different depositional regime.

H1A-4) Rates are variable through the Holocene, but have substantially increased since construction of the Grand Ditch. This suggests the Grand Ditch has altered the rate of deposition beyond what has occurred in the historical range of variability, and may suggest a fundamentally different depositional regime.

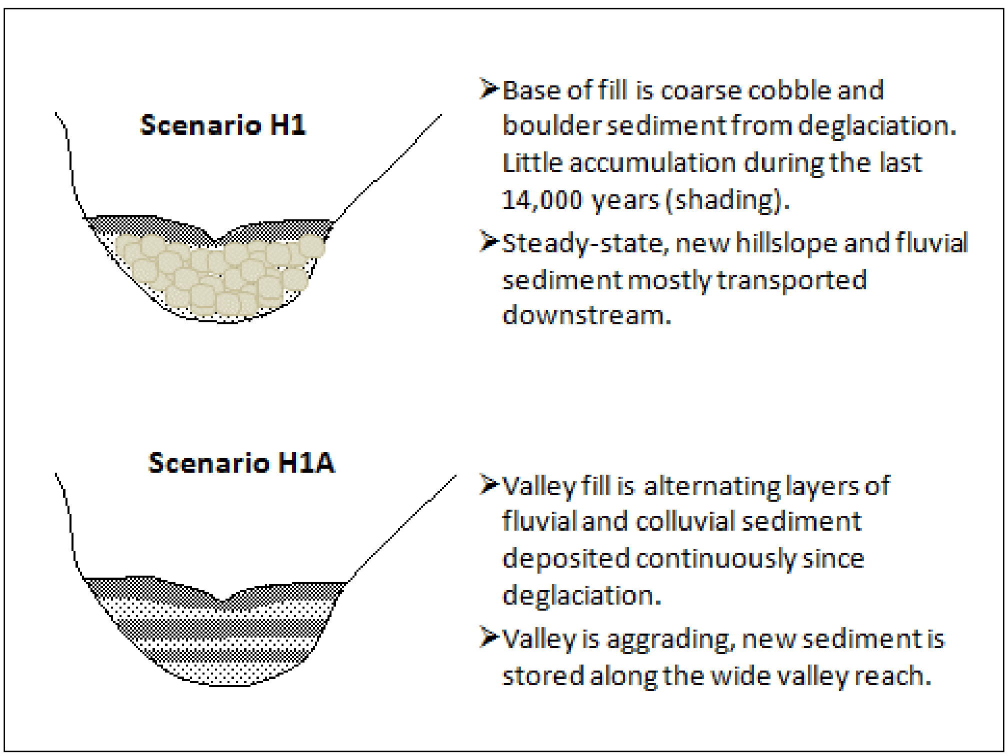

Figure 3.1. Scenario H1 represents a potential process of valley fill where a thin layer of fluvial and colluvial sediment is overlying a thick sequence of glacially derived coarse sediment. H1A would be identified by continuing aggradation in the 14,000 years since glacial retreat with several layers of alternating fine and coarse deposits.

Debris flows have occurred in areas not affected by the Grand Ditch, such as the east side of the Colorado River valley (Figure 2.1), so coarse sediment has presumably entered the valley bottom throughout the postglacial period. The absence of continuing sediment accumulation on the valley bottom would suggest that the channel and floodplain are in steady-state such that incoming sediment is transported downstream with little long-term storage. In this case, the upper Colorado River might be capable of transporting the sediment from the 2003 Grand Ditch failure downstream with little or no restoration, and the effects of the failure would be transient. Alternatively, the increase in frequency and volume of sediment entering the valley bottom as a result of repeated failures along the Grand Ditch might overwhelm sediment transport capacity and establish a new regime of sediment accumulation that would result in persistent features. In scenario H1A, the valley fill consists of alternating layers of fine (fluvial) and coarse (colluvial) sediment. Alternating fluvial and colluvial deposition is more likely to reflect continuing sediment deposition since deglaciation, suggesting that the upper Colorado River is limited in its ability to transport sediment. The 2003 sediment inputs in scenario H1A are more likely to create persistent impacts along the channel and floodplain and restoration measures might be necessary to return the valley to desired conditions.

3.2 Methods

Multiple field methods were used to investigate pre-2003 debris flow processes in the Lulu City wetland and to develop the information necessary to test the hypotheses posed in the previous section. Analyses included historic aerial photograph interpretation, ground penetrating radar (GPR) surveys, and trenching, coring, and radiocarbon dating of valley-bottom sediments to map sediment deposits, assess aggradational rates, and quantify processes (channel, overbank, hillslope, beaver dams, peat) of alluvial fill within the Lulu City wetland.

3.2.1 Aerial photo analysis

Aerial photographs were assembled and analyzed for evidence of previous debris-flow deposits, channel planform changes, channel migration, and beaver ponds in the Lulu City wetland. The wetland area was defined as non-forested valley bottom, the extent of which has not changed substantially since 1937. Imagery from 1937 (1: 23,000[1]), 1953 (1: 63,360), 1969 (1: 15,840), 1987 (1: 15,840), 2001 (1: 4,000), 2004 (digital image, resolution= 15 cm), and 2009 (resolution =1 m) cover the entire study area (Appendix A). The 1937 and 1953 images are black and white while later images are in color. Photos were scanned, imported into ArcGIS v9.3, and rectified. Debris-flow deposits, channel location, beaver ponds, and vegetation changes in the wetland were interpreted by comparison with contemporary examples; i.e., modern beaver ponds and debris-flow deposits were identified in the field and in recent imagery, and similar features were recognized in historical imagery. Debris-flow deposits were identified primarily through identification of unvegetated sediments, and an investigation of hillslope and tributary scars from hillslopes and the Grand Ditch was conducted to corroborate the interpretation of wetland debris-flow deposits with possible source areas. Channel migration was assessed by tracing channel centerlines in each image wherever a dominant channel was present. Beaver ponds were identified from ponded

[1] No documentation with photo. Scale assumed based on the relatively consistent scale of aerial photos of Colorado in 1937.

water or broad, unvegetated sections of the channel upstream of a defined, cross-channel obstruction (beaver dam). In general, temporal and spatial variations in vegetation were not distinguished due to the resolution of the aerial photos, although establishment of trees in the imagery is discernable and noted. The short growing season at the high elevation site and the inherent obstacles to aerial photo interpretation suggest that trees would likely have to be a decade or more in age before being recognized in photos.

3.2.2 Ground penetrating radar (GPR)

GPR has proven to be an efficient, non-invasive, and effective method of imaging sedimentary deposits in a number of environments including internal structures in sediment [*Hugenholtz et al.*, 2007; *Schrott and Sass*, 2008], pond and reservoir sediments [*Buynevich and Fitzgerald*, 2003; *Hunter et al.*, 2003], peatlands [*Comas et al.*, 2004; *Jol*, 2009; *Rosa et al.*, 2009], alluvial fill [*Woodward et al.*, 2003; *Hickin et al.*, 2007], deltas [*Roberts et al.*, 2003], rock glaciers [*Berthling et al.*, 2000; *Degenhardt et al.*, 2003], and wetlands [*Bristow and Jol*, 2003; *Baker and Jol*, 2007; *Jol*, 2009]. GPR is a method in which a high-frequency electromagnetic pulse is transmitted into the ground and partially reflected back to the surface where there are changes in the electrical properties of the sub-surface materials. These reflections may identify contacts between deposits of different grain size, mineralogy, water content, organic content, and bedrock [*Davis and Annan*, 1989].

Because of the remote location and corresponding logistical challenges of conducting backcountry field work, a trial survey was conducted at the study site to test different frequencies prior to the comprehensive survey of the wetland. Frequencies of 50, 100, and 200 MHz were tested, with depths of penetration of approximately 8, 4, and 2 m, respectively. Theoretical vertical resolution of the radar signal is calculated using the equation

$$Rv = \frac{\lambda}{4} = \frac{\left(\frac{V}{F}\right)}{4} \qquad (3.1)$$

Where *Rv* is the vertical resolution (m), λ is the wavelength (m), *V* is the wave velocity through the soil, and *F* is the central frequency of the antenna [*Reynolds*, 1997]. The calculated theoretical vertical resolutions for the 50, 100, and 200 MHz antennas are 0.25, 0.125, and 0.063 m, respectively. However, since the central frequency actually returned to the antennas is lower (~40, 70, and 125 MHz, respectively, for the data collected), the actual resolutions are calculated to be 0.31, 0.18, and 0.1 m for the 50, 100, and 200 MHz antennas, respectively. The 100 MHz antennas were selected for the comprehensive survey, providing a balance of penetration and resolution. A pilot study along XS2 was conducted in October 2008. The comprehensive survey was conducted during July 2009.

A reflection-type survey in step mode using a Sensors and Software PulseEkko 100 GPR system was used for all surveys. Seven cross-sectional (perpendicular to the strike of the valley) transects and two longitudinal (parallel to the strike of the valley) transects were surveyed with the 100 MHz antennas (Figure 3.2). XS0, XS1, XS2, and the portion of Long W between XS0 and XS2 were additionally surveyed with the 200 MHz antennas to provide higher resolution of the near-surface deposits. In sum, ~3 km of GPR surveys were conducted.

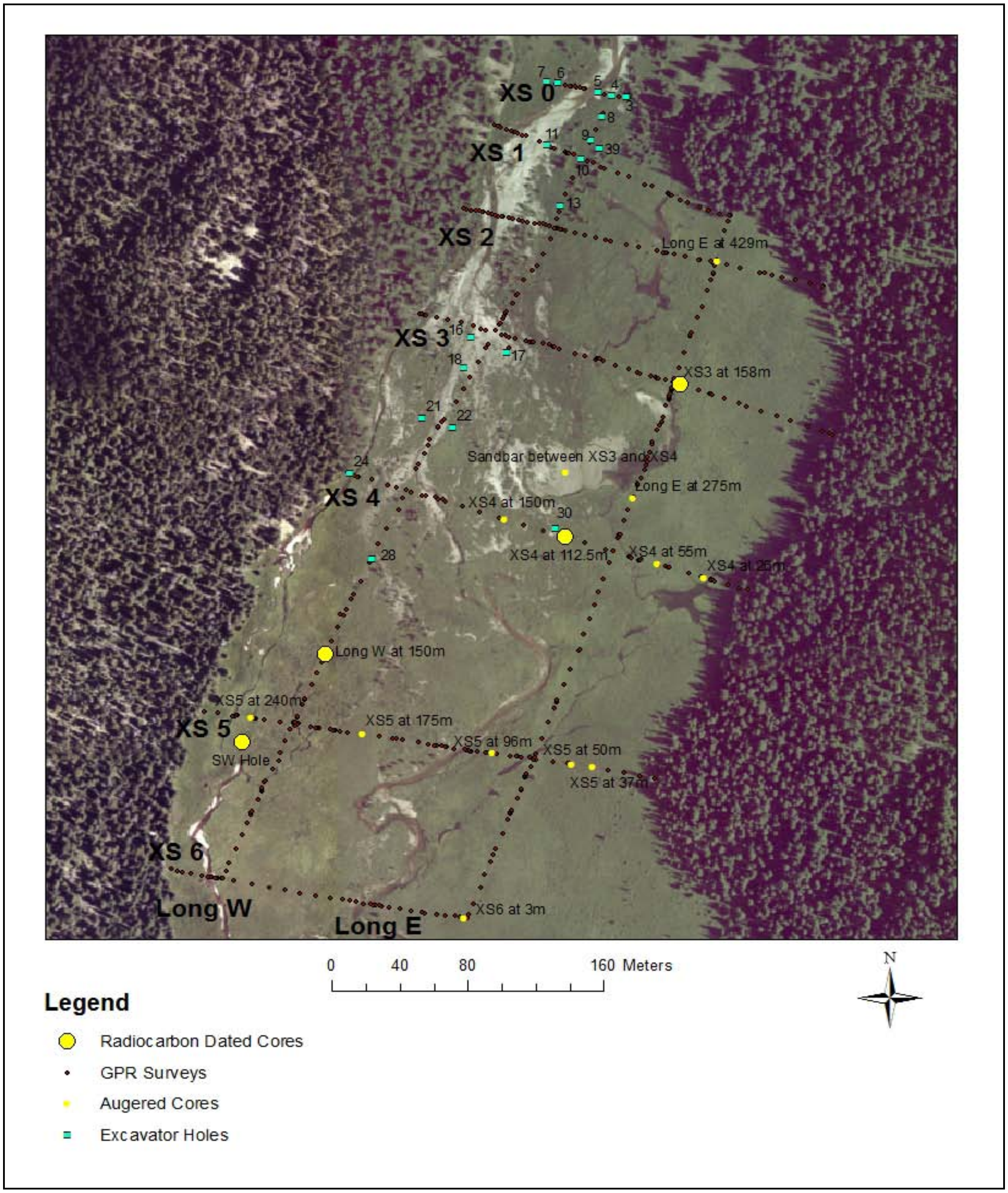

Figure 3.2. Location of GPR transects, cores, radiocarbon-dated cores, and excavator pits, Lulu City wetland. Cores were obtained using hand augers and reached maximum depths of 3.5 m; excavator holes were dug using a Bobcat excavator and reached maximum depths of 1.9 m. Radiocarbon samples were collected from augered cores and submitted for analysis. GPR cross sectional and longitudinal transects were conducted primarily with 100 MHz antenna and reflections collected every 25 cm. Streamflow is from top of figure toward bottom.

Antennae were oriented parallel to the direction of the motion along transects. Antenna separation was 1 m for the 100 MHZ antennas and 0.5 m for the 200 MHz antennas. Common midpoint (CMP) surveys were conducted on cross sections 2 and 4 to measure radar velocities. Both CMP surveys yielded average radar velocities of ~ 0.05 m/ns (Figure 3.3). This velocity is consistent with established rates for wet sand [*Baker et al.*, 2007], a widespread sediment in the Lulu City wetland.

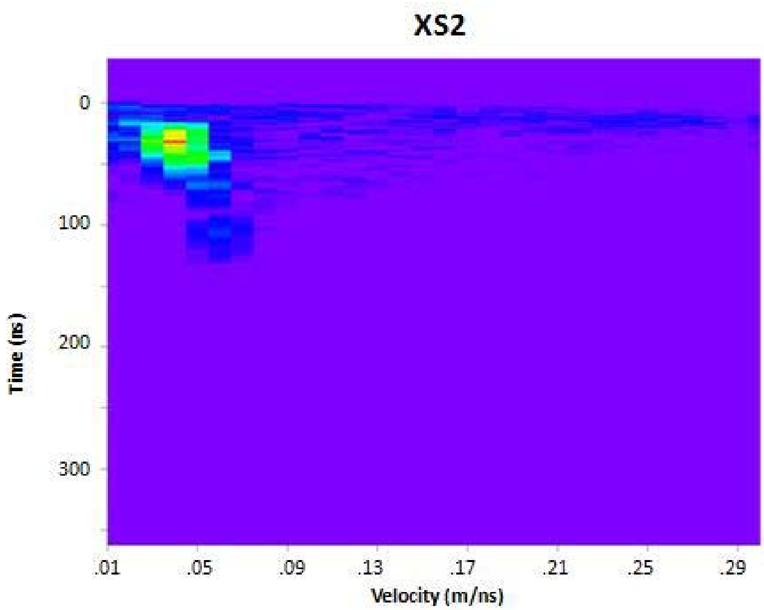

Figure 3.3. XS2 CMP survey velocities are indicated by warm colors over depth. Warm colors indicate electromagnetic propagation velocities and can be used to convert the time of radar return signals to depth in the GPR reflection surveys. In XS2 as well as XS4, a velocity of 0.05 m/ns was observed. The velocity of 0.05 m/ns was applied to all GPR transects to convert reflection time to depth.

A topographic survey was conducted along the GPR transects using a TOP-CON Total Station. Points were surveyed at a spacing of ~5 m across the low gradient wetland, with additional points surveyed at breaks in slope. The topographic survey was applied to GPR transects so that reflections throughout the wetland were referenced to a fixed datum rather than the ground surface.

3.2.3 Data processing

GPR data were processed using Ekko View Deluxe software from Sensors and Software. The data were dewowed to remove low-frequency, slow decay noise, often associated with GPR signals. A timezero correction was applied to account for timezero drift and ensure that ground-surface reflections were aligned horizontally. Surveyed topography was then added to each transect so that reflections were displayed relative to an absolute datum. Three versions of each transect were generated: 1) with an Automatic Gain Control (AGC) with window width = 3 and maximum gain = 50; 2) with a Spreading and Exponential Compensation (SEC) gain of attenuation = 1.5 and maximum gain = 40. The AGC gain is useful in stratigraphic analysis to amplify reflections and define continuity of strata, but the AGC processing obscures the relative amplitude of different reflections, whereas the SEC preserves relative amplitude information although continuity may be lost; and 3) a migration filter was applied to the data with the AGC gain. The migration filter is a method of de-scattering diffractions that may occur at point targets such as boulders. Several different migration velocities were tested and a velocity of 0.10 m/ns was selected as the velocity that best collapsed diffractions while preserving other reflection data [*Annan*, 1993; *Sensors and Software Inc.*, 2003]. Interpretation of the GPR data was conducted using all three of the aforementioned methods, as each expresses and preserves different qualities of interest in the data. Images from all migrated transects are presented in Appendix C.

GPR penetration depths averaged ~4 m, with a range from 2-6 m. Penetration was shallowest in coarse substrate (e.g., XS0 and XS6) and deepest in fine deposits (e.g., XS3). In general, GPR penetration depth is similar to the maximum depths reached with hand augers and the depths of the oldest radiocarbon samples. Thus, GPR surveys generally represent the last 4000 years and interpretations of how GPR signals relate to grain-size distributions were ground-truthed both laterally and vertically by auger cores and excavator pits.

The processed GPR reflection images were exported from Ekko View Deluxe into a JPEG image file and interpreted in Adobe Photoshop. GPR data were initially categorized and interpreted using a radar facies analysis [*Beres Jr and Haeni*, 1991] in which packages of reflections were identified from the GPR data based on the spatial continuity, configuration, amplitude, and frequency (thickness) of the reflections. Those packages were colored in Adobe Photoshop and compared to soil descriptions from the hand-augered cores and excavator-dug pits. The interpretation of radar images was then iteratively adjusted as needed so that the categorization of radar-facies was in agreement with soil observations. Differentiated packages of facies may, and often do, include different types of deposits. Dominant trends are distinguished, not individual deposits.

3.2.4 Sediment descriptions and inferred depositional processes

Sediment descriptions from 15 hand-augered and 19 excavator-dug soil pits were used to verify GPR interpretation and quantify depositional processes (Figure 3.2).

Hand-augered holes were dug with an 8.3 cm (3.25 inches) diameter, bucket-type auger. The maximum depth was 3.5 m, and depths typically ranged from 1-3 m. The excavator-pits were dug using a 46 cm (18 inches) bucket. Maximum depth was 1.9 m. Deposits were described based on grain size, sorting, angularity, color, and organic content (Appendix B), with approximate depth of major changes in any of these characteristics noted in the descriptions.

Depositional processes were inferred primarily based on observations of contemporary deposits in Lulu City wetland of overbank, in-channel, beaver pond fill, peat, and debris-flow deposits. In the literature, and as observed at the Lulu City wetland, overbank deposits are described as well sorted, planar features of sand and finer material that is deposited out of suspension [*Brookfield*, 2004]. Contemporary in-channel surficial deposits were observed and described as rounded to sub angular gravels. Peat is identified as anaerobic preservation of dead vegetation, commonly as intertwined fibrous mats of plant material. It is important to acknowledge that peat production is not a sedimentation process. Peat is generated in groundwater-dominated systems that do not receive substantial sediment inputs [*Cowardin et al.*, 1979; *Nichols*, 2009]. Peat production occurs in stable, groundwater-fed locations, such as bogs and fens that accumulate organic matter faster than it is decomposed. Organic content of peat can be as high as 95% [*Bell*, 1992]. Organic-rich pond sediment (gyttja) is a facies of fine, black sediment and particulate organic matter [*Hansen*, 1959] and does not have the fibrous, woody character of peat. In the modern wetland, such deposits were found in relic beaver ponds, and thus I assume gyttja to be beaver-pond fill, which is characterized in the literature as fine, organic-rich, stratified sediments [*Dalquest et al.*, 1990; *Butler and Malanson*, 1995]. In contrast, in the contemporary Lulu City wetland, there are also several abandoned beaver ponds, no longer in the active channel, that are filled with thick deposits of sorted sand from recent debris flows (Appendix A). It is therefore plausible that historic ponds were similarly filled with sorted fluvial or debris-flow sand deposits.

The 2003 debris-flow deposit varies spatially throughout the upper Colorado River watershed. Along Lulu Creek near the initiation point (Figure 2.1), the deposit consists of sand to boulder size sediment and logs. Along the Colorado River downstream of the confluence with Lulu Creek, the deposit is sand to cobble sized material. In the Lulu City wetland, the deposits are well-sorted sand and gravel. Debris-flow deposits are characteristically poorly sorted [*Nichols*, 2009]. However, because the debris-flow initiation zone was ~2 km upstream from the wetland and occurred during high discharge, deposits are well sorted and indistinguishable from high energy, high sediment load fluvial deposits. This exemplifies the concept of a disturbance cascade presented by Nakamura et al. [2000], who proposed a down-watershed gradient of processes and severity of disruption initiated by a single hillslope failure.

The similarity of debris flow, overbank, and episodically filled pond deposits presented a challenge for interpretation. Furthermore, stratigraphic investigations were conducted using a hand auger, which disturbed bedding and sorting that may have been present and occasionally fractured gravels, disguising particle rounding. The sampling obstacles and facies similarities made refined facies descriptions impossible. Additionally, the resolution of the GPR did not allow thin beds to be distinguished. An approach was therefore taken to broadly categorize depositional regimes. Depositional environments were broadly grouped into higher energy (debris flow, overbank, and in-channel fluvial) and lower energy (peat, beaver pond fill, and overbank) process regimes. Overbank deposits are included in both low-energy and high-energy divisions. This was necessary because overbank deposits were ubiquitous throughout the wetland and the resolution of the GPR was commonly not sufficient to resolve individual deposits. Thus, low-energy deposits are regimes that fluctuated between peat or pond accumulation and received overbank deposits of sand and silt, whereas the high-energy division received coarse (gravel and larger) fluvial and colluvial deposits, but also received finer overbank deposition. This division proved extremely useful for the broad characterization of aggradational processes over thousands of years.

3.2.5 Quantifying aggradation rates

Eleven samples from four vertical profiles were dated using conventional radiocarbon analysis. Eight of the samples were peat while three were gyttja. Radiocarbon analyses were conducted by the University of Arizona Environmental Isotopes Laboratory. Aggradation rates were then computed for each vertical profile, assuming constant rates of fill between the dated samples and/or the modern ground surface. Dated materials were composite samples: fine material of varied sources (gyttja), or accumulated *in situ* plant matter (peat). Ages therefore represent averages across the period of accumulation, rather than event-based dates such as can be acquired through dating wood or charcoal fragments. Peat, however, has an advantage of being derived from short-lived material that is not transported.

3.3 Results and discussion

3.3.1 Aerial photo analysis

The 1937 image shows a single-thread meandering channel in the center of the wetland (Figure 3.4). Active deposition and minor braiding are visible at the head of the wetland. One beaver pond is visible, although all five ponds visible in the 1969 image may have been present though not visible due to the low resolution of the 1937 photo. The 1953 image shows extensive deposition in the head of the wetland and no main channel is present. Instead, a braided, delta-like environment exists. The 1969 image shows additional deposition in the form of either debris-flow or splay deposits and a poorly defined channel in the northern wetland is pushed to the west side of the valley by the recent deposits. The 1987 image shows minor deposition in the form of either debris-flow or splay deposits and sparse conifer growth in areas of previously identified deposition. The 1969 and 1987 channel locations are the same. The 2001 image shows minor splay deposition and channel position is generally unchanged, though there is no dominant channel. The conifers visible in 1987 are more distinct in 2001. The 2004 image shows deposition from the 2003 debris flow (Figure 3.5). Channel position is generally unchanged from prior photos, though there is no well-defined channel. The 2009 image shows reworking of the 2003 debris-flow sediment. Channel position is generally unchanged between 2003 and 2009, with no well-defined channel, although some channelization and migration towards the center of the valley is visible.

In summary, the 1937 channel was a single-thread, meandering channel. The current topographic low path through the wetland is in the location of the 1937 channel through the center of the wetland, but post-1937 deposits have pushed the channel to the west against the valley wall. Substantial deposition visible in the 1953 and 1969 photos, as well as minor deposition in 1987, suggest repeated debris flows and/or flood disturbances. I interpret the 1937 channel as a model of “recovered” channel condition (recovered from debris flows prior to 1937). The assumption inherent in this interpretation is that, in the absence of debris-flow related disturbance, the Colorado River in the Lulu City wetland would assume a single-thread planform.

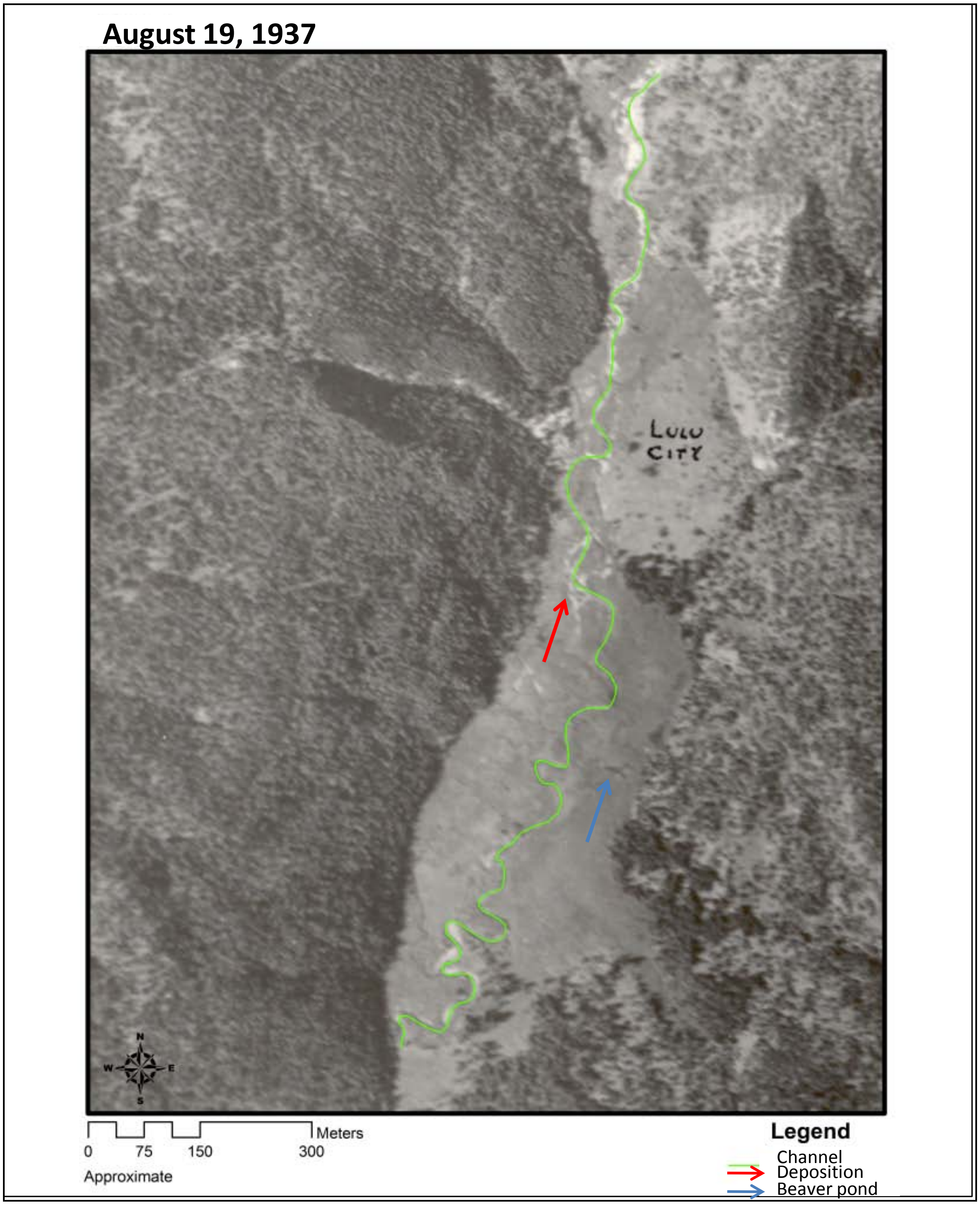

Figure 3.4. The 1937 aerial photo is the oldest available photo. The image shows a single-thread meandering channel through most of the Lulu City wetland. Only minor deposition and potentially minor braiding is visible at the head of the wetland. One beaver pond is visible, though others are expected to have been present but not visible until later aerial photos.

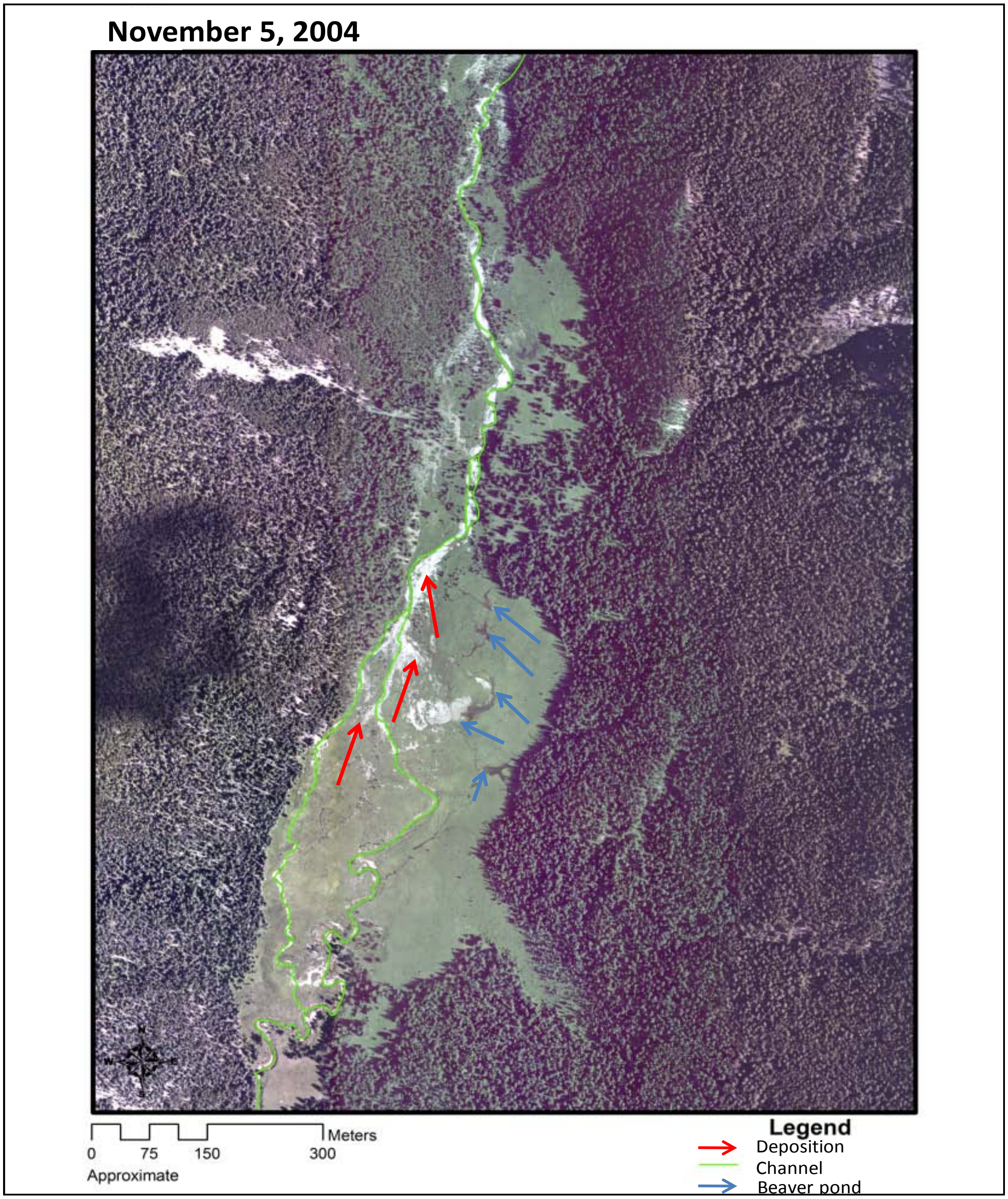

Figure 3.5. The 2004 image shows deposition from the 2003 debris flow. The channel is against the western valley wall in the north, and bifurcated in the central and southern wetland. Several abandoned beaver ponds are visible in the northeast portion of the wetland.

The 1937 channel in Lulu City wetland is close to the braiding threshold based on discharge (estimated 3.6 m^3/s from Table 4.4) and channel slope (0.09%) proposed by Leopold and Wolman [1957]. Similarly, the van den Berg [1995] unit stream-power braiding threshold predicts a braided planform if median grain size (D_{50}) is less than 3-15 mm for estimated channel widths of 2-4 m. The historic D_{50} in the undisturbed wetland channel is unknown, but is expected to be in that range of 3-15 mm based on current grain sizes in the wetland and channel upstream. The proximity to the braiding thresholds proposed by Leopold and Wolman and van den Berg suggests a system that can be either meandering or braided, depending on the substrate, bank material and vegetation, and especially discharge and sediment inputs. In the Lulu City wetland, bank stability induced at least in part by thick wetland vegetation, suggests a tendency towards stable banks and a meandering planform during undisturbed periods [*Knighton*, 1998; *Bledsoe and Watson*, 2001; *Braudrick et al.*, 2009; *Tal et al.*, 2010]. Furthermore, the single-thread, meandering planform identified in the 1937 aerial photo suggests that despite potential increases in sediment loads resulting from Grand Ditch construction, mining, deforestation, and fire, the Lulu City wetland tends towards a stable, meandering planform.

The 1987 and 2001 images display minimal deposition and those images are interpreted as the most recovered condition in the period of record of aerial photography. However, neither of those images suggests significant progress towards a single-thread channel, and deposits are expected to be persistent features. This implies that the elevated disturbances and sediment inputs to the wetland since 1937 have dominated wetland processes. The inability of the Colorado River in Lulu City wetland to rework deposits and re-establish a dominant channel is likely also a result of the water diversion that reduces the erosive and sediment-transporting capabilities of the channel. The absence of a distinct channel in 2009 is consistent with 1987 and 2001 when major channelization was also absent.

The presence of conifer trees barely visible in the 1987 photo, and clear in the 2001 photo, suggests a shift to mesic species from riparian and wetland communities. While wetland to mesic succession is proposed as a natural process [*Kangas*, 1990; *Glenn-Lewin et al.*, 1992], there is no specific reason to presume that shift was inevitable at the Lulu City wetland, and many have argued that peatlands can persist indefinitely in the absence of climatic change [*Cooper*, 1990; *Klinger et al.*, 1990; *Klinger*, 1996]. Peat production has been temporally sporadic on the west side of the wetland, but the appearance of conifers suggests a shift that is likely unprecedented for several thousand years. The complete series of aerial photos is presented in Appendix A.

3.3.2 Ground penetrating radar

GPR surveys assisted in distinguishing major differences in facies regimes or, for purposes of this thesis, the higher and lower energy depositional environments. Low-energy regimes (peat, overbank) are characteristically free of diffractions, and commonly horizontal and continuous where overbank deposition and peat are interbedded. Massive peat is free of reflection horizons [*Halleux*, 1990] or may show weak reflections due to variation in composition. High-energy environments may display diffractions from cobbles or larger material [*Clement and Murray*, 2007] and demonstrate fluvial reworking that prevents horizontally continuous reflections. However, sorted debris flows were similar to low-energy overbank deposits because they may be laterally continuous and free from the diffractions caused by large clasts. In cases where subdivisions within the low or high energy categories were possible, I noted gyttja, peat, and coarse (cobble or boulder) sediment deposits.

Distinct differences are apparent between deposits on the west and east sides throughout most of the wetland (Figure 3.6). The east side of the wetland from XS1 to XS5 is distinctly horizontal or sub-horizontal and laterally continuous through the entire vertical section imaged by the GPR (Figure 3.7). This form represents stable, low energy environments without any fluvial reworking or channel migration.

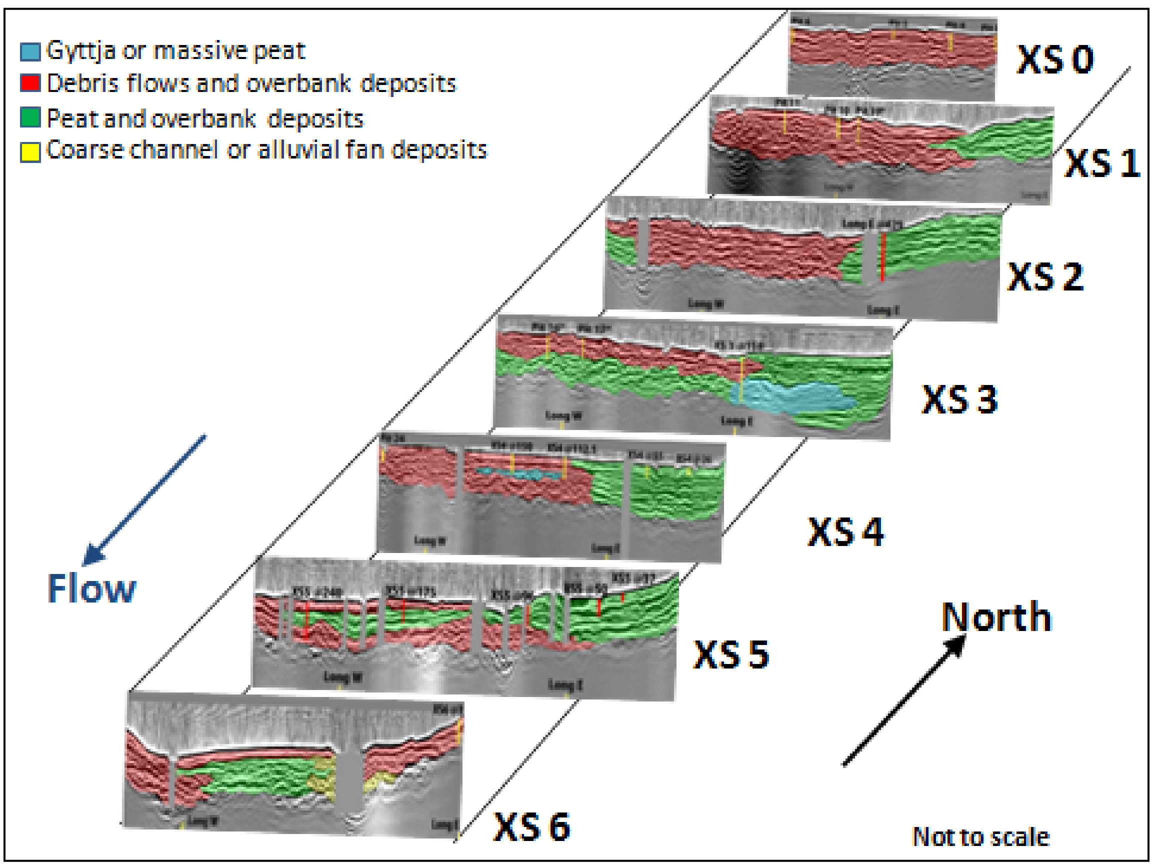

Figure 3.6. GPR surveys show distinctly different facies on the west and east sides of the Lulu City wetland. The east side is dominated by peat and overbank deposits between XS1 and XS5 with no fluvial reworking. The west side is vertically and laterally heterogeneous, although deposits are debris-flow dominated.

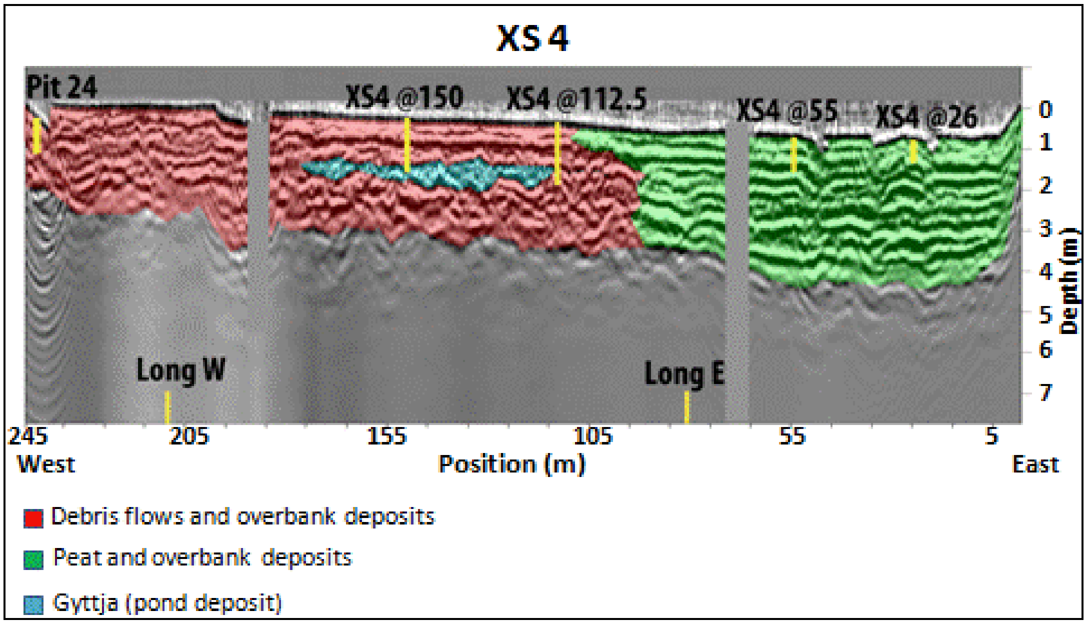

Figure 3.7. The GPR survey of XS4 penetrated up to 4 m on the east side of the valley. Labels at the top of the image are excavator or auger-hole identifiers. Yellow lines are to scale and represent the depth of those holes. At the bottom of the image, lines denote where XS4 crosses the Long W and Long E transects. Gray bars are areas where GPR data could not be collected. The west side of the valley is dominated by debris flows and overbank deposition. The east side is stable, non-erosional, peat and overbank deposition.

