Fluvial Geomorphology Assessment of the Lower Winooski River, Vermont

Prepared for

Winooski Valley Park District
Burlington, VT

Winooski Gorge (looking downstream)

Prepared by

Field Geology Services
Farmington, ME

August 2006

Table of Contents

List of Figures

List of Tables

List of Appendices

EXECUTIVE SUMMARY

A Phase 1 and Phase 2 geomorphic assessment of the lower Winooski River were completed in Summer 2005. The morphology of the six distinct reaches identified in the 21.7 miles downstream of Alder Brook reflects the geological and human conditions that continue to constrain the location and form of the channel. Winooski Gorge was carved approximately 10,000 years ago as the Champlain Sea drained from the valley and the river encountered rock fractures formed during the uplift of the Green Mountains hundreds of millions of years ago. While the reaches upstream and downstream of the gorge are alluvial channels with broad floodplains, their morphology are strongly influenced by the gorge. A convoluted meander with high sinuosity has developed upstream of the gorge due to a backwater, or ponding, effect that occurs at the entrance to the gorge during large floods. Downstream, a broad floodplain has been carved where the river exits the narrow gorge and encounters easily erodible deltaic sands deposited in the Champlain Sea. While the broad floodplain was likely carved contemporaneously with the gorge thousands of years ago, the reach remains sensitive to large floods as evidenced by the formation of a large, now forested, gravel bar formed during the 1927 flood. At Muddy Brook Park, one of several Winooski Valley Park District properties along the Winooski River, preferential erosion of sandy river banks compared to the bouldery channel substrate, has created a channel with a naturally high width:depth ratio, a result of variations in post-glacial sediments deposited thousands of years ago.

Human land use since European settlement of the region has exerted a strong influence on the existing channel conditions in the Intervale, a broad floodplain developed on what is possibly an old delta of Lake Champlain. The Winooski River in this area experienced minor incision and widening in response, potentially, to four different human impacts: 1) reductions in sediment load accompanying 20th Century reforestation of the watershed; 2) sediment storage behind dams; 3) removal of wood from the river channel; and 4) minor channel straightening. The channel incision and widening is evidenced by minor differences in floodplain elevations along the channel (i.e., low incision ratios), a decrease in channel migration rates during the 20th Century, and high width:depth ratios of the channel. Bank erosion and bank armoring along nearly 20 percent of the Intervale are in response to ongoing planform changes (i.e., changes in meandering patterns) as the river reestablishes an equilibrium condition following the incision and subsequent widening phase of the channel.

During times of greater channel migration and rapid shifts in channel position (i.e., channel avulsions), a complex patchwork of wetland habitats were likely present as old oxbows were in different stages of successional development depending on the length of time since abandonment from the main channel. Restoring the ecological diversity associated with these different habitats would require a return to more dynamic stream processes associated with greater sediment loads, larger flood flows, more wood in the channel, and frequent ice jams. Improved bank stability and habitat conditions will accompany the reestablishment of equilibrium conditions, a process that will likely take several decades or centuries to occur without intervention because upstream dams have reduced sediment loads and flood discharges. Riparian buffer restoration will lead to increased wood inputs over several decades, perhaps speeding the natural evolutionary development of an equilibrium condition and leading to more rapid improvements in bank stability. More aggressive restoration measures, such as the addition of engineered woody debris jams in the river, could lead to greater habitat diversity, decreases in sediment and nutrient delivery to Lake Champlain, and improved bank stability over a shorter time frame. However, potential risks associated with increased flooding and greater concentrations of wood in the channel will need to be carefully analyzed to alleviate landowner concerns prior to implementation.

1.0 INTRODUCTION

This report describes the results and recommendations of a fluvial geomorphology assessment of the lower Winooski River completed for the Winooski Valley Park District, which manages several parks along the river (Figures 1 and 2). The assessment covered the 21.7 miles downstream of Alder Brook, although the Winooski River extends much further upstream with a total watershed area of 1,063 mi^2 where it enters Lake Champlain in Burlington, Vermont. The geomorphic assessment provides an opportunity for the park district to better manage bank erosion problems along the river while educating the public about riverine processes and the geological history of the Winooski Valley. Towards this end, the purpose of this geomorphology assessment was four fold: 1) complete a Phase 1 assessment of the Winooski River between Lake Champlain and Alder Brook; 2) complete a Phase 2 assessment of four reaches representative of conditions on the river; 3) provide recommendations on restoring channel stability and aquatic habitat based on the results of the Phase 1 and Phase 2 assessment; and 4) develop six interpretive signs to be located at various parks along the river.

Recognizing the value of fluvial geomorphology to improve bank stability and reduce sediment production, the State of Vermont has developed a three phase Stream Geomorphic Assessment Handbook to reveal the underlying causes for erosion and channel instability (Vermont Agency of Natural Resources, 2006). The assessment of the lower Winooski River employed the first two phases of the handbook. Phase 1 of Vermont's Stream Geomorphic Assessment Handbook utilizes topographic maps, aerial photographs, and archival records to characterize natural conditions and human land uses in the watershed. Topographic surveying and other fieldwork during Phase 2 of the assessment provides information on the existing morphology of the channel and how the channel is responding to the natural conditions and human land uses identified in Phase 1. The Phase 1 and Phase 2 results were entered into a web-based data management system administered by Vermont's River Management Program with summary tables of the results provided in Appendix 1. A number of channel features, including sites of bank erosion and armoring, were mapped continuously along the length of the lower Winooski River and used to create GIS shapefiles with the Feature Indexing Tool created for Vermont's River Management Program (Appendix 2).

2.0 PHASE 1 ASSESSMENT

2.1 Subdividing Reaches

Since different portions of a river might respond differently to the same natural and human factors, the first assessment task is to subdivide the river into distinct reaches. Within a given reach, the river is assumed to respond similarly to changing watershed conditions while adjacent reaches may respond differently. Break points between different reaches are made on the presence of one or more of the following conditions: natural grade control; change in valley slope; constriction of valley width; expansion of valley width; or confluence of a major tributary comprising more than 10 percent of the watershed upstream of the reach break. Grade controls are resistant features crossing the channel (e.g., waterfalls, dams) that tend to prevent the upstream or downstream transfer of channel instabilities. Human factors are generally ignored in the identification of reach breaks, but are analyzed as part of a Phase 2 assessment.

Six reaches of uneven length were identified on the lower Winooski River using topographic maps. The reaches were numbered consecutively from the downstream end of the river and designated R01, R02, etc. to indicate that the reaches are located on the mainstem of one of the larger rivers in Vermont (Figure 2 and Table 1). Reach R07 (i.e., upstream of Alder Brook) was not analyzed as part of this study but the reach break was identified to determine the upstream limit of Reach R06. Three of the reach breaks occur at points of flow expansion, two at flow constrictions, and one at the confluence of a major tributary (i.e., Alder Brook). The Essex Junction Dam is located at Reach Break R06 and is built at one of the natural valley constrictions where a natural grade control (i.e., waterfall) also occurs (Figure 2).

Reaches downstream of constrictions occupy more confined valleys where the river channel has a greater likelihood of flowing against glacial sediments or bedrock exposed along high valley walls. The potential for high rates of sediment production from glacial sediments or the likelihood of encountering natural grade controls (i.e., ledge crossing the channel) in these narrower valleys can affect channel morphology differently than reaches occupying wide valleys where the channel generally encounters floodplain sediments only. Flow expansion at the downstream ends of confined reaches can lead to greater channel response and adjustments in the less confined reaches downstream.

Reaches downstream of tributary confluences will generally have a morphology different than reaches immediately upstream of the confluence because of the introduction of sediment at the confluence. The morphological impacts of tributary confluences, as well as valley constrictions and expansions, are generally most noticeable at or near the reach break. Consequently, the locations of the reach breaks themselves are likely points of channel instability with active bar formation, bank erosion, and channel migration possible. Delineating the reach breaks and understanding the morphological conditions present in each reach are critical for identifying the natural and human conditions leading to erosion and channel instability.

2.2 Natural Conditions

An analysis of valley confinement, valley slope, and other natural conditions help establish the reference channel condition that would be expected to develop in each reach in the absence of human influence. (Departures from this reference condition can later be identified during the Phase 2 assessment to determine how the stream is responding to human land use and land management practices). The lower Winooski River is characterized by an alternating pattern between confined and unconfined reaches. Reaches R04, R02, and R01 are in valleys broad enough to support the unconstrained meandering of the channel across a floodplain, characteristic of a “C” or “E” reference stream type as defined by Rosgen (1996). Riffle-pool or dune-ripple bed forms would be expected in these three reaches with channel gradients ranging from 0.01 percent in

Reach R01 (i.e., the Intervale) to 0.55 percent in Reach R02 where Winooski Falls accounts for much of the steeper gradient (Appendix 1). In contrast Reaches R06, R05, and R03 are in narrower valleys where channel planform is constrained by the valley walls, leading to straighter channels more characteristic of a “B” reference stream type (Rosgen, 1996). Step-pool bedforms would be expected to form where the channel is alluvial (i.e., flowing through sediment that can be transported), but bedrock controls are present in portions of Reach R06 and R03 (i.e., Winooski Gorge) while large boulders, inherited from underlying glacial deposits, armor the channel bottom in Reach R05 (Figure 3).

Channel migration and meandering is possible in broad valleys where the channel can shift across the floodplain over time. While no evidence exists for dramatic changes in channel position in the 20th Century, historical maps demonstrate more significant shifts in channel position in Reach R01 (i.e., the Intervale) during the 19th Century (Figure 4 and Appendix 3). Abandoned oxbows seen on aerial photographs provide evidence of much more dramatic channel migration over several centuries or millennia, but the relative rate of these changes compared to the 19th Century is unknown (Figure 5). The Intervale (Reach R01) is very broad and the Winooski River in this reach appears to flow over a former delta that built out into Lake Champlain over thousands of years. The resulting low gradient on the Intervale (0.01 percent) further promotes channel migration, because flow is more easily diverted from a straight path over gentler gradients. Reaches R02 and R04 are also unconfined but show no evidence of significant channel migration, perhaps due to much steeper gradients (> 0.13 percent)(Appendix 3). While historical channel migration is limited to the Intervale, all three unconfined reaches (R01, R02, and R04) have a meandering planform with relatively high sinuosities compared to the other, narrower, reaches (Table 1).

2.3 Human Land Use and Constraints

Superimposed on the natural watershed characteristics that are controlling channel morphology are numerous human land uses that can potentially alter the expected natural reference stream type. The Phase 1 assessment assigns an impact rating (e.g., high, low, and not significant) for several human activities and morphological conditions that are possibly indicative of a channel response to human impacts (Table 2). A higher impact score indicates a greater likelihood that the channel is responding to one or more human land uses in the watershed. While the impact rating scores are based on all of the human activities and morphological parameters (Table 2 and Appendix 1), the following summary focuses only on those considered to have a potential influence on the lower Winooski River.

2.3a – Watershed impacts

Extensive land clearance in the watershed can increase runoff and sediment delivery to the river channel. In the 19th Century most of the Winooski River watershed was cleared of its forest cover for agriculture (Figure 6a), a condition that persists today along valley bottoms where agriculture and urbanization are important (Figure 6b).

Hillslopes in the watershed are now largely tree covered (Figure 6b), but the river's morphology may still reflect events that occurred several decades ago. A change to a more forested land cover results in a reduction of peak discharge through increased evapotranspiration. Under the current conditions of forested hillslopes, a National Weather Service study demonstrated that the peak stage of the Winooski River would have been over 4.0 feet lower compared to the 1927 flood for the same amount of rainfall (Greg Hanson, personal communication, 2006). Consequently, the damages wrought by the 1927 flood along the length of the Winooski River would have been greatly reduced had there been a greater forest cover throughout the watershed (Figure 7).

Despite the increased forest cover, the valleys still remain developed and used for agriculture such that more than 10 percent of the entire Winooski River watershed is cleared. Consequently, the land cover impact score for all six reaches on the lower Winooski River is "high" (Appendix 1). Rapid growth in and around the greater Burlington area is partly responsible for this high impact. However, much of this development is restricted to high terraces isolated from the river, so the impact of this development is likely greater on smaller tributaries than the much larger Winooski River.

Likely accompanying 19th Century and earlier land clearance in the watershed was the loss of wood from the river channel. Before European settlement of the region, thick forests were probably present along the lower Winooski River with large woody debris falling into the stream channel and creating debris jams, at least along the margins of the wide Winooski River. Much of this wood may have been purposefully removed from the channel to improve navigation for boats, particularly in the Intervale (Reach R01), and to reduce flooding caused by log jams forming in the river. The recruitment of new wood in the channel was also greatly reduced by the clearing of forests on the floodplain for agricultural purposes. While much of this activity occurred over 100 years ago, wood is still largely absent from the river channel to this day despite the regrowth, in places, of a riparian buffer (Figure 8).