The west side of the valley is more complex. In the west, where debris-flow deposits are visible in aerial photos from 1953, 1969, 1987, and 2004 (Appendix A), there is a surficial sequence, as expected, of several gravel to cobble sized deposits (Figure 3.8) that fine down-valley from gravel/coble at the north end to sand/gravel at the southern end. The entire sequence of deposits from the last approximately two centuries has an estimated volume of ~80,000 m^3 based on interpolated hole and GPR data. At XS0-XS2 at the north end of the wetland, the surficial sequence of coarse deposits makes up the entire imaged sequence of 2-4 m. At XS3, the debris-flow sequence is underlain by peat and vegetated fine sediments that appear to have hummocks or have been crossed by channels over time. At XS4, debris flows comprise the upper ~1.5 m. Below, pond sediments are identified by auger core XS4 @112.5 m. Below that is a sequence of debris-flow or other colluvial deposits. At XS5, recent debris flows composed of sorted sand and gravel comprise the upper ~1 m. Below is a low-energy sequence of peat, gyttja, and overbank deposits 1-2 m thick. This is underlain by hillslope inputs, one of which I interpret as deriving directly from the valley wall because it is poorly sorted. XS6 is different from upstream cross sections on both west and east sides of the valley, with direct hillslope inputs suggested by the alluvial fan on the east and by dipping strata on the west. The center of XS6 has debris-flow deposits on the surface, underlain by peat and overbank deposits to the west of center, and coarse deposits to the right of center that may be coarse fan deposits from the east or coarse channel-lag deposits.

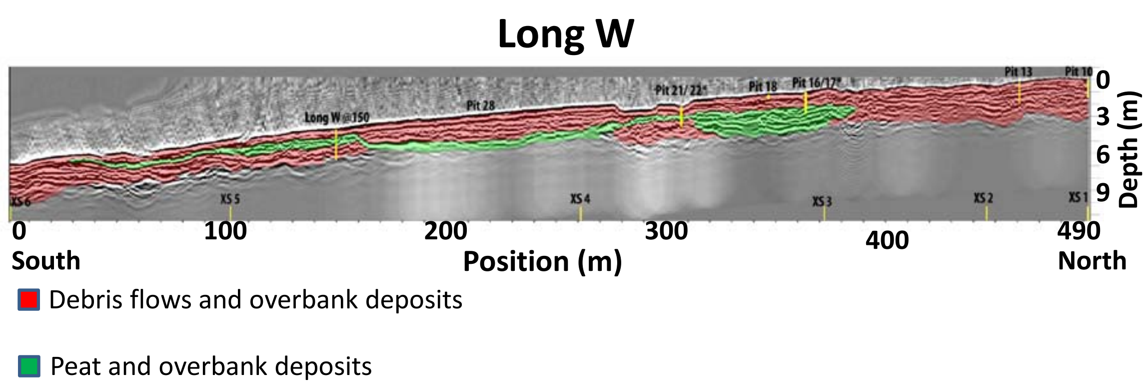

Figure 3.8. The west side of the wetland is vertically and laterally heterogeneous. The northern wetland is dominated by coarse deposits throughout the imaged profile. Central and southern regions indicate a more stable regime that was present prior to recent deposits.

In summary, the west side of the wetland is vertically and laterally heterogeneous, with down-valley fining, although coarse deposits in the southwest suggest direct colluvial inputs in the form of debris flows, landslides, or avalanches. The distance between GPR cross sections, however, makes it difficult to map individual deposits. Finer grained soils and peat were present prior to the surficial series of coarse deposits, although coarse deposits are identified below that, suggesting high-energy fluvial and colluvial inputs were a natural occurrence. The east side of the wetland has been consistently dominated by peat and overbank deposition throughout the entire imaged and sampled sequence. Debris flows are also documented in the northeast and southeast corners of the valley, likely from the tributary fans that enter the valley from the east (Figure 3.5).

Interpretation of GPR relied heavily upon ground-truthing from auger and excavator holes. The similarity of sorted debris-flow and overbank deposits makes extrapolation difficult and interpretation of strata distant from or deeper than holes has a potential for greater error than deposits near augered or excavated holes. Nonetheless, the distribution of auger holes and excavated holes provided good spatial coverage for interpreting the aggradational history of the valley up to the GPR and sampling depth limitations (~3.5 m). All GPR transects are interpreted and presented in Appendix C.

3.3.3 Aggradational processes

Depositional processes were inferred from GPR surveys and stratigraphic descriptions from the 19 excavator-dug and 15 hand-augered holes. In addition, radiocarbon dating of peat and gyttja was used to identify the timing of depositional transitions (Table 3.1).

Table 3.1. Radiocarbon sample descriptions

Location[1]	Depth (cm)	Age (years before present (2009))	Material
Long W @ 150 m	80	189 ± 40	Peat
Long W @ 150 m	115	734 ± 40	Peat
Long W @ 150 m	175	2399 ± 65	Organic-rich fine sediment
SW hole	50	109 ± 33 [2]	Peat
SW hole	144	2334 ± 45	Peat
SW hole	313	4089 ± 50	Peat
SW hole	337	4249 ± 50	Peat
XS3 @ 158 m	110-125	679 ± 45	Organic-rich fine sediment
XS3 @ 158 m	155-170	1459 ± 50	Peat
XS3 @ 158 m	320-330	3389 ± 65	Peat
XS4@ 112.5 m	125	299 ± 45	Organic-rich fine sediment and wood pieces

1) Figure 3.2
2) <120 (99.4 ±0.4 pMC)

Recent aggradational processes on the west side of the wetland are distinct from pre-settlement processes. Radiocarbon dates suggest peat and organic-rich soil development and accumulation ceased at Long W@150 m in the central west portion of the wetland (Figure 3.2) concurrent with human impacts of the 19th and 20th century. Long W@150 m (Figure 3.9) had been a peatland for ~545 years and accumulated 35 cm of peat until three sediment deposits occurred in the past ~189 years, accumulating 70 cm of sediment (Table 3.1). Furthermore, Long W@150 m was beyond the area of deposition in 2003, suggesting that higher-energy debris flows, capable of deposition in the southern wetland, have occurred in the past two centuries.

Similarly, the core at SW Hole in the southwest indicates it had been a peatland with no substantial sediment deposition for ~2225 years until 50 cm of sand was deposited in the past ~109 years (Figure 3.10). Also, at XS3@158 m in the northeastern part of the wetland, aggradation was dominated by gradual processes of peat production and pond filling from ~3389-679 yr BP (Figure 3.11). During this period, four sand-to-gravel sized deposits are preserved, with thicknesses ranging from 5 to 25 cm. Recent sand and gravel deposits are substantially larger in thickness, ranging from 15 to 65 cm.

Recent changes in depositional regime at XS4@112.5 m are not apparent, perhaps because the auger only penetrated through one deposit under the dated pond sediments and it is therefore difficult to infer the aggradational history there. Interpretation of the GPR image suggests previous coarse sediment deposition. The most recent sample of organic-rich sediments is ~299 years old, though only 5 cm of that layer is preserved, suggesting only a brief period of gradual sedimentation in a regime dominated by episodic debris flows and overbank deposits.

Sediment Descriptions from Long W @150 m

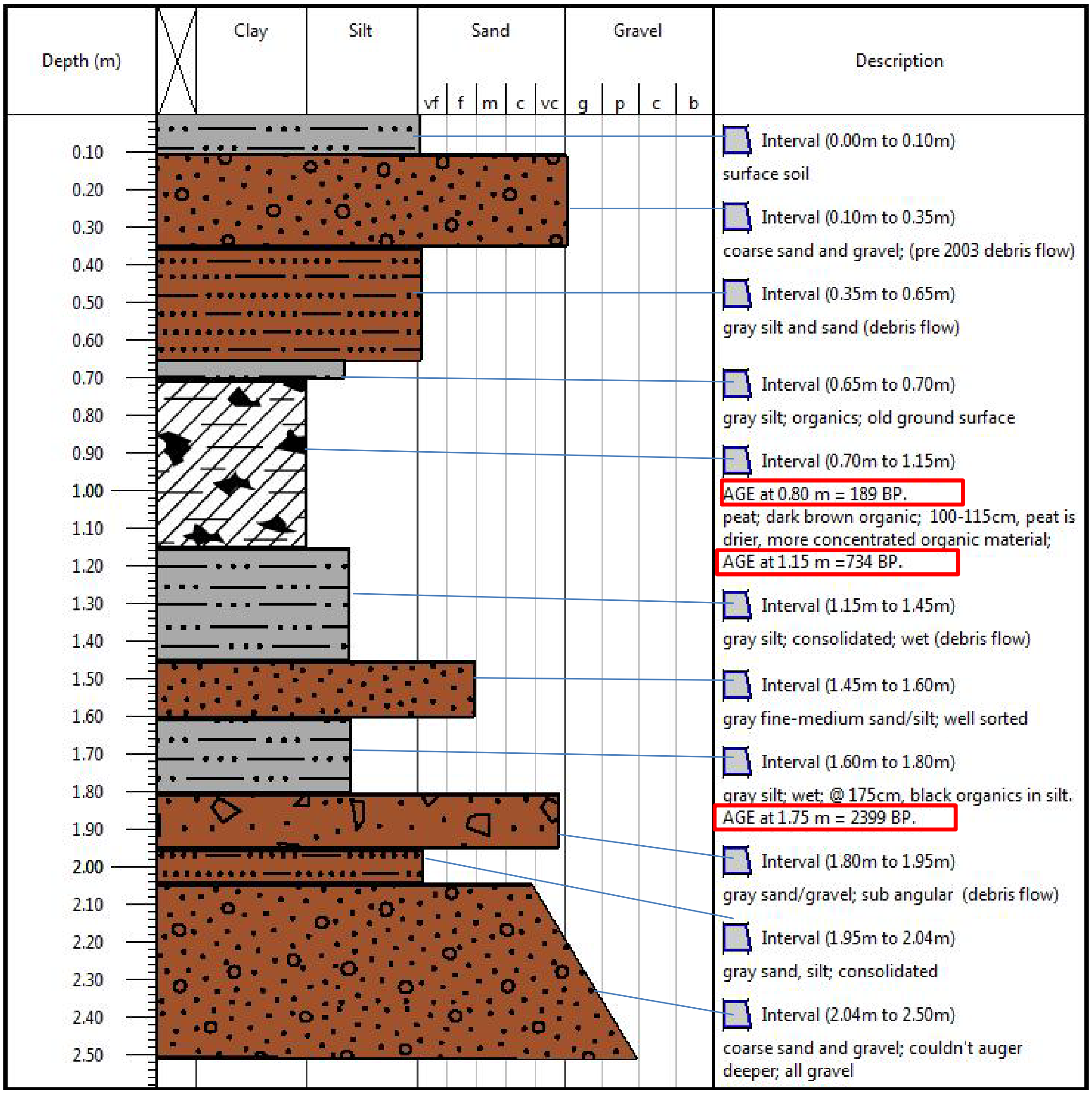

Figure 3.9. Long W @150 m is in the southwest portion of the wetland between XS4 and XS5. Ages obtained from radiocarbon dating are outlined in red for emphasis. Dates from 1.15 m and 0.8 m depth indicate 35 cm of peat accumulation in the ~545 years prior to 65 cm of sediment deposition in the past two centuries.

Sediment Descriptions from SW Hole

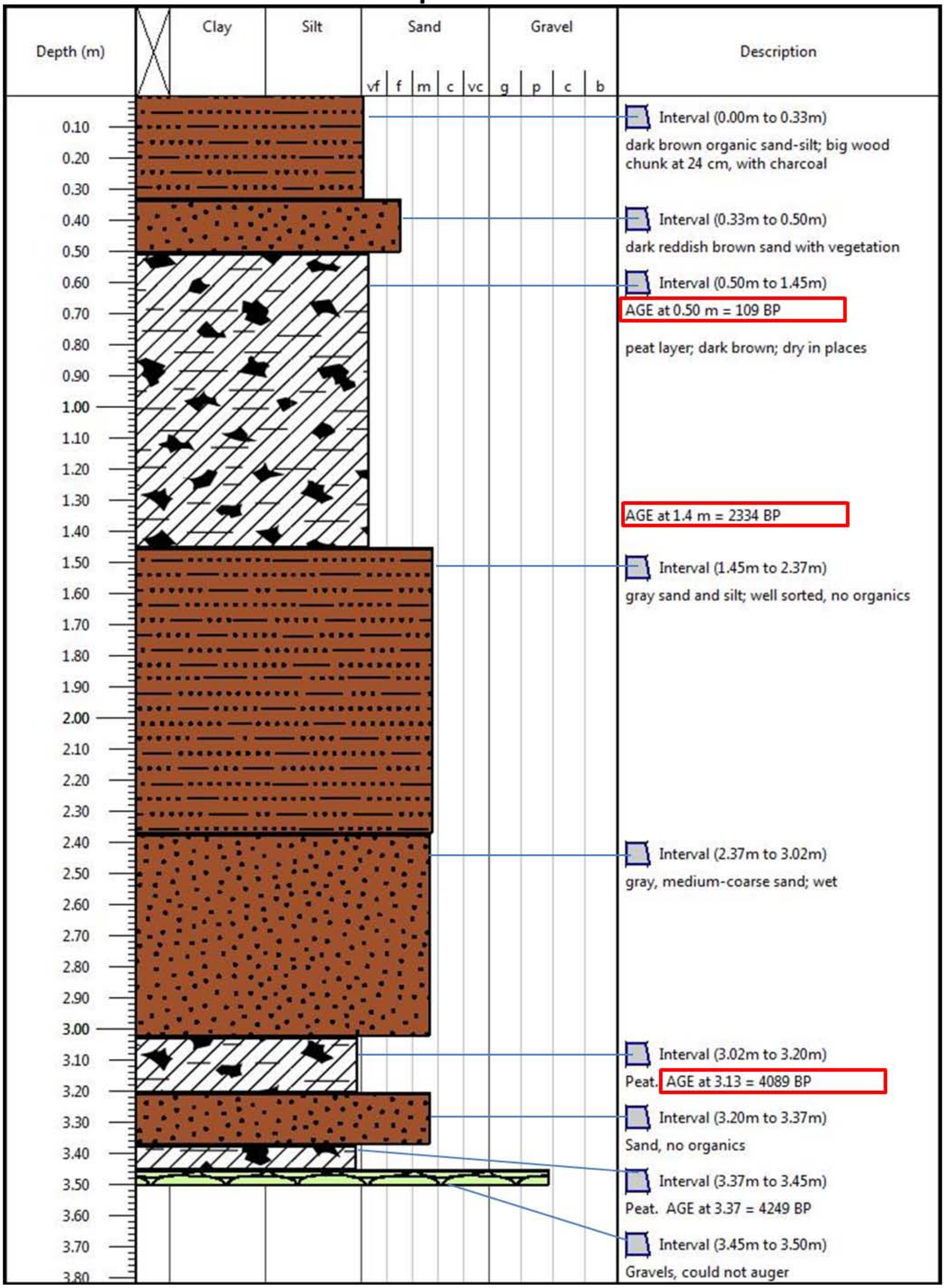

Figure 3.10. SW Hole is in the southwest portion of the wetland. This was dug with shovels to ~2 m, then augered to 3.5 m. Radiocarbon dates from 0.5 and 1.4 m depth indicate 90 cm of peat accumulation in ~2200 years prior to ~50 cm of sediment deposition in the past two centuries.

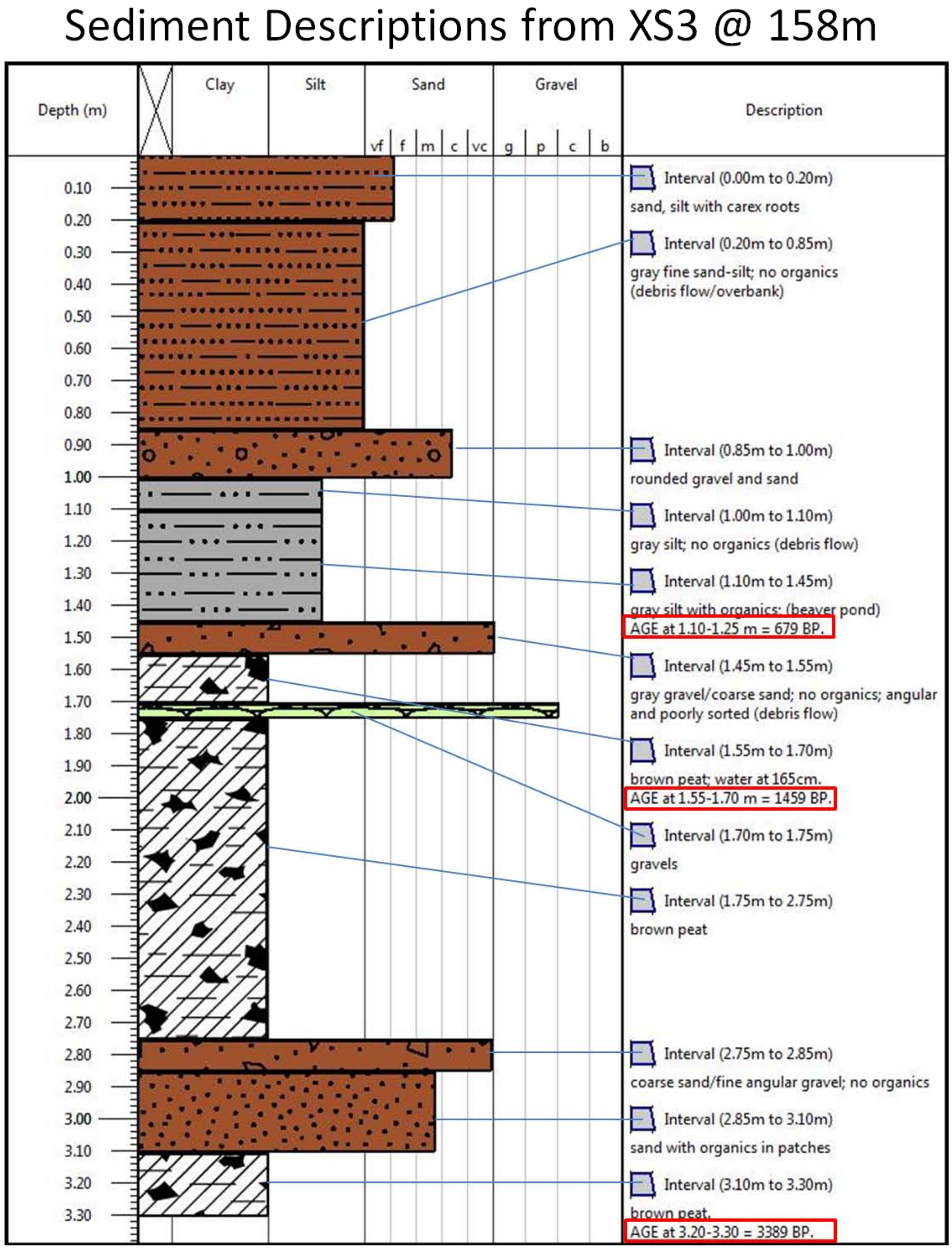

Figure 3.11. XS3 @ 158 m is in the northeast portion of the wetland. The most recent radiocarbon date is from a historic beaver pond at ~1.2 m depth and is dated as ~679 yr BP. Previously, peat was the dominant aggradational process, although four coarse deposits are present from ~679 to 2289 yr BP.

Six of the deepest auger and excavator pits were selected from across the wetland to establish a quantitative estimate of the relative contributions of different aggradational processes (Table 3.2). XS5 @240 m, Pit 17 on XS3, and Pit 11 on XS1 were selected to represent the western portion of the wetland (Figure 3.2). XS5 @50 m, XS3 @158 m, and Long E @429 m on XS2 were selected for the eastern portion of the wetland.

Table 3.2. Approximate relative contributions of aggradational processes

	Debris Flow (%)	Overbank or sorted debris flow (%)	Peat (%)	Gyttja (beaver pond) (%)
West	50	35	10	5
East	10	30	50	10

The east side of the wetland aggraded primarily through peat (~50%) and overbank deposition (~30%). The west side of the wetland has aggraded primarily through debris flows (~50%) and overbank deposition (~35%). Differences in process from west to east are likely influenced by several factors including the tributary fan that forces the channel to the west, groundwater that supports peat production in the east, and more recently, localized deposition at the head of the wetland that pushed the active channel to the west. Beaver dams in the northern part of the wetland may have encouraged deposition at the head of the wetland and facilitated the avulsion towards the west that occurred between 1937 and 1969 (Appendix A).

Although recent deposits to the west side of the valley appear to differ from the immediately preceding deposits, several pre-impact debris-flow deposits of the past 4000 yr show similar textures. The increased frequency and greater magnitude (thickness) of recent events, however, distinguishes them from older deposits. Beaver pond fill was expected to be more common in the wetland, but less than ~10% of the wetland fill can be attributed to this process. This result is supported by geomorphic investigations of modern beaver dynamics downstream on the Colorado River that suggest dams in higher order streams function primarily by encouraging overbank deposition. In-channel deposition is less likely to be preserved due to frequent breaching of dams and removal of in-channel sediment [*Westbrook et al.*, 2010]. Stratigraphic descriptions from all 19 excavator-dug and 15 hand-augered holes are presented in Appendix B.

3.3.4 Aggradation Rates

Aggradation rates in Lulu City wetland range from 4 to 15 cm/100 yr for most of the period sampled for this study, but then increase to over 40 cm/100 yr during the past 100-200 years (Figure 3.12). Similar rates of ~40 cm/100 yr for the past one to two centuries occur at three dated profiles: Long W @150 m, SW Hole, and XS4 @112.5 m. The fourth dated profile is at XS3@158 m where the uppermost (youngest) date is ~620 yr BP and 1.1-1.25 m below the ground surface. The aggradation rate of the past 1-2 centuries at XS3@158 m is likely similar to that at the other profiles. At a similar depth, Long W @150 m is dated at ~ 734 yr BP (Table 3.1), but because a later sample is dated at ~189 yr BP, the higher aggradation rates of the past two centuries can be distinguished. This is not possible at XS3@158 m because temporal resolution of aggradation rates is limited by the samples collected and the assumption of constant rates of aggradation between known dates is likely invalid. It is possible that aggradation rates would be spatially heterogeneous throughout the wetland, although given the strong correlation of other dated samples, and the similarity in the depth of the Long W @150 m sample, XS3@158 is expected to have followed a similar pattern of rapid aggradation during the past two centuries (Figure 3.13).

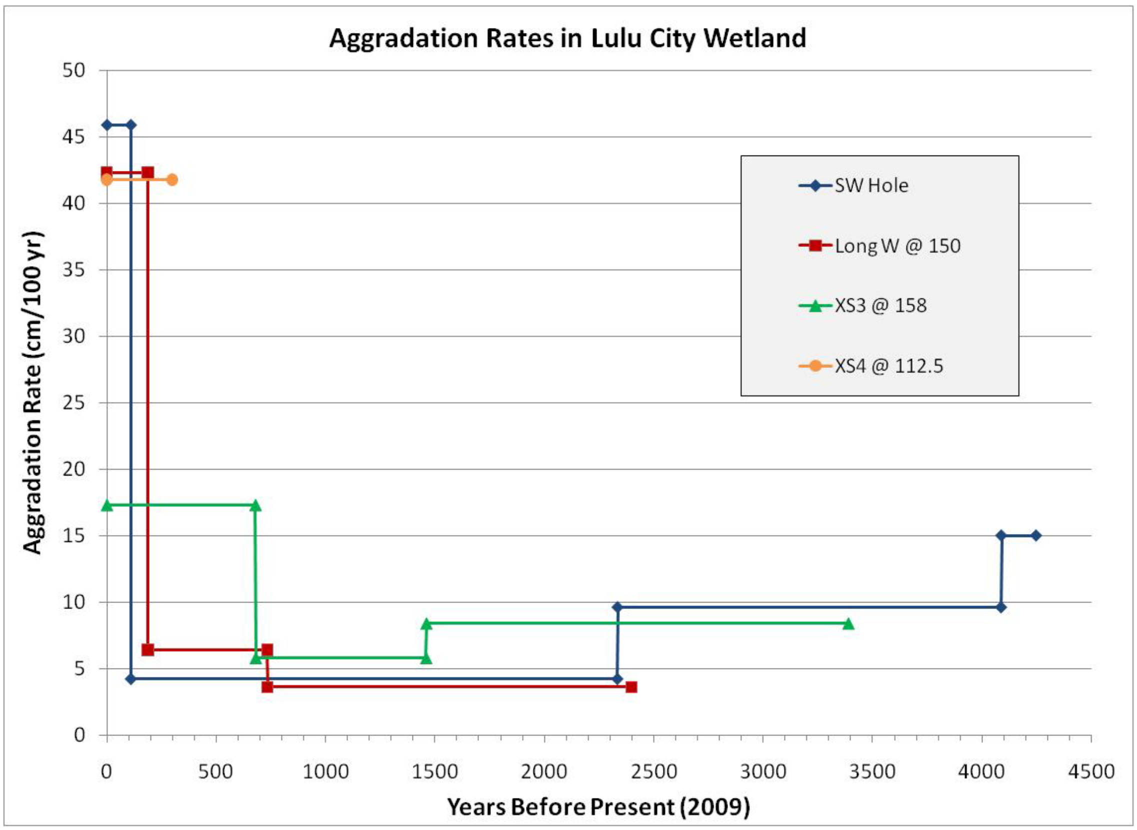

Figure 3.12. Aggradation rates were calculated based on the mean radiocarbon age for each sample and assuming constant rates between each age control point. Each age control point is indicated by a symbol. Locations of radiocarbon-dated cores presented in Figure 3.2.

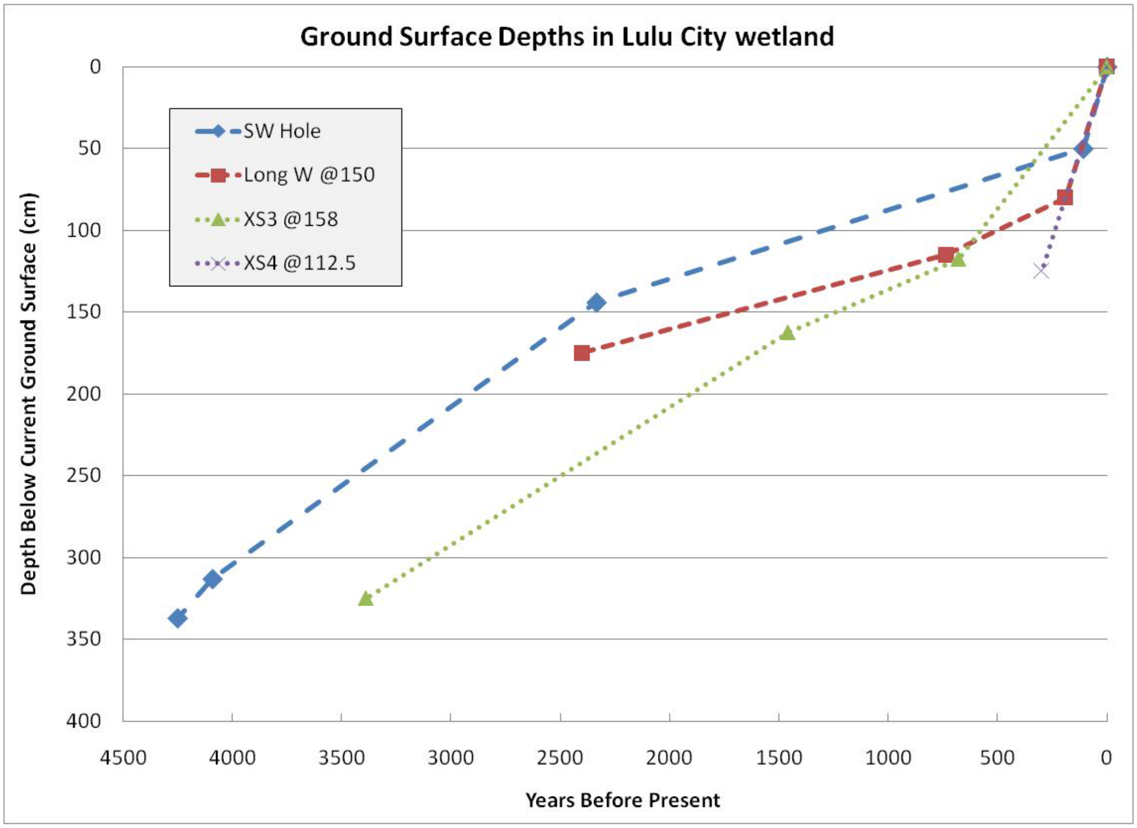

Figure 3.13. The ground surface over time at dated profile locations is generally consistent throughout the Lulu City wetland, assuming no loss of elevation (e.g., deposition and subsequent erosion, or compaction) between dated samples. Steeper slopes indicate faster aggradation rates. Each age control point is indicated by a symbol. Locations of radiocarbon-dated cores are presented in Figure 3.2.

Variation in pre-disturbance aggradation rates is also apparent. Aggradation occurred faster during the period from ~4000-2500 yr BP than from ~2500-200 yr BP (Figure 3.12, and represented by the steeper slope seen on Figure 3.13). The higher aggradation from ~4000-2500 yr BP corresponds to a period recognized as climatically distinct. The period from ~4000-2000 yr BP was generally cooler and drier than present [*Fall*, 1997], while the last ~2000 yr were generally similar to the modern climate [*Vierling*, 1998], although cooler and more severe temperatures were present during the Little Ice Age from ~700 to 100 yr BP [*Fall*, 1985; *Doerner*, 2007]. Peat aggradation rates are positively correlated with precipitation and temperature, though local controls can also influence growth [*Ovenden*, 1990]. Peat production is therefore expected to have been slower between ~4000-2500 yr BP. However, variation in peat accumulation rates is expected to be low relative to the variability in sedimentary processes. Long-term variability in peat accumulation rates is typically minimal [*Blaauw and Christen*, 2005], while sediment deposition can vary over orders of magnitude depending on the time scale and magnitude of climatic change [*Sadler*, 1981]. Variability in aggradation rates is therefore more likely to be controlled by sediment inputs than by peat accumulation. In forested watersheds, precipitation is negatively correlated with increased sediment yields because precipitation induces vegetative growth and soil stability [*Langbein and Schumm*, 1958; *Knighton*, 1998]. Sedimentation rates are therefore expected to have been higher between ~4000-2500 yr BP. Following these expected results, the profile at SW Hole (Figure 3.10) demonstrates a regime from ~4100-2300 yr BP dominated by sediment deposition, with peat persisting from ~2300 yr BP until modern sediment deposits of the past century. Conversely, the profile at XS3 @158 m is peat-dominated from ~3400-1500 yr BP and sediment-dominated after 1500 yr BP. The processes of aggradation are spatially varied and the influence of climate on vegetative and erosive processes is complex. With a limited number of samples, spatial and temporal correlation is uncertain, but results generally support H1A-2 and H1A-4: significant variations in Holocene aggradation rate associated with climatic variability, and significant increases in the recent aggradation rate beyond the range of earlier Holocene variability.

Uncertainty emerges when comparing the modern (100-200 yr) aggradation rate to longer (~2000 yr) time periods because the episodic and spatially varied processes of sediment deposition make extrapolation difficult. Previous investigators have shown that mean accumulation rates decrease with longer sample periods [*Sadler*, 1981; *Mcshea and Raup*, 1986; *Schumm*, 1998]. In this study, this uncertainty is minimized because climatic variability in the Colorado Rockies during the Holocene is much less than the variability seen at longer time scales [*Short*, 1985; *Crowley and North*, 1988].

Additionally, there is the question of validity in comparing the currently deposited material to what will be ultimately preserved. Even recognizing the Lulu City wetland to be a depositional zone in an overall trajectory of aggradation, it is reasonable to expect some fluvial reworking and transport out of the wetland. Indeed, the question of transient versus persistent features is central to this assessment of the impacts from recent Grand Ditch-caused debris flows. Comparing the rate of recent *deposition* to the historic rate of *preservation* is of limited usefulness. Furthermore, as deposits to the head of the wetland increase the valley gradient, the aggradation itself should lead to greater transport capacity and a potential mechanism for lowering sediment preservation rates. As mentioned previously, for more than 3000 years the eastern portion of the wetland has aggraded almost exclusively from peat production and overbank deposition without any fluvial reworking or channel migration into the region, whereas the west side of the wetland has filled primarily through debris flows and overbank deposition. The uniform, horizontal reflections in the GPR surveys of XS2-XS5 (Figures 3.6 and 3.7) indicate that the preserved deposits are from peat and overbank deposition, and the absence of fluvial reworking of sediments suggests that the aggradation has been *purely* depositional. Interestingly, although the east and west sides of the wetland have been dominated by different processes, over the past 3000+ years aggradation has occurred at roughly the same rates (Figure 3.12). This suggests that the wetland topography is in a state of dynamic adjustment. Aggradation in the west might disconnect the floodplain from the channel and thus overbank deposits would be confined to the east. Peat production in the east may similarly elevate and disconnect the eastern side of the valley bottom from the river, encouraging overbank deposition in the west. Similar equilibrium adjustments may also occur longitudinally. Deposition at the head of the wetland increases the channel slope and facilitates reworking of those deposits and/or deposition farther downstream. The dichotomy of aggradational processes on the east and west sides of the valley suggests deposits will be preserved. Because east and west have aggraded at similar rates historically and recent aggradation rates are of a similar magnitude throughout the radiocarbon-dated profiles in the wetland, I predict that the east side will continue to be purely depositional and I assume the recent debris-flow deposits will persist. Modern aggradation rates thus can be compared to historic rates without introducing bias into the interpretations.

3.4 Conclusions

Modern deposits have substantially altered the rate of aggradation throughout the Lulu City wetland. The conceptual models presented as H1A-2 and H1A-4 are therefore supported. Aggradation rates were variable through the late Holocene, perhaps in relation to climatically driven changes in sediment yield, valley-bottom depositional processes, and peat production rates. The Grand Ditch and earlier land-use changes (mining, timber harvesting, etc.) have altered the rate of deposition beyond that present prior to Euro-American settlement of the region. Inferred rates of aggradation range from 4-15 cm/100 yr from ~4250 yr BP until ~ 200 yr BP. Rates are generally consistent throughout the Lulu City wetland. Similarly, modern rates (~45 cm/100 yr) of the past approximately two centuries are consistent throughout the wetland and approximately six times higher than historic rates. The east side of the wetland has been stable for 3000+ years with peat accumulation and overbank deposition as the dominant processes of fill. Deposits are therefore expected to be persistent features of the landscape. Aggradation was primarily through debris flows and overbank deposition on the west side of the valley. Beaver-pond fill makes up less than 10% of the upper 2-3 m of valley fill. Peat was present in the west (SW Hole and Long W @150 m), the top of which was dated at roughly the time of human impacts (~130 yr BP). This suggests that land-use and Grand Ditch sediment inputs shifted not only the rate of aggradation but also the mechanisms of fill. Further corroborating these interpretations and scenarios of H1A-2 and H1A-4, aerial photos dating back to 1937 suggest repeated large-scale deposition on the west side of the valley.

Although debris-flow deposits are spatially heterogeneous in the wetland, making generalization difficult, the 2003 deposit is not unusually large in either thickness or spatial extent when compared to other deposits of the past two centuries.

The southernmost extent of the 2003 deposit was near Pit 28 (Figure 3.2). Deposits at Long W@150 and SW Hole are ~60 and ~150 m farther south, respectively, and were therefore likely deposited by larger events. Similarly, deposits equal to or thicker than 2003 are visible in the majority of holes in the west side of the wetland (Appendix B).

Correlation with other studies relating climatic variability and aggradation rates is not feasible. Studies such as that at La Poudre Pass (J. Doerner, unpublished report, 2005) were conducted in fens or other temporally stable peatlands because continuous preservation allows for unbroken pollen and fossil preservation throughout the entire sequence [*Elias*, 1985]. Aggradational processes at Lulu City wetland included colluvial and fluvial inputs in addition to the peat accumulation. Furthermore, peat accumulation rates ranged from 1.0 to 1.7 cm/100 yr from 100 to 6750 yr BP at the La Poudre Pass site. Peat accumulation rates (where basal and top of peat ages were obtained for individual peat sections) in the Lulu City wetland were 4.0 cm/100 yr at SW Hole from ~109 to 2334 yr BP, and 6.4 cm/100 yr at Long W@150 from ~189 to 734 yr BP. The difference in peat accumulation rates suggests that even in the absence of human disturbance or sediment deposition, substantial differences in peat accumulation rates exist between the Lulu City wetland and the La Poudre pass site (5 km and less than 300 m higher than the Lulu City wetland). Differences in peat accumulation rates at the two sites may be a result of climatic or groundwater differences. Similarly, rates of aggradation in case studies throughout the Rocky Mountains are dominated by local-scale watershed controls, as evidenced by significant variation in aggradation rates between five alpine bogs in the San Juan Mountains that are relatively close to one another [*Andrews et al.*, 1975]. In Yellowstone National Park, 30% of deposits were attributed to fire-induced erosion, and aggradation has been correlated with climates conducive to fire [*Meyer et al.*, 1995]. In contrast, less than five pieces of charcoal were found in the Lulu City wetland. The San Juan and Yellowstone examples highlight the complex dynamics of sedimentation and aggradation. Comparison is therefore only useful when watershed characteristics, processes of fill (relative contribution of colluvial, fluvial, peat and beaver pond), and climatic variation are similar.

4. Post-Debris Flow Channel Response: Contemporary Hydrology and Sediment Transport in the Upper Colorado River

4.1 Introduction

Disturbance is an integral ecosystem process, as it drives habitat heterogeneity and encourages species richness by allowing for both colonizing species and resident species [*Connell*, 1978; *Reice et al.*, 1990]. If the disturbances are too frequent, resident species will be uncompetitive. If disturbances are too infrequent, the most competitive residents will proliferate and limit species richness by excluding colonizing generalist species. The complex temporal and spatial dynamics of disturbance and recovery are of fundamental importance to the study of riverine geomorphology, water quality, and ecology [*Niemi et al.*, 1990; *Turner et al.*, 1993; *Benda et al.*, 2004]. Commonly, post-disturbance colonization is rapid, with most studies showing recovery of species richness and abundance within three years except in instances of persistent alteration to physical habitat [*Yount and Niemi*, 1990; *Detenbeck et al.*, 1992]. Ecosystem recovery following a debris flow was studied at H.J Andrews Experimental Forest in the Cascade Mountains of Oregon [*Lamberti et al.*, 1991]. Within one year, macroinvertebrates recovered to upstream densities and taxonomic richness. Similarly, cutthroat trout also recovered to pre-disturbance population levels within the first year. Populations exhibited significant temporal variations in abundance, suggesting ecosystem volatility [*Lamberti et al.*, 1991] that may have resulted from persistent geomorphic instability of the channel. Recovery of communities in the upper Colorado River watershed following the 2003 debris flow depends partly on recovery of pre-disturbance channel form.

The transient-form ratio (TFr in equation 1.1) is used as a measure of channel recovery following the 2003 debris flow in the upper Colorado River watershed. If significant recovery of geomorphic processes and forms occurred between 2003 and 2009, the disturbance will be interpreted as transient and less problematic from a management perspective. This research does not seek to quantify whether disturbance has become too frequent, but rather to quantify post-debris flow processes and to assess the geomorphic condition and trajectory of the upper Colorado River between the Crooked Tree (CT) and Gravel Beach (GB) gaging stations (Figure 4.1) after 2003. There are no pre-disturbance data, but after six years of post-disturbance monitoring, the trajectory of recovery is summarized to assess whether 1) the channel has adjusted to the imposed inputs of flow and sediment and 2) the current (2004-2009) sediment regime is expected to persist. This chapter addresses only channel response to the 2003 disturbance and does not consider floodplain, wetland, or biotic response. In order to address the research objectives, flow, sediment transport, bed particle size distribution, and channel cross sections were monitored from 2004-2009. All data prior to 2008 were provided by Sara Rathburn (pers. comm., 2009).