2.3b – River corridor impacts

Land use in the river corridor, the area within four bankfull widths of the channel, can have a greater impact on channel morphology than land use in the larger watershed. An unforested corridor exposes erodible floodplain soils, increasing the potential for bank erosion and channel avulsions (i.e., a rapid shift in channel position caused when a new channel is carved through the floodplain during a large flood). Agricultural use and urban development exceeds 10 percent of the total area in the river corridor of the lower Winooski River, resulting in a "high" impact score for corridor land cover in all six reaches assessed. The impact is probably less than implied in Reach R03 where the development is actually high above the Winooski Gorge or in R02 and R06 where development is on hillslopes beyond the margin of the floodplain. The corridor impact in the other reaches is further magnified where a buffer of trees in the riparian corridor is absent or very narrow (< 25 ft). River banks are more susceptible to erosion where trees and the soil binding strength of their roots are absent. While a riparian buffer does exist along portions of all six reaches, the impact rating for riparian buffer width is "high" in

Reach R01 and R04 where the buffer is less than 25 feet wide along one or both banks for more than 75 percent of the reach length.

2.3c – In-channel impacts

Several dams are present in the Winooski River watershed with three on the lower Winooski River: Winooski Falls Dam in Reach R02, Winooski Gorge Dam in Reach R03, and Essex Junction Dam in Reach R06 (Appendix 2). These dams are currently used to generate hydroelectric power but earlier dams in Winooski and Essex Junction were used to power industries in the area. All three dams are located on natural bedrock waterfalls or constricted by bedrock valley walls. In the upper watershed, three flood control dams were built in the 1930's after the devastating flooding of November 1927. These dams, along with reforestation of the watershed, have reduced flood discharges considerably by storing runoff during heavy rains and releasing the water slowly over a greater length of time. The highest peak discharge at Essex Junction since 1927, 45,000 ft^3/s in March 1936, is less than half the November 1927 record peak of 113,000 ft^3/s and occurred before all of the flood control structures were complete (see http://nwis.waterdata.usgs.gov/vt/nwis/peak/?site_no=04290500&amp). The reduction of flood peaks by dams in the upper watershed and the storage of sediment behind all of the dams in the watershed, particularly those on the lower Winooski River, have the potential to alter channel morphology. Although dams are not present in each reach, their presence may engender upstream and downstream channel adjustments. Consequently, the impact rating for flow regulation is "high" for all six reaches assessed.

Other human activities in the river channel can also have a significant impact on channel morphology. Evidence for channel straightening is limited to the upstream end of Reach R01 where sediment deposition may have historically been high as the valley width expands and valley slope flattens (Figure 9). The straightening occurred prior to 1802 (Figure 4 and Appendix 3) and deposition at the mouth of an abandoned position of Sunderland Brook appears responsible for nudging the Winooski River to the southwest, thereby recreating a low amplitude meander along the straightened portion of the channel (Figure 9). While additional straightening may have occurred in this and other reaches (except through Winooski Gorge in Reach R03), map and field evidence is inconclusive in this regard. As a result, the impact rating for channel straightening is "low" for Reach R01 and "not significant" for the other five reaches.

Bank armoring with large rocks (i.e., riprap) can prevent bank erosion where applied, but can also create channel instabilities that transfer the erosion to adjacent portions of the river bank. Bank armoring is observed in all of the reaches, even in the bedrock lined Winooski Gorge at railroad bridge abutments (Reach R03)(Appendix 2). The total amount of riprap in any one reach is less than 10 percent of the reach length such that the bank armoring impact rating is "not significant" in all six reaches. Much of the armoring occurs at bridge crossings where the rock protects abutments. Although several current or previous crossings are found in most of the reaches (only Reach R04 has no bridge crossings), their spans are sufficient enough to not cause a constriction of the channel that would impact channel morphology during small to moderate floods.

(Separate bridge and culvert assessments were not completed as part of this study to evaluate floodplain constrictions that could cause channel responses during larger floods).

2.3d – Total impact score

Accounting for all of the human activities and morphological parameters for which an impact rating is assigned (Table 2), Reach R01 has the highest impact score on the lower Winooski River, reflecting the heavy land use in the corridor, sediment deposition in the broad valley, and straightening of a short portion of the channel (Appendix 1). Reaches R02 and R04 also have relatively high impact scores owing to their presence in alluvial valleys where the channel is more responsive to watershed, corridor, and in-channel impacts. Reaches R05 and R06 have lower impact scores, because the narrow floodplain limits natural channel migration and meander growth. The Essex Junction Dam impounds the lower 0.5 mile of Reach R06, essentially drowning the former channel. While this is a severe impact in and of itself, other channel conditions for which impact scores are assigned are less apt to occur within the impoundment. The Winooski Gorge (Reach R03), not surprisingly, has the lowest impact score given the resistance to channel modification offered by the bedrock valley walls.

3.0 PHASE 2 ASSESSMENT

The Phase 1 assessment identifies human land uses and constraints that might result in morphological adjustments. The Phase 2 assessment is designed to identify if and how the channel is responding (or has responded) to these human activities. The channel morphology in each reach is also a reflection of the region's geological setting and flood history. Phase 2 assessments on the lower Winooski River were limited to four of the five reaches in which the Winooski Valley Park District manages parklands: Reach R01 (Derway Island Natural Preserve, Heineburg Wetlands, Macrae Farm, and Ethan Allen Homestead); Reach R02 (Salmon Hole and Winooski Nature Trail); Reach R04 (Woodside Park); and Reach R05 (Muddy Brook Park)(Table 1). The Winooski Gorge and associated park were not assessed given that the bedrock constraints limit channel responsiveness to large floods and human activities in the channel, river corridor, or larger watershed. The Phase 2 results for the lower Winooski River are discussed below, from upstream to downstream, with related cross sectional data, substrate particle size analyses (i.e., pebble counts), and ground photographs presented in Appendix 4. The values cited for various morphological parameters (i.e., entrenchment ratios, width:depth ratios, sinuosity, etc.) are recorded on the Phase 1 and Phase 2 summary sheets in Appendix 1.

3.1 Reach R05

The channel morphology of Reach R05 is largely determined by the immediate geological surroundings that reveal the postglacial history of the region. Ice in the Champlain Valley was over 1.5 miles thick during the last Ice Age and its weight depressed the land below sea level. Consequently, when the ice sheet retreated north of the St. Lawrence Valley approximately 12,000 years ago, the ocean was able to flood into the Champlain Valley, creating an inland arm of the Atlantic Ocean known as the Champlain Sea. Boulders embedded in icebergs that calved off of the retreating ice sheet fell to the bottom of the Champlain Sea, which was otherwise covered in fine clay deposited in the still waters of the ocean bottom. Eventually, sand covered the bouldery clay as the ancient Winooski River built a delta out into the sea. Over a period of 2,000 years, the land surface rebounded above sea level, the ocean receded from the valley, and Lake Champlain was formed at a level 200 feet lower than the Champlain Sea. The modern Winooski River, draining to a point much lower than the delta surface created in the Champlain Sea, carved through the delta sands and, where encountering a buried ridge of bedrock, incised the narrow Winooski Gorge (Wright, 2003). The erosion continued in Reach R05 until the river reached the bouldery clay underneath the delta sands. Unable to move the boulders, the river now flows over a lag deposit, or armor, of boulders still seen on the river's bottom (Figure 3). The river may also flow across ridges of bedrock that further arrests channel incision and maintains the river's current level.

Reach R05 still remains bounded on both sides by the flat delta terraces left isolated high above the river by the Winooski River's incision with the Burlington International Airport built on the terrace surface southwest of the river. Consequently, the reach has only a narrow floodplain with an entrenchment ratio, as defined by Rosgen (1996), of only 1.3, reflecting the river's inability to spread out across a wide floodplain during a large flood. Without a broad floodplain, stream power is contained within the channel and the bed and banks are exposed to greater erosive forces. This has resulted in the very coarse armoring of the channel bed (> 15 percent boulders) as all of the finer particles have been swept downstream by floods (Figure 3). Unable to erode the armored channel bed, the river has preferentially eroded the banks composed of loose deltaic sands, giving rise to a relatively wide and shallow channel (width:depth ratio > 30)(Figure 10). While channels with high width:depth ratios are typically associated with human impacts, the morphology of Reach R05 is merely the result of natural variations in composition between the river's bed and banks. The lack of extensive erosion and deposition in the reach is limited, suggesting the river channel's dimensions are largely in equilibrium with watershed conditions.

Erosion and deposition that is present in Reach R05 is related to localized constrictions or sediment inputs. For example, an outcrop of bedrock protrudes into the channel near the downstream end of the reach, creating a minor channel constriction. A large mid-channel bar has formed upstream of the outcrop as the water's velocity decreases when the river flows against the outcrop (Figure 11).

3.2 Reach R04

Reach R04 is characterized by a broad floodplain (entrenchment ratio = 14.2) and high sinuosity (= 2.47) resulting from a single high amplitude meander formed upstream of Winooski Gorge (Figure 12). The meander has persisted in the same position since at least 1857 (Appendix 3) and was probably formed by floodwaters impounded upstream of the constriction leading into Winooski Gorge. The 1927 flood event, while creating side channels through Woodside Park (Figure 12), was not sufficient to alter the meander path, suggesting even larger floods occurred prior to 1857. Alternatively, smaller floods charged with wood prior to European Settlement of the region may have created a debris jam at the entrance of Winooski Gorge that backed water up into Reach R04. Whatever the cause, the backwatering of the valley behind Winooski Gorge would enable the river's flow to be easily diverted and prone to developing a high amplitude meander as seen in Reach R04. The high meander width ratio of this meander (> 10), a value typically associated with human induced aggradation, is in this case a consequence of natural flooding processes through and upstream of Winooski Gorge.

Bank erosion is limited along the reach (< 5 percent) and found on the outside bends of meanders (Figure 12), indicating that the channel form is stable and not undergoing widespread adjustments. Although the river could take a much shorter path by cutting across the meander, the unusual meander form is likely to persist into the future with flood chutes providing relief during extreme events as in 1927 (Figure 12). Large sections of the reach have only a thin riparian buffer and these sections might be particularly sensitive to accelerated erosion. A high eroding bank of post glacial sediments at the apex of the narrow meander could supply excess sediment to the reach, but the lack of point bars or mid-channel bars in the reach suggest the river is able to accommodate the extra sediment from the bank without causing local instabilities.

3.3 Reach R02

Reach R02 is divided into two sub-reaches (Figure 13). The downstream sub-reach (Subreach R02-A) is characterized by bedrock ledges and waterfalls with Winooski Falls, on which a dam is built, representing the biggest single drop. Much of the northern bank in this subreach is armored with cement or is confined by the foundation of the old Winooski Mill building. The Town of Winooski is built on a sloping surface down to the river's edge means that only buildings along the river's edge are flooded during large discharge events (Figure 7). The channel's high width:depth ratio (> 60) is the result of bedrock constraints on the channel bottom preventing the development of a deeper channel. Erosion is observed within the subreach, but occurs only at the base of a steep bedrock cliff below Winooski Falls and is not symptomatic of widespread instabilities. The bedrock constraints within the reach mean that the reach is not sensitive to change and will not likely respond to future natural or human perturbations in watershed or channel conditions.

The very wide floodplain in Subreach R02-B (entrenchment ratio = 14.5) stands in sharp contrast to the Winooski Gorge (Reach R03) upstream and the bedrock confined subreach downstream (R02-A)(Figure 13). Its creation is probably related to the formation of Winooski Gorge as the river incised through deltaic sediments after the draining of the Champlain Sea (see discussion above in Section 3.1). The large flows or series of flows that carved Winooski Gorge would have expanded rapidly and easily eroded the loose deltaic sands exposed along the valley side slopes as the flow exited the bedrock confines of the gorge. This effect may have been further enhanced by eddies formed as water was backed up behind the bedrock constrictions at Winooski Falls. The resulting flat floodplain is now characterized by split flow around a large island and a large marshy area to the north. The marsh was likely an active flow path in the past and was conveying some flow during the 1927 flood as evidenced by historic oblique aerial photographs available at the University of Vermont's Landscape Change Program website (www.uvm.edu/perkins/landscape/).

While the broad valley in which Subreach R02-B is found was formed by post-glacial events thousands of years ago, morphological features found along the modern channel are likely the result of the 1927 flood. The channel is slightly incised into a low ridge on the floodplain between the channel and marshy area occupying the northern half of the valley (Figure 14). Between this ridge and the channel is a flat surface with a grove of trees that are roughly all the same size (Figure 15). The uniformity in size of the trees suggests that they all began growing at the same time with their large size likely consistent with initial germination shortly after 1927. Although well wooded now, this forested surface is interpreted to be a gravel bar deposited by the 1927 flood after eroding an approximately 70-foot wide portion of the floodplain. If this interpretation is correct, the low ridge between the bar and marshy area to the north represents the remaining remnant of a more extensive floodplain existing prior to the 1927 flood. The forested bar surface represents the current floodplain level and deposition of finer sediment on its surface by smaller floods may eventually raise the surface back to the height of the older floodplain. However, this process is likely being slowed by the reduction of sediment loads to the reach due to sediment storage behind upstream dams. No significant erosion is observed in the reach, so the sediment deficit downstream of the dams does not appear sufficient to initiate widespread channel response.