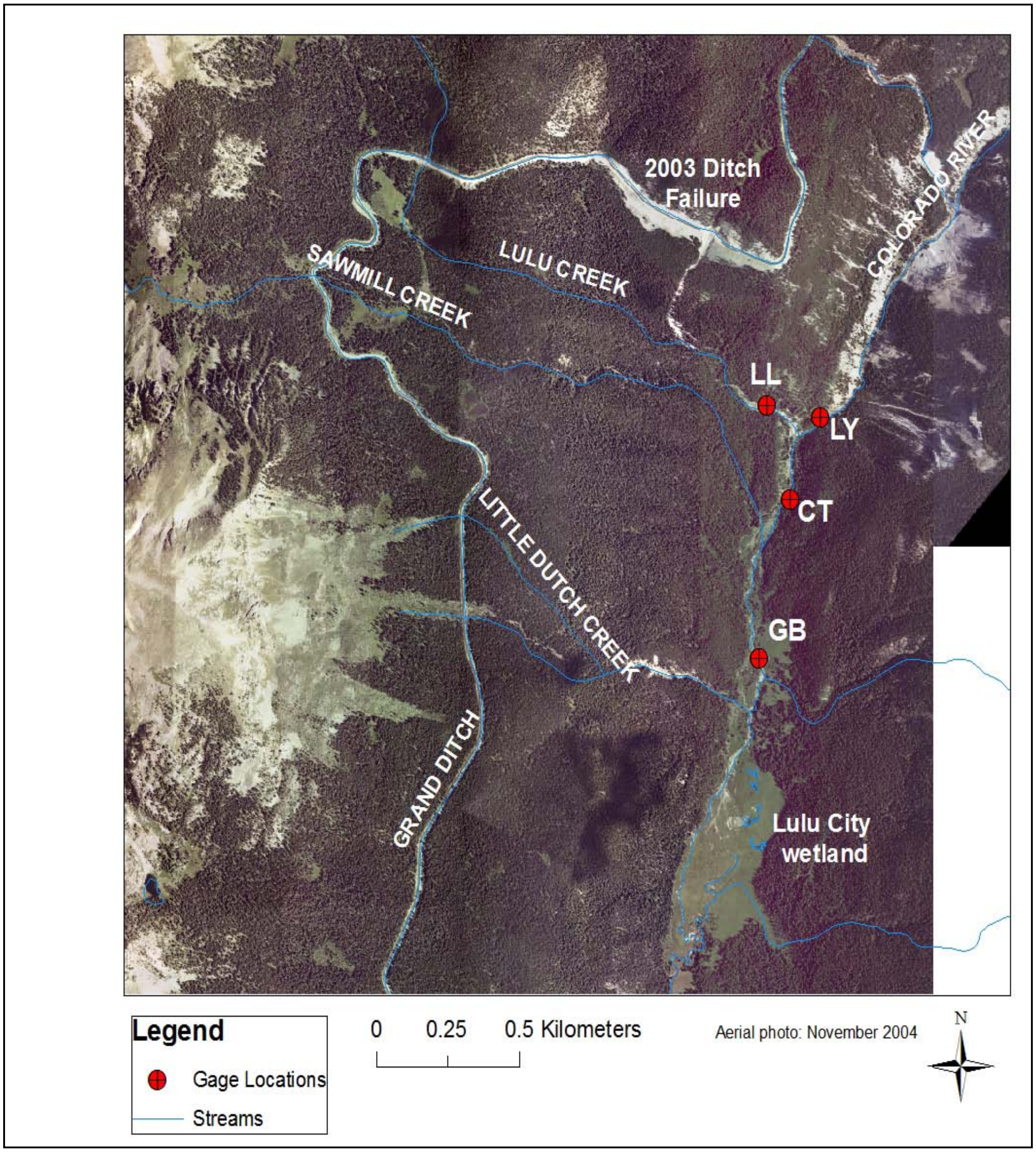

Figure 4.1. Four gages are located in the study area: LY is Colorado River at Little Yellowstone, CT is Colorado River at Crooked Tree, GB is Colorado River at Gravel Beach, LL is lower Lulu Creek. Flow on Colorado River is from upper portion of figure toward bottom. Grand Ditch flow is from the bottom of the figure to the top.

As part of the evaluation of channel recovery, bankfull discharge (Q_{bf}) of the 2009 channel at CT and GB is compared to analogs of bankfull discharge, including effective discharge (Q_{eff}) and the 1.5-year recurrence interval flow ($Q_{1.5}$). Alluvial rivers adjust channel geometry in response to imposed conditions of inflowing water and sediment. The concept of channel-forming discharge can be defined as the single discharge most responsible for maintaining channel form, or more precisely as the single discharge that would, if held constant over time, maintain a given channel geometry and slope [*Copeland et al.*, 2000]. Two analogs of channel-forming discharge have been proposed; 1) bankfull discharge, or the discharge that completely fills the channel [*Leopold et al.*, 1964], and 2) effective discharge, or the discharge that transports the most sediment over time [*Wolman and Miller*, 1960]. Furthermore, linkages between channel-forming discharge, Q_{bf}, Q_{eff}, and $Q_{1.5}$ have been investigated. Emmett and Wolman [2001] found the recurrence interval of Q_{eff} at five Rocky Mountain streams ranged from 1.5 to 1.7 years, and averaged 1.6 years. Leopold et al. [1964] suggested the 1.5-year flow typically approximates Q_{eff}. At 15 gaging stations in the Yampa basin of Colorado and Wyoming, Andrews [1980] found Q_{eff} had a recurrence interval of 1.2 to 3.3 years, with 50% of sites between 1.25 and 1.75 years. At all 15 sites, Andrews also found Q_{bf} and Q_{eff} to be essentially equal. Similarly, in a survey of 36 streams in western North America, Williams [1978] found the 1.5-year flow best approximates Q_{eff}. Of these studies, the Emmett and Wolman [2001] and Andrews [1980] field sites are most comparable to the study sites on the upper Colorado River, suggesting that Q_{eff} would likely have a recurrence interval of ~1.5 years. There is some concern that reducing the inherent variability in hydrology and sediment transport to a single discharge is a spurious oversimplification of complex geomorphic processes that evolve over varying time scales. Infrequent floods exert a stronger influence on channel form in systems with variable hydrology and high boundary roughness (E. Wohl, pers.

comm., 2010). Similarly, relationships between Q_{bf}, Q_{eff}, and $Q_{1.5}$ have been shown to be unreliable in flashy or variable hydrologic systems [*Stevens et al.*, 1975; *Graf*, 1988]. Agreements between channel-forming discharge and Q_{bf}, Q_{eff}, and $Q_{1.5}$ are strongest in snowmelt systems with coarse substrate [*Doyle et al.*, 2007], such as the upper Colorado River in the study area.

Because relationships between Q_{bf}, Q_{eff}, and $Q_{1.5}$ have been established for stable systems, I investigated these relationships to test channel recovery. All three analogs of channel-forming discharge should be equivalent in a stable system. Specifically, I compared Q_{bf} of the channel present in 2009 to a value of Q_{eff} that was based on observed sediment transport from 2004-2009. If Q_{bf} and Q_{eff} are similar, this suggests that the 2009 channel has adapted to the imposed inputs of sediment and water of the post-debris flow system. Additionally, Q_{bf} was compared to $Q_{1.5}$. $Q_{1.5}$ does not explicitly account for sediment transport in the potentially disturbed Colorado River. Therefore, if Q_{bf} is similar to $Q_{1.5}$, this supports the interpretation that the 2009 channel has recovered from the 2003 debris flow.

A practical outcome is also achieved through the comparison of Q_{bf}, Q_{eff}, and $Q_{1.5}$. Channel restoration is typically based on a single design discharge [*Soar and Thorne*, 2000] incorporating Q_{bf}, Q_{eff}, $Q_{1.5}$, or a combination thereof [*Copeland et al.*, 2000; *Doyle et al.*, 2007]. When considering restoration strategies for the upper Colorado River downstream from the Lulu Creek junction (sites CT and GB, Figure 4.1), Q_{eff} and/or $Q_{1.5}$ can be used. Therefore, if the current Q_{bf} configuration is similar to Q_{eff}

and $Q_{1.5}$, channel restoration may not be necessary. Three scenarios of channel recovery are proposed.

H1) The channel is still on a trajectory of adjustment to the disturbance of 2003. H1 is supported if: 1) channel geometry has not stabilized from 2003 to 2009, 2) sediment transport from 2003 to 2009 is elevated and variable due to pulses of debris-flow deposits being reworked by fluvial processes, and 3) effective discharge is substantially different from bankfull discharge.

H1A) In response to the 2003 debris flow, channel form has achieved a stable state that is different than pre-disturbance conditions. H1A is supported if 1) channel geometry has stabilized by 2009, 2) sediment transport is elevated and variable compared to the undisturbed Little Yellowstone (LY) site, and 3) the effective discharge and bankfull discharge are similar.

H1B) The impact of disturbance is diminished such that recovered processes and forms are present. The 2009 channel is similar to the pre-disturbance condition. H1B is supported if 1) channel geometry is stable by 2009, 2) sediment transport is not elevated or variable compared to LY, 3) the bed has armored, and 4) effective discharge, bankfull discharge, and the 1.5-year discharge are all similar.

4.2 Methods

4.2.1 Discharge

Four Solinst Levelogger Gold recording pressure transducers were installed on Lulu Creek, Sawmill Creek, and the Colorado River (Figure 4.1) in 2008 and 2009 to record stage at 15-minute intervals. The Lower Lulu Creek (LL), Colorado River at Little Yellowstone (LY), Colorado River at Crooked Tree (CT) and Colorado River at Gravel Beach (GB) gages were installed in June 2008 (Table 4.1). Gages were operated only during summer runoff. Prior to the recording gages, four discharge measurements in

2004 and four in 2005 occurred during summer runoff when sediment samples were collected. The Colorado River below Baker Gulch USGS stream gage (# 09010500) record was used to provide a context of stream flow conditions from 1953-present. The Baker Gulch gage is ~13 km downstream of the GB site, with a watershed area of 166 km^2. The GB watershed makes up ~17% of the area of the Baker Gulch gage watershed. Thus, stream flow trends are expected to be well represented by the Baker Gulch gage.

Table 4.1. Overview of stream gage locations

Station	**Monitoring Period**	**Automated Gage Period[1]**	**Describes**
LY	2004-2009	2008-2009	Undisturbed reference reach for Colorado River
CT	2004-2009	2008-2009	Reach impacted by 2003 debris flow
GB	2004-2009	2008-2009	Reach impacted by 2003 debris flow
LL	2008-2009	2008-2009	Reach impacted by 2003 debris flow

1) 2008: gages operated June 25 to October 10
   2009: gages operated May 2 to September 16

A record of streamflow was developed in two steps in accordance with U.S. Geological Survey (USGS) flow protocol [*Rantz*, 1982]. A record of water levels was compiled from the recorded electronic data and calibrated with field observations; the field observations of water level derive from staff plates, so that water levels can be referenced to a fixed datum. Second, streamflow was measured at a range of discharges using the velocity-area method with velocity measurements made at 0.6 of flow depth using a one-dimensional Marsh McBirney electromagnetic velocity meter and a USGS-style top-setting wading rod. An empirical stage-discharge relationship (rating curve) was developed for each site based on field measurements of stage and streamflow. This rating curve was then applied to the 15-minute stage record to produce a continuous discharge record. Flow measurements were conducted approximately bi-weekly during the snowmelt period to establish rating curves across a range of discharges. To account for temporary changes in bed elevation that may have occurred, stage shifts were applied to the stage record as needed to make measured discharge match the stage-discharge rating curve [*Rantz*, 1982]. Additional field measurements and observations at each station were used to verify the electronic record. Observations recorded during site visits included: water level (gage height) at the staff plate, high-water marks, the presence of log jams or snow bridges that may temporarily raise water levels, and signs of sedimentation or scour.

4.2.2 Sediment transport

4.2.2.1 Suspended sediment transport

Suspended sediment transport measurements began during the snowmelt runoff period in 2004 at stations LY, CT, and GB (S. Rathburn, pers. comm., 2008) (Table 4.2). Measurements at LY, CT, and GB continued in 2005, 2008, and 2009. Suspended sediment sampling at LL was added in 2008. Samples were collected at a range of discharges to facilitate the development of sediment rating curves (Figure 4.2). Results from LL are not presented here due to the limited number of samples after only two years of monitoring. Suspended sediment was measured along fixed cross sections at established stream gage locations. Samples were collected using a DH-48 depth-integrated sampler with ~5 lateral sampling locations at equal-width increments across the channel [*Thomas*, 1985; *Edwards and Glysson*, 1998]. Sediment samples were processed at the Colorado State University sedimentology lab, as follows: sample volume was measured, filtered through a 45 micron glass fiber filter, dried for 24 hours at 105 °C, and weighed. A concentration of sediment mass per volume of water (mg/l) was calculated for each sample.

Table 4.2. Suspended sediment sampling dates. Data for 2004 and 2005 from S. Rathburn.

	LY	CT	GB	LL
4/1/04	X	X		
4/29/04	X	X	X	
5/21/04	X	X	X	
6/7/04	X	X	X	
4/22/05		X	X	
5/17/05	X	X	X	
5/24/05	X	X	X	
6/7/05	X	X	X	
6/12/08	X	X	X	
6/20/08	X	X	X	
6/26/08	X	X	X	X
7/1/08	X	X	X	X
7/8/08	X	X	X	X
7/16/08	X	X		X
5/28/09	X	X	X	X
6/5/09	X	X	X	X
6/15/09		X	X	X
6/17/09		X	X	X
6/24/09	X	X	X	X
7/16/09			X	

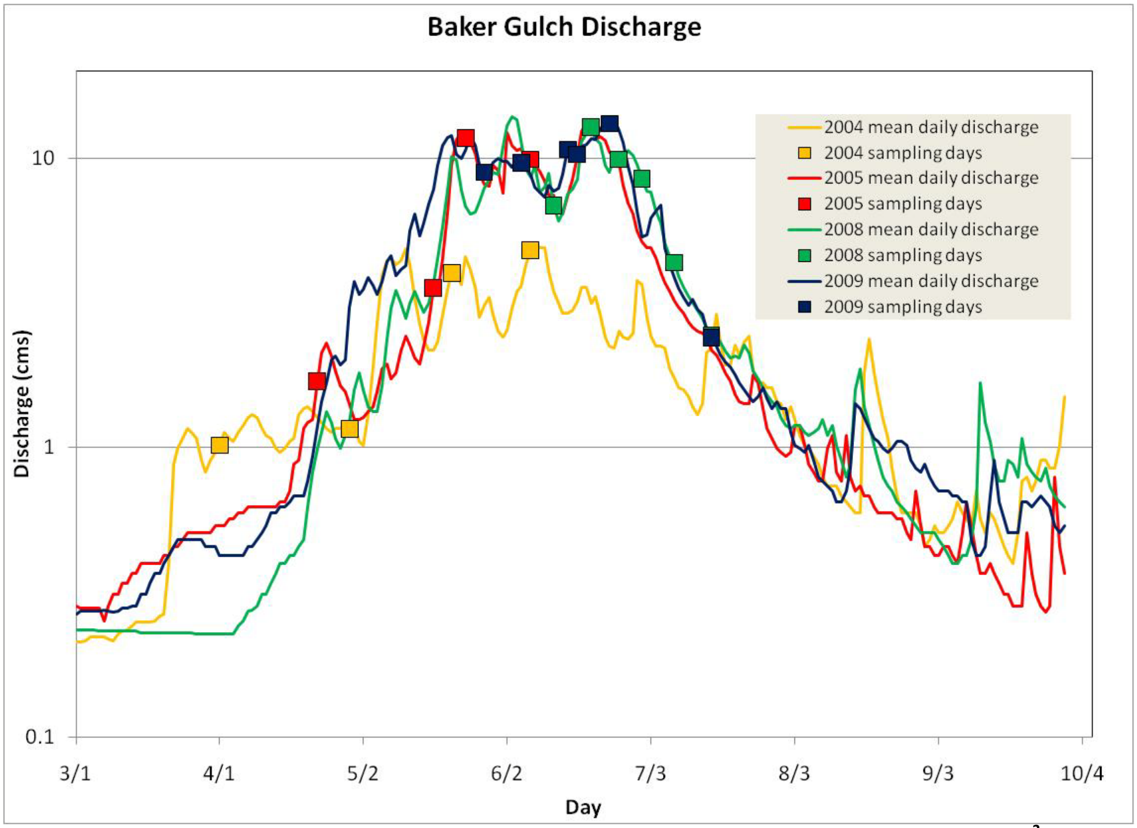

Figure 4.2. Discharge in 2004 was the lowest the during the study period with a peak discharge of 5.1 m^3/s on June 8. Discharge in 2005 was the second highest the during the study period with a peak discharge of 14.8 m^3/s on June 19. Discharge in 2008 was the highest of the study period with a peak discharge of 15.2 m^3/s on June 3. Discharge in 2009 was moderate with a peak discharge of 14.0 m^3/s on June 23. The Baker Gulch is used as a long-term proxy for discharge in the study area. Indicated sampling days are days when suspended and/or bedload samples were collected in the study area.

4.2.2.2 Bedload sediment transport

Bedload transport measurements began in 2004 at stations LY, CT, and GB, and continued in 2005, 2008, and 2009 (Table 4.3 and Figure 4.2). No bedload was sampled at LL because the steep-gradient step-pool morphology made accurate bedload sampling difficult. Bedload sediment transport was measured using a 76 mm Helley-Smith bedload sampler. Two-minute samples were collected at two locations on each cross section; approximately 1/3 channel width from the left edge of water and 1/3 from the right edge of water. An estimate of active bed width was calculated based on measured depths and velocities across the channel. Active bedload transport was assumed constant across the entire bed or until velocity and/or depth became very low at the channel margins. Using this method of approximation, active channel widths were estimated at 50 to 80% of the total wetted channel width. Experiments on the variability of bed-load transport across channels are mixed, though these estimates are appropriate based on visual observation and fit within the wide range presented in published literature. A study on the Colorado River ~12 km downstream of the study site suggests equal mobility across the channel, with variation in grain sizes accounting for the transport in lower shear stress zones [*Clayton and Pitlick*, 2007].

Table 4.3. Bedload sediment sampling dates. Data for 2004 and 2005 from S. Rathburn.

	LY	**CT**	**GB**
4/1/04		X	
4/29/04	X	X	X
5/21/04	X	X	X
6/7/04	X	X	X
4/22/05		X	X
5/17/05	X	X	X
5/24/05	X	X	X
6/7/05	X	X	X
6/12/08	X	X	X
6/20/08	X	X	X
6/26/08[1]			
7/1/08		X	X
7/8/08[1]			
7/16/08[1]			
5/28/09[1]			
6/5/09[1]			
6/15/09		X	X
6/17/09		X	X
6/24/09	X	X	X
7/16/09[1]			

1) Only suspended sediment sampled on 6/26/08 7/8/08, 7/16/08, 5/28/09, 6/5/09, 7/16/09

Bedload sampling with the Helley-Smith sampler in coarse-bedded, Rocky Mountain rivers has been shown to oversample transport at lower discharges by as much as 2-4 orders of magnitude when compared to bedload traps [*Bunte et al.*, 2004; *Bunte et al.*, 2008]. The oversampling is likely a result of bed disturbance caused by placement of the sampler. The sediment transport rates reported here are thus treated as representing maximum estimates of actual transport at low flows.

Sampling was completed following USGS sediment transport sampling protocol [*Edwards and Glysson*, 1998]. Bedload samples were dried, weighed and sieved in the sedimentology lab at Colorado State University. Total bedload transport was calculated by multiplying the active width by the average unit transport rate of the weighed bedload transport samples.

4.2.3 Bed particle size distribution

Wolman pebble counts were conducted in 2004, 2007, 2008, and 2009 at LY, CT, and GB to quantify the distribution of grain sizes on the channel bed and monitor channel adjustment following the sediment input of the 2003 debris flow [*Wolman*, 1954]. A gravelometer and grid were used to conduct the pebble counts. Forty to 100 clasts were sampled across the entire channel at riffles on established stream gage cross sections.

4.2.4 Post-debris flow channel response

Channel cross sections and adjacent floodplains were surveyed in 2003 and 2007 at thirteen locations on the Colorado River and Lulu Creek using a TOP-CON Total Station (S. Rathburn, pers. comm., 2008). X, Y, and Z positions were surveyed relative to established benchmarks. Repeat cross section surveys quantify aggradation or degradation as well as channel migration. Photographic documentation of channel change was also conducted throughout the area impacted by the 2003 debris flow. Channel migration, removal of large instream wood, aggradation, degradation, and bed material sorting were documented if present based on repeat grain-size counts, surveys, and photographs.

4.2.5 Channel-forming discharge

4.2.5.1 Recurrence interval estimate

Channel-forming discharge was estimated using a recurrence interval of 1.5 years from the annual maximum series. This represents an average of recurrence interval values suggested by Williams [1978], Andrews [1980], Leopold et al. [1964], and Emmet and Wolman [2001]. The 1.5-year flow at the Baker Gulch USGS gage is 12.3 m^3/s. The peak flow at Baker Gulch in 2009 (June 23) was 14.0 m^3/s. Therefore, the discharge on June 23, 2009 (14.0 m^3/s) can be scaled by 88%, to equal 12.3 m^3/s, which is taken as the 1.5-year flow. Due to the absence of a long-term gage at the study sites, I assumed that a value of 88% of the peak flow on June 23, 2009 would be an appropriate approximation of the 1.5-yr flow at the GB and CT reaches.

4.2.5.2 Effective discharge calculation

Effective discharge is calculated by multiplying a sediment rating curve by a flow duration curve that is divided into bins. Bedload sediment-discharge rating curves were established from samples collected at GB and CT from 2004-2009. Flow duration curves for GB and CT were synthesized by creating a dimensionless discharge curve from the Baker Gulch gage due to the absence of a long-term gage at the study site [*Biedenharn et al.*, 2000; *Soar and Thorne*, 2000]. The 2-year flow (Q_2) was estimated from regional regression equations using StreamStats software from the USGS [Ries, 2004; *Capesius and Stephens*, 2010]. Each day in the long-term daily flow record at Baker Gulch was divided by the predicted Q_2 for Baker Gulch. This created a dimensionless curve of exceedance probability versus dimensionless discharge (Q/Q_2) for Baker Gulch. Applying the same dimensionless curve to the CT and GB sites, the estimated Q_2 values for GB and CT were multiplied against the dimensionless flow series to create a synthetic daily flow record. The daily flow record was broken into ~20 bins. The sediment rating curve was applied to each bin and multiplied by the probability of that range of discharges. The peak of the effectiveness curve represents the range of flows that over time transports the most sediment [*Biedenharn et al.*, 2000; *Emmett and Wolman*, 2001].

This method of flow synthesis assumes the Grand Ditch diversion alters flows equally at the study area and the Baker Gulch gage. Grand Ditch operations, however, control where excess water is spilled into the Colorado River. During peak runoff, when runoff from the upper tributaries exceeds the capacity of the Grand Ditch, excess water could be spilled into lower Lulu Creek or it could be spilled into streams downstream of the study site. It is possible that water is diverted *into* Lulu Creek and then the Colorado River from tributaries up to 10 km to the south of Lulu Creek because Lulu Creek is the closest spillway to the worker's camp on the Grand Ditch and is used as the northernmost location to spill water. This suggests high flows may be more frequent at GB and CT than at Baker Gulch, and thus estimates of Q_{eff} may be under-predicted. However, at CT and GB, ~40-50% of the watershed area is above the Grand Ditch, while at Baker Gulch ~35% is above the Grand Ditch. This suggests there is the potential for a slightly higher percentage of flow extraction in the study area than at Baker Gulch, and estimates of Q_{eff} may be over-predicted. The relative magnitude of flow input into the study area by Grand Ditch spilling compared to the potential for greater diversion is not quantified. However, because the two potential deviations from expected results are in opposite directions, the estimate of Q_{eff} is considered to be acceptable.

4.2.5.3 Morphologic bankfull observation

Bankfull discharge was estimated using field observations of morphologic bankfull stage and stage-discharge rating relationships. Alternatively, when possible, measurements of discharge were directly taken at bankfull flows (Figure 4.3). Bankfull identification was clear at GB, as both banks had breaks in slope at the same elevation. The right bank at CT is bedrock controlled and therefore bankfull was identified solely on a break in slope from the left bank.


Figure 4.3. Discharge measurement taken at bankfull discharge at GB, June 24, 2009. View is looking downstream.

4.2.6 Total yield

The suspended and bedload sediment-rating curves were applied to the 15-minute datalogger flow record, and the total quantity of bedload, suspended load, and total load was calculated for the period of record during 2008 and 2009. The 2008 record is from June 25 to October 10 and does not capture the rising limb or runoff peak. The 2009 record is from May 2 to September 16 and captures the complete snowmelt period.

4.3 Results and discussion

4.3.1 Discharge

Flow and sediment monitoring were conducted at stations GB, LY, and CT in 2004, 2005, 2008, and 2009. At the Baker Gulch USGS gage, 2004 had extremely low flows and peak flows from 2005, 2008, and 2009 were all 10-20% less than the long-term 2-year return interval flow (Figure 4.4).

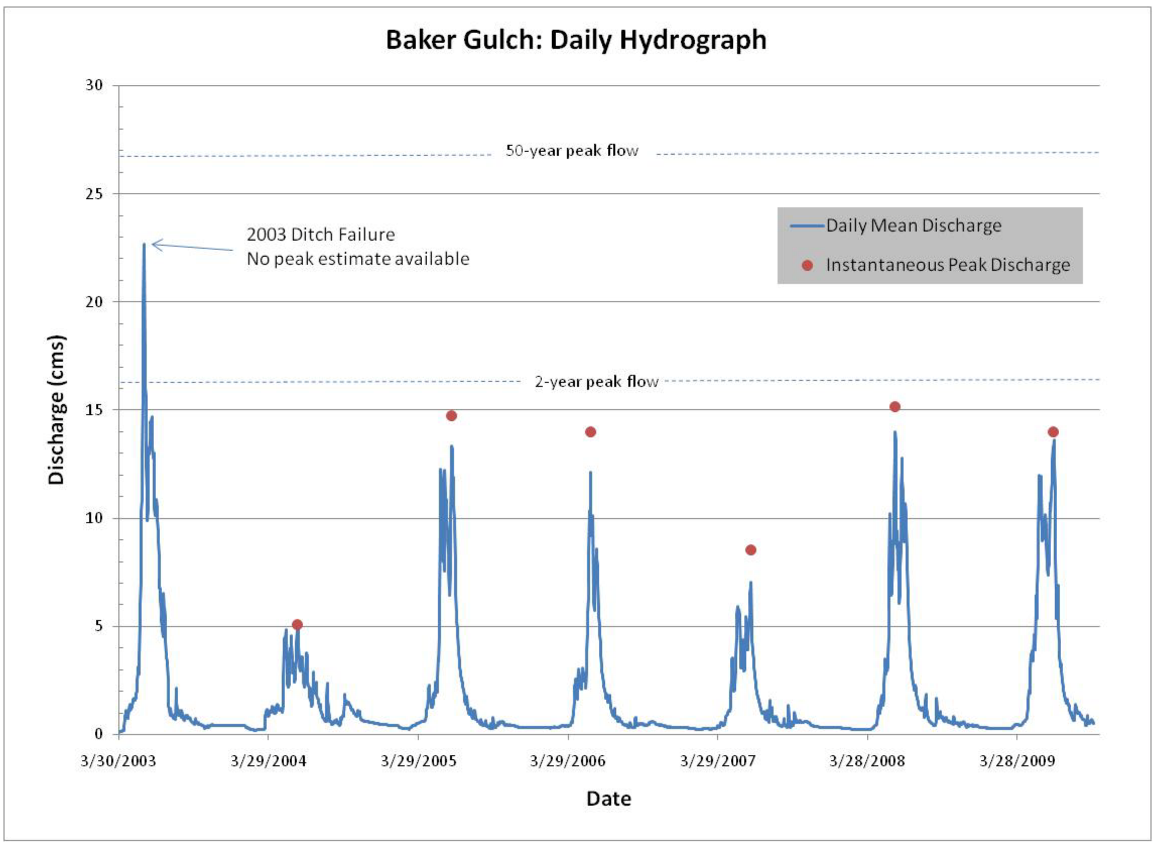

Figure 4.4. Mean daily discharge at Baker Gulch USGS gage during the study period from 2003-2009. All years after 2003 were lower than the average peak. The period of record at Baker Gulch is 1953-present.

Flow monitoring in the study area during 2008 and 2009 was supported by recording stream gages and provides insight into flow manipulation and diurnal cycles.

The 2008 hydrograph suggests that Grand Ditch operations may be capable not only of an overall reduction in flow, but also of actually increasing flows in specific reaches (Figure 4.5). For example, during receding flows in 2008, Grand Ditch capacity was exceeded and Lulu Creek was used as the primary spillway. Pronounced daily fluctuations occur as water is released into Lulu Creek. On July 5, 2008, Grand Ditch capacity appears sufficient to transport all inflowing runoff and a dramatic decline in flow occurred in Lulu Creek. This suggests the impacts of the Grand Ditch diversion are most severe during late summer when high elevation snowmelt is the primary source of runoff and the Grand Ditch is capable of diverting all runoff.

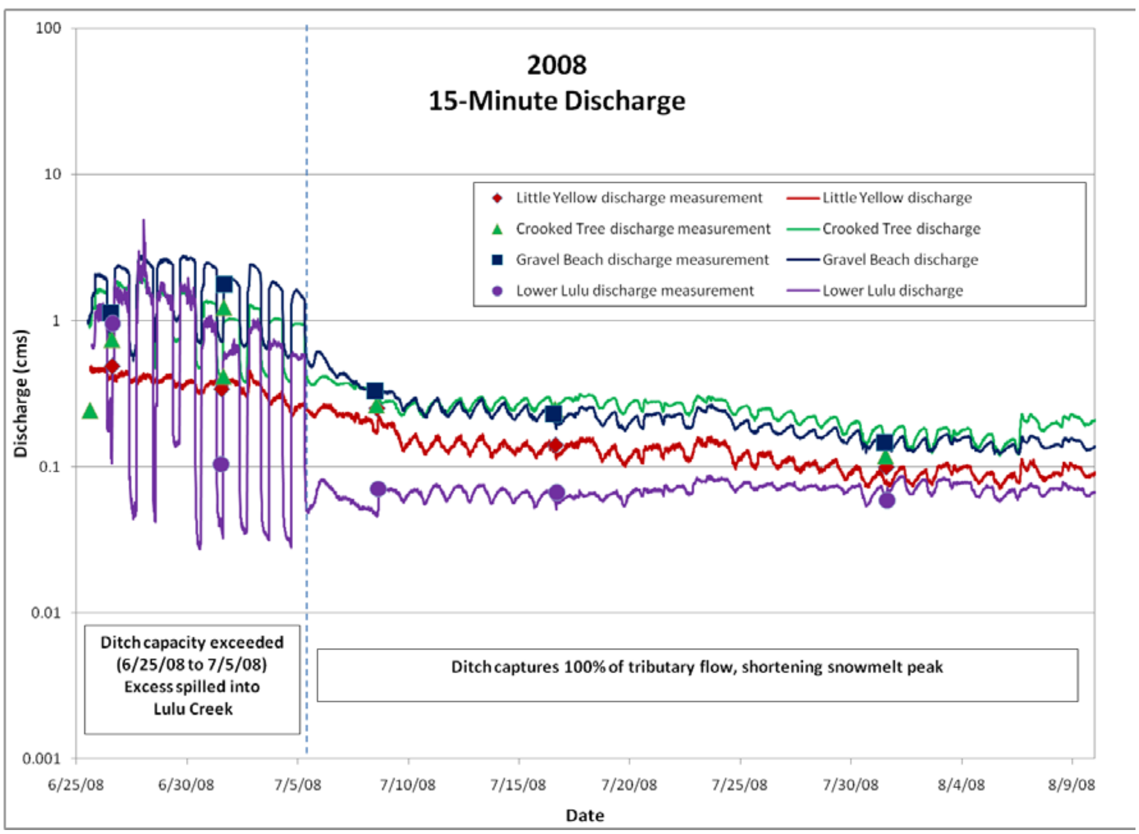

Figure 4.5. 15-minute discharge record for 2008 from LY, CT, GB, and LL sites shows discharges into Lulu Creek from the Grand Ditch. After July 5 no discharges from Grand Ditch occur.

The summer of 2009 was unusually wet in the Front Range of Colorado, where farmers reduced irrigation and the Grand Ditch diversion was not needed. By June 13, Long Draw Reservoir was full and the Grand Ditch diversion was shut off from June 13 to June 25, allowing natural runoff (Figure 4.6). Based on the shape of the hydrograph, the true snowmelt peak likely occurred on May 21, yet the Grand Ditch shutoff in late June added sufficient water to cause peak discharge in the Colorado River on June 24. A second period of "natural" flow occurred August 9 to September 9, when Grand Ditch repairs were conducted along the site of the 2003 breach. These periods of natural flow allow visualization of the downstream impacts of the diversion (Figure 4.7).

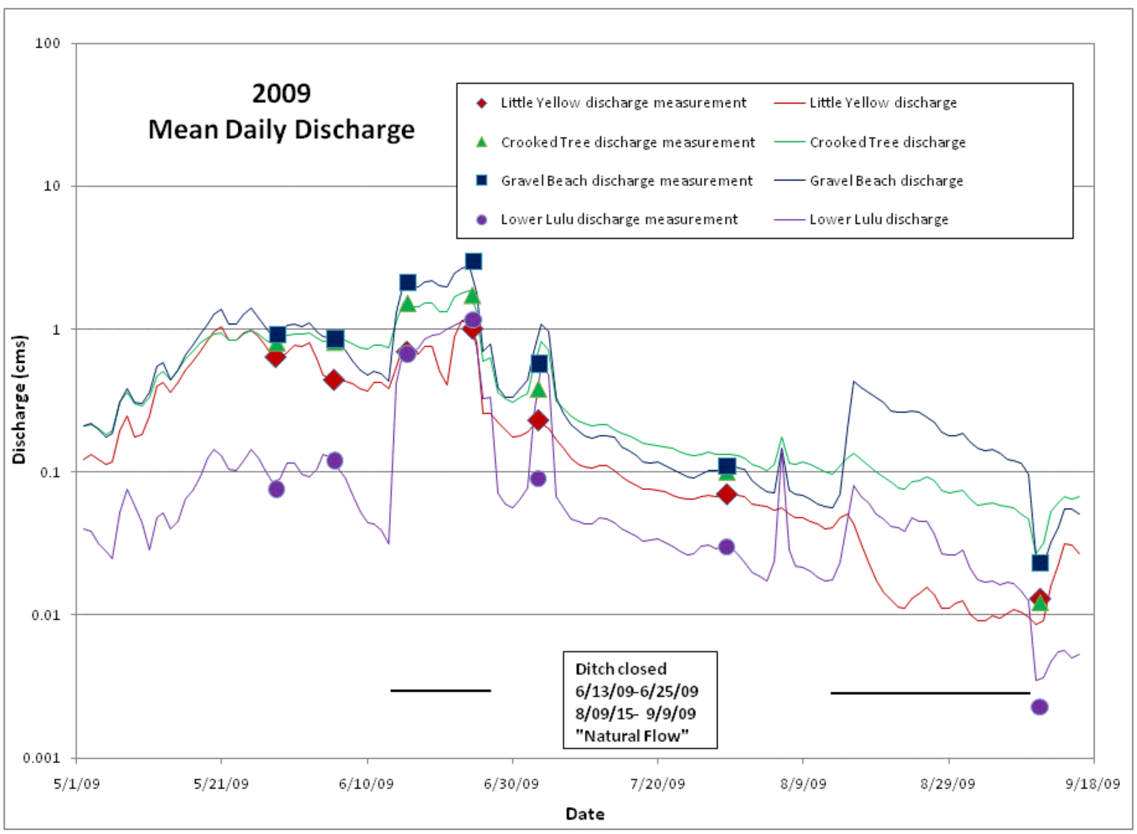

Figure 4.6. Mean daily discharge for 2009 from LY, CT, GB, and LL sites shows two periods where the Grand Ditch did not operate and flow was not diverted out of the Colorado River.

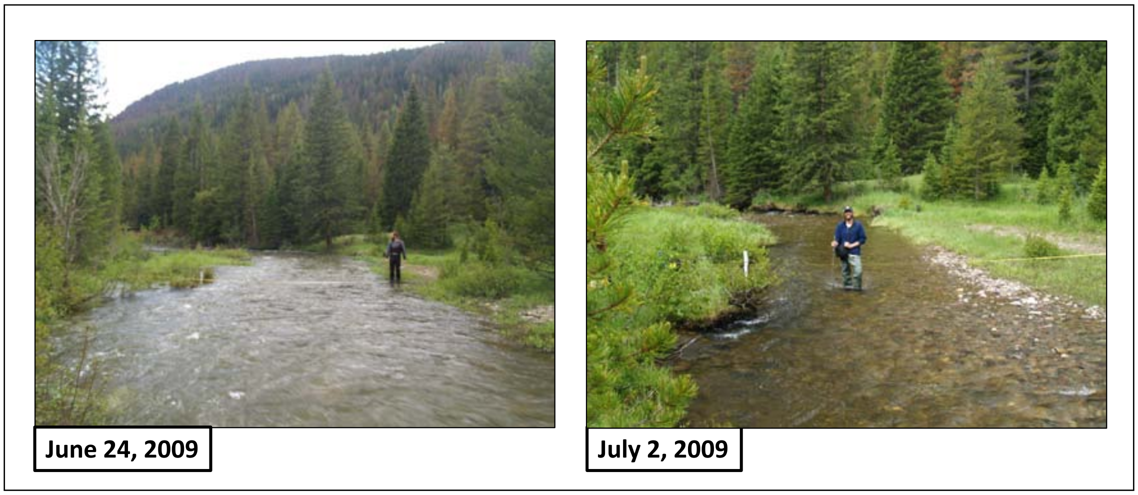

Figure 4.7. Repeat photo of the Colorado River at Lost Creek (~1 km downstream from the Lulu City wetland). June 24 is while the Grand Ditch diversion was not operating and "natural" flow occurred in the Colorado River. July 2 demonstrates the quantity of diverted flow. Both views are facing downstream.

4.3.2 Sediment transport

4.3.2.1 Suspended sediment transport

For most discharges, the LY site transports as much or more suspended sediment than other sites (Figure 4.8). The similar sediment transport relationship from LY to CT and GB is surprising as the LY site was unaffected by the 2003 debris flow, suggesting that the system, even in areas impacted by the debris flow, is limited in fine sediment. The absence of fine sediment at CT and GB suggests that runoff in 2003 likely transported all available fine sediment introduced by the debris flow. The higher loads at LY may be explained by the exposed bedrock lithology and lack of hillslope vegetation upstream, which includes steep and weathered volcanic bedrock that may produce a more consistent supply of fine sediment than the more vegetated hillslopes at other sites.

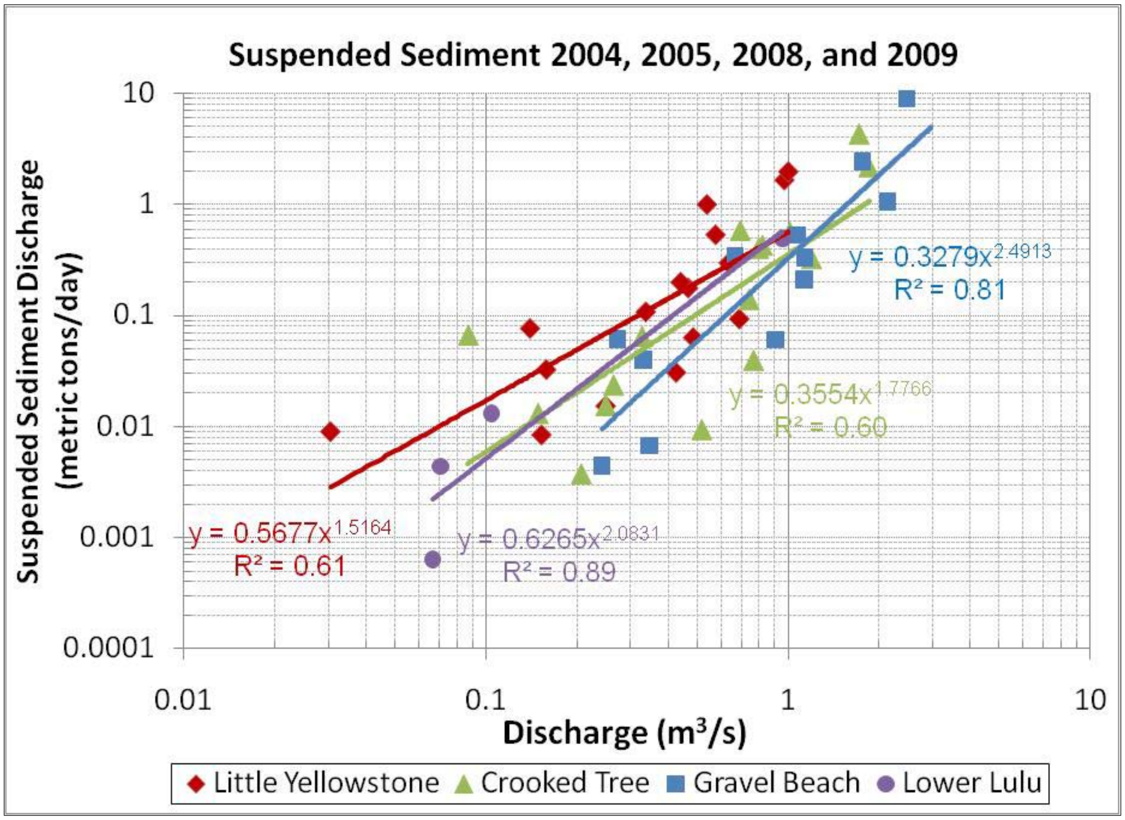

Figure 4.8. Suspended sediment rating curves for LY, CT, GB, and LL sites are all similar.

A separate analysis was conducted at each sampling site to evaluate differences in suspended sediment transport in the years immediately following the debris flow (2004-2005) and later years (2008-2009). Samples were categorized as rising or falling limb samples to investigate hysteresis. Although there is considerable scatter in the data, regression lines are consistent at LY between the 2004-2005 and 2008-2009 periods (Figure 4.9). This is expected, as LY was not affected by the 2003 debris flow and is therefore not expected to exhibit temporal trends in the following years. Clockwise hysteresis is suggested by the data, but considerable scatter and a limited sample size prevent definitive analysis (Figure 4.10).

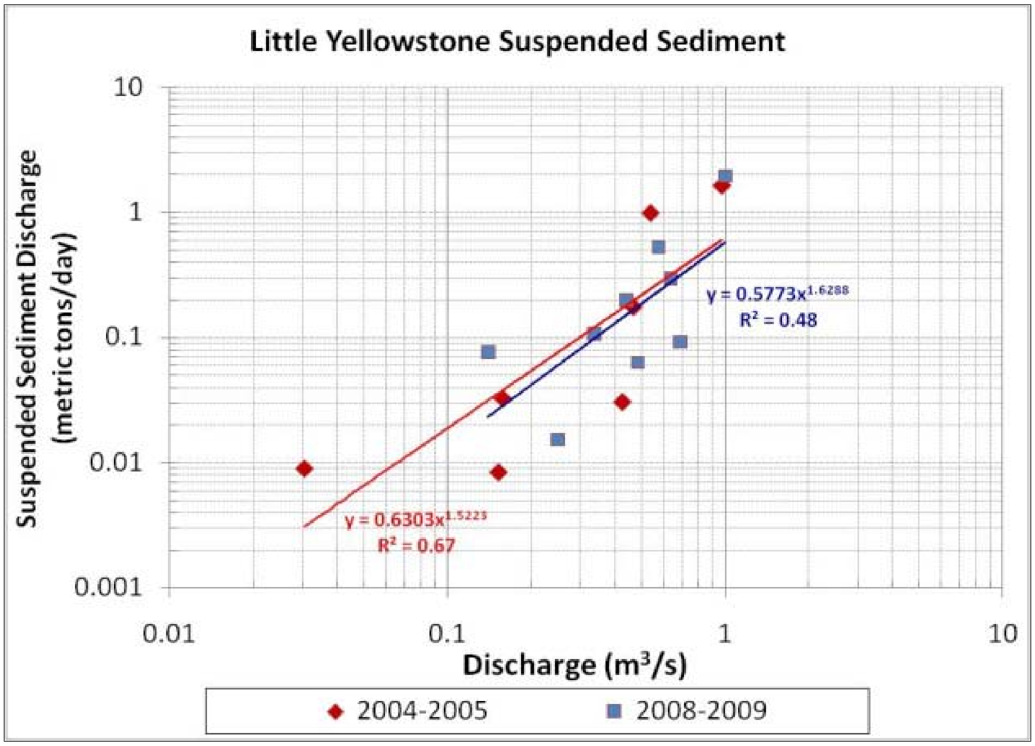

Figure 4.9. LY suspended sediment rating curve comparison of 2004-2005 with 2008-2009. LY is upstream and unaffected by the 2003 debris flow, and no temporal trend is apparent.

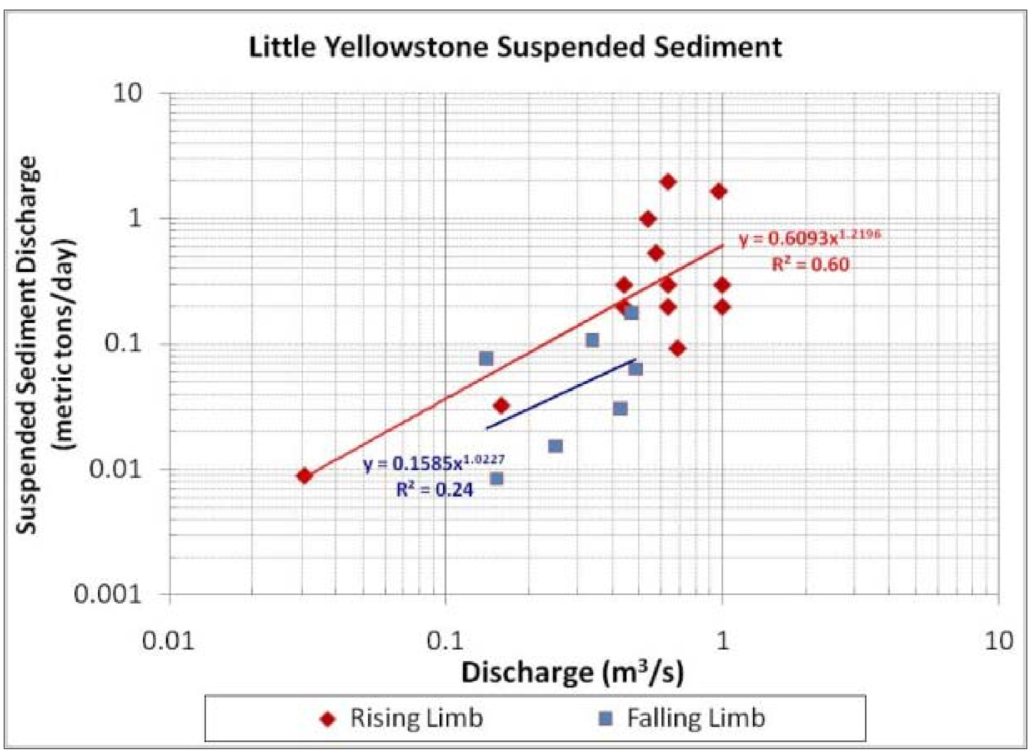

Figure 4.10. LY suspended sediment rating curve comparison of rising and falling limb flows. Data suggest clockwise hysteresis, which suggests depletion of fine sediment during the snowmelt period.

At CT, 2004-2005 suspended sediment samples can be distinguished from 2008-2009 by the magnitude of scatter in the 2004-2005 samples (Figure 4.11). This suggests that considerable fluvial reworking of debris-flow sediments was occurring during the earlier sampling interval, that pulses of fine sediment were alternately transported or stored, and therefore that the sediment-discharge relationship is poorly defined. The consistent sediment rating curve from 2008-2009 suggests that most available sediments have been flushed from the system and that new sediment is now being steadily supplied as it is remobilized by gradual reworking of bed and bank material. Again, an apparent clockwise hysteresis is present, suggesting an overall limited supply of fine sediment for the period of 2004-2009 (Figure 4.12).

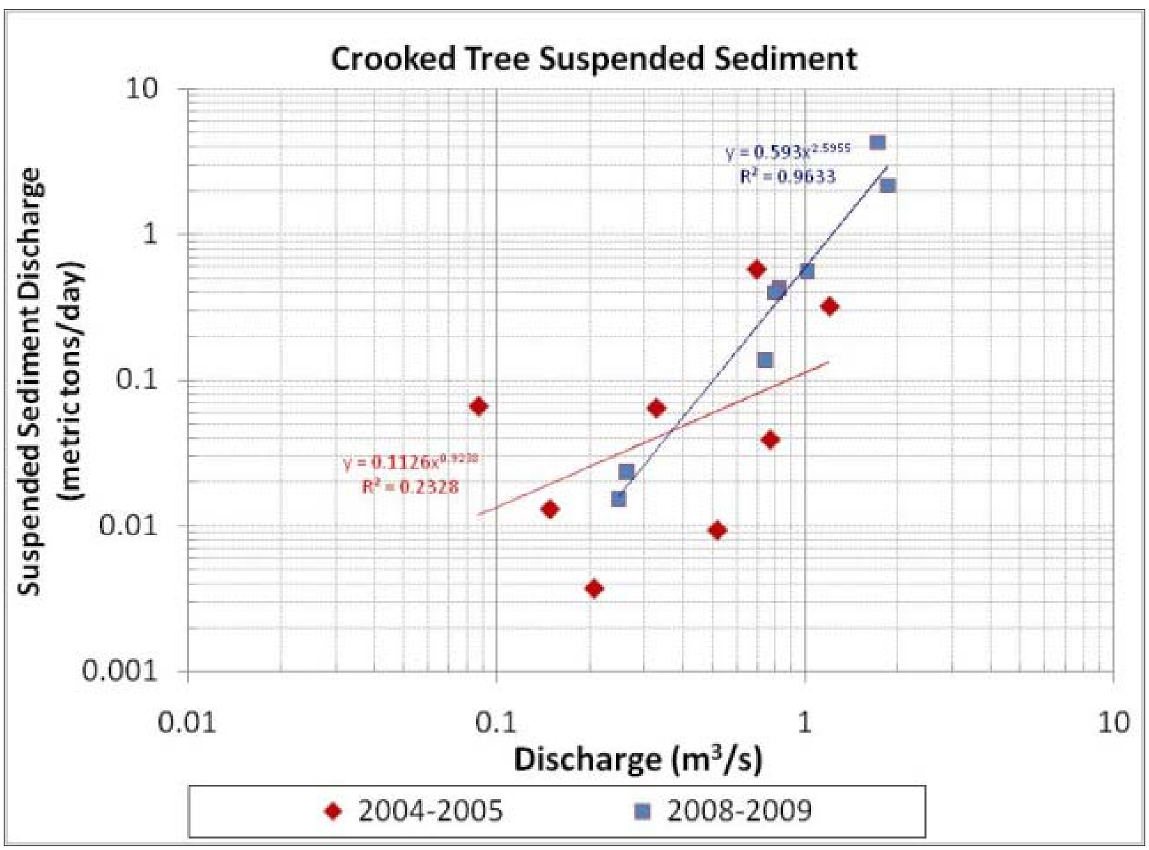

Figure 4.11. CT suspended sediment rating curve comparison of 2004-2005 with 2008-2009. Variability decreases in 2008-2009.

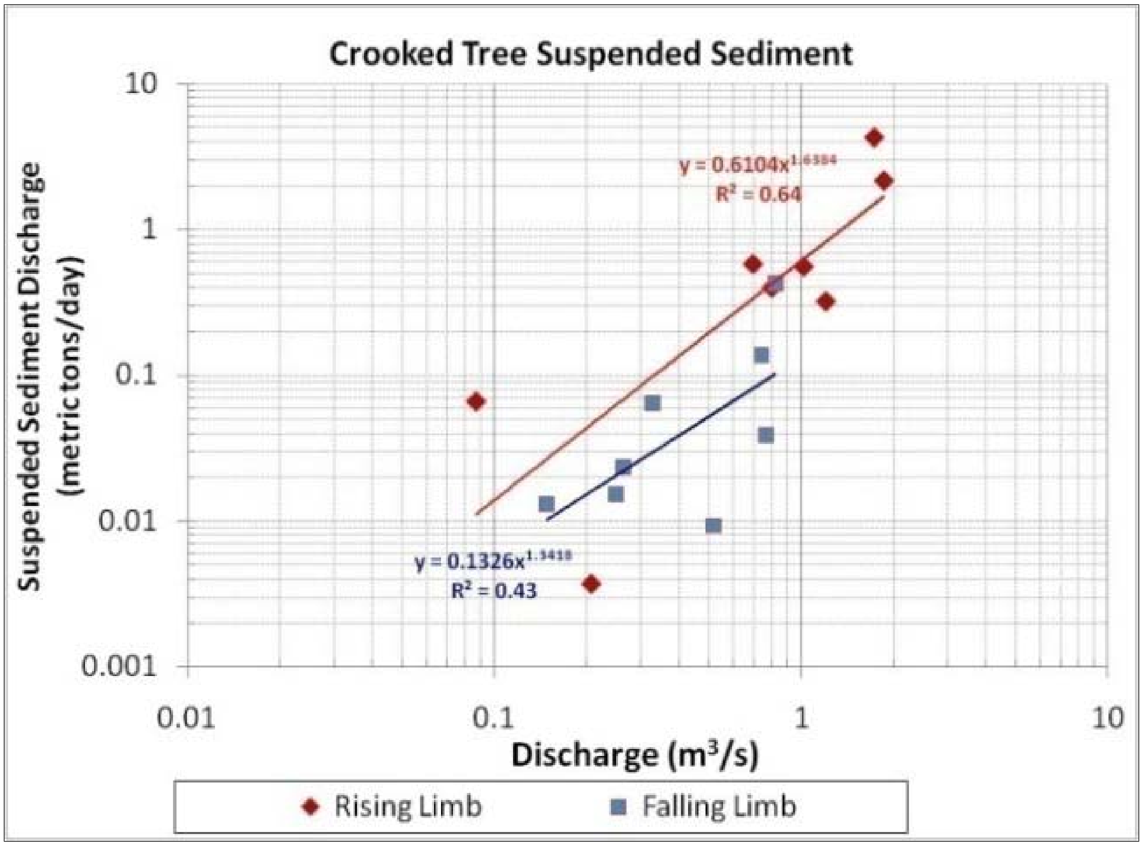

Figure 4.12. CT suspended sediment rating curve comparison of rising and falling limb flows. Data suggest clockwise hysteresis.

At GB, the trends in suspended sediment are less apparent. There are higher concentrations of suspended sediment during 2008-2009 than in 2004-2005 (Figure 4.13). This suggests that temporary storage immediately following the debris flow was stable during 2004-2005 and sediment delivery to the downstream GB site increased as upstream log jams were cleared and channelization and reworking occurred. Similarly, at low discharge there is no evidence of hysteresis (Figure 4.14). This suggests sediment is controlled by a supply that may be introduced during or after peak runoff and supports the theory that upstream channel processes are introducing sediment.

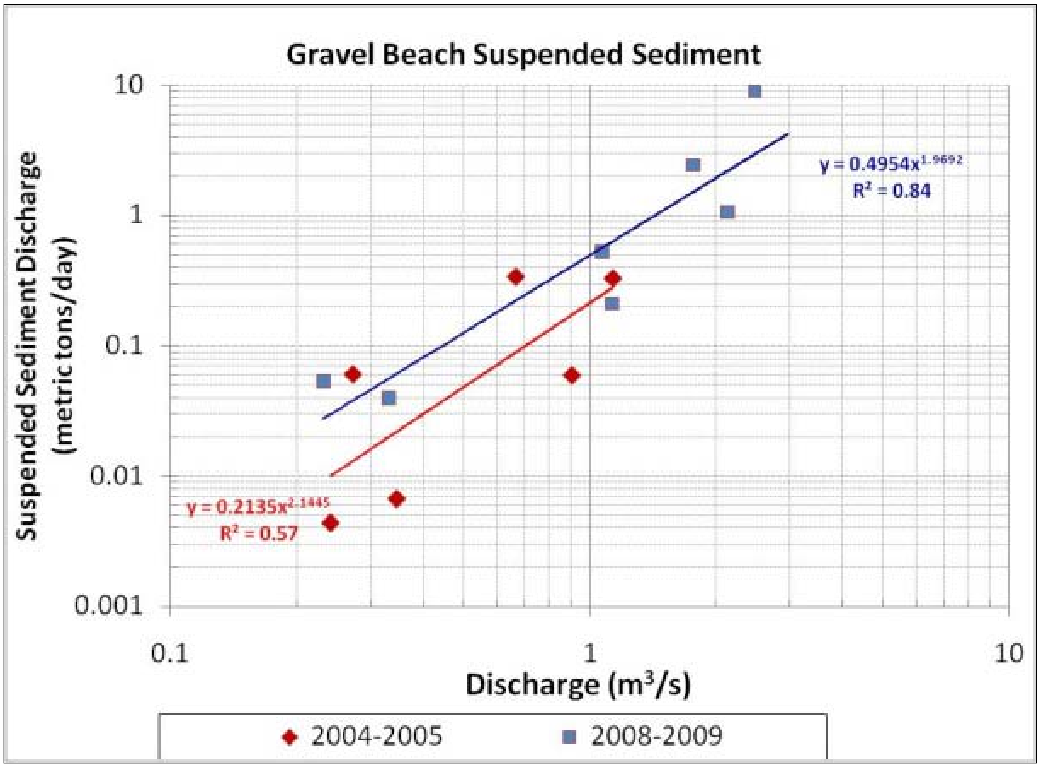

Figure 4.13. GB suspended sediment rating curve comparison of 2004-2005 with 2008-2009. Suspended sediment concentrations are higher in 2008-2009.

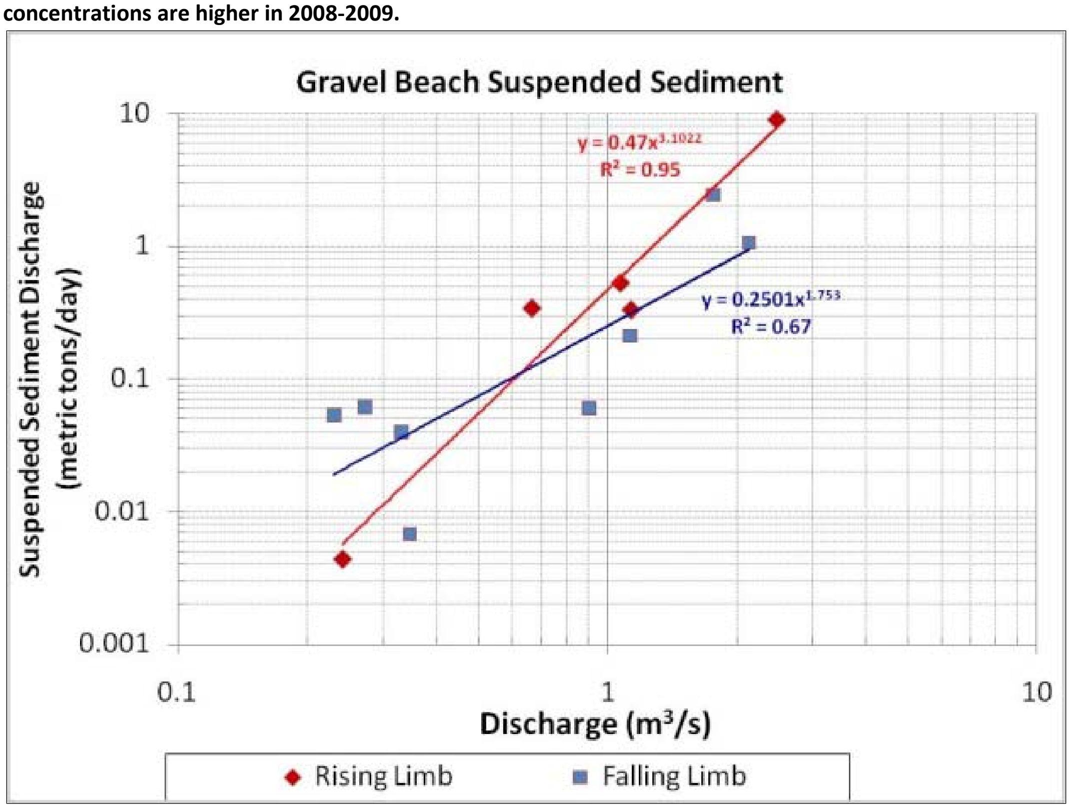

Figure 4.14. GB suspended sediment rating curve comparison of rising and falling limb flows. Data do not suggest hysteresis at low flows.

4.3.2.2 Bedload sediment transport

No clear differences exist in the bedload transport rates of LY, CT, and GB (Figure 4.15). Furthermore, there is no evidence for a trend between the periods of 2004-2005 and 2008-2009 (Figures 4.16-4.18). This suggests there was, and continues to be, a supply of coarse material available for transport.

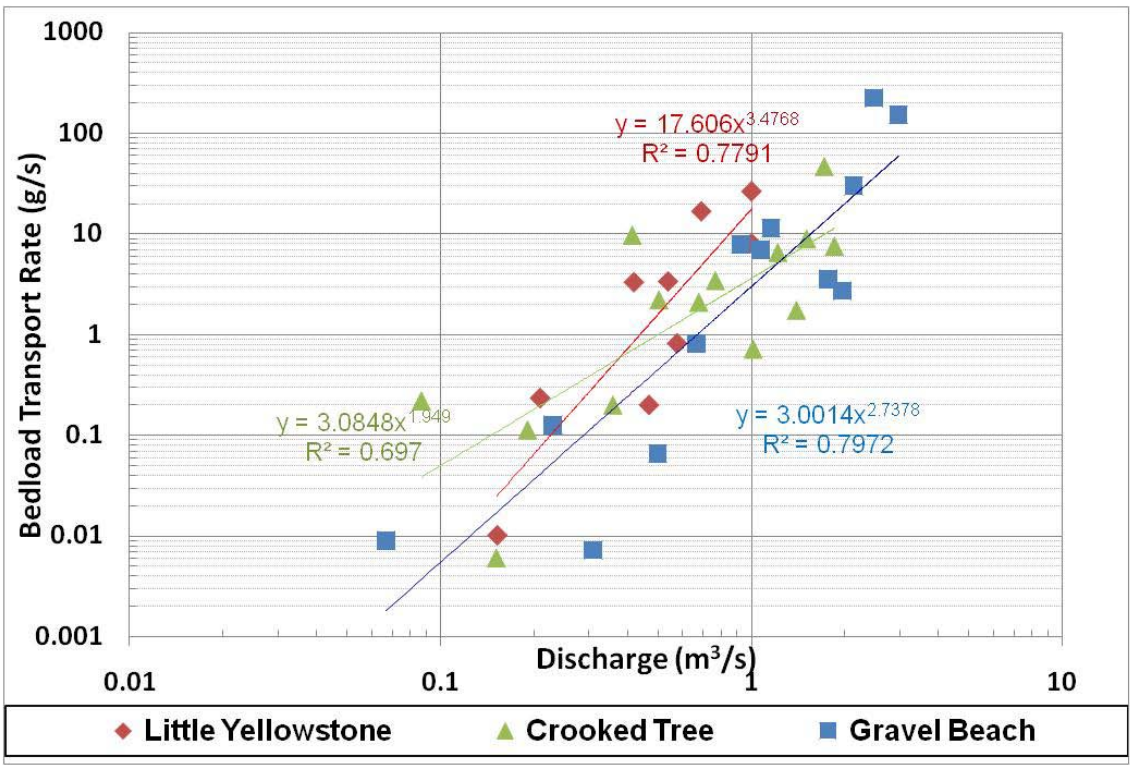

Figure 4.15. Bedload transport rating curves for LY, CT, and GB are similar at all three stations.

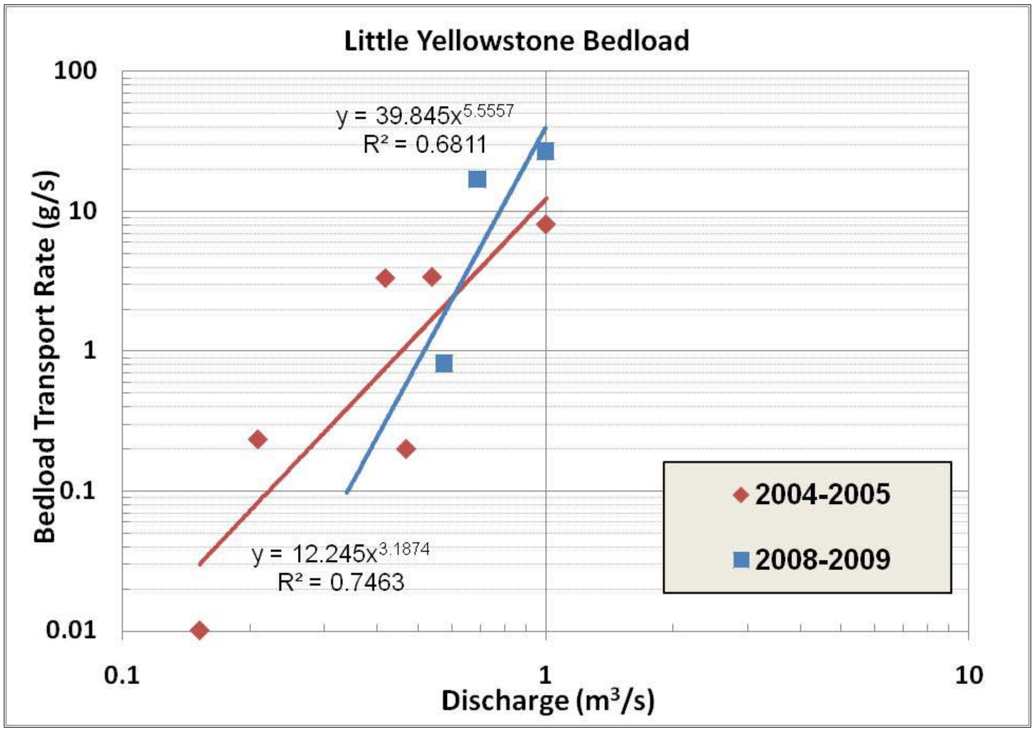

Figure 4.16. LY bedload sediment rating curve comparison of 2004-2005 with 2008-2009. LY was not affected by the 2003 debris flow and no change in bedload transport is seen.

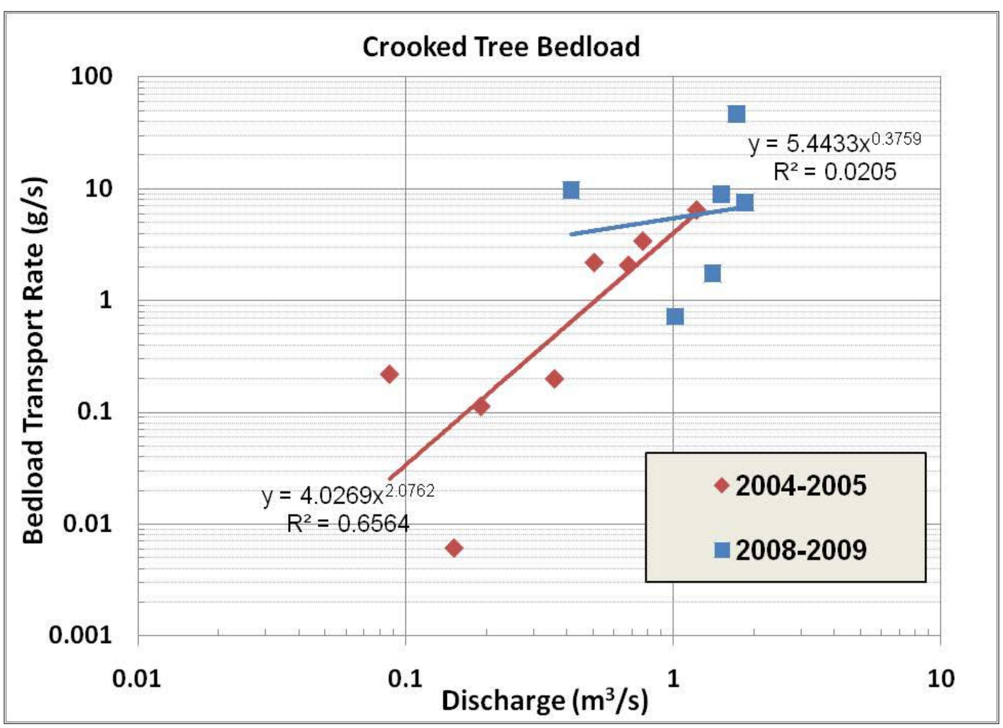

Figure 4.17. CT bedload sediment rating curve comparison of 2004-2005 with 2008-2009. There is no change in bedload transport.

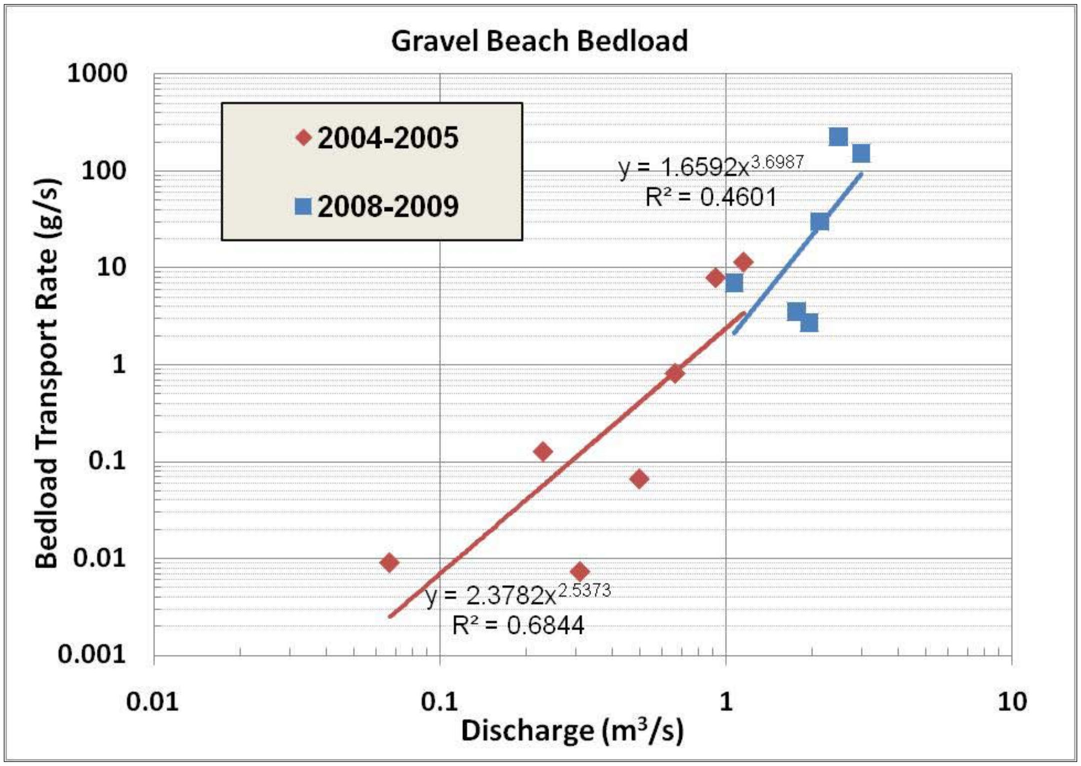

Figure 4.18. GB bedload sediment rating curve comparison of 2004-2005 with 2008-2009. There is no change in bedload transport.

4.3.3 Bed particle size distribution

The channel at LY was altered in 2005 when a large tree fell and changed hydraulics in the channel. This disturbed the cross section significantly and bed particle size distributions are not comparable between 2004 and later years. No change is detected in size distribution between 2007, 2008, and 2009 (Figure 4.19).

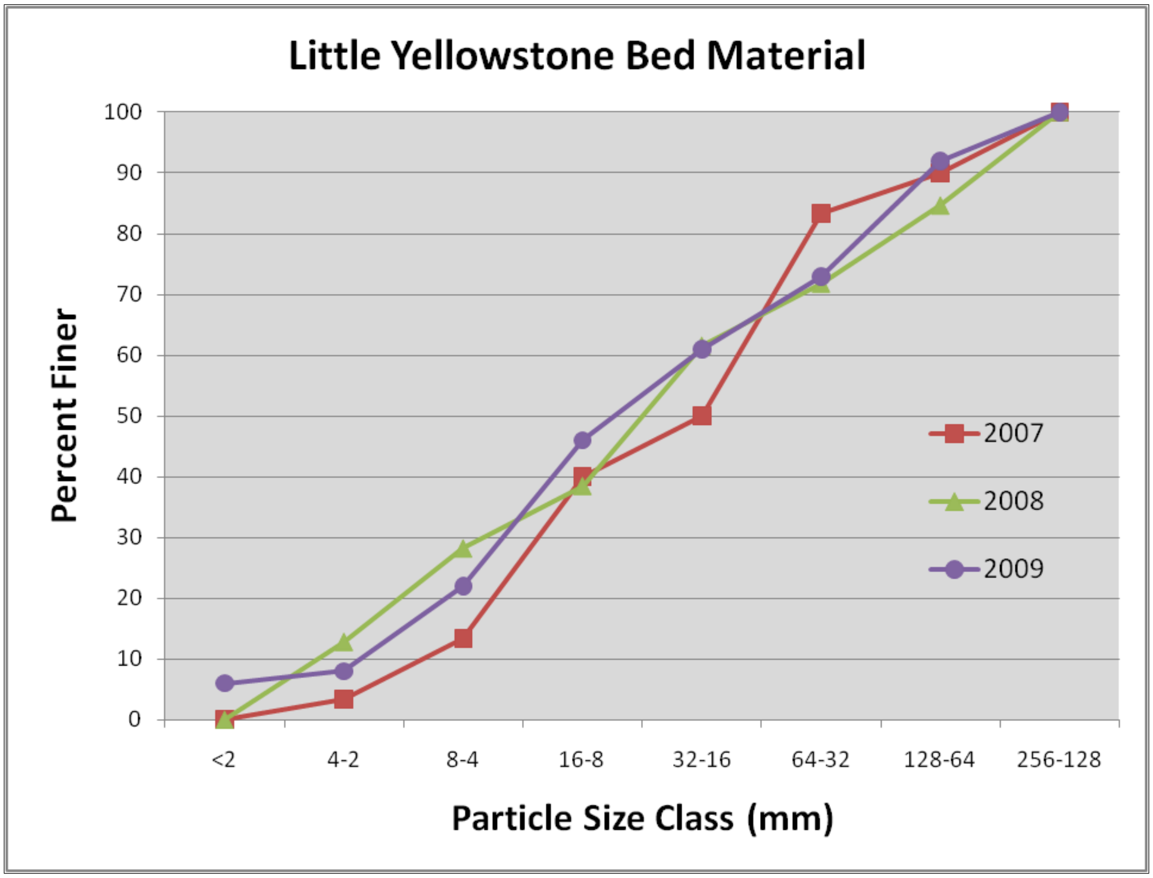

Figure 4.19. LY bed material size distribution 2007-2009. No change is detected during this period. LY was upstream of the 2003 debris flow and therefore not affected.

At CT, bed fining occurs from 2004 to 2007, followed by coarsening in 2008 and 2009, resulting in a bed grain-size distribution similar to 2004 (Figure 4.20). This trend suggests there was a pulse of fine sediment deposited in 2007. The removal of that material and subsequent coarsening suggest that bed armoring was occurring between 2007 and 2009.

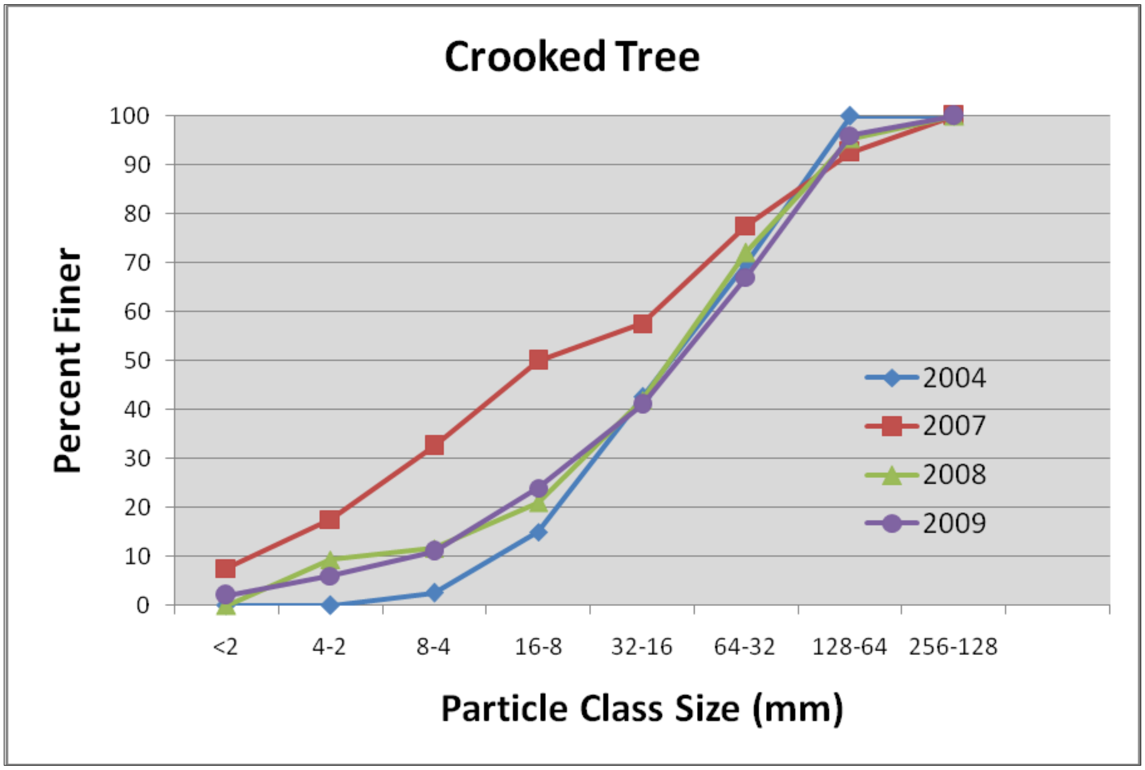

Figure 4.20. CT bed material size distribution 2004 and 2007-2009. Fining of the bed occurred in 2007, followed by coarsening in 2008 and no change in 2009.

At GB, the 2005 bed particle distribution is bi-modal, with few clasts between 2 and 16 mm in size (Figure 4.21). The abundance of sand without small gravels suggests a backwater or other fine-sediment depositional zone with an otherwise coarse bed. As at CT, the bed fined in 2007, then coarsened slightly in 2008, and further coarsened in 2009. In particular, the smallest particle sizes were removed from 2008 to 2009. The general coarsening of the bed from 2007-2009 and the pronounced removal of the smallest fractions suggests bed armoring.

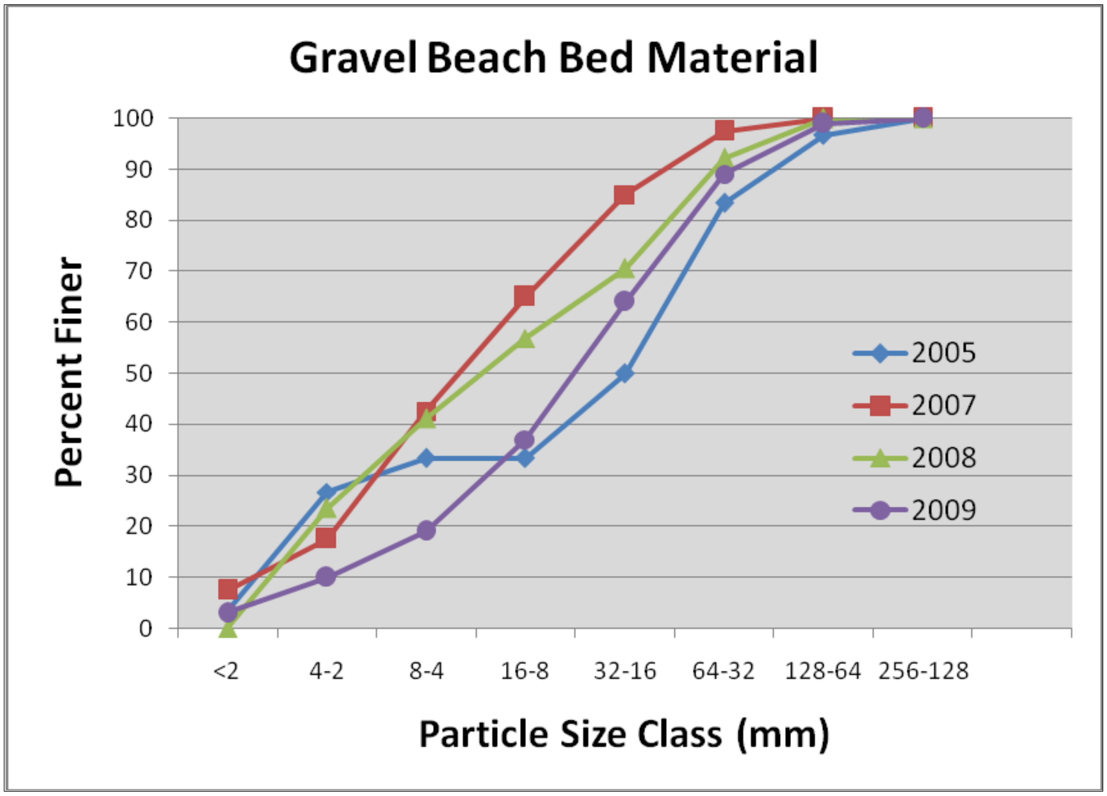

Figure 4.21. GB bed material size distribution 2005 and 2007-2009. Fining of the bed occurred in 2007, followed by coarsening in 2008 and 2009.

4.3.4 Post-debris flow channel response

No significant aggradation, degradation, or avulsion has occurred since 2003 along the Colorado River (Figure 4.22). Lulu Creek has undergone significant reworking, but the impacted area along the Colorado River has been stable. The below-average runoff since 2003 and the reduced transport capacity from the diversion both likely limit channel migration. Repeat photos show impressive reworking had already occurred by 2004, with channelization, removal of large instream wood, and fining of bed-material grain sizes in the active channel (Figure 4.23). Channel change is relatively minor after 2004.

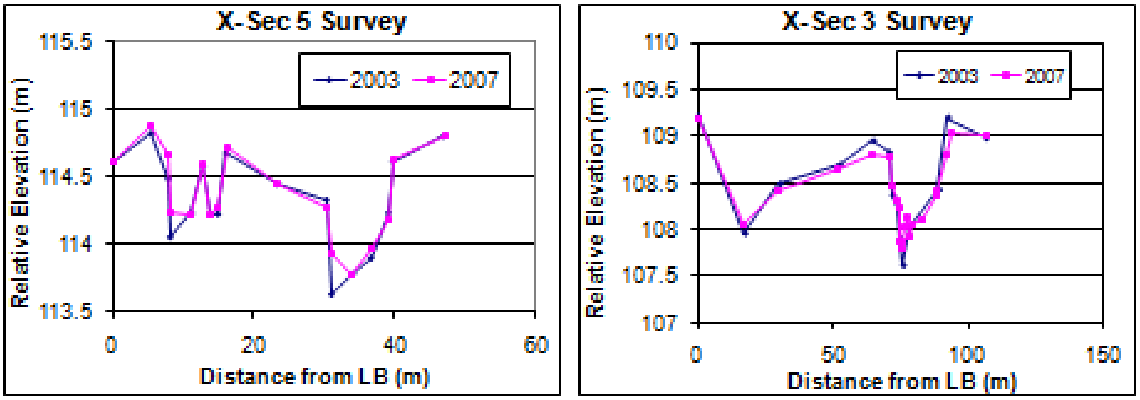

Figure 4.22. Repeat surveys at cross section 5 (250 m downstream of CT) and cross section 3 (20 m upstream of GB), 2003 and 2007. At cross section 5, 20-30 cm of aggradation occurred in the main channel. At cross section 3, no net change was observed.