The high incision ratio (> 1.4) in the reach reflects the difference in height between the remnant floodplain and the gravel bar (i.e., the emerging floodplain). While a high incision ratio is sometimes symptomatic of a direct response to human activities such as channel straightening, the condition in Subreach R02-B appears to be the result of a single large flood in November 1927. The dramatic effects of the flood, however, may have been amplified by the removal of the riparian buffer along the stream, land clearance in the larger watershed, and other human activities.

3.4 Reach R01

Downstream of Winooski Falls the river has a very low gradient as it begins to flow across a very broad floodplain known as the Intervale, possibly an old delta built out into Lake Champlain over thousands of years. The Intervale is almost 2 miles wide at Pine Island but then narrows to less than 0.5 mile wide downstream. Bedrock controls may control this constriction as water depths over 20 feet are observed in the apex of a narrow meander bend 900 feet upstream of the Route 127 Bridge where the Intervale is at its narrowest.

Reach R01 is the most typically alluvial stream on the lower Winooski River, meaning that the channel is free to migrate across its floodplain without constraint. The other two alluvial reaches assessed (R04 and R02-B) are too short to avoid the influences of upstream and downstream constrictions at Winooski Gorge and Winooski Falls as discussed in Sections 3.2 and 3.3 above. Old oxbows seen across the Intervale (Figure 5) bespeak of a time prior to European settlement when channel migration and avulsions were more common than the 20th Century when very few changes occurred (Figure 4). Historical maps do show some continued channel migration, even into a high bank across the river from Derway Island (Springston, 2002), although these historical changes have occurred within a much narrower belt width than at earlier times (Figure 4). Bank retreat at the Ethan Allen Homestead has progressed, in places, at a rate possibly greater than 2 ft/yr since 1947 (Figure 16). The most active areas of erosion tend to occur where no riparian buffer is present (Figure 16). Erosion progresses slower when a riparian buffer is present because roots help bind the soil together. Furthermore, as trees are undermined by erosion, they fall onto the bank or at the base of the bank and, at least temporarily, protect the bank surface and toe from further scour.

The meander bend at the Ethan Allen Homestead is just downstream of where artificial channel straightening occurred prior to 1802 (Figure 9). Greater sediment transfer through straightened reaches leads to greater deposition and migration rates in downstream meanders. Unvegetated point bars, mid-channel bars, diagonal bars, and a high width:depth ratio (> 20) at the Ethan Allen Homestead are all indicative of increased rates of sediment deposition in the meander bend (Figure 16). While point bars and other depositional features are observed elsewhere in Reach R01, they are largest and most numerous in the meander bend surrounding the Ethan Allen Homestead. The incidence of erosion is also greatest at this location compared to the rest of the reach (Appendix 2). Without straightening, sediment delivered to the reach would be more equally distributed through two meanders, but, as a result of cutting off one meander by straightening, excess sediment has been delivered to the downstream meander. The depositional features, high width:depth ratio, and increased bank erosion may indicate that straightening upstream that occurred over 200 years ago continues to impact the river near the Ethan Allen Homestead to this day.

Erosion occurs along 12 percent of the total length of Reach R01 with an additional 5 percent of the banks armored with large rocks. This relatively high rate of erosion and bank protection suggests the channel is actively responding to changing watershed conditions. The lack of a riparian buffer along much of the reach makes the highly erodible sandy soils in Reach R01 (Appendix 1) even more sensitive to bank erosion as the channel responds to reduced sediment loads or increased erosive power. Sediment levels in Reach R01 are probably much reduced from earlier in the 20th Century because of the storage of sediment behind dams further upstream. Also, reforestation of the region has greatly reduced sediment supply to the river system compared to the 19th Century when much of the watershed was cleared (Figure 6; Bierman et al., 1997). Erosion in Reach R01 may be further enhanced by the lack of wood in the river system. Water velocities increase when roughness elements such as wood are removed from the channel. Without wood to slow the river’s velocity, especially along the banks, greater amounts of erosion result.

Minor channel incision in the reach is indicated by a low incision ratio (= 1.1) and the lack of activity in oxbows still connected to the main channel. Flow still enters the oxbows during floods, but they are not as active as might be expected if the current river bed was slightly higher. Erosion within Reach R01 is mostly focused on the outside bends of meanders with point bars forming on inside bends, suggesting the river is no longer actively incising. The patterns of erosion are consistent with a new meandering planform developing after the earlier incision and widening phase that accompanied the removal of wood from the channel, construction of dams, and reforestation of the watershed.

4.0 RECOMMENDATIONS ON RESTORING CHANNEL STABILITY AND AQUATIC HABITAT

With an understanding of how different reaches of the lower Winooski River are responding to natural and human conditions in the watershed, recommendations can be made on how to best restore channel stability and aquatic habitat. The focus of the following discussion of restoration options is on the Intervale (Reach R01) where human activities have had the greatest impact on channel stability and aquatic habitat. Morphological conditions along the other reaches assessed during Phase 2 are more a consequence of natural constraints: multiple flow paths on Subreach R02-B are formed by rapid flow expansion out of Winooski Gorge, the high amplitude meander developed in Reach R04 is formed behind the constriction at the entrance to the gorge, and the high width:depth ratio in Reach R05 is the result of differences in composition between bed (boulders) and bank (sand). These natural constraints are likely to persist for centuries or longer, so restoration efforts are unlikely to result in sustainable improvements. For example, multiple flow paths are likely to reappear during large flow events in Subreach R02-B if an attempt were made to create a single flow path. For the Intervale, five potential restoration and management options are presented below with a discussion of the advantages and disadvantages of each: 1) do nothing; 2) construction of rock revetments; 3) installation of log deflectors; 4) planting of riparian buffers; and 5) addition of engineered woody debris jams in the channel.

4.1 Do Nothing

Three human activities in the watershed and channel are potentially responsible for the minor channel incision that occurred in the Intervale and resulted in the currently high incidence of bank erosion. First, sediment supply throughout Vermont is greatly reduced from 19th Century levels as a result of the reforestation of watersheds (Bierman et al., 1997). Reductions in sediment supply to the lower Winooski River have been further enhanced by sediment retention behind dams. As sediment supply is reduced, the river has excess capacity, or becomes “hungry”, to carry sediment, leading to erosion of the bed and banks of the channel. A final human impact leading to increased erosion in the Intervale was the removal of wood from the river channel that most likely accompanied 19th Century and earlier land clearance. Wood removal would have taken away material protecting the banks from the river’s flow while simultaneously increasing the river’s erosive force by reducing the number of roughness elements (i.e., obstacles in the channel) that slow flood flow velocities. A previous period of minor channel incision along Reach R01 is indicated by low incision ratios (< 1.2)(Appendix 1) and a lack of major changes in channel position during the 20th Century compared to earlier times (Figures 4 and 5; Appendix 3). Currently, bank erosion is focused on the outside bends of meanders, especially where point bars are forming on the inside bends. This progression from an incising channel to one where channel widening and planform changes (i.e., changes in meander shape) are occurring as the result of bank erosion is characteristic of a channel progressing through a channel evolutionary process (Schumm, 2005) that results in the reestablishment of river equilibrium.

If no management activities were to occur on the Intervale, bank erosion would persist as the channel continues to develop a meandering planform in equilibrium with the current sediment supply and discharge patterns in the watershed. With the growth of point bars and slight increase in the bed elevation of the channel that would accompany deposition, old oxbows and abandoned meanders near the current channel will receive increasingly greater amounts of flow over time and may eventually become reactivated or even, perhaps, capture the majority of the river's flow. As the channel becomes reconnected with old abandoned meanders, flows will spread out over a greater area and lead to deposition in side channels and on the floodplain. Increased access to side channels and the floodplain will decrease flood flow velocities in the channel and, therefore, reduce bank erosion. A reduction in bank erosion and increased sediment storage on the floodplain will also reduce sediment inputs and nutrients to Lake Champlain. While doing nothing would ultimately lead to positive outcomes (e.g., reduced bank erosion and decreased nutrient inputs), this natural channel evolutionary process would likely take more than a century given the effect of dams in reducing sediment supply and flood discharges, two important components in driving channel changes. Ice jams are also an important mechanism for causing avulsions and channel change, but their historical significance on the lower Winooski River is not known.

Recognizing that equilibrium will be achieved through continued bank erosion, widening, and planform changes, the creation of corridor protection zones along the river would provide the necessary space required for the channel to reach equilibrium while reducing the number of potential conflicts these adjustments will have to humans. Protection zones should ideally be at least six times the channel width, or 1,620 feet in the Intervale (Appendix 1), to accommodate future bank widening and reactivation of old meanders. However, much narrower zones can still provide significant benefits, especially if wider protection zones are created over short distances where river migration will be less constrained. Protection zones can be established through land use planning, the acquisition of conservation easements, or other land management practices, but only in areas where municipalities and private landowners are agreeable to such changes. Discussions with landowners and other public education efforts can be used to demonstrate how the creation of corridor protection zones can allow the river to reach an equilibrium condition without engaging in expensive restoration activities and, over the long term, reduce the rate of bank erosion that threatens agricultural land and human infrastructure. Developing maps comparing areas where corridor protection would be most beneficial (e.g., at old meanders) with property boundaries of willing landowners is the best way to initiate a corridor protection planning process.

Pros:
- No implementation costs
- No adverse impacts resulting from site specific restoration activities
- Very little infrastructure currently at risk in the Intervale
- Long term reductions in bank erosion and nutrient inputs to Lake Champlain

Cons:
- Continued erosion of agricultural fields
- Slow increase in floodplain inundation as channel bed elevation increases
- Recovery time very slow

4.2 Construction of Rock Revetments

Bank erosion in the Intervale has traditionally been dealt with by constructing rock revetments (i.e., riprap)(Figure 17). Five percent of the banks in the Intervale have been treated with riprap (Appendices 1 and 2). Rock revetments prevent further erosion of the bank by protecting the finer particles in the bank material from the force of the flowing water. While the judicious use of rock revetments to protect threatened infrastructure (i.e., bridge abutments) would have only minimal impacts on channel stability, the widespread application of rock armor to prevent erosion could prevent the channel from making the necessary adjustments to reach the equilibrium condition described above in Section 4.1. Rivers approaching an equilibrium state achieve a condition where erosion and deposition is equally distributed along the entire length of the river. If a little bit of erosion occurs on the outside bends of meanders, an equal amount of deposition also occurs on the inside bend of the meander such that the river's dimensions remain the same through time. By preventing erosion from occurring where a rock revetment is constructed, a greater rate of erosion will occur in an adjacent area to compensate for the sediment not eroded from the protected bank. As a result, the total amount of sediment moving through the system remains the same and nutrient inputs to Lake Champlain would remain the same despite preventing erosion with riprap at certain specific points along the banks. Long term reductions in bank erosion throughout the Intervale and decreases in sediment and nutrient inputs into the lake will only result with greater access to the floodplain and side channels where flood flow velocities can be attenuated and excess sediment stored. The widespread application of rock revetments on eroding banks will maintain, if not increase, channel constraints that create the high flood flow velocities in the channel needed to generate bank erosion and deliver sediment to Lake Champlain.

Pros:
- Eliminate erosion at treated sites, thereby protecting infrastructure and agricultural fields
- Provide time for riparian plantings within treated area to mature

Cons:
- Promotes accelerated erosion elsewhere
- Expensive if properly constructed
- Inconsistent with natural evolution of channel towards equilibrium condition
- Little infrastructure in immediate need of protection

4.3 Installation of Log Deflectors

Log deflectors installed in the bank and built out into the river can deflect water away from the bank and prevent or slow erosion. The deflectors also provide cover habitat for fish and pools can be scoured at the ends of the deflectors to provide further cover. Deflectors were installed at the Ethan Allen Homestead in conjunction with riparian buffer plantings in 1999. Most of the deflectors have since been dislodged from the bank or severely damaged (Figure 18a), but recession of the bank in this locality may have been slowed sufficiently to enable the buffer plantings to become well established (Figure 18b). Even where log deflectors are not damaged by bank erosion, they would be only temporary features as they would slowly decompose over time. Consequently, their benefit would be to reduce rates of bank erosion over short time periods while riparian buffer plantings installed with the project had time to mature. Because the log deflectors would deteriorate over time, they would not prevent the long term achievement of channel equilibrium. However, the cost of installation compared to their short-lived nature and higher risk of failure might preclude their widespread use.