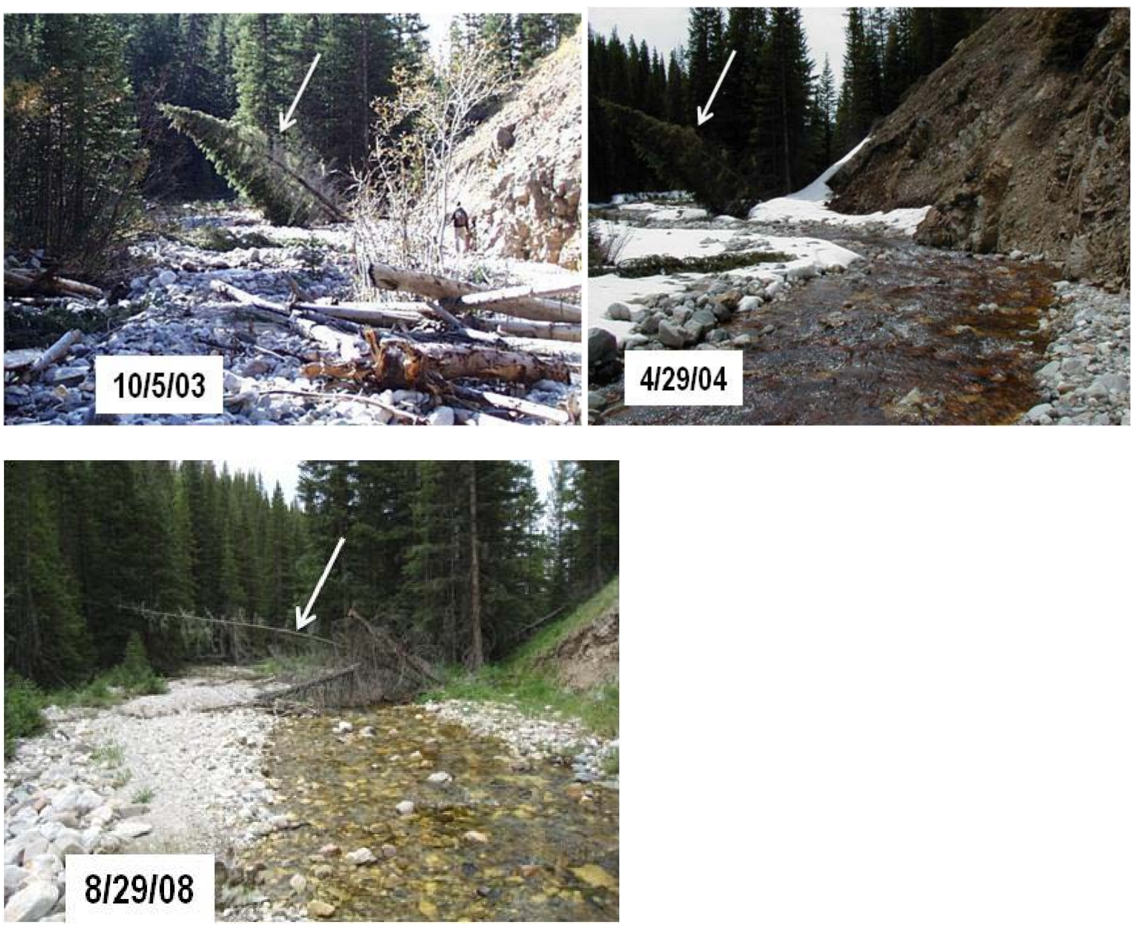

Figure 4.23. Repeat photos taken ~ 100 m downstream from CT in 2003, 2004, and 2008. Photos show major reworking of bed material and removal of large instream wood occurred from 2003-2004. After 2004, channel change is minor, with continued sorting of gravels. This trend is consistent along the Colorado River. Photos by Sara Rathburn

4.3.5 Channel-forming discharge

In 2009, Q_{bf} was 1.7 m^3/s at CT and 3.0 m^3/s at GB (Table 4.4). For both reaches, Q_{bf} is ~10-25% less than estimates of Q_{eff} and $Q_{1.5}$. The discrepancy between Q_{eff} and $Q_{1.5}$ is ~14% at CT and ~18% at GB. This variation is considered to be well within the natural range of variation for relationships of Q_{bf}, Q_{eff} and $Q_{1.5}$ [*Williams*, 1978; *Andrews*, 1980; *Emmett and Wolman*, 2001]. The current channel configuration is therefore considered to be not only adapted to the post-debris-flow condition, but no evidence exists to suggest that present channel geometry is different than expectations of a completely recovered condition, suggesting that H1B describes the present condition of the upper Colorado River in the study area in that recovered processes and forms are present.

Table 4.4. Comparison of Q_{bf}, Q_{eff} and $Q_{1.5}$

Station	**Geomorphic bankfull (m^3/s)**	**Effective discharge- (m^3/s)**	**Recurrence interval (m^3/s)**	**Difference between Q_{bf} and other estimates**
CT	1.7	2.2	1.9	11-23%
GB	3.0	3.3	4.0	9-25%

4.3.6 Total yield

Bedload and suspended sediment transport rating curves were applied to stream gage records to create a continuous record of sediment transport. The summed transport quantities are used to estimate the annual sediment budget (Table 4.5). Because the gages were not installed until June 25 in 2008 (after peak flow), the estimate for 2008 is significantly lower than the true quantity of transport. The 2009 record captured almost the entire runoff period and is therefore expected to provide a reasonable estimate of total sediment transport. An assumed sediment density of 2.65 g/cm^3 [*Garde and Ranga Raju*, 1985] was applied to the transport estimate, to provide an estimate of the volume of sediment transported. The years 2008 and 2009 are slightly below average runoff years (Figure 4.4). Sediment transport during those years is assumed to be similarly below average.

Table 4.5. Total load estimates

Station	**Year [1]**	**Bedload (kg)**	**Suspended Load (kg)**	**Total Load (kg)**	**Total Volume (m^3)**
LY	2008	571	2644	3215	1.2
LY	2009	27487	15833	43320	16.4
CT	2008	4825	6732	11557	4.4
CT	2009	14629	19564	34194	12.9
GB	2008	16252	16751	33003	12.5
GB	2009	37296	39561	76857	29.0

1) 2008 is June 25 to October 10
2009 is May 2 to September 16

The scenario presented as H1B is supported whereby sediment transport at CT and GB is not elevated relative to unaffected LY. The trajectory of recovery along the Colorado River at GB and CT indicates that a largely recovered channel form is present. The channel geometry of the Colorado River downstream from the confluence with Lulu Creek was stable from 2004-2009. No significant changes in bed elevation or channel width have occurred. However, the quasi-equilibrium suggested by stable channel geometry has not been tested by flows above bankfull. It is unknown whether the channel is prone to major adjustment in the future due to available sediment from the 2003 debris flow. Sediment transport is not elevated, as demonstrated by the similarity in rating curves at GB and CT with the unimpacted reach at LY, the absence of available fine sediment, and bed armoring indicated by pebble counts. Effective discharge, bankfull discharge, and the 1.5-year discharge are all similar.

4.4 Conclusion

Results indicate that Grand Ditch operations play a considerable role in not only how much water is delivered to the Colorado River but also where. Despite the potential instability caused by extreme fluctuations in stage, the post-2003 trajectory of natural channel recovery of geomorphic process seems to be rapid. This suggests that the channel form and sediment transport processes were largely recovered by 2009, nearing conditions similar to LY, which has not received a debris flow in several decades. The present bankfull capacity is appropriate, not only to the current loads of flow and sediment (effective discharge capacity estimate), but also to long-term expectations (recurrence interval capacity estimate). The bed shows signs of armoring, indicating fine material has been removed from the system. Channel cross sections have been stable. This assessment of recovery suggests impacts to the Colorado River upstream of the Lulu City wetland are transient features. Full geomorphic recovery time is understood to be less than the expected recurrence interval of disturbance. Thus TFr < 1, indicating that stable channel forms will recover and persist.

$$TFr = \frac{mean\ relaxation\ time}{mean\ recurrence\ time\ of\ events}$$

The assessment of rapid recovery is limited, however, to in-channel physical forms and processes. Impacts resulting from heightened sediment inputs and an elevated disturbance regime may affect instream biologic processes, as well as riparian vegetation. Debris-flow berms may prevent floodplain connectivity, and the reduced transport capacity due to the Grand Ditch diversion likely inhibits channel migration and reworking of the flood plain. Those issues are beyond the scope of this project, but should be considered when assessing restoration opportunities.

Ideally, restoration planning utilizes data and insights about the past and present to forecast for conditions of the future. In the headwaters of the Colorado River, imminent change is expected due to the pine beetle kill now affecting lodgepole pine throughout the Rocky Mountains [*Kegley and Safranyik*, 2001]. Sediment yield and runoff may both change in the coming years as tree mortality changes hillslope conditions [*Hélie et al.*, 2005]. Furthermore, climate change will likely alter hydrology and biogeochemical cycling regimes directly and may also lead to changes in vegetation, fire, and pest regimes that will in turn alter water and sediment delivery from the hillslopes. High elevation areas may be particularly sensitive to pest invasion from warming temperatures [*Logan et al.*, 2001; *Williams and Liebhold*, 2002]. A watershed-scale approach is therefore mandated, as recreating specific channel forms in a transitional system is an unattainable and misguided aspiration [*Williams et al.*, 1997; *National Research Council*, 1999; *Wohl et al.*, 2005].

5. Opportunities for Restoration

The purpose of this research was to investigate valley processes in the upper Colorado River watershed in order to provide a context for restoration. My research objective was not to present restoration recommendations. However, in the course of this work, a few points have been identified that may be useful for restoration planning. Whatever restoration measures are ultimately chosen, it is essential that physical and ecological goals be clearly established, comprehensive monitoring be conducted, and ongoing restoration measures be implemented accordingly to increase efficacy. Monitoring is especially critical in this restoration project because the ongoing presence of the Grand Ditch highlights the possibility that future impacts may one day require restoration. Whatever restoration insights can be discovered through this project will likely be useful in the future management of the area.

5.1 Lulu City wetland

The GPR surveys and soil pits in the west side of the wetland identified organic soils 1-2 m below the present ground surface. Mechanical excavation down to this surface would provide a soil conducive to vegetative restoration and may in fact still contain viable seeds of historically present wetland species. Removal of the ~80,000 m^3 of coarse deposits over the organic soils in the west side of the wetland is one opportunity to recover ground-water levels on the west side of the wetland. Similarly, microhabitats from variation in soil properties and hyporheic connectivity to the main channel were likely present prior to the 2003 debris flow, and might be restored via surface excavation. However, by recognizing that the wetland is in a state of longitudinal and cross-sectional topographic balance, it is understood that excavation on the west side of the valley will likely disconnect the east side of the valley from overbank processes, and may serve to lower groundwater levels on the east side by creating a groundwater drainage pathway towards the excavated topographic low. Because the west side of the wetland is a zone of active deposition, the excavated topographic low will be expected to aggrade, achieving an eventual re-balancing with the east side. However, based on the calculated sediment yields from the past two years, in the absence of debris-flow inputs, a timespan of centuries to millennia is needed to transport 80,000 m^3 of sediment into the wetland. Furthermore, wetlands and peatlands along the Colorado River valley are already vulnerable due to decreased groundwater levels due to the Grand Ditch diversion [*Woods*, 2000]. A thorough investigation of potential impacts to the east side of the wetland should be conducted before considering excavation of sediments on the west side of the valley.

An alternate recommendation would be to leave the coarse deposits and encourage overbank and in-channel fine-sediment deposition in order to maintain lateral connectivity with the east side of the wetland and restore hospitable conditions on the west side. In-channel and overbank sediment trapping could be accomplished through the construction of artificial beaver dams. Beaver dams historically played a critical role in mountain rivers for physical processes such as encouraging overbank flooding, as well as groundwater hydrologic controls including maintaining an elevated and more stable water table [*Westbrook et al.*, 2006]. These processes may be initiated through artificial beaver dam construction in order to restore the processes that sustain the riparian vegetation needed by the beaver [*Pollock et al.*, 2007]. Encouraging in-channel aggradation and overbank deposition through beaver dams (constructed or natural) accomplishes the dual goals of lateral connectivity and soil restoration [*Beechie et al.*, 2007]. Artificial beaver dams have been constructed in Benewah Creek, Idaho [*Devries et al.*, 2009] as a precursor to beaver re-introduction. Other artificial beaver dam construction projects have been implemented to restore physical processes such as hyporheic exchange [*Lautz et al.*, 2005].

5.2 Colorado River between Lulu Creek and the Lulu City wetland

The results from repeat cross-sectional surveys and sediment sampling suggest that no restoration is necessary to restore physical forms and processes in the Colorado River. However, connectivity to the flood plain to sustain riparian vegetation may require the removal of sediment deposits in selected locations. Also, the stability that has characterized the post-2003 channel should continue to be monitored, especially in the event of overbank flows. Furthermore, if coarse sediments are excavated from the wetland, the resulting base-level change may potentially destabilize the upstream channel. Grade control or other channel stabilizing measures may then be warranted.

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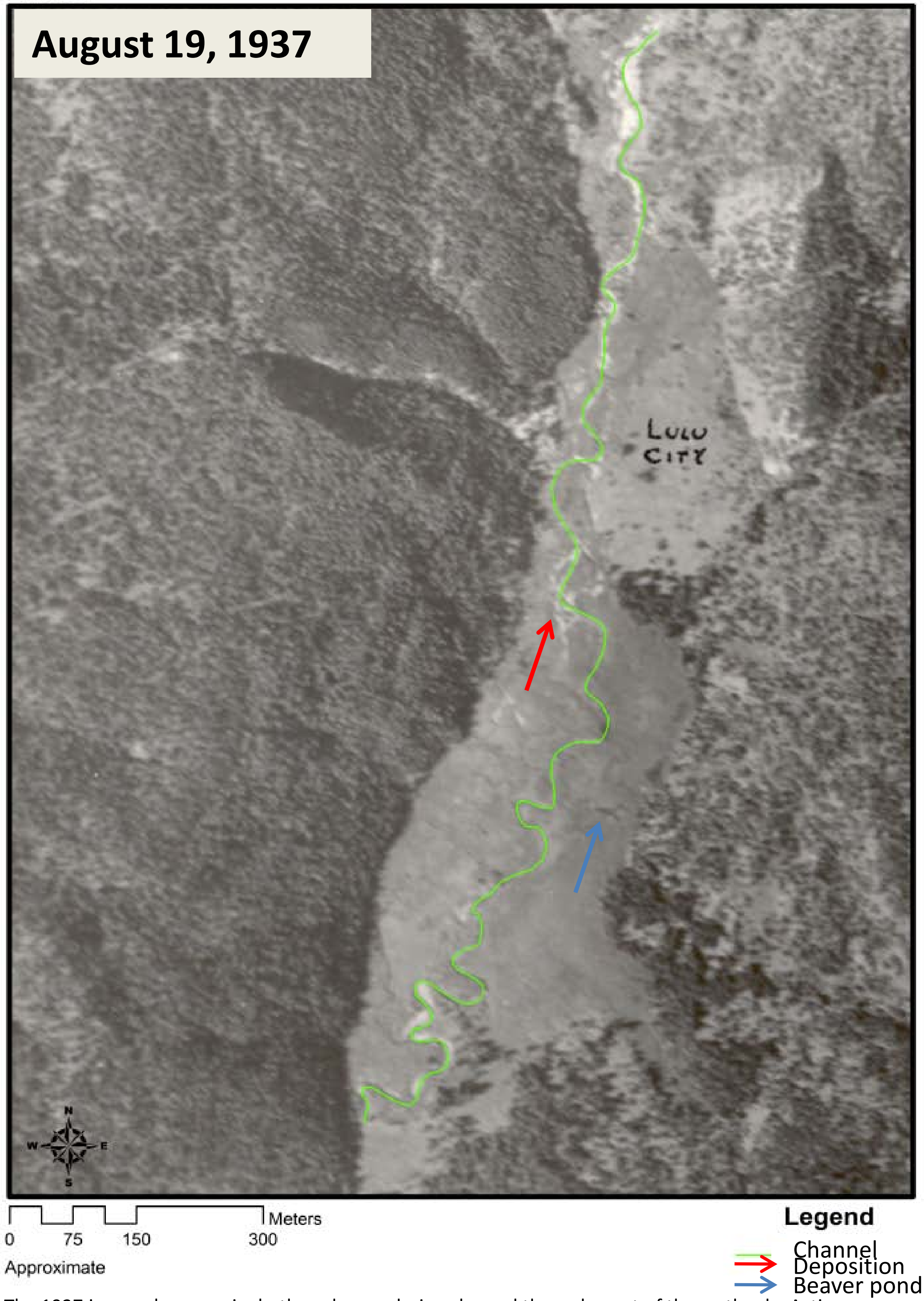
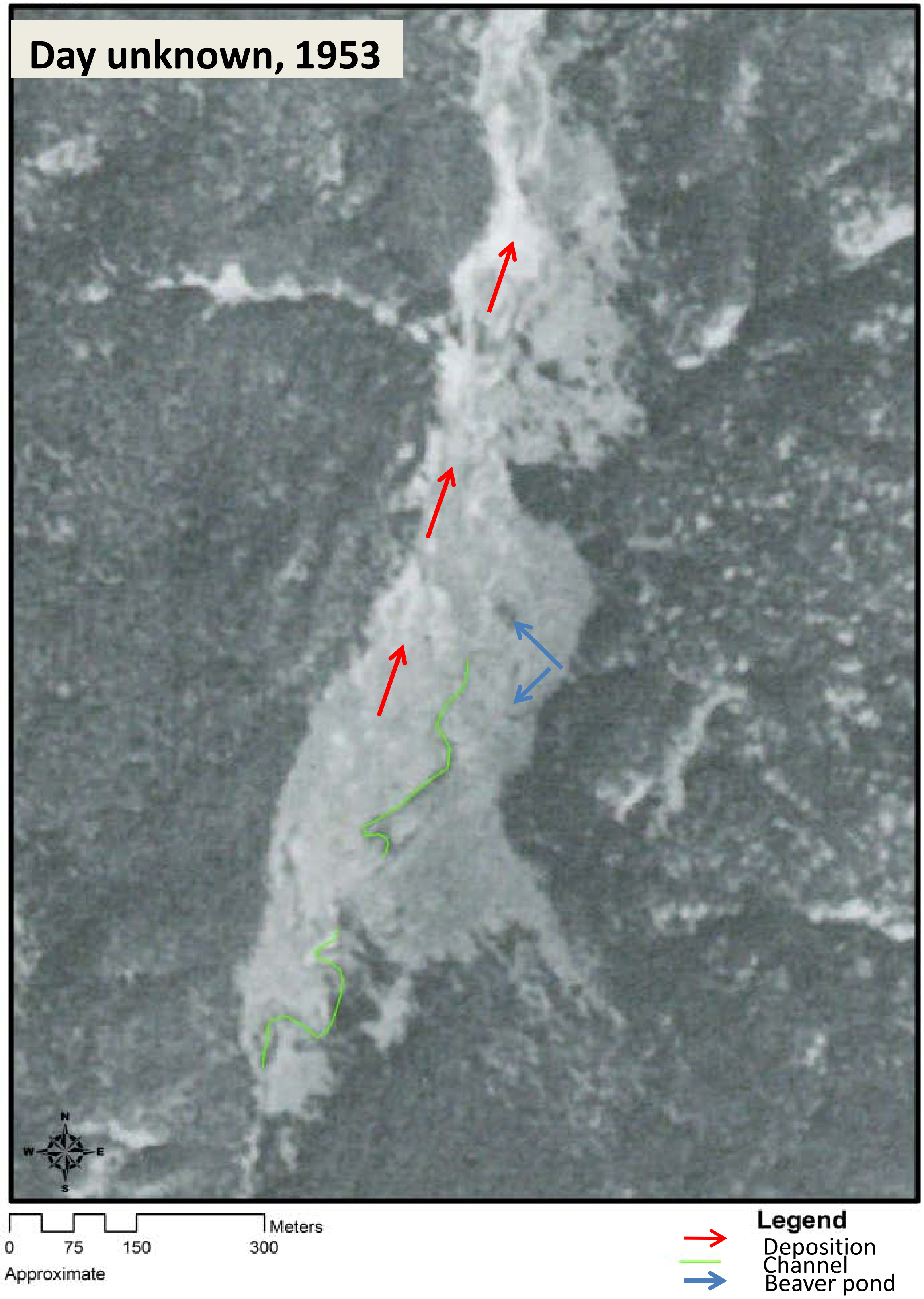
Appendix A

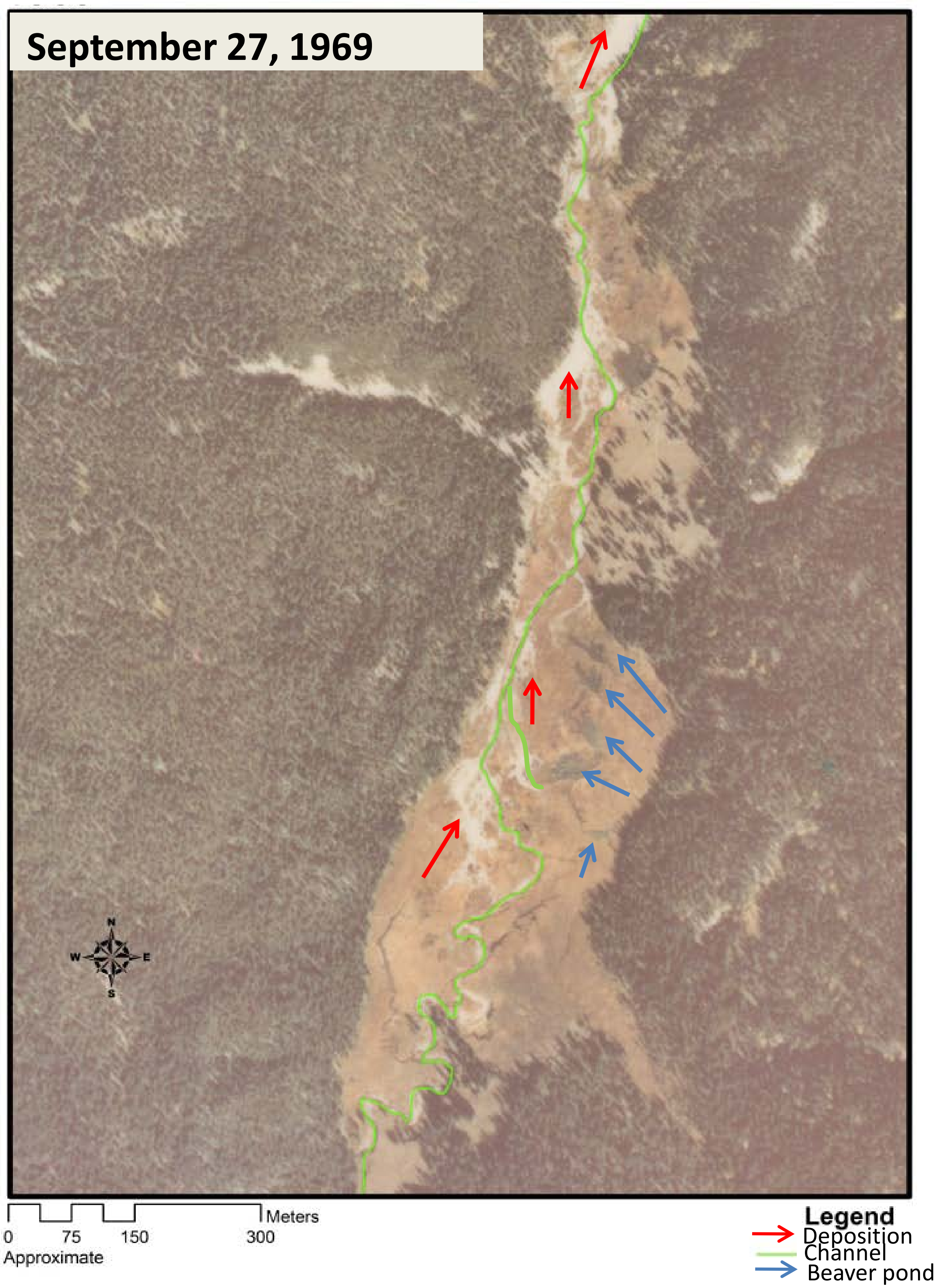
Historic Aerial Photos



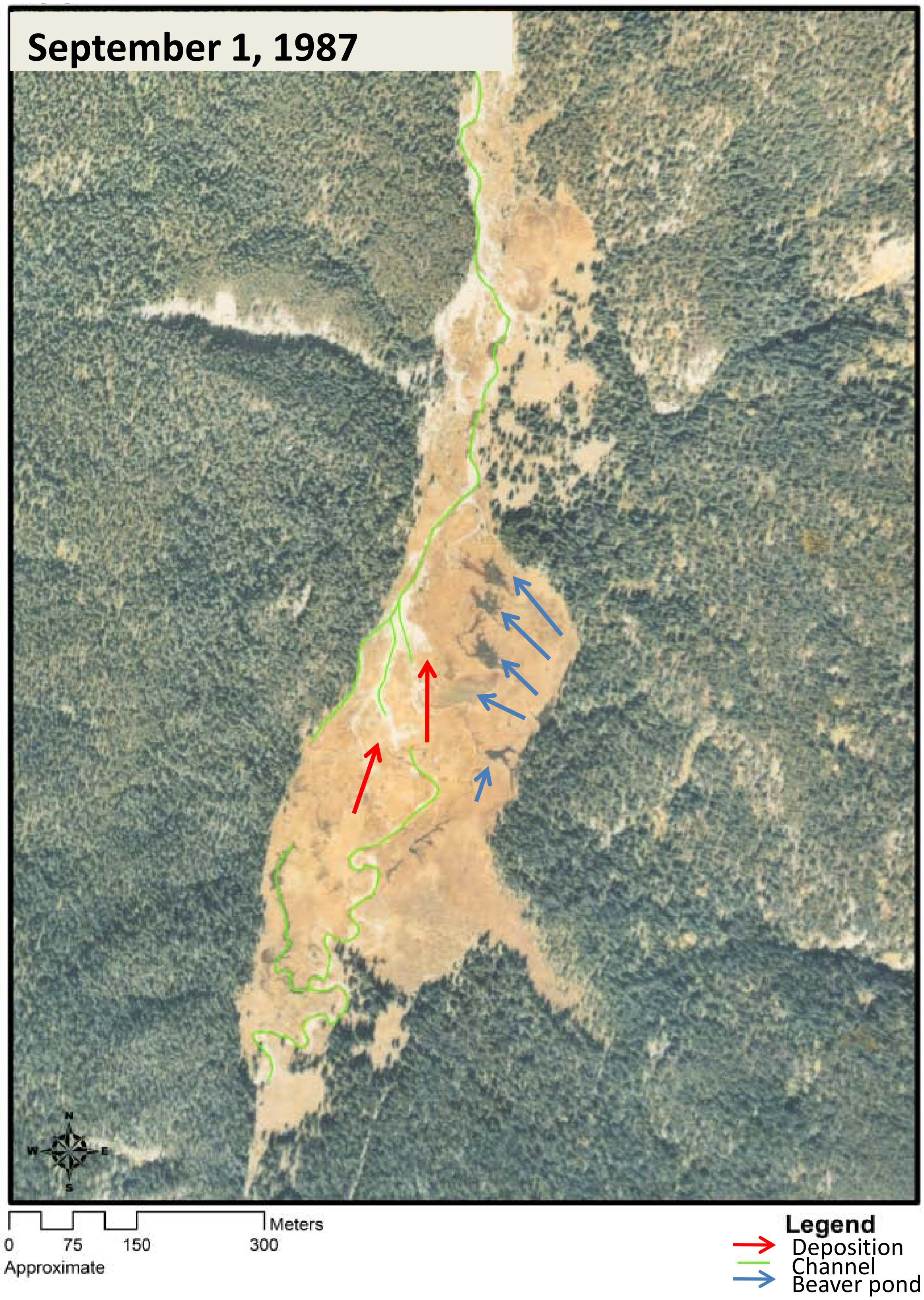
The 1937 image shows a single-thread meandering channel through most of the wetland. Active deposition and minor braiding is visible at the head of the wetland. One beaver pond is visible, though more may be present and not apparent due to low resolution of the photo.



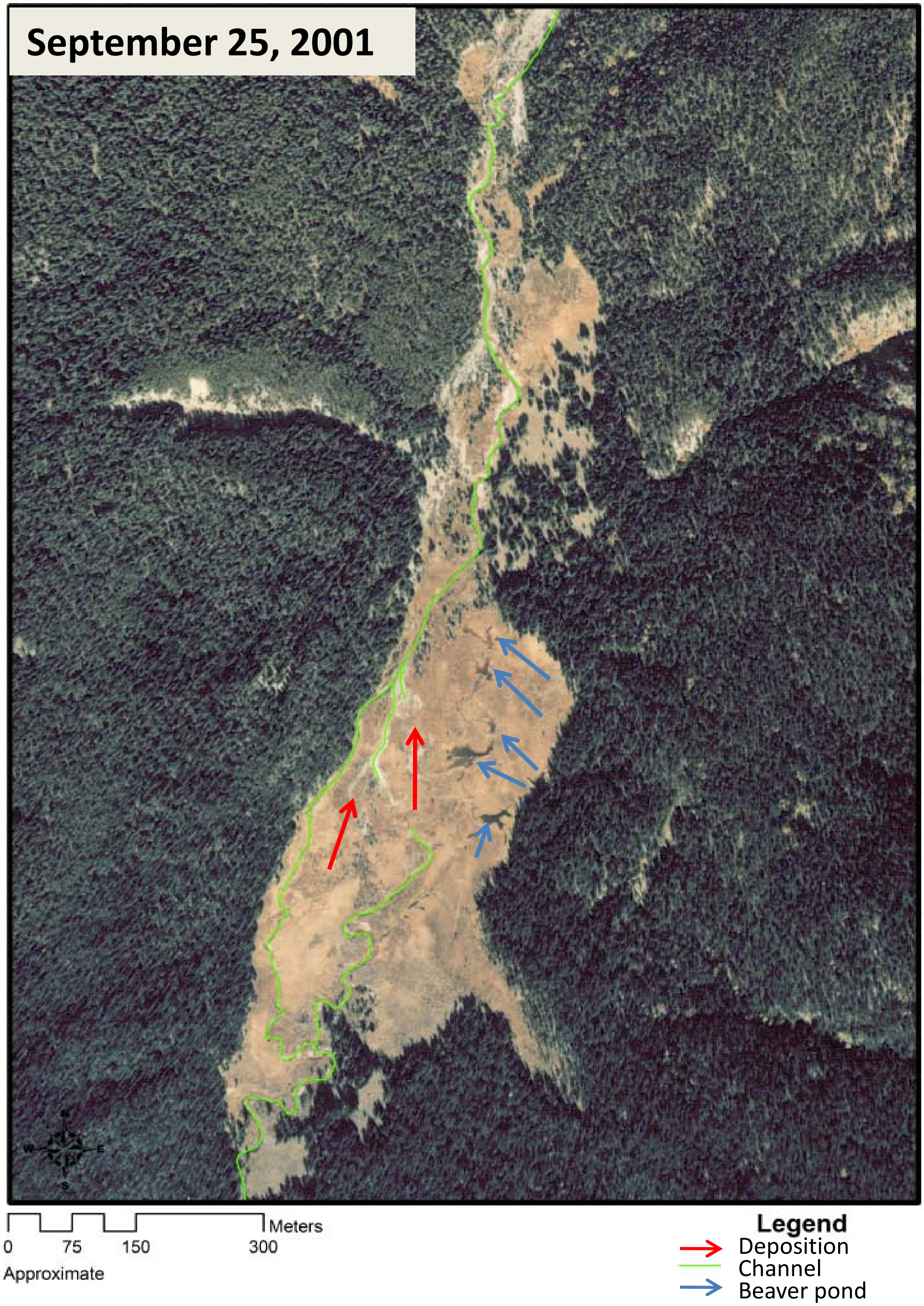
The 1953 image shows extensive deposition in the northwest corner of the wetland. Except in segments where the 1937 channel is still intact, there is no main channel. A second beaver pond is visible, though more may have been present but not visible due to low resolution.



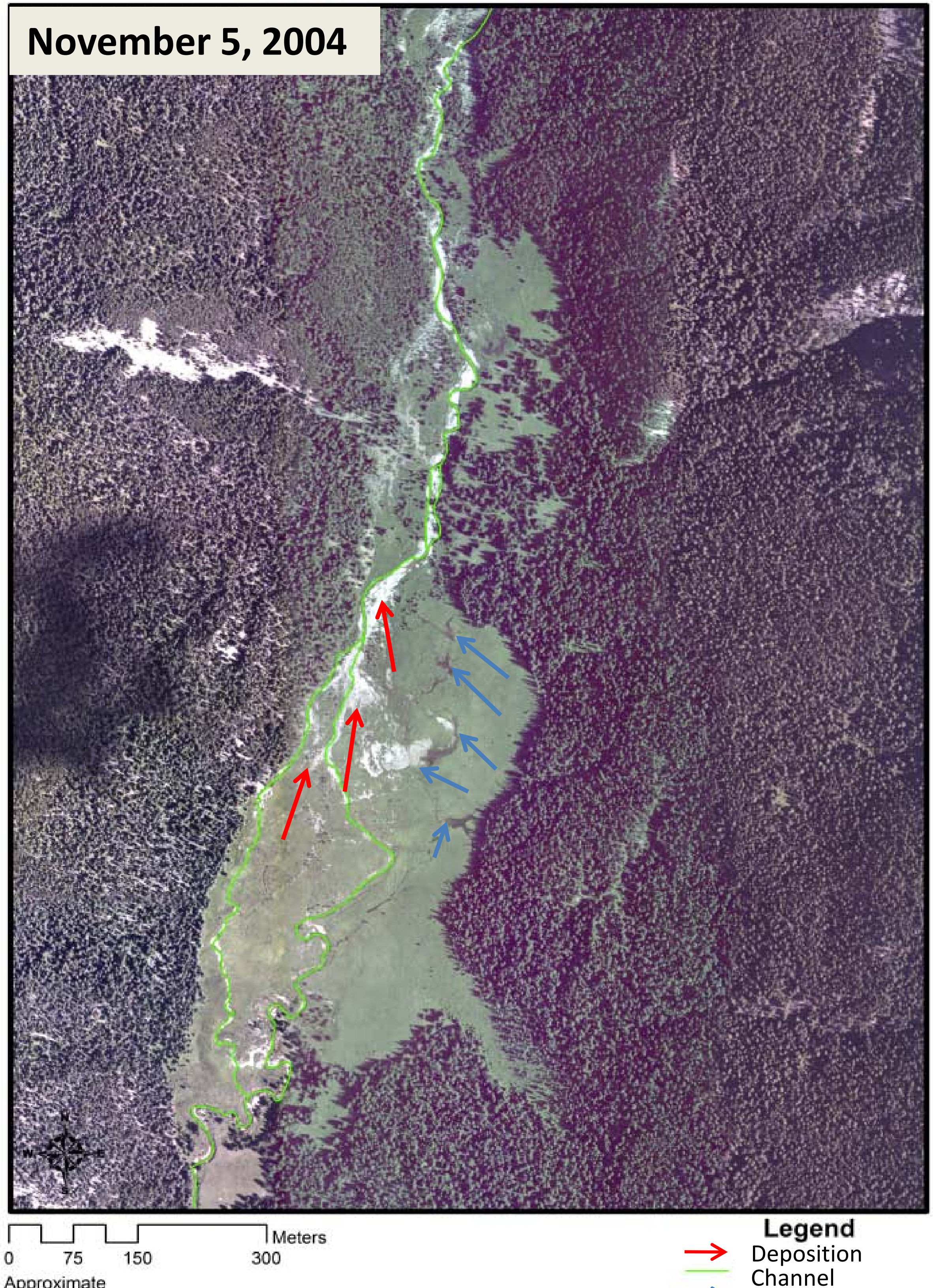
The 1969 image shows moderate deposition in the form of either debris flow or splay deposits. A poorly defined channel is present in the northern wetland, though now on the west side of the valley. In addition to previously identified ponds, three more are visible.



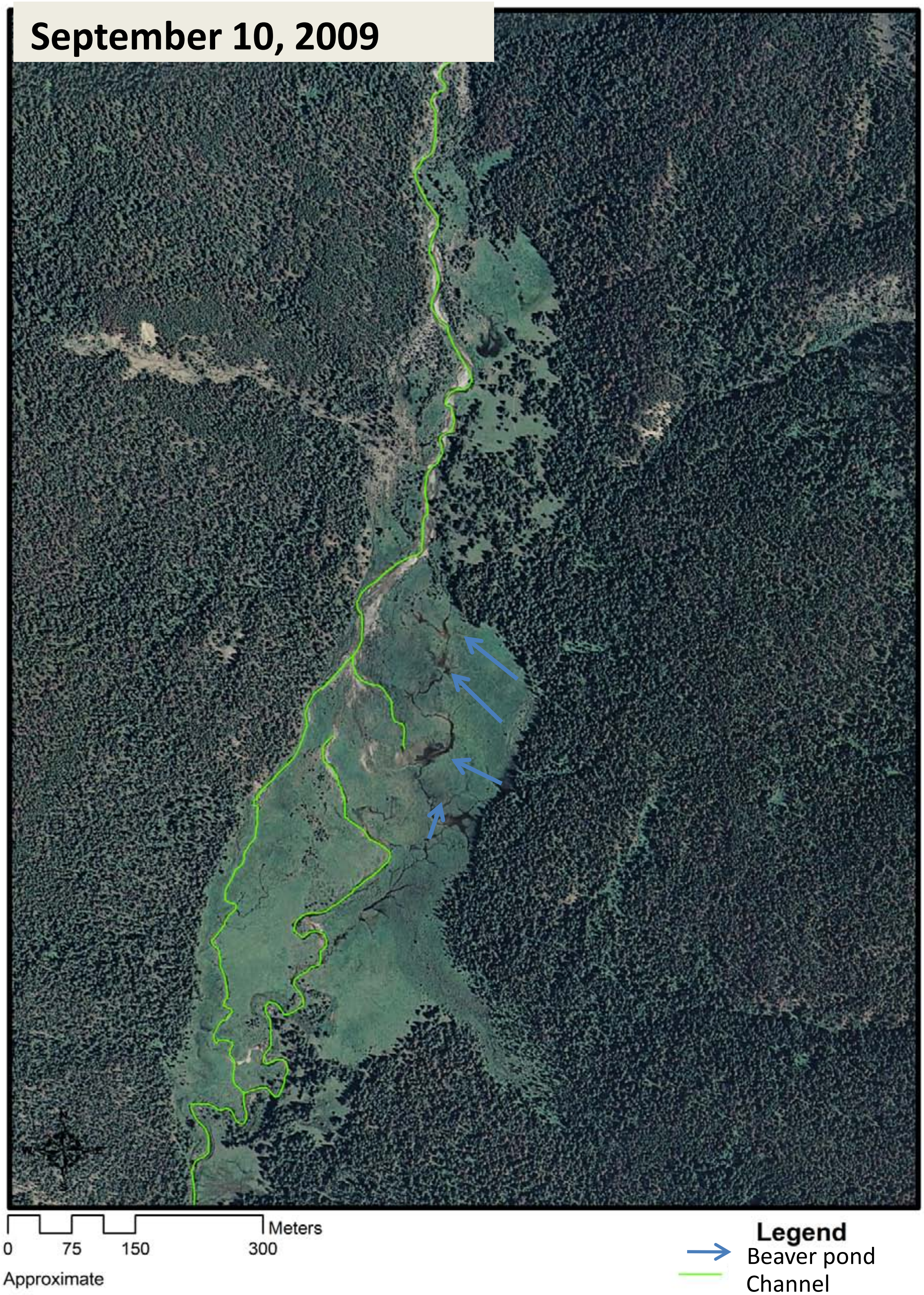
The 1987 image shows minor deposition in the form of either debris flow or splay deposits. The 1969 channel is generally unchanged, though poorly defined. Previously identified beaver ponds are still present. A few conifer trees are green and visible, in northern and western portions of the wetland.



The 2001 image shows minor splay deposition. Channel position is generally unchanged, though there is no dominant channel. Previously identified beaver ponds are still present. Conifer trees are green and visible in areas of previous deposition on the west side of the wetland.



The 2004 image shows deposition from the 2003 debris flow. Channel position is generally unchanged, though there is no well defined channel. Previously identified beaver ponds are still present.

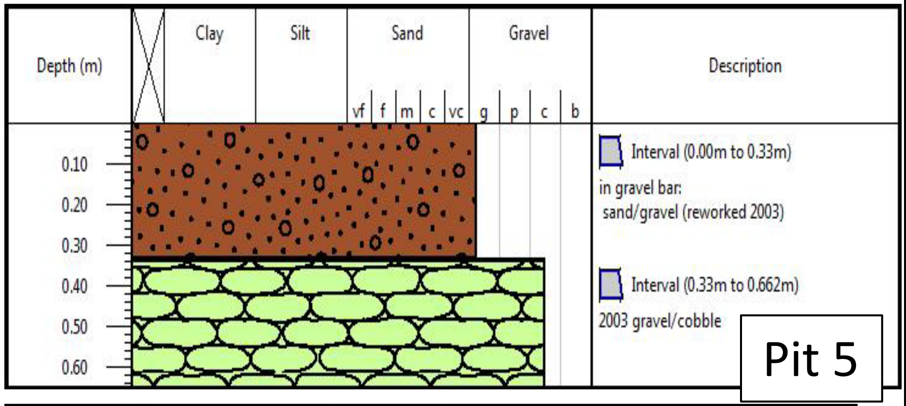


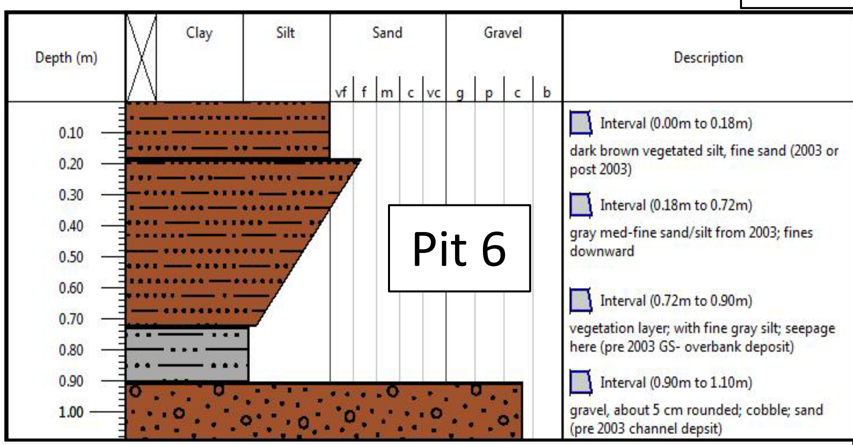
The 2009 image shows additional reworking of the 2003 debris flow sediment. Channel position is generally unchanged, with no well defined channel, although some migration towards the center of the valley is occurring. Previously identified beaver ponds are still present.

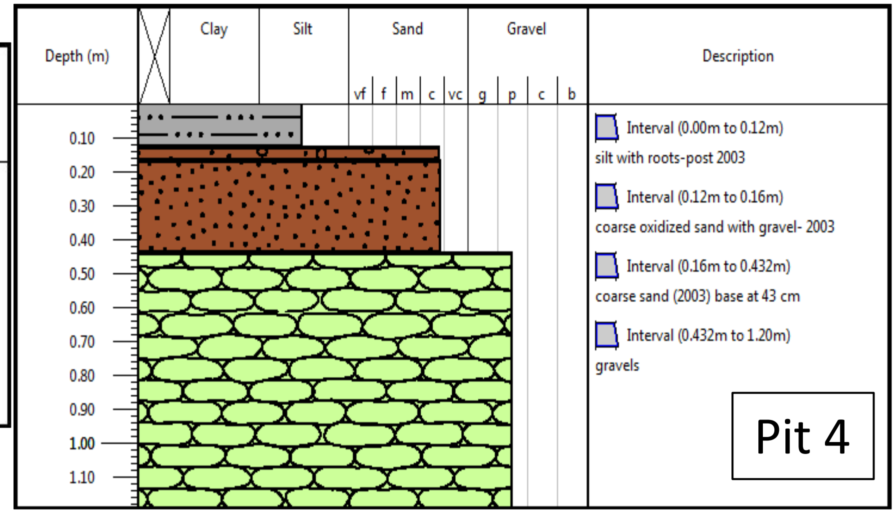
Appendix B

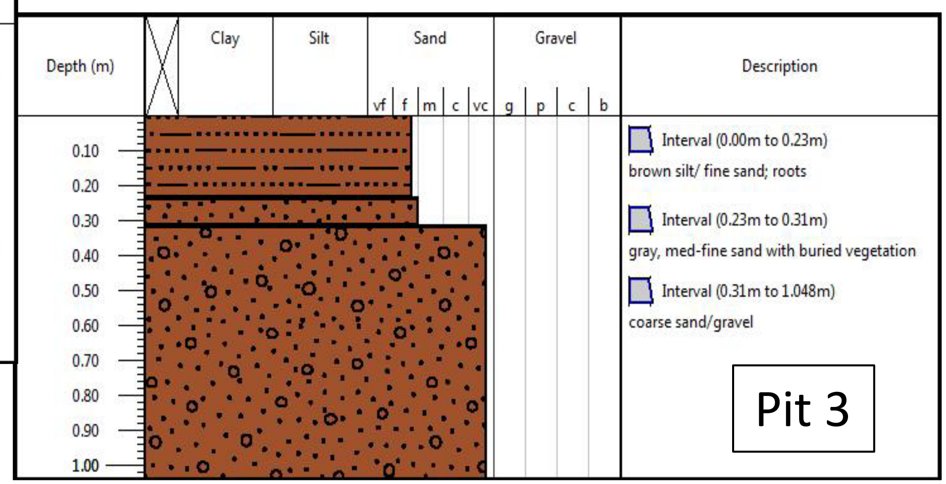
Sediment Descriptions

XS 0

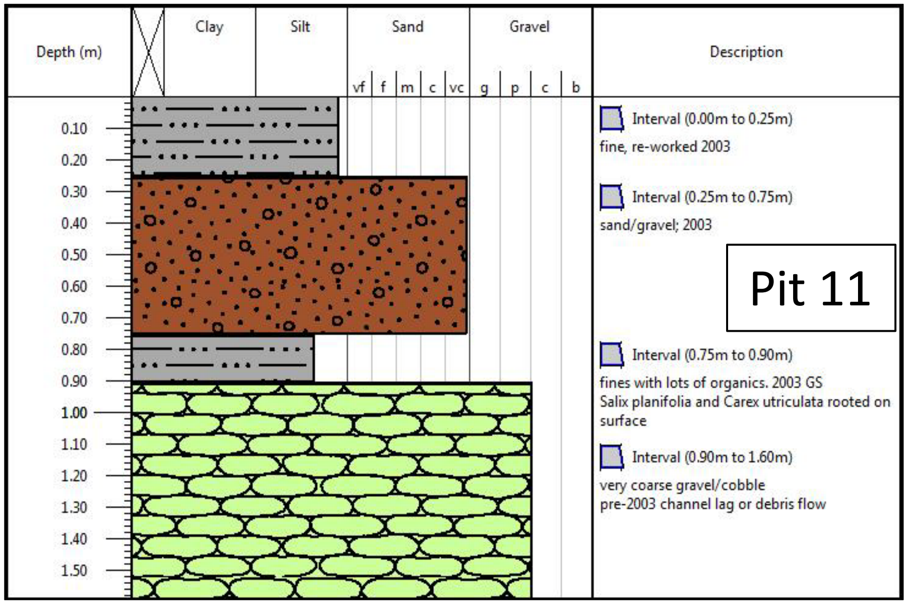

Depth (m)
Clay
Silt
Sand
Gravel
vf f m c vc g p c b
Description
0.10 0.20 0.30 0.40 0.50 0.60
Interval (0.00m to 0.33m)
in gravel bar:
sand/gravel (reworked 2003)
Interval (0.33m to 0.662m)
2003 gravel/cobble
Pit 5

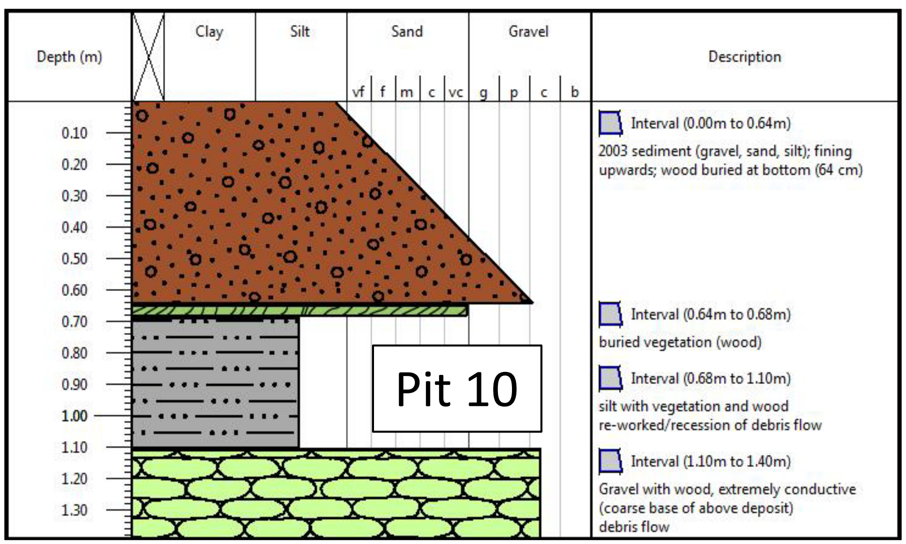

Depth (m)
Clay
Silt
Sand
Gravel
vf f m c vc g p c b
Description
0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90 1.00
Pit 6
Interval (0.00m to 0.18m)
dark brown vegetated silt, fine sand (2003 or post 2003)
Interval (0.18m to 0.72m)
gray med-fine sand/silt from 2003; fines downward
Interval (0.72m to 0.90m)
vegetation layer; with fine gray silt; seepage here (pre 2003 GS- overbank deposit)
Interval (0.90m to 1.10m)
gravel, about 5 cm rounded; cobble; sand (pre 2003 channel depsit)

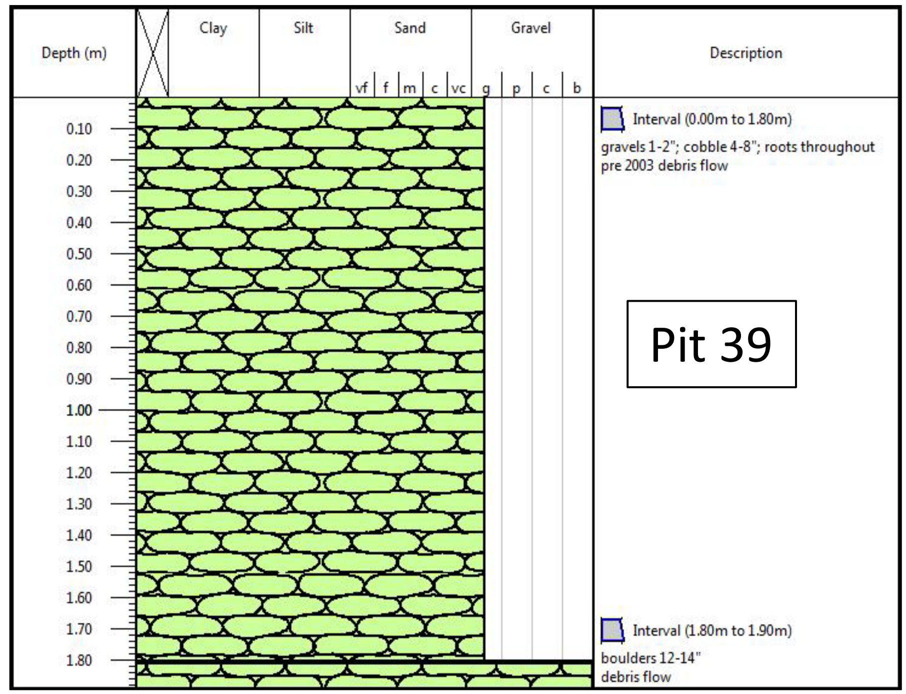

Depth (m)
Clay
Silt
Sand
Gravel
vf f m c vc g p c b
Description
0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90 1.00 1.10
Interval (0.00m to 0.12m)
silt with roots-post 2003
Interval (0.12m to 0.16m)
coarse oxidized sand with gravel- 2003
Interval (0.16m to 0.432m)
coarse sand (2003) base at 43 cm
Interval (0.432m to 1.20m)
gravels
Pit 4


Depth (m)
Clay
Silt
Sand
Gravel
vf f m c vc g p c b
Description
0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90 1.00
Interval (0.00m to 0.23m)
brown silt/ fine sand; roots
Interval (0.23m to 0.31m)
gray, med-fine sand with buried vegetation
Interval (0.31m to 1.048m)
coarse sand/gravel
Pit 3

XS 1

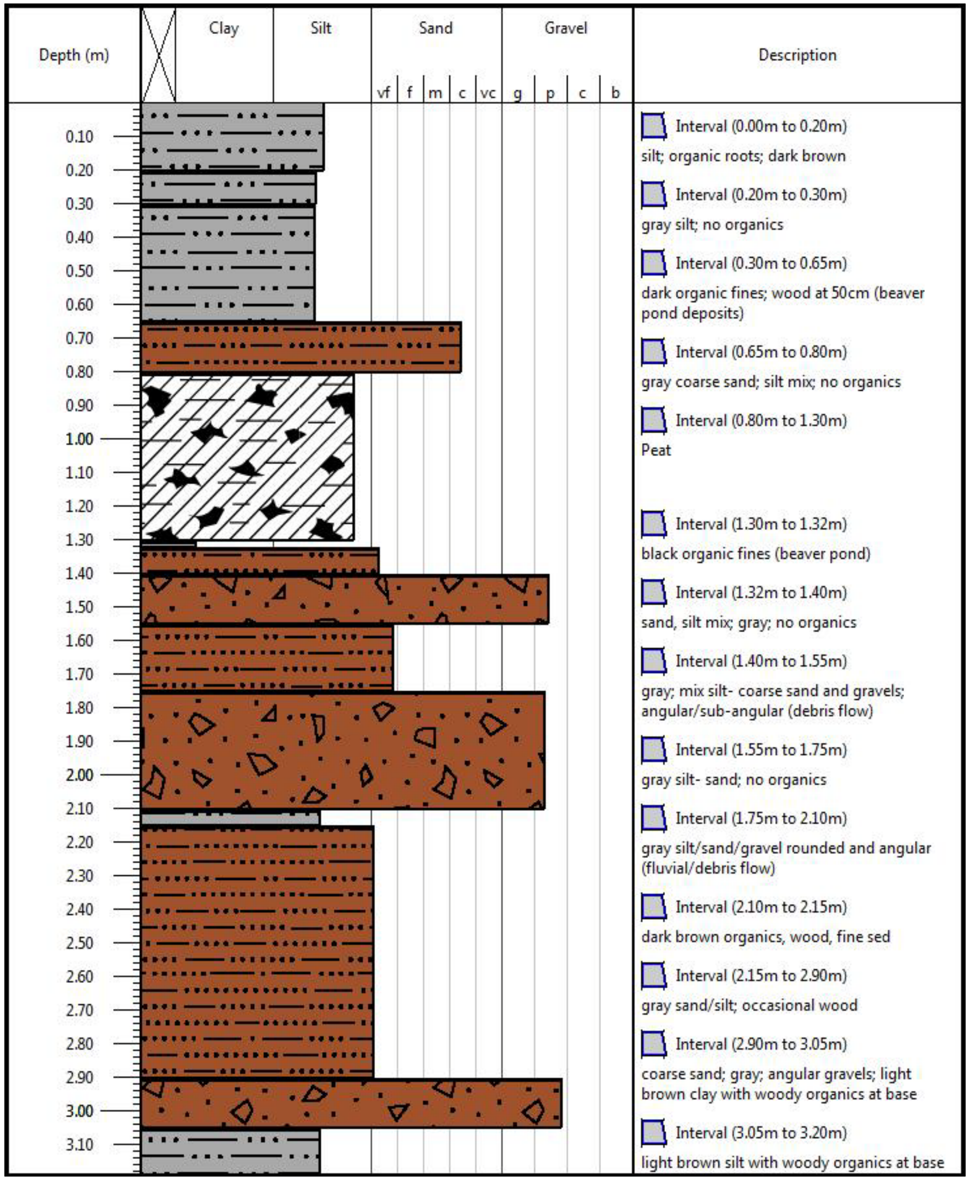

Pit 11
Depth (m)
Clay
Silt
Sand
vf f m c vc
Gravel
g p c b
Description
0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90 1.00 1.10 1.20 1.30 1.40 1.50
Interval (0.00m to 0.25m)
fine, re-worked 2003
Interval (0.25m to 0.75m)
sand/gravel; 2003
Interval (0.75m to 0.90m)
fines with lots of organics. 2003 GS
Salix planifolia and Carex utriculata rooted on surface
Interval (0.90m to 1.60m)
very coarse gravel/cobble
pre-2003 channel lag or debris flow


Pit 10
Depth (m)
Clay
Silt
Sand
vf f m c vc
Gravel
g p c b
Description
0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90 1.00 1.10 1.20 1.30
Interval (0.00m to 0.64m)
2003 sediment (gravel, sand, silt); fining upwards; wood buried at bottom (64 cm)
Interval (0.64m to 0.68m)
buried vegetation (wood)
Interval (0.68m to 1.10m)
silt with vegetation and wood
re-worked/recession of debris flow
Interval (1.10m to 1.40m)
Gravel with wood, extremely conductive
(coarse base of above deposit)
debris flow

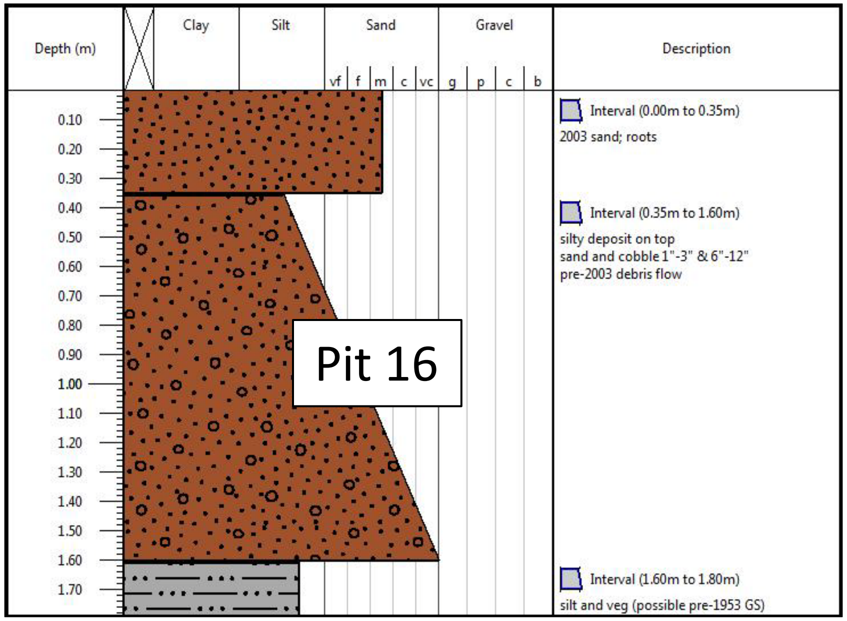

Pit 39
Depth (m)
Clay
Silt
Sand
vf f m c vc
Gravel
g p c b
Description
0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90 1.00 1.10 1.20 1.30 1.40 1.50 1.60 1.70 1.80
Interval (0.00m to 1.80m)
gravels 1-2"; cobble 4-8"; roots throughout
pre 2003 debris flow
Interval (1.80m to 1.90m)
boulders 12-14"
debris flow

XS 2

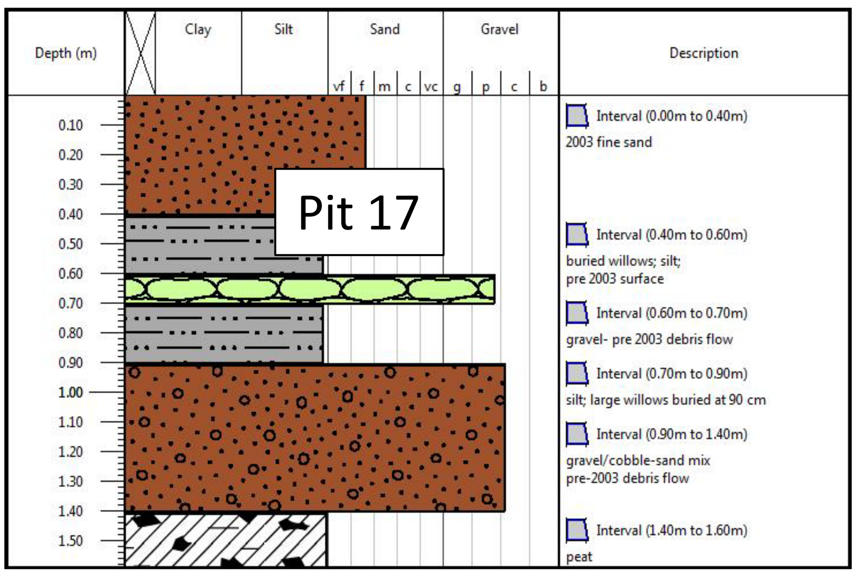
Long E @ 429m



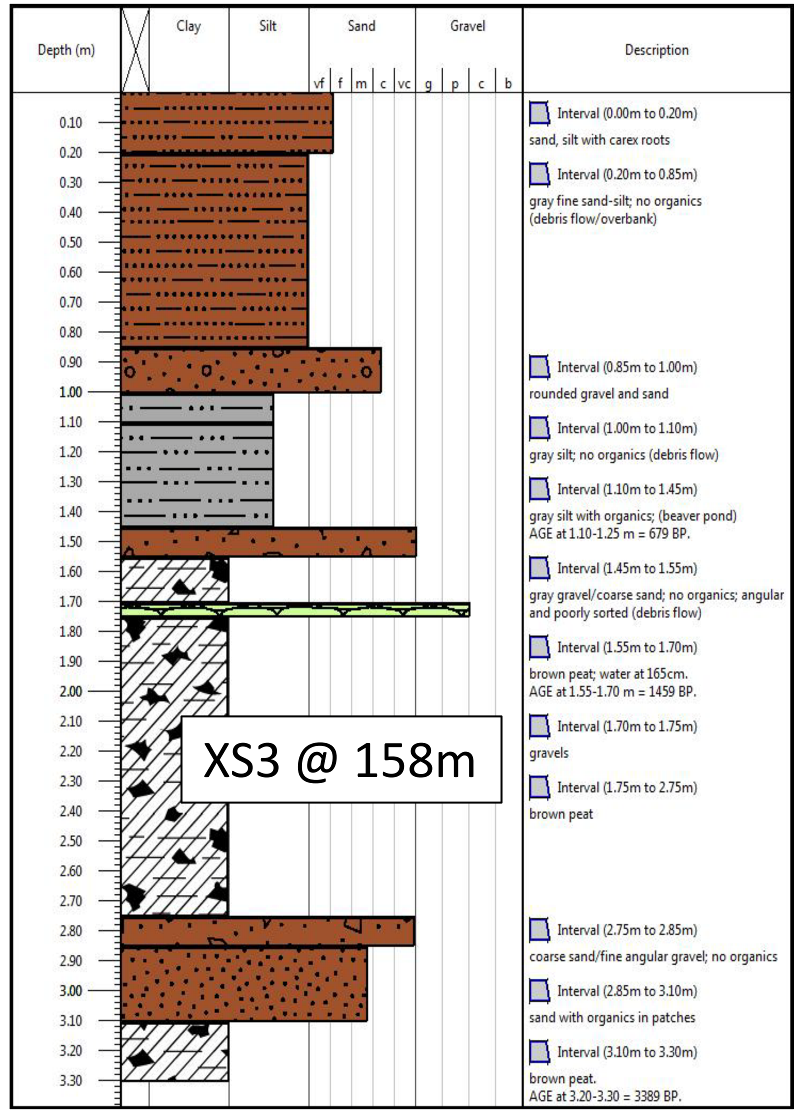
XS 3



Pit 16
Depth (m)
Clay
Silt
Sand
Gravel
vf f m c vc g p c b
Description
Interval (0.00m to 0.35m)
2003 sand; roots
Interval (0.35m to 1.60m)
silty deposit on top
sand and cobble 1"-3" & 6"-12"
pre-2003 debris flow
Interval (1.60m to 1.80m)
silt and veg (possible pre-1953 GS)

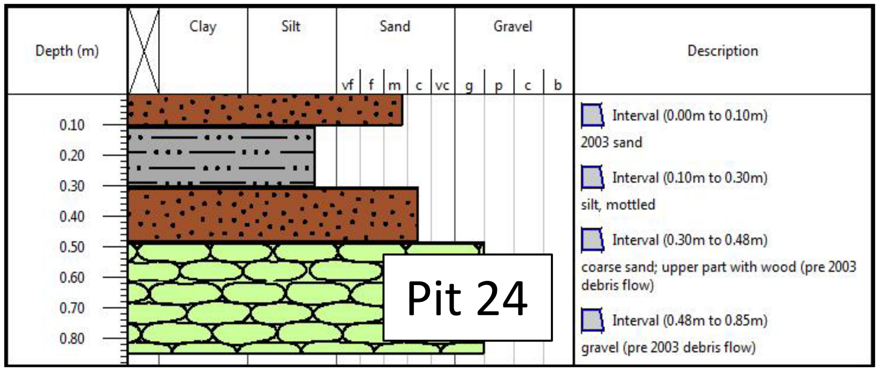


Pit 17
Depth (m)
Clay
Silt
Sand
Gravel
vf f m c vc g p c b
Description
Interval (0.00m to 0.40m)
2003 fine sand
Interval (0.40m to 0.60m)
buried willows; silt;
pre 2003 surface
Interval (0.60m to 0.70m)
gravel- pre 2003 debris flow
Interval (0.70m to 0.90m)
silt; large willows buried at 90 cm
Interval (0.90m to 1.40m)
gravel/cobble-sand mix
pre-2003 debris flow
Interval (1.40m to 1.60m)
peat

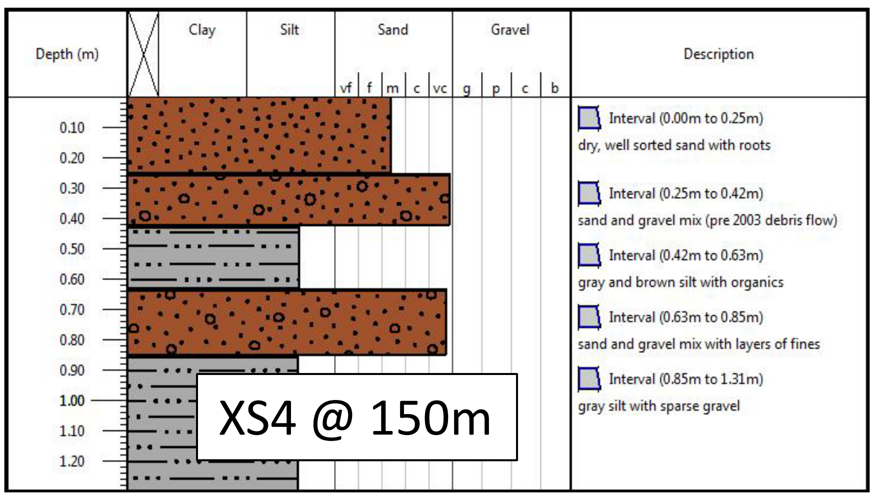


XS3 @ 158m
Depth (m)
Clay
Silt
Sand
Gravel
vf f m c vc g p c b
Description
Interval (0.00m to 0.20m)
sand, silt with carex roots
Interval (0.20m to 0.85m)
gray fine sand-silt; no organics
(debris flow/overbank)
Interval (0.85m to 1.00m)
rounded gravel and sand
Interval (1.00m to 1.10m)
gray silt; no organics (debris flow)
Interval (1.10m to 1.45m)
gray silt with organics; (beaver pond)
AGE at 1.10-1.25 m = 679 BP.
Interval (1.45m to 1.55m)
gray gravel/coarse sand; no organics; angular
and poorly sorted (debris flow)
Interval (1.55m to 1.70m)
brown peat; water at 165cm.
AGE at 1.55-1.70 m = 1459 BP.
Interval (1.70m to 1.75m)
gravels
Interval (1.75m to 2.75m)
brown peat
Interval (2.75m to 2.85m)
coarse sand/fine angular gravel; no organics
Interval (2.85m to 3.10m)
sand with organics in patches
Interval (3.10m to 3.30m)
brown peat.
AGE at 3.20-3.30 = 3389 BP.

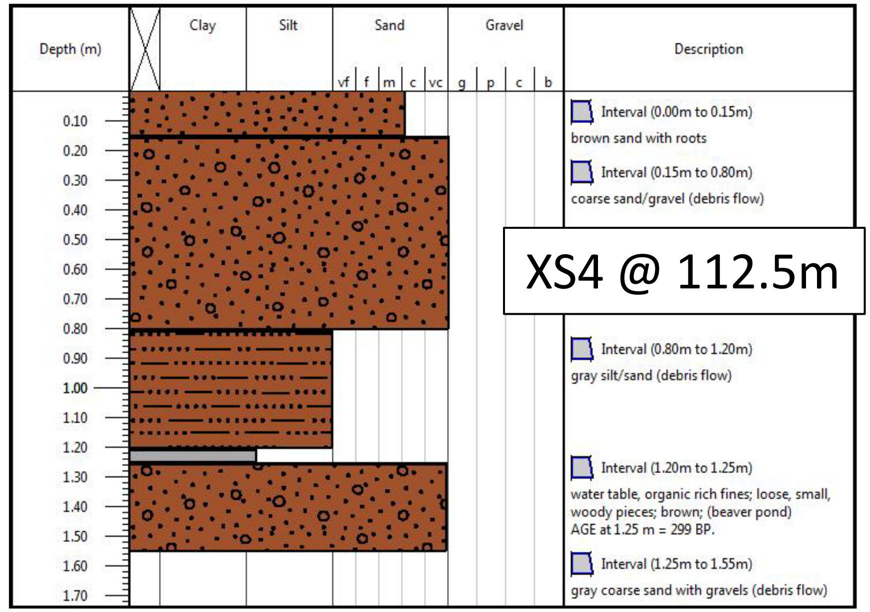
XS 4



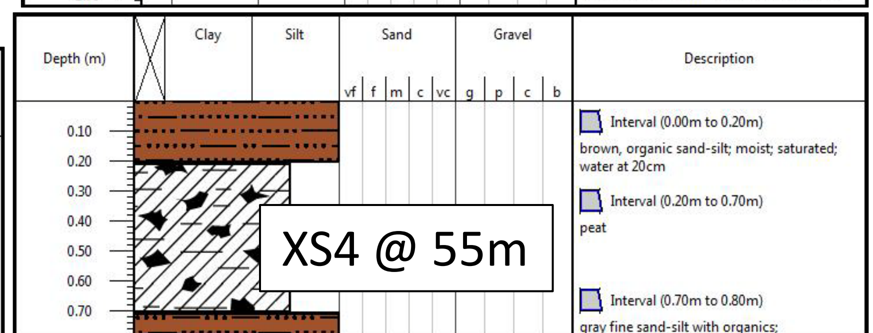
Pit 24
Depth (m)
Clay
Silt
Sand
Gravel
vf f m c vc g p c b
Description
0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80
Interval (0.00m to 0.10m)
2003 sand
Interval (0.10m to 0.30m)
silt, mottled
Interval (0.30m to 0.48m)
coarse sand; upper part with wood (pre 2003 debris flow)
Interval (0.48m to 0.85m)
gravel (pre 2003 debris flow)



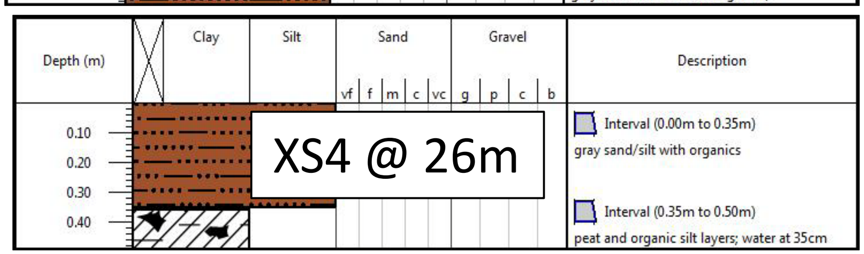
XS4 @ 150m
Depth (m)
Clay
Silt
Sand
Gravel
vf f m c vc g p c b
Description
0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90 1.00 1.10 1.20
Interval (0.00m to 0.25m)
dry, well sorted sand with roots
Interval (0.25m to 0.42m)
sand and gravel mix (pre 2003 debris flow)
Interval (0.42m to 0.63m)
gray and brown silt with organics
Interval (0.63m to 0.85m)
sand and gravel mix with layers of fines
Interval (0.85m to 1.31m)
gray silt with sparse gravel



XS4 @ 112.5m
Depth (m)
Clay
Silt
Sand
Gravel
vf f m c vc g p c b
Description
0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90 1.00 1.10 1.20 1.30 1.40 1.50 1.60 1.70
Interval (0.00m to 0.15m)
brown sand with roots
Interval (0.15m to 0.80m)
coarse sand/gravel (debris flow)
Interval (0.80m to 1.20m)
gray silt/sand (debris flow)
Interval (1.20m to 1.25m)
water table, organic rich fines; loose, small, woody pieces; brown; (beaver pond)
AGE at 1.25 m = 299 BP.
Interval (1.25m to 1.55m)
gray coarse sand with gravels (debris flow)

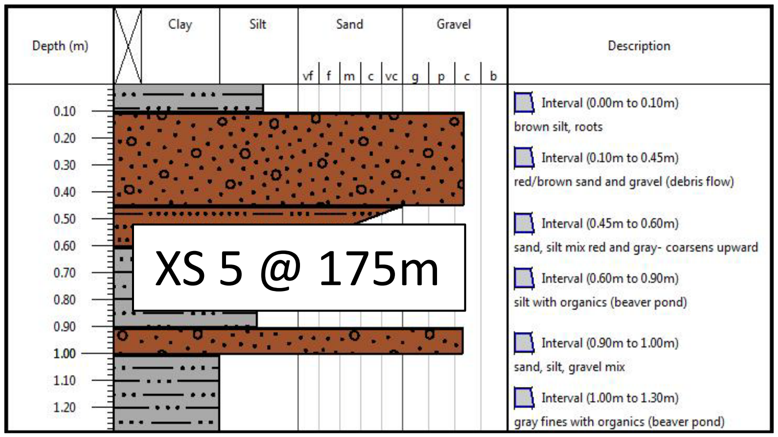


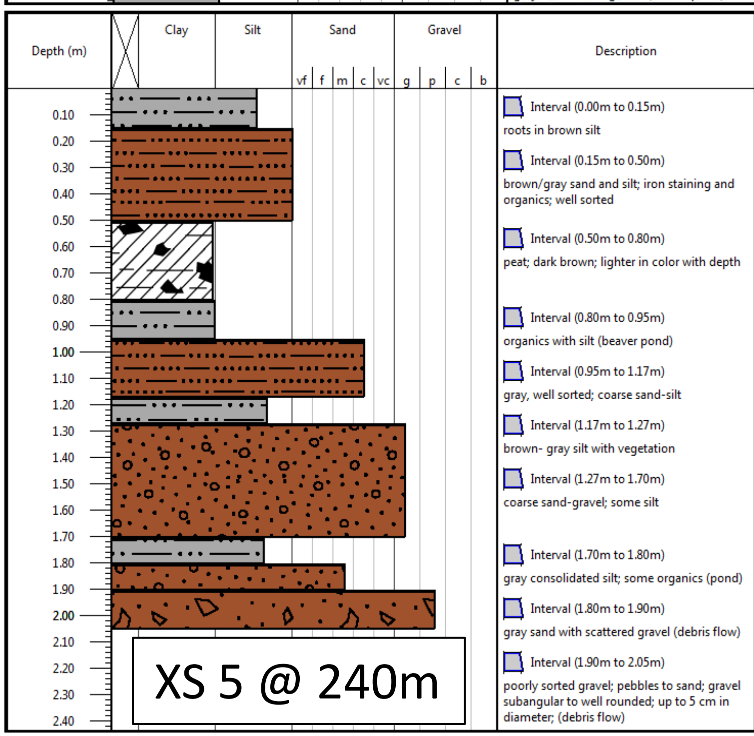
XS4 @ 55m
Depth (m)
Clay
Silt
Sand
Gravel
vf f m c vc g p c b
Description
0.10 0.20 0.30 0.40 0.50 0.60 0.70
Interval (0.00m to 0.20m)
brown, organic sand-silt; moist; saturated; water at 20cm
Interval (0.20m to 0.70m)
peat
Interval (0.70m to 0.80m)
gray fine sand-silt with organics;

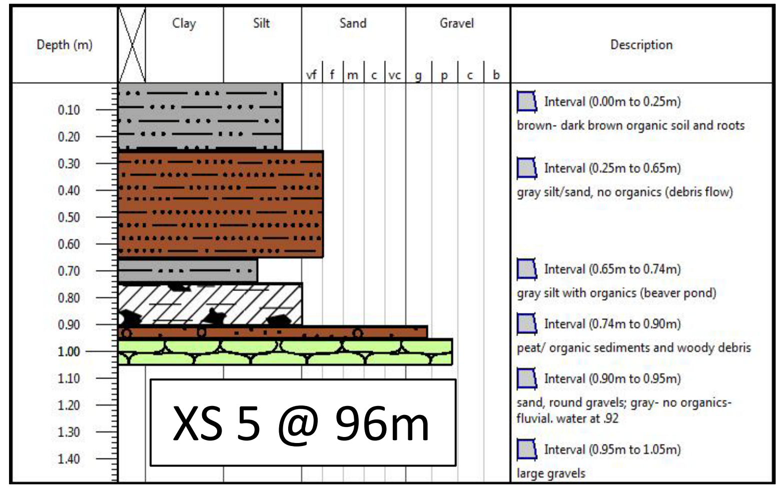


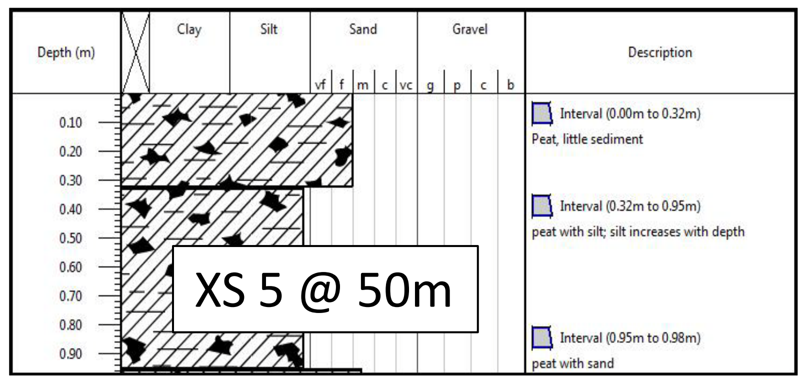
XS4 @ 26m
Depth (m)
Clay
Silt
Sand
Gravel
vf f m c vc g p c b
Description
0.10 0.20 0.30 0.40
Interval (0.00m to 0.35m)
gray sand/silt with organics
Interval (0.35m to 0.50m)
peat and organic silt layers; water at 35cm

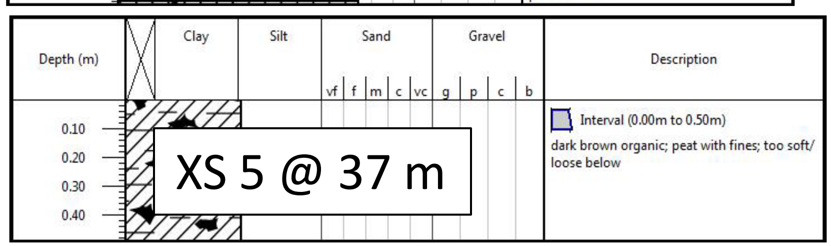
XS 5


XS 5 @ 175m
Depth (m)
Clay
Silt
Sand
Gravel
vf f m c vc g p c b
Description
0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90 1.00 1.10 1.20
Interval (0.00m to 0.10m)
brown silt, roots
Interval (0.10m to 0.45m)
red/brown sand and gravel (debris flow)
Interval (0.45m to 0.60m)
sand, silt mix red and gray- coarsens upward
Interval (0.60m to 0.90m)
silt with organics (beaver pond)
Interval (0.90m to 1.00m)
sand, silt, gravel mix
Interval (1.00m to 1.30m)
gray fines with organics (beaver pond)

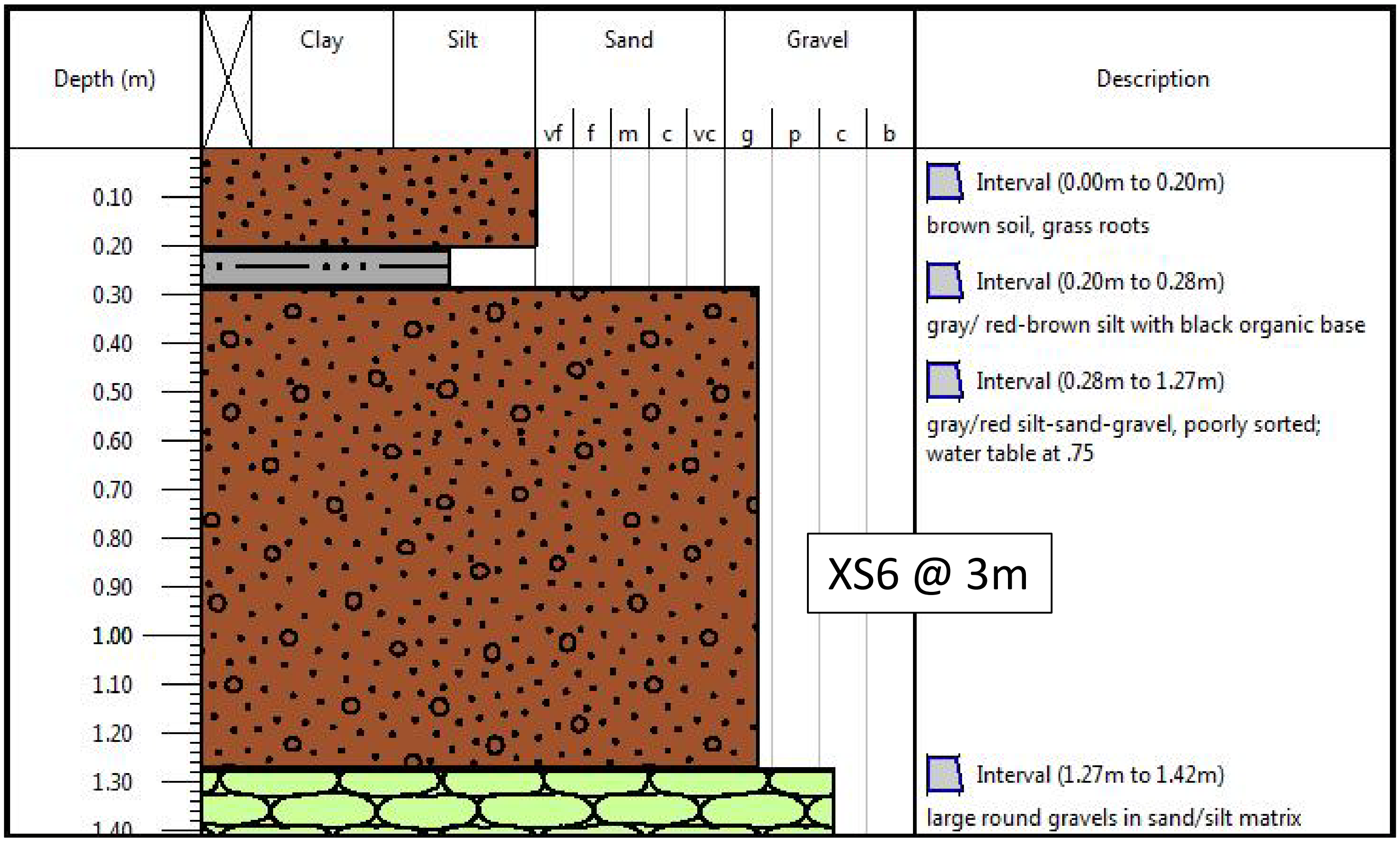

XS 5 @ 240m
Depth (m)
Clay
Silt
Sand
Gravel
vf f m c vc g p c b
Description
0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90 1.00 1.10 1.20 1.30 1.40 1.50 1.60 1.70 1.80 1.90 2.00 2.10 2.20 2.30 2.40
Interval (0.00m to 0.15m)
roots in brown silt
Interval (0.15m to 0.50m)
brown/gray sand and silt; iron staining and organics; well sorted
Interval (0.50m to 0.80m)
peat; dark brown; lighter in color with depth
Interval (0.80m to 0.95m)
organics with silt (beaver pond)
Interval (0.95m to 1.17m)
gray, well sorted; coarse sand-silt
Interval (1.17m to 1.27m)
brown- gray silt with vegetation
Interval (1.27m to 1.70m)
coarse sand-gravel; some silt
Interval (1.70m to 1.80m)
gray consolidated silt; some organics (pond)
Interval (1.80m to 1.90m)
gray sand with scattered gravel (debris flow)
Interval (1.90m to 2.05m)
poorly sorted gravel; pebbles to sand; gravel subangular to well rounded; up to 5 cm in diameter; (debris flow)