Pros:
- Temporarily slow rate of bank erosion
- Provide time for riparian plantings within treated area to mature
- Create cover and pool habitat

Cons:
- Risk of failure due to continued erosion around and between installed structures
- High cost of installation may prevent widespread application

4.4 Planting of Riparian Buffers

Planting the riparian zone with fast rooting native trees and shrubs would speed up the natural process of revegetation in the riparian zone that is occurring already in parts of the Intervale. As the trees mature, the roots would increase the soil binding strength and help resist the erosive forces of flood flows in the channel. Erosion would not be completely stopped by the vegetation, so the long term development of an equilibrium condition might be slowed but not stopped. A riparian buffer along the entire length of the Intervale would mean that all points along the river banks would be equally erodible (assuming a uniform soil type) whereas unvegetated areas are currently more susceptible to erosion. Given that the equilibrium tendency of the river is to uniformly spread erosion out over a greater distance rather than have erosion focused in a small area, the planting of riparian buffers is consistent with the natural evolution of the channel. While the slower rate of erosion might increase the length of time until equilibrium is achieved, the reduced rates of erosion would result in less sediment and nutrient delivery to Lake Champlain at any one time. The ecological and water quality impacts to the lake would, therefore, likely be reduced by spreading out the inputs of sediment and nutrients over a longer time period.

The growth of trees on the floodplain would also increase the resistance of floodplain soils to erosion. Water flowing over bare soils on the floodplain has the power to scour new channels and create additional sources of sediment and nutrient inputs over and beyond what is derived from bank erosion alone. In rare cases, the floodplain scour might cause an avulsion, whereby the channel's position might rapidly shift out of the current channel and into a new position. The establishment of a riparian buffer would tend to baffle floodplain flows, reduce their velocity, and encourage the deposition of fine sediment rather than erosion of floodplain soils. Consequently, riparian buffer plantings would enhance floodplain deposition and reduce fine sediment inputs to Lake Champlain.

Continued, albeit slower, bank erosion where a riparian buffer has become established will result in mature trees being undermined. This will provide a source of wood to the channel, an essential component of good fish habitat. Riparian buffer plantings also provide other important habitat benefits including increased shading, development of overhanging bank cover, and improved water quality by buffering contaminants introduced by overland flow across the floodplain. The establishment of a riparian buffer should be encouraged along the entire length of the river, not only where bank erosion is currently active. Planting trees in areas that are relatively stable will allow trees a chance to mature and be better able to resist strong flows if the location of erosive forces shifts over time. Buffer plantings occurring where erosion is currently active should be of sufficient width, so there is ample time for the trees to mature before the river bank is undermining them. Trees that do not have time to develop a large root mass will not slow the rate of erosion. Planting of fast rooting trees and shrubs on the bank slope and top edge of the bank may help slow the rate of erosion more immediately by baffling flows and providing surface protection while other trees with larger, but more slowly growing root masses, are planted further back from the slope and have more time to mature. Where banks are vertical, portions of the upper bank could be reshaped so a gentler bank slope results, on which shrubs and other vegetation could be more easily planted.

Pros:
- Improve aquatic and riparian habitat – shading, cover, wood inputs to stream
- Reduce rate of bank erosion
- Allow for more uniform rates of erosion throughout reach
- Relatively low cost to implement
- Consistent with natural evolution of channel equilibrium

Cons:
- Initial high mortality rates of plantings
- Concerted maintenance efforts needed to succeed

- No immediate impact – several decades needed for vegetation to mature
- Continued bank erosion may cause loss of vegetation before maturation

4.5 Addition of Engineered Woody Debris Jams in the Channel

Flood flows, sediment, and ice jams were identified in Section 4.1 as important elements in driving channel changes and the establishment of equilibrium conditions in the Intervale. A fourth important element is wood. The likely purposeful removal of wood from the channel in the 19th Century and earlier is one possible reason for minor channel incision, currently high rates of bank erosion, and an apparent reduced rate of channel migration across the Intervale during the 20th Century (Figures 4 and 5). While the addition of wood to the channel will slowly occur with the reestablishment of a riparian buffer, the addition of engineered woody debris jams in the channel could provide more immediate and beneficial impacts. Woody debris jams placed along the margins of the channel immediately downstream of the upstream ends of abandoned oxbows could promote deposition and a localized increase in bed elevation that would divert additional flow and sediments into the old meanders. Reactivation of the old meanders would have both morphological and ecological benefits. Spreading flow out into multiple channels will decrease flow velocities, reduce erosive forces in the main channel, and eventually result in increased bank stability. Some of the sediment transported into the reactivated meanders will be deposited as flow spreads out, thereby leading to long-term storage and reduced sediment and nutrient inputs to Lake Champlain. While the meanders could be reactivated without engineered wood jams by excavating the bed of the old meanders to a level even with the current channel, this process would be more expensive and would have greater short term environmental impacts due to the use of heavy equipment in the channel. The use of engineered wood jams to accomplish the reactivation of the oxbows would more closely mimic natural processes as wood becomes more abundant in the river channel.

Prior to the wood removal that likely accompanied European settlement of the region, naturally forming woody debris jams likely diverted flow into alternate flow paths and led to the abandonment of others. The debris jams were likely mobile, changing positions with subsequent large flows. Consequently, with each large flow, new meanders may have been created while others were abandoned. Over time, several abandoned meanders would be present on the landscape. Wetland areas would form in these oxbows with different stages of vegetational succession present in each depending upon the length of time since abandonment. In this way, a patchwork of different wetland types would exist with a unique assemblage of plant and animal species occupying the different habitats. These habitats might vary from an open river channel to ones that are inundated with water during only portions of the year. With a decline in the frequency with which meanders were abandoned, the ecological diversity would also decline as succession in the various oxbows progressed without newly abandoned meanders forming to replace the early successional phases. While recreation of a diverse patchwork of habitats might be difficult with the addition of just a few engineered woody debris jams in the channel, the reactivation of formerly abandoned meanders would increase ecological diversity by creating new flow regimes in the Intervale.

The habitat benefits to be gained by the addition of woody debris jams would have to be carefully weighed against increased flooding that might accompany such a restoration scheme. The addition of wood in the channel will increase the roughness in the channel and reduce flood flow velocities. Consequently, for the same flood discharge, the water surface elevation will increase such that a discharge that previously would have reached the top of the river banks might spill out onto the floodplain with the addition of wood in the channel. While the addition of only a few small debris jams along the margins of the channel would presumably have only a negligible effect on flood elevations elsewhere, careful hydraulic modeling would be necessary to alleviate landowner concerns associated with increased flooding. In addition, the debris jams would also need to be carefully engineered to ensure that they will remain intact and stationary, so a large mass of logs do not break free and create hazards at bridges or other human infrastructure downstream.

Pros:
- Speed up natural evolution of channel towards equilibrium conditions
- Improve habitat diversity
- Reduce bank erosion
- Store sediment and nutrients in reactivated channels before transported to Lake Champlain

Cons:
- Minor scour downstream of debris jams could destabilize banks locally
- Increased overbank flooding
- Potential landowner resistance
- Risk of wood breaking free and jeopardizing downstream infrastructure
- High implementation and design costs
- Interfere with boating

5.0 DEVELOPMENT OF INTERPRETIVE SIGNS

The text and images for six interpretive signs were developed to improve the public's understanding of the geological and human history of the lower Winooski River and its influence on the current position and form of the river channel (Appendix 5). The layout for two of the signs was also created (Appendix 5). The signs once fully developed will be placed at parks managed by the Winooski Valley Park District and taken together will highlight a progression though geological and human history. The first sign will be placed at Salmon Hole and discusses the tropical seas in which the rippled sandstones at the edge of the river formed hundreds of millions of years ago. The second sign, also at Salmon Hole, focuses on the tectonic processes that uplifted the Green Mountains, creating the fractures in the rock along which the river currently flows at Salmon Hole and Winooski Gorge upstream. The third sign at Muddy Brook features the glacial history that created the various deposits through which the wide shallow channel formed (as further described in Section 3.1 above). The fourth sign will be placed at the Ethan Allen Homestead and describes the greater frequency of channel migration that occurred prior to the 20th Century when more wood was present in the channel and flood discharges were less controlled. The fifth sign will describe the now wooded gravel bar deposited during the 1927 flood adjacent to the river at Winooski Nature Trail. The final sign will review how the complex geological and human history described in the earlier signs have combined to create the convoluted meander and side channels present at Woodside Park. By visiting the signs individually or in sequence, visitors to the parks will gain a better sense of how the river's form is shaped by events and processes that began hundreds of millions of years ago but continue to this day.

6.0 CONCLUSIONS

A fluvial geomorphic assessment of the lower Winooski River identified the major geological and human conditions that control river processes and morphology. The river's bed and banks are constrained by bedrock in many locations, particularly through the Winooski Gorge, with flow constriction entering the gorge and flow expansion at the downstream end exerting a strong influence on the morphology of adjacent reaches. Upstream, a large convoluted high amplitude meander has persisted for over a century, the result of flood waters impounded behind the gorge. Downstream of the gorge, the channel remains sensitive to large floods where flow expansion has given rise to the natural development of multiple flow paths. The morphology of the channel at Muddy Brook Park near the Burlington International Airport is less affected by Winooski Gorge but is controlled by other geological constraints. Compositional differences between the channel bed (boulders) and banks (sand) has given rise to a naturally wide and shallow channel. Channel morphology in the Intervale has been the most impacted by human activities but the naturally low slope and sandy soils make the reach sensitive to change. Minor channel incision resulted from sediment retention behind dams, decreased sediment inputs due to watershed reforestation, and increased flood flow when wood was removed from the channel. These human impacts have led to the currently high rates of bank erosion as the channel moves through a series of adjustments that will ultimately lead to a new equilibrium condition.

Many morphological conditions documented during the assessment, such as high width:depth ratios, multiple flow paths, and high amplitude meanders, are often associated with human impacts to channel stability, but on the lower Winooski River are frequently the result of natural conditions. Understanding the geological and human conditions giving rise to the channel morphologies observed is critical for successfully managing channel instabilities and restoring aquatic habitat. While creating a single channel downstream of Winooski Gorge, for example, could lead to temporary improvements in aquatic habitat, such restoration efforts are unlikely to be sustainable if the surrounding geological setting promotes flow expansion and the long-term development of multiple flow paths.

Within this context, the Intervale provides the best opportunities for restoration given the past adjustments to human activities and potential responsiveness to future management efforts. The present high rates of bank erosion are likely to decrease over time as the channel approaches a new equilibrium condition over several decades or centuries. Attempts to armor the channel with rock riprap can arrest bank erosion in localized areas, but its widespread application can lead to prolonged instability by preventing the channel adjustments needed to achieve equilibrium. Speeding up the evolutionary development of an equilibrium condition could be accomplished through the addition of engineered woody debris jams at the margins of the channel. While bank stability could be improved, habitat diversity increased, and sediment and nutrient inputs to Lake Champlain reduced, implementation of woody debris jams would be complicated by increases in flooding and potential damage to infrastructure associated with an unplanned for release of logs downstream. Riparian buffer restoration can, over the long term, lead to the same benefits as adding woody debris jams to the channel, but without the short term consequences that might lead to landowner resistance. Public education efforts using interpretive signs and other means will be necessary to gain wider support for management activities that lead to sustainable improvements in channel stability and aquatic habitat.

7.0 REFERENCES

Bierman, P., Lini A., Zehfuss, P., Church A., Davis, P.T., Southon, J., and Baldwin, L., 1997, Postglacial Ponds and Alluvial Fans: Recorders of Holocene Landscape History: GSA Today, v. 7, p. 1-8.