XS 5 @ 96m
Depth (m)
Clay
Silt
Sand
Gravel
vf f m c vc g p c b
Description
0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90 1.00 1.10 1.20 1.30 1.40
Interval (0.00m to 0.25m)
brown- dark brown organic soil and roots
Interval (0.25m to 0.65m)
gray silt/sand, no organics (debris flow)
Interval (0.65m to 0.74m)
gray silt with organics (beaver pond)
Interval (0.74m to 0.90m)
peat/ organic sediments and woody debris
Interval (0.90m to 0.95m)
sand, round gravels; gray- no organics- fluvial. water at .92
Interval (0.95m to 1.05m)
large gravels


XS 5 @ 50m
Depth (m)
Clay
Silt
Sand
Gravel
vf f m c vc g p c b
Description
0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90
Interval (0.00m to 0.32m)
Peat, little sediment
Interval (0.32m to 0.95m)
peat with silt; silt increases with depth
Interval (0.95m to 0.98m)
peat with sand

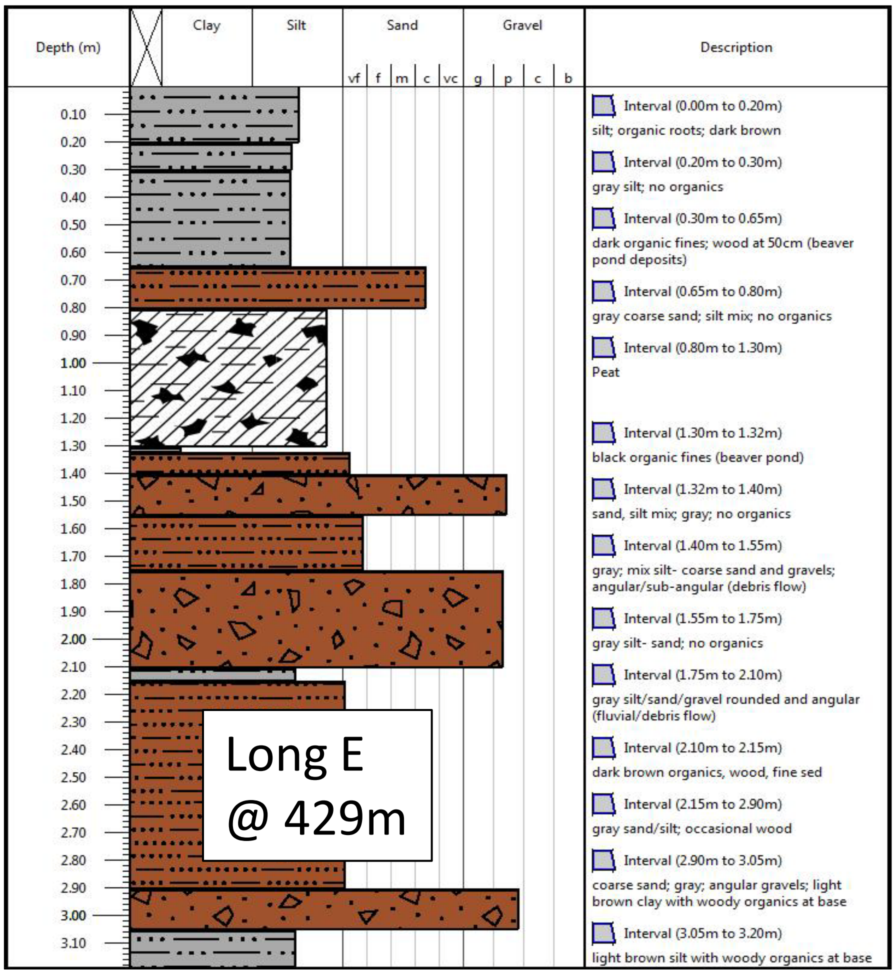

XS 5 @ 37 m
Depth (m)
Clay
Silt
Sand
Gravel
vf f m c vc g p c b
Description
0.10 0.20 0.30 0.40
Interval (0.00m to 0.50m)
dark brown organic; peat with fines; too soft/ loose below

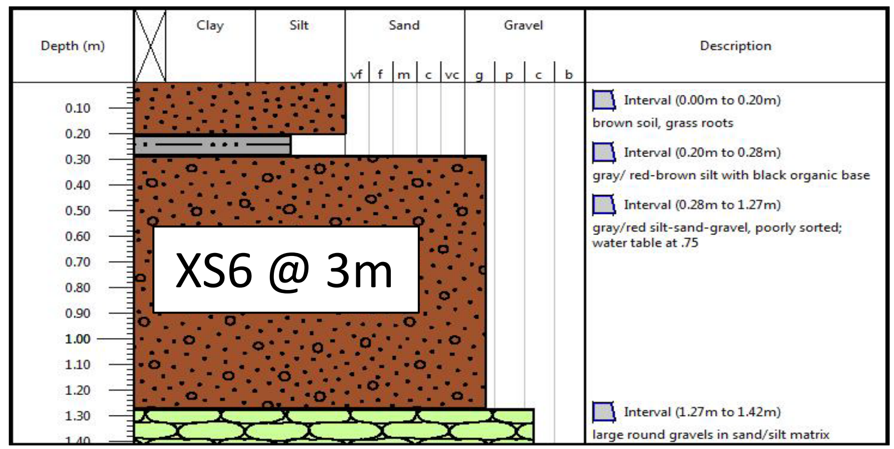
XS 6



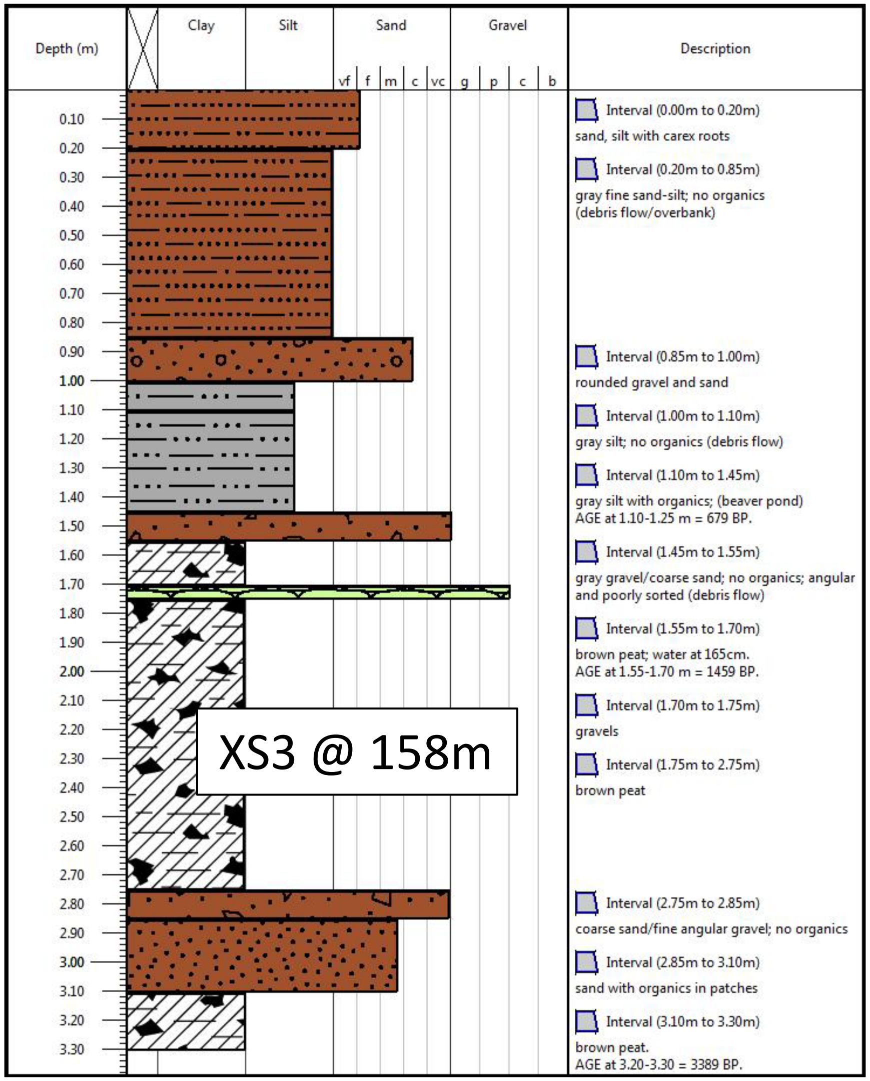
Depth (m)
Clay
Silt
Sand
vf
f
m
c
vc
Gravel
g
p
c
b
Description
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
1.00
1.10
1.20
1.30
1.40
Interval (0.00m to 0.20m)
brown soil, grass roots
Interval (0.20m to 0.28m)
gray/ red-brown silt with black organic base
Interval (0.28m to 1.27m)
gray/red silt-sand-gravel, poorly sorted;
water table at .75
Interval (1.27m to 1.42m)
large round gravels in sand/silt matrix
XS6 @ 3m

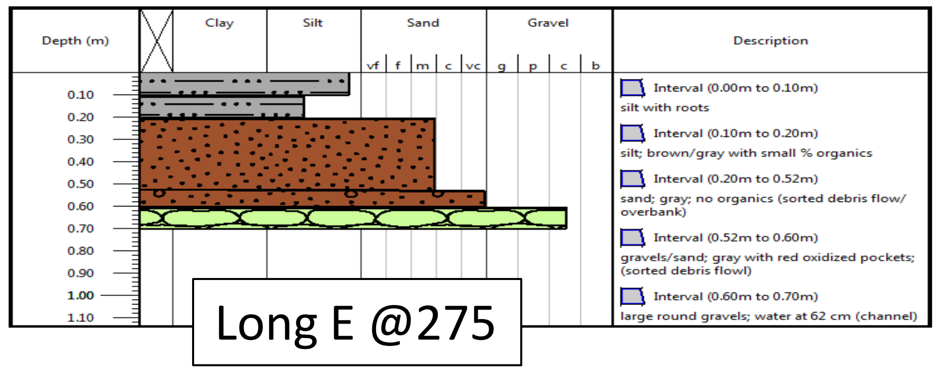
Long E


Depth (m)
Clay
Silt
Sand
Gravel
vf f m c vc g p c b
Description
0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90 1.00 1.10 1.20 1.30 1.40 1.50 1.60 1.70 1.80 1.90 2.00 2.10 2.20 2.30 2.40 2.50 2.60 2.70 2.80 2.90 3.00 3.10
Interval (0.00m to 0.20m)
silt; organic roots; dark brown
Interval (0.20m to 0.30m)
gray silt; no organics
Interval (0.30m to 0.65m)
dark organic fines; wood at 50cm (beaver pond deposits)
Interval (0.65m to 0.80m)
gray coarse sand; silt mix; no organics
Interval (0.80m to 1.30m)
Peat
Interval (1.30m to 1.32m)
black organic fines (beaver pond)
Interval (1.32m to 1.40m)
sand, silt mix; gray; no organics
Interval (1.40m to 1.55m)
gray; mix silt- coarse sand and gravels; angular/sub-angular (debris flow)
Interval (1.55m to 1.75m)
gray silt- sand; no organics
Interval (1.75m to 2.10m)
gray silt/sand/gravel rounded and angular (fluvial/debris flow)
Interval (2.10m to 2.15m)
dark brown organics, wood, fine sed
Interval (2.15m to 2.90m)
gray sand/silt; occasional wood
Interval (2.90m to 3.05m)
coarse sand; gray; angular gravels; light brown clay with woody organics at base
Interval (3.05m to 3.20m)
light brown silt with woody organics at base
Long E @ 429m

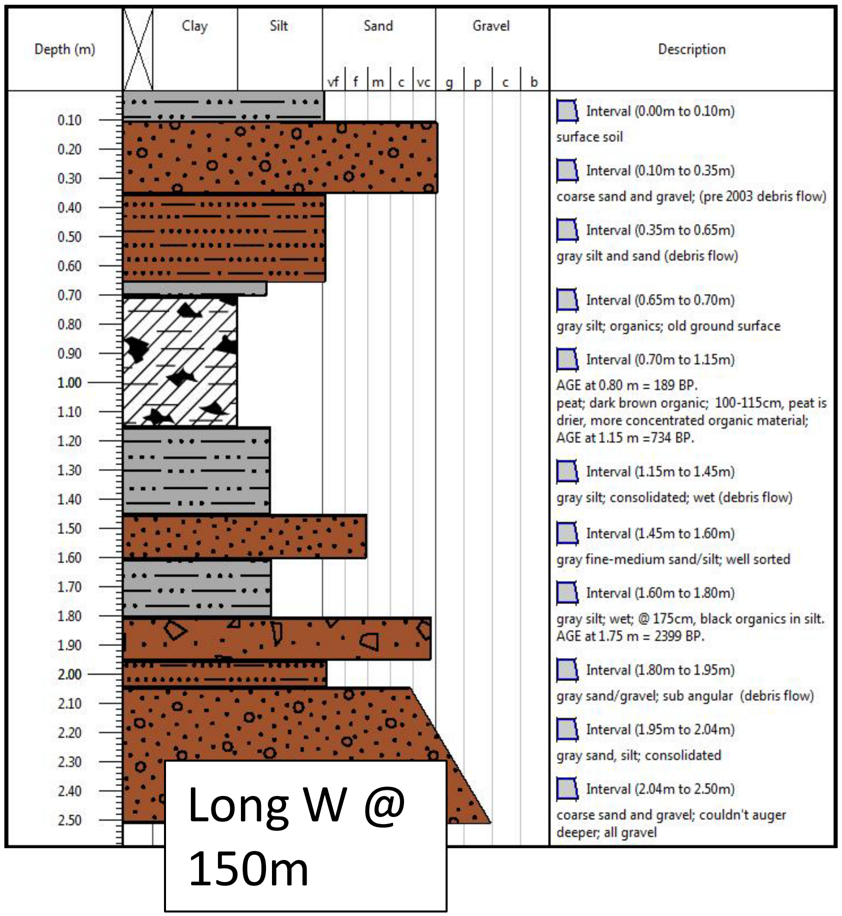

Depth (m)
Clay
Silt
Sand
Gravel
vf f m c vc g p c b
Description
0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90 1.00 1.10 1.20 1.30
Interval (0.00m to 0.20m)
brown soil, grass roots
Interval (0.20m to 0.28m)
gray/ red-brown silt with black organic base
Interval (0.28m to 1.27m)
gray/red silt-sand-gravel, poorly sorted; water table at .75
Interval (1.27m to 1.42m)
large round gravels in sand/silt matrix
XS6 @ 3m

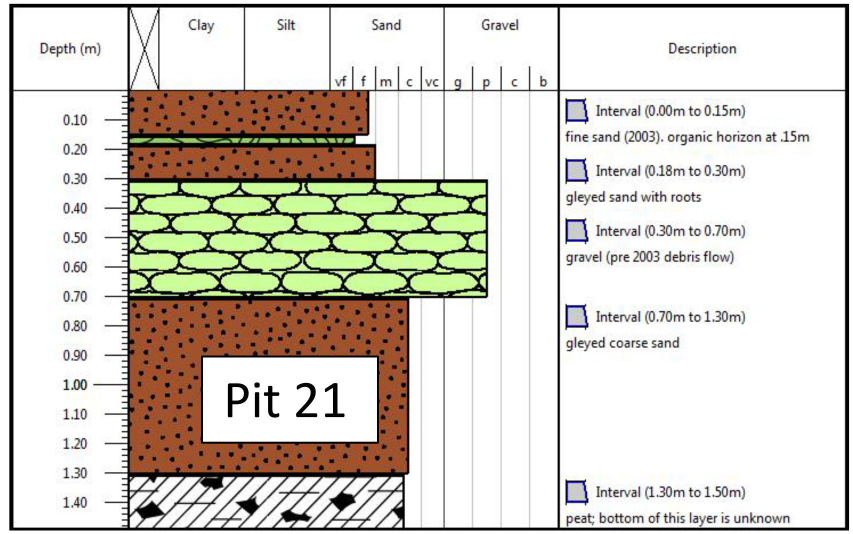
Long E

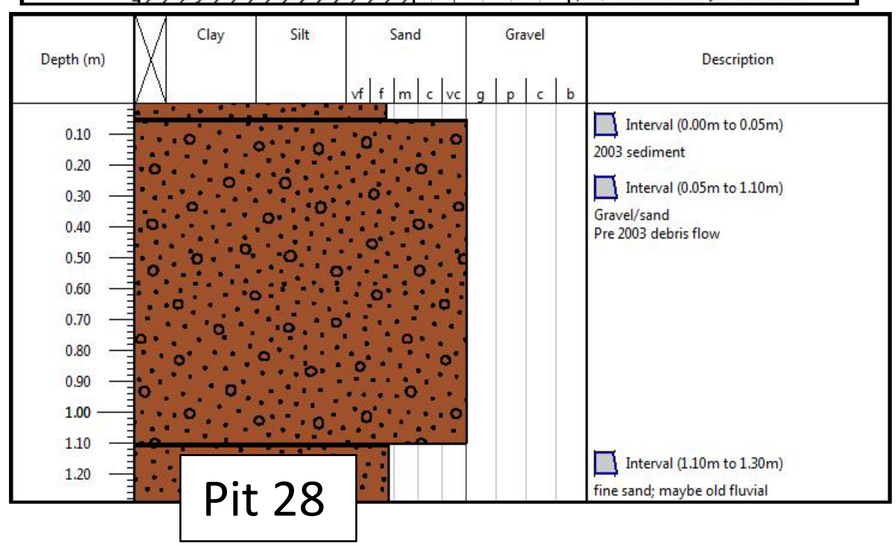

XS3 @ 158m
Depth (m)
Clay
Silt
Sand
vf f m c vc
Gravel
g p c b
Description
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
1.00
1.10
1.20
1.30
1.40
1.50
1.60
1.70
1.80
1.90
2.00
2.10
2.20
2.30
2.40
2.50
2.60
2.70
2.80
2.90
3.00
3.10
3.20
3.30
Interval (0.00m to 0.20m)
sand, silt with carex roots
Interval (0.20m to 0.85m)
gray fine sand-silt; no organics (debris flow/overbank)
Interval (0.85m to 1.00m)
rounded gravel and sand
Interval (1.00m to 1.10m)
gray silt; no organics (debris flow)
Interval (1.10m to 1.45m)
gray silt with organics; (beaver pond) AGE at 1.10-1.25 m = 679 BP.
Interval (1.45m to 1.55m)
gray gravel/coarse sand; no organics; angular and poorly sorted (debris flow)
Interval (1.55m to 1.70m)
brown peat; water at 165cm. AGE at 1.55-1.70 m = 1459 BP.
Interval (1.70m to 1.75m)
gravels
Interval (1.75m to 2.75m)
brown peat
Interval (2.75m to 2.85m)
coarse sand/fine angular gravel; no organics
Interval (2.85m to 3.10m)
sand with organics in patches
Interval (3.10m to 3.30m)
brown peat. AGE at 3.20-3.30 = 3389 BP.


Long E @275
Depth (m)
Clay
Silt
Sand
vf f m c vc
Gravel
g p c b
Description
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
1.00
1.10
Interval (0.00m to 0.10m)
silt with roots
Interval (0.10m to 0.20m)
silt; brown/gray with small % organics
Interval (0.20m to 0.52m)
sand; gray; no organics (sorted debris flow/ overbank)
Interval (0.52m to 0.60m)
gravels/sand; gray with red oxidized pockets; (sorted debris flowl)
Interval (0.60m to 0.70m)
large round gravels; water at 62 cm (channel)

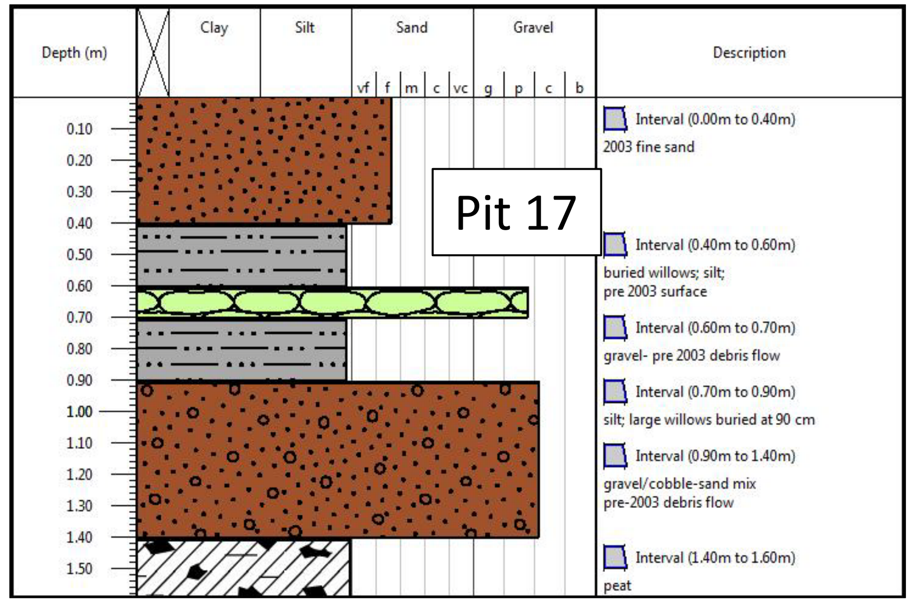
Long W


Depth (m)
Clay
Silt
Sand
vf f m c vc
Gravel
g p c b
Description
0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90 1.00 1.10 1.20 1.30 1.40 1.50 1.60 1.70 1.80 1.90 2.00 2.10 2.20 2.30 2.40 2.50
Interval (0.00m to 0.10m)
surface soil
Interval (0.10m to 0.35m)
coarse sand and gravel; (pre 2003 debris flow)
Interval (0.35m to 0.65m)
gray silt and sand (debris flow)
Interval (0.65m to 0.70m)
gray silt; organics; old ground surface
Interval (0.70m to 1.15m)
AGE at 0.80 m = 189 BP.
peat; dark brown organic; 100-115cm, peat is drier, more concentrated organic material;
AGE at 1.15 m =734 BP.
Interval (1.15m to 1.45m)
gray silt; consolidated; wet (debris flow)
Interval (1.45m to 1.60m)
gray fine-medium sand/silt; well sorted
Interval (1.60m to 1.80m)
gray silt; wet; @ 175cm, black organics in silt.
AGE at 1.75 m = 2399 BP.
Interval (1.80m to 1.95m)
gray sand/gravel; sub angular (debris flow)
Interval (1.95m to 2.04m)
gray sand, silt; consolidated
Interval (2.04m to 2.50m)
coarse sand and gravel; couldn't auger deeper; all gravel
Long W @ 150m

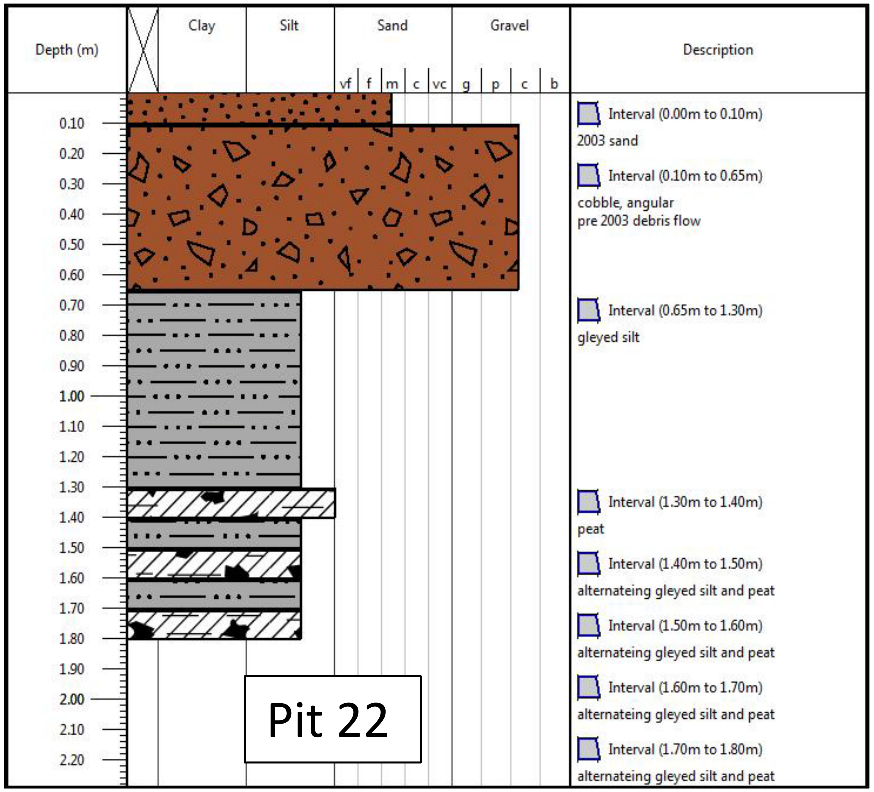

Depth (m)
Clay
Silt
Sand
vf f m c vc
Gravel
g p c b
Description
0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90 1.00 1.10 1.20 1.30 1.40
Interval (0.00m to 0.15m)
fine sand (2003). organic horizon at .15m
Interval (0.18m to 0.30m)
gleyed sand with roots
Interval (0.30m to 0.70m)
gravel (pre 2003 debris flow)
Interval (0.70m to 1.30m)
gleyed coarse sand
Interval (1.30m to 1.50m)
peat; bottom of this layer is unknown
Pit 21


Depth (m)
Clay
Silt
Sand
vf f m c vc
Gravel
g p c b
Description
0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90 1.00 1.10 1.20
Interval (0.00m to 0.05m)
2003 sediment
Interval (0.05m to 1.10m)
Gravel/sand
Pre 2003 debris flow
Interval (1.10m to 1.30m)
fine sand; maybe old fluvial
Pit 28

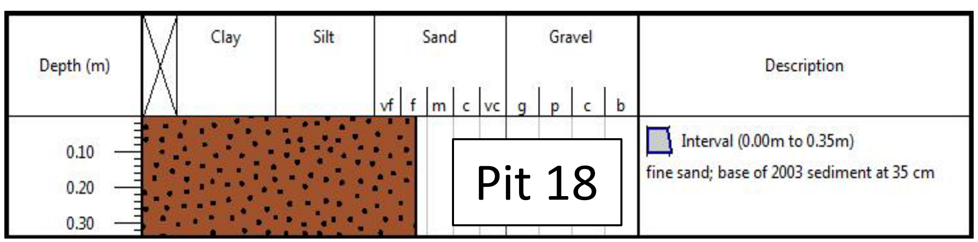
Long W



Pit 17
Depth (m)
Clay
Silt
Sand
Gravel
vf f m c vc g p c b
Description
0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90 1.00 1.10 1.20 1.30 1.40 1.50
Interval (0.00m to 0.40m)
2003 fine sand
Interval (0.40m to 0.60m)
buried willows; silt;
pre 2003 surface
Interval (0.60m to 0.70m)
gravel- pre 2003 debris flow
Interval (0.70m to 0.90m)
silt; large willows buried at 90 cm
Interval (0.90m to 1.40m)
gravel/cobble-sand mix
pre-2003 debris flow
Interval (1.40m to 1.60m)
peat

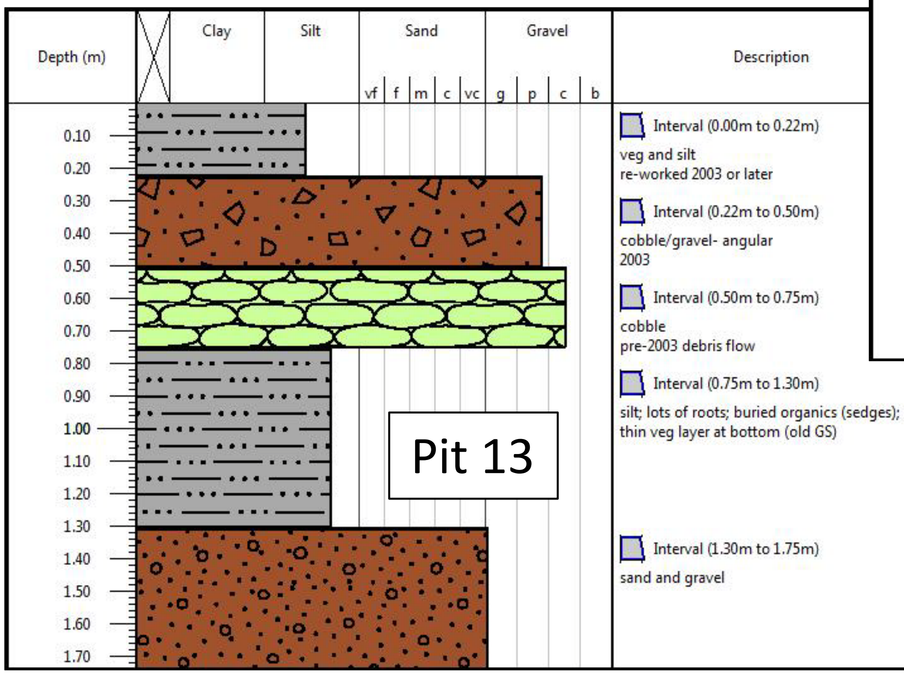


Pit 22
Depth (m)
Clay
Silt
Sand
Gravel
vf f m c vc g p c b
Description
0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90 1.00 1.10 1.20 1.30 1.40 1.50 1.60 1.70 1.80 1.90 2.00 2.10 2.20
Interval (0.00m to 0.10m)
2003 sand
Interval (0.10m to 0.65m)
cobble, angular
pre 2003 debris flow
Interval (0.65m to 1.30m)
gleyed silt
Interval (1.30m to 1.40m)
peat
Interval (1.40m to 1.50m)
alternateing gleyed silt and peat
Interval (1.50m to 1.60m)
alternateing gleyed silt and peat
Interval (1.60m to 1.70m)
alternateing gleyed silt and peat
Interval (1.70m to 1.80m)
alternateing gleyed silt and peat

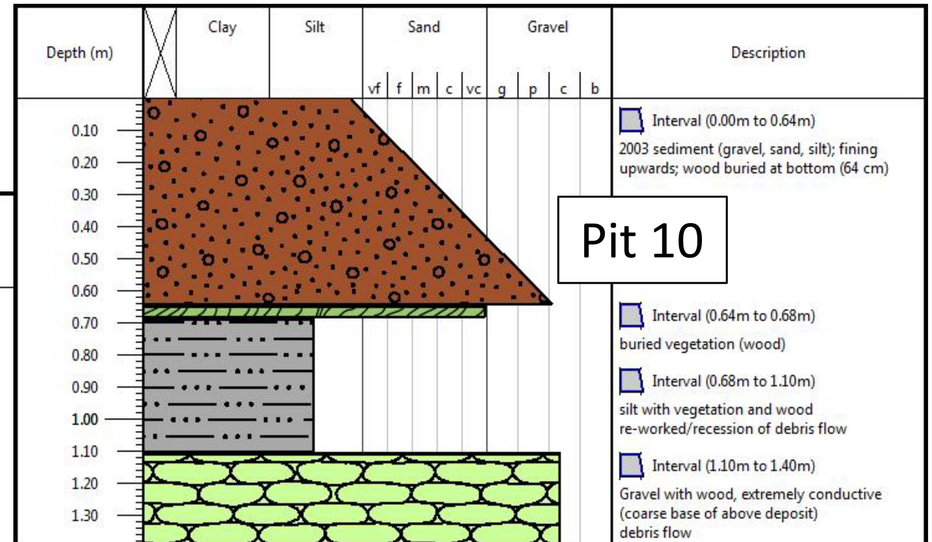


Pit 18
Depth (m)
Clay
Silt
Sand
Gravel
vf f m c vc g p c b
Description
0.10 0.20 0.30
Interval (0.00m to 0.35m)
fine sand; base of 2003 sediment at 35 cm

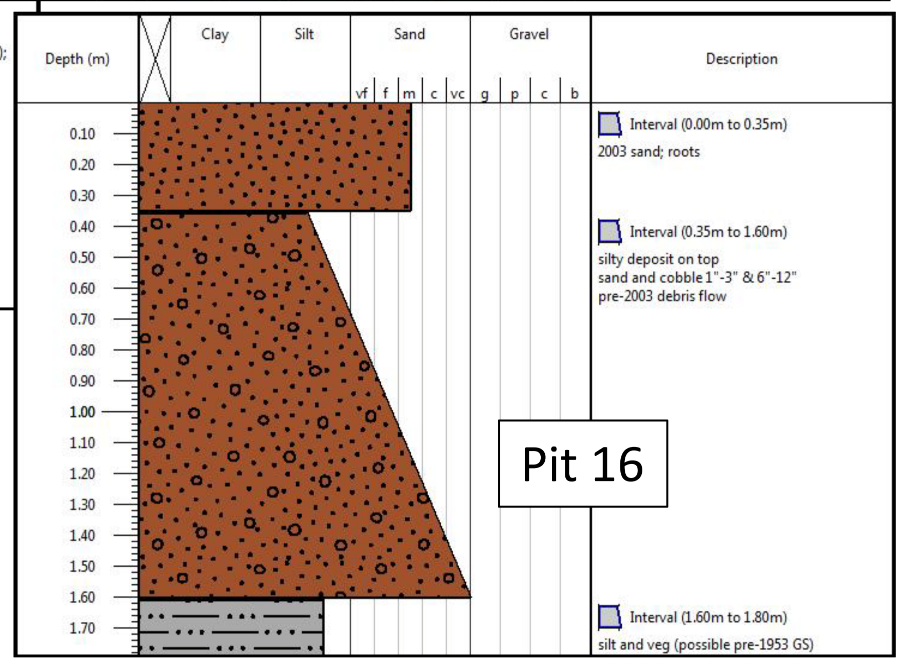
Long W



Pit 13
Depth (m)
Clay
Silt
Sand
Gravel
vf f m c vc g p c b
Description
0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90 1.00 1.10 1.20 1.30 1.40 1.50 1.60 1.70
Interval (0.00m to 0.22m)
veg and silt
re-worked 2003 or later
Interval (0.22m to 0.50m)
cobble/gravel- angular
2003
Interval (0.50m to 0.75m)
cobble
pre-2003 debris flow
Interval (0.75m to 1.30m)
silt; lots of roots; buried organics (sedges);
thin veg layer at bottom (old GS)
Interval (1.30m to 1.75m)
sand and gravel

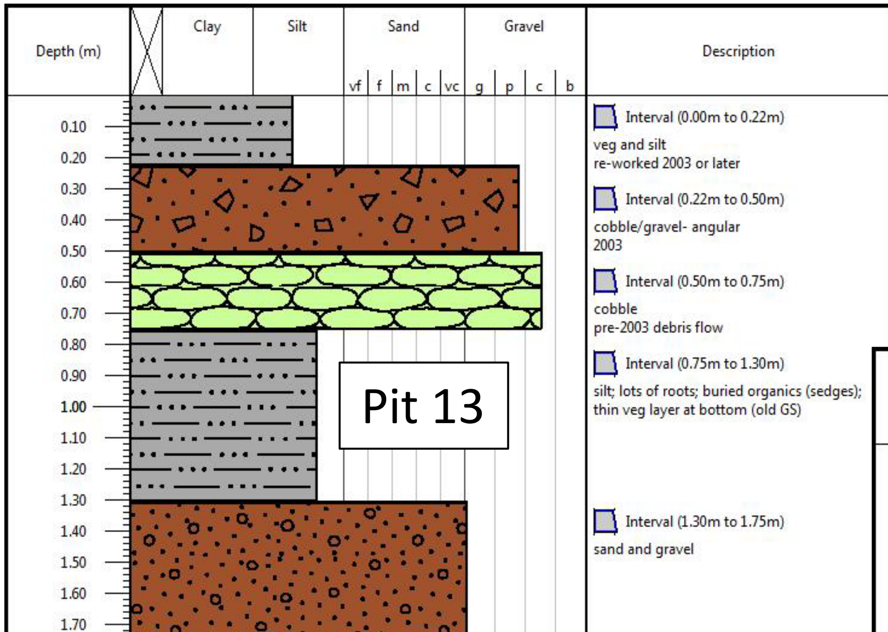


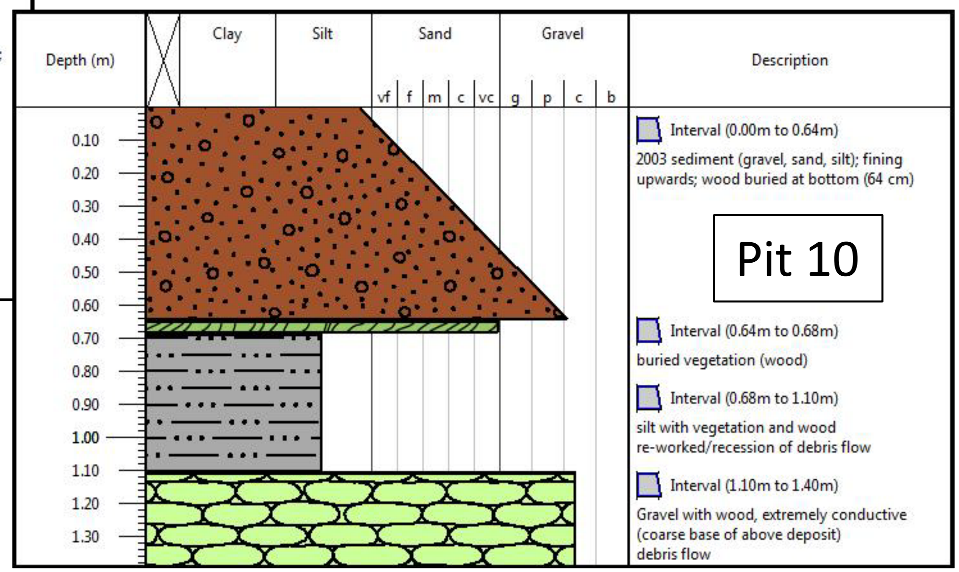
Pit 10
Depth (m)
Clay
Silt
Sand
Gravel
vf f m c vc g p c b
Description
0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90 1.00 1.10 1.20 1.30
Interval (0.00m to 0.64m)
2003 sediment (gravel, sand, silt); fining
upwards; wood buried at bottom (64 cm)
Interval (0.64m to 0.68m)
buried vegetation (wood)
Interval (0.68m to 1.10m)
silt with vegetation and wood
re-worked/recession of debris flow
Interval (1.10m to 1.40m)
Gravel with wood, extremely conductive
(coarse base of above deposit)
debris flow



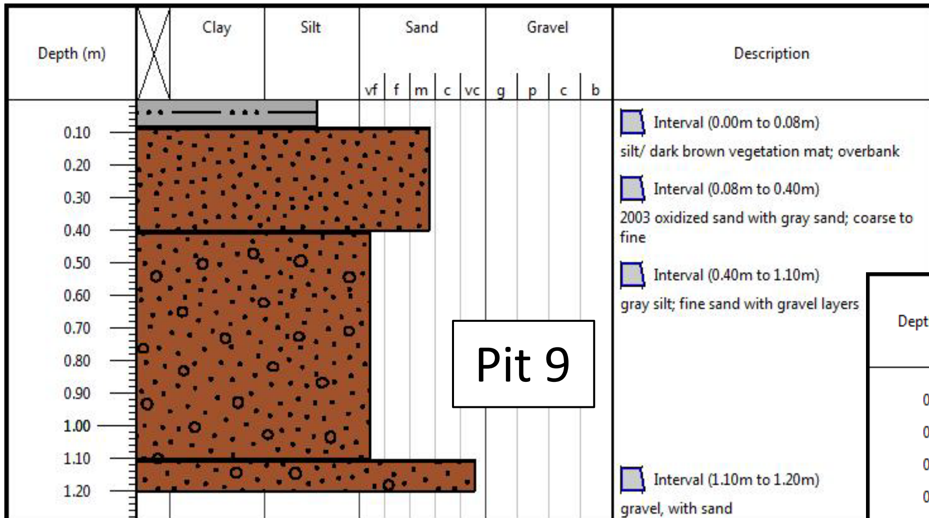
Pit 16
Depth (m)
Clay
Silt
Sand
Gravel
vf f m c vc g p c b
Description
0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90 1.00 1.10 1.20 1.30 1.40 1.50 1.60 1.70
Interval (0.00m to 0.35m)
2003 sand; roots
Interval (0.35m to 1.60m)
silty deposit on top
sand and cobble 1"-3" & 6"-12"
pre-2003 debris flow
Interval (1.60m to 1.80m)
silt and veg (possible pre-1953 GS)