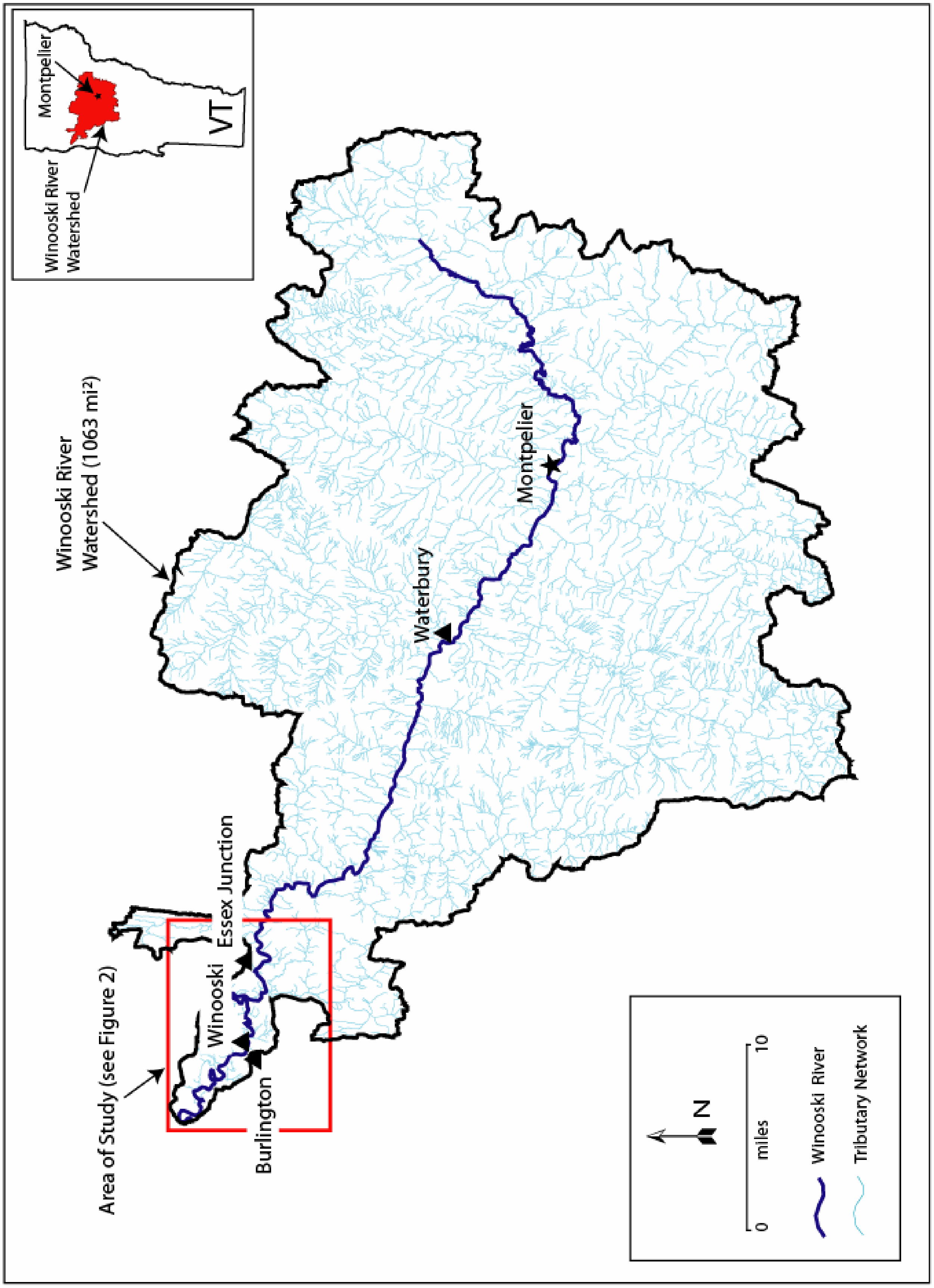
Rosgen, D.L., 1996, Applied River Morphology: Wildland Hydrology: Pagosa Springs, CO.

Schumm, S.A., 2005, River Variability and Complexity: Cambridge University Press: New York.

Springston, G., 2002, Analysis of streambank retreat on the north shore of the Winooski River in Colchester, Vermont: Written communication to Lawrence Becker, State Geologist, Vermont Geological Survey.

Vermont Agency of Natural Resources, 2006, Vermont Stream Geomorphic Assessment Handbook: Unpublished report available at http://www.anr.state.vt.us/dec/waterq/rivers/htm/rv_geoassesspro.htm.

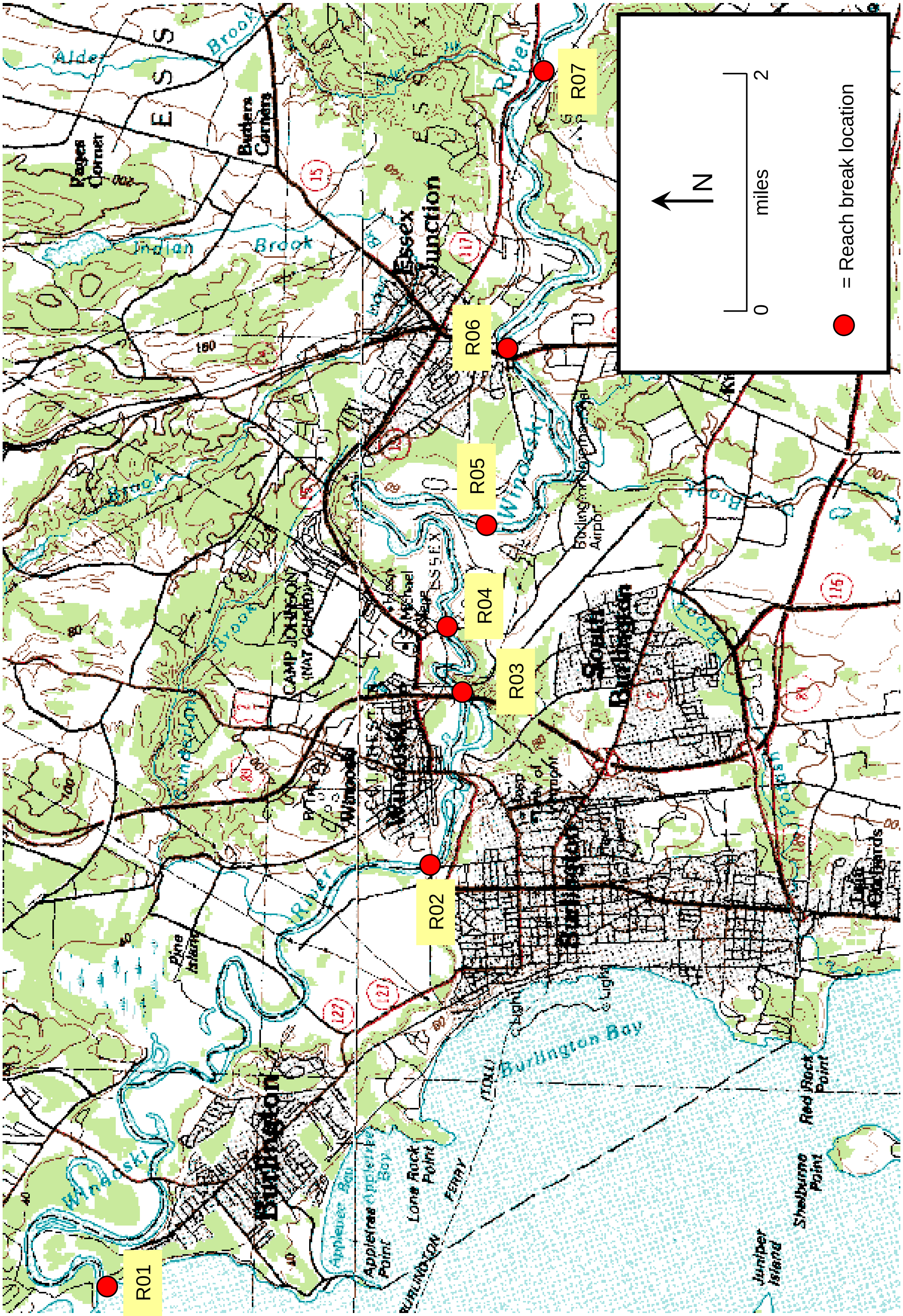
Wright, S., 2003, Glacial geology of the Burlington and Colchester 7.5 minute quadrangles, northern Vermont: Vermont Geological Survey, Waterbury, VT.



Lower Winooski River Fluvial Geomorphology Assessment - Figure 1

Field Geology Services

Location of Lower Winooski River Reach Breaks



Field Geology Services

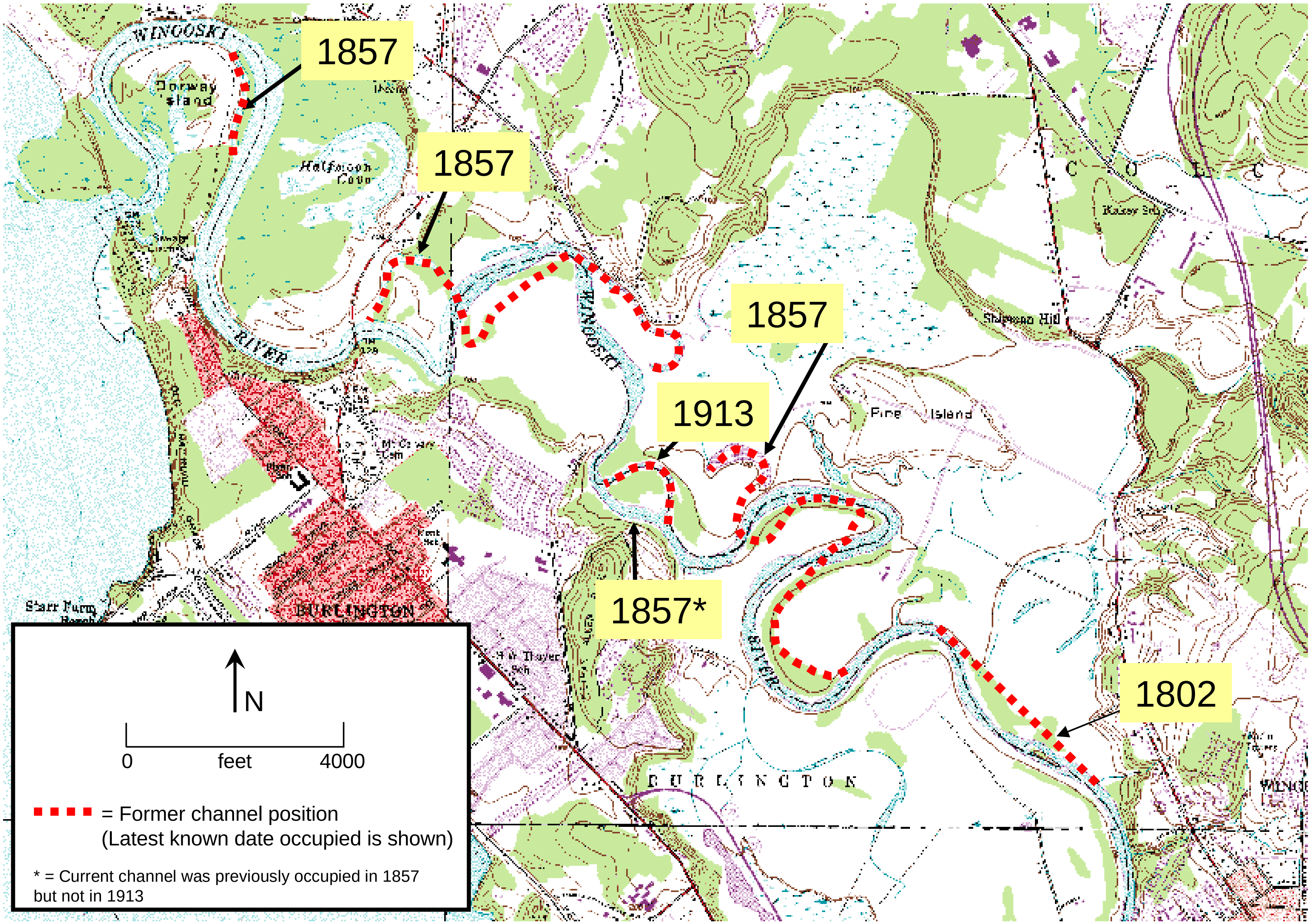
Boulders Armoring Channel Bottom in Reach R05