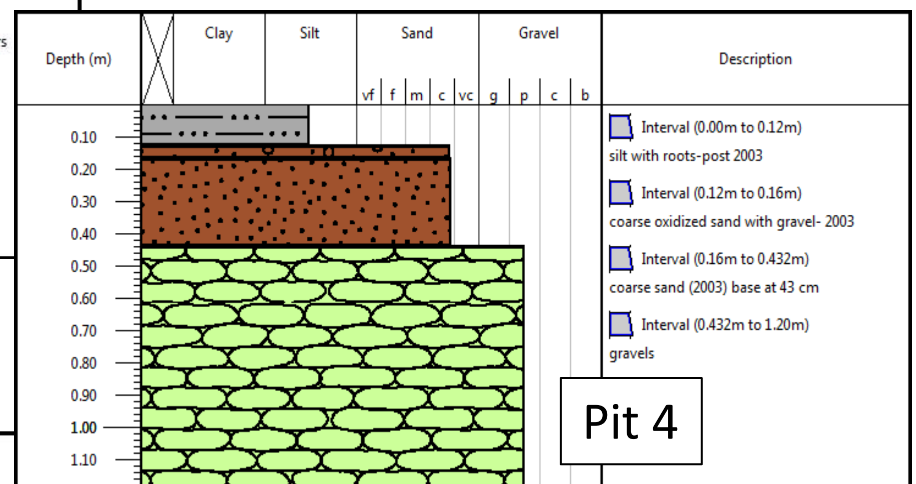
Long W 200 MHz

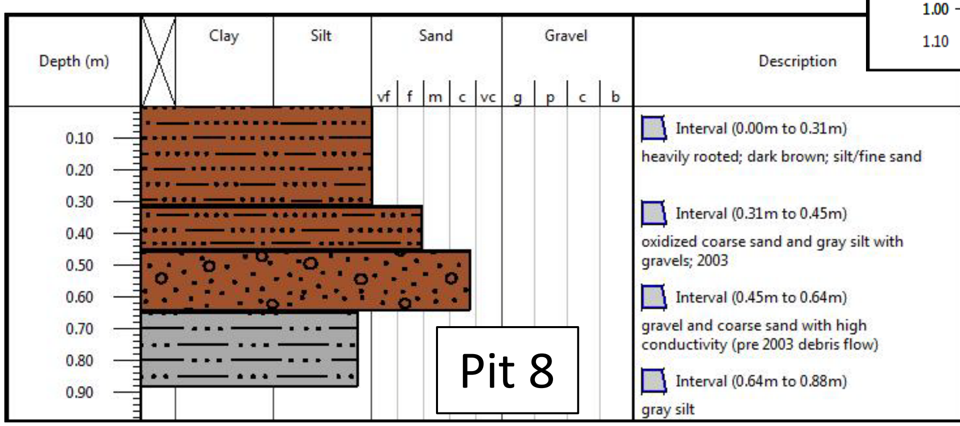




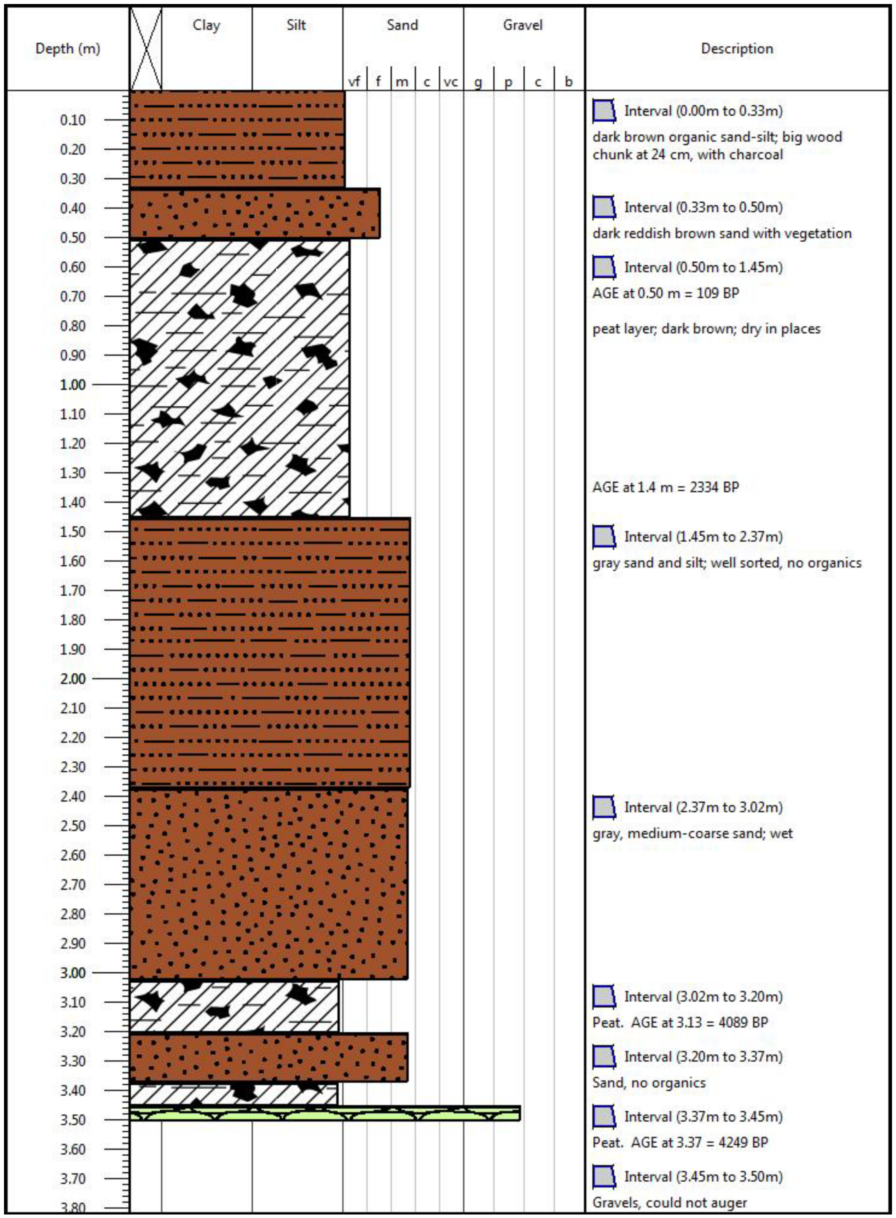
Long W 200 MHz





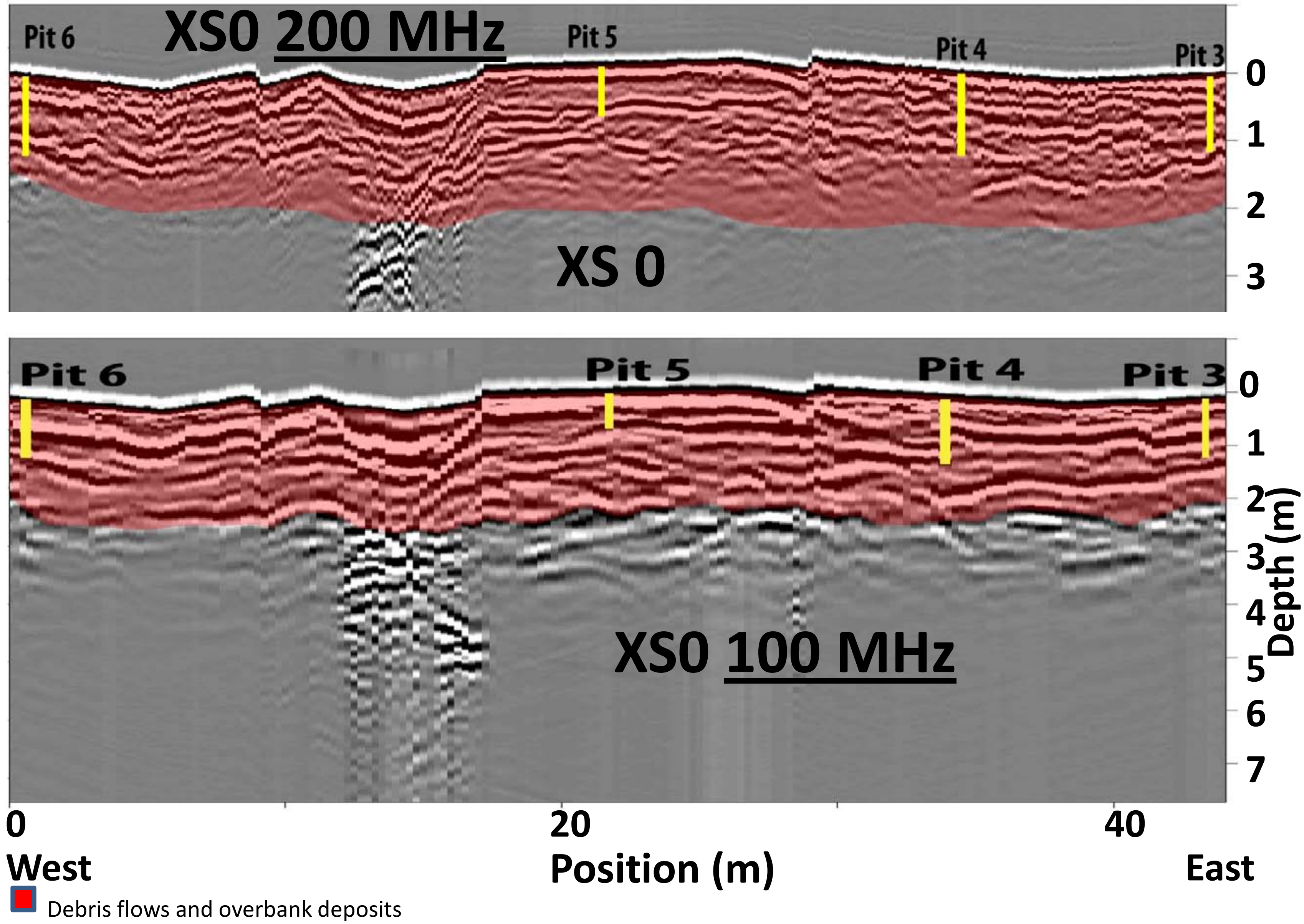


SW Hole

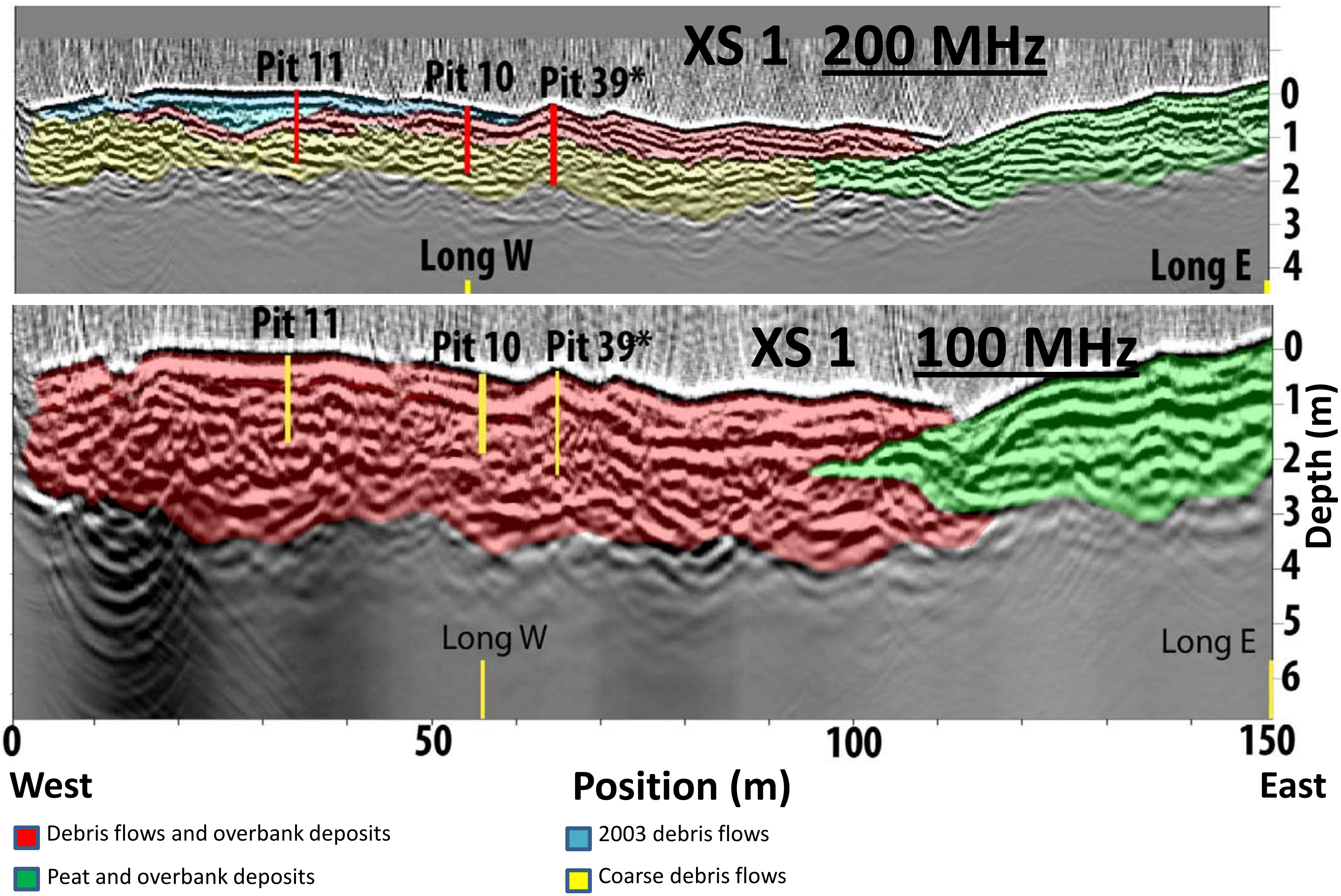

Depth (m)
Clay
Silt
Sand
vf f m c vc
Gravel
g p c b
Description
0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90 1.00 1.10 1.20 1.30 1.40 1.50 1.60 1.70 1.80 1.90 2.00 2.10 2.20 2.30 2.40 2.50 2.60 2.70 2.80 2.90 3.00 3.10 3.20 3.30 3.40 3.50 3.60 3.70 3.80
Interval (0.00m to 0.33m)
dark brown organic sand-silt; big wood chunk at 24 cm, with charcoal
Interval (0.33m to 0.50m)
dark reddish brown sand with vegetation
Interval (0.50m to 1.45m)
AGE at 0.50 m = 109 BP
peat layer; dark brown; dry in places
AGE at 1.4 m = 2334 BP
Interval (1.45m to 2.37m)
gray sand and silt; well sorted, no organics
Interval (2.37m to 3.02m)
gray, medium-coarse sand; wet
Interval (3.02m to 3.20m)
Peat. AGE at 3.13 = 4089 BP
Interval (3.20m to 3.37m)
Sand, no organics
Interval (3.37m to 3.45m)
Peat. AGE at 3.37 = 4249 BP
Interval (3.45m to 3.50m)
Gravels, could not auger

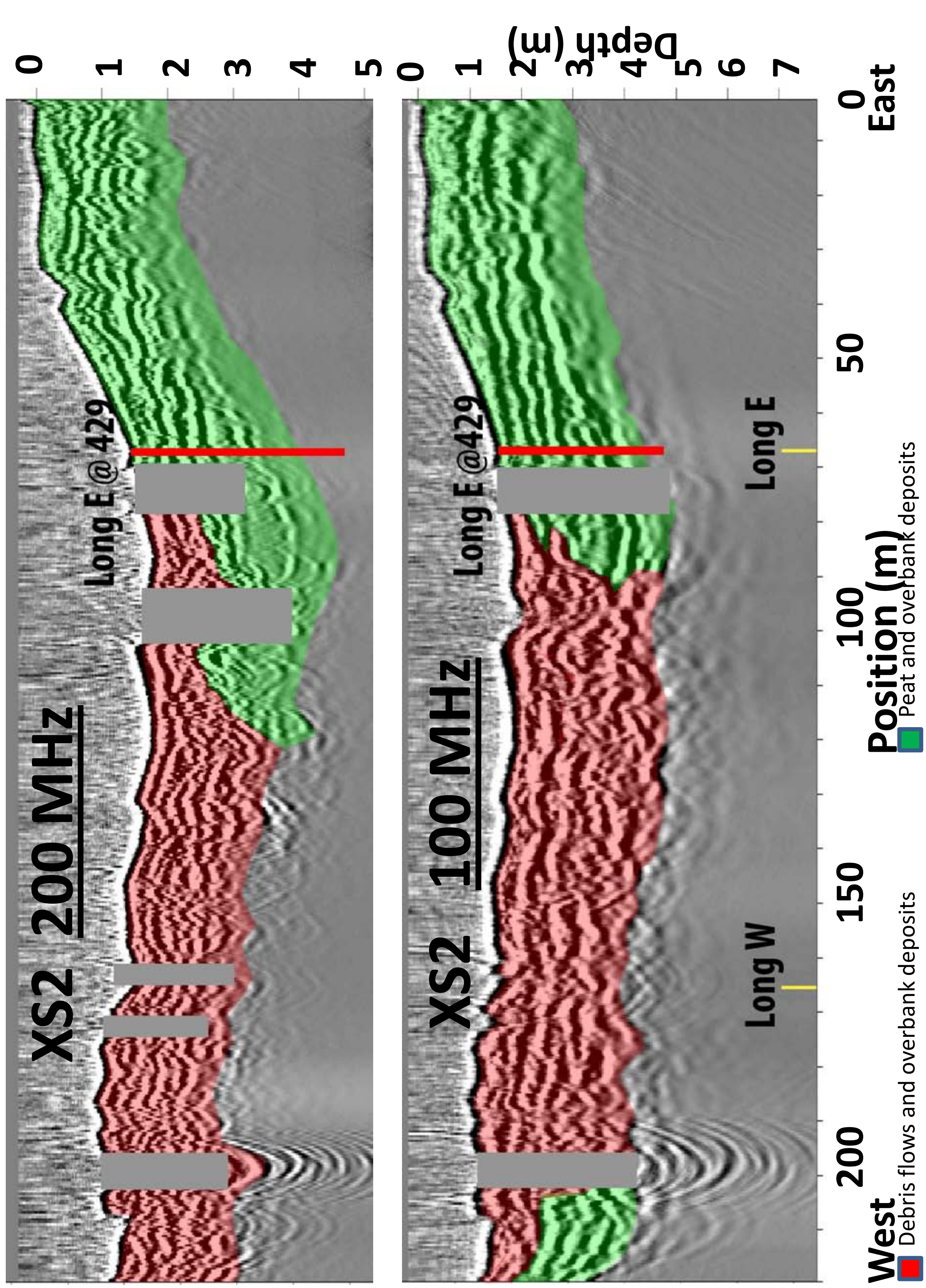
Appendix C

Ground Penetrating Radar Transects



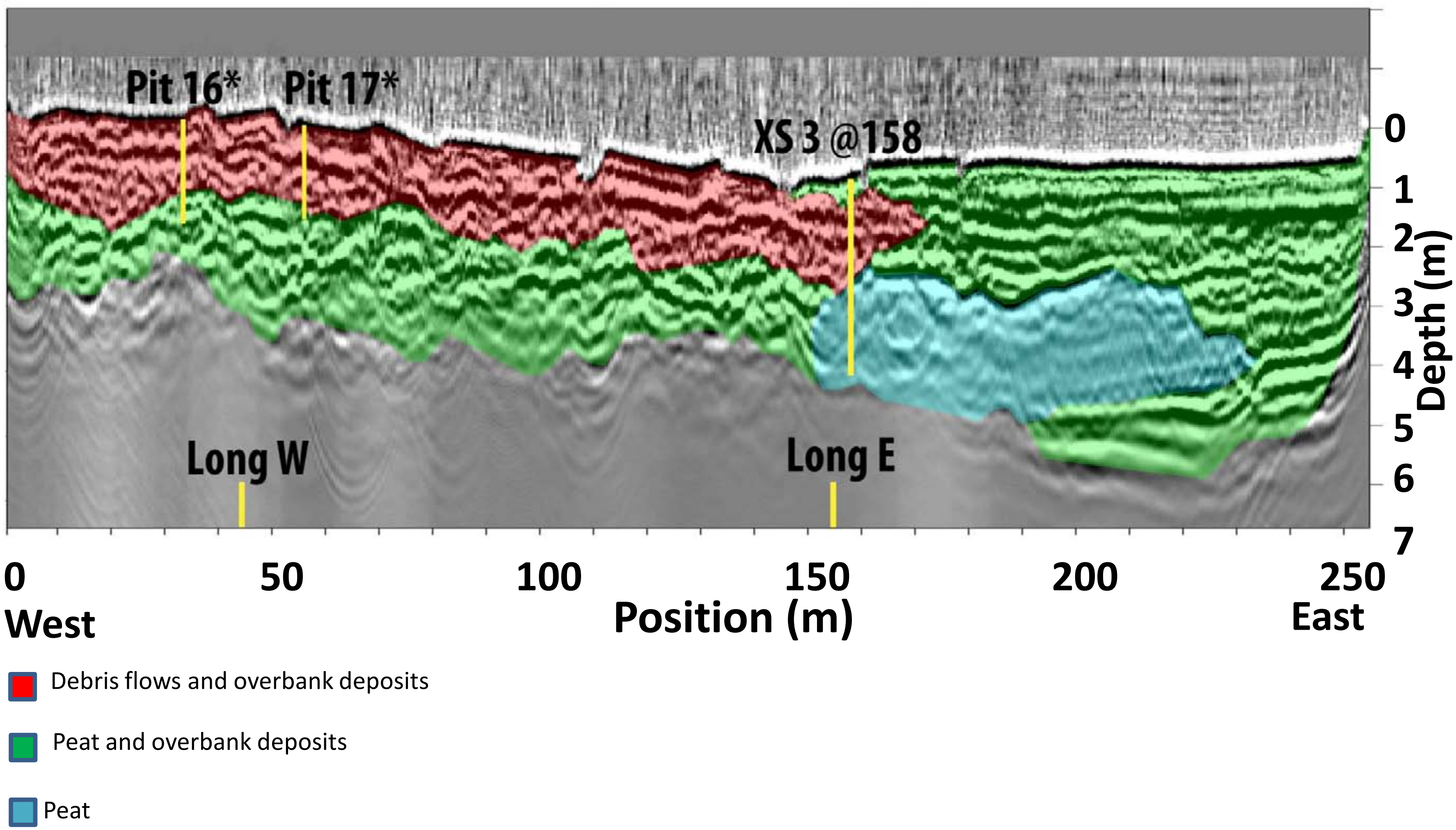
XS0 200 MHz
Pit 6
Pit 5
Pit 4
Pit 3
XS 0
0
1
2
3
Pit 6
Pit 5
Pit 4
Pit 3
XS0 100 MHz
Depth (m)
0
1
2
3
4
5
6
7
0
20
40
West
Position (m)
East
Debris flows and overbank deposits


XS 1 200 MHz
Pit 11
Pit 10
Pit 39*
Long W
Long E
0
1
2
3
4
XS 1 100 MHz
Pit 11
Pit 10
Pit 39*
Long W
Long E
0
1
2
3
4
5
6
Depth (m)
0
50
100
150
West
Position (m)
East
Debris flows and overbank deposits
Peat and overbank deposits
2003 debris flows
Coarse debris flows

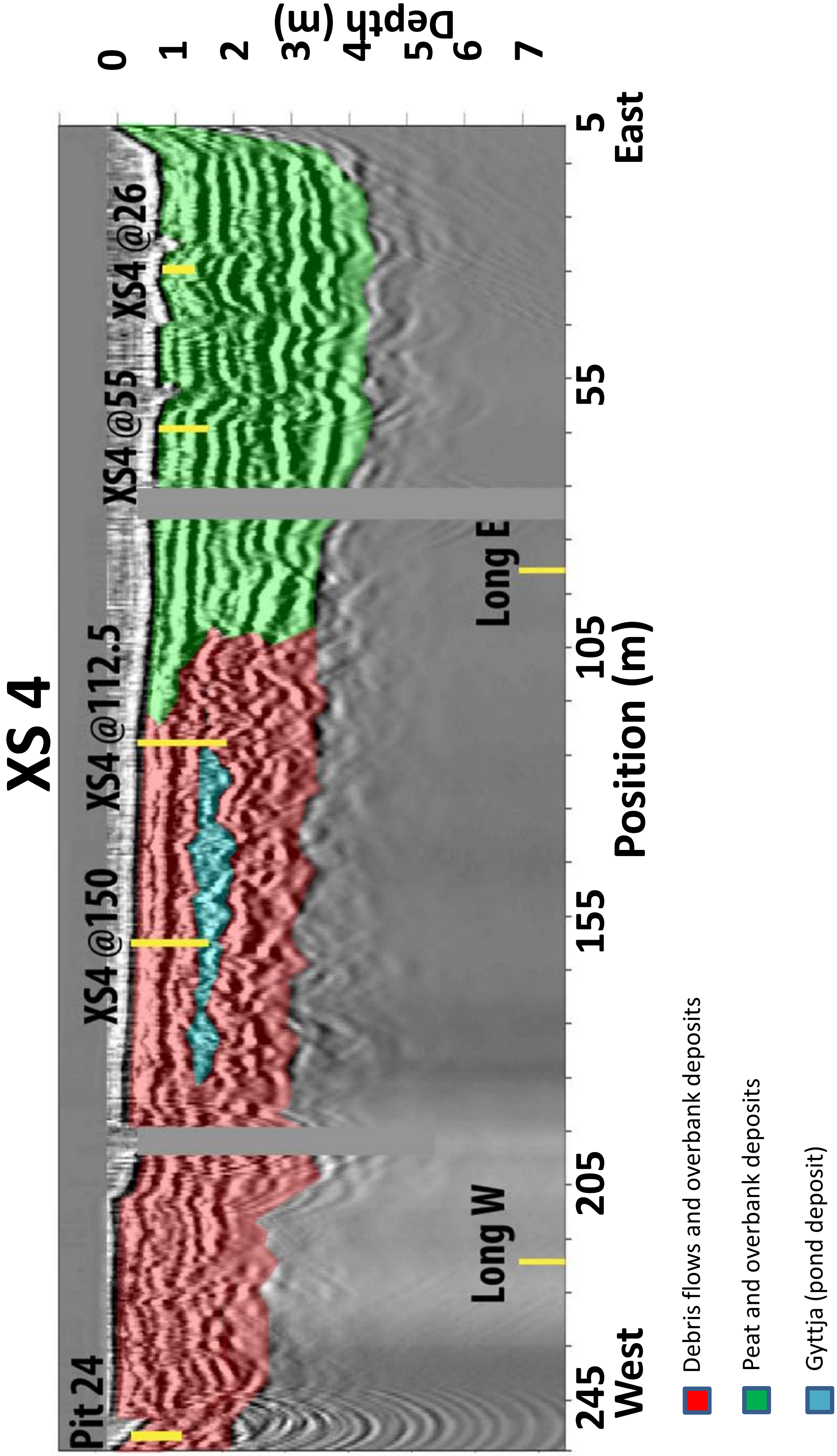


XS2 200 MHz
XS2 100 MHz
Long E @429
Long E @429
Long W
Long E
Depth (m)
Position (m)
West
East
Debris flows and overbank deposits
Peat and overbank deposits

XS 3

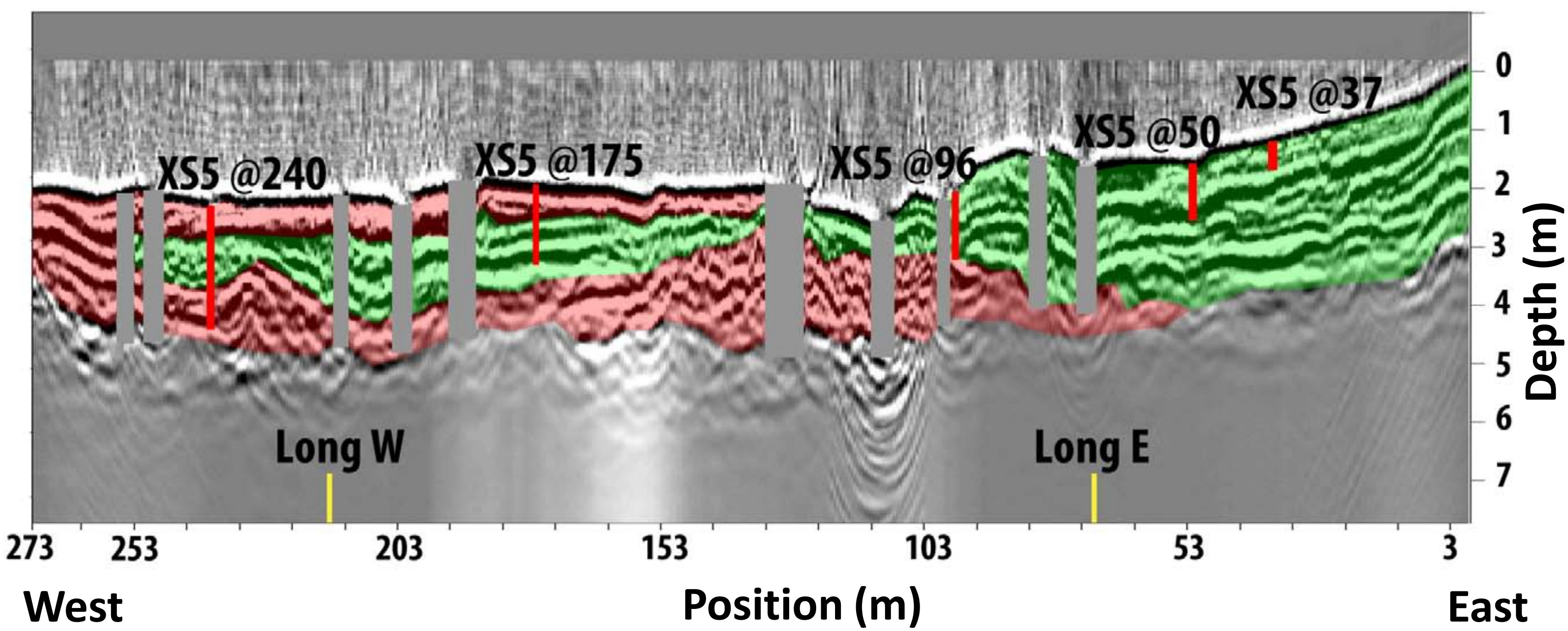


Pit 16*
Pit 17*
XS 3 @158
Long W
Long E
0
1
2
3
4
5
6
7
Depth (m)
0
50
100
150
200
250
West
Position (m)
East
Debris flows and overbank deposits
Peat and overbank deposits
Peat



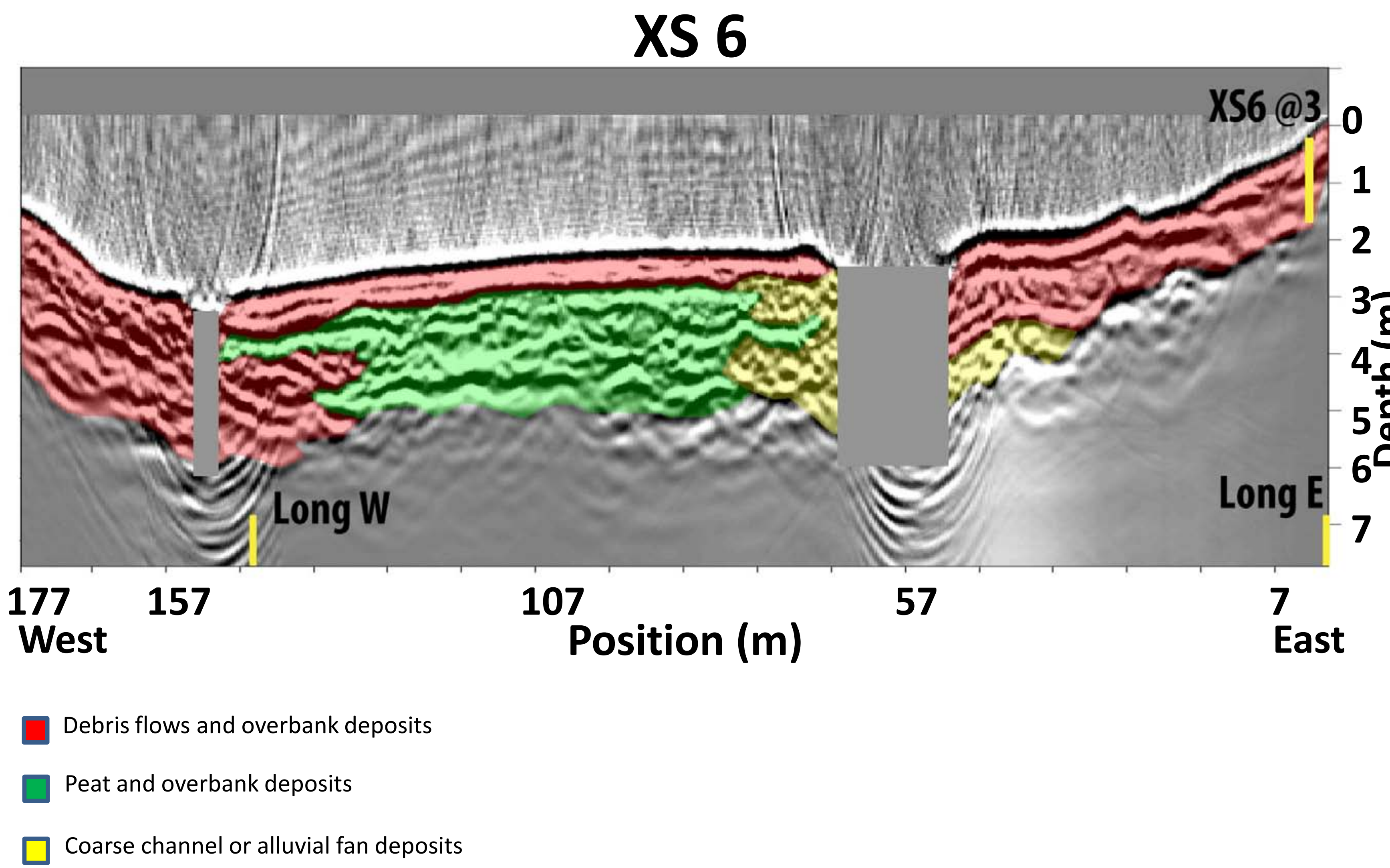
XS 4
Depth (m)
0
1
2
3
4
5
6
7
Position (m)
West
East
245
205
155
105
55
5
Pit 24
XS4 @150
XS4 @112.5
XS4 @55
XS4 @26
Long W
Long E
Debris flows and overbank deposits
Peat and overbank deposits
Gyttja (pond deposit)

XS 5

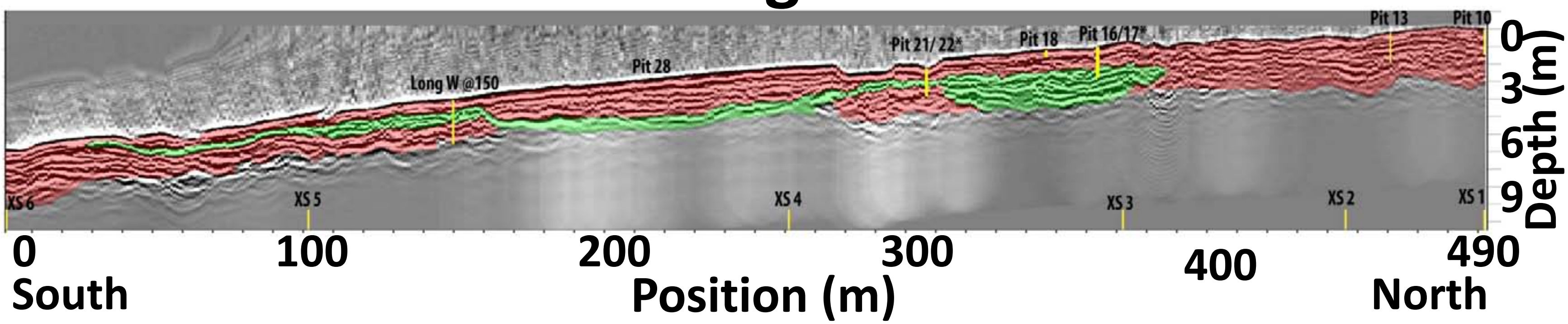


Debris flows and overbank deposits

Peat and overbank deposits

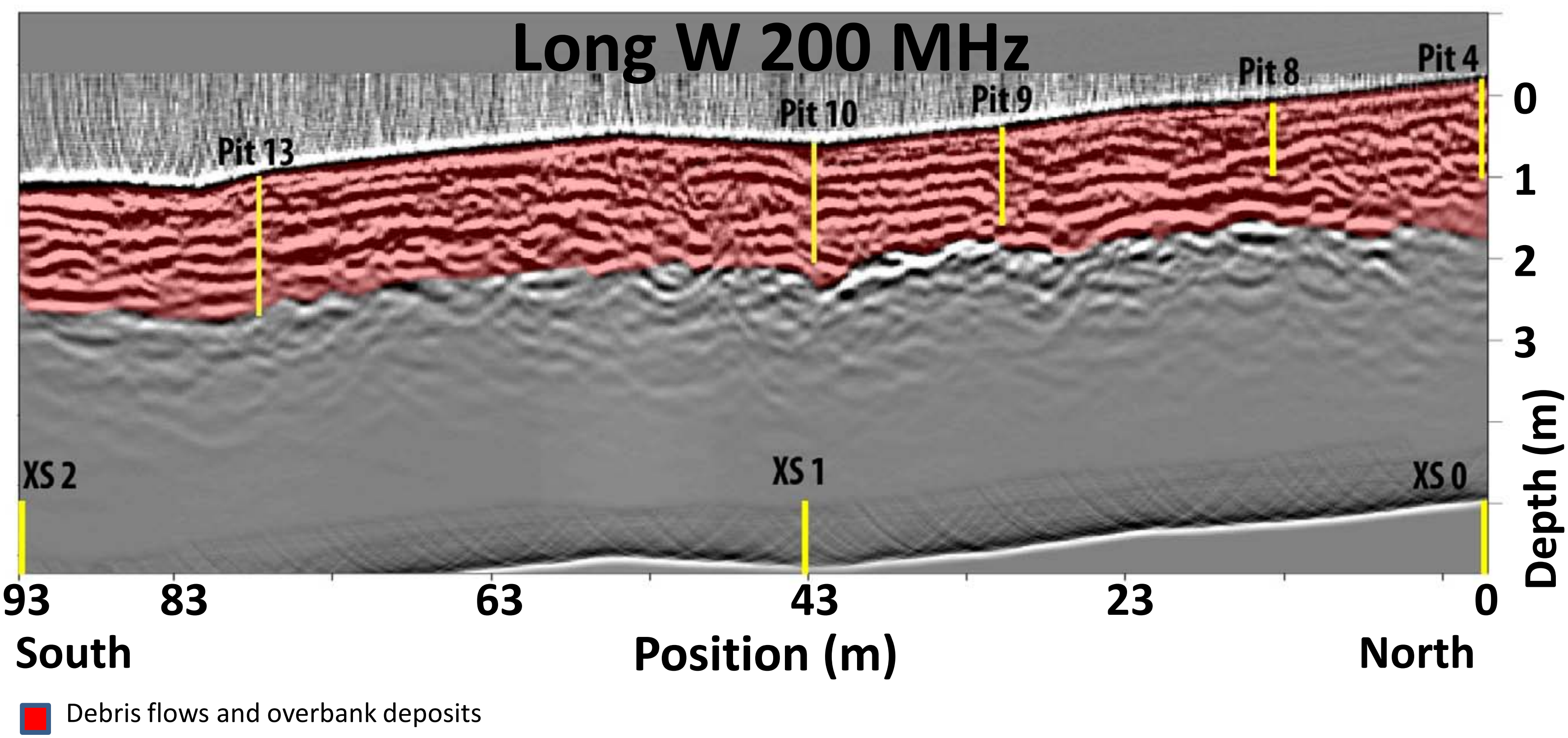

XS 6
XS6 @3
Long W
Long E
0
1
2
3
4
5
6
7
Depth (m)
177
157
107
57
7
West
East
Position (m)
Debris flows and overbank deposits
Peat and overbank deposits
Coarse channel or alluvial fan deposits

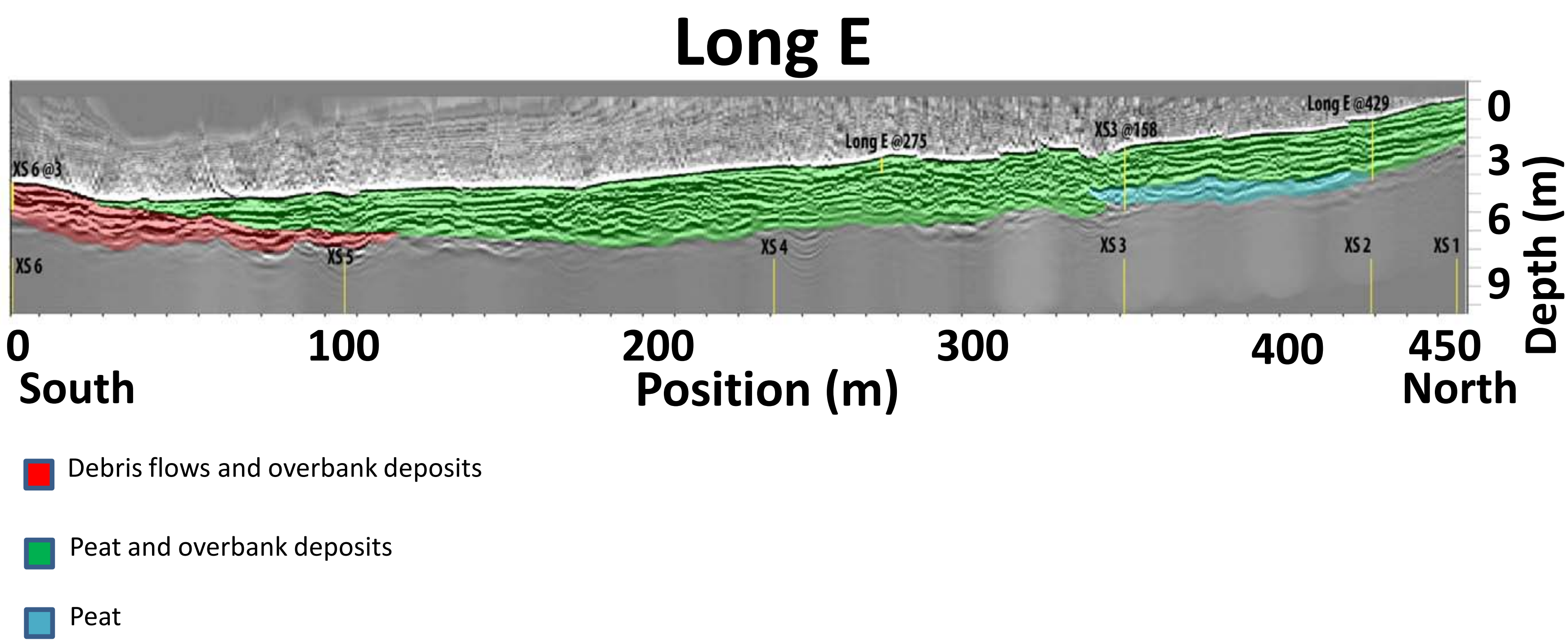
Long W



Debris flows and overbank deposits

Peat and overbank deposits


Long W 200 MHz
Pit 13
Pit 10
Pit 9
Pit 8
Pit 4
0
1
2
3
Depth (m)
XS 2
XS 1
XS 0
93
83
63
43
23
0
South
Position (m)
North
Debris flows and overbank deposits


Long E
XS 6 @3
Long E @275
XS3 @158
Long E @429
XS 6
XS 5
XS 4
XS 3
XS 2
XS 1
0
3
6
9
Depth (m)
0
100
200
300
400
450
South
Position (m)
North
Debris flows and overbank deposits
Peat and overbank deposits
Peat