Note: Looking downstream from Muddy Brook Park

Field Geology Services
Fluvial Geomorphology

Lower Winooski River Fluvial Geomorphology Assessment – Figure 3

Changes in Channel Position During the 19th and 20th Centuries

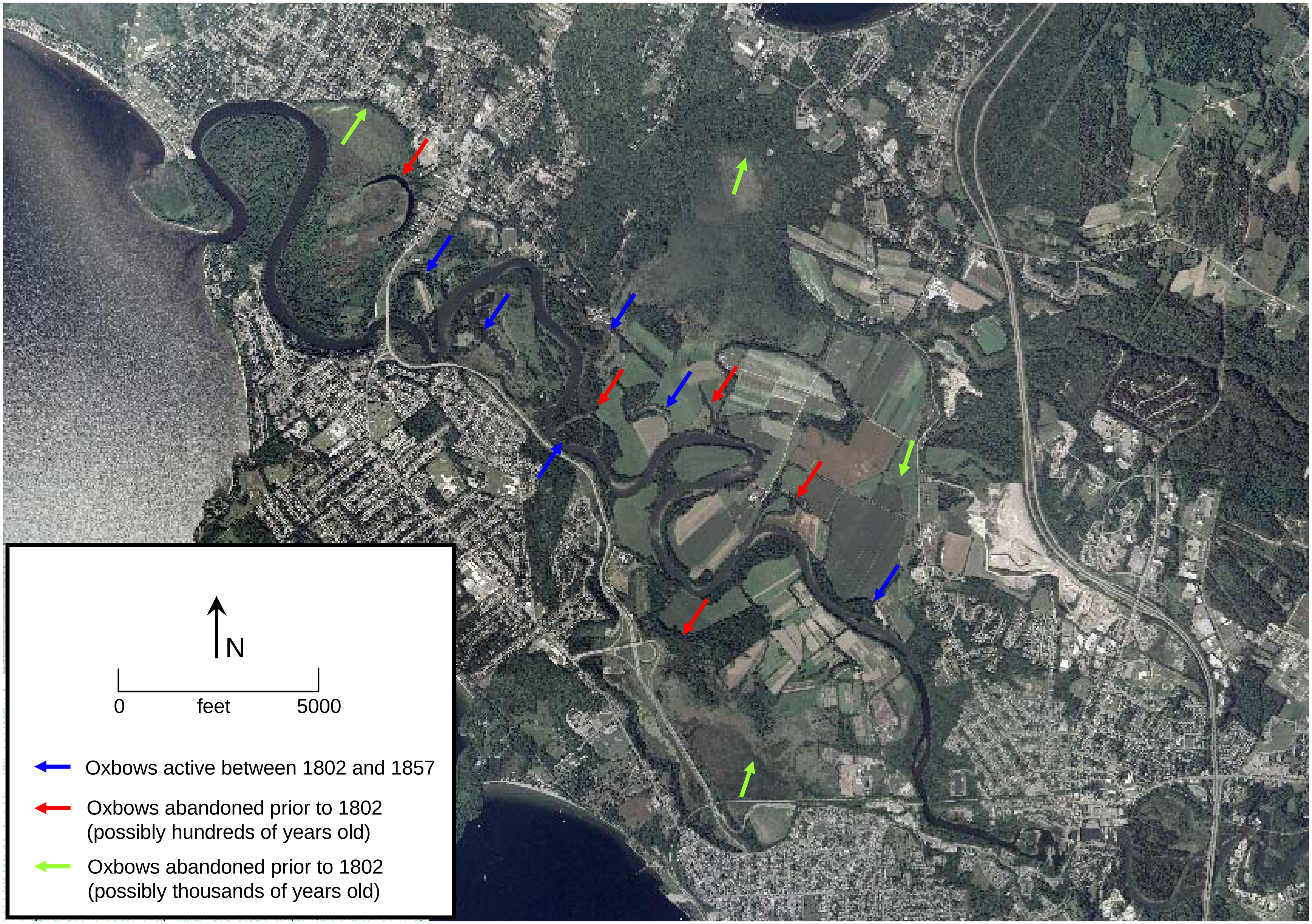


Note: Former channel positions shown are approximate. See Appendix 3 for historical maps from which data is drawn.

Field Geology Services

Lower Winooski River Fluvial Geomorphology Assessment – Figure 4

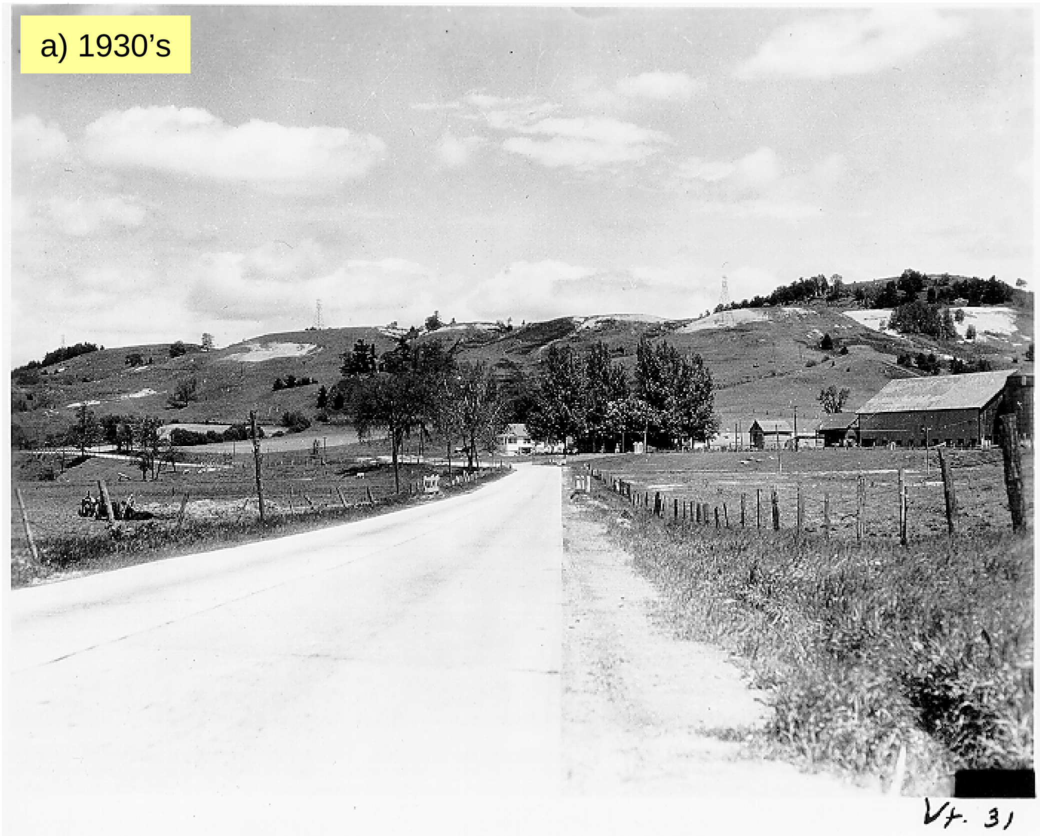
Former Channel Positions Abandoned Prior to 1900



Field Geology Services

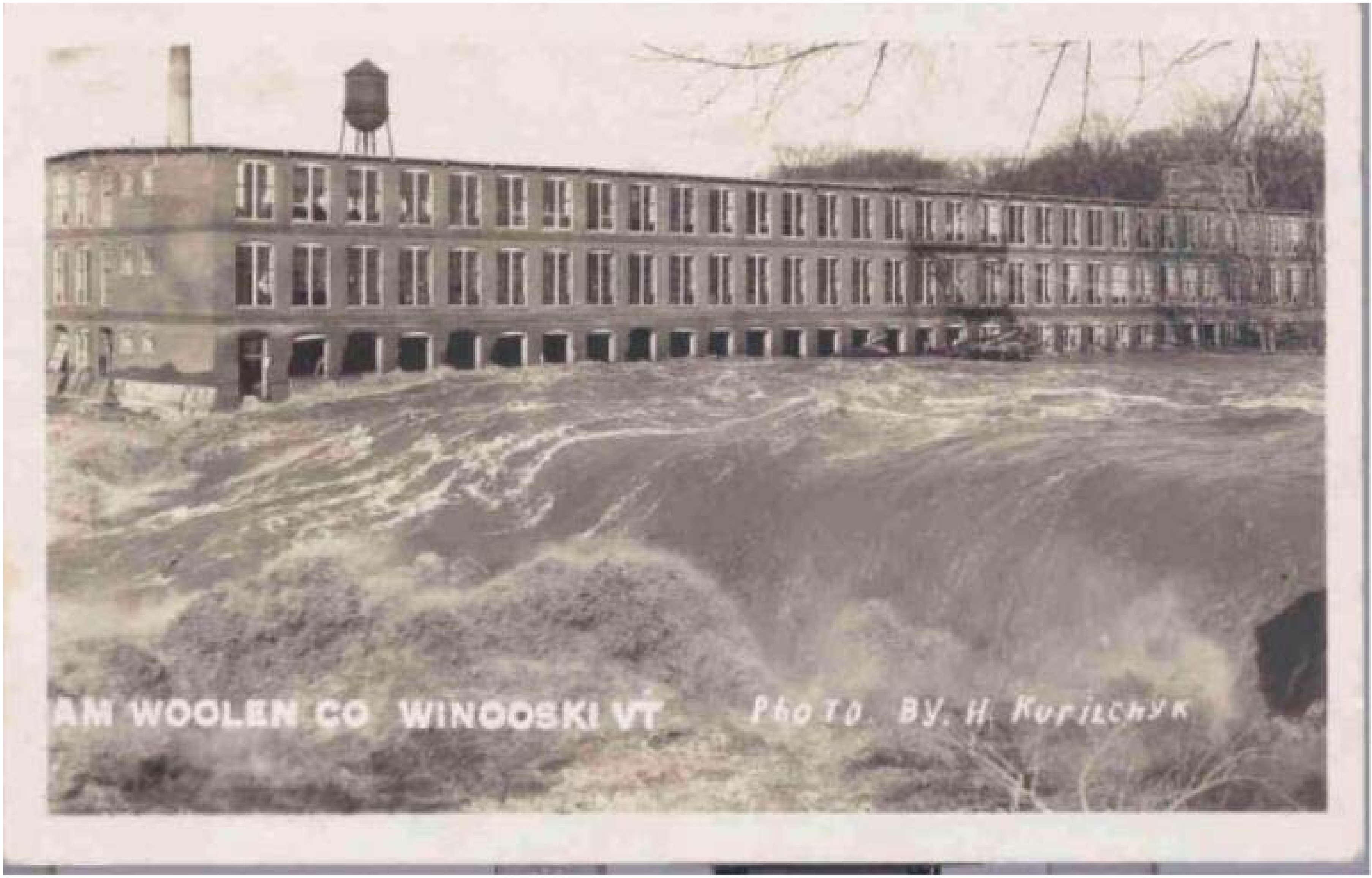
Lower Winooski River Fluvial Geomorphology Assessment – Figure 5

Changing Land Use in the Winooski River Watershed



Note: Photos taken at same location in Richmond, VT. Note increased forest cover on hillslopes. Courtesy of NRCS.

Winooski River Flooding Winooski Mills in November 1927



Courtesy of University of Vermont's Perkins Museum of Geology Landscape Change Program

Field Geology Services
Fluvial Geomorphology

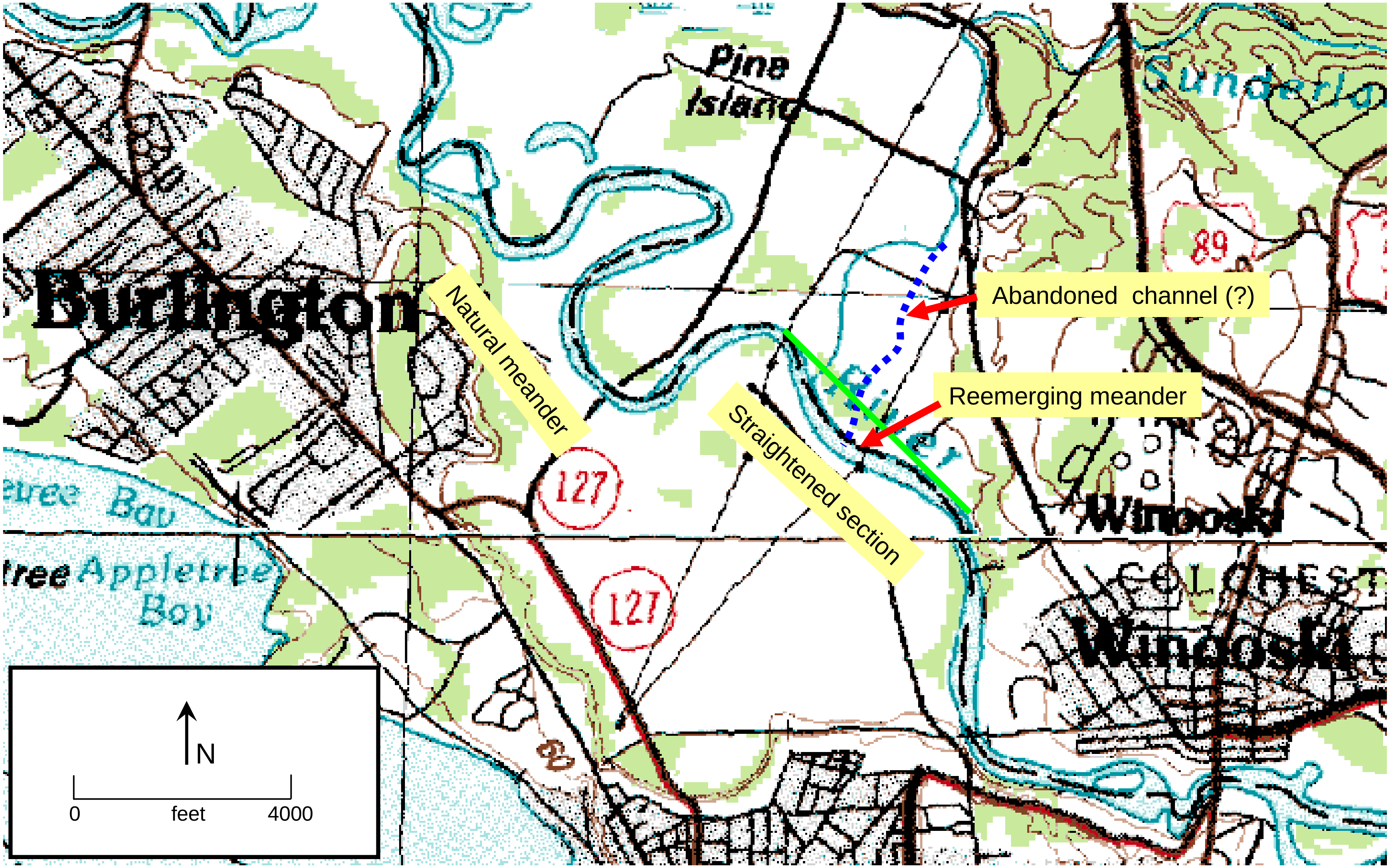
Winooski River with No Wood in Channel (Reach R01)

Note how wooded buffer on the banks of the river contrasts with the lack of wood in the channel

Field Geology Services
Fluvial Geomorphology

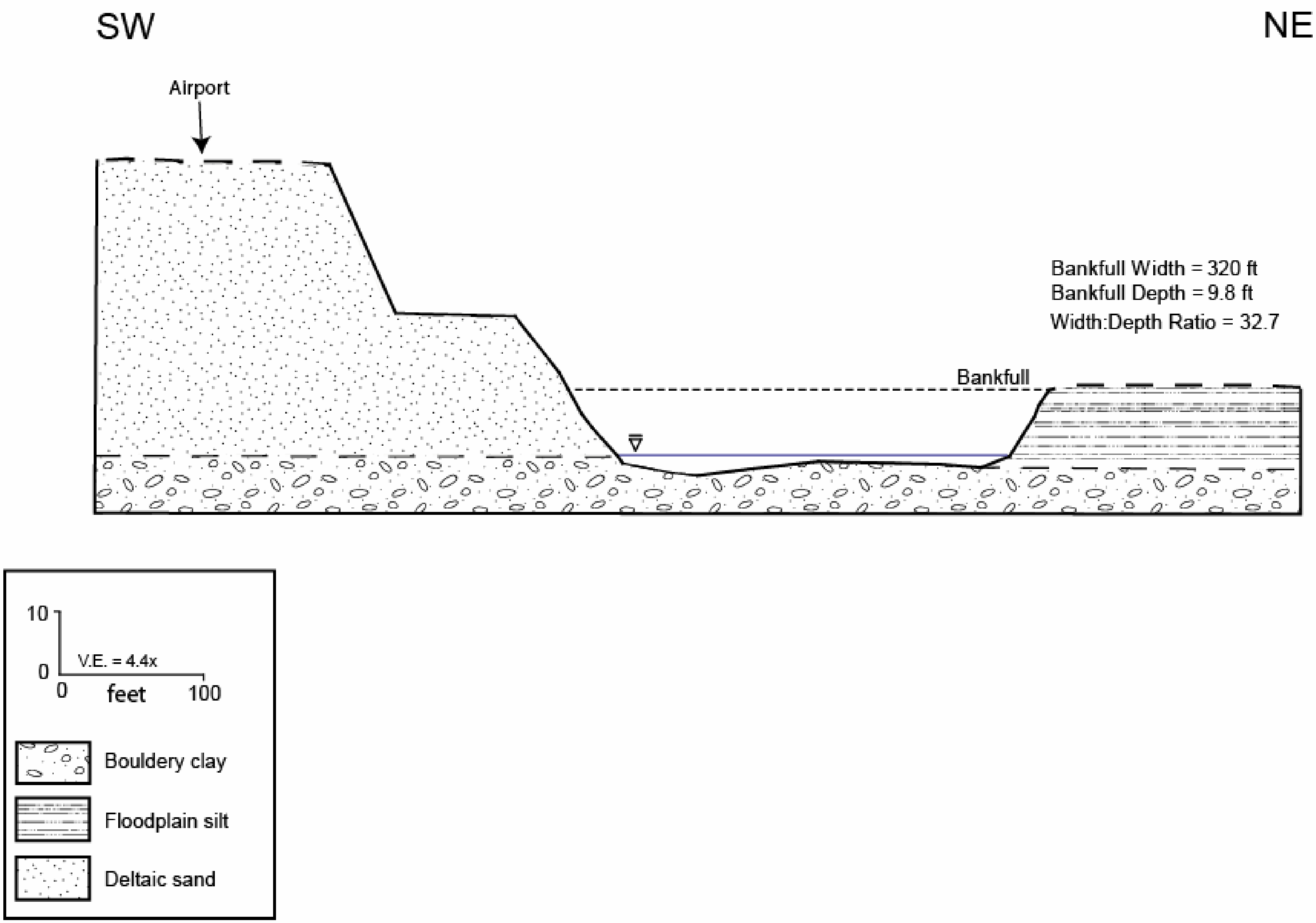
Lower Winooski River Fluvial Geomorphology Assessment – Figure 8

Straightened Section of the Winooski River (Reach R01)



Note: Position of the Winooski River in 1802 is shown in green

Winooski River Cross Section at Muddy Brook Park (Reach R05)



Note how bed of channel is composed of bouldery clay and southern bank is composed of deltaic sands. Deltaic sands are not shown on northern side of river but are present at the edge of the narrow floodplain.

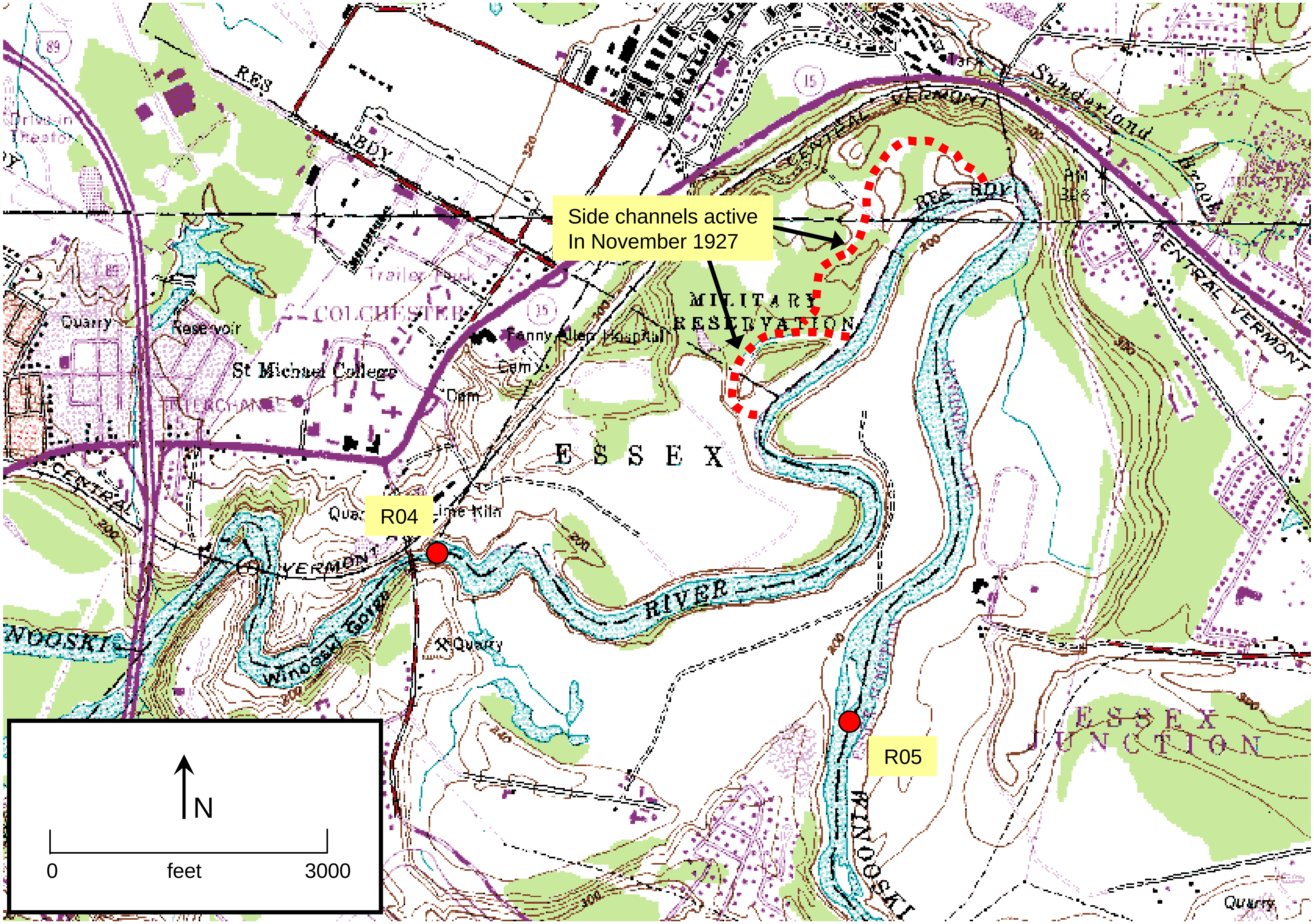
Field Geology Services

Deposition Upstream of Bedrock Constriction (Reach R05)

Field Geology Services

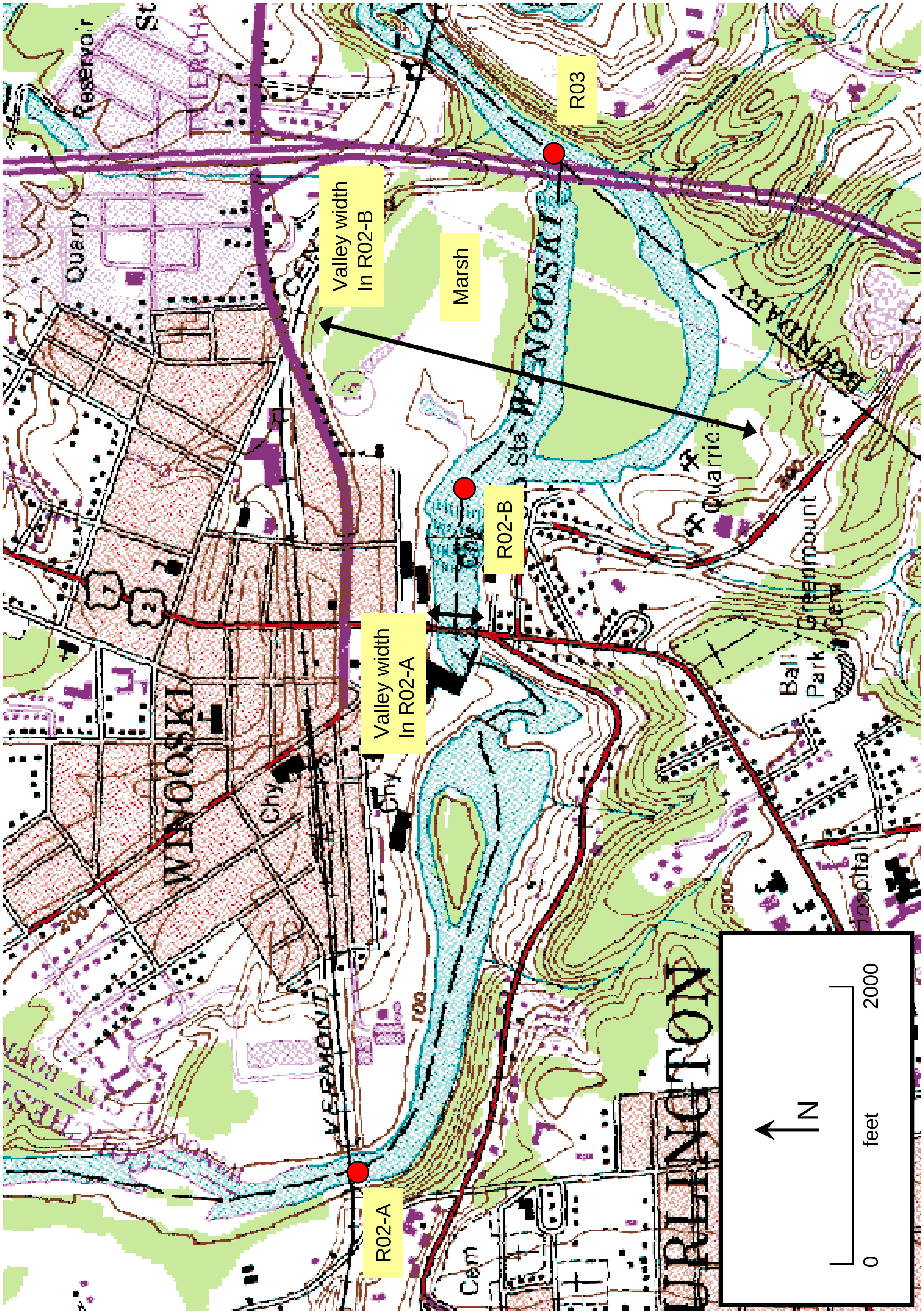
Lower Winooski River Fluvial Geomorphology Assessment – Figure 11

Convoluted Meander and Side Channels Upstream of Winooski Gorge (Reach R04)



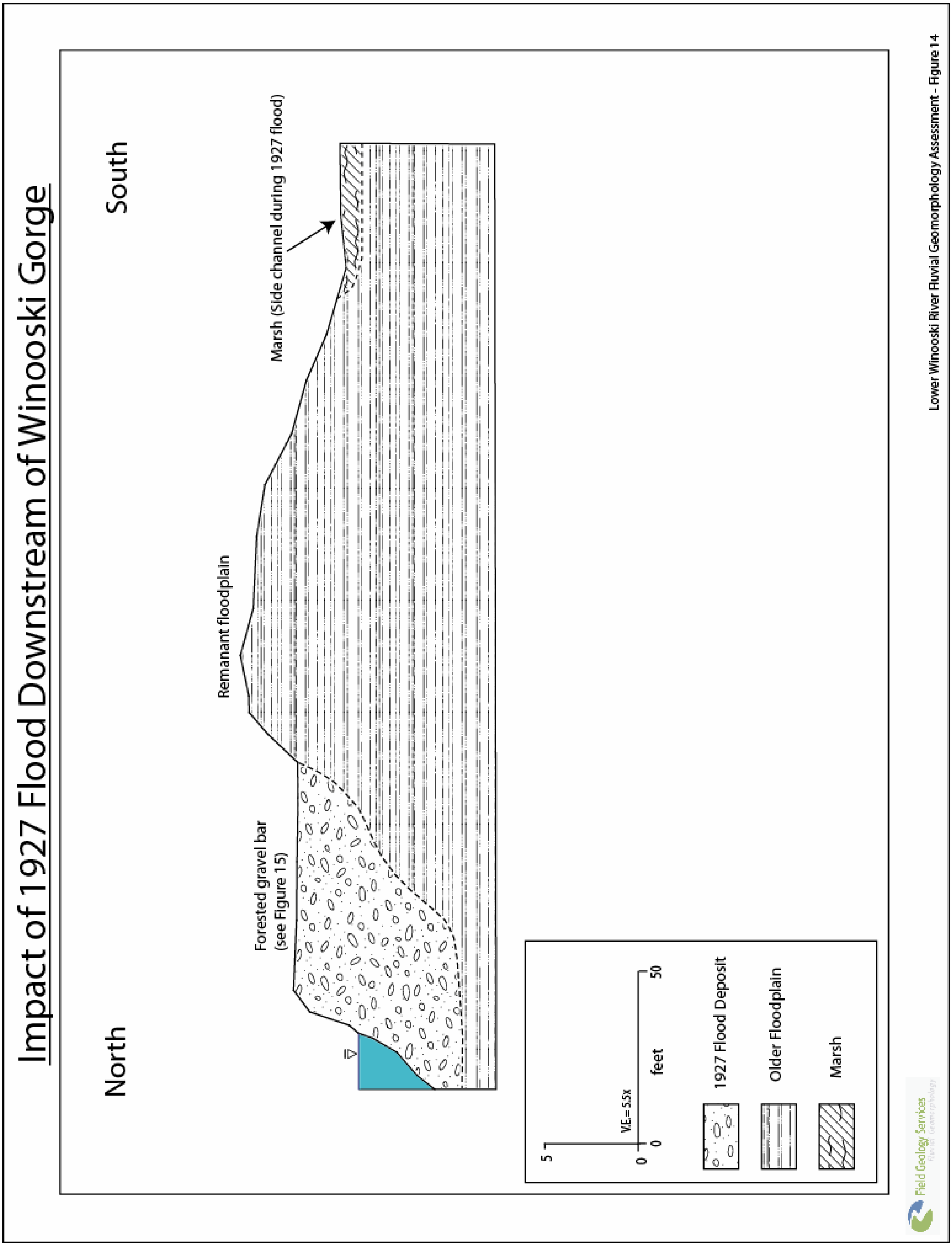
Field Geology Services

Variations in Floodplain Width in Reach R02



Note: Valley is 8 times wider in R02-B compared to R02-A

Lower Winooski River Fluvial Geomorphology Assessment – Figure 13

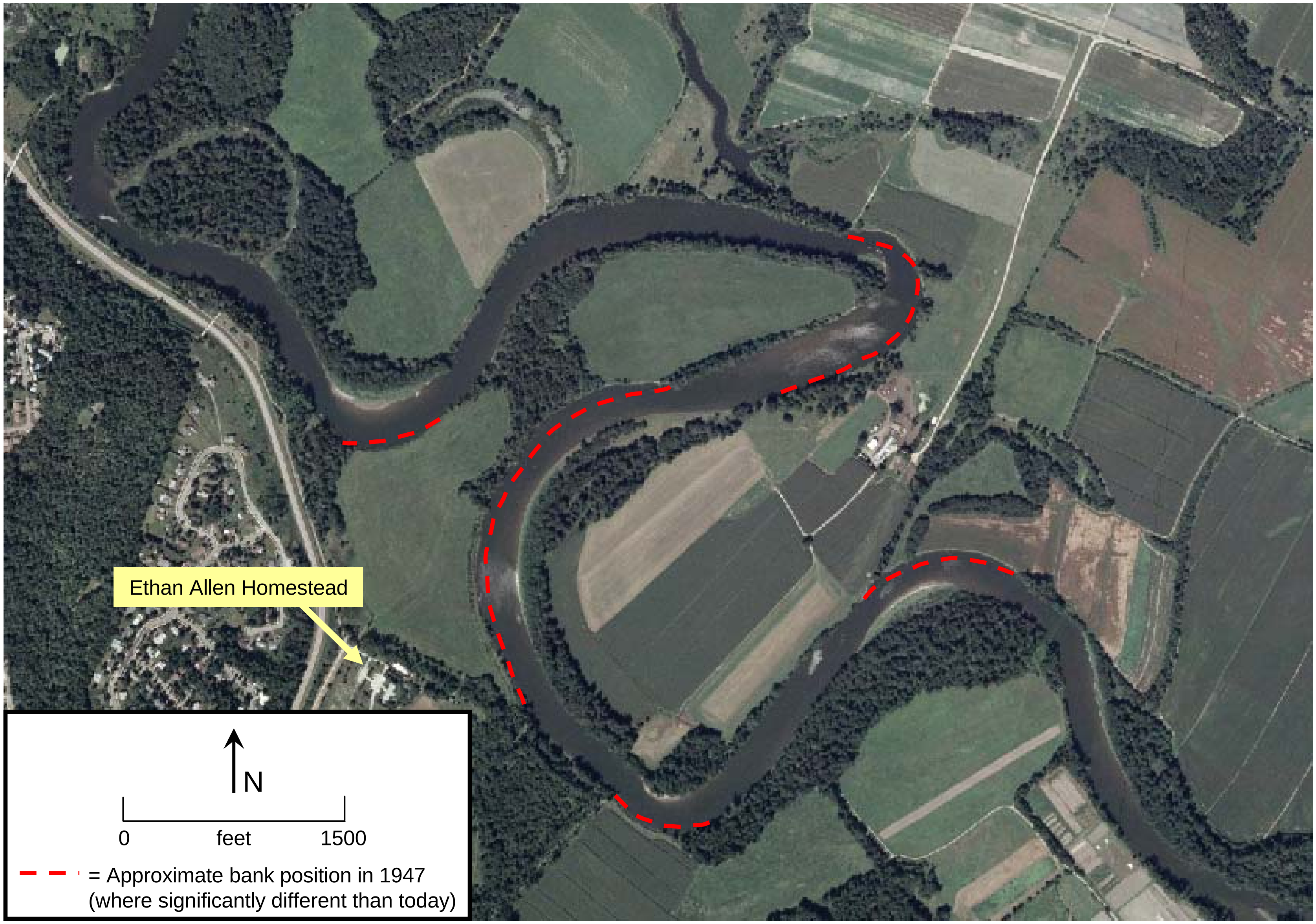


Impact of 1927 Flood Downstream of Winooski Gorge

Forest Growing on Gravel Bar Deposited During 1927 Flood

Field Geology Services
Fluvial Geomorphology

Areas of Bank Retreat Since 1947 Near Ethan Allen Homestead



Field Geology Services
Fluvial Geomorphology

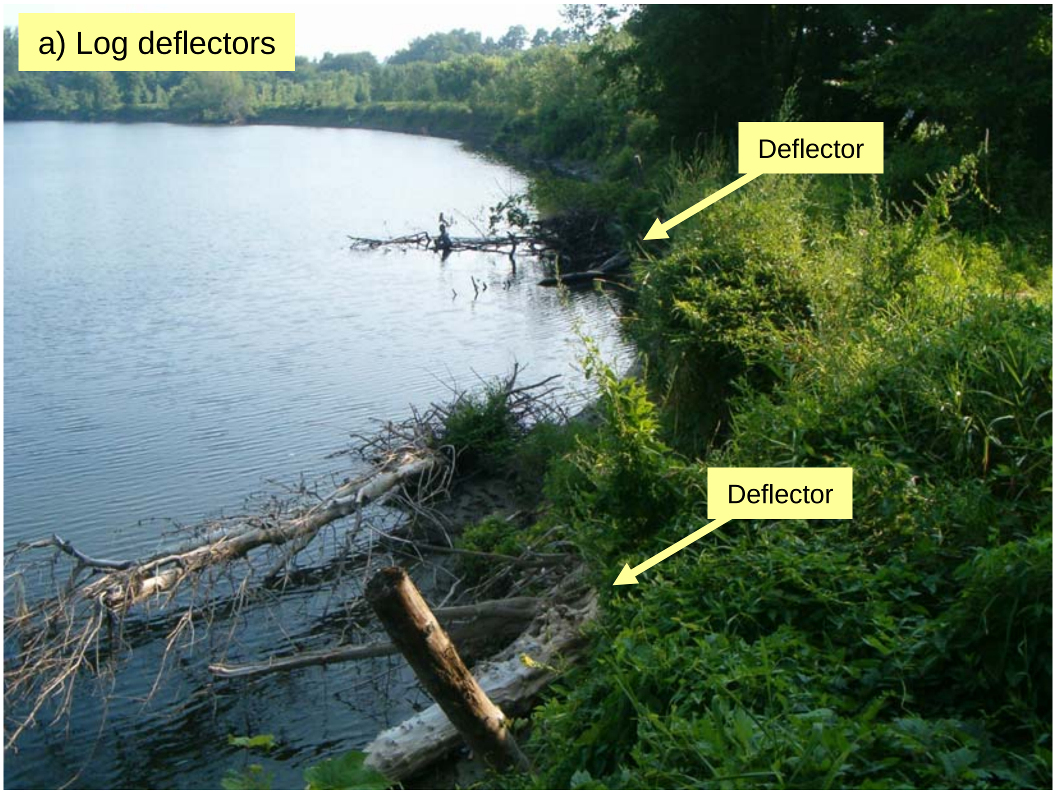
Lower Winooski River Fluvial Geomorphology Assessment – Figure 16

Rock Revement in Intervale (Reach R01)

Lower Winooski River Fluvial Geomorphology Assessment – Figure 17

Field Geology Services
Fluvial Geomorphology

Bank Stabilization Efforts at Ethan Allen Homestead



Note: Looking upstream. Several other log deflectors removed by erosion towards top of photo

Morphological Parameters of Reaches

Reach #	Cause of Reach Break	Phase 2 Assessment Completed?	Valley Confinement	Channel Gradient (%)	Sinuosity	Amount of Channel Migration
R01	Lake Champlain	Yes	Very broad	0.01	1.76	Low
R02	Expansion	Yes	Narrow	0.55	1.19	Not significant
R03	Expansion	No	Narrowly confined	0.17	1.00	Not significant
R04	Constriction	Yes	Very broad	0.13	2.47	Not significant
R05	Expansion	Yes	Semi-confined	0.63	1.02	Not significant
R06	Constriction	No	Semi-confined	0.04	1.04	Not significant

Lower Winooski River Fluvial Geomorphology Assessment - Table 1

Human Activities and Morphological Parameters Used for Determining an Impact Rating

Human Activities
Watershed land cover
Corridor land cover
Riparian buffer width
Flow regulation
Bridges and culverts
Bank armoring
Straightening
Dredging
Berms and roads
River corridor development

Morphological Parameters
Depositional features
Meander migration
Meander width ratio
Wavelength ratio
Bank erosion
Ice/debris jam potential

Lower Winooski River Fluvial Geomorphology Assessment - Table 